Linking farm economics and hydrology: Model integration for watershed-level irrigation management applied to Chile

Dissertation

Submitted in fulfillment of the requirements for the degree ‘Doktor der Agrarwissenschaften’ (Dr.sc.agr. / Ph.D. in Agricultural sciences)

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Date of oral examination: September 25, 2009  

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Additional examiners, if any: Prof. Dr. rer. nat. Volker Wulfmeyer  
Vice-Dean and Head of the Committee: Prof. Dr. sc. agr. Dr. h.c, Werner Bessei
Declaration

I hereby declare

- that I have written this thesis without any help from others and without the use of documents and aides other than those cited

- that I have acknowledged all used sources and that I have cited them correctly according to established academic citation rules.


All graphs by the author unless otherwise noted. All GIS maps created within the project team and with the author.
If you have a reason for a move,
Don’t move – it is most probably wrong.

If you found two reasons to move,
Then immerse yourself in deeper analysis.

If you found three reasons at three levels,
The tactical, the strategical and the holistic,
Then move, and win.

(Oliver Lenz, teaching the *Essence of Go*)

---

**Acknowledgments**

First of all, I would like to thank my supervisor Thomas Berger, whose vision on integrated modelling initiated this project that is oriented toward local problems which were identified with local stakeholders. Also, his openness toward other disciplines is a rare virtue in science, and I hope that the lessons learned in this project will stimulate future research in stakeholder-oriented Natural Resource Management.

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Abstract

As largest user of fresh water, the agricultural sector must resolve conflict of objectives ranging from economic goals of farmers to societal and environmental targets. Research must deliver tools to manage these objectives simultaneously. Single disciplines have resolved numerous problems with disciplinary solutions. However, problems emerging from interactions and feedbacks between disciplines can only be assessed with interdisciplinary tools and managed by institutions that coordinate across departments. Such complex problems are becoming an epochal task for Natural Resource Management (NRM).

A number of modeling tools exist for irrigation management at watershed level that quantify biophysical processes and water quality. Simultaneously, agricultural economics developed production planning methods for allocating water resources optimally. However, integrated planning support tools are not available that take into account both domains and their interactions.

Within a larger research project, it was the objective of this Ph.D. project to develop and test methods that integrate two complex modelling softwares for irrigation management. The distributed runoff model WaSiM-ETH quantifies water flows and evapotranspiration. The dynamic land use model MP-MAS is a multi-agent system in which farmers use economic reasoning to derive cropping decisions under given environmental conditions. Furthermore, the MP-MAS software contains the bucket model EDIC, which parameterizes the distribution of water from rivers to individual farmers through the canal system. Finally, the MP-MAS software was extended with a crop yield model with complementary irrigation.

Model integration is understood as service provided within a research context. This context is defined by the study region, the project setting and by the strategic decisions within the research project - such as the choice of partner institutions and disciplines. Within the Maule River watershed in Chile (Linares Province, Region VII), the project ‘Integrating Governance and Modeling’ assessed the use of water in agriculture. Empirical research questions as well as modeling software were also part of this research context.

Integration requires the conceptual, the technical and the procedural level. Conceptual integration describes processes and interactions between farmers, the canal system as distribution infrastructure and the natural system. It also describes how farmers plan and produce within this environment. Here, scale-dependent processes like irrigation efficiency or access to water by individuals were scrutinized. Technical integration is the implementation of the conceptual system into source code, e.g. by adapting legacy software, and by creating a software layer for hierarchical coupling of all software components. Procedural integration is the calibration, analysis, error eradication and validation of these models within the research context.

Calibration and analysis of integrated model components is a step-by-step procedure. For all relevant processes and interactions, empirical data was first compiled and cross-evaluated. Then, standalone model components were calibrated so that interactions were parameterized as boundary conditions that are consistent across all disciplines. Empirical data pinpointed conceptual inconsistencies in the description of interactions, and standalone models were improved together with project partners. Ultimately, model components were coupled in such ways that interactions can be analyzed dynamically at minimum model- and software complexity.

The calibration process along transdisciplinary cause-effect-chains resulted in the improvement of disciplinary models and model results. For example, the relevance of access to water beyond
legalized water rights became apparent when empirical data and models were combined. Also, the calibration of the EDIC model required consistent use of data from all four disciplines and improved the calibration of the MP-MAS model. For the WaSIIM-ETH model, an irrigation module was developed that is consistent across scales and reflects the needs of extension workers. Finally, model integration and coupling is discussed as research process. The process of calibrating a model with four components is not only a technical challenge for modellers and data management, but also a procedural challenge with regards to cooperation beyond disciplinary institutions and cultures. The structure of the integration process should be robust against errors and equally facilitate knowledge transfer between disciplines, iterative calibration across disciplines. Finally, success factors are suggested to reduce transaction cost during the integration process.

**Zusammenfassung**


Technische Integration beschreibt dann die Implementierung des konzeptionellen Systems in Computermodelle bzw. in die existierende Modellsoftware, sowie die Programmierung einer zusätzlichen Softwareebene für die hierarchische Kopplung der Modellkomponenten.


Additional Material

Additional material, documentation and technical reports can be downloaded from the following website:


Specifically, the following electronic appendix gives detailed information on the EDIC model and the WASIM-ETH irrigation module, as well as a technical description of model coupling.


**Electronic Chapters**

<p>| A | Review Of Literature On Irrigation Modelling | 1 |
| B | EDIC Sector Routing Model For Irrigation | 13 |
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<tr>
<td>AdC</td>
<td>Asociación de Canalistas (Canal Associations)</td>
</tr>
<tr>
<td>BEFM</td>
<td>Bio-Economic Farm Models</td>
</tr>
<tr>
<td>C &amp; V</td>
<td>Calibration and Validation</td>
</tr>
<tr>
<td>CdA</td>
<td>Comunidades de Agua (Water Communities)</td>
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<tr>
<td>CLD</td>
<td>Causal Loop Diagram</td>
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<tr>
<td>CGIAR</td>
<td>Consultative Group on International Agricultural Research</td>
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<tr>
<td>CIRH</td>
<td>Centro de Información de Recursos Hídricos</td>
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<tr>
<td>CNR</td>
<td>Comission Nacional de Riego (National Irrigation Commission)</td>
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<tr>
<td>CoV</td>
<td>coefficient of variation</td>
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<tr>
<td>CWB</td>
<td>Crop Water Demand</td>
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<td>DGA</td>
<td>Direccion General de Aguas</td>
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<td>DGR</td>
<td>Direccion General de Riego</td>
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<tr>
<td>DMIP</td>
<td>Distributed Model Intercomparison Project</td>
</tr>
<tr>
<td>DOH</td>
<td>Direccion de Obra Hidraulicas</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agricultural Organization</td>
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<tr>
<td>FdCC</td>
<td>Federación de canalistas de Chile (Federation of Canal Users)</td>
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<tr>
<td>FdS</td>
<td>Fondo de Solidaridad</td>
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<tr>
<td>GUI</td>
<td>Guided User Interface</td>
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<td>HRB</td>
<td>Hectares de Riego Basico, Equivalent unit of irrigated land</td>
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<tr>
<td>IA-NRM</td>
<td>Integrated assessment models for natural resource management</td>
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<td>IAM</td>
<td>Integrated Assessment Models</td>
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<td>IEMSS</td>
<td>International Congress on Environmental Modelling and Software</td>
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<tr>
<td>IFPRI</td>
<td>International Food Policy Research Institute</td>
</tr>
<tr>
<td>IIIMS</td>
<td>Integrated Irrigation Modelling System</td>
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<td>IMF</td>
<td>Integrated Modelling Framework</td>
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<tr>
<td>IMS</td>
<td>Integrating Modelling System</td>
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<tr>
<td>INDAP</td>
<td>Instituto de Desarollo Agropecuario</td>
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<tr>
<td>INIA</td>
<td>Instituto Nacional de Investigacion Agricola</td>
</tr>
<tr>
<td>IWMI</td>
<td>International Water Management Institute</td>
</tr>
<tr>
<td>JdV</td>
<td>Juntas de Vigilancia (Watch Committees)</td>
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<tr>
<td>MCM</td>
<td>multi-component models</td>
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<tr>
<td>MIC</td>
<td>Mesa Inter-institutional de Coordination (Roundtable for Inter-institutional Coordination)</td>
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<td>MILP</td>
<td>mixed integer linear programming</td>
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<td>MP</td>
<td>mathematical programming</td>
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<td>The Mathematical Programming Multi-agent System</td>
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<td>NRM</td>
<td>Natural Resource Management</td>
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<td>NRS</td>
<td>Natural Resource Systems</td>
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<td>NRW</td>
<td>Australian Department of Natural Resources and Water</td>
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<tr>
<td>OFC</td>
<td>objective function coefficients</td>
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<tr>
<td>OoM</td>
<td>orders of magnitude</td>
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<td>OSS</td>
<td>Open Source Software</td>
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<td>PTFs</td>
<td>pedotransfer functions</td>
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<td>SAG</td>
<td>Servicio Agricola Ganadero</td>
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<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
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<tr>
<td>WAStM-ETH</td>
<td>WAtter BAalance SImulation Model</td>
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<td>WUA</td>
<td>Water User Association</td>
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Chapter 1

Motivation

Natural Resource Management (NRM) revolves around the description, assessment, management and valuation of natural resource systems. These systems are characterized by human-environment interactions whose analysis is complex, because the conceptualization of such systems requires knowledge that academia today creates and propagates within multiple and separate scientific disciplines. Management of natural resources requires actions from multiple and often dispersed actors (IAASTD 2008b, Synthesis report, NRM). However, the maintenance of natural resource systems is fundamental for the structure and function of agricultural systems and for social and environmental sustainability, in support of life on earth. Historically the path of global agricultural development has been narrowly focused on increased productivity rather than on a more holistic integration of NRM with food and nutritional security. A holistic, or systems-oriented approach, is preferable because it can address the difficult issues associated with the complexity of food and other production systems in different ecologies, locations and cultures, (IAASTD, Executive Summary 2008, p. 18)

At the regional and local level, the structural interaction pattern of human-environmental vary widely (Kasperson, Kasperson and Turner II 1995): Rarely can a single dominant human driving force be discerned that, by itself, explains the dynamics of natural resource systems and their degradation, or that captures the complexity of this change. Kasperson et. al. define the ‘Regional Dynamics of Change’ as ‘the interplay among the trends of environmental change, vulnerabilities and fragility, human driving forces, and societal responses’. Such dynamics can only be understood in the broad context of culture, institutions, economy, and ecology.

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1The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) is a unique international effort that evaluated the relevance, quality and effectiveness of agricultural knowledge, science, and technology (AKST), and the effectiveness of public and private sector policies, as well as institutional arrangements in relation to AKST. It is ‘unique in the history of agricultural science assessments, in that it assesses both formal science and technology and local and traditional knowledge, […] and recognizes that multiple perspectives exist on the role and nature of AKST’. Fifty-eight governments (including India, China, UK, France, Ghana, Brazil, Saudi Arabia) agreed that this report is ‘a constructive initiative and important contribution that all governments need to take forward to ensure that agricultural knowledge, science and technology fulfills its potential to meet the development and sustainability goals of the reduction of hunger and poverty, the improvement of rural livelihoods and human health, and facilitating equitable, socially, environmentally and economically sustainable development’ (IAASTD, Statement by Governments).

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the perspective of academia, understanding and assessing these regional dynamics of change requires integration across multiple theories and embedding these into the local context (ibid.).

In many regions and for an increasing number of issues, our civilization appears to lack the management capabilities necessary to sustain our natural resource base. NRM based on a partial understanding of systems, has produced successes in dealing with some global problems, such as ozone layer depletion, while we continue to struggle with other problems, such as deforestation, the loss of (agro)biodiversity, groundwater depletion and water quality loss, urban sprawl and soil degradation. Resource management is becoming the defining challenge of the 21st century, as reflected in, for example, the Challenge Program on Water & Food ². However, Natural Resource Systems are complex to describe because this description requires knowledge from multiple disciplines. Assessment, learning and mitigation of symptoms were identified as challenges of NRM, which science has been dealing with (IAASTD 2008b). The integration across disciplines within academia for holistic approaches, and the coordination of research with other institutions (ranging from government bodies to civil society), was identified as the core structural challenges for Agricultural research (IAASTD 2008b).

Water scarcity and food. The FAO (2007) defines water scarcity as ‘imbalances between availability and demand, the degradation of groundwater and surface water quality, intersectoral competition, and interregional and international conflicts’ (p.3). The agriculture sector is the largest consumer of water, especially after the large-scale water development projects of the 1970s were implemented. FAO recognized that, as a result of the Green Revolution, the ‘growing scarcity and competition for water stand as major threats to future advances in poverty alleviation, especially in rural areas. […] The rural poor are coming to see entitlement and access to water for food production, livestock and domestic purposes as more critical than access to primary health care and education (FAO 2007, p.6)’. Water scarcity must be addressed at the regional scale, within a river basin or sub-basin. With limited supply, water management becomes a problem of prioritizing among competing interests, uses, development paths and technical measures (ibid.).

Economics is the scientific discipline that analyses the allocation of scarce goods. Using a standard definition, a good is called relatively scarce if its use carries non-vanishing but finite opportunity costs³, and market solutions are prominent to manage water scarcity (Rosegrant andBinswanger 1994, Johansson et al. 2002, Rosegrant et al. 2003). However, the negotiation power of the advocates for the competing water uses are different, ranging from monolithic large enterprises with specialized and well-paid layers and lobbyists, over well-organized farmer groups which also have access to the political sphere, to spatially dispersed and unorganized small farmers, and ultimately to the environment with its intrinsic values and ecosystem services that are not reflected by markets. This unequal negotiation powers will result in transaction costs for the individual water user, but also for non-optimal outcomes at national level (Binswanger andDeininger 1997).

From the policy perspective, the challenges of water management are to find institutional and legal set-ups that can coordinate among these competing uses in an efficient and equitable manner. Management of water scarcity requires orchestration of ‘knowledge, expertise and investment at political, institutional and technical levels’ (FAO 2007, p. 7).

²http://www.waterandfood.org/themes.html
³They call it absolutely scarce if there is no substitute for it.
To scientifically assess benefits from water usage in irrigated agriculture, especially at the level of watersheds, the combination of a micro-level economic perspective with a meso-level hydrological perspective is needed (Molden et al. 2003). Such an assessment would include the disciplinary domains of hydrology, agronomy, economics and those sciences dealing with the institutional framework. (McKinney et al. 1999) proposes to combine economic models with hydrological models to analyze long-term policy goals and short-term incentives for natural resource users in its spatial and temporal complexity.

In the international debate on Integrated Water Resource Management, the Chilean institutional setup is often recognized as a role model for development (Rosegrant and Binswanger 1994, Hearne and Easter 1995). International attention has been focused on the fact that water rights can be traded separately from land (Donoso 2003). The Chilean water management model combines this market-oriented approach to management with decentralized management by a hierarchy of water user organizations with national subsidy policies targeted at both infrastructure projects and vulnerable groups.

On the other hand, Bauer (1997) stresses that the Chilean experience is specific to its historical and cultural context. Empirical evidence for the distributional and rural development impact of the water rights system is mixed (compare Brehm and Quiroz 1995, Hadjigeorgalis 1999 and Bauer 2004). A round table of experts that evaluated the Chilean water code (Donoso 2003) highlighted the importance of the interaction between the water trading system and many contextual factors. These experts agree that the Chilean water trading system has been successful in some ways (especially for mining companies and drinking water acquisition), but more attention must be paid to the system’s historical, cultural, institutional and legal contexts. Furthermore, markets did not resolve the inefficiency of water use in all sectors, nor did they resolve environmental and ecological problems (ibid, p. 61).

To analyze cause-effect mechanisms in the Chilean context, an integrated but highly resolved model tool was proposed by (Berger and Ringler 2002), to push forward the theoretical understanding and derive insights that are relevant for policy planning.
Chapter 2

Objectives And Research Question

Contents

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2.1 Problem Statement

To face the challenge of water scarcity that was outlined in the Motivation, inter- and transdisciplinary assessment and modelling is accepted as way forward within science. Projects use modelling as method to integrate information on processes that multiple disciplines have assessed. Such research is increasingly performed in large research settings that involve multiple institutes, disciplines and researchers. Within such projects, model integration is only one of many project components. Methods for model integration must be chosen accordingly.

Recent attempts to integrate socioeconomic and hydrological models for irrigation management exist. However, these attempts have neither brought forth a generic model tool that is practically applied by watershed managers, nor was systematic procedural knowledge published on how to handle complex irrigation modelling. Especially modelling tools that capture micro-level processes (farm-level economics, access to water) and connect to phenomena and politics at meso- and macro-level (watershed institutions, national policies) are lacking (Berger and Ringler 2002). The development of an integrated planning support system thus became one objective of the project ’Integrating Governance and Modelling’ (Berger, Birner, Díaz, McCarthy and Wittmer 2007a).

Existing methods are revised and shortcomings identified for the development and application of such integrated modeling system (Chapter 3.2). Furthermore, to evaluate the usefulness and applicability of such methods, a set of criteria is needed.
2.2 Basic Concepts and Definitions: Systems, Models and Integrated Modelling

Before defining research objectives and a research question, a few definitions on terminology are required.

A ‘system’ is defined as a set of entities and interactions that together are regarded as a whole. These parts (or sub-systems, if they themselves are systems) are linked to each other in relations/interactions and thus form a structure (latin: *construere*, build). The description of a system is characterized by its degree of abstraction (material, conceptual, theoretic), by its complexity, determinacy (deterministic or probabilistic), self-containment (open or closed), and its finality (its degree of ‘purposiveness’) and dynamic stability (its persistence or change in structure) (Müller and Müller 2003).

The ‘holon’. In a hierarchical system with subsystems, Koestler (1967) introduced the concept of the holon, as an entity that is autonomous in some sense, yet clearly belongs to a larger system that defines and influences its properties. Within an organism, a holon may be an organ such as the heart or the kidney, which again consists of many different cells, but which also plays a confined role within the larger context. In ecosystems, a niche that is defined both spatially and functionally, such as a riverbed, a swamp or a coral reef may be thought of as a holon. In economics, a firm may be seen as a holon, but so may the full production chain. The delineation of a system into holons is an epistemological challenge, because it involves subjective judgment and is ‘about choosing which story is being told about a set of events, because there are always multiple possible meanings to any situation’ (Bland and Bell 2007). The modeller’s misjudgment on the relevance of a context dramatically alters his description and thus his understanding of the system.

‘Agents’. In the context of agent-based modelling software, ‘agents’ are used as units of autonomous decision making, as an enclosed holon that perceives its environment, interprets these perceptions (cognition) and chooses a strategy of action in response to these perceptions. This strategy often describes goal-oriented (purposeful, teleologic) behavior (Wooldridge 2001). While the term is very general, in multi-agent systems for land use modelling, agents are usually resource user and/or resource managers, and interaction usually occurs between the agent and a landscape, and directly between agents (Parker, Manson, Janssen, Hoffman, and Deadman 2003). Spatial changes to the landscape that are induced by agents also cause indirect agent-agent interactions. In our model, unless otherwise specified, the term ‘agent’ is used to describe software representatives of farmers. Other formal agents include Water User Organizations (WUO), as well as land and water markets.

‘Complexity’ (latin: *complecere*, to embrace) refers to the situation in which the numerous parts are linked via interaction rules and that these rules create behavior that is complicated to derive from the basic rules. This complication may either be caused by the complexity of the behavior, or by the difficulty to find an adequate description of the system itself and its interactions. Thus, complexity embraces systems with very simple rules that show complex behavior, as preferably studied in system dynamics, as well as systems with ‘complex’ rules that may even show simple behavior (see Section 3.1.1, page 13) (Müller and Müller 2003).

A ‘Model’ can be regarded metaphorically as a map of a real system. The modelling process itself requires analysis of whether this representation (e.g. a collection of theories, assumptions and hypothesis) actually captures those processes that characterize the system of interest. Then,
a formal mathematical model \( P \) maps a set of input variables \( I \) into output variables \( O \) (Müller and Müller 2003, p. 46):

\[
I \xrightarrow{P} O
\]

After this conceptualization, system analysis evaluates this map \( P \). A ‘computer model’ or ‘modeling software’ is the implementation of a formal model into computer code. In our context, only quantitative models that can be represented in computer code are considered in this study.

A ‘complex domain computer model’ is software that incorporates a collection of process descriptions, usually from closely related disciplines, e.g. a model that describes surface hydrology, hydro-geology, ground water hydrology and plant physiology that is related to water uptake. In economics, a complex domain computer model could describe consumption, production and investment decisions as represented by the income strategy of optimizing agents. However, one should note that the division of a system into ‘disciplines’ is not a property of the system itself, but of those who analyze it: disciplinary systems do not exist, while disciplinary analysis (or models) of systems has proved a successful method in the scientific domain (Mittelstraß 2003).

‘Integrated modelling’ is the process of finding an adequate representation of a system across disciplinary boundaries and analyzing and communicating its results. Because disciplinary domains are socially constructed, the process of integrated modelling requires methods that link scientific disciplines. Such methods range from theoretical work on conceptualization to the technical work of linking domain computer models and the communication work necessary for building shared understanding amongst researchers, and even to pedagogical and psychological work to foster researchers’ appreciation for each other’s disciplines.

‘Computer Model-based Integrated Modelling’ can be broken down into the following steps: planning of a research process and a research objective (choice of research structure and definition of study system), the acquisition of data and knowledge about the study system, the conceptualization of the system studied and the formalization of this conceptual model into a mathematical description (conceptualization), its implementation into software or the selection of one or more existing computer models and their linkage, model parameterization/calibration, systematic analysis of the computer model and interpretation (model integration), and communication of lessons learned (outreach). Here, the conceptualization of a system and the planning of a research process are intrinsically linked, because the understanding of a system determines the choice of project partners.

‘Model integration’ is delineated from this full integrated modelling process. As one task within the integrated modelling process, model integration is not equivalent with the full project because the project framework (such as project structure, project partners, project resources and the project time line) was already determined exogenously if model integration is not done by the same person that outlines the project – even if some flexibility remains. Model integration is of formal as well as of technical nature and its tasks range from specifying cause-effect-loops within the conceptual framework to software implementation and testing. Model integration may include the selection of adequate theories within the conceptual framework. An adequate translation of such conceptual model into a formal model is the next step, the implementation of this formal model into a computer model (or the selection and/or adjustment of existing code). The calibration and interpretation of the resulting computer model is the work step that creates results with empirical implications. For model integration, the system entities that were identified as relevant during the conceptual and planning phase, the resources and the scientific disciplines involved – in short, the wider project setting – must be taken as given. Especially for interdisciplinary projects, model software selection and the calibration of the full model or model
components may or may not be performed by the same person who implements. In the wider sense, even integrated analysis of model input- and output data is part of or a form of model integration.

‘Hierarchical model coupling’ (often simply called ‘model coupling’), as elaborated in Chapter 3.2.2, is one method to perform Model Integration. Data-level integrated analysis of model inputs and outputs, iterated exchange of data between models, the use of a software platform with specialized tools to link functional modules (an ‘Integrated modelling Framework’) or the use of framework-independent model libraries are other approaches to technically implement Model Integration (see Section 3.2.2 for elaboration).

For reasons of brevity, the rest of this study will refer to a ‘computer model’ simply as ‘model’, and to a ‘complex, domain computer model’ as a ‘complex model’. Furthermore, ‘integrated modelling’ refers to computer model-based integrated modelling and thus to the full project cycle, while ‘model integration’ is the process of linking two computer models for that aim. ‘Model coupling’ refers to the dynamic exchange of data between models at runtime.

‘Model uncertainty’ is the degree of error that is embedded within the model. Walker et al. (2003) define model uncertainty as ‘any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system’ and along three dimensions: its location within a model, its level (from determinacy to complete ignorance) and its nature (inherent stochasticity to determinism). Their study discusses various sources of uncertainty, for example within measured parameters and the data that is available and missing, within the process description of the conceptual model, and the uncertainty associated to the technical components: the source code and adequate model use. Uncertainty within the scientific assessment process and the communication and reception of model results remains external to their concept of uncertainty.

‘Model selection’, as term, is used with two meanings: model software selection and conceptual model selection. The former is the decision which existing or new software source code is used to compute a model, the latter is the process of determining which processes are included in the system representation.

Figure 2.1 — Equifinal model outcomes at larger scales \( \hat{O}(X) \), for equal starting data and boundary conditions are caused by equifinal model formulations \( f \) and \( f' \), or by aggregation routines \( \hat{O} \).

‘Equifinality’ means that two or more models of the same system (or parameterizations of the
same model) reproduce independent data that was not used for calibration equally well (Beven 2001). A transition from an initial state of the system at time 0, \( \vec{X}_0 \), to a later state \( \vec{X}_n \) may be described with various model realizations \( f, f', f'' \), and validation tests for the existing data cannot determine which model realization should be preferred (Fig. 2.1). Such uncertainties are structural and can make ‘optimal’ calibration strategies invalid methods, but require Bayesian approaches that maintain a multiplicity of representations (Beven and Binley 1992).

Furthermore, if direct model outputs \( \vec{X}_n \) are computed at a micro scale and are aggregated with some operator \( \hat{O}(\ldots) \) (mean, sum, median over space or time), then different outputs \( \vec{X}_n \) and \( \vec{X}''_n \) can be projected into the same value \( \hat{O}(\vec{X}_n) = \hat{O}(\vec{X}''_n) \). For a validation data set with only two points in time (\( t_0 \) and \( t_n \)), validation cannot reveal significant deviations between model horizons \( X_m, t_0 < t_m < t_n \) and reality, so temporal or spatial inter- and extrapolations are often not valid. This phenomenon is less significant if time series data exists. This is often the case in natural sciences but rarely for detailed socioeconomic systems.

In the case study that is presented here, within the farm economics assessment, two censi were used at two time horizons that resolve economic data at farm level and which is referenced spatially at district level. Even though data at two time horizons is not satisfying for the calibration of a dynamic model, it is far more than most studies have access to and must be considered an excellent data base. Also, hydrological measurements exist as daily time series, but only few flow stations exist and limit our understanding of smaller spatial scales. However, the lack of temporal resolution for socioeconomic processes, and the lack of spatial resolution for biophysical processes is typical for integrated assessment, and methods are needed to deal with it, taking into account that possibilities for equifinal model realizations are the norm rather than an exception. Within hydrology, (Beven 2001) developed the ‘generalised uncertainty likelihood estimation’ (GLUE), a Bayesian approach that maintains multiple model realizations (called ‘behavioral parameterizations’) to deal with equifinality. For multi-agent systems, Brenner and Werker (2006) developed a method for ‘heterodox’ simulation. Both require the use multiple model realizations and cross-model analysis (ensemble modelling) and are procedurally and technically demanding.

Equifinality can produce various types of errors. In general, if correct results are produced for the wrong reason, then any conclusion that builds on variations of the false logical components will cause prediction error. Furthermore, if the equifinal function \( f' \) correctly parameterizes an internal process for the default condition, than changes in this internal process may lead to prediction errors. To identify equifinality errors, more data must be incorporated into the model – either as additional calibration/validation of internal processes, or as logical tests used to reject possible solutions.

‘Model utility’. Lindenschmidt et al. (2005) analyzed the trade-off between model detail and model generality. For a modular and multi-scale hydrological application, the model utility (its ability to predict outcomes) is a compromise between accuracy in system description (the quantity of the processes modeled) and the quality and quantity of data needed to parameterize these processes. In theory, accurate specification would allow perfect description of the system, if necessary data were available in ‘sufficient’ resolution. Also, with an increase in detail in one process domain, the processes of other domains must be equally refined. In practice, every detail introduced into a model adds to the model’s sensitivity to data gaps (see Fig. 2.2). With increasing ‘model complexity’ on the x-axis, Lindenschmidt showed that methodological uncertainty decreases because processes are captured more appropriately and
CHAPTER 2. OBJECTIVES AND RESEARCH QUESTION

Figure 2.2 — Model utility is a trade-off between accuracy of presentation and data quality/availability (modified from Lindenschmidt 2005)

more consistently with scientific knowledge. On the other hand, parameter uncertainty as well as the importance of input data errors increases with increasing complexity of the model. For such detailed models, especially if the aggregation and disaggregation of variables across scales is frequent, then model calibration and the corroboration of model results requires enormous amounts of data and resources (Lindenschmidt et al. 2005). The concept of ‘model utility’ is used to measure how useful a model is for deriving policy implications, as a compromise between overly aggregated models that carry structural uncertainty and overly detailed models that cannot be parameterized.

2.3 Objectives Of Ph.D. Thesis And Research Hypothesis

This Ph.D. thesis attempts to contribute to the methodological challenge of model integration within the international research project ‘Integrating Governance and Modelling’. The global relevance of this methodological objective for resource management was recognized by the funding agency, the CGIAR Challenge Program on Water & Food. The objective of this Ph.D. is to develop, implement and test a method for the integration of two complex models, as a contribution to and within this project. The purpose of this method is to support a research project in meeting its objectives. Therefore, the falsifiable (and thus negatively formulated) null hypothesis of this dissertation is

The integration of two existing complex models MP-MAS/EDIC and WASIM-ETH, using the method defined in Section 2.2 and specified in Section 4.4, is not feasible conceptually and technically. The calibration and analysis of such a modelling system cannot improve the usefulness of these complex models for empirical irrigation management.

The research hypothesis is driven by a methodological research question on how to integrate legacy code models. As such, the Ph.D. project is not focused on an empirical question in the study region, but instead develops and applies the proposed method of model integration.
2.4. RESEARCH QUESTIONS

Furthermore, the selection of models and model source code was determined within the project and precedes this hypothesis. It is thus treated as a boundary condition to this integration study.

The application of this method is evaluated in a single research project, which is the IGM project that was described. Any inference on the coupling method, derived from a single case study, must be qualitative in nature and any generalization is epistemically constrained. However, many lessons that are systemic in nature and do not result from the specific context of this project can be induced.

2.4 Research Questions

The objectives stated above are met by answering the following research questions:

1. **What guidelines and methods exist for model integration and how can they be adapted to this particular project context?**

   A literature review on irrigation modelling within the hydrological and economic disciplines is complemented with a review across disciplines on model integration. This interdisciplinary review looks at general modelling literature, software options for model coupling and at more general guidelines on integrated modelling and model software selection. In those cases when scientific literature is not available, grey sources are also reviewed.

2. **How can the two complex models MP-MAS/EDIC and WASIM-ETH be coupled conceptually and technically?**

   Four levels of interaction that are relevant for the description of a fully coupled modelling system are:

   (a) The description of a physical-hydrological system (modelled within WaSiM-ETH) and the physical irrigation itself (outputs of the irrigation and canal model EDIC);
   
   (b) The distribution of water from canals (modelled within EDIC) to individual farmers (modelled within EDIC) and their access to water;
   
   (c) The irrigation decision of farmers (modelled within MP-MAS) under dynamic meteorological conditions (is imposed by EDIC)
   
   (d) Full dynamic coupling and interactions

   Other interaction levels are disregarded at this point, for example the growth of crops in a model with daily time steps (a fully integrated plant growth model). For now, the crop growth model that is already integrated into MP-MAS, with monthly time steps and simplified growth function, is maintained.

   Integration requires the conceptualization of interactions between the models encoded in the software, according to the Chilean context and according to scientific theory. Conceptual consistency must address temporal and spatial scales and the processes inherently linked to these scales. Furthermore, interaction variables that were previously parameterised as constant boundary conditions to a disciplinary model are now dynamic. Not only these interaction variables must be calibrated, but also impact of the new dynamics on system must be addressed.
The functional design is then implemented into software code, as dynamic coupling of two existing software codes. This is either done by processing data that describes interaction variables in an external software layer, or by adapting the legacy source code of the original models, if logically required. Finally, full model coupling is implemented for the two adapted legacy codes and data processing routines.

3. **How can the interactions be calibrated in such complex, integrated modelling?** Calibration proceeds along the four interaction levels outlined in Research Question 2. For Interaction Level I, the calibration and validation is performed by a project colleague and local expert within the IGM project. Interaction Level II is addressed through an empirical question within this Ph.D, specified further in research question 4. Interaction Level III is calibrated in close cooperation with project members that focus on farm decision making and calibration of the economic model component, MPMAS. Empirical calibration of the full dynamic coupling is not anticipated within this project phase, because it requires re-visiting of all model components by all team members. Sensitivity to indicative interaction variables and boundary conditions is documented as part of the analysis after model calibration.

4. **What is the impact of improved canal conductive efficiency on different farm groups within the study region of the Maule watershed?**

This empirical question is included with the aim of testing the usefulness of the integration method with regard to planning support. Farmers are grouped using economic strata and the study region is subdivided into irrigation sectors. Impacts from the irrigation infrastructure improvement are measured as land use change, income, their assets. The distribution of these variables within a sector and the full population of farmers is also evaluated.
Chapter 3

Theory On Model Integration For Natural Resource Management (NRM)

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3.1 Integrated Modelling And Model Integration

3.1.1 Integration And Its Role In Natural Resource Management

NRM and the nature of complexity

Simple systems with fully known rules can behave in surprisingly complex ways. The most well-known example may be the ancient Asian board game GO, which is regarded as the new ‘drosophila of artificial intelligence’ (John McCarthy). With only three or four very simple rules, this board game GO creates emergence and unstable patterns that can suddenly collapse, which are by orders of magnitude more complex than chess, the old drosophila of AI. Despite today’s considerable computational power and the perfectly defined rules of the GO problem, computers still cannot manage the vast number of options available in the game and therefore the human
brain still prevails over the computer in GO. This board game is an example of enormously complex behavior in a system with trivial and perfectly known rules.

In contrast, many natural resource systems are complex because they involve multiple rules (processes and interactions) and a manifold of relevant scales. Moreover, these multiple scales and processes are dealt with by different branches of academia and therefore may fall through the cracks of a reductionist assessment framework that are carried out along the lines of disciplines. As consequence, academic institutional filtering can create systemic blindness to certain feedbacks. Even systems with surprisingly simple dynamics may thus become too complex to describe (e.g. the Syndromes of Global Change, Schellnhuber et al. 1997, also Petschel-Held et al. 1999). For example, the global deforestation rate that mainly transforms forests into agricultural land is stable at 1.3%. According to INPE data, the annual forest loss in amazon is fairly constant with $6900 \pm 1900 \text{km}^2$. Also at national level, these rates are rather constant. According to FAO data, the total area that is available for agricultural production remained fairly constant over the last decades as well (IAASTD 2008b). Thus, the loss of agricultural land due to soil degradation must also occur at a fairly constant rate. Carbon emissions, bio-diversity loss, desertification, urban sprawl and overfishing are other human-environmental interactions that continue at nearly constant rates, fluctuating only slightly in speed, but not in direction. From the point of view of system dynamics, the temporal development of forest cover, soil quality or carbon content can well be represented with a linear or exponential model and a small random component. In this sense, human-biophysical interaction processes are dynamically simple even though the underlying systems show complex interactions.

In NRM, the term ‘complexity’ is often used very different than in many other branches of complexity science: systems are conceptually difficult to describe, if chains of interactions are long and have many links. Feedbacks occur at and between scales and disciplines. However, the observed temporal dynamics of system behavior is not necessarily that complex. Mostly, the task of NR managers is to reverse steady trends rather than to control oscillatory chaos. It is thus the first challenge of software systems to capture these long chains of reasoning properly across scientific domains, before the issue of mathematical complexity is even touched.

As consequence, integrated and complex models usually behave simple and nearly linear (Toth 2003). To describe system behavior, it is usually sufficient to analyse changes of trends, rather than patterns or fluctuations. To understand the underlying cause-effect patterns remains a challenge.

Transdisciplinarity and NRM

The transdisciplinary paradigm to sustainability management calls for a systems perspective that is problem-oriented and focuses on transformation process, rather than on symptoms (Mogalle 2001, p. 37). Mittelstraß (2003), who coined the term in 1992 defines it as a setting and style

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1See WBGU (1996) for a description for complex human-environment interactions as causal loop diagrams, which became known as ‘Spaghetti diagrams’.

2Exceptions are Vietnam and Cambodia which changed their governance system, and Nigeria and Sudan with social unrest. In these countries, deforestation rates accelerated by a factor 3-4, INPE data

3System complexity can also be located at the decision level, where institutions are too loosely defined, too fragmented or even missing so that it remains impossible to resolve a problem that is fully understood politically, for example the over-fishing of global marine resources.
of work (‘Arbeitsstil’), as a principle of research within the realm of academia. Even though this paradigm is typically used for other scientific fields (nano technology, information and neuro sciences), this definition applies to the problem of natural research management and agriculture. It is in line with the Memorandum on Future Perspectives of Agricultural Science and Research of the German funding organization (DFG 2004), which defines agriculture as a system science that must integrate natural sciences and technology with socioeconomic aspects and must develop content wise as well as in the structures of its institutions.

Key aspects of transdisciplinary work include the orientation to a practical problem, a shared analysis of that problem from the perspectives of several disciplines, the freedom to choose those methods most appropriate to the problem, and a solution that is adequate for the specific context (Jaeger and M. 1998). In this respect, knowledge is categorized into system knowledge, a vision (‘Zielwissen’ or goal knowledge), and transformation knowledge. At the operational level, transdisciplinary research must address the epistemic foundation and methodology, as well as the institutional framework of academia, which constrains the research efforts, but which also changes with these research efforts (Mogalle 2001, p. 100). Integration methods must thus address two key dimensions (Scholz and Tietje 1995): the nature of the system that is analyzed and the nature of the assessment process itself.

**Integration is an epistemic challenge**

Since the Enlightenment, the scientific world has been specializing into an ever growing number of disciplines. Today, few students study philosophy and even epistemology is often not part of the standard curriculum. This specialization is based on reductionism, which is the understanding that real-world systems (such as ‘a watershed’, ‘the human’, or ‘academia’) can be divided into discrete sub-systems. The system of science then applies the methods of its own sub-systems, the disciplines, to describe the real-world phenomenon. The sum of these descriptions fosters a particular conceptualization of the system in question (see e.g. Oppenheim and Putnam 1958, Nagel 1979).

During the 19th and 20th century, reductionist science brought humanity great successes: humans walked on the moon and at the bottom of the sea, peered into the micro cosmos and modern medicine reduced suffering. However, the reductionist system of science has also made it possible for civilization to exploit the world’s natural resources more efficiently and at a greater scale than ever before. The consequences of this human power are only slowly being recognized, while human-environmental systems face accelerating and vicious cycles of resource degradation (WBGU 1996, Petschel-Held et al. 1999). Within recent decades, far-sighted scientists and governments have carried out a number of global assessments on the state of the global environment (UNEP 1995, IPCC WGII 2001, IPCC 2007, MA 2005) and, especially for the agricultural sector, on the ability of research institutions and exiting technology to deal with challenges arising from this predominant human land use (IAASTD 2008b).

As a consequence of our thinking and also of the structure of our institutions, multi-level effects and feedbacks across system components observed by separate disciplines have become a core driver of unsustainable development in agriculture. These feedbacks often slip through the assessment framework of disciplinary quantitative methods. As stated in the IAASTD, ‘the widespread realization that despite significant scientific and technological achievements in our ability to increase agricultural productivity, we have been less attentive to some of the unintended social and environmental consequences of our achievements (IAASTD 2008b)’.
CHAPTER 3. THEORY ON MODEL INTEGRATION FOR NRM

Already a decade earlier, Lubchenco (1998) had called for a new research and management approach in Science: “Innovative mechanisms are needed to facilitate the investigation of complex, interdisciplinary problems that span multiple spatial and temporal scales; to encourage interagency and international cooperation on societal problems; and to construct more effective bridges between policy, management, and science, as well as between the public and private sectors.” Scientific and bureaucratic inability to assess and manage complexity is the core reason for pathological shortcomings in sustainability science and its inability manage human-environmental systems successfully.

Many authors call for transdisciplinary research, to encounter these shortcomings. Ravetz (2006) points out the need for a structural reform of NRM research frameworks. He argues that the disciplinary structure of resource management organizations has become a core inhibitor of sustainable development.

3.1.2 Integrated Modelling And NRM

Integrated modelling approaches for irrigation

It is becoming general knowledge that water is increasingly the most relevant production constraint for the long-term survival of humankind. Reports on global water scarcity were published by United Nations (HDR 2006, . . . ), by the World Bank (World Bank 1993), by CGIAR centers such as IFPRI (Rosegrant et al. 2003) and IWMI (Molle et al. 2007), and in popular books (Postel 1999, Lomborg 2004 or Pearce 2007). Access to drinking water and sanitation was recently accepted as human right4. For rural areas, irrigated agriculture consumes around 78% of water supplies (World Bank).

On the production side, improving water usage in agriculture is an imperative (Molden 1997), for which a good understanding of irrigation water flows and balances at irrigation sector level and at watershed is essential (Droogers et al. 2000). For a review of modelling approaches, see Chapter A of the Electronic Appendix.

The physical understanding of water processes must be complemented by an understanding of water-governing institutions (Rosegrant et al. 2005), from the demand perspective (Hoekstra and Chapagain 2007), from the perspective of producers that interact with other producers (Berger et al. 2007a), and ultimately from the perspective of an integrated food chain. Only this food chain perspective on the globally integrated commodity markets allows for an analysis of who produces for which consumers and who actually benefits from an improved production technology – in other words, how are total benefits generated shared among producers, marketers, food processors and finally consumers.

Optimal control models at aggregate scale are still prominent in policy analysis. They are simple to understand, require relatively little data and their result is an ‘optimal allocation strategy’ from a set of predetermined options, which is easy to communicate to policy makers. However, this normative approach cannot offer insights into the transformation process towards this ‘optimal’ goal itself, because dynamic effects are not resolved, for example resource capture (Homer-Dixon 2001) and path dependencies (Berger and Ringler 2002).

To capture ecological and socioeconomic interactions in irrigation management, models must simulate the goal-oriented nature of human action. To study how the micro-level behavior of

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4General Comment No. 15 (2002) on Articles 11 and 12 of the International Covenant on Economic, Social and Cultural Rights
3.1. INTEGRATED MODELLING AND MODEL INTEGRATION

(a) Integration of systems and research results
(b) Integration of data and results
(c) Integration and exchange of data
(d) Integration of interactions
(e) Integration of heterogeneous interactions

Figure 3.1 — Approaches to System Integration

many individuals feeds back into a larger scale, multi-agent models are becoming prominent – with a decision framework that either relies on rules, on utility optimization or on mixed forms. In addition, such tools enable collective action research (Ostrom, Gardner, and Walker 1994) and the exploration of institutional mechanisms (Dinar and Letey 1996) at meso- and macro level, but pose technical and epistemic difficulties (McKinney et al. 1999). The management of micro-meso-macro interactions requires a shift in research paradigm, improved data availability and computational capacities that have only become available in recent years (Berger 2001, Day 2005). Specifically, empirical agent-based systems are promoted as a promising method to model the usage of natural resources from a disaggregated perspective and the feedbacks of this usage on the system itself Hormann (2005). Empirical and agent-based economics allow the comparative analysis between economically efficient outcomes at aggregate scales with individually optimal outcomes, but also carries huge potential for analysis of institutions, resource use and emergent phenomena (Tesfatsion 2003).
CHAPTER 3. THEORY ON MODEL INTEGRATION FOR NRM

Integrated modelling as a process

Science is currently at the learning stage with regard to representing and modelling complex phenomena, such as path dependencies, emergent phenomena, adaptive behavior of individuals Parker et al. (2003). Such problems were theoretically posed as early as the 1970s (e.g. Day 1971), but methodologically unresolved because of scale issues and complexity.

Integrated modelling is the process of finding a representation of a system across disciplinary boundaries and analyzing its results. Particularly in the field of agriculture and NRM, integrated modelling approaches that are both multidisciplinary and cross-sectoral and combine different modelling techniques will best serve the ‘objective of improving understanding of land-use change processes’ (Lambin, Rounsevell and Geist 2000). However, the extension of the assessment framework for natural resource management into the micro-scale brings with it an enormous quantity of conceptual, methodological and epistemic issues, which in turn has fostered a multitude of scientific approaches (Mogalle 2001).

As a tool for global and regional planning support, integrated modelling of human-environment interactions is increasingly recognized (Rotmans and Vellinga 1998). However, the computationally and conceptually heavy-weight models require new analytical frameworks and new techniques for integration. In addition, the need to involve stakeholders and policy makers is especially recognized (Toth 2003). For local-level management decisions, empirically based, multi-agent models are being combined with collective action theory and game-theoretic approaches (Janssen and Ostrom 2006). Within the context of Chilean watershed management institutions, Berger et al. (2007a) outline potential uses of an empirically calibrated MP-MAS model for the provision of public goods, e.g. the evaluation of canal infrastructure, maintenance, and monitoring; but also the governance of these.

Integrated modelling as an organisational challenge

Model-supported, integrated system descriptions – integrated modelling – may be carried out by an individual, who combines the following capabilities: the person masters more than one discipline. (S)he feels comfortable with the development of modelling software. (S)he also knows and understands the system that is researched, has the capacity to gather the data needed to parameterize and calibrate the model – either by him/herself, or by contracting someone. (S)he must also have the communication skills to communicate project results. If the objective of a project is NRM, then this communication cannot only be geared towards the scientific audience, but must be conveyed to the relevant policy makers who actually manage the resources. Last but not least, the person must have the resources to do all this – in finance, knowledge and time.

Alternatively, integrated modelling may be pursued within the context of a project team, as process that bridges between disciplines. Here, integrated modelling may be categorized into five classes according to their level of integration (Figure 3.1.2). Always, a transdisciplinary team caries out project planning in all five classes. Likewise, final project results generally draw on the findings of all disciplines involved. However, the integration classes differ in in the amount

5Other assessment dimensions, such as the environmental services and other intrinsic values, are relevant but disregarded at this point in order to focus this Ph.D. thesis on the methodological challenge of expanding a socio-economic model dynamically and embedding it into its hydrological environment.
of interaction, and thus the transaction costs, that is demanded from disciplinary partners. Inter-
actions may include communication about concepts, the organisation of data collection and data
management, the timely sharing of data, models and model results, the technical implementation
of new software, the calibration of disciplinary models and interactions across disciplines, the
analysis of disciplinary and integrated model components and the communication of results.

The five integration classes vary in several aspects. In the simplest form (a), only planning
and sharing of results occurs with a transdisciplinary perspective and all research is carried out
by disciplines. In class (b), a common driver of change is parameterized and the same database
is used as ‘external’ boundary condition. In class (c), interaction variables between both dis-
ciplinary domains are addressed by exchanging the results of domain models, as (‘internal’) boundary condition. These ‘internal’ boundary conditions describe interactions between both
disciplinary domains that are part of the larger, integrated system that is analysed. In class (d),
these ‘internal’ boundary conditions are described dynamically, as interaction process between
two sub systems (compare Section 5.1.3). To a certain extend, interactions and feedback dynam-
ics can now be quantified in space and time.

Ultimately, class (e) focuses the analysis on the heterogeneity of interactions between dif-
ferent substantiations of the sub systems. For example, one location downstream a river may
be dominated by one type of farmers, let’s say small scale farmers that target local markets. Another location that is upstream of the former may be dominated by a different form of agricul-
ture, using large-scale irrigation schemes and targeting export markets. A common driver, such
as a global crash of market prices for food products, will at both locations trigger interactions
between the farming community and the hydro-physical sub system, however these interactions
will probably differ. Furthermore, the interaction between both locations, the upstream and the
downstream location, is a function of the different human-environmental interactions upstream
and downstream. Finally, local markets and export markets will also react differently to the com-
mon driver, the market crash, and require appropriate adaptation strategies that differ between
both farmer groups.

To look at the outcome of human-environmental interactions that differ in two locations,
the heterogeneity of both locations must be understood and modeled adequately. This requires
recognition at the project’s organisational level: the choice of data that is collected across both
locations, the analysis of interactions in both locations, and the interaction between both loca-
tions. Here, a location is regarded as a holon that contains all disciplinary sub systems, and
integration is performed within this holon and also in its relation with other locations that are
also holons. However, the organisation of a research project for a holon approach is difficult in
praxis: The number of interactions between disciplinary researchers is large and increases ex-
ponentially with additional new holon (see definitions in Section 2.2 and elaboration in Section
3.1.2).

Planning a modelling study

Most NRM projects aim to produce insights that are target at policy makers or other stakehold-
ers who participate in an integrated modelling study. However, policy makers as prime users\(^6\)
are seldom involved in modelling itself. In most cases, technical users (research staff) operate,
implement, calibrates and verify modelling software. Project managers must oversee these tech-

\(^6\)For elaboration of user groups, see (Rizzoli et al. 2005).
technical users and usually are responsible for communicating results and insights. While prime users drive the framing of research questions, details are formulated within the modeling community by experts. Other stakeholders who are neither policy makers nor technical users (other end-users) may also be involved in a modeling process, and are thus also users (developed along from Huigen 2006).

The following perspectives should be distinguished in an integrated modeling process:

The conceptual or system perspective. This perspective focuses on the study region and the entities and processes within this study region. Furthermore, it defines which processes are relevant, as well as the causal chain of interactions, either in a qualitative or quantitative manner.

The technical or software perspective. This perspective focuses on the development of the software back-end. One dimension of this is the storage of data and the management of data within the project team. A second dimension is extension of source code and technical verification, the sequencing of model computations, the technical definition of data exchange between models, and the translation of data from one format to another.

The institutional or research perspective. This perspective relates to the working context, the organizational setting of and the institutions involved in an integrated modeling project. Relevant questions are: How do individuals with specialized knowledge operate within the process, how do they interact and communicate with each other, and how do project partners share resources? Differences between disciplines range from culture, paradigm, language and ontology, to thinking in different temporal and spatial scales, different units of analysis. Also, methodologies (data collection and analysis) fundamentally can differ. Additionally, procedural differences – such as communication conventions within and amongst disciplines, as well as with stakeholders – also exist and pose challenges to integration.

Taking into account these perspectives, the integrated modeling process must be structured accordingly. For river management Refsgaard and Henriksen (2004) suggests a ‘Model study plan’ as process guidance. Before actual modeling activities start, stakeholders and the modeling team is requested to agree on a set of question (quoted from Refsgaard and Henriksen 2004):

- Why is modelling required for this particular model study?
- What is the overall modelling approach and which work should be carried out? Who will do the modelling work?
- Who should do the technical reviews? Which stakeholders/public should be involved and to what degree?
- What are the resources available for the project?

Refsgaard and Henriksen (2004) emphasize to assess a strategy and criteria for model quality assurance or uncertainty assessment, at the stage of Use case definition, and recommends the following steps:

1. Building the knowledge base is separated into two processes: the conceptualization of the problem at hand, but also at the collection of data according to data needs of some model.
2. **Model software selection and set-up** is ideally now decided on, in accordance to data available, and the conceptualization of a problem. Eventually, further details of the model must be implemented.

3. **Calibration and validation** Once the model set-up is technically finished, it can be calibrated to available data, and ‘validated’ against independent field data. Similar to an error analysis, an uncertainty analyses is recommended to analyse, document and communicate the robustness of results.

4. **Simulation of scenarios and evaluation** is the technical step during which policy questions are modeled based on base-line scenario, and policy scenarios identified with or by stakeholders. Finally, the robustness of a recommendation is assessed with uncertainty assessment and communicated, as part of the policy recommendation.

One should note that the both organizational structure was taken for granted as institutional setting to modelling-supported river catchment management. The project, a consortium of twelve scientific institutes and universities, are located within the European Union, and thus subject to similar funding mechanisms, and to similar framing effects due to project setups.

**Integrated modelling within the organizational context**

Integrated research is conducted within academia, within its organizational set-up and its disciplinary departments, institutes and faculties. By definition, integrated research will cross boundaries within this organization and researchers will be confronted with the different scales, cultures, epistemologies and ontologies of other disciplinary domains. One dimension of software development for integrated research is thus how it performs within the governance structures of academia and different research projects (Miller and Erickson 2006).

For the sake of integration guidelines, I suggest three institutional project set-ups. The first I call the ‘pillars approach’, which is equivalent to the ‘side by side of disciplines that Baumgartner et al. (2009) describes (Fig. 3.2 a). Here, project planning and project evaluation is performed in interdisciplinary teams. Based on preliminary studies, the problem of research is dissected into sub-problems, attributed to disciplines and funding allocated. At a later stage, results from disciplines are gathered and evaluated by a scientist who writes the integration chapter. In this setting, all relevant system interactions must be known in advance, so that they are properly incorporated during the partition (and budgeting) phase. Otherwise, they will be systematically ignored.

The second approach is the ‘cross-link – interface approach’ (Fig. 3.2 b). Here, a common frame of analysis is defined during planning. The problem is dissected and attributed to disciplines, but planning defines the assessment frame and interaction interfaces rather than the problems that are analyzed. During project execution, ‘integrative variables’ are used to assess interdisciplinary interactions.

The third approach is called the ‘holon’ approach. Local settings are seen as organs or semi-closed compartments. This assessment approach assumes a general cause-effect model, but realizes that these will reveal themselves differently within the local characteristics of each ‘holon’. At the micro scale, interactions within each holon are assumed to be more relevant than those between holons. Here, socioeconomic and biophysical disciplines are integrated, for

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7see Definition in Footnote 2.2
example by looking at the socioeconomic drivers of soil management of a farm if the holon is a farm, or by understanding the impact of water user organizations on canal maintenance and the physical routing, if the holon is an irrigation sector (Fig. 3.2 c). At a macro scale, the interactions between holons determine the outcomes (Ahl and Allen 1996). Following the above examples, nutrients and agrochemicals leak from one farm to the other. The neighboring farm-holon causes negative or positive externalities, which again influence the interactions of a complex biophysical-socioeconomic system. Methodologically, a 3-stage assessment involves first, the development of a qualitative cause-effect model (the general rules), based on which research is then organized around holons. Within a holon, a cross-link – interface approach is used, and interactions within each holon are analyzed. In the third stage, these findings are up-scaled and interactions at the meso scale are integrated to analyze micro and macro outcomes. This stage looks at how an upstream forestry sector that causes soil erosion and clogs downstream canals impacts on the institution of downstream water user organizations. Here, interactions are both biophysical and social, because water user organizations interact with the owners of an upstream forestry plantation through the social and the economic domain. Looking at the heterogeneity of interactions, one can ask: What are characteristics of different downstream irrigation sector ‘holons’, how do water user organizations of these perform with regards to upstream externalities and why can some water user organizations deal with externalities better than others?

From the research perspective, the first approach is least satisfying, while the third is most complete (Giampietro 2004). Yet structurally and methodologically, the first approach matches the institutional context of organizations and funding mechanisms in academia best, while the third has structural inconsistencies with the division of labor in academia, with its hierarchal setting and with funding mechanisms.

For many ecologists, insights from hierarchy theory (Ahl and Allen 1996) have revolutionized the assessment framework and lessons are now being applied to research in agriculture. For agro-ecological research, Wagenet (1999) found that, under conventional research that is organized in disciplinary pillars (and less so in a cross-link/interface approach), the scientific capability to scale up (generalize from micro scale information) is far more advanced than its ability to scale down (assess micro scale impacts from macro scale processes), as demonstrated for soil and nutrient processes. We can thus measure the micro scale, but it is a major challenge to predict how macro-scale actions trickle down and shape the micro scale.
Despite institutional difficulties, important steps toward the operationalization of an holon approach have been undertaken. Methodologically, Giampietro lists farming systems research, the individualization of decision theory in economics, multi-agent systems and the linking of these with spatial analysis of land use as promising and innovative pillars that in their whole can support such holon approach.

The farming systems approach (e.g. Doppler 1994 or Dixon et al. 2001) is an example that captures complex interactions at the micro level and then develops a typology of these micro-level systems. However, to incorporate dynamic interactions and meso-scale processes (such as emergence), the farming systems approach must be integrated into a larger framework (Giampietro 2004).

Practical examples for successful application of an holon approach in research are still rare, but emerging. Most prominently, the regional report of the Millennium Ecosystem Assessment (Cork, Petschel-Held, Peterson, Bennett and Zurek 2006) uses both qualitative and quantitative analysis to organize and analyze regional case studies. At first, general cause-effect models were developed as a common research framework, using methods from Petschel-Held et al. (1999). Then, local groups of scientists took a quantitative case study approach to analyze how different meso scale interactions emerge and finally synthesized their findings into the common framework (Cork et al. 2006).

modelling software that is developed to analyze system behavior within the context of an holon approach, will have to be developed in the current organizational structure of academia. Thus, a good method balances pragmatic feasibility and paradigmatic openness.

### 3.1.3 Model Integration for Natural Resource Management

An integrated modelling system to support planning for Natural Resource Management, must deal with complex system as previously defined: interdisciplinary and comprising feedback cycles across disciplines and with many links. As such, software development is done in teams with high levels of disciplinary specialization. Knowledge requirements are significant and costly to acquire, and none or few individuals have full insight into all technical and theoretical details of such a modelling system.

From gray literature, the procedure ‘Integration on Demand’ is briefly introduced, as existing procedural guidelines for model coupling. Then, insights into user-oriented software development are summarized, because the resulting modelling software should be a product that matches user’s requirements. In addition to these, I recommend further gray literature, such as the ‘Harmoni-CA Planning Framework’ – a broad attempt developed within the Harmoni-CA project (Becker and Hattermann 2005). Also, the project SEAMLESS systematized ‘Modelling Framework (SeamFrame) requirements’ (Rizzoli et al. 2005).

**Model integration ‘on demand’**

The objective of ‘Integration on Demand’ (IoD) is to guide model integration within research projects holistically, by structuring the modelling process. The framework guides communication among project members, in order to ensure goal-oriented and well-grounded work. The IoD framework defines a Model Use Case as a set of procedures which are codified as a sequence of hand-on tasks (research question -> functional analysis -> technical analysis -> technical implementation -> model calibration -> model analysis).
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The development of IoD started within the project ‘Integrating Governance and Modelling’ (Huigen 2006), when IGM was already advanced beyond the point of model software selection. Even though IGM already passed the stage when IoD should start, key insights from IoD were valuable for our project, and our experience also produced lessons that may feed back into IoD. When applying IoD, all project members were cognitively aware of the cyclic nature of all technical steps.

A specific Model Use Case is defined as the process elaborating a specific research problem, which starts with the formulating of a research question and ends with the creation and communication of answers to it, through the analysis of one or more scenario. The Use Case description that follows was adapted from an internal project report (Huigen 2006), which adapted guidelines to organize software planning processes efficiently from IT companies to the scientific context. Within the business sector, such guidelines aim to develop software with a high degree of flexibility and re-usability.

The key steps of IoD at its development stage during the time of model architecture selection (2006).

1. **Formulate the research questions** precisely, stating all variables, their resolution in space and time, the policy indicators involved.

2. **Select the research questions** that can be answered within the project, balancing research objectives, project resources and data availability.

3. **Information analysis and functional design.** Scientific theories and concepts are elaborated in great detail and knowledge is communicated within the project. Concepts should be stated in abstract terms, such as entities and processes, rather than in technical terms (variables). Scales and scale transitions must also be elaborated.

4. **Technical design** translates the conceptual structure of the information analysis into a form that can then be translated into software code. At this point, concepts are matched with models and eventual gaps between those models re identified. Strategies to close these gaps are developed, possibly necessitating a return to the functional design phase.

At the 2006 stage of IoD, specific insights and guidelines on how to manage and structure an integrated modelling process with restricted resources are also not given. Also, some shortcomings were experienced that relate to the specificities of research projects.

**User-oriented development of software**

The objectives of software development usually focus on the needs of a user community (see Section 3.2.4). Taking such user-oriented approach, the team of the (ongoing) research project SEAMLESS (Rizzoli et al. 2005) was inspired by the 'Architecture Trade-off Analysis' (Van der Wal et al. 2005). In this approach, steps in software development include:

1. Definition of expected software uses;

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8 More detail to develop a project research question is given in (Huigen 2006).

9 ATA was developed by the publicly funded Software Engineering Institute. See http://www.sei.cmu.edu/architecture/ata_method.html.
2. Analysis of the software requirements and the resources needed for development;

3. Selection of software architecture;

4. Documentation and communication of software architecture to end users, based on a simplified ‘dummy’ front-end;

5. Evaluation of user responses to software architecture;

6. Implementation of software;

7. Monitoring and evaluation to ensure that implementation conforms with user’s requirements.

This procedure highlights the need for the early inclusion of future model users in the development process, in order to receive and incorporate their feedback at an early planning stage. SEAMLESS defined prime users (the modelling team), end users (target audience) and technical users (modellers and developers. Additionally, the managers of modelling projects may be added as separate user category.

The ATA framework does not address the specific challenges of implementing such system within the research domain.

**Development levels of modelling software**

The applicability and reliability of a modelling software, and the cost of improving and adapting a software to a specific case depends on the development stages of modelling software. It can be assessed along three dimensions: its testing in applied case studies, its generality with respect to the range of research questions, and its ease of use. For these categories, Argent (2004) distinguishes four stages of model development:

I: The **New-born stage**. The model was created to describe and analyze one specific phenomenon.

II: The **Infant stage**. A Stage-I-model was reused for one or few other case studies, with an equivalent or similar processes dominating system behavior.

III: The **Research stage**. The model can be flexibly adapted to a range of situations and problems, and is sufficiently broad to incorporate the peculiarities of these cases.

IV: The **Service stage**. The model has entered the ‘realm of planning and policy analysis. […] The use of the model is often divorced from the underlying theory and concepts. At times, the users are not even familiar with the model workings, and the model operates largely as a black box (Argent 2004)’. Analysis tools are offered and data processing is resource efficient because an adequate toolbox allows for the quick and timely creation of graphs. Additionally, input data requirements are flexible and adjusted to localities.

Beyond these technical descriptions, the modelling purposes of these development stages are also distinct, as are their institutional research contexts; the type of knowledge and the learning objective varies which model users aspire to. In Stage I, the aim is to learn about some little-understood phenomenon or to demonstrate that a phenomenon can be modeled with existing
theory. In Stage II, the aim is to show that such phenomenon is relevant in another context. Methodologically, an existing model at infant stage is applied to a new case study and minor adjustments are made if necessary. Modelling results from Stages I and II are mostly communicated within the realm of academia.

In Stage III, researchers choose a well-tested modelling tool to quantify a phenomena that occurs simultaneously with other processes, which makes it necessary to use a multi-phenomena (and eventually quiet complex) model. Users require considerable technical knowledge, and may work under the umbrella of an applied research project or for a public institution. Modelling results may be communicated in technical reports, in academic publications and also as public services (e.g. flood forecasting).

In Stage IV, the model has finally become a commonplace tool with a wide user community. The modelling purpose shifts from learning to the realm of planning. In addition to applied scientists, targeted users also include consultants, with project horizons of just a few weeks, and limited resources to learn or to deal with data manipulation. Thus, the importance of ready-to-use databases and simple front-ends with automatic graphical outputs, to facilitate easy and quick communication of results is of key importance. In addition, results are reported in legally defined reporting standards (e.g. environmental impact assessments).

Models that are designed in the academic context of research purposes generally fall into Stages I and II, with some reaching Stage III. The pace of development remains rapid, with new versions of the software and evolving data formats.

The integration of such software into a modelling framework may pose challenges: software at early development stages I and II remains little tested, and the diffusion of technical knowledge about the software is limited to few experts. Technically, such software was often developed for a single purpose, and the integration of additional assumptions may pose significant difficulties and costs. At early development stages, user interfaces are usually lacking or minimal.

At stage IV, user interfaces are best developed. However, the software overhead of advanced user interfaces may be complex (front-ends, back-ends, parallel processing extensions). It may be difficult to adapt such existing software package to a new problem – such as the integration into a modelling frameworks or conceptual model extensions.

The knowledge domain of model software

The building blocks of model integration projects are models, which is software code in this context. Therefore lessons from software architecture are a very useful starting point for model integration. However, some differences between commercial software components and research models exist and these have important implications for the planning process. Because structural uncertainties increase when moving from the realm of high accuracy of natural sciences into the realm of complexity in social sciences, the relevance of these issues depend on the specific Model Use Case. Ideas were compiled from discussions with other scientists and from paths of literature.

*Models cannot be treated as black boxes.* The purpose of model integration is to extend a logical chain of reason beyond the scope of a single model, by integrating across scales or across disciplines. Nevertheless, this logical chain of reasoning is only as strong as its weakest link and errors propagate through this chain in a non-linear manner (e.g. Knopf et al. 2006). Thus,
models that use structurally uncertain assumptions must be treated as white boxes and only functionally completely described components (e.g. pure data handling, ‘true’ model components) may be wrapped into black box layers.

The objective of NRM modelling is to learn about a system that is only partially understood, especially in the face of complex interactions and multiple feedbacks. Models yield output data and only the interpretation of these data can result in learning. Outputs from complex and “over-integrated” models are useless if they offer less insights into the system than the evaluation of input data and expert knowledge provide or if interactions and errors cannot be located within the system. Commercial software on the other hand is often designed to fulfill a well-specified technical task, and outputs are the objectives (e.g. a human resource data bank).

Models are knowledge-intense. The calibration, validation, analysis and interpretation of complex models requires a significant part of the knowledge obtained during a full university career. The development of models requires scientific background about the discipline, insights into numerical mathematics and software algorithms, and programming skills. The application and interpretation requires experience in the field, while the use of models in policy processes additionally requires a great deal of communication competence.

(Scientific) modelling processes require iterative learning. The understanding of a single equation within the human brain occurs over several phases: even after years of using an equation, new implications can emerge and initiate a new level of understanding in the scientist – models require continuous learning. Thus, the planning process of model planning/development, model integration, calibration and validation cannot be seen as separate project phases, with well-defined termination points related to software engineering. In scientific practice, models are developed, calibrated with data, and conceptually improved after either data demands were found excessive or model outcomes were shown to be inadequate to explain observations. New data allows for the development of concepts but also for re-calibration – a circle that continues until a model is sufficiently robust to match observations with model outcomes. The scientific learning process, which is additionally lengthened by the data collection process, is iterative by its very nature).

Models are used and developed by scientists. Commercial software development projects are characterized by a long and time-intensive period of planning and a short and intense implementation time with highly-paid IT specialists. Subsequently, employees are ordered to use the final product. In contrast, the scientist iteratively modifies the model concept and develops its source code, with his evolving understanding of the system. The high cost that the permanent involvement of professional IT specialists requires (including transaction, planning and waiting) is usually not feasible within scientific projects, so programming is usually done by scientists themselves.

In summary, a model development process must be flexible enough to ensure that scientists remain involved in the model development, without requiring highly specialized IT knowledge and high overhead costs. Models should remain transparent, so that logical errors can be identified and do not lead to false outcomes or to false conclusions from model interpretation. Meanwhile, model components, in interdisciplinary models, must maintain disciplinary integrity, so that they are accepted and can be used and validated within their accepted disciplines.

\textsuperscript{10}Scientific learning is distinguished here from models that consultants calibrate for legal purposes, because the objective here is not learning but fulfillment of some well-defined procedure.
CHAPTER 3. THEORY ON MODEL INTEGRATION FOR NRM

Theoretical validity from an assessment perspective

When analyzing any system, it is often helpful to look at it on three perspectives; to define a micro, meso and macro scale. This categorization can be temporal (short-term, mid-term, long-term), it can be spatial (field, farm and watershed), or the decision type (lifestyle, strategy, tactics). How these boundaries are actually drawn depends on the assessment objective.

Integrated assessment models for natural resource management (IA-NRM) often include one or more actors within the system that are teleological (goal-oriented). Within such systems, each teleological actor (the ‘agent’) can be a person or any other entity that acts and reacts. Therefore, in addition to the scales already mentioned, IA-NRM with goal-oriented agents can look at systems on another set of three perspectives; the agent (micro-level), policy makers (the macro-level) and regional institutions and rules (meso-level), which are an intermediate step between the former two.

The first perspective targets the agent and assesses how his micro-level strategies perform within a macro-level context. Here, the aim is to identify and analyze which strategy performs best for the individual agent. The second perspective targets macro-level policy makers and assesses how macro-level contexts should be shaped, in order to reach macro-level targets. Here, the aggregate outcomes of micro-level behavior are analyzed and may include micro-level performance and aggregates of it. A third perspective targets the meso level. This third level assesses how meso-level rules and institutions behave and how these should be shaped to foster performance at macro- and at micro-level. The analysis of interactions among agents, of collective action, of emergence, of local institutions and of most infrastructure investments requires this meso-level perspective. Furthermore, meso-level entities can interact with one another, adding a further dimension of complexity.

For defining an integrated assessment model for NRM with goal-oriented agents, it will be relevant to define which of these perspectives is taken, as it will define which processes should be incorporated internally (dynamically or statically) or left as boundary conditions, and how the decisions at the micro level are parameterized to the model.
3.2 Literature Review On Model Integration

3.2.1 Objective Of Chapter

The objective of integrated modelling is to summarize existing knowledge and mirror cause-effect relationships of a specific problem – if possible including the social, environmental, economic and institutional dimensions (Rotmans and van Asselt 2001). This causal description can be done in a qualitative sense with conceptual models and in a quantitative sense, through formal computer models.

A modularized input-output structure makes it possible to extend and link a software with further modules (Rotmans and van Asselt 2001). During the 1990’s, IAM were primarily used as global environmental policy support tools, for example, for the assessment of climate change scenarios (Van Der Sluijs 1996). Integrated assessment models have evolved to become planning support tools, which assist rational, informed decision-making on complex and uncertain issues and over longer time scales (Parson 1995, 1996). While first IAMs were developed for single experts, many models now aim to assist collaborative decision groups in assessing feasible policy options.

In this chapter, guidance and lessons for model coupling are derived. This precludes a review scientific methods used to perform model integration, both from the technical domain of computer software and from the conceptual domain of conceptual integration.

Section 3.2.2 reviews existing research and approaches on model coupling software. Then, I show a lack of guidelines on model integration, especially in the support of those steps of an integration cycle that precedes model software selection and the selection of the integration framework (Section 3.2.2).

As part of the introduction, three general modelling challenges are defined, as are four model development levels. These will be referred to frequently over the whole thesis, as crosscutting issues that are not unique to model integration, however are permanently relevant.

3.2.2 Model Integration As A Problem Of Software Design

Integrated modelling requires the linking of multiple components from different disciplines. To reduce the repetitive efforts of scientists in re-coding and testing model components, the demand for re-usable and component-based models is increasing (see Jones et al. 2001 or Rizzoli et al. 2005). However, models are often developed within disciplines with limited access to IT knowledge and the frequent re-invention of similar solutions is lamented by several authors (for a review, see Argent 2004).

A small set of software solutions currently dominates the integrated modelling literature. Each has its own advantages and disadvantages, while the levels of adoption by the research community vary. In order to organize further analysis, a typology of software solutions for integrated modelling is defined in this section. The language on integration levels and systematization was taken from (Brandmeyer and Karimi 2000), and extended to Argent (2004) and recent discussions from Donatelli and Rizzoli (2008), and is illustrated in Figure 3.3. Six software designs for model integration are distinguished and will be discussed below:

1. Data-level integration and loose coupling (not depicted), where data from multiple disciplines is cross-linked or a data base is shared with modellers from multiple disciplines.
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Data-level integration is the first step of any successful model coupling.

2. Dynamic coupling passes data in real-time between two or more models. It is further sub-classified:

(a) **Embedded coupling** with one source code is the reimplementation of other models into an existing code. The results are multi-component and complex models, which currently dominate research (Fig. 3.3, 2.a). This multi-component model usually handles space and time internally.

(b) **Embedded regression-type meta models** are parameterizations of simple functions with a ‘meta’ model, such as a simple regression-based equation which can then be easily embedded into an existing code. Because of their very short run-time, meta models are often used for the economic assessment of large modelling experiments, e.g. for optimal control problems in climate policy (Fig. 3.3, 2.b).

(c) **Hierarchical coupling**, where two source codes are connected in a pre-specified way, and timing and data exchange is managed externally (Figure 3.3, 2.c).

3. **Integrated modelling frameworks** (IMF) are a collection of model components, data processing and visualization tools. Model components can be combined and connected, while tools facilitate analysis and communication (Fig. 3.3, 3).

4. **Framework-independent components** aimed at the permeability between model integration frameworks, in response to the low practical acceptance of IMF in academia (Fig. 3.3 4).

In the following, each of these design typologies will be summarized in more detail.

**Data-level integration**

The first type of model integration is ‘data sharing and data transfer’. As most basic integration, input data for all models is linked and evaluated coherently, without even using models. In a second step, model outputs are returned into a common and related data base, and data evaluation is performed across all disciplines. Every GIS data-base and every relational data base are examples for data-level integration.

**Loose coupling**

Here, output data is transferred from one model to another. Technical work includes extraction, conversion and re-formating of data – either by hand or automatically with scripts.

In loose coupling, a common data management system, e.g. a GIS, is used to pass data from one model to another, in both directions. One model is run over the full time period, and results are passed to another model as (external) boundary conditions.

Micro-Macro coupling is a common application: a micro-level crop growth model is executed in a single cell for different land use scenarios that are defined with the model. Modellers can then extract variables of interest, and feed them into a catchment-level model. The results of the catchment model can later be fed back to the micro-level model, in order to analyze how large-scale patterns trickle down into micro processes. Eventually, the change of micro processes can be used to analyze a second macro run. With the term ‘shared coupling’, Brandmeyer refers to multiple models that share inputs from the same data base (eventually using generic
3.2. LITERATURE REVIEW ON MODEL INTEGRATION

(2.a) Embedded coupling within one source code, (eventual re-implementation)

(2.b) Embedded regression-type meta model

(2.c) Hierarchical coupling

(3) Integrated modelling system (IMS)

(4) Framework-independent components facilitate the integration into existing IMS

Figure 3.3 — Solutions for software integration (extended from Brandmayer 2000). Most recent development toward framework-independent components was added, based on Donatelli & Rizzoli 2007

data formats) and/or the shared use of output processing units (guided user interface), e.g. by incorporating model-specific VisualBasic interfaces into ArcGIS that allow for convenient linkage. However, models remain separate entities. The distinction between shared and loose coupling, as suggested by Brandmeyer, is procedural rather than structural and the line between loose coupling, e.g. with ArcGIS or EXCEL macros to re-format data, and shared coupling, with a VisualBasic interface, remains thin.

Dynamic coupling

Dynamic coupling refers to a tighter form of software integration, where models can exchange information at runtime. Depending on the technical software solution to do so, three types are discussed here: embedded coupling (often referred to as complex- or multi-purpose model), meta-model coupling and hierarchical coupling of standalone models.

Multi-component embedded models use a single source code, with multiple modules and components. These multi-purpose models are typically developed from a single-purpose model, by extending and (re-)implementing further modules as new (internal) components (Section 3.2.2).

‘Regression-type meta models’ use the outputs of one complex or empirically calibrated/validated model to parameterize regression-based transfer functions, the meta model. Quick runtime, low data quantities and simple implementation are core advantages, which even allow for repeated solutions in optimization models.
The third type, ‘Hierarchical coupling’, maintains two (or more) independent source codes, and realizes coupling via data exchange – either dynamically or via files. This coupling is referred to as ‘hierarchical coupling of models’.

Frequently, researchers use the term ‘dynamic’ coupling as the technical exchange of an internal (embedded) with an external module, for example because the module embedded within a complex multi-component model is not satisfying. In the suggested terminology, the model was already dynamically coupled, because two (sub-)models already existed and data was already exchanged at runtime. However, the transition from an embedded module to an external module requires to extend the modelling software technically, either to hierarchical coupling or to an integrated framework. If new processes and interactions must be defined within this extension (new interaction processes and variables, additional spatial and temporal rescaling, additional feedback loops), then this software extension also requires conceptual model integration. The technical transition from embedded coupling to hierarchical coupling – or an ‘integrated modelling framework’ – is of technical nature and a task of software engineering.

**Multi-component embedded models**

A large diversity of multi-component models exist, in which modules for specific processes are directly embedded within a single source code. These modules are selected and used by the modeller according to the particular case study objectives. Such models often originate from disciplinary, single-purpose models that were then utilized, extended and tested in other contexts. Thus, the source code evolved over time. Researchers augmented the basic model with new modules and eventually created a multi-disciplinary model system. Inside of the ‘legacy code’ of such a multi-component model, the knowledge, experience and work efforts of hundreds of researchers is often embedded. Also, many of these models offer alternative specifications (modules) for the same task (e.g. evapotranspiration), each with different data requirements or focusing on different scales.

Classified along the ‘levels of development’ suggested by Argent (2004), examples of these models are MIKE-SHE\(^{11}\) and SWAT\(^{12}\) for level (IV), DHSVM\(^{13}\), WASIM-ETH\(^{14}\) (Schulla and Jasper 2007), HBV\(^{15}\), PRMS-MMS\(^{16}\), ACRU\(^{17}\) (Schulze and Smithers 2003) (Level III), and the MP-MAS multi-agent model and Cai’s sector-level model (Cai, Ringler and Rosegrant 2007) (Level II). These two Level-II models were developed for a single use case and are in the process of replication and extension.

Often, these complex models contain components that are a simplified version of other complex models, which operate at a different scale. An example, the SWAT model describes integrated land use-hydrological interactions and contains field-level modules that were derived from...

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\(^{11}\)DHI, the former Danish Hydraulic Institute, now private consultant & research institute [http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx](http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx)

\(^{12}\)Grassland, Soil & Water Research Laboratory, USDA-ARS, [http://www.brc.tamus.edu/swat/](http://www.brc.tamus.edu/swat/)

\(^{13}\)University of Washington, [http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/index.shtml](http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/index.shtml)


\(^{15}\)SMHI International Consulting Services, [http://www.smhi.se/foretag/m/hbv_demo/html/welcome.html](http://www.smhi.se/foretag/m/hbv_demo/html/welcome.html)


\(^{17}\)Agricultural Catchments Research Unit, developed at in Agricultural Engineering of the University of Natal and now maintained with Water Research Commission funding.
the field-level plant growth model EPIC (Williams et al. 1984) and its extension, APEX. EPIC, which uses daily times and represents plant growth and nutrient dynamics, soil erosion and crop management, was extended for the small catchment scale with hydrological applications. Field-level processes within SWAT can be parameterized with results from EPIC to capture micro-level land use dynamics internally. In practice, the distinction between embedded meta models and complex models is thus fluent.

Technically, several aspects of multi-component models (MCM) are relevant with regard to model integration. First, each MCM contains an internal time stepper, the component that unambiguously defines the model time (‘sequencing’). From such an internal timing loop, submodules are called. Furthermore, the task of input data handling, internalized pre-processing (e.g. interpolation from time series, scaling, aggregation), may also be a task the model facilitates. Furthermore, data handling between modules is of key importance. Even if implemented in object-oriented languages, sub modules often ‘know’ and access data that is owned by other modules, by passing memory pointers from one component to the other. The use of pointers renders duplication of data unnecessary, with great runtime improvements – which maybe the greatest advantage of this modelling approach. But this advantage is also the largest structural shortcoming as will be discussed further below, especially if modularization and integration with other modules is aimed for.

**Regression-type meta models**

In theory, every functional form can be approximated with a polynomial, as data-based, mechanistic model (DBMM). Such a data-based model has low runtime, and serves as a representation of one sub system, for example by parameterizing the response of (computationally intensive) climate models to a range of economic mitigation policies into a polynomial, which then can then be used in optimization models.

Data-based mechanistic models decompose a complex, process-oriented model into linear response function to individual signals (called impulse-response functions, see Young 1998). A linear regression is the most simple DBMM; it only takes linear terms from a single time step. A second-order polynomial (the second-order TAYLOR expansion) also estimates interaction terms and quadratic terms. Further complexity is added if terms also take into consideration the "echo" from earlier time steps. For each output variable, the decomposition of model outputs can be automated\(^{18}\). If feedbacks are spatial maps or other functions, these simple relations have to be broadened. The regression is then based on a superposition of decomposed functions (Campbell et al. 2006).

Theoretically, the use of polynomial-type meta models is not restricted and can capture any form of dynamics (Young and Garnier 2006). However, a separate meta model is required for each interaction variable. Also, this estimation may vary in different parameter regions, and with changing external conditions. The number of model runs needed to estimate a meta model limits its applicability, depending on the specific model case. In practice, the simplification process when estimating a meta model induces learning, because it needs a good conceptualizations the system, and a harmonization of scales (Rotmans and van Asselt 2001).

Regarding software implementation, the difference between embedded process-oriented models and embedded data-based mechanistic models are not precise, so that in the further discussion, this category will be subsumed under embedded models.

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\(^{18}\)See CAPTAIN toolbox, [http://www.es.lancs.ac.uk/cres/captain/](http://www.es.lancs.ac.uk/cres/captain/)
Hierarchical coupling of models

Unlike embedded models, hierarchically coupled models remain fully separated software entities – either within object-oriented environment or as separate executables. Hierarchical coupling requires a set of services such as starting (initialization), sequencing, interrupting and stopping a model system, and the handling of data exchange between inter-operating simulations. The handling of time, especially in coupled economic-hydrological models, will be elaborated further in Section 5.2.

As an alternative to multi-component models, a hierarchical framework was tested by several research groups, as a hard-coded coupling of two or more models with dynamic exchange of data. Applications range from water quality studies (e.g. Lindenschmidt et al. 2007, using the High Level Architecture platform) to surface-subsurface interactions. Integrated, watershed-level irrigation models are also often coupled: Wolf et al. (2003) combine a root zone model ANIMO with the watershed model SWAP to analyze nitrate leaching. Conan et al. (2003) use ModFlow and SWAT for nitrate leaching from irrigated areas. Similarly, Krause and Bronstert (2004) and (2006) couples the ground water model MODFLOW with surface components of WASIM-ETH, to assess surface water – ground water interactions in a meso-scale basin in Germany. While experience on model integration for geo-chemical and physical models is improving, these approaches remain purely within the domain of the natural sciences.

Ahrends et al. (2008) coupled a field-level economic optimization model with the distributed hydrological model WASIM-ETH, specified with a RICHARDS equation unsaturated zone, full surface components, and a 3D ground water model. The GAMS-based nonlinear economic model optimizes irrigation at monthly time steps, for two agricultural land use scenarios comprised of four locally typical crops. Coupling was done with an interpreter language, and both model components were wrapped and invoked from this interpreter, so that the biophysical model could be iterated as part of an optimization. This optimization takes into account plant area, irrigation tables, yields and crop prices. Timing is controlled by a sequencer. The WASIM-ETH model is fully wrapped, and repeatedly called until (1) the system complies with a hydrological constraint, the reservoir level, and (2) the farm outcomes are optimal. This approach provides important insights, but runtime requirements of an iteratively called hydrological model constrain more complex economic questions. The importance of iterative use of biophysical components within socioeconomic models is elaborated in more detail in Section 5.2.2.

A study from Hansen, Refsgaard and Ernstsen (2007), which claims to be the ‘only agricultural catchment model that offers physical description of the whole catchment; unsaturated zone, saturated zone, and interactions between groundwater and surface water’ (ibid, p. 15), gives insights into resolution and runtime issues. Hansen couples the multi-component model MIKE-SHE for the hydrological domains within the land phase of the hydrological cycle, with a one-dimensional river flow model MIKE 11 and the unsaturated zone model DAISY, at hourly time steps. Integrated software solutions for MIKE SHE/MIKE 11 allowed for dynamic coupling that includes iterative calls to sub modules, while results from DAISY were loosely coupled through pre-processing, in order to analyze the effect of nitrate leaching from different cropping patterns on groundwater and surface water nitrate load (see also Ph.D. thesis, Hansen 2006).

When incorporating the heterogeneity of 3561 different soils and cropping patterns from DAISY into the catchment model, Hansen found that – in his study – the simplification/aggregation of land use patterns has a significant effect on model performance. However, he encountered
difficulties in identifying the relevant parameters that are responsible for catchment-level observations and suggests soil parameters, crop types and the ground water level as minimum set of key parameters. Finally, his model allowed for a reasonable reduction to 117 DAISY patterns, which were then statistically remapped to the full catchment and reduced runtime by a factor $\frac{1}{30}$. This analysis by Hansen exemplifies how a compromise in model resolution and runtime can improve model utility (see also p. 9). Such reduction of runtime enables to assess hierarchical models with automated uncertainty methods (e.g. sensitivity analysis) and to estimate macro-level impacts of uncertainty in micro-level parameters.

**Integrated modelling frameworks (IMF)**

An Integrated modelling Framework (IMF) can be defined as “analogous to a software framework, with the specialization in providing reusable components for building mathematical models (Rizzoli et al. 2005, p.5)”. Later in the same project, it was defined as “an extension of a framework, which supports multiple modelling domains and paradigms (SEAMLESS Report 6, Rizzoli et al. 2005, Executive summary)”.

The IMF's primary purpose is to link existing model implementations’ in order to save resources on component-development (Evert et al. 2005). Others phrased the aim as assisting scientists to avoid re-inventing the wheel, by developing “reusable tools for data manipulation, analysis and visualisation (Argent et al. 2005)”.

Generally, IMFs apply a modular design in software architecture. A software component is defined as ‘a unit of composition with contractually specified interfaces and explicit context dependencies (Szypersky et al. 2002, in Donatelli and Rizzoli 2008)’. A component can be developed by third parties, must have clear interfaces and must be easily interchangeable. Technically, the strict adherence to object-orientation prohibits globally defined variables or the alien use of internal data structures, e.g. by passing pointers, which is common practice in multi-component embedded models to increase runtime.

The range of IMFs available to researchers is rapidly growing\(^\text{19}\). The SEAMLESS definition mentioned above also incorporates mathematical standard frameworks, with their wide range of toolboxes (MatLab\textsuperscript{\textregistered}, Mathematica\textsuperscript{\textregistered}, GAMS\textsuperscript{\textregistered}), and frameworks targeted at specific uses, such as watershed modelling. Standard frameworks such as MatLab\textsuperscript{\textregistered} offer highly advanced tools for data handling, analysis and visualization, but may require re-implementation for a specific module, while targeted frameworks already incorporate analysis tools. Examples include ECOLEGO\(^\text{20}\) for risk assessment in dynamic system simulations, the Earth System modelling Framework ESMF\(^\text{21}\) that was developed for meteorological and climatic applications, the Australian Integrated Catchment Management System (ICMS)\(^\text{22}\), the Spatial Modelling Environment\(^\text{23}\) (SME), the environmental computing framework TARSIER \(^\text{24}\) and the ongoing develop-

\(^{19}\)For an exhaustive review, see the collection from Andrea Rizzoli, accessed on Aug 02, 2008 http://www.idsia.ch/~andrea/simtools.html#enviro

\(^{20}\)Ecolego: http://www.facilia.se/ecolego/

\(^{21}\)http://www.esmf.ucar.edu/

\(^{22}\)CSIRO Land and Water; Cooperative Research Centre for Catchment Hydrology (2001): http://www.cbr.clw.csiro.au/icms

\(^{23}\)Thomas Maxwell (1997), http://www.sourceforge.net/smodenv

\(^{24}\)TARSIER: http://ecoviz.csumb.edu/tarsier/
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An IMF for environmental modelling typically has the following features:

- a development environment in which new components can be built or existing components can be adapted and integrated into the framework;
- a library of model components that were previously integrated, tested and are available for re-use;
- a library of modelling tools that fulfill common tasks, which include data processing, data analysis and visualization;
- a template on which model components and modelling tools can be arranged and combined, which defines time sequencing, a spatial cellular components and data management;
- an integrated system for documentation and communication, both of data and models. A general but semantically transparent language such as XML is often used.

Other desirable features include a central server for maintenance of component- and tool libraries; a system or peer group of source code quality assurance; and finally, a model execution system that facilitates large-scale computation and data handling, e.g. parallel computing for parameter variation experiments (Argent 2004).

One ‘slim’ example that successfully integrates surface land use, surface hydrology, groundwater hydrology and a GIS data base is the PIHM-GIS framework (Bhatt, Kumar and Duffy 2008). This IMS combines an open-source GIS platform with a toolbox of model components that are easily amendable and a growing collection of post-processing routines. Specifically, the PIHM-GIS uses triangular spatial resolution, which greatly facilitates the handling of multiple scales and the modelling of different areas in different resolutions, as the case study allows and as runtime consideration demands. Components are compiled into a single source code.

As more complex example, the SEAMLESS modelling framework was developed for agricultural planning support in Europe (see text box). With regard to quality assurance, neither uncertainty assessment nor quality assurance is mentioned within project documents. Structural validity control is mentioned only in one of the project assumptions: Nr. 8 (see Ewert et al. 2006a, p. 42) states that a ‘project implemented in SEAMLESS-IF requires interdisciplinary scientific expertise on the agricultural systems and technical expertise on SEAMLESS-IF itself, to confront the risk of error propagation due to the complexity of the system simulated’. The only further reference to quality, uncertainty or error is made with respect to data quality.

In comparison to Multi-Component Embedded Models, the IMFs combine increased generality with an increased level of abstraction. The IT knowledge required is also broader and beyond a single programming language that typical modellers have if trained in disciplines, and the involvement of IT specialists cause large overhead costs. As a result, most large software applications are typically hosted in specialized (often public) modelling agencies with adequate technical support that guarantee continuity. Very few projects are hosted at Universities (compare ESMF homepage).

\[\text{TIME: http://www.toolkit.net.au}\]

\[\text{HLA in Germany: http://www.kompetenzzentrum-hla.de}\]
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In addition to the development of model components, research on model ontology and model semantics are currently the core focus of research within SEAMLESS. Of a total of 90 project publications, these two topics are represented with 31 (ontology) / 30 (semantics) journal or conference articles, which reflects the current state of research on IMFs. Furthermore, methods for Integrated Assessment is covered with 10, policy indicators with 8 and others topics (database, user involvement and evaluation/application) with another 10 papers.

Lessons on the use of Integrated modelling Frameworks have been and are being developed (for a review, see Argent 2004). Argent et al. (2005) compared three modelling frameworks for environmental applications; ICMS, SME and TARSIER. While the goal of running the same model in all frameworks was not achieved, different strengths and weaknesses of these model systems became apparent. A valuable lesson is that frameworks tend to be promoted by developers and that a neutral selection of IMFs, based on objective criteria, is rare.

The SEAMLESS modelling framework for agricultural assessment

To analyse the dynamics of farming systems, which are under constant pressure to innovate and change, the EU-funded project SEAMLESS-IF suggests ‘an integrated framework offering a generic, flexible, modular and operational structure’ for an ex-ante assessment of agricultural, environmental and rural development policies. The program brings together 29 research institutions from thirteen European countries, from Mali and from the USA. The software spine is an OpenMI+ Framework Architecture (SOFA) infrastructure layer that will guide users choosing the appropriate models, model/tool combinations and data bases for the various policy evaluations of agricultural systems (Ittersum et al. 2006).

The software offers a collection of models, infrastructure software to link these models, tools for data manipulation and reformating, a set of indicators, and finally tools for visualization.

Key importance is given to the need for “pan-European databases for environmental, economic and social issues. Some indicators, particularly social and institutional ones, will be assessed directly from data or via a post-model analysis”.

Models as framework-independent components

The core criticism of Integrated modelling Frameworks is that application outside of their developing community is rare, and if someone reuses it then seldom more than once (Donatelli and Rizzoli 2008). One reason for this is, according to these authors, that “targeting a model component to match a specific interface requested by a modelling framework decreases its re-usability” outside of this framework. In other words, the costly adaption of one model to one framework will cause a path dependency that research managers are not willing to pay. If research managers are assumed to be rational, they will ponder research returns, management risks (e.g. the resource requirements for maintenance of the software system, the appearance of new errors, knowledge management and continuity within the research group) and the additional time required to shift from the current modus vivendere to the new framework. In recognition of this problem Donatelli developed two components that ‘target the intrinsic re-usability and interchangeability of model components’ within the ongoing EU project SEAMless: a solar-radiation

\[\text{http://www.seamless-ip.org/SEAMLESS-IF.htm, on 19.12.2007}\]

\[\text{Project webpage, on 20.12.2007 http://www.seamless-ip.org/Nutshell.htm}\]
model (Donatelli, Bellochi and Carlini 2006b) and a component that computes reference evapotranspiration (Donatelli, Bellochi and Carlini 2006a).

Framework-independent components are libraries of models that use a data exchange standard, which can then be included into any IMF that is compliant to this standard. In addition to a data standard, framework-independent components require structural standards such as generic call formats, and documentation standards. Instead of linking their products into a specific IMF, model developers can adhere to this data exchange standard and to the structural standard, and their product can be re-used from a wide community. Also, the transition from integrating a component into one or a multitude of competing IMF’s toward framework-independent standards will greatly facilitate the diffusion of knowledge on coupling. The further section summarizes a newly evolving paradigm as a crosscutting theme during IEMSS conference 2008 discussions rather than an established method. However, the recognized need for a general framework standard within the leading scientists in integrated environmental modelling is relevant for those who are now outlining medium-term projects. Thus, this section is targeted to model developers in a language that IT specialists would not necessarily find appropriate.

Framework-independent component design is based on a strictly object-oriented software architecture. Input data is stored in a general template class, the DomainClass. For each parameter, this class contains (a) a specification of values, including min/max values and default values, and (b) an error handling component, the PreconditionClass. The model must be implemented in an application programming interface (API), e.g. in a Create-Set-Call pattern that is invoked by the interface (Donatelli and Rizzoli 2008).

Models are implemented as ‘stateless’ entities, which are fully determined by the DomainClass used to instantiate them, and lack any memory to past events. The use of such a framework-independent component requires the capacity for a full memory dump and re-initialization at any invocation event at reasonable runtime and the creation of specific interfaces, the scripting of which can be automated with an appropriate data ontology. Finally, each model is encapsulated within a StrategyContainer, which combines the model component itself and an interface class for a specific environment/framework. Strategies may be simple or composed, in other words a strategy can contain further strategies/models. For implementation, a specific strategy has to be defined. Within the framework, a model instance is then called with:

\[ \text{update}(\text{DomainClass} \, d, \, \text{Strategy} \, s) \]

Several IT solutions are currently being developed that facilitate the generation of framework-independent components. A prominent standard for data interchange is the OpenMI standard for model coupling (Blind and Gregersen 2005 and Tindall 2005). Funded by the European Commission, this project seeks to develop a standard for modelling interfaces for river catchment management. The lessons learned within the OpenMI project also contributed to the recognition for a structural or meta standard for model components.

A key difference with the bi-directional (send-receive) philosophy of hierarchical couplers, the OpenMI is based on a ‘listener-events’ paradigm, which conforms with the DataType/Strategy method. Within a model, different ‘listeners’ invoke sets of events that include both computation and communication of data. The listener receives a reference to the object that was modified and must then call a function to ‘pull’ the information from the model. A model can further ‘introspect’ and ‘reflect’, i.e. describe its status as a component of the coupling framework. This means that meta data describes how and when information may be communicated, which
types of listeners exist, and which methods should be called from each listener. The OpenMI platform supports the automatization of the sequencing of data exchange, with a routine that uses the introspection of all models and subsequently suggests sequencing options.

A standard framework such as the OpenMI will offer great advantages. Already, function libraries for re-scaling, interpolation and re-formatting of data are evolving. Furthermore, distributed computing under Java and C#, using the .NET-framework can be supported through generic functions, to facilitate parallel computing within a network. In theory, the framework is platform independent.

On the other hand, the source code of existing modelling software is usually not compatible (‘compliant’) with these new standards of OpenMI. Depending on the type of model, the efforts required to upgrade legacy code can be considerable (conference participants reported half a (wo)man-year of the original model developer for a process-oriented hydrological model). Furthermore, the platforms Linux and Unix were insufficiently tested during 2004, as was communicated to us by developers.

As a strategy to bring forward framework-independent modelling, libraries of models that fulfill the same or similar functions within IMS are being developed. These allow for the detailed and case-specific adaptation of model systems to specific scales and problems. These libraries allow for ensemble modelling, which is the application of multiple different models to the same problem – both for validation and to improve model outputs. A model result is called robust if it it is stable over all models tested. For example, Guber et al. (2006) compiled 22 different pedo-transfer models, applied all of them in 60 locations, and compared results with individual model runs and with laboratory experiments. Guber et al. found significant improvement for mean ensemble model runs. Similarly, Kraft et al. 2008 is compiling solute and flux libraries for catchment models and uses the Simplified Wrapper and Interface Generator (SWIG, www.swig.org) to provide interfaces for other model frameworks.

The combination of framework-independent model libraries, automated parsing of interfaces, ensemble modelling and ultimately data interoperability is likely to revolutionize environmental modelling over the next decade.

### 3.2.3 Crosscutting Software Issues

Independent of the integration level, a few practical software issues are frequently mentioned (e.g. HarmonIt 2002, Ahuja et al. 2005, Rizzoli et al. 2005), especially in gray literature. Because they are highly relevant for the practical side of a model integration process, they are briefly described in this section.

#### Documentation

The first software issue relates to the quality of documentation regarding the underlying theories and assumptions of the model and how assumptions were implemented technically. Journal publications are often too condensed and user manuals lack the technical detail. Furthermore, documentation also includes the readability of the source code, which normally improves with reuse by others and over time.
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Property rights and license costs

Software reuse outside of the developing team requires careful consideration of property rights with regard to access to the source code, but also the re-distribution of changes and improvements. Models may be accessible but protected or inaccessible. Rights on components, such as graphical user interfaces, are often handled separately. Also, software might work well with other licensed software, so that a freely distributed data processing tool might require very costly commercial packages (e.g., a GIS system). Quickly, these systems become too costly, especially in large and de-centrally organized research projects with partner institutes in developing countries.

Platforms

A closely related issue is portability between operating systems, especially between Windows and AIX/Linux. Portability issues not only concern the source code itself, but also tools, front-ends and back-ends. Especially for large computation experiments, for sensitivity analysis and for parallel processing, AIX/Linux is a de-facto standard environment, while many front-ends, such as spreadsheets and GIS software, are more readily available (or preferred by users) on Windows machines. Intermediaries, e.g., web-services, can be used to transfer data from one system to another, but then additional budget must be assigned to IT specialists.

Data formats and data interoperability

Another specific challenge of integrated assessment is that scientific disciplines use specific data formats and data standards that have evolved within disciplines. In IT, data frameworks exist that describe data content (e.g., using the Extensible Markup Language XML, see Argent and Krämerkämper 2002). Furthermore, data standards are becoming widely used (e.g., Network Common Data Form netCDF29). While data description standards use a common language that multiple programs can interpret consistently, the data standard netCDF also offers I/O functions in languages like C, C++, JAVA, FORTRAN, to facilitate the passing of data between applications and platforms. The particular format netCDF is restricted to handle in n-dimensional arrays and coordinate systems, as “a collection of self-describing, portable objects that can be accessed through a simple interface (The NetCDF Users Guide)”. Because NetCDF is limited to spatial data and arrays only, it is useful in the domain of the natural science, but not adequate to handle socioeconomic information.

Efforts are ongoing to standardize data exchange platforms, under the term ‘data interoperability’ (Dibner and Arctur 2008). Within the EU project SEAMLESS (Blind and Gregersen 2005), an integrated data base for agricultural EU data is being compiled and will become openly accessible. It includes more than 350 table structures, with more than 500 relations (Janssen et al. 2008).

However, decisions regarding data formats in research projects are not simply technical IT problems. Instead, especially with the integration of socioeconomic models and biophysical models, data format decisions must consider the institutional contexts of individuals and their computational capacities and software preferences. For example, the data standard NetCDF® and data management systems such as R® and MatLab® are widely used in the natural science,

29http://www.unidata.ucar.edu/software/netcdf
3.2. LITERATURE REVIEW ON MODEL INTEGRATION

while Excel, GAMS and SPSS are de-facto standards in many socioeconomic departments. Often, from a procedural point of view, the optimal IT solution is not implementable within the institutional context and is thus not realistic within a project framework. Instead, data formats must match the preferences of all project partners, in order to achieve general acceptance and use.

Inter-operable solutions within the IT field exist, but diffusion into the research community is still limited. The diffusion and acceptance of such IT solutions requires (a) awareness and knowledge about them, (b) sufficient confidence to use them, (c) and on-going access to financial and human resources that are required for adaption (Dibner and Arctur 2008).

Data management

It is the norm rather than the exception that data sources have different frames of reference: Socio-economic data are collected at the district level, as sub samples that allow for the parameterization of distribution functions. Satellite data are coarse maps with few categories. Agricultural censuses or registries may be very detailed, but their use may be restricted by privacy regulations. A shared database requires agreement on a common resolution. Again, this is a source of error because of averaging, statistical extrapolation, or spatial randomization of coarse data. It requires additional resources to create translation functions for each domain, to analyze the uncertainty this creates, and to document the whole process.

Data managers, disciplinary scientists and project managers thus need to agree on and implement a common sampling frame (Berger and Schreinemachers 2006). Such a data frame is constrained by scientific and statistical considerations, limited by data availability, and must be based on a team compromise, taking into account all team members, the distribution of costs between them for data generation, and computational capacities.

In publicly funded institutions with long-term perspectives, integrated information systems are being implemented, e.g. for multi-scale water management in Australia (Herron et al. 2008). Knowledge management systems facilitate the communication and documentation within integrated projects. Targeted at EU-type, large and international projects, Scholten et al. (2007) developed a modelling support tool (MoST) that is designed to meet the modeller’s requirements across scientific domains, for a wide range of user types, application purposes, and job complexity. However, for relatively small research projects, linking to such new information management systems is still in its infancy.

Innovation and software diffusion process in research

In 1999, Eric Raymond’s famous manifesto The Cathedral and the Bazaar convincingly contributed to the acceptance of a new software development paradigm that is ‘adaptive, thousand-eyed and evolutionary’ – and contrasted to the ‘centralistic’ or ‘hierarchical’ or ‘closed’ software that many software companies favour. Leading to a break-through of Open Source Software (OSS), he convinced the Linux developers to open the Kernel source code to the world wide web. The deep openness and responsiveness to users and customers also lead to an unforeseen improvement of software quality, which allowed the Linux System to develop from a prototype into a de facto standard for computation-intensive modelling software, in less than 10 years\textsuperscript{30}.

\textsuperscript{30}The characterization of a bazaar as ‘chaotic’, or even ‘anarchist’ is misleading, as it is based on the unwritten law, and conflicts are resolved on the basis of the strongest written law a Muslim knows. Raymond understands
Nakakoji et al. (2002) looks at evolution patterns of OSS for different software purposes. She distinguishes three classes of OSS: exploration-oriented, which aims at pushing the front line of software development forward in a collaborative style, utility-oriented OSS, which evolve from partial solution for a particular functionality, and service-oriented OSS, for already evolved applications with a large user community. Her studies suggest that exploration-oriented softwares are organized as ‘cathedral-type’ structures with a central leader, which strongest weakness is its tendency to split into separate branches. Utility-oriented packages are often organized as bazaar, to satisfy a wide range of individual needs. The centrifugal forces of specialized, but parallel applications are causing a tournament-style evolution of many projects. Finally, more advanced and utilized OSS are evolving at slowed pace, which is controlled by a central council. Examples include the Apache server, PostgreSQL databases, and the Linux kernel. This service-oriented type has reached a degree of structural stability, and constant interfaces. Indeed, the stability and reliability of an internal layer offers space for bazaar-type outer-layer applications.

Despite the generally acknowledged need for model reuse and despite the availability of software frameworks that were created to facilitate this reuse, Voinov et al. (2008) questions ‘why open source has been so successful for software development, yet open models are still quite exotic’. He identifies reasons both in the nature of modelling software and in the characteristics of the research community (its motivations, technical skills and communication capacities). For the time being, the management of most modelling software has not yet reached the maturity of Open Source Software.

Scientists are likely to adopt IT solutions if they reduce development costs. Because the free-rider principle can also be applied to research processes, contributions to software systems at early development stages are difficult to obtain and development of new software requires large initial efforts Dibner and Arctur 2008. Later, the development of software packages has increasing returns to scale. Thus, after the initial creation of multiple software solutions that co-exist in parallel, few or only one solution tend to dominate the market.

Dibner explains the adoption process of inter-operable software solutions with Roger’s diffusion theory (see also page 137). Whether a software solution can evolve into a standard depends much on how it is adopted by users. Path dependency becomes the primary challenge to the enduring acceptance of a software. Thus, to establish a standard it is necessary to promote a software within the wider user community.

To describe the promotion of an integrated software solution, Dibner and Arctur uses language from the business world, which again was taken from the Japanese philosophy of war (Moore 1991), and recommends concerted action to establish a common standard to inter-operable software solutions:

1. Target the point of attack, by assessing and defining the product needs of the user community – in universities and in specialized research agencies;

2. Assemble innovation forces, by bringing together existing and accepted solutions from different branches of IT and modelling research;

3. Define the battle, by outlining how models and institutions can be involved in the use and application of such standards; and finally

4. Launch the invasion, as concerted action of development, communication outreach, funding – and a long-term commitment of relevant institutions that encourages bandwagon effects.

The OpenMI as data interchange standard, which was developed with the support of the European Commission, is a good example of an emerging standard, which many IT specialists like and which has been prominent in recent conference literature\(^{32}\).

### Quality Assurance

Quality assurance and uncertainty management remain the Achilles heel of all large and complex models, independent of the software architecture chosen.

Source code verification becomes increasingly complex, especially if modules cannot be initialized and run separately, or if an integrated model system is implemented in multiple languages that a single person cannot overview because of knowledge constraints. Especially if multiple individuals share the responsibility for a source code that describes a single cause-effect chain, then technical uncertainty increases.

Also, adding a new component can reveal earlier mistakes in data that were concealed before: a developer of a widely used catchment model SWAT reported ‘interesting’ behavior when the model was extended by a dynamic organic carbon module: miss-specification of formerly non-sensitive data suddenly invokes unexpected and false model behavior. Furthermore, adding new modules (integration) can reveal source code errors, which may have been similarly compensated for, i.e. with calibration parameters that are false but ‘behavioral’ (e.g. the ‘effective soil porosity correction’). Such compensation among errors is typical for complex systems with high degrees of freedom, which allow for a wide range of equifinal parameterizations (Beven 2001).

Within the Distributed Model Intercomparison Project (DMIP), the performance of several models was compared in ensemble modelling experiments (Georgakakos et al. 2004). Participants concluded that the mean over the results of all models consistently outperformed each single model. However, the modelling of nested sub basins with varying sizes is especially demanding (Smith et al. 2004 and Reed et al. 2004).

The technique of ensemble modelling compares multiple model realizations for a single problem. Here, an outcome is robust if all models show the same pattern, and uncertainty is large where strong deviations occur. This method is generally accepted for climate change modelling, but resource needs are beyond the scope of hydrological or socioeconomic studies within the existing research context. To explore the method of ensemble modelling in land use hydrology Furthermore, Viney et al. (2005) parameterized, calibrated and validated an ensemble of ten catchment models with varying complexity, for the same basin (a small tributary to the Rhine), and compared performance\(^{33}\). This study, which involved 18 authors (with their research groups), compared how models handle preprocessing of ‘typical’ raw data, but structural differences in the models through the use of an artificial dataset with high resolution. The study reveals strong

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\(^{32}\)For a list of ongoing conferences on the OpenMI, see the project WIKI [http://public.deltasres.nl/display/OPENMI/Conferences](http://public.deltasres.nl/display/OPENMI/Conferences)

\(^{33}\)Models used are DHSVM, HBV, IHACRES, LASCAM, MIKE SHE, PRMS-MMS, SLURP, TOPLATS, SWAT, WASIM-ETH
model uncertainty in distributed models that is caused by data preprocessing and concludes that semi-distributed models perform better with regards to global sensitivity.

### 3.2.4 Procedural Guidelines On Model integration

On the quest for procedural knowledge and insights on how to integrate models for the specific NRM questions and relate to the project context of a group project, the literature from multiple disciplines was reviewed for guidelines. Research communities using integrated models deal with topics ranging from spatial modelling techniques (e.g. International Conference on Integrating GIS and Environmental modelling\(^{34}\) or the EcoMod network on integrated economic and environmental modelling\(^{35}\)), to agent-based modelling methods (e.g. International Conference on Autonomous Agents, Melbourne), integrated modelling for water management (e.g. International Conference on Adaptive & Integrated Water Management\(^{36}\)), and methodological issues (e.g. International Environmental Modelling and Software Society\(^{37}\) or the MODCOM conferences from the ‘Modelling and Simulation Society of Australia and New Zealand’). The number of projects that are carried out in the realm of integrated modelling for water management is increasing and each project provides new lessons.

Before adapting a method for model integration of interdisciplinary models, it should be clarified that this method is adequate with respect to the research topic and system under analysis, but also with the process constraints within the research context, in order to achieve optimal results. The ‘optimal’ solution takes into account both technical objectives and resource requirements in terms of human resources, as well as time and financial needs. The final solution is usually a compromise from each point of view.

There is a mature body of literature on model evaluation guidelines (e.g. Moriasi et al. 2007) and on good modelling practices and principles. For model-supported quality assurance in water management, the EU project HarmoniQuA (Refsgaard et al. 2005) compiles modelling guidelines for uncertainty communication in large projects (Van Der Sluijs et al. 2005 and Refsgaard et al. 2007). Similarly, codified guidelines define the responsibility of scientists to communicate uncertainties, (e.g. Walker et al. 2003, Van Der Sluijs et al. 2005 or Refsgaard et al. 2007, Funtowicz et al. 1999).

Letcher et al. (2007) suggest a “generalised framework for integrated assessment modelling of water allocation options”, which “provides a generic conceptual model for a nodal network approach to considering water allocation”. This framework offers a terminology to describe and document system components within an interdisciplinary and integrated assessment, but does not provide insights on further organizational characteristics of the assessment process itself.

For model-assisted stakeholder processes, uncertainty management has become a prerequisite and a cross-cutting issue in all water management conferences (see Pahl-Wostl 2002 or her homepage for an overview\(^{38}\)). One pillar of such stakeholder processes is the institutional context of the case study regions. The participation of researchers can influence these institutions.

\(^{34}\)http://www.ncgia.ucsb.edu/conf/

\(^{35}\)http://www.ecomod.net/

\(^{36}\)http://www.newater.uos.de/caiwa/

\(^{37}\)http://www.iemss.org

\(^{38}\)http://www.usf.uni-osnabrueck.de/~pahl/forschung/publikationen.en.htm
so it is important (however not always given) that researchers develop an awareness for this. Because consequences are not always favourable (see Work package 5, Harmoni-CA 2004\textsuperscript{39}). An increased awareness of the institutional context is one way to overcome disciplinary biases and to avoid past mistakes, which Ashby (2001) calls ‘the rational fool syndrome’ in natural resource management science. These mistakes range from unintended consequences at longer time scales or in other sectors, or low performance under less-than-perfect climatic conditions. The participation of a wide range of stakeholders is expected to raise awareness for such unintended results and thus improve policy outcomes.

Output-oriented watershed managers must prioritize and select an adequate model for a specific problem. Boorman et al. (2007) recently notes that guidance on the handling of models ‘is relevant once the modelling process is underway, but at the start of this process it is necessary to select the model to be used, […] but] there is little practical advice on model [software] selection’ (p. 634). Therefore, Boorman develops a selection protocol. Key aspects of Boorman’s selection protocol including modelling objectives, model functionalities, data requirements and output formats, and the interaction with end users. Optional factors are the model’s temporal and spatial resolution, its adequacy in process representation and complexity, parameterization and data, sensitivity and analysis, model validity and verification, further development and efforts needed to do so, and documentation. Both conceptual model selection and the selection of a software is done by water managers (as users of modelling results) in conjunction with the modellers (as users of the modelling software). Drawing on Oreskes et al. (1994), the duty of a modeller is to demonstrate the ‘level of correspondence’ between the model and the real world. The Boorman’s model selection protocol is thus a codified and organized way to demonstrate this suitability to the water manager.

The setting in which agent-based modelling is done is very heterogenous. It ranges from research projects of individual scientists or a Ph.D. thesis (e.g. Berger 2000 or Huigen 2004); medium-sized research projects on companion modelling and role-playing games with key informant groups (Barreteau et al. 2001, Becu et al. 2007, Barreteau and Abrami 2007) and consensus-building as stakeholder process (Etienne et al. 2003). Other project organization settings are large international project consortia where scientists are located in different places (15 institutes from 12 disciplines in 10 countries), projects that are fully executed within a single organization or university (10 disciplines that reside in the same institution) or within specialized modelling agencies with permanent technical staff (weather forecast services, oceanographic or climate centers, watershed management centers). No comparative literature was found on which research setting is appropriate for which type of modelling objective and on which modelling objectives should be aspired within which organizational form of a research. However, the research setting does impact on which calibration and quality assurance methods are feasible within a project frame, related to the frequency of interaction, the cultural homogeneity of staff, flexibility in funding and technical support.

The mature body of literature on how to use a model is in sharp contrast with the comparative lack of guidance on how to select a model, and Boorman et al. must largely rely on grey literature, on experience and communication with other researchers in compiling a model selection protocol. For Integrated modelling Systems, the grey literature published by SEAMLESS

\textsuperscript{39}http://www.harmoni-ca.info/
CHAPTER 3. THEORY ON MODEL INTEGRATION FOR NRM

(see Section 3.2.2) was found very helpful because it describes work processes as well. Furthermore, the developers of most modelling systems usually indicate how to use their specific system. However, no guidelines were found that support the selection of methods for integrated modelling, answering the question ‘Which integration approach is appropriate to a specific research context?’ In the next chapter, a set of criteria is defined to foster the development and codification of such knowledge.

3.3 Discussion

It is neither intuitive nor trivial to decide on an approach to model integration: the architecture of coupling and the selection of model components must be matched with the resources required for software-intensive model coupling. Ultimately, these resources must be justified by an improved quality of information/knowledge that a model gives, within the time frame dictated by the funding mechanism. Unforeseen and seemingly minor details, such as a hidden assumption in one component, a scale mismatch, a missing logical link and or a mismatch of paradigms may erode the validity of the entire integration effort. In practice, Donatelli and Rizzoli (2008) claim that few integrated modelling frameworks are actually practically applied outside their developing community. He uses the use of the software by third parties as a benchmark. The use of that software shows that a public good with value was created, and justifies the initial funding with public money.

I showed that – considering the large number of projects on integrated modelling – surprisingly few lessons on the research process itself are documented. Especially the interplay between the institutional setting of academic project, the integration methods, and the technical as well as human resource requirements is rarely discussed in the literature. To make the investment into future research projects more effective, it is necessary to summarize and mainstream existing lessons.

It is self-evident that the development of international software standards, as is the goal of the OPENMI project, necessitates long-term commitment from a developing team and from their funders. The successful development of standards builds on the institutional leverage of the promoting agency to build confidence in the targeted community of adopters, on high-quality communication and successful communication between developers and reach applied researchers, and on the considerable efforts of innovative individuals (Dibner and Arctur, see also Section on data interoperability on p. 41). If standards have not reached the necessary maturity, then they are not an option for the majority of scientists.

There are existing IMFs from which researcher can choose. However, while most systems on offer were tested by external groups, these tests seldom go beyond a single case study or a specific set of problems. The entry barrier for non-specialists to become acquainted with the framework and to re-factor and integrate their own models into the standard remain high (Donatelli and Rizzoli 2008). On the other hand, components that are offered are usually simple, ‘atomic’ models. Research and funding mechanisms have led to what Evert et al. (2005) calls a large set of YAMF’s (Yet Another modelling Framework), with high investments of human and financial resources, but low adoption rates amongst non-developers.

Embedded, multi-component models similarly tend to produce legacy code, which is knowledge from good scientists embedded in badly structured software, because the original developer, often during his/her Ph.D. thesis, never envisioned the continued use of it, and was not
trained in software development. An advantage that embedded models have, in comparison to all component-based models and all script languages, is the deep linkage of components through direct access on memory (pointers), which increases computational speed, often by orders of magnitude. However, the core disadvantage is also the entanglement of code through these same memory operations, which hinder the distributed and parallel development of software code and preclude the integration of embedded models into component-based modelling frameworks.

Dynamic coupling is a straightforward approach that is consistent with the mind-sets of researchers, and with the institutional setting of most research organizations. On the one hand, the integrity and independence of research and data structures is fully maintained, while the software overhead needed to ‘migrate’ a model into a ‘compliant’ format is by far lower than for an IMF. However, few of the examples published actually seem to be re-used, and particularly ‘hierarchical’ or dynamic coupling systems often remain single-case efforts.

A model-integration protocol, which not only enumerates the ‘theoretically desirable’ technical work steps in a normative manner, but also highlights the specific difficulties related to the research context of a project, was not found. Thus, the method used for model integration described in this thesis builds on lessons from various disciplines, but cannot be attributed to a single source.

Furthermore, the number of lessons on model integration is increasing with each project. However, they seldom explicitly analyze the inter-relationship between scientific objectives and research structures within the model integration approach chosen, nor do they discuss the type and quality of results.
Chapter 4

Method And Material: Integration Of Legacy Models

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This chapter outlines the integration task and its context. It starts with a description of the system itself, which is Region VII of Chile (Linares Province) as the study region. It is the project ‘Integrating Governance and Modelling’ as the research context, which frames the integration task and defines research objectives, research partners (institutions and staff), the time frame and the resources available for integration and data acquisition. Also, at this level many technical decisions are made, such as the selection of modelling softwares to describe disciplinary sub systems. These existing ‘legacy’ models are also described in Section 4.3. Taking into account the system, the project objectives and constrains, the method for model integration is then described in Section 4.4.
4.1 The Study Region: Region VII, Linares Province

Since the 1990s, Chile has become a model for successful free market economies, pairing a strong specialization into few competitive commodities and raw materials, with strong government that proactively supports its producers.

With its unique location in the southern hemisphere, export agriculture for Northern markets has experienced rapid and sustained growth. An agricultural sector that is focused on high-quality products generates impressive revenues for producers, processors and traders and contributes significant resources to the government budget. Moreover, it absorbs unqualified and skilled labor and gives the nation a positive image. However, with increasingly modern production systems on one side and the remaining traditional systems, Chile’s income disparity has became one of the most extreme in the world and equitable access to productive resources is a core development objective (Lopez and Anriquez 2007).

4.1.1 The Environmental Setting

The study area corresponds to the Maule watershed, in particular its tributary sub-watersheds, the Putagán, Ancoa, Achibueno and Longaví Rivers. The area is in the 7th Region of Chile (Maule Region).

The study area covers 5300 km$^2$. The highest elevations are found in the east in the Andes Mountains, with altitudes around 3000 amsl. To the west, the land falls to 100 amsl. Agricultural production occurs on the plain to the west of the mountains, at altitudes of 100 to 200 m.

The predominant climate of the area is Mediterranean, with some variation with latitude, longitude and altitude. Four sub-zones can be identified as follows: The Eastern Region, corresponding to the heights of the Andes Mountains, has heavy snow in the winter and abundant precipitation (1,700 to 1,800 mm). The Foothills Region has a temperate climate, warmer than the Eastern Region, with five months of drought. There is less precipitation than in the Eastern Region. Winter and spring frosts limit agricultural activity. The Intermediate Region enjoys a temperate climate with a long warm season (more than 6 months) and the possibility of frost during the winter time. Precipitation is primarily in the form of rainfall and occurs primarily from June to August. The Coastal Region has a warm climate with homogeneous temperatures due to the influence of the Pacific Ocean. Although the dry season is long, there is a high relative humidity (more than 80%) due to the maritime effect, which decreases the water stress of vegetation. The Putagán, Ancoa, Achibueno and Longaví Rivers originate in headwater areas located in the Andes Mountains and later mouth into the Loncomilla River, which flows from the south to the north. In the eastern part of the study area, the Andean Melado River (located outside outside of the study area) contributes water flows of up to 20 m$^3$/s to the study area through the Melado Canal. Its impact is particularly important during the driest summer months of the year.

The basement is exposed in the eastern part of the Longaví River Basin at the foothills of the Andes Mountains; it consists primarily of andesitic lava and pyroclastic breccias. In the central and western part of the study area the basement is located at a depth of around 100 m. The crystalline rocks have been and continue to be eroded by rivers and glaciers. Upon arrival in the central valley, the rivers broaden and flow velocity slows due to a decrease in the rate of descent, resulting in the deposition of sediments; additional glacial erosion contributed and contributes to sediment transport and deposition in the eastern part of the central valley. Therefore, the Longaví River Valley shows both glacial and fluvioglacial erosion and sediment deposition (subparagraph...
4.1. THE STUDY REGION: REGION VII, LINARES PROVINCE

cited from Theune 2007, Ch. 5).

The majority of the rock of the Longaví River Basin consists of unconsolidated sediments with particles sizes that range from clay (<200 µm) to gravel and rocks with diameters of 30 cm, which allow relatively easy digging of wells. Further analysis of data from DOH suggests that the soil layer thickness ranges from 1 and 3 m, before the unconsolidated sediments starts (Theune 2007, Ch. 5).

4.1.2 The Maule Irrigation System And Irrigation Infrastructure

Until the beginning of the 20th century, the Maule Region was covered with a dense network of irrigation canals (Ministerio de Agricultura 2005), mostly because of uncoordinated private initiatives. In 1915, the government began constructing all major irrigation infrastructures. From the beginning, government initiatives were based on a user-pays approach and intended to devolve ownership of the infrastructure, as well as responsibility for its maintenance, to local user organizations. Both aspects were rarely realized until major program was initiated in 2002 (ibid, p. 10). In retrospective, the Ministry of Agriculture states that the ‘development of irrigation was not as successful as aspired’ (ibid, p.10), because of a lack of financial resources, lack of clarity regarding property rights to these projects, and local and regional political pressure. When implemented, the realization of infrastructure construction projects was often too slow and not in line with national priorities, instead responding to local and sectoral objectives. As a result, the government places high importance on multi-sectoral planning and aspires to cooperate closely with future users (ibid).

There are three main irrigation areas in the Maule region: Maule Sur, Melozal and the Melado system. The system Maule Sur is situated in the province of Linares, and includes the municipalities of Colbun, Yerbas Buenas, San Javier and Villa Alegre. It covers approx. 50,000 irrigated hectares. The canals are administered by the provincial association Maule Sur (SORPAM) and other minor associations. The system Melozal is located in the provinces Linares and San Javier, west of the river Loncomilla. With 12 m³/s, it irrigates approx. 7,000 ha.

The system Melado captures water from the Melado River in the Andes and discharges this into the Ancoa, Putagan and Achibueno Rivers, which carry their natural runoff into the area as well. The network of irrigation canals reaches approx. 55,000 hectares and is located between Putagan and Longaví Rivers. It can be further subdivided into the areas (1) north of Achibueno River, (2) south of Achibueno River, and (3) the area between Achibueno and Liguay Rivers.

Important major canals are the Robleria and Llepo Canals that depart from the Ancoa River, the Longaví Canal that departs from the Achibueno River, the Putagan-Matanza Canal that departs from the Putagan River and the Liguay Canal that departs from the Liguay river.

The area currently receives water from two major reservoirs, Laguna de Maule and Bullileo. The Laguna de Maule reservoir has a capacity of 1.570 Mio m³, which is shared between irrigators, the electric company ENDESA and other uses. An agreement between the Direccion de Riego and ENDESA ensures that the maximum winter demand of ENDESA is limited to 250 Mio m³, while 800 Mio m³ is reserved for irrigation and is overseen by the Junta de Vigilancia del rio Maule. The study area receives some of these flows (we call them ‘external inflows’ because the reservoir itself is outside the study region), especially affecting the northern-most sectors. The second reservoir, Bullileo, is located 52 km east of Parral and has a capacity of 60 Mio m³ or 32,400 ha. Water is fed into the Bullileo River, which later discharges into Longaví River, and is administrated by the Junta de Vigilancia del Rio Longaví.

In 2008, the construction of a third reservoir has begun, which will enclose the Ancoa river.
(a) The study area (map by Alexandra Theune)

(b) Elevation and rivers (map by Hamil Uribe)
4.1. THE STUDY REGION: REGION VII, LINARES PROVINCE

4.1.3 The Agricultural Sector In The Maule Region (VII)

Agricultural crops in the Maule Region. In the Maule Region, 200,000 ha of agricultural land are made up of 130,000 ha of staple crops, 53,000 ha fruit plantations, and approximately 15,000 ha vegetable production. Intense forestry production (pine, eucalyptus and poplar) is often practiced in the foothills of the Andes, on soils that are (or have become) inadequate for agricultural uses (ODEPA).

In the national context, the Maule Region produces 19% of the total staples and 22% of the total fruits. The region is well-known for the production of export fruits, especially apples (59.25% of national production), cherries (41.8%) and kiwi fruits (51.5%). In terms of annual staple crops, for the years 2000 / 2005, the area surrounding Parral is Chile’s primary producer of rice (70% / 78%), while also producing significant shares of the total beans (50% / 53%), chick peas (40% / 44%), sun flower seeds (34% / 36 %), lentils (24% / 30%) and sugar beets (34% / 26%) (ODEPA).

The most notable trend between 1995 and 2006 was the rapid decline of rainfed winter wheat production, in response to increasing maize production. Sugar beets, which were produced in the context of direct contracts with a local sugar refinery, have ceased to be important, because import tariffs were abandoned in 2001. Potato and rice production was relatively stable, while the production of beans declined considerably from 18,000 tons in 1994, to less than 12,000 tons in 2006.

During the last decade, the production of berries for export has gained importance, especially raspberry and blueberry production. While raspberries are often grown by small producers, with low levels of technological inputs, the blueberry requires large technological investments from medium-sized farms. Because of the high volatility of the price for raspberries on international markets, producers have repeatedly entered and abandoned production. In contrast, labor-intensive blueberry production is experiencing slow growth (SEREMI, personal communication).

At national and region levels, the peak demand for labor is experienced in the harvest season (January - March, see Figure 4.1). Particularly in the Maule region, a significant shift in labor requirement is observable, between December/January and February/March. This shift can be
CHAPTER 4. METHOD AND MATERIAL: INTEGRATION OF LEGACY MODELS

Figure 4.2 — Production of major agricultural commodities in Chile and in Region VII

partially attributed to the rising importance of labor-intensive berry production and to a lesser degree by the shift from rainfed winter wheat to maize cultivation.

Vegetable production remains fairly stable, while SEREMI reports a slow and constant decline in the number of producers (4.1.3, b). Production is mostly carried out by small producers and marketed nationally and locally. A notable exception is asparagus, which is also exported.

The sharp decline the production staples in 1998/9 is related to a prolonged drought, which forced farmers to abandon low-value crops. Wheat and rice were hardest hit (≈ 50% losses), but beans, potato and maize were also adversely affected. Almost no impact was observed for irrigated sugar beets. In contrast, apple production collapsed in 1999/2000. According to expert opinion, this collapse was also a result of the previous year’s drought: farmers experienced a shortage of water in March 1999, which decimated the subsequent season’s production.
4.1. THE STUDY REGION: REGION VII, LINARES PROVINCE

4.1.4 The Population Of Farmers And Land Endowments

The study area contains approximately farm 18,000 properties that belong to 15,000 holdings with an average area of 28 ha. Water rights are held by 6,500 holdings. Furthermore, some of these holdings have a common owner, but attribution is unclear – it is advantageous for tax purposes to assign holdings to relatives. To define farm agents for the computer model, the number of holdings was used. In total, the number of independent actors in the area is about 1000 actors lower than the data suggests.

Four farm categories were defined by land holding area: subsistence farms (0 – 5 ha), small farms (5 – 25 ha), medium farms (25 – 60 ha) and large farms (above 60 ha). Subsistence farms below 3.5 ha (≈ 2 ha irrigation equivalent) were not considered within this model, because it is believed that the economic assumption of income maximization does not hold for such enterprises. Instead, most of these very small farms are part-time or hobby farms.

Before these numbers were estimated, agricultural land was filtered and only those soils suitable for production (I - IV) were considered. Histograms of the resulting maps reveal that 59% of all farms are small or medium in size and that these farms own around 70% of the total area. Subsistence farms make up 38% of farms, but only account for 5% of the area, while large farms (3%) control 24% of the area suitable for agriculture. A comparison of total land ownership of any soil quality reveals that large areas of less suitable soils are owned by large holdings (often used for grazing or forestry), while medium and small holdings primarily own land that is suitable for agriculture.

4.1.5 Water Rights In Chile.

In Chile, water management has always been linked to agricultural development policies. Its legal basis is the Water Code, which has evolved dynamically under different political climates. In 1981, the socialist code of 1973 was reformed and a totally market-oriented policy was adopted (Bauer 2005). This Water Code defined water as a ‘public property for private uses and defines water rights as a water equivalent, measured in [liters/second]. Entitlements to surface water can be traded freely and transferred to other use, once they are inscribed (‘legalized’) with the Direccion General de Aguas (DGA).

Even today, many farmers have not yet fully legalized their water rights with the government, a process that is costly and paper works that consume time and require good literacy. Nationally, Hearne et al. (2005) estimate that 10 to 50 percent of all rights are still not legalized and remain ‘customary’. Though protected by law (Donoso 2006), the values of such customary rights are usually not defined precisely, nor whether these rights are permanent or ‘eventual’, or if flows may be used continuously or discontinuously (JdV Longavi 2005). Many water user organizations still rely on traditional rules to distribute water to farmers.

Water rights of all farmers are managed by water user organisations (Juntas de Vigilancia), which ensure that all farmers receive their water entitlements. Due to the volatility of river flows, available water can be less than the amount that right holders are entitled to. In such years, most user organizations interpret water rights ‘traditionally’ as percentages of river flows (Hearne and Easter 1995) and every right holder suffers equally from a proportional reduction of water delivery. For a detailed discussion on access to water, see Section 7.5.1.
4.2 The Project ‘Integrating Governance And Modelling’

The method for model coupling and the integrated model system that is presented in this thesis was developed within and for the project Integrating Governance and Modelling, a project within the CGIAR Challenge Program on Water & Food\(^1\) (CPWF). This section summarizes the project objectives, which frame this thesis. The method of model coupling that is proposed here, as model integration method that is intended to contribute to this project, must be evaluated within this context of project objectives.

The objective the CPWF is to develop research-based knowledge and methods that can help increase the productivity of water for food and thus secure sustainable livelihoods. The project’s objective is to explore policy options that improve the management of water resources at both the local and the regional levels, aided by integrated computer models that resolve the micro-scale. Furthermore, this project analyzes existing governance structures and their ability to distribute water equitably and efficiently.

The project is divided into two case studies, one in Chile and one in Ghana. The market-oriented water policies in Chile are examined as a role model for water management\(^2\). More specifically, the case study in Chile aims to assess challenges in water management through a participatory approach with key stakeholders, to identify policy options to address these challenges, along with developing policy evaluation criteria. Based on the water management challenges faced by the modelling team, an integrated model system using MP-MAS was adapted, so that specific model use cases are developed jointly with farmer organizations and governmental institutions.

During the project, an interdisciplinary data base was compiled, which combines GIS data, socioeconomic data from census and farm surveys, crop production data, plant data, canal data, and registries on land use and water rights. Stakeholder meetings were organized, policy questions identified and subsequently transformed into use cases.

Under a (semi-)predictive modelling paradigm, a model system was built that integrates the watershed-scale distributed hydrological model WASIM-ETH (Schulla and Jasper 2007) with a bio-economic, agent-based model MP-MAS used for agricultural water use analysis (Berger, Birner, Díaz, McCarthy and Wittmer 2007a). Furthermore, components were added to the MP-MAS model, to account for specific stakeholder requests and project necessities.

General objectives of IGM project. The objective of the IGM project is to contribute to the development of integrated land and water resource management systems that are economically efficient, environmentally sustainable and socially acceptable. Increasing the understanding of institutional water management systems and developing integrated simulation models that can be used as decision-making tools by multi-stakeholder governance systems are two means by which to achieve this objective. Integrated models can help quantify externalities and trade-offs between goals of economic growth, reduced vulnerability, food security, environmental sustainability and social equity.

Furthermore, it is necessary to examine possible long term impacts of predicted changes in climate and to evaluate the effects of alternative policies under different climate scenarios. Decision-tools based on simulation models help to identify technical, economic and institutional

\(^{1}\)http://www.waterandfood.org/
\(^{2}\)Project website http://www.igm.uni-hohenheim.de/igm
options that increase water productivity and reduce vulnerability to market fluctuations and climate variability. However, selecting and implementing such policy options requires negotiation amongst stakeholders. Therefore, the project aims to contribute to the design and implementation of governance structures that produce efficient, equitable and environmentally sustainable outcomes.

Specific project objectives related to this Ph.D. thesis  To meet these general project objectives within the case study of the Maule watershed, Chile, the following specific objectives evolved:

- Identify stakeholders’ problems with water management and policy options to address these problems, along with policy evaluation criteria.
- Extend computer simulation models in order to be able to integrate stakeholders’ priorities and climate variability and change.
- Use agent-based simulation models to evaluate the policy options identified by the stakeholders.
- Develop decision-making tools that visualize the outputs of simulation models in a form that is accessible and helpful to the stakeholders.

To fulfill these objectives, the project IGM developed priorities of work. In this decision process, equal weight was given to the voice of each team member.

Project work priorities included institutional mapping of the area and a comprehensive review of stakeholder priorities. Data collection included a survey of approximately 280 farm households, the compilation of a GIS data base, a collection of land ownership and water rights registries from responsible local institutions for the complete research area, and several smaller surveys. The hydrological project members decided to use the WASIM-ETH hydrological model to replicate the water cycle, which is strongly influenced by human irrigation decisions. The model offers an irrigation module plus several options that are of interest in later stages (snow, groundwater module). Within the economic team, the multi-agent model MP-MAS was calibrated to reproduce farming decisions at the individual and at population level. Even though an calibrated model existed, concerted efforts were needed to extend the MP-MAS to new economic data and also to capture processes not previously included in the economic model. These included water rights registries at individual level, improved river flows, impact of water scarcity and canal conductive efficiency, irrigation efficiency, surplus water, the handling of deficit irrigation and risk management of farmers, and the calibration of these processes.

The team decision to couple the MP-MAS model dynamically with the WASIM-ETH model to capture river flows as well as return flows raises several methodological, conceptual and technical challenges. With regard to modelling, tasks included re-factoring of and extensions to the MP-MAS model as well as to the WASIM-ETH model. These model extensions proceeded from conceptual interpretation, to the identification and implementation of additional processes and the handling of data and the management of model scenarios. Secondly, the WASIM-ETH irrigation module was extended in order to connect the cause-effect chain of model coupling.
4.3 The Legacy Models WASIM-ETH, MP-MAS, EDIC And CropWAT

The materials of this dissertation are three legacy models, which are used in the project summarized above. Based on meteorological data and upstream flow measurements, the hydrological model WASIM-ETH simulates river flows, runoff, infiltration, soil moisture and percolation as well as evapotranspiration. The agricultural economics model MP-MAS simulates a population of farmers and their cropping decisions, by representing each farmer in the study region as an agent that endows assets and decides according to these assets, with the aim to maximize his utility. The routing model EDIC is used to capture canal flows and also to deal with water that returns into the canals, for example resulting from the use inefficient irrigation methods to produce crops. Finally, the MP-MAS model contains a module that simulates plant water demand and yields under water deficit, resembling the FAO model CropWAT.

4.3.1 WASIM-ETH

The WAter BA lance SI mulation Model WASIM-ETH is a process-based and distributed hydrological model (Schulla and Jasper 2007). For each grid cell, vegetation cover can be parameterized (single or multi-layered). Processes include interception, surface evaporation, infiltration into the top soil layer, and surface runoff. The model also includes an unsaturated 1D-vadose zone module based on Richards equation and using van Genuchten soil hydraulic parameterization. Actual evaporation and plant water uptake (transpiration) is limited by $ET_{pot}$. Transpiration depends on infiltration, vertical flows between the soil layers, root characteristics, water saturation and actual capillary pressure (suction). Excess soil water percolates as groundwater recharge, if it is not taken up by plants.

The evapotranspiration module parameterizes each land use type separately, for several physically-based modules. Potential and actual transpiration and evaporation from the surface and the interception layer is computed separately for each time step, for single-layer or multi-layer vegetation.

Routing of surface water is based on a sub-watershed approach, derived from a topographic analysis. Water channeled between sub-watersheds is either physically modeled or externally parameterized as extractions, inflows or bypasses. Return flows at the watershed level are captured through surface runoff that re-enters the river system or as groundwater that returns to the surface as base flow. Groundwater flow can be parameterized, or dynamically modeled with a 3-dimensional advection model (either with the internal groundwater module, or coupled to MODFLOW). An interface for full parallelization is provided. The flexibility, the good reproduction of both above-ground vegetation characteristics and the vadose zone, and the coupling with MODFLOW, make WASIM-ETH a good choice for modelling irrigation. However, the irrigation module was only tested in a few previous cases.

The WASIM-ETH irrigation module allows for the extraction of water from reservoirs, ground water or rivers. Furthermore, the original module allows for three forms of irrigation; automatic, by event or by a table. The automatic mode irrigates an area as soon as soil moisture is below the wilting point. This option allows for little direct control, which makes it inappropriate for coupling purposes. The event-mode requires rotations, but runoff losses are extremely sensitive to soil surface characteristics. The third mode is the one we use: Constant or linearly changing water tables specify how much water is used on which day of the year. Several changes were made to the irrigation module in WASIM-ETH, as extensions, in order to bridge conceptual gaps to MP-MAS (see Electronic Appendix C).
4.3. MP-MAS

The Mathematical Programming Multi-agent System MP-MAS is an agent-based model that can be attributed to adaptive economics. The core component is an empirically parameterized population of farmers that seeks optimal income strategies under asset constraints. The description of the population captures heterogeneous asset endowments, expectation building of farmers and their agricultural cropping activities. Furthermore, interactions between agents can be specified and a range of specialized modules exist (Berger 2001). The MP-MAS model is documented in Berger 2001, in Schreinemachers and Berger (2006) and in the MP-MAS Manual (Berger, Schreinemachers and Arnold 2007b). Please refer to these publications for a complete mathematical description.

The population of agents is spatially distributed over an agricultural landscape (Berger, Schreinemachers and Arnold 2007b). Key parameters are the number of farm agents, their family size and asset distribution (labor endowment, capital, water rights, land, the quality of soils etc.). Each agent acts as an individual entity, allocating assets to a set of activities in order to satisfy his/her utility function.

The mathematical programming (MP) approach is well-established in agricultural economics. It is flexible and can be tailored to suit local needs. The technical coefficients of the MP matrix are either constant parameters (production technologies), updated as external scenarios (prices) or are dynamically determined during runtime (e.g. effective irrigation water requirement). Using mixed integer linear programming (MILP), the system uses constrained optimization calculus within the domain of economic theory, but also allows for the extension of agent behavior far into the domain of rule-based behavior (Berger and Schreinemachers 2006).

Day’s human decision paradigm

The representation of income-generating farm decisions is based on economic theory. Within economics, we chose the paradigm of adaptive economics. Decisions, the outcomes of these decisions and how these outcomes impact on future decision making is modeled recursively, evolutionarily and adaptively, within a multi-agent framework. The paradigm of adaptive economics was introduced in 1971 by Richard H. Day. He later re-formulated core ideas of his concepts on the “microeconomic foundation for macroeconomic structure” in 2005.

Day defines rationality as “the capacity to exercise conscious, systematic, logical thought including the careful identification of things, the perception of causal relationships among them and the construction of logical procedures for solving problems or deciding among conceivable plans and actions” (Day 2005, p. 3). Within adaptive economics, the neoclassic assumption of perfect foresight and omniscience is relaxed. Both the acquisition of knowledge and decision making are regarded as costly processes. In adaptive economics, a rational human being is conceptualized as minimizing the costs of knowledge acquisition and the decision process is conceptualized as consisting of three steps or levels. In the first, humans consciously or subconsciously take up a lifestyle paradigm, which determines individual preferences, needs and wants, and narrows the range of options a human actually considers, as well as setting boundaries to the types of information in which s/he is willing to invest. Secondly, humans make strategic or directional choices. The strategic choice implies a bundle of decisions, but also requires refinement in day-to-day interactions. These daily decisions, which result from and are confined to the lifestyle and strategy, are called tactics. The adaptive economics paradigm assumes that humans permanently seek information related to their strategic choice, in order to improve and adapt the tactical decisions in daily life.
Within evolutionary economics, rational action is reflected in three flexibility levels: the lifestyle paradigm is usually assumed as constant over modelling time. Strategies adapt slowly to changing external conditions and with improved information on the range of processes considered. In addition, strategies may also slowly adapt with the incorporation of new processes or perspectives into decision-making. Tactical choices take into account the daily environment and may swiftly shift from one action to the other. Hence, tactical choices determine short-term system behavior.

Changes in lifestyle occur on a time-scale of at least ten years, but more commonly persist over a generation (25-30 years). In an economic assessment with a time span of 5-15 years, these slow changes are hypothetical and difficult to measure. Shifts in lifestyle paradigms, as emergent phenomena, are not generally the focus of adaptive economics, but may be analyzed as a special use case.

In evolutionary economics, economic behavior is formulated as a sequence of expectation-based decisions that lead to actual activities and actual outcome. These outcomes become the basis for future decisions and recursive learning can be mimicked. By doing so, the continuous time trajectory is broken up into discrete decision intervals. At each interval, actions are chosen from a set of available options, which are defined by the human’s strategic choice and, ultimately, by his/her lifestyle paradigm. Due to learning, each decision takes into account the historical time path (experience) and the anticipated future (expectations). The inter-temporal nature of a decision is represented as dynamic optimization. However, any long-term decision may be revoked once new information is acquired (Day 2005).

The complex, multi-agent model MP-MAS uses this concept of evolutionary economics. Originally, a spatial economic sector model (Balmann 1997) demonstrated the effects of spatial heterogeneity on farm rents and on structural change. Making use of increasing computer power, Berger (2001) extended this approach into a Multiagent model and made allowances for the heterogeneity of asset endowments and innovativeness. Berger first analyzed the inherent drifts in a heterogeneous recursive model at micro scale, and additionally parameterized how new technologies diffuse through a farming population and analyzed how this diffusion process impacts on different groups of farmers. Here, farming decisions were empirically calibrated to household survey data, in order to assess the impact of opening the Chilean agricultural market to Mercosur³.

The Chilean realization of MP-MAS models farmer agents as pursuing a lifestyle of income optimization based on farming and off-farm labor at minimum wage. If economic outcomes are too negative, it is within the rational logic of this model to quit farming, in order to work in a more productive setting. This exit option may be interpreted as migration to nearby cities.

Farmers may pursue different strategies, which are modeled as fixed constraints. For example, vegetable farming is a strategy that will not be taken up by dairy farmers from one day to another and vice versa. Thus, because it is observable that farmers adhere to a farming strategy, we assume certain inertia of agents to adhere to their type of farming, beyond economically rationalizing reasons. Thus, from a set of cropping options that fall within one strategy, the optimal combination is chosen by the agent. Innovativeness, a lifestyle (and thus constant) choice, is a

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³Chile signed an association agreement with Mercosur — at that time Argentina, Brazil, Paraguay, and Uruguay, which liberalized agricultural commodity markets in October 1996.
4.3. THE LEGACY MODELS WASIM-ETH, MP-MAS, EDIC AND CROPWAT

personal characteristic that enables agents to include new production technologies into their set of viable options. Innovativeness may thus be an important quality in a changing world.

The basic equations

The production plan. The Chilean MP-MAS model uses a three-stage decision process. The central farming decision is the annual production plan \( PP^* \) that maximizes the utility function \( U \), building on the theory of constrained rationality (Hazell and Norton 1986). This plan maximizes the production function \( PP \), which takes into account the current state of the farmer: his asset endowment \( A \), the production technologies \( T \) that are available to him, and other constraints such as his liquidity \( L \). The function also depends on his expectations (denoted with a tilde) on the natural/environmental conditions \( \tilde{N} \), as well as on some personal characteristics such as risk preferences \( \text{risk} \).

\[
PP^{*t} = \max_{PP(A,T,L,\tilde{N},\text{risk})\geq 0} \tilde{U}^t \quad (4.1)
\]

Also, all inputs are greater than zero \( A, T, L \geq 0 \). For each agent, a decision matrix is build, based on its personal characteristics \( A, T, L, \tilde{N} \) and risk.

An objective function \( U \) is further defined that specifies expected revenues from this production plan \( PP^* \) under expected market conditions \( \tilde{M} \).

\[
U^t = \text{Rev}(PP^t, \tilde{M}^t) \quad (4.2)
\]

The revenue function depends on the production plan and on how its success was affected by the realization of conditions natural system, and on market prices at the time that the product is harvested and then sold. In detail, each agent’s production activities \( PP^t \) are the result of a production planning decision \( PP \), which was estimated through the maximization of expected utility under constrained endowment of productive assets (Hazell and Norton 1986). Numerically, this optimization problem is solved with a Mixed-Integer Linear Programming (MILP) library (IBM OSL).

Using the notation of Schreinemachers (2005), the farm production planning problem is described as inter-temporal utility (or profit) maximization problem, which distributes a set of inputs \( \text{INP} \) to production technologies \( T \), in order to produce some marketable (or auto-consumable) products \( \text{OUT} \). The utility function (4.2) thus becomes

\[
U^t = \text{Rev}(\tilde{M}^t, PP^t) = p_{t1} \cdot \text{OUT}(PP^t) - p_{t2} \cdot \text{INP}(PP^t) - p_{t3} \cdot \text{FIX} + p_{t4} \cdot \text{FUT} \quad (4.3)
\]

Here, the variables \( \tilde{M}^t = [p_{t1}^t, p_{t2}^t, p_{t3}^t, p_{t4}^t] \) are market prices for produce, and input costs and the market cost related to fix costs at time \( t \). FIX denotes fix costs, and FUT are expected future outputs from investments, expressed as an annuity at price \( p_{t4}^t \).

Inputs are constrained by the agent’s asset endowment \( A \) at the time of production, the production constraint:

\[
PP^t \cdot \text{INP} \leq A
\]

Numerically, this optimization problem is solved with a Mixed-Integer Linear Programming (MILP) library (IBM OSL).
In addition to the mere combination of activities under asset constraints, the MILP framework allows complex specifications, including soil constraints, rotational constraints, and labor allocation under opportunity costs. Even ‘if/then’-rules that are common in rule-based multi-agent models can be implemented within the MILP framework, to represent local non-market production and investment constraints (Schreinemachers and Berger 2006).

Production technology dynamics. The technologies available to each agent depend on his investment goods $I^t$ and further personal characteristics $m$, such as knowledge and his aptitude to take up innovative technologies adopt, but also on his peer network that accumulates experience with these technologies, adopt.

$$T^{t+1} = T^t(I^t, \text{adopt}^t, \text{adopt}^t)$$ (4.4)

Asset dynamics and the investment decision. The endowment of production assets of each agent is a dynamic variable. With aging, production assets can deteriorate and may be lost. New investments $\Delta I$ allow for the acquisition of new production assets and to apply new technologies that require these.

The investment decision takes into account the condition of financial markets $F$ (or, rather the expectations $\tilde{F}$ on it), and the annualized future utility gain $\Delta U$ expected from such investment. The productivity of investment goods decrease with time (aging), or increase with new investments, so that

$$I^{t+1} = I^t + \text{aging}(I^t) + \Delta I^t \left( \frac{\partial U}{\partial I} \right)$$ (4.5)

The investment model uses Berger’s (2001) framework. The inter-annual aspects of investment analysis are reduced to a single period problem, using the annuity values of pre-harvest costs, post-harvest costs, and dept-servicing; and the opportunity costs of own funding (as depreciation of own funds).

Liquidity dynamics is the amount of cash that is readily available to the farmer and is computed at the end of each cropping season. Taking into account asset transactions $\Delta A$ (investments, land and water markets), the annual revenues add to each farmer’s liquidity, while amortizations $X$ for investments are subtracted.

$$\Delta L^t = Rev^t(PP^t, M^t) - X^t(\Delta I^t, \text{interests}^t) \pm \Delta A^t$$ (4.6)

and

$$L^{t+1} = L^t + \Delta L^t$$ (4.7)

See Schreinemachers (2005) for an elaboration of the extended, three-stage non-separable decision process, which includes the investment decision, the production decision, and the consumption decision.

The expectations dynamics for each agent are boundary conditions for the future states of the environment $z$ in which the agent operates. Depending on model realization, these expectations may evolve in time, and may incorporate the error of former expectations $z - \tilde{z}$, on the personal aptitude to learn $\lambda$, or even on the expectations $E$ of peers:
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\[ E^{t+1} = E^t + \lambda \cdot \Delta E^t \left( (z - \tilde{z}), \sum_{i \in \text{peers}} (w^{i,i} \cdot \tilde{E}^{i,i}) \right) \] (4.8)

where \( w^{i,i} \) is a weighting factor that represents the closeness of agent \( i \) to another agent \( i \), and \( E^i \) are the characteristic expectations of another agent \( i \). Environmental variables may be market prices and costs, meteorological conditions, water availability of an individual farmer or any other.

A variety of learning rules have been implemented, and the inclusion of other rules is relatively simple, but calibration may turn out very complex. Thus, simple rules are recommended unless this rule is the explicit topic of research.

**Interactions among farm agents and emergent properties**

The objective of Multi-agent modelling is the analysis of interaction among farmers and of emergent properties that could not be seen through the analysis of individuals. The MP-MAS model offers a range of interactions of farm agents, which are summarized. In addition to ‘real’ interactions, the distribution of assets and incomes itself is a property of the full system, with dynamics that require dynamic and disaggregated techniques that MP-MAS offers.

**The distribution of assets and incomes** is not a ‘real’ interaction, even though several processes may be triggered through it. The distribution is computed with indices such as the Gini (Atkinson 1983), an aggregate property that characterizes the whole farming population. Over time and with recursive updating of agent assets, the distribution of agent properties across the population diverges with respect to income, liquidity and asset endowment. Monitoring the changes in distribution gives insight into the impact of policies on different farm groups. The study and understanding of such dynamic processes is an important end in itself, and MP-MAS may offer relevant insights.

**Diffusion of innovation.** The adoption rate thus depends on others’ behavior peers\(^{DoI} \), and also on personal characteristics with regards to adoption of new technologies, \((s, m)^{DoI} \). Following Roger’s theory on innovation that assumes a bell-shaped diffusion process (Rogers 1995), network-specific thresholds are used to determine when and if a farmer takes over the technology that other peers have tested:

\[ T^{t+1} = T^t + \Delta T^t \left( \text{peers}^{DoI}, (s, m)^{DoI} \right) \] (4.9)

Berger (2001) used MP-MAS to analyse farm profits for various adoption scenarios. He simulates how late adopters slowly quit farming because the high opportunity costs for their land and non-farm income opportunities make farming less profitable. This effect resembles a ‘treadmill’, which was first proposed by Cochrane (1979): If an improved production technology results in a supply increase and also in a price decrease, then the social outcome of such innovation can be neutralize or even negative if evaluated for the total population of producers. It will have redistributive effects within the population, benefiting some innovative farmers while most other have no or negative benefits. This effect now called COCHRANES treadmill.
Other modules

Dependent on model objectives, this basic model can be extended to consider complex household characteristics, such as consumption, the use of livestock to manage risk, the differentiation of labor constraints into home-, field- and off-farm labor, and the specific labor constraints of women and elders. Network effects are modeled as the diffusion of innovation. In addition, a soil nutrient dynamics module was extended.

In addition to the multi-agent mode, the individual decisions of MP-MAS agents can be analyzed in standalone mode, where a single decision for one year is resolved. Furthermore, a sensitivity analysis mode allows for the repeated resolution of a decision under variation of parameters.

A module that is specifically important for the application in this thesis is the crop growth model CropWAT, which is a parameteric description of crop yield deficit under water stress. This well-established and empirically robust model from the FAO (Brouwer and Heibloem 1986) estimates yield deficit from the water deficit ratio, based on empirically measured crop coefficients. The water deficit ratio relates the real of plants to their potential evapotranspiration under unconstrained condition. Such parameteric model is used because it drastically reduces the number of empirical parameters that are needed to estimate yield deficit, compared to other, process-based crop growth models. In the MP-MAS context, this yield reduction diminishes the economic returns of farmers.
4.3. THE LEGACY MODELS WASIM-ETH, MP-MAS, EDIC AND CROPWAT

4.3.3 EDIC

The model EDIC (extended) is a lumped irrigation model for catchment-level analysis. Irrigation sectors are resolved as nodes of a linked network. Within sector, the model estimates reuse of irrigation water. Between irrigation sectors, flows of spillover water occur that can be re-utilized by other users downstream (‘return flows’). These return flows are parameterized as proportional to within-sector reuse, as surface and near-surface flows. Spillover water is created by inefficient irrigation and depends on the quantity of water irrigated as well as on the specific efficiency of the irrigation method (see Section B.3 ‘Irrigation methods at field scale’ in Electronic Appendix B as well as model extensions in Section 6.3).

The study area contains four rivers: Putagan, Ancoa, Achibueno and Longavi. Finally, all four rivers discharge into the river Loncomilla.

The study region is first divided into the four catchments and then subdivided into irrigation sectors. Each irrigation sector is an area that shares the same principal irrigation infrastructure and have access to the same rivers. Specifically, sectors share ‘bocatomas’, where water is taken from the river, and main canals. For this model, the sector division from Berger (2001) was maintained, which again builds on MOP (1992).

The water of river falls under the jurisdiction and management responsibility of one watershed organization, called Junta de Vigilancia These Junta d.V. take water from the rivers and deliver it into irrigation canals. They also oversee water rights and enforce that farmers comply with these (see Figure 4.3 Black arrows mark access to irrigation canals through water rights. Red arrows mark the path of return flows). Within the EDIC model, water rights are defined as a percentage of total river flow during one month.

The model assumes that water can be distributed freely within each irrigation sector but not between sectors because it was of little relevance in practice. Each sector pools reuse water and
other characteristics, such as canal conductive efficiency, are assumed as homogeneous.

However, return flows occur between sectors. These are flows of spillover water caused by inefficient irrigation methods, as inter-sectoral interactions. Parameterization was done by local experts (MOP 1992), and a topographic overland flow was added (see Section 7.4 and Electronic Appendix B).

Inter alia, the extended model allows calibration to complex parameters such as irrigation security at the level of irrigation priority group and also for individual crops. For calibration and also parameter sensitivity experiments, the EDIC model was re-implemented in MatLab® for optimal runtime (see Section 7.4).

### 4.3.4 CropWAT and Modelling Crop Yield Under Irrigation

The modelling of plant water demand, supplemental irrigation and yields follows the FAO CropWAT approach (Allen, Pereira, Raes and Smith 1998). Here, a reference crop is modeled and corrected with measured correction factors to obtain crop-specific values. Also, the yield estimation under deficit follows a factor approach.

#### Estimation of water deficit

As part of the MP-MAs model, plant water deficit is computed, as input to the estimation of water-related yield reduction.

Crop water demand (CWD) is the water a crop needs to obtain full yield. It can either be met from precipitation (P) or through supplemental irrigation (IRR). However, neither the irrigation water that farmers apply to a field nor the precipitation can be fully utilized by a plant, and thus efficiency factors \( \eta_{IRR} \) and \( \eta_{P} \) apply. The total water that a plant receives (TWR) is thus

\[
TWR = \eta_{IRR} \cdot IRR + \eta_{P} \cdot P
\]

(4.10)

The irrigation efficiency factor \( \eta_{IRR} \) is a property of the on-field irrigation method, and ranges between 0.9 for localized systems such as drip irrigation to 0.3 for simple flooding (see Section B.3, Electronic Appendix).

The efficiency factor for precipitation \( \eta_{P} \) depends on the growth stage of a plant, and also from the intensity of an irrigation event. It is used to define ‘effective’ precipitation as the amount of precipitation water that is available to plants, \( \hat{P} = \eta_{P} \cdot P \). A simple regression function is used to estimate this factor to estimate the effective precipitation that plants use, with factors \( a_{i} \) estimated using local measurement values and \( \hat{P} \) limited to the interval \([0, P]\) (see MP-MAS Manual, Berger et al. 2007b):

\[
\hat{P} \approx a_{0} + a_{1} \cdot \text{CWD} + a_{2} \cdot \text{CWD}^{2} + a_{3} \cdot P + a_{4} \cdot P^{2} + a_{5} \cdot \text{CWD} \cdot P
\]

(4.11)

The monthly water supply factor \( k_{m}^{m} \) is the ratio between monthly crop water demand and the total water supply; which is one or less:

\[
k_{r}^{m} = \min(1, \frac{TWR^{m}}{\text{CWD}^{m}})
\]

(4.12)

The monthly irrigation demand \( D_{IRR}^{m} \) of each plant also follows from plant water demand, precipitation and the efficiency of the irrigation method used (for units and details, see Berger et al. 2007b).

\[
D_{IRR}^{m} = (CWD^{m} - \hat{P}) / \eta_{IRR}
\]

(4.13)
4.3. THE LEGACY MODELS WASIM-ETH, MP-MAS, EDIC AND CROPWAT

Estimating yields under water deficit

To estimate yields, the ratio of monthly water demand and supply $k_{m}^r$ is averaged to determine the annual crop yield deficit factor $k_r$, using the arithmetic mean of all relevant $k_{m}^r$ of the cropping season.

$$k_r = \frac{\sum_{m=1}^{M} k_{m}^r}{M}$$  \hspace{1cm} (4.14)

Following the simplified CropWAT factor approach, the annual crop yield is the yield under unconstrained conditions $Y_{\text{max}}$ reduced with the yield reduction factor $k_r$. Following Berger 2001, if the yield reduction factor $k_r$ is less than 0.5, then the yield is zero.

$$Y = \begin{cases}  k_r \cdot Y_{\text{max}} & \text{if } k_r \geq 0.5 \\  0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (4.15)
4.4 Coupling Of Legacy Models

4.4.1 Software Requirements And Constraints

Model objectives and intended software use

The research project that frames this study aims to extend an integrated analysis of heterogeneity to the micro-scale. Specifically, it aims to ‘help quantify externalities and trade-offs between goals of economic growth, reduced vulnerability, food security, environmental sustainability and social equity’ (Project objectives). Furthermore, as elaborated in Section 2.1, the project aims to identify stakeholders’ problems with water management, along with policy options to address these problems and policy evaluation criteria to assess the policy options. In addition, the project aims to extend computer simulation models in order to be able to integrate stakeholders’ priorities, climate variability and climate change. Finally, the project aims to use agent-based simulation models to evaluate the policy options identified by the stakeholders.

The adequacy of model scales

A model software must represent all processes and interactions that are relevant to the research question and at the adequate scales (Ewert et al. 2006b). If interactions and feedbacks extend across different scales, variables may require aggregation and disaggregation functions. These rescaling is a source of additional uncertainty and may require calibration and data.

Micro processes that are not resolved by a model require ‘effective’ representation for which the model reproduces the behavior of the system adequately at the scale of interest. For example, soil oxygen content is used in many crop growth models. In reality, even soil with high oxygen content contains anaerobic micro-sites. In soils that are best described as having intermediate oxygen content, such micro-sites are created by strongly respiring micro-organisms to enable important chemical processes, e.g. nitrogen fixation. However, for plant growth purposes, it is neither advisable nor feasible to resolve a model at the resolution and detail needed to represent the real biophysical processes. For watershed-level models, micro-pockets are ignored and average conditions must be assumed. Then, empirical or effective formulas are translate measurement data to the model scale. In some instances, processes that would be physically or chemically ‘forbidden’ at these effective conditions can then occur. An example is nitrogen fixation as an obligatory anaerobic process in tiny soil pockets. The soil oxygen content at model conditions should never allow such fixation because micro pockets are not resolved. If nitrogen fixation is a process of interest, then the effective soil oxygen threshold must be positive.

Emergent phenomena are processes at macro scale that are caused by the superimposed drift or behavior of many sub systems. Examples include regional climate change after large deforestation, local prices on small markets, for example when local supply drops during a drought, or social phenomena that result from information flows, e.g. fashion or revolutions.

The model software must represent the adequate scale and it must describe scale transitions properly, especially macro scale phenomena and effective treatment of micro scale processes.

The integration approach

Three organizational approaches to system integration were suggested in Section 3.1.2: the integration of results, the cross-link – interface approach and the holon approach. For this model integration study, the ‘cross-link – interface approach’ is chosen (Figure 3.2 b on page 22) —
for data acquisition, model integration and integrated modelling. Procedurally, it is the simplest organizational structure that can fulfill the research objectives. However, resulting from this approach, the specific interactions between farmers and the bio-physical sphere inside a single sector are not measured specifically. These are thus not available for model calibration or validation. Also, the heterogeneity across sectors is acknowledged, but detailed data to support any reasoning on causes of this heterogeneity is beyond the scope of this study.

Process and resource needs/constraints

Finally, the choice of the coupling setup is constrained by resources available. It is important to match the expectations to a coupled model with the resources available and other process constraints.

Project staff and human resources. Full-time staff within the project ‘Integrating Governance and Modelling’, whose work directly relates to model integration and model development, include a hydrologist (core task: data collection and analysis of hydrological model), a research assistant with an agricultural economics background (data collection and communication), and this Ph.D. thesis, which is focused on integration and model coupling. Senior team members guided and supported software development. The permanent project staff works in three research institutions in Chile and Germany. Furthermore, several individuals contributed to the project via their master thesis, as student assistants, or through part-time or short- and medium-term contracts.

The selection of legacy models. At an early stage of the project, disciplinary partners selected two model software packages. The socioeconomic modelling software MP-MAS for farm-based multi-agent simulation also has biophysical capabilities, including the sector routing model EDIC. The second modelling software WASIM-ETH is a distributed, process-oriented surface water balance and runoff model has extended capabilities such as land use and evapotranspiration, groundwater flow simulation and module to simulate irrigation. Model selection precedes the model coupling decision and is external of this case study. The source code for both models is available.

Data collection framework. Data collection and analysis is the responsibility of disciplinary partners. To ensure consistency, a common sampling frame was first established with the full group, in order to maintain statistical validity and consistency in scales and resolution. The socio-economic survey was executed under the supervision of the disciplinary stuff and within their institutions; funding was shared in early stages of the integrated modelling cycle. Questionnaires and other proposals were communicated to all project members, whose suggestions were incorporated before the 2006 survey. Crop data and hydrological data was compiled by the hydrological partner, from 2005 to 2007.

4.4.2 Architecture Of Coupled Modelling Software

Use Case analysis was performed in the project team. After balancing research objectives and resource requirements for different software options, capacities within the project, and the development stage of the model software that the project uses, a hierarchical approach to dynamic
coupling was chosen (Figure 3.3). The aim of this model coupling is to demonstrate the conceptual and technical feasibility of model integration through the coupling of two complex models, MP-MAS and WaSiM-ETH. Both of these legacy softwares are already multi-component models for multiple modelling objectives. Neither of these modelling softwares was structured for the purpose of deep integration and model coupling, or for irrigation management in the way intended by the project. Thus, it is necessary to adapt both source codes for coupling and also for the objective of irrigation management.

The selected coupling framework builds time stepping that is coordinated by a central entity, the ‘sequencer’. Furthermore, this sequencer synchronizes the timely translation and transformation of data and handling of model components and output files (Mehl 1994).

The models MP-MAS, EDIC and WaSiM were coupled technically and also linked to a coherent database (Figure 4.5). However, all models maintain standalone functionality and can be calibrated separately by domain experts and with domain data. The framework also allows for the dynamic coupling of the components, such that agricultural land use is computed from the socioeconomic model at a yearly time step and reported to the hydrological model through a translation interface. Data is passed between applications using the Typed Data Transfer library (see Section 6.4.2).

The standalone mode is useful for sensitivity analysis, but also facilitates work flows in a complex project setting. Coupled modes are used to calibrate and analyze the impact of interaction variables. Our IMS uses the following components:

**The legacy models** are MP-MAS with CropWAT equations, WaSiM-ETH and EDIC. All models were adapted and extended to incorporate new interaction processes that become relevant in a coupled system;
4.4. COUPLING OF LEGACY MODELS

Figure 4.5 — An integrated model system that allows for standalone and coupled model runs

An interdisciplinary database for consistent updating of variables that are used by more than one model component.

The considerable complexity of our modelling framework requires large sets of input data. The same data affects various sub-modules, which have different people working on them (see Figure 4.5). All sub-modules require distinct data formats. In addition, certain data (e.g. the efficiency parameter of an irrigation activity) might affect various calculations (all cropping activities using this technology). To keep data consistent within the coupled model, we have based input data in the normalized form of a relational database (see Section 6.4.2).

A translation layer reformats and translates data between the different reference systems.

A central and hierarchical sequencer, which controls data interchange between all other modules. The four model components (MP-MAS, WASIM-ETH, EDIC and CropWAT) are combined into a single model framework. Thus, they can capture the impact of the irrigation decisions of the entire population of farmers on the hydrological system, along with the spatial interactions occurring within this system, and ultimately the impact of policy options. Hydrological processes in their natural landscape are represented in WASIM-ETH. The EDIC sectoral model captures meso-scale hydrological processes, water management decisions, small-scale infrastructure projects, upstream-downstream generation of externalities (especially water quantity), and inter-sector allocation of water. MP-MAS represents the heterogeneous individual farms consistently with survey and census data. Disaggregated impacts of parameter changes (e.g. policy scenarios or re-conceptualization) on different types of farms can be represented and
analyzed dynamically.

We refrained from internalizing institutional models, which would add additional degrees of freedom to the IMS. Instead, we assume external institutional scenarios.
Chapter 5
Conceptual Model Integration

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Conceptual Model Integration (Chapter 5) describes the study system conceptually, with regards to all entities and interactions that can be modelled with the modelling software. Core interactions between the three disciplinary domains (the economic farm agent, the river system and the canal system) are described theoretically, especially irrigation efficiency and the pool of non-attributed water. The second interaction level is the manner that farmers interact with their dynamic environment: their cropping decisions with changing external conditions and farmers’ access to water.

5.1 The System: Entities, Interactions and Feedbacks

Before delving into the model integration itself, we briefly review the system that is being modeled conceptually. For an description of the watershed in the Maule region, see the Technical
5.1.1 System Entities

The core entity of the system are the farm agents, who are members of a population of farmers, and their decision making. Other entities are the water user organizations and irrigation sectors. Furthermore, spatial levels are connected via components that include innovation networks, return flows, canal infrastructure and rules dealing with excess water.

The spatial extent of each entity defines the level at which the interaction processes occur and what rescaling of variables/parameters is necessary for transforming variables of one level to another. Obeying the principle of Ockham’s Razor (see definition on page 126), it is useful to define no more than three spatial levels within a system. These are then called the micro, meso and macro levels (see Figure 5.1). Processes that cause interactions between levels, and thus require rescaling, include return flows and cyclic reuse within the hydrological sub-system; interaction networks between farm agents in the socioeconomic sub-system; crops (crop growth); and canals and the redistribution rules within irrigation sectors.

Crops and crop growth are plants homogeneously growing on one plot. Characteristics of these plants are defined externally and use local data (Uribe and Arnold 2008).

Irrigation water is an key input factor of crop growth, especially during the dry summer months between November and February.

Farmers use traditional methods such as flooding or furrows (for row crops and trees). Advanced irrigation methods are classified (see Martínez 2001 or Phocaides 2000) into low-pressure systems that apply water to the root zone (micro sprinkler, drip) and high-pressure systems that apply water from above (sprinkler, movable guns, pigote), which resemble precipitation most closely. Irrigation methods differ in investment costs, labor requirements and irrigation efficiency.

Irrigation is the main surface water use is in the study area is irrigation and the distribution of this water is regulated through Water Rights. Although groundwater is abundant, its use is comparatively minimal\(^1\). The surface water is taken from the rivers through one of approx. 50 intake structures named ‘bocatomas’. An extensive channel network, covering most of the agricultural area, allows for the distribution of water. The farmers can use the water from an intake point according to the amount of Water Rights that they have.

A Cropping activity (Cropping) is a technology that farmers use to transform a set of inputs (water, seeds, labor and fertilizer) into a set of outputs (crop yields). The efficiency of this transformation is a characteristic of this technology and may require additional infrastructure or investment goods that are not consumed during the transformation (machinery, animals for

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\(^1\) Since recently, farmers in the study area increasingly rely on ground water wells or deep aquifer wells for drip irrigation, because the water is constantly available, independent of variations in weather, and low in suspended particles and other chemical or microbiological contamination. They use surface water for surface irrigation methods. For sprinkler irrigation, water is used from surface water, from ponding, and from deep wells - depending on the crops used, water availability, and position within the irrigation system, which affects both quality and reliability of access to surface water. As a further interconnection, the percolation from the surface irrigation methods, used on the same or on neighbouring farms, to groundwater positively influences ground water availability (personal communication\(^2\)).
5.1. THE SYSTEM: ENTITIES, INTERACTIONS AND FEEDBACKS

Farm agents. Each farm household in the study region is represented statistically as one farm agent, with specific characteristics and specific interactions. Characteristics include asset endowments: liquidity; land of particular soil suitability types; water rights to particular water sources; machinery suitable for one or a set of cropping activities; ownership of perennial crops and of livestock; and access to credit. Furthermore, agents have knowledge about a set of cropping technologies $T$, which enables the agents to use these technologies. This knowledge depends on the agent’s peer group and personal aptitude (see “Diffusion of innovation”).

Populations of farmers (not depicted) are farmers with diverse characteristics (assets, innovativeness and learning behavior). Each farmer may interact with other farmers directly or indirectly, as defined by other modules. The distribution of characteristics changes over time, resulting from their individual behavior, interactions with others or a general shift of the external environment.

The farm planning decision (Planning). At the beginning of each period, each farm agent makes a farm plan, which consists of an investment decision and a production decision. Both decisions take into account individual asset endowment $A^1$, known technologies $T^1$, and further constraints such as liquidity $L^1$, market expectations $< M >^1$ and natural conditions $< N >^1$. The latter consist of expected surface water delivery $< SW >^1$, expected internal reuse $< IR >^1$, expected return flows $< RF >^1$ and expected ground water availability $< GW >^1$, and further personal characteristics $P^1$. Through learning, farmers may adjust their expectations to observed outcomes.

The production decision allocates available resources over available activities, which are combined such that the solution of an objective function is maximized. The objective function is usually specified as a revenue function. The result of this optimization problem is the production plan $PP$, a set of cropping activities with specific areas, inputs and expected outputs.

Irrigation sectors / hydrological units (Sector). Each agent belongs to a hydrological entity
called an irrigation sector, which is defined by the canal system, by access to a river and other freshwater sources, and by the water user organizations that deliver the water. At the sector level, parameters include routing of return flows from upstream sectors, access to water and canal efficiency, as well as institutional delivery efficiency. In addition, soil moisture, precipitation and ground water level are characteristics of the sector.

Water user associations distribute water from all rivers to farmers, according to the farmers’ water use rights. Additionally, the organizations take care of canal maintenance and investments into canal infrastructure. Furthermore, the WUA determine how farmers in a sector deal with excess water; this forms the basis for the rule by which excess water is distributed.

Innovation networks (Network) Each agent belongs to innovation networks, in knowledge about the appropriateness of new cropping activities is exchanged. An agent adopts a new technology if a certain percentage of his peers also use the technology successfully. This percentage is an individual characteristic of the agent and is termed the adoption threshold.

5.1.2 System Dynamics And Feedbacks

Several model variables vary over time, and require dynamic calibration and analysis. These are some external boundary conditions (market prices for inputs and outputs, but also the annual weather with precipitation, temperature and initial river flows) and internal model variables.

Internal variables can be physical (surface and groundwater flows, crop growth) and socioeconomic (farm incomes and the change of asset endowments, such as the deterioration and renewal of machinery). Furthermore, the diffusion of innovation extends the range of activities that farmers can select, and learning/adaptation alters their decision framework (see Fig. 5.2).
Planning, crop production and income dynamics describe the impact of recursive decision making on a single farm agent. Based on his expectations on future development, the agent makes a production plan, invests, and then engages in cropping activities. The produce from these cropping activities are then marketed (or used for home consumption), which creates income and a change in liquidity. Eventually, new investments can alter the agent’s production possibilities in proximate years (Berger, Schreinemachers and Arnold 2007b).

Market dynamics are parameterized as external price changes, as external changes in input costs (labor, fertilizer, machinery) and as financial products (interest rate on credits). In the Chilean case study, no feedback on market dynamics must be considered for those products that are primarily exported. Chile’s share of the global market is not sufficiently large on the global market to cause such feedbacks.

Surface water interactions occur at the sector level. The Chile model realization primarily focuses on within-sector interactions (internal reuse of water, ground water, canal infrastructure and delivery institution) and on between-sector interactions (return flows). Additional interactions include land and water rental markets. As a consequence of inefficient irrigation methods, unused water rights, and inefficiencies in the canal system and the delivery institution, a share of water is delivered to the rightful owner, but another share is delivered to a ‘common’ stock, which can be accessed by every agent in the sector. The ratio of ‘legalized’ delivery and ‘non-attributed’ depends on sector characteristics. For more details, see Section 6.3.2 and also Electronic Appendix B).

Ground water availability depends on aggregate usage and recharge of ground water within a sector, and on physical properties of the sector. Groundwater recharge is a result of rainfall (especially in winter) and of inefficient irrigation (surface and furrow). Ground water is also extracted, through investment into shallow wells/ponds.

Weather dynamics are also parameterized externally. Depending on model realization, these are variability in the flow of fresh water sources, precipitation, and ground water/soil moisture.

Technological innovation expands the set of cropping activities available to each farm agent. Initially when a new technology is introduced to the system (externally), only a few farm agents (innovators) are willing to accept it. Dependent on the individual adoption threshold, the technology diffuses from innovators to early and later adopters, and finally to laggards (Berger 2000).

Asset and income distribution are emergent phenomena that result from the characteristics of all individual farm agents. Distribution is not modeled as an entity itself, but distributional dynamics can offer core insights into how policy changes and external dynamics influence the overall welfare of the farm population.

Learning & Adaptation are personal characteristics of each farm agent. The agent forms expectations on climate, on markets, and on interactions with other farmers and sectors. The model is first analysed with constant (representative or effective) boundary conditions and a minimum of interactions. Later, with dynamic boundary conditions and stronger interactions,
the learning in response to such changes impacts on planning outcomes.

5.1.3 External And Internal Boundary Conditions, Interaction Variables

**External boundary conditions** are those parameters that characterize processes not internal to the study system. By definition, external boundary conditions cannot be affected significantly by the study system itself or level of integration or model coupling.

For the system of this case study, external boundary conditions are conceptualized in Section 5.1 and elaborated in the Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’. They vary in type; examples range from precipitation, snow melt, river water that is pumped into the study area through the Melado canal or the Canal Maule Sur, market prices of farm products and farm inputs (including labor), temperature and solar radiation, characteristics of soils and production technologies (including field-level efficiency of the irrigation equipment) and plant physiological parameters. Furthermore, the distribution of farm properties is given as is the distribution of water rights across sectors, which also defines the abstraction of irrigation water from natural flows into irrigation canals.

Some external boundary are not known and can only be estimated with calibration, for example canal conductive efficiency or farm-level irrigation efficiency.

**Internal boundary conditions or interaction variables.** During model coupling, the individual modules are first calibrated as standalone models and only later integrated into a dynamic model coupling scheme. Those variables that are interaction variables in the coupling scheme, but are boundary conditions to the standalone model components, can be called ‘internal boundary conditions’. Model coupling is a method aimed to improve our understanding on internal boundaries and on how these effect feedbacks between sub systems.

Examples of the study system are reuse of water within irrigation sectors, land use, the quantity of irrigation water applied to fields, the takings of water from irrigation canals by farmers, and the growth- or yield response of crops to irrigation.

**Shared data** is data that is used by more than one module but may be interpreted differently. Both external and internal boundary conditions can be shared data.

In our case, external boundary conditions that are shared include the distribution of water rights across sectors (input to all three models), crop physiological parameters (input to all three models), precipitation (input to all three models), and inflows into the study area (input to the models EDIC and the WASIM-ETH).

Internal boundary conditions that are shared include land use (used by WASIM-ETH and EDIC as input while being an output of MP-MAS), effective irrigation efficiency at sector level (input to MP-MAS and WASIM-ETHand calculated in EDIC as internal reuse), the percentage of the amount of irrigation water that is actually used, and the spatial distribution of irrigation water to crops (input to WASIM-ETH and EDIC).

While absolute precipitation is an external boundary condition, the precipitation that actually is received by plants effectively is also an internal boundary condition. A correction for effective precipitation is used by the models MP-MAS and EDIC, while WASIM-ETH balances precipitation flows as interception, runoff, evaporation and infiltration. A second internal boundary condition is actual plant growth. Here, MP-MAS uses both the CropWAT approach and ma-
5.2. **TIME AND SPACE ACROSS MODELS**

5.2.1 **Spatial Entities Within The Models**

The coupling framework must simulate the relevant processes at their relevant scales. This requires the identification of those processes and scales, and subsequently a setup that adequately represents them, without excessive computational effort. With Use-Case Analysis, relevant processes as well as temporal and spatial scales were identified for both the hydrological and the farm level model components.

For the farm agent model, these are the entities of crop production and investment in irrigation technologies. These are plots of homogeneous cropping activities, which are distributed over homogeneous nutrient response units (or soil types). In the context of Chile, a spatial resolution of 1-ha for a grid cell is appropriate, which also is the lowest resolution of a Response Unit (definition follows).

The relevant temporal scale for farm agent production decisions is the cropping season, while irrigation decisions are undertaken on a monthly basis or on a crop-growth-stage basis. A monthly resolution is also adequate for estimating crop yields under water deficit, because empirical data is available at such resolution only. In contrast, investment analysis requires a longer time horizon of three to ten years.

The resolution of the hydrological component of the model must also reflect the scales of the relevant processes. Hydrological experts and water managers from the study region requested a model that can resolve (a) surface and near-surface return flows, (b) spatially explicit treatment...
of real and potential evapotranspiration, (c) soil storage of water, and (d) runoff. Furthermore, model extension should incorporate ground water because its usage is becoming an increasingly relevant source of irrigation water. Other processes are snow accumulation (also under climate change), canal routing and the generation of ground water in the forested Andean area.

The spatial and temporal scales were determined as follows: The hydrological model runs in daily time intervals with either a 100, 500 or 2000 m grid length (1, 25 or 400 ha). The multi-agent economic module runs in monthly time intervals and with a spatial resolution of 1 ha. Daily hydrological data are aggregated into monthly values, and passed to the MP-MAS system. A spatial rescaling routine was developed (see Report ‘Technical Coupling Manual’).

**The multi agent model MP-MAS/EDIC** internally uses various different entities, which are defined here: grid cells, parcels and response units and finally sectors. Input data are read maps in ASCII format, which can be created with GIS programs conveniently. One grid entity is called grid cell and also parcel. The cropping decision is undertaken within the level of "Response Units" (RU), also called soil suitability units, which are homogeneously treated parcels. The outcome of this economic decision making is a set of plots as land use. Each plot uses single cropping activity located within the same RU (see also Fig. 5.3).

Further entities are irrigation sectors, water user associations, and ultimately river catchments (currently no interactions defined specifically at catchment level).

**Parcels** The smallest scale of the agent model is a grid cell, or parcel. Computationally, each parcel is treated as a class with certain properties: it has an ID, a location within the landscape, an owner (and user, if the land rental model is used). It is characterized by the soil suitability and eventually by other soil parameters.

**Response units (RU)** is a set of parcels of a single farmer that he treats as homogeneous with respect to crop use, mainly to keep Mathematical Programming simple. Parcels are aggregated into one RU, which is the entity of the agent’s decision making. Usually, soils of equal or similar type are aggregated into one RU, or soils at similar state of nutrient deficiency. Thus, the agent can decide on a set of different activities ("plots") within each RU.

**A Plot** is the percentage of one RU cropped with one activity. Agents allocate resources over their land assets, and decide on a set of cropping activities, each on one plot.

**At irrigation sector** level, water is allocated to agents through institutional rules. All RUs are fully contained within one sector. In case that water modules are not used, other institutions might be located at sector level.

**Water User Organizations** are institutions responsible for a set of irrigation sectors within one sub catchment. They represent institutions coinciding with boundaries of a natural biophysical system; their responsibility is the supervision of the distribution of water between irrigation sectors, but also maintenance work at subcatchment level. Further responsibilities might include conflict settlement, sometimes market cooperatives, and decisions for larger investments (dams, 2nd-order channels).

Numerical limits of the multi agent module are posed in two ways: to keep a MILP matrix easily (and quickly) solvable and numerically stable, no more than 20 or 30 integer components (undividable model entities) are desirable. Secondly, the size of a parcel is confined by data
availability. If coupling to hydrological component such as WaSiM-ETH is used, a higher spatial resolution quickly expands model runtime.

The hydrological model WaSiM-ETH uses two spatial levels:

Homogeneous grid cells are the level of soil and surface processes, at which potential evapotranspiration, precipitation and irrigation, interception, infiltration, root water uptake and interflow within the unsaturated zone, and percolation is computed. The unsaturated zone model is 1-dimensional. Irrigation water may be obtained locally from groundwater, or from storages at sub catchment level (ponds, reservoirs or pour point).

Sub watersheds define an area that drains through a single pour point. It’s limits are either water divides, or pour points of upstream sub water sheds. Processes offered between sub watersheds are routing, canal flows, drainage, river abstractions and inflows. Within the model, these processes are modelled at the location of the pour point. Also, surface water abstractions for irrigation are taken from the pour point.

Sub catchments are not congruent with irrigation sectors. The former are defined by natural topography and river flows, while the latter are determined by irrigation canals that are often perpendicular to rivers, and often follow contour lines of the topography. At meso scale, a scale mismatch between topographically defined sub catchments and human-made infrastructure was the intentioned by engineers, and is thus irresolvable.

Ground water flows can either be modeled physically, and flows between neighboring cells are then modeled. Alternatively, a regression-based model can be parameterized, and ground water levels between neighboring cells are then interpolated to mimic gradient flow. It is the only interaction between grid cells within one sub catchment.

5.2.2 Time Handling In A Mixed Economic–Biophysical Model

Time in process-based models. In natural sciences, the concept of time is linear, forward, and continuous. Models (and events) are discretized for computer models, because of run time and because of data scarcity. With sufficient data, more accuracy is generally expected if the temporal resolution of a model is increased (with spatial resolution accordingly).

The solution of some equations, for example the computation of soil moisture with the Richards equation within WaSiM-ETH, require iterative numerical schemes. Within each cell, this scheme is repeated until gradients of moisture and energy are in equilibrium.

Time in economic decision models. In economic theory, farm production planning is based on expectations about future conditions of the farm, the environment and the market. If perfect foresight is assumed for human action, as many neoclassical models do, then a rational decision of an agent takes into account realistic outcomes of all options that are available to him. For integrated modelling, this means that first, the agent has to identify all possible options to act, then the model has to be re-instantiated for each of these options, and the best option is finally chosen. Furthermore, perfect foresight also implies that the actor knows and takes into account how other agents will act, he will encourage others to procure common goods, but himself free-ride if his contributions are not matched by direct returns. Numerically, the modelling of such
interaction are excessive, because all options need to be computed, and iterated to account for others’ decisions as well.

Within the theory of adaptive economics, the approach to rationality (see Section 4.3.2 or Day 2005) is numerically slightly less demanding. Here, rationality also takes into account the costs of information gathering, and the efforts that a decision with ‘perfect foresight’ would require. For repeated decisions, heuristic rules are used, which build on experience and mimicking. Furthermore, rationalizing only use the individual knowledge, which is bounded the cost to acquire it, by the lifestyle paradigm and by experience. Conceptually, this paradigm translates into a mixed model, with perfect foresight for some processes, with rules and with adaptive learning algorithms for others.

An adaptive economics model should generate correct predictions for some system components (called ‘perfect forecasts’ hereafter), especially for expectations on processes that farmers know much about. Perfect expectations are less relevant for highly complex or highly uncertain matters.

Technically, forecasting for decision making requires running model components over the full time horizon of the expectation, and use model results as input for decision making, an optimizing module. Heuristics and adaptive learning behavior are computationally less demanding ways to create expectations. However, these are theoretically not consistent with the strict economic assumption on rationality.

Section 5.3.1 deals with the conceptual challenge of forecasting in a dynamic environment.

5.3 The Farmer’s Environment: Irrigation Sectors And Interaction Processes

Farmers take into account the environmental conditions – precipitation, soil quality and quantity, irrigation water availability, climatic conditions and weather. In the study region, irrigation water is mainly taken from four Andean rivers. However, the actual water takings of any farmer are not from the river itself, but water is allocated through water user organizations and an intricate system of major and minor canals and infrastructure elements.

To link the impact of water takings to the initial amount of water provided in the rivers, connecting processes must be understood in detail. This section conceptualizes the passing of water from the river to the farm.

5.3.1 Irrigation Modelling With EDIC

For the original integration of the EDIC and the Mp-MAS model (Berger 2001), water rights data only existed at the sector level. These water rights were then disaggregated, and allocated to individual farmers within this sector using a lottery. Furthermore, the original model computed return flows within each sector and from other sectors as a flow proportional to the total amount of water that was actually used for irrigation. This return flow was then re-distributed to agents using two different mechanisms: distribution is proportional to the amount of land, or it is proportional to the number of water rights that the farmer owns.

The original 2001 Mp-MAS/EDIC model had three major shortcomings, which were resolved as part of this thesis. First, only about 50% of all agents hold legalized water rights. The rest of all agents receive water through less formal arrangements, which are either customary rights or
non-governed access to non-attributed water. Second, not only return flows within and outside of a sector contribute to the stock of non-attributed water. Other sources are surplus water and canal losses. These other sources exceed return flows considerably, especially around the driest months.

Third, the original model, as embedded within the full MP-MAS framework, was too complex to determine the calibration parameters $\beta_j$ and $\gamma_j$, which determine the share of water that is lost within the sector. The EDIC model can numerically create water. The variable ‘within-sector loss’ was added to the original model, which closes the water balance (see Technical Report ‘The sector irrigation model EDIC’, equations for reuse (eq. 1.17), the balance and losses (eq 1.18) ). At the default value 1.0 for the calibration parameters $\beta_j$ and $\gamma_j$, ‘within-sector loss’ are negative and thus a false source of irrigation water. The extended model now allows for the computation of the balance for each sector including the actual loss percentage, and for the calibration of the parameters.

Conceptualization of these processes is outlined in the following sections, and implementation is described in Section 6.3.2.

5.3.2 Irrigation Efficiency As Scale-dependent Index

If modelling across multiple spatial scales, the models must explicitly treat the cyclic reuse of water along these scales. Below-scale reuse is invisible at larger scales because losses have been already reused. Thus, an index such as irrigation efficiency is dependent on the assessment scale.

In engineering, efficiency is usually a unit-less ratio. For the engineering of irrigation systems, Heermann (1992) formulated irrigation efficiency at the field level, which many authors name application efficiency:

$$\eta_{\text{application}} = \frac{V_{ET_{\text{real}}}}{V_{\text{applied}}}$$

where $V_{ET_{\text{real}}}$ is the volume of irrigation water needed so that crop evapotranspiration does not cause water stress, which reduces yields or other undesirable effects, and $V_{\text{applied}}$ is the volume of water that is applied to the field.

Discussion of this concept dates back to Brown (1920, in Fairweather et al. 2004, p.9), who relates the area of crop brought to maturity with the volume of irrigation water applied, and Fortier (1928), who stresses that the amount of ‘permissible waste’ is also determined by other factors, such as economical considerations. Israelsen (1932) widened the concept: he maintained the numerator as the evapotranspiration from crops, and used several denominators to measure ‘water uptake’, e.g. the quantity diverted from a river, from the main irrigation canal or into the farm.

The cyclic reuse of water within an irrigation sub-watershed limits the adequacy of the on-field irrigation efficiency concept for watershed-scale river management, because values depend on the choice of the denominator.

Scientists and strategic water managers therefore have recently developed the concept of water use efficiency and standards for water accounting (Molden 1997). Water use efficiency describes the relationship between water, as a production input, and an agriculture product, as output. The unit is benefit per volume, and is thus not an efficiency measure in the engineering sense, but rather a benchmarking index.
The reuse of water ‘losses’ due to inefficient irrigation systems plays an important role within the water balance, and ultimately of the water supply for downstream users. At watershed level, Molle, Wester and Hirsch (2007) give an example for the analysis of a closing (temporally over-committed) watershed, the Jordan river. They state that “local efficiency concerns eventually translate into macro-level allocation and equity concerns. As watersheds close, the complexity of water paths increases and management becomes more arduous” (p. 599). At project scale, Allen and Willardson (1996) report on a study in Little Willow, Idaho, where (on-farm) efficiency \( \eta_{\text{on-farm}} = \eta_{\text{farm-distrib}} \cdot \eta_{\text{field-application}} \) is only 0.3. Due to geology and topography, this efficiency rises to 0.6 at irrigation project scale.

Water use efficiency has become a predominant concept (Perry 2007), used by government institutions such as the International Water Management Institute (IWMI), the Australian Department of Natural Resources and Water (NRW), the Food and Agricultural Organization (FAO), and the United States Department of Agriculture (USDA).

Other authors warn that such estimates are extreme and reuse is scientifically over-rated and politically misleading. Lankford (2006) points out that maintaining the on-field perspective is helpful, because this is the scale at which farmers and farm organizations operate and think. With regard to monitoring, the field or on-farm level is accessible, transparent and immediate, while the assessment of watershed-level processes is blurred by the compensation of data errors between on-field efficiency, cyclic reuse and transfers between sectors. In a decision process, water users can exploit this lack of clarity to avoid real water savings.

For modellers, cyclic reuse below the assessment scale makes empirical calibration with measured data nearly impossible, if data cannot be measured directly at the relevant scale: rescaling errors and measurement errors on cyclic flow fully compensate each other – a typical case of an under-defined system with equifinality (Beven 2001).

Fairweather et al. (2004) differentiates indices according to their levels of analysis and use three spatial levels: the field, the farm, and the ‘scheme,’ a term used for the larger system (i.e. the watershed or an irrigation sector).

Water reuse occurs inside the farm (as tail water and drainage returns), at meso scale between farms within an irrigation unit (e.g. an irrigation sector that belongs to the same canal system), or at macro scale between irrigation units/sectors. Ultimately, both meso and macro reuse are somehow linked to conveyance efficiency \( \eta_{\text{convey}} \), because water is not only lost in canals, but often enters as return flows into canals, or from one defective canal into another. A single canal might thus have conveyance efficiency beyond 1 \( (\eta_{\text{convey}} > 1) \).

**Irrigation efficiency at farm level.** Ultimately, the efficiency of water application to crops is measured for individual irrigation methods and the technical capacity of the farmer to irrigate and prepare the fields such that plants make optimal use of irrigation water. This application efficiency \( \eta_{\text{field-application}} \) is measured at field level. This application efficiency, together with farm-level conveyance to fields (on-farm storage losses and on-farm distribution efficiency, \( \eta_{\text{farm-distrib}} \)) can be summarized as on-farm efficiency:

\[
\eta_{\text{on-farm}} = \eta_{\text{farm-distrib}} \cdot \eta_{\text{field-application}}
\] (5.2)

**Irrigation efficiency at sector level.** The delivery of water through the canal system to a farm is called conveyance efficiency \( \eta_{\text{convey}} \) and accounts for losses within the canal system.
However, these canal losses together with return flows from farms into the canal system add to the amount of irrigation water available and thus the efficiency of water use at sector level. Together, conveyance efficiency $\eta_{\text{convey}} \leq 1$ and the within-sector reuse factor $\zeta_{\text{reuse}} \geq 1$ form sector-level irrigation efficiency $\eta_{\text{sector}}$.

$$\eta_{\text{sector}} = \eta_{\text{convey}} \cdot \zeta_{\text{reuse}} \leq 1$$  \hspace{1cm} (5.3)

Additional seepage from neighboring sectors may further increase the amount of water available, which may be expressed with a further factor $\zeta_{\text{return flow}} \geq 1$. The resulting efficiency $\eta_{\text{sector}} \cdot \zeta_{\text{return flow}}$ can exceed 1.0.

**Irrigation efficiency at watershed level.** If viewed from the watershed level, then return flows that are reused within a farm or sector, or are used downstream in other sectors, are invisible at the outflow of the river. Upstream efficiency increases that do not lead to downstream flows may add to the benefits of the new users, but does not increase downstream water flow (dry-water savings).

Also at the sector or watershed level, Huffaker and Whittlesey (2000) use the term allocative efficiency to measure economically optimal assignation of water among sectors or other spatial units. The watershed-level perspective (Molden 1997) compares water use efficiency in several societal sectors, considers environmental concerns and – especially if fossil water from aquifers is used – also compares with future opportunity costs.

**Indicators beyond the efficiency concept.** The core criticism of both farm and field level efficiency as irrigation management objectives is that they promote engineering solutions that are not always adequate: (a) monitoring at any but the field scales is not feasible, and (b) both measures lack interpretative power, especially because low amounts of irrigation water will always result in perfect efficiency ($\eta_{\text{field-application}} \approx 1$), and (c) the concept does not allow for the consideration of return flows, which may result in effective conveyance efficiency $\eta_{\text{convey}}$ of larger than one.

Other measures were suggested that have different units and are not confined to the interval $[0, 1]$. An indicator that takes into account direct and indirect costs and benefits from irrigation is allocative efficiency at farm level, a measure that considers input costs and output value. In production economics (Ellis 1993), the analysis of economically optimal, rather than physically efficient technologies, also takes into account the rational behavior of farmers and focuses on the adjustment of inputs and outputs to price ratios. At farm levels, management considerations can be considered that might conflict with yield-centered optimization of irrigation management practices, including energy costs and labor constraints.

Monetary returns to water may be regarded as the transformation of water into crop yields into profit. Here, benefits from water use can either be expressed in monetary terms $\zeta_{\text{monetary}}[\$/m^3]$, or, more broadly, in welfare units $\zeta_{\text{welfare}}$. A full system perspective also includes further dimensions, such as long-term sustainability or environmental outcomes $\zeta_{\text{sustainable}}$. 
CHAPTER 5. CONCEPTUAL MODEL INTEGRATION

Figure 5.4 — Causal loop diagram for water redistribution within the irrigation sector. Surplus water is re-distributed according to some area share, and water rights are re-valued from institutions according to some reuse factor $1 + \beta$. The canal models modify the relation between $\beta_j$ and $\gamma_j$ and losses, and also if and how canal losses contribute to surplus water.

5.3.3 Non-Attributed Water and Its Sources: Surplus water, return flows and canal conductive losses

Spillover or ‘non-attributed’ water is a pool of water that was either abandoned by its owners or somehow ended up in the canal after having been abstracted from the original water system, without anyone having a legal claim to it. Farmers without water rights may benefit from this pool of spillover water as an important agricultural input. The model differentiates three sources of non-attributed water: surplus water that farmers receive but do not need, return flows from the use of inefficient irrigation methods, and canal conductive losses.

Surplus water

Surplus water is the water that farmers are legally entitled to use, but do not use after it has been extracted from the rivers into canals (Donoso 2006). This surplus water may percolate to groundwater, return to the rivers or be used by other farmers.

Usually, higher-level institutions, such as the JdV, supply the water that a sector is entitled to use, while surplus water is managed within the sector. Local experts state that surplus water is seldom regulated; usually, farms experiencing water shortage simply make use of it.

Surplus water $S_i$ that one agent $i$ produces is defined as that water that agents are entitled to use $W_i$, but choose not to because plant irrigation demand $D_i$ is already satisfied. The original model was extended so that surplus water is first aggregated for each sector $j$ and then re-distributed to all farms (Fig. 5.4).

$$S_j = \sum_{i \in j} S_i = \sum_{i \in j} W_i - D_i$$

Return flows from inefficient irrigation

Some of the drainage from inefficient irrigation also returns into the canal system. This return flow may be re-used by other irrigators downstream the canal. The water that returns from fields
into main canals and the river system is called *return flows*.

Two levels of return flows can be distinguished conceptually: return flows that are used within the same irrigation canal (sectors that correspond to water user organizations), and water that returns to major canals or rivers and is used elsewhere. A third level of return flows that is directly re-used within the same farm is disregarded, for reasons explained above.

**Canal conductive efficiency and losses**

Processes that determine canal conductive efficiency are seepage through lining material and leakage through larger openings and cracks, and over-flow during high-flow times (FAO Training Manual 7, 1992). Each irrigation sector contains a hierarchy of larger and smaller canals of different designs, adding to several hundred canals within the model area. While some larger canals are lined in concrete and have minimal seepage/leakage, the maze of smaller canals is dominated by simple ditches without lining.

It is not possible to parameterize this complex canal system at field resolution. However, the overall conductive efficiency for each irrigation sector was estimated through farm interviews. A consultant asked a sample of farmers which proportion of their water rights equivalents were actually delivered (see Section 7.5.1).

A percentage of canal losses returns the canal system and adds to the pool of non-attributed water.
5.4 Farmers Dealing With Their Environment

5.4.1 Cropping Decisions In A Dynamic Environment

To incorporate the knowledge of farm agents on this temporal variability, a set of learning models was parameterized. A forecast function for river flows was also implemented for annual hydrological planning: in the Chilean context, river water originates from snow melt and snow accumulation is known at an early stage in the year. With this module, forecasts for yearly flow are decent, while long-term fluctuations are difficult to project. Thus, production decisions are based on forecasts for the current year, while expectations for investment decisions are made for a typical year.

Decisions and time horizons

Every planning process has a certain time horizon. Conceptually, Day categorizes long-term lifestyle, mid-term strategic and short-term tactical decisions (see Section 4.3.2, p. 59). The annual production decision of an economically rational agent is done for a single year, so expectations on biophysical and market conditions should reflect this temporal perspective. Here, investment capital is taken as given and fixed costs are not considered (Brandes, Recke and Berger 1997). Within the cropping decision of MP-MAS, the following parameters are accounted for: yield expectations, water supply expectations, plant water demand expectations, price expectations.

The second type of annual decision is the investment decision. An investment decision is based on a time horizon of three to ten years, depending on the lifetime and amortization rate of an investment good. Expectation building is thus also required over this longer time horizon.

Irrigation and physical interaction with the hydrosphere occurs at a much shorter time interval. In our case, the irrigation decision occurs at a monthly interval as minimum resolution of the decision model. This means that farm agents react to ‘typical hydro-meteorological conditions for this month’. For the irrigation decision, the agent must accurately know these physical boundary conditions.

Expectations and foresight with dynamic meteorological boundary conditions

The economic outcomes and their impact on a farm agent equally depend on the actual conditions of the year and on the agent’s ability to create a crop plan that is adequate for such conditions. If actual conditions are modeled with increasing complexity, but the quality of the agents’ crop plans are too simplistic within a complex and changing environment, then the outcome of the plan is poor. With the same planning capabilities, agents must perform worse in a complex environment than in a simpler one. Thus, if the environmental model environment of the agent becomes more complex, the planning model must also be enhanced.

There is a second theoretic reason to put emphasis on the agent’s planning capability. Perfect foresight is a typical assumption in neoclassical and conventional agricultural economics. MP-MAS is an extension of these conventional models in several ways: As a multi-agent model, it allows for the assessment of interactions. As model with dynamic environmental boundary conditions, it looks at inter-temporal economic processes. As adaptive model, it looks at one possibility to model learning within such environment. However, the benchmark of ‘perfect
foresight’ should always be the goal, to derive a complex model through step-by-step relaxation of the conventional economic assumptions. Only in such step-by-step (also called *ceteris paribus*) relaxation of assumptions, the relevance of each assumption on its own can be analyzed and be embedded into the conventional economic theory. The agents’ planning capability should thus range from perfect knowledge about the future to increasing use of simpler rules.

The MP-MAS model offers four types of expectation building. (1) For some processes, perfect foresight allows agents to read future values or prices directly or perform simple computations directly based on these. Some expectations can use external data (price, river flows and precipitation) or make simple computations based on these (e.g. plant water deficit for each crop in each month and thus monthly irrigation demand). (2) With naive expectations, the coming year is assumed to equal the previous year. (3) With constant expectations, agents always assume a ‘typical’ year which must be defined. (4) Adaptive expectations compute a moving average over the past, the length of which is determined by an adaptivity parameter $\lambda$, that is used for updating expectations $\hat{X}$ for any variable $X$.

$$\hat{X}^{t+1} = (1 - \lambda) \cdot \hat{X}^t + \lambda X^t$$  \hspace{1cm} (5.4)

Naive expectations are equivalent with adaptive expectations that use instant adaptation ($\lambda = 1$), and constant expectations use infinitively slow adaptation ($\lambda = 0$). Usually, adaptive expectations with $0.2 < \lambda < 0.5$ are a good method to simulate learning behavior and the adaptation to a changing environment, especially if dealing with trends (compare Berger 2001).

For the dynamic Chilean model, farm planning occurs at two time horizons: the production horizon of the upcoming year, and the investment horizon of several years. There are two factors that complicate expectation building.

First, if environmental conditions would fluctuate randomly, then expectation building for both time horizons could be treated equally. However, the Chilean context has two important factors: first, the El Niño cycle dominates the inter-annual variation of precipitation and winter temperatures (see Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’, Sections 2.4 – 7). Here, the annual variation of weather conditions follows the pattern of fluctuations with a frequency of approximately seven years. Adaptive expectations are a good method to follow a trend, but less adequate to deal with such fluctuations. To illustrate this, Figure 5.5 shows four different parameterizations of adaptive expectations, with the memory $\lambda = [0, 0.25, 0.5, 1]$. For the precipitation station in San Manuel, the average planning error and its standard deviation is as follows (and similar for other stations):

<table>
<thead>
<tr>
<th>Expectations: Error [mm]</th>
<th>Constant $\lambda = 0$</th>
<th>Adaptive $\lambda = 0.25$</th>
<th>Adaptive $\lambda = 0.5$</th>
<th>Adaptive $\lambda = 0.75$</th>
<th>Naive $\lambda = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error</td>
<td>0.0</td>
<td>-0.9</td>
<td>0.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Standard deviation of error</td>
<td>87.7</td>
<td>97.0</td>
<td>105.8</td>
<td>117.4</td>
<td>135.2</td>
</tr>
<tr>
<td>Mean typical error assuming investment good with 5-year return</td>
<td>42.0</td>
<td>45.9</td>
<td>49.7</td>
<td>53.3</td>
<td>59.2</td>
</tr>
</tbody>
</table>

For the fluctuation of precipitation data, it is apparent that constant expectations out-perform any other form of expectation building.

To test the performance for investment planning, a similar computation was done for a 5-year horizon, with the same data. Each year, the adapted expectations were computed as were the deviation from measurements for the current and the following four years. For each year, the average absolute deviation was then taken, as ‘typical’ error. The third row in the table gives this.
CHAPTER 5. CONCEPTUAL MODEL INTEGRATION

Figure 5.5 — Expectation building and precipitation data. Total measured precipitation during the irrigation season (Dec-Mar) and expectations with different adaptive parameter $\lambda$. For values of 0 and 1, adaptive expectations become constant and naive expectations respectively.

typical error during a 5-year planning horizon, averaged over all years. Again, constant expectations out-perform all other expectations, with naive expectations performing worst.

The second complication in expectation building is specific to the local geography of Maule region. Even at the beginning of the year, water delivery for the complete cropping season is known with comparatively low uncertainty. Every year, precipitation accumulates in the Andean mountains as snowfall during the winter and melting water is released as river flow during most of the year. In typical years, this runoff lasts until late in the cropping season. Both precipitation and the temperature in higher areas determine the total winter snow accumulation, which in turn determines the magnitude of river flows during the spring melt and summer, which is used for irrigation. Public institutions disseminate data on snow accumulation every spring, before sowing has started. In addition, many farmers receive water from reliable sources, such as the Melado canal that is connected to a reservoir. Furthermore, precipitation as the other water source of plants is less than 10 mm during the dry months (Jan-Mar) with high certainty. Thus, farmers already have reasonably good estimates on the total water availability of each year, which can be used for production planning.

Hence, the specific context gives relatively little uncertainty regarding precipitation conditions on an annual basis. On the other hand, nothing is known about the year that follows. For this reason, the annual forecast for runoff in rivers is fairly good, while very little information is available for medium-term investment planning.

In summary, the expectation building process about future environmental conditions (both nature and markets) plays a central role in the economic planning process. As the MP-MAS model is extended from ‘typical’ natural conditions to temporally and spatially variable conditions, the relative importance of expectation building increases. While the empirical measurement of expectation building is not the aim of this study, its high relevance at least requires some consideration within the conceptual model. The final integrated model is thus designed to allow sensitivity analyses of variable planning modes. Planning should not only be varied in the magnitude of $\lambda$, but instead, adequate expectation models must take into account the role of uncertainty within a planning decision, e.g. for annual and longer-term time horizons of a decision.
5.4. FARMERS DEALING WITH THEIR ENVIRONMENT

5.4.2 Farmers’ Access To Water

Water rights in Chile

The Chilean Water Code (1981) defined water as a ‘public property for private use’. Entitlements to surface water then became a property right that is not only freely tradable but may also be transferred to other uses. The water code defines water rights as a flow volume per unit of time, also called the water equivalent value [liters/second]. Water rights from each farmer are registered with the Juntas de Vigilancia, who ensures that all farmers receive their water accordingly. Water rights are further specified as permanent or eventual: holders of permanent rights can access water under any hydrological conditions, while holders of eventual rights only receive water if is available.

With the volatility of river flows, the available water can be less than the amount that even permanent right holders are entitled to receive. In such years, most user organizations interpret water rights traditionally, as percentages of river flows (rights for drinking water supply supersede this rule and are served first, see Hearne and Easter 1995). In such years, the total available river water is distributed to all water right holders so everyone suffers equally from a proportional reduction of water delivery.

Even today, many farmers have not yet fully inscribed their water rights with the government, a costly process that locals call ‘legalizing’ or ‘constituting’ the traditional rights. At the national level, Hearne and Donoso (2005) estimate the share of these ‘customary’ rights to be between 10% and 50% of all rights. Though protected by law (Donoso 2006), the values of such customary rights are usually not defined precisely, nor whether these rights are permanent or eventual, or if flows may be used continuously or discontinuously (JdV Longavi 2005). Many water user organizations still rely on traditional rules to distribute water to farmers.

Access to non-attributed canal water

The total irrigation water supply to farms exceed the net water abstractions from rivers, because return flows and other non-attributed sources of water can also be used for irrigation. Two mechanisms are suggested here to model this additional productive asset.

1. **Institutionalization of access to non-attributed water.**

   Juntas de Vigilancia acknowledge the existence of non-attributed water as a resource that can be managed and distributed to farmers.

   One way to distribute this water is by increasing the existing water equivalent values proportionally by some factor $1/\eta_{\text{sector}}$. Here, all farmers that hold water rights receive an additional share of water. There is a slight redistributional impact, because the suggested rule averages inefficiency over all water rights. Those right holders that manage efficiently then receive a ‘transfer’ of water from those that irrigate less efficiently. JdV can determine and adjust this increase factor $1/\eta_{\text{sector}}$ over the years.

   Over the years, water right equivalence values were determined empirically by measuring river outflows, and then determining how water can be distributed to water right holders. Partly, this control cycle already internalizes return flows into the equivalent values of water rights. Any gain in irrigation efficiency must then be compensated for by reducing the equivalence values.
The re-distribution of non-attributed water through user organizations has a large impact on water rights holders. While water is redistributed from efficient to inefficient irrigators, it does not give any benefits to non-right holders.

2. Alternative allocations of non-attributed water.

Surplus water is not legally owned by anyone, and thus using it cannot be considered stealing. It is difficult to quantify how farmers access this non-attributed water. Some of it may be distributed through non-formal agreements and customary rights, the remainder may simply return to the rivers. Also, JdV may reduce the total abstraction from rivers into canals, as long as these canals carry sufficient water to serve all water rights. Donoso (2006) points out that legalized water rights are mostly classified as consumptive, while customary water rights as often interpreted as partly non-consumptive. A holder of customary water can thus only use a fraction of his water and the remaining part is already allocated to other right holders. To avoid conflicts, farmers that have customary rights and surplus water have an incentive to ‘spoil’ this water, for example by irrigating unproductive land and pastures.

The causal mechanisms how farmers access non-attributed water is thus complex and may even vary between hydrological years. However, only 50% of all farmers in our region hold legalized water rights (see Section 7.5.1). Water rights registries were compared with crop production data from the agricultural census. With such data analysis, it is apparent that small farmers especially rely on water access through customary rights or even solely on access to non-attributed water (see also analysis in Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’).

Modeling access to water for farm agents

To model water distribution from rivers to farmers with the original model, water rights registries were not available and assets were quasi-randomly attributed to farms so that 1996 land use was reproduced. As an essential production input, all farmers obtained some water rights.

With improved registry data that allows data-based attribution of land and water, we were confronted with a paradox: only 2301 of the 3594 agents own water rights at all, and several of these own far less water than required to crop their land. For January of a representative year, the average water endowment was computed per hectare, and farmers are counted for each farm size stratum. Assuming a typical crop irrigation requirement for one hectare of 0.5 - 1 liters/second, about 29% of all farmers have adequate endowment of water rights in a normal year (23% in a moderately dry year). How do those without adequate water rights operate their farms?

Observing this phenomena, (Donoso 2006) mentions spillover or ‘surplus’ water that is abandoned by their owners after having been abstracted from the original water system. Owners are believed to leave this surplus water in the canals once the irrigation demand of their crops was met. Those without rights benefit from this pool of spillover water an agricultural input. Other sources of spillover water are inefficiencies of the canals and also of the on-field irrigation methods. Experts acknowledge the abundance of spillover water in most years, and describe the difficulty of enforcing the modest maintenance fees that are attached to legalized water rights in the presence of this free resource. Only in years with stronger droughts, does this pool of spillover water dries out, leading to aggressive and sometimes violent conflicts over water access. For such an informal or even non-regulated resource, empirical data is non-existent. Due to
Table 5.1 — Number of farmers and their level of water endowment, expressed in water right equivalents per hectare. Values are given for normal/moderately dry years.

<table>
<thead>
<tr>
<th>Water Endowment group (liter/second per hectare)</th>
<th>Specialized small farm [3.5 - 5 ha]</th>
<th>Small farm [5 - 25 ha]</th>
<th>Medium farm [25 - 60 ha]</th>
<th>Large farm [60 - 200 ha]</th>
<th>absolute</th>
<th>percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>184</td>
<td>943</td>
<td>126</td>
<td>40</td>
<td>1293</td>
<td>36%</td>
</tr>
<tr>
<td>&gt; 0 - 0.1</td>
<td>4 / 6</td>
<td>173 / 212</td>
<td>63 / 86</td>
<td>33 / 45</td>
<td>273 / 349</td>
<td>8% / 10%</td>
</tr>
<tr>
<td>&gt; 0.1 - 0.25</td>
<td>13 / 16</td>
<td>238 / 305</td>
<td>108 / 132</td>
<td>33 / 27</td>
<td>392 / 480</td>
<td>11% / 13%</td>
</tr>
<tr>
<td>&gt; 0.25 - 0.5</td>
<td>10 / 12</td>
<td>422 / 463</td>
<td>133 / 142</td>
<td>27 / 28</td>
<td>592 / 645</td>
<td>16% / 18%</td>
</tr>
<tr>
<td>&gt; 0.5 - 1</td>
<td>24 / 24</td>
<td>522 / 434</td>
<td>128 / 92</td>
<td>14 / 10</td>
<td>688 / 560</td>
<td>19% / 16%</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>46 / 39</td>
<td>266 / 207</td>
<td>35 / 15</td>
<td>9 / 6</td>
<td>356 / 267</td>
<td>10% / 7%</td>
</tr>
<tr>
<td>Total</td>
<td>281</td>
<td>2564</td>
<td>593</td>
<td>156</td>
<td>3594</td>
<td>100%</td>
</tr>
</tbody>
</table>

its enormous importance for farmers, any economic production analysis must take it into account and include it in an integrated model.

Repartitioning rules for non-attributed water. Total water delivery $T_i$ to each agent $i$ combines waters from legalized sources according to water rights and from the pool of non-attributed water:

$$T_i = \text{legalized access to water} + \text{non-attributed access to water} = L_i(WR_{i,x,j}^r, Q^r, \eta_c) + f_2 (\text{canal inefficiencies} + S_j + RF_j)$$

where legalized access is a function $L_i$ of water rights $WR_{i,x,j}^r$ that the agent $i$ of sector $j$ holds to a river $r$, the river flow $Q^r$ and the efficiency $\eta_c$ with which this water is delivered from the river to the farm agent.

Non-attributed water originates from local ‘losses’ that re-enter the canal system. Canal conductive efficiency $\eta_c$ describes the efficiency of water delivery from the sector to the farm household. The rest $1 - \eta_c$ is partially lost to sinks and partially contributes to non-attributed water. Surplus water $S_j$ is the water that farmers receive, but do not use because their irrigation demand is already met. Return flows $RF_j$ originate from inefficient irrigation methods within the same sector $j$, or from other sectors upstream.

For the analysis of the impact of canal conductive efficiency on individual farmers, four model specifications (Canal modes) were implemented. These modes are descriptive in nature and capture the effect of sector-level institutions and infrastructure and the handling of surplus water. The empirical model is intended to demonstrate the effect of sector-level processes and for uncertainty analysis.

The original Edic model is constructed in a way that a high proportion of internal reuse also increases the access to water delivery proportionally with water endowments. Only return flows from upstream sectors are redistributed through an area share. Thus, the impact of canal losses on the distribution of access to water is minimal and limited to return flows. This agent-level proportional and cyclic treatment of reuse is equivalent to two model assumptions:

1. Water management institutions increase the value of water equivalences to the share of water that is not used, while excluding non-right-holders access to the fraction that was not consumed by rights holders (Institutionalized reuse).
2. Inefficiency occurs on-farm but rather homogeneously across the irrigating population (On-farm reuse).

Return flows to other sectors originate both from surface and lateral runoff. Sector level losses, expressed as the difference between $\beta_j$ and $\beta_{j,max}$, are deducted from the proportional increase of reuse and also from return flows.

$T_j$ is the total sector-level inflow, adding external deliveries for all water rights that are held within the sector $j$, for all inflows $r$.

$$T_j = \sum_r \sum_{i \in j} Q^r \ WR^r_{i \times j}$$

Canal losses $C_j$ that may be reused depend on canal efficiency and a new parameter $\beta_c$, which determines how much of the canal water losses remain in the surface zone as non-attributed water and can thus be reused by others. Following the original EDIC model, the rest $(1 - \beta_c)$ is then partitioned to both lateral flows and deep losses by a ratio of 3 : 2 according to the original EDIC model.

$$C_j = \beta_c (1 - \eta_c) T_j$$

(5.5)

In detail, the share of water lost in canals, $(1 - \eta_c) \in [0, 1]$, is partitioned among (internal) surface reuse, deep losses (which are taken out of the system), and lateral losses (which contribute to return flows into downstream sectors). The partitioning between lateral flows and deep losses is currently hard-coded, with 3/5 of shares going to lateral flows and 2/5 to deep losses.

For $\beta_c = 0$, canal efficiency does not increase the pool of non-attributed water and the model is equivalent to the original EDIC model. With $\beta_c = 1$, water fully adds to non-attributed water.

**Mode A – Proportional repartitioning (Institutionalized/on-farm reuse).** In Mode A, canal efficiency $\eta_c$ is fully handled through the proportional scaling of on-field irrigation efficiency parameters for on-field losses, return flows and internal reuse.

The water quantity $L_i$ that is accessed through legalized water rights depends on canal conductive efficiency, on the river flows, and on the water rights to each river. The total net water delivery $T_i$ that each agent receives depends on this legalized portion plus access to non-attributed water flows:

$$L_i = \eta_c \cdot \sum_r Q^r WR^r_{i \times j}$$

$$T_i = L_i + \zeta^{WR} \cdot C_j + \frac{A_i}{A_j} \cdot (RF_j + S_j)$$

(5.6)

with reuse from canal losses $C_j$ in sector $j$ and the quantity-weighted proportion of the water rights to the whole sector

$$\zeta^{WR} = \frac{\sum_r Q^r \ WR^r_{i \times j}}{\sum_r \sum_{i \in j} Q^r \ WR^r_{i \times j} = \sum_r Q^r \ WR^r_{i \times j}} = \frac{\sum_r Q^r \ WR^r_{i \times j}}{T_j}$$

(5.7)

The third term of eq. (5.6) deals with surplus water $S_j$ and return flows $RF_j$ into sector $j$ independently from the individual’s water rights and proportional to area size, using the share of
the agent’s irrigable farmland to the total irrigable area of the sector $A_j = \sum_{i \in j} A_i$.

Substituting (5.5) and (5.7) into (5.6), the agent’s total water delivery can be expressed as function of $\beta_c$:

$$T_i = (\beta_c + \eta_c - \beta_c \eta_c) \cdot \sum_r Q^r \cdot \text{WR}_i \cdot \text{RF}_j + \beta_c \cdot (\text{RF}_j + S_j)$$

(5.8)

This equation also points out that canal losses are fully re-distributed to those farmers holding legalized water rights. Effectively, the ‘Mode A’ canal model increases sector-level irrigation efficiency without benefiting farmers that rely on non-attributed water.

**Mode B – Redistribution proportional to land.** In Mode B, the amount of water that originates from canal conductive efficiency $1 - \eta_c$ is redistributed to all agents within the sector, proportional to the share of irrigated land owned by the agent. Additionally, a certain percentage of water is simply lost – these losses are determined by a second parameter, $l_c \in [0, 1]$. Canal losses are deducted from the net inflows of the farm agent, but re-distributed as area share:

$$T_i = L_i + \frac{A_i}{A_j} \cdot (C_j + \text{RF}_j + S_j)$$

(5.9)

**Mode C – Small farmers benefit over-proportionally.** To test stronger re-distribution, in Mode C a ‘root’-function is assumed to relate farm size and the benefits from non-attributed water, instead of the linear relationship postulated in Mode B. Thus, if canal inefficiency contributes to non-attributed water, it has redistributive impact and benefits small farms (Figure 5.6):

$$f(\lambda_c, i) = \frac{\lambda_c \cdot (A_i)^{1/\lambda_c}}{A_i}$$

For a re-distributive parameter $\lambda = 1$, Mode C becomes equivalent to Mode B.

$$T_i = L_i + f(\lambda_c, i) \cdot C_j + \frac{A_i}{A_j} \cdot (\text{RF}_j + S_j)$$

(5.10)

**Mode X – Mix of Modes A & C.** Mode X combines Modes A and C equally. Thus, canal conductive efficiency has both proportional scaling and redistributive effects. The above formulas are thus slightly modified, and both the share of water rights from Mode A and the redistributive factor $f(\lambda_c, i)$ are weighted equally, giving

$$T_i = L_i + \frac{C^\text{WR} + f(\lambda_c, i)}{2} \cdot C_j + \frac{A_i}{A_j} \cdot (\text{RF}_j + S_j)$$

(5.11)

The equal share of both Modes A and C is hard-coded.

**Net water delivery** The net water delivery to each agent also takes into account the internal reuse that is postulated in the EDIC model. Thus, the final net delivery to each agent depends on delivery from legalized rights, non-attributed water (and also from water rental, if that module is activated), and increases by that factor (see EDIC Manual, Arnold 2007):

$$N_i = \frac{T_i}{U_j}$$

(5.12)
Figure 5.6 — Redistribution of non-attributed water in Mode X, with a nonlinear parameter $\lambda$ that, the higher it is, gives more canal return flows to small farmers.
Chapter 6

Technical Model Integration

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Technical Model Integration (Chapter 6) describes how software solutions of the conceptual extensions and the hierarchical coupling were implemented. With integration, the modelling objectives of the legacy models were expanded toward a broader and more integrated system description. Thus, several processes within (or at the limits) of the original disciplines became relevant and required to enhance the original legacy model source codes. Changes include an improved irrigation module of the WASIM-ETH model and several extensions of the multi-agent model MP-MAS and the node-link sector irrigation model EDIC. Also, models were re-factored as pre-condition for hierarchical model coupling (Sections 6.1-6.3). The implementation of the hierarchical coupling scheme is summarized (Section 6.4. For detailed technical descriptions, see the Technical Report ‘Coupling Manual’). Finally, a hierarchy of different levels of model coupling is summarized (Section 6.5).
6.1 Extension Of The Legacy Model WASIM-ETH: The Irrigation Module

The WASIM-ETH irrigation module was used only in very few applications, and the WASIM-ETH source code was considerably extended for other applications. Within this module, a few bugs were found and reported to the programmer. Also, the handling of boundary processes was extended. Processes that were improved are irrigation efficiency, mixed surface-water – ground water irrigation, the use of crop-coefficients to parameterize evapotranspiration (reference surface approach). Furthermore, the irrigation restriction was modified. Details are elaborated in the Technical Report ‘Coupling Manual’, A.3 Irrigation modelling with WASIM-ETH as well as in Arnold et al. 2008a, Uribe et al. 2008a, Uribe, Arnold, Arumí, Berger and Rivera 2009. This section gives a brief overview on technical implementations; see Section 7.3 for indicative modelling results.

The reference surface approach is a new module to compute potential evapotranspiration. It builds on the existing PENMAN-MONTEITH module. To compute \( ET_{pot}^{crop} \) for agricultural crops, it first computes \( ET_{pot}^{ref} \) for reference crops, and later applies a monthly factor \( k_{crop}^{m} \) which is a parameter. Outside of the cropping season, evaporation of bare soil is assumed. Otherwise, an additional land use (cover crops) must be specified.

Parameterization of irrigation efficiency allows to specify surface irrigation at ‘average’ or ‘effective’ values and at large areas. Actual fields (5 hectare and less) are flooded for short one-day intervals, and these irrigation ‘pulses’ rotate. With resolution of 40 hectares per grid cell, these pulses of water uptakes even out. On the other hand, relevant physical occur because of this pulsed characteristic, and continuous computation of physical processes would undermine model validity. In order to model irrigation processes at watershed level it is not feasible to increase model resolution. To capture the sub-grid infiltration processes, we used measured data to parameterize (and calibrate) deep percolation and surface runoff\(^1\).

Specification of water rights was implemented at input level. Water rights are used to route irrigation water from one river to another area, which may be located in another sub watershed (canal abstractions).

Dealing with the maximum irrigation restriction was completely re-worked. The original small-watershed implementation assumed short and infrequent irrigation pulses which significantly alter downstream water availability and variability. Instead, a large-scale assumption was implemented (Version Arnold) with semi-constant irrigation water uptake per watershed, and further a data-based method (Version Uribe, ‘Irrigation water abstraction with iteration’). This version abstracts irrigation water in one model run, re-injects and irrigates with this water in a second round. A third round is used to estimate return flows and additional irrigation because of return flows.

Handling of files was modified so that the location of daily grid and stack files can be handled externally. New files are exported: The irrigation restriction, the irrigation column finally applied, and spatial maps of irrigation water.

The anaerobic growth restriction can be switched off. Regular irrigation at daily time steps results in water clogging. During one day (and time step), the top soil horizon completely fills with water. This is a numerical artefact rather than an actual process, so growth restrictions were switched off.

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\(^1\)To develop theory-based rescaling, further studies with high resolution models (10 m grid length) and using SAINT-VENANT equation are recommended, which require annual measurements on soil moisture, runoff and infiltration for a variety of soil types and slopes.
6.2 Extension Of The Legacy Model MP-MAS

This section gives an overview of programming works needed to prepare the MP-MAS software for hierarchical coupling.

6.2.1 Making MP-MAS Fit for Coupling: 
Re-Factoring of Source Code

Modularization and re-factoring has four objectives. First, the handling of input and output data as well as data exchange is simplified. Second, strict and consistent handling of time within the model source code is required, so that the complete data for one time step is available. Third, source code modularization and the use of generic handling of data and functions is a pre-condition to expand model complexity and to implement further levels of detail, because otherwise source code becomes too complex and difficult to manage. Forth, modularization is a procedural requirement for source code management, because it greatly simplifies simultaneous implementation with groups of programmers.

Modularization and re-factoring was among the activities during this Ph.D. thesis that took most time and effort. Tasks included the wrapping of data into container classes and the extension of these container classes; the re-organization of data handling into generic functions that are based on data types ('ContentType'); modularization of the source code and especially the initialization and data reading routine; management and handling of time; modular and generic handling of spatial data; the handling of input arguments.

A ContentType as general identifier for data across models was introduced and implemented that all model components use consistently. Each variable and input file is associated with an entry in the enum-type "ContentType". As slim header, this typology is imported by all model components. The variable 'precipitation' can thus be identified uniquely with the same type 'contentPrecip', which greatly reduces modelling error and enhances the transparency of source code and concepts. Using this ContentType, data can be freely passed between model entities and between models by using generic functions and generic data contains. At the appropriate model layer, this data is then translated into specific calls, using a specific switch-statement.

Modularization of source code. To facilitate coupling, but also to allow co-development with multiple programmers, the original source code has been modularized and re-classified. MP-MAS source code now consists of two main entities: The utility classes and the MP-MAS classes. Utility classes, including all data container classes and string and stream handling functions, can be used and compiled independently from MP-MAS source code, which greatly facilitates coupling to other programs. The MP-MAS classes are further divided into agents, crops, landscape, markets, solvers, and others (see source code documentation).

Modularization of the model initialization routine. For most data, initialization was wrapped into single classes, so that the model can be instantiated separately from MP-MAS, e.g. by other model components. Most notably, the spatial grid is now independent from all other files. Without further source code modifications, it can be run as cellular automata model, fully independent from other MP-MAS agent components. Furthermore, a shared log file that is used by MP-MAS
and also by all other model components. To verify source code, it contains entries for each time step of all components.

The management of time. For coupling, a stringent adherence to time stepping was implemented. This requires global time handling which is forward in time only, and iteration over expectation horizons that is local and strictly separated from global time handling, so that all model components thus strictly use local time stepping.

Improved handling of spatial data. Originally, spatial maps have been imported at sector level, which required the creation of $N_{\text{sectors}} \cdot N_{\text{var}}$ maps. Now, maps are imported at catchment level. Then, information is internally passed to the landscape class, currently held by the sector class. For the Chilean model, this reduces the number of input maps by a factor 20.

Furthermore, access to spatial information was re-implemented, and now uses generic functions with ContentType. This ‘wraps’ the landscape class and greatly reduces source code complexity. Also, spatial information can now be passed back and forth between the LP decision matrix and the cellular automata (see detailed description in Section D.1.1 of the Electronic Appendix).

Improved handling of model arguments. Model parameters can easily be passed as input arguments to MP-MAS in any order. Also, these arguments are flexible, which greatly speeds up doing small changes. Test flags (-T##) control different output levels to screen and file, and spatial exports are governed with -A##. Random numbers are generated according to a seed (-S##). Other switches include directory management, switching of modules and special data handling.

Re-organisation of spatial handling. To reduce source code complexity, the landscape class that handles spatially distributed data is ‘wrapped’ and is now access through a single function rather than separate with functions for each variable. Furthermore, this spatial information is re-linked from the LP solution (see Technical Appendix D.1.1).

Grid-level or sector-level handling of spatial data. Data may either be handled heterogeneously at grid-level, or it may be homogenized and stored as single value, at sector level.

6.2.2 Extensions of the MP-MAS Model

Dynamic meteorological and river flow data

The original MP-MAS model read river flow data for a typical, representative or effective meteorological year. Input data for crop irrigation demand was corrected with ‘effective’ precipitation, defined as the amount of precipitation that plants can take up. This effective precipitation was also read from file and no further consideration of precipitation was needed.

The model was extended so that supplementary irrigation and now also accepts time series data for actual precipitation in each sector, as described in Section 4.3.4. The computation of all crop parameters that are used must be repeated for each year and performed for each irrigation sector, because the amount of precipitation may vary by sector and year.

River flows were also extended, from the static year to dynamic time series. Data is read for each river.

For both river flow and precipitation, the ‘typical’ year is still read in, as initialization for expectations and if the model is run in static mode.
Precipitation and supplementary irrigation

The original MP-MAS model (Berger 2001) was extended to deal with precipitation that varies over the years and also for each irrigation sector, as outlined in 4.3.4. Effective precipitation, which used to be read from an external file, is now computed within the model using actual precipitation data. For each crop that is planted in each sector, the annual cycle of plant demand for effective irrigation water is now computed separately for each year. Also, the original model assumed fixed yields for rainfed crops, because ‘representative’ meteorological conditions were assumed.

The extended model now computes yields for rainfed crops as a function of the annual precipitation cycle. In the original model with static/constant meteorological conditions, rainfed crops were water-constrained. The model parameterizes these actual yields in a representative year $Y_{\text{stat}}$. To depict yield fluctuations adequately, these empirically estimated values had to be re-visited: the original model would not properly represent yields in wet years because no yields beyond this value could be obtained. For the dynamic case, a larger value $Y_{\text{max, dyn}} > Y_{\text{stat}}$ so that in the long run average, farmers harvest that yield under representative environment conditions, $Y \approx Y_{\text{stat}}$ (see also 7.6).

Water Rights by individual agents

Water rights are defined as a proportion of the total irrigation water supply of an irrigation sector that an agent is allowed to use. This proportion is assumed constant over the whole year and during all years in the simulation run (MP-MAS Manual). The original MP-MAS model defines water rights as total endowment at sector level $WR_{r,j}$ and then randomly distributed water rights to individual agents, but considering the total area that each agent owns to avoid asset endowments that create non-viable farm enterprises.

MP-MAS was extended. For each agent, it is now possible to define what proportion of the total irrigation water supply of a sector and of each inflow is attributed to each agent $WR_{r,i}$. The total water supply $S$ that each agent $i$ (who farms in sector $j$) receives is then

$$S_{t,i} = \sum_{r=1 \ldots R} F_{r,t} \cdot WR_{r,j} \cdot WR_{r,i}$$

(6.1)

with the flow $F$ of each river $r$ at time $t$.

Agent-specific water rights are read from file and parameterized empirically.

Separation of production planning and investment planning

Some of the expected crop coefficients, for example crop irrigation demand, are computed dynamically using the expected precipitation data. If expected precipitation varies between a medium-term investment decision and the short-term production decision, then the LP matrix that is used for the optimization has to be adjusted accordingly for each of those decisions. To do so, the function that computes these coefficients on an annual basis was modified. It was separated into a sub function that parameterizes the dynamic parameters of the LP, and into the optimization function itself.
CHAPTER 6. TECHNICAL MODEL INTEGRATION

Expectation building and learning

**Adaptive expectations.** The original model uses a single and constant learning parameter $\lambda = 0.5$. As part of the CNR Use Case, this original model was extended. First, different learning parameters $\lambda_i$ were introduced for water, for prices and for yields. Additionally, expectations are built separately for the (mid-term) investment decision and the short-term production decision, again with separate learning parameters.

This divide was necessary because either the adaptivity of agents is adequate to react to price- and water dynamics in their production, which causes over-emphasis of short term trends in the investment model (e.g. agents invest in apple plantations after two wet years because they received plenty of non-attributed water during this time, and then go bankrupt during the first 4-year drought). If adaptivity to price- and water signals was decreased, then farmers under-produced even if prices rose significantly over two years.

Thus, expectation building for (mid-term) investments and (short-term) planning can be separated conceptually and technically. This enables farm agents to have slowly adapting expectations for mid-term decisions, while reacting quickly to production signals.

The parameters that were used for all model experiments are listed here: (a) For mid-term decision and expectation building, agents use data for the ‘typical’ year that was read from file. Agents perform the investment decision based on these mid-term expectations. The decision LP is updated with mid-term technical coefficients and expected asset endowments, regarding non-attributed water, water entitlements and prices. (b) For the production decision, agents build short-term expectations on the coming year. The decision LP is updated with short-term technical coefficients and expected asset endowments, regarding non-attributed water $Ext_i$, water entitlements $W_i$ and prices $p$.

The original empirical value $\lambda = 0.5$ can then be parameterized in more detail. The following parameterization was used as standard:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{p,\text{mid-term}}$</td>
<td>0.2</td>
<td>Adaptivity of investment decision to prices</td>
</tr>
<tr>
<td>$\lambda_{p,\text{short-term}}$</td>
<td>0.6</td>
<td>Adaptivity of production decision to prices</td>
</tr>
<tr>
<td>$\lambda_{W,\text{mid-term}}$</td>
<td>0.2</td>
<td>Adaptivity of investment decision to water entitlement fluctuations</td>
</tr>
<tr>
<td>$\lambda_{W,\text{short-term}}$</td>
<td>0.6</td>
<td>Adaptivity of production decision to water entitlement fluctuations</td>
</tr>
<tr>
<td>$\lambda_{Ext,\text{mid-term}}$</td>
<td>0.2</td>
<td>Adaptivity of investment decision to variability of non-attributed water</td>
</tr>
<tr>
<td>$\lambda_{Ext,\text{short-term}}$</td>
<td>0.6</td>
<td>Adaptivity of production decision to variability of non-attributed water</td>
</tr>
</tbody>
</table>

In addition, the model can be run in a second mode. Here, surplus water is used for production planning, but not for investment planning. This mode is a first (and preliminary) means by which to incorporate the risk aversion of farmers.

Finally, for some decisions (especially the decision to deal with lack of irrigation water), experience has established very robust decision rules, so rationalizing that requires foresight is not required, and the heuristic that was implemented by Berger 2001 is used. In short, this irritation priority rule by crop group distributes water in cases of shortage to those crops that typically give highest profits. The grouping of these crops is an input parameter and was determined with farmers (see Section 7.4.2).
6.2. EXTENSION OF THE LEGACY MODEL MP-MAS

Figure 6.1 — Time handling within MP-MAS. Agents go through each year three times: Once when updating their decisions, ones (implicitly) within the production decision, and then during the real year.

Forecasting. For decisions with very high certainty, a forecasting function was implemented. Here, the model handles ‘real’ model time separately from ‘virtual’ model time within expectation building and ‘forecasting’ (for implementation, see Section D.1.2). During expectation building for decision making, farm agents can initialize local model components or request input data that describe future boundary conditions (river flows, input and output prices, real and effective precipitation) to obtain perfect foresight at that virtual model time. Complex interactions such as the behavior of others are not forecasted but adaptive expectation rules are used.

Modules for rational expectation building (forecasting) need to be ‘stateless’ and quick in runtime. Modular functions were implemented. These can be used for the building of expectations for mid-term decision and later to build short-term expectations for shorter-term production decisions. Finally, the full model runs to produce ‘real’ model outcomes (see Fig. 6.1).

Forecasting meteorological conditions. In the Chilean context of Region VII, river flows originate in the Andean mountains, where glaciers and snow melt create runoff. The snow accumulation during winter is a strong indicator for water availability over the year, which is known even at the beginning of the cropping season. Thus, farmers receive a decent forecast at least for the amount of irrigation water that will be available in that year. To capture this annual forecast as model benchmark, a forecast function was implemented.

Technically, the data for river inflows are stored in a catchment-level variable \( N \) for one year. This variable is overwritten before the investment planning, again before production planning and again for the ‘real’ model. For each planning level, agent-level expectations either change adaptively. Then, adaptive expectations use water availability from the last year. Otherwise, rational forecasting is used with a globally defined forecast error parameter \( f_{error} \).
For planning, a forecast function relates the ‘real’ data, if known, to the ’typical’ year, using one error parameter $f_{\text{error}}$:

$$N_{\text{forecast}} = N_{\text{real}} + f_{\text{error}} \cdot (N_{\text{typical}} - N_{\text{real}}) \quad \text{(if } N_{\text{forecast}} < 0, \text{ then } N_{\text{forecast}} = 0)$$

For $f_{\text{error}} = 0.0$, the forecast is perfect. For $f_{\text{error}} = 1.0$, it gives the typical year. Any values between 0 and 1 are interpolations, and values outside of this interval are (permitted) forecast errors.

Forecasting was separated between investment and production planning. Typically, investment planning uses a forecast error $f_{\text{error}} = 0.0$, which gives the average year. Production planning uses perfect forecast ($f_{\text{error}} = 1.0$).
6.3 Extensions Of The MP-MAS-EDIC Linkage

6.3.1 Improvements Of The MP-MAS/EDIC Linkage

A detailed description of the implementation of the extended EDIC model is given as part of the Technical Report ‘The sector irrigation model EDIC’ (Arnold 2009). It contains the function calls, a code diagram and also mentions output files.

6.3.2 Farm Agents And Water Supply: Modelling Of ‘Legalized’ Water Rights And Access To Non-Attributed Water

Within the model, farm-level irrigation decisions are based on expected water availability, which the farmer can assess at a daily basis. Thus, a farmer’s irrigation decision is based on the water that he receives at a given point in time. The exact amount of water that is available for each farmer actually depends on the behavior of others, specifically the use non-attributed water within an irrigation sector and from other sectors. Such interactions can only be solved iteratively.

Technically, the estimation of non-attributed water within a sector (surplus water, reuse, canal losses) is handled separately from water that originates from other sectors (‘return flows’).

In a first step, the distribution of water to farmers and their irrigation decision of crops is solved for all holders of legal water rights. This first round is used to estimate the amount of surplus water available, and a preliminary weighted average of irrigation efficiency for this sector is computed. Canal losses that also contribute to non-attributed water mostly depend on the water that enters the sector and are thus independent of how much water is actually utilized. Using the averaged irrigation efficiency, the within-sector reuse is also added.

In a second step, the total of non-attributed water in this sector is added. In the second iteration round, farmers also have access to non-attributed water through the repartition rule. This water may significantly increase the irrigation area in those months when water is abundant in the rivers, as many farmers benefit from surplus water. In water-scarce months, the share of surplus water is significantly smaller because farmers with legalized water rights fully utilize them. Only those shares from inefficient irrigation and canal losses are thus available. The second step re-attributes water to those farmers that already are fully satisfied, and even now some water remains in the canals.

If needed, a third iteration step may be calculated to distribute the remaining water. Practically, this third round resulted in very little change and was thus switched off at source code level.

Technical implementation Additional water from canals is added when the non-attributed water is computed\(^4\), together with return flows and surplus water. The hydrological model is iterated twice for every month; the first round estimates water supply from water rights and then computes the surplus water. In the second round, agents receive water from all sources. Agents separately ‘remember’ water delivery through water rights and through surplus water, and then build expectations according to the learning model.

\(^4\)MP-MAS function sector::computeReturnFlowsForAgent()
6.4 Hierarchical Model Coupling

This section summarizes the technical implementation of the hierarchically coupled system: work steps, data and data handling, sequencing of model components and data exchange.

6.4.1 Implementation Work Steps

The following steps were identified as a sequence of tasks for the technical implementation of integrated model software\

Integrated (relational) data base The integration of data first requires agreement on one or a few common computer systems. Important elements include a data base, a program to manage spatial data, and a program that can be easily used for data entry. Next, common data units and resolution must be agreed upon (particularly with regard to spatial resolution). Third, the linking of data necessitates the use of common IDs and the linkage of spatial maps to tables or other relational data bases. Fourth, a common frame of reference is required. Fifth, a common format is needed to communicate and document data types, data sources and data quality (meta data). Finally, once a common data base was created, specific functions to translate data into model inputs can be created. Also, a common data base greatly facilitates the data analysis across disciplinary domains (see Section 6.4.2 for structure and Technical Report 9.2.3 for an analysis within the Case Study Chile).

Common data formats A modelling system consists of multiple tasks, the solution of which is often distributed over more than one application (software). These applications can be models, translation routines, output processing routines, a user interface, one or more back-ends for post-processing and analysis, or a database. In order to keep development and transaction costs low, a small set of simple data formats is required. These data formats should be simple to understand, multi-purpose and well-documented, and understood by all team members. Their use simplifies team discussion by providing a common language and allows for the simple exchange of data, in unambiguous formats (Section 6.4.2).

From data to model input Once an integrated data base, with a common sampling frame exists, and data formats are agreed on, then data translations from that data base into model input must be conceptualized, planned and built. Each discipline may be responsible for developing such routines, especially if data for one specific model is only needed by one user or one group.

The handling of data between container classes (and model interfaces) requires a set of routines. All routines are relevant for the team members that deal with the technical tasks of integration. Those members that work in a single discipline might only use a few routines and a well-defined set of data; they should be spared of software overhead.

However, the data used by various groups requires a different treatment: Data errors are frequent, and probably inevitable, in most settings in natural resource management. Thus, if mistakes are spotted by one discipline, they should be corrected centrally and updated for all other disciplines building on the same data. The transformation of raw data into model input is then not a task that occurs at one time (at the beginning of a project), but rather a cyclic and iterative process of

\[\text{Within this Ph.D. thesis, these tasks were implemented and classification was done ex-post. For future projects, systematic adherence to this (or similar) language and a step-by-step planning and implementation along these lines is recommended.}\]
cleaning a complex, integrated data base, assembled from multiple sources. This iterative and cyclic process should be regarded as an inherent characteristic of integrated modelling and thus taken into account during the planning stage.

**From model output to data base formats** For processing, visualization and interpretation of model results, the outputs are required in format that are compatible with input data formats, in order to analyze how input data influence model outputs. It is both practical and efficient to use the formats of the integrated data base, so that routines for data management and analysis can be reused. Also, project members can familiarize themselves with the common data formats, which increases acceptance of integration efforts in disciplines and reduces transaction costs.

**From model output to model input** The translation of model outputs into inputs for other models requires conceptualization and documentation. If this translation is frequently required within the integrated model system, for example during iterative calibration across models or dynamic coupling, then the cost of automating (scripting) this process is justified.

Two options exist. First, model outputs can be translated into the existing data formats used in the integrated data base, fed back to it, and then re-translated into input data for any other model. The advantage is that only existing routines are used to re-import model outputs (Figure 6.2, solid arrows).

However, the common data frame might require transformations with accompanying and undesirable loss of data. In this case, it might prove better to channel data directly back into a translation routine that creates model inputs. Again, the use of common data formats allows for the reuse of existing functions, which can avoid additional debugging and thus bring down development costs (Figure 6.2, dotted arrows).

**Handling of input/output files** In addition to the creation of model inputs, the resulting files must be handled for the analysis of the input-output behavior of the formal map, for error analysis and finally for the representation and communication of model results.

Also, intermediate model results may also have to be saved – in great detail during the calibration phase, later only if relevant for graphical or statistical analysis. Thus, the definition of which outputs are stored should be flexible and easily adjustable in different modelling stages.
CHAPTER 6. TECHNICAL MODEL INTEGRATION

Complex models may produce such large or very large amounts of files, that full storage of large variation experiments may be neither feasible nor desirable. Instead, only a subset of outputs may need to be extracted and stored in an accessible format.

For file-based coupling, good modularization of work makes it desirable to store model input data for one model separately from the outputs of other models or from the processing routines (scripts or executables). File-based coupling thus involves the location of output files, the creation of model inputs using automated scripts, the handling (and eventual deletion) of output files, and the creation and location of model input.

Our implementation is documented in Section 6.4.2.

**Sequencing at runtime** The dynamic coupling of models, with fully automated exchange of data (either through files or directly), builds on the previously outlined steps: The comprehension and conceptualization of data and their formats; the handling of these formats; the translation of data between the different frames needed by models; the passing of (transformed) data from one model to the other; the handling of files; and the requests of models to use these data as inputs, in order to generate further outputs.

The execution of one model may be stalled for some time, finalized and re-initialized from data during each time step using a wrapper, and executed once or even several times during each time step. Many frameworks used within natural sciences, such as ocean-atmosphere interactions, or for meteorologic-hydrological interactions, usually assume single execution of models that run forward in time. Especially for socioeconomic-environmental interaction, the impact of planning and expectation building for ‘typical’ natural conditions make repeated runs of natural science models necessary.

For our implementation, see Section 6.4.3.

**Integration into generic framework environments.** Frameworks exist that facilitate such model-to-model data exchange. Recently, in hydrology, the development of the OpenMI standard was financed by the European Commission, as a generic coupling device (Tindall 2005). The framework facilitates data exchange, offers interfaces for (and an evolving library of) data exchange protocols, and facilitates sequencing. However, the structure of a model must fit this framework. Therefore, it must be ‘migrated’, and should be de-composed into single-purpose components with well-defined data interfaces (see Sections 3.2.2 ff. for a details). The use of integrated frameworks facilitates some technical tasks and – to some extend – improves re-usability\(^6\). However, a framework also gives an additional IT overhead.

Technical implementation details are described in the Electronic Appendix Part D.

### 6.4.2 Data Handling

**An interdisciplinar database for shared data**

The rules to manage relational databases are strict: One information shall only appear once within a data set, and all other references to this data link to the same instance. Technically, the database contains various *entities* (here: soils, crops, WASIM-ETH land use, cropping activity, irrigation technology). Each entity is specified with a number of *attributes*, normally columns.

\(^6\)Compare page 37, especially experience from Donatelli and Rizzoli (2008)
in a table. Each row in the table is called an instances. For example, the instance ‘high-yield maize production with surface irrigation and medium machinery use on Soil type III’ of the entity ‘cropping activity’ specifies all its attributes (labor demand at different times, soil type, water demand, irrigation technology type, machinery type).

Every instance owns a unique ID, usually called primary key PK. This key can be referenced from any other entity to link one of its attributes. It is then called foreign key because it links to a ‘foreign’ entity and its attributes. Such connection between two entities with foreign keys is called relation. Figure 6.3 describes the most relevant entities for integration, and their relations: Soil types, crop types, WASIM-ETH land use, production activities and irrigation technologies. For now, all related input data are stored in EXCEL®-sheets, and are linked via the functions vlookup or index.

Furthermore, GIS maps and water rights registries also use the same foreign keys to link data across disciplines and project partners.

![Entity-Relation-Model of input data to both MP-MAS and WASIM-ETH. New attributes are shown in normal script, foreign keys are bold and underlined, hyper links are italic. Most raster maps specify content only through object IDs, and properties are referenced through the object attributes or foreign keys (only a small extract is depicted!).](image)

**Figure 6.3** — Entity-Relation-Model of input data to both MP-MAS and WASIM-ETH. New attributes are shown in normal script, foreign keys are bold and underlined, hyper links are italic. Most raster maps specify content only through object IDs, and properties are referenced through the object attributes or foreign keys (only a small extract is depicted!).

**Input data formats and platforms**

In line with the integration approach chosen in the project, management of data remains the responsibility of the respective disciplines and with project partners. Thus, data management systems were also chosen by partners, according to the requirements of disciplinary models. Frequent interaction between disciplines via email and visits were important in defining shared data (see Section 5.1.3) and data formats. Finally, a pragmatic approach was chosen in which only a subset of shared data is commonly handled.
Socio-economic input data were organized in Microsoft Excel® spreadsheets, in combination with a Visual Basic front-end. The specific advantage of a spreadsheet program is that project staff and students are already familiar with some features of the program and that it is therefore a relatively quick process for them to learn additional features (data base functionalities etc.). Furthermore, stakeholders and external users can easily learn the first steps of input data management, which reduces the entry barrier. For teaching and extension, a spreadsheet-based application proved to be successful. Finally, adaptation of data structure to model extensions remains relatively easy, because no major IT knowledge is required for carrying out such changes in Microsoft Excel®. The entry barrier for Visual Basic is moderate.

Model outputs are farm-agent specific tables (with IDs), spatial maps, and detailed ASCII sheets for debugging and calibration, but also for detailed analysis. The heterogeneity of these data outputs demands both data base capacities and strong statistical routines. In addition, scenario and sensitivity analysis necessitates the comparison of all these data outputs, in an automated form. For simple and small models, post-processing options are also offered in Excel®, otherwise either Stata® and/or in MatLab® may be used. New spatial output maps can be directly imported into GIS.

Pre-processing and special applications that require both complex data transformations and spatial capabilities are beyond the capabilities of Excel®, and often beyond common features of advanced GIS programs. These were done with the scripting program MatLab®. In later project stages, Add-Ins for GIS programs may prove worthwhile. As a second step, specific data handling routines were directly implemented in model source code (C++), if they proved successful and useful for other MP-MAS case studies.

For calibration purposes, the re-implementation of small model components, either in Excel® or MatLab®, proved very helpful – to foster understanding, but also because sensitivity experiments could be carried out without all the software overhead. For example, for EDIC sensitivity experiments, the run time for a single year was reduced from 2 minutes (mostly spent reading and processing the spatial MP-MAS data that was later not used) to 0.3 seconds.

Hydrological data was collected in both ArcGIS® (Windows-based), as spreadsheets, and in the ASCII format that is required by WASIM-ETH.

Data container classes

In our system, five data container classes were implemented and are used:

1. **Matrix data**, passed with two integers that specify rows and columns, and followed by a block of floating values, was greatly extended (class \texttt{MatrixDouble});

2. **Grid maps** in ASCII format, with a header including the size (rows, columns), the position, the resolution and the ’nodata’ value, followed by a block of floating values (class \texttt{Raster2D}). This class can read outputs from GIS programs, but also binary files from WASIM-ETH;

3. **Stacks of grid maps**, which are three-dimensional arrays (class \texttt{Raster3D}) composed of \texttt{Raster2D} entities;

4. **ASCII Tables**, store data from tables with different column types (strings, double, integers), with column names. The input data includes two header lines (name and data type) and tab-separated entries. The name should be unique (no duplication allowed), and data types
are either strings (‘s’) or doubles (‘d’). The first column contains a unique list of ID values (class InfoTable);

5. **MTX files** contain MILP decision matrices, including large additional information for the MILP solver (class LpProblem);

For all classes, data creation and importing is simple with spreadsheet programs (MS-EXCEL, OpenOffice), with script languages (MatLab®, STATA®), with ArcGIS® and others. However, the amount of meta data included is sometimes not fully satisfactory.

**Data transfer between executables using the TDT library**

The **Typed Data Transfer (TDT) Library** was developed in Potsdam Institute for Climate impact research, by Ciaron Linstead (2005). It provides a simple, consistent interface for the transmission of data between programs in a platform- and language-independent way. It moves the complexities of handling data types and data sources into a self-contained library of functions. In this way, complex data types (i.e. data types composed of elements with different data types, like a ‘struct’ in C) can be passed between TDT-enabled programs with a single function call.

The speed of transferring blocks of homogeneous data (like arrays) is practically the same as with the non-TDT method. The TDT functions are written in C, and are provided with Fortran interface functions for using the library in Fortran programs. Opening and closing of sockets and files are handled by TDT functions, and data is written or read by means of a call to the appropriate TDT function.

Apart from adding function calls the code, a programmer must also provide an XML (eX-tensible Markup Language) description of the data to be transferred and a configuration file for each program, also in XML. Each data structure being transferred needs its own XML description, each of which may be in separate XML files, or in just one (quoted from Linstead 2005, compare Figure 6.4).
**Description of data transfer classes**  Two data container classes are used to transfer data: a matrix class (`MatrixDouble`), and a class containing raster data (`Raster2D`, also `Raster3D` which is a stack of the former). Both classes contain functions `sendViaTDT` and `receiveViaTDT`, which open up channels and transfer data.

*Class MatrixDouble* contains matrix data. Functionalities include treatment of individual rows and columns, saving and loading from file, output to screen, and simple math operations.

*Class Raster2D* contains information used in raster file format: the span of a raster (number of rows and columns), the x- and y-coordinate of the origin (left upper cell), the size of each cell, and which data is used as nodata value. Then, it contains a matrix of values (type `MatrixDouble`). The class can be used as storage for spatial data, for saving and loading, for translation, and for data exchange.

*Class Raster3D* is simply a stack of Raster2D objects, used for more convenient handling of many Raster2D objects. It also contains TDT transfer functions `sendViaTDT/receiveViaTDT`.

**Integer values** are send as matrix with a single member.

**Strings** are converted into a matrix of ASCII codes and then transferred as values, using the globally defined functions `receiveStringViaTDT` and `sendStringViaTDT` (located in file `MatrixDouble.cpp`, but not members to the class `MatrixDouble`).

For a listing of data files, see also the Technical Report ‘Coupling Manual’, B.3 *TDT Description Files*.

**Data transfer between executables using files**

If data is not transferred directly via TDT, it can be read from input files directly, as boundary conditions without feedback. This ‘file-based coupling’ facilitates the calibration process, but also the model development.

### 6.4.3 Sequencing Diagram Of Coupled Runs

**Sequencing**

This section describes the sequencing of model execution and data exchange, and lists the data being exchanged. For a detailed technical description of data handling and preprocessing see the Technical Coupling Manual (Arnold 2008).

Figure 6.5 summarizes data exchange: The hydrological model, which operates in daily time intervals, is depicted in blue. Orange shows the MP-MAS model. Grey represents the containers for data storage. Time runs from left to right, and arrows depict data flows.

Processes within the hydrological model are conceptualized as continuous, but daily time steps are computed to keep runtime reasonable. The MP-MAS model is conceptualized as sequence of discrete decisions, and behavior is updated after these decisions. The annual cropping decision and monthly irrigation decisions are thus linked to the semi-continuous hydrological sphere.

In addition to water availability in rivers, which is inevitably passed from WASIM-ETH to MP-MAS, further data exchange from WASIM-ETH to MP-MAS can be specified external
within the MP-MAS input files, and is independent from the rest of sequencing. This additional data is called ‘transfer data’, and may be real or potential evapotranspiration, precipitation, soil moisture or any other grid-type data that has a ContentType. After each (monthly coupling) time step, the data manager reads this transferred data from WASIM-ETH outputs, re-formats it according to MP-MAS needs, and passes it on to MP-MAS. Finally, within MP-MAS, it is specified who to use this data.

To ensure numerical stability, the hydrological model is initialized and runs for a number of years (spinup), and results of this "spinup-run" are stored and used for further initializations. Similarly, MP-MAS also performs spinups (see section 6.1). Because a memory dump is currently not possible, model coupling is thus suppressed, and effective data is read to memory.

After each month, model execution stops, and the memory of WASIM-ETH is fully dumped to files. In the beginning of the cropping season, farm agents determine their irrigation methods (investment decision) and their crops (production decision) for that season. The outcome of these decisions is (a) a land use map, and (b) a map of irrigation methods that determines irrigation efficiency. Then, the WASIM-ETH land use map is updated with MP-MAS outputs.

WASIM-ETH is executed for one month, which we call ‘DRY’ month. Effective irrigation water at sector-level is defined as the actual water that is abstracted from the river (or reservoir) for irrigation, and it includes inter-sectoral return flows, while intra-sectoral cyclic flows were crossed out. During the dry run, this effective irrigation water is abstracted from the rivers according to water right entitlements of each sector, but not applied to the field – the DRY run.

---

**Figure 6.5** — Sequencing and data exchange, over time (left to right)
After the month is computed with dry fields, WASIM-ETH performs a memory dump, and the daily value of river abstractions is available. They are added up over the month, and passed to MP-MAS as total water that is available for irrigation ($IN_{dry}$), but does not incorporate return flows from upstream sectors. Furthermore, the spatial maps data from these ‘dry’ fields are evaluated – as daily maps, as monthly sums, or as monthly means, depending on WASIM-ETH specification and data. Finally, a stack of ‘transfer data’ ($Map3D_{dry}$) is passed to MP-MAS.7

Based on irrigation water availability and on ‘transfer data’, MP-MAS agents perform the irrigation decision, using the priority heuristic. As a result, spatial maps with irrigation water are created, and returned to WASIM-ETH. Now, the model is re-initialized a second time, and irrigation water is now applied to the fields – the irrigation run. In the end of this run, the equivalent data analysis is repeated, and actual river flows as well as $Map3D_{irr}$ is returned to MP-MAS. The irrigation decision is repeated with actual flows $IN_{irr}$, because now also return flows from irrigation in upstream catchments is incorporated. The difference map $Map3D_{\Delta} = Map3D_{irr} - Map3D_{dry}$ is an estimate for the impact of irrigation.

The model was constructed to permit further iterations, but experiments showed quick convergence. This monthly loop is repeated until the end of the cropping season is reached, and a new cropping year begins.

Additional details that proved relevant is background irrigation in areas outside of our model region, and corrections for inflows from external basins (Sorpam river, Liguay, Maule Sur).

Furthermore, the current realization of the sequencing allows runtime improvements in the order of 20-40 % with the same model setup, while file operations take the largest time. If the full MP-MAS is used, and WASIM-ETH is run at 500 m$^2$ grid length, then sequencing and data exchange uses approx. 5% of runtime.

Functional diagrams: The sequencer

The sequencer executable consists of data initialization functions and the core time loop, which handles time stepping of all other executables.

In the beginning, the sequencer is initialized with the same time handler data that is also read from MP-MAS and other executables. Other shared input files are a description of which data is transferred8, the xml description of the data container classes and configuration files9, the name of WASIM-ETH files10, and a default file which contains the input- and output directories11.

According to the time handler, it loops over a number of years and, within it, months. In the beginning of each year, it handles the passing of annual information (land use, irrigation methods). Then, it by standard performs a ‘dry’ run, where irrigation water is abstracted from the rivers according to water rights but not returned to the field. Inter alia, areas outside of the study area that impact on it contain (externally defined) background irrigation. Then, river flow data (and any other spatial grid, as defined in dataexchange.ini) is passed to MP-MAS.

---

7Currently, this data is not interpreted from MP-MAS to decrease model complexity. The source code permits three levels of evaluation: (a) sector-level averages are computed; (b) for each MP-MAS cropping activity as solution of the LP, the average value for all cells that use this activity is computed and passed to the agent; or (c) it is written into the parcels.
8dataexchange.ini
9xmlfiles/[filename]
10wasimFilenames.ini
11AllDefaults_coupl.txt
Agents make irrigation decision and report the outcome back to the controller. If not a single field is irrigated, then no further irrigation is performed\(^\text{12}\). If MP-MAS is active and farm agents irrigated, then a second WASIM-ETH run is performed.

The function performs the following tasks (for function names, see Figure 6.6):

- It creates a separate directory for variable data (‘output data’), from which the WASIM-ETH model is also initialized and which it over-writes.

- It transfers the irrigation map ([mm/parcel]) from MP-MAS to the data manager, which categorizes the irrigation columns and creates the irrigation table for later use in the control file.

- It sends all information (time span, all directories etc.) to the data manager to creates an WASIM-ETH input file (‘control file’) in the output directory. The previously created irrigation_table is appended to it.

- It calls the WASIM-ETH wrapper to start WASIM-ETH.

\(^{12}\)Here, rivers contain less water than in reality, because irrigation water is only abstracted and no return flows exist. Thus care is required when interpreting results.
After WASIM-ETH is finished, it calls the data manager to extract the information needed from WASIM-ETH output data, and transfers it to MP-MAS.

An edited extract of the most relevant MP-MAS source code is given in the Report ‘Technical Coupling Manual’.

**File-based management of data transfer**

As mentioned, data transfer and handling of data transfer is controlled with an input file, the ‘SpatialExchangeInfo’. It contains four columns: an ID that corresponds to ContentType (see page 99), a specification if data should be treated as monthly data (e.g. when saving maps, for later analysis). Furthermore, a column specifies if data should be maintained at cell level or aggregated at sector level. In the former case, a case statement\(^{13}\) needs to be specified or an error is returned. In the latter, data is copied into the temporary array in CropMixClass, which corresponds to the activities in the solution vector that were spatially distributed. Agents need to call (and interpret) this data, using the function \texttt{interpretTempInCropMixClass(Content cont, int m)}.

In summary, the coupling scheme is generic enough to pass any type of data between WASIM-ETH and MP-MAS, and even import other spatial data from raster files. The interpretation of this data remains a case-specific modelling task.

### 6.4.4 Correction For Processes Below Model Resolution

**Irrigation efficiency and cyclic flow of water at sub basin level.** MP-MAS requires the representation of field processes, while WASIM-ETH can only resolve spatial interactions at sub basin level. WASIM-ETH thus cannot handle cyclic flows within one sub basin. As elaborated in detail in Technical Report ‘Coupling Manual’, A.3 \textit{Irrigation modelling with WASIM-ETH}, an averaged factor that translates field-level irrigation efficiency to sub basin level irrigation efficiency is computed within the EDIC model for each sector. The resulting corrected irrigation efficiency at sub basin already removes that fraction of flows that returns from one field to another field of the same sub basin, for example by a neighboring farmer.

Technically, all spatial maps of irrigation quantities at field level, as provided by the MP-MAS model, are thus diminished by the share of cyclic reuse \(1 + \beta_j\) within each sector \(j\).

---

\(^{13}\)see \texttt{double sector::getContentFromSectorLevel(Content cont)} and \texttt{setContentViewToSectorLevel(Content, Raster2D&)}
### 6.4. HIERARCHICAL MODEL COUPLING

**Figure 6.7 — File-based definition of transfer data using the ContentType**

<table>
<thead>
<tr>
<th>Tested</th>
<th>ContentType</th>
<th>Origin/Type</th>
<th>ID</th>
<th>Is Monthly</th>
<th>Is Sector Level</th>
<th>Get from Wasim</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>contFarmID,</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>contPopID,</td>
<td>input</td>
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<td>0</td>
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</tr>
<tr>
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<td>input</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>contCluid,</td>
<td>input</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>input</td>
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</tr>
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<td>0</td>
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<td>0</td>
</tr>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
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<td>control</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>contSoilMoist1</td>
<td>Coupling/Wasim</td>
<td>26</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>contSoilMoist2</td>
<td>Coupling/Wasim</td>
<td>27</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>contSoilMoist3</td>
<td>Coupling/Wasim</td>
<td>28</td>
<td>1</td>
<td>1</td>
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6.4.5 Runtime And Memory Requirements

In MP-MAS, the largest single set of input data is the MILP decision matrix of the agent decision, and the maps that characterize the study area. The MILP is stored in a central entity and accessed by all agents. Each agent only holds data on its asset endowment and individual characteristics, including his fields. Some spatial data is duplicated, once in the grid-based landscape and once as a property of the agent’s field. With regards to runtime, the solution of the MILP optimization problem consumes approximately 70-90% of model runtime, depending on model specification. In general, model runtime and memory usage rise linearly with the number of agents and the complexity of the MILP matrix (e.g. integer problems). For the study region and 5000 agents, one cropping season runs for approximately 35 minutes on a 2GHz Linux computer.

In WASIM-ETH, the most significant set of data is the soil module, with 10 soil layers that each holds parameters. The iterative solution of the Richards equation is by far the longest process, which iteratively computes the soil moisture and plant water uptake within the soil layers. In general, model runtime and memory usage rise linearly with the number of grid cells. For the study region and a resolution of 4 km2 grid cells (2 km length), one month runs for approximately 2 minutes on a 2GHz Linux computer (one complete year computes for 7 minutes because model initialization and writing of data to files is lengthy).

The coupling scheme itself takes little time. With every cropping season, the spatial rescaling routine creates a translation matrix that maps each high-resolution MP-MAS grid cell to a low-resolution WASIM-ETH grid cell. The creation of this matrix is the most significant computation and takes 45 seconds on a 2GHz Linux computer. Runtime of other data transactions are not significant.

6.5 Summary On Model Setup Options

For calibration, validation or for specific policy questions, it is not necessary to run a fully coupled MP-MAS – WASIM-ETH model. Full coupling is only reasonable if feedback processes through coupling variables are sensitive, and if the precision obtained with coupling is relevant for the policy question. Unfortunately, it is often difficult to decide which process of in complex conceptual model is actually relevant, because it may require in-depth data and model analysis. To facilitate model analysis, the level of technical model complexity can be adjusted to the question analyzed and to the sensitive variables.

A pyramid of modelling options exists for specific objectives (see also Fig. 4.4 on page 70). In this section, these model options are documented, their use is explained and some conceptual limitations for later use in calibration are discussed.

EDIC standalone is a sector routing model that computes the outcomes of externally determined land use and irrigation plans. It computes within-sector reuse and how much return flows are created that will flow into other sectors. The actual flows are also parameterized externally though. Within the EDIC sector model, plant water demands are reduced by precipitation, and method-specific irrigation efficiency factors are applied. If water demand exceeds water supply, then deficit irrigation is computed. Again, plants are served in the order of priority groups, at sector level.
Two realizations were implemented, which are conceptually identical. The first is a complete re-implementation in MatLab®, which reads the most basal data table (ActivityKey, MethodKey and CropKey) as well as time series on river, sector-level aggregates of water rights per river, and between-sector routing parameters for return flows. Data is reformatted internally before a complete memory dump is performed. Runtime is 1 second for one year and 23 seconds for 50 years on a 2-Gig LapTop, and reading of the (dumped) memory is also below 1 second. For parameter sensitivity experiments, automated sampling can be applied (Latin Hypercube, etc).

The second option is a variation on the full MP-MAS input data. The full data is created, but instead of the full agent population, only one agent per sector is created14. Using a trick, the cropping decision for each sector agent is then assigned from external data land use. Land use categories are automatically distributed over all cropping methods in a way that is consistent with the soil suitability mapping etc. (external land use, called EDIC/EXTLU). The yield model and water deficit computations are called as usual. EDIC/EXTLU was used for technical verification of source code, and to test parameter scenarios for the EDIC model. It can also be used as a shortcut to test the fully coupled MP-MAS –EDIC –Wasim-ETH at low runtime (see further below). For calibration and sensitivity experiments, the creation of the full MP-MAS input data and the reading of it into memory, (especially the matrix and all spatial maps) remains a bottle neck for runtime, which is approx. 3 minutes for one model run, plus input data creation.

Wasim-ETH++/CoupITest The coupling between MP-MAS and Wasim-ETH was developed based on a test mode, even before EDIC/EXTLU was available. This test model only reads basic data15 into MP-MAS, and directly performs the mirror version of the MP-MAS time loop. Instead of agents, externally created land use maps (specified as ActivityID) are read into the memory. Using the ActivityKey, this map is translated into a land use map and into two irrigation maps: the irrigation method, and the irrigation quantity. An annual map with irrigation methods and monthly maps with irrigation tables are created based on the ActivityKey, which is also read from file.

The map with activities was created from a table (SectorID x ActivityID), which again was estimated with census data (1996) and a survey (2005). Randomly, cropping activities were distributed spatially, maintaining soil suitability and irrigation methods consistently.

14This requires an adaptation of the input maps and of the decision matrix.
15BasicData.dat and TimeHandler.dat
CHAPTER 6. TECHNICAL MODEL INTEGRATION

**MP-MAS–EDIC**  The full MP-MAS–EDIC model was developed from the original model (Berger 2000). It was extended by several features (see Section 6.1).

**MP-MAS–EDIC–WaSiM-ETH**  The fully coupled model contains the three spatial levels (agents–sectors–watershed) that was described in the previous sections. Conceptually, it slightly differs from the MP-MAS–EDIC realization in the interpretation of inflows and the partitioning of these to sectors. External inflows are not interpreted as rivers, but as the total water that is available at one sub watershed defined in WaSiM-ETH.

Water rights, also as percentages of the river, are directly coded within the WaSiM-ETH routing model. Water is abstracted from the rivers, while respecting a minimum river flow, and a maximum canal capacity. Then, it is routed into the target sub watersheds for irrigation, and send to MP-MAS. These inflows are assigned to sectors based on area shares\(^{16}\). To account for cyclic reuse, irrigation maps are corrected by the internal reuse factor. Otherwise, all other model features remain fully intact.

This setup is the most complete, but also takes longest time and most parameters. The complexity and depth of coupling can be varied: theoretically, a brought range of data can be exchanged (evapotranspiration deficit, soil moisture, precipitation, potential evapotranspiration, etc). On the other hand, interaction data require precise calibration and convenient handling. Calibration of a fully coupled model simultaneously should tackle WaSiM-ETH behavior, MP-MAS expectation building and MP-MAS behavior simultaneously. Furthermore, each coupled variable must be validated and models must be sensitive to it.

\(^{16}\)Percentage Water Rights of the Region.dat file are reinterpreted into area shares \(\frac{\text{Area sector}}{\text{Area watershed}}\).
Chapter 7

Model Calibration And Analysis

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7.6 Calibrating MP-MAS To Dynamic Weather Conditions .......................... 189
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Model Calibration and Analysis (Chapter 7) responds to Research Question 3:

How can the interactions in such complex, integrated modelling be calibrated?

The chapter first describes the process of calibration and analysis of integrated model components. An iterative approach was taken to ensure the consistent representation of interactions between modules, to deal with runtime restrictions. Within the project context, modules are managed by separate research groups. Knowledge about model concepts and the capability to technically use the modelling software is distributed over a group of researchers. Thus, calibration is not only an iterative process between model components, but calibration becomes an institutionally complex task between spatially distant institutions, with boundaries between disciplines, cultures and languages.

Hence, Section 7.1 first introduces calibration approaches, especially in multi-agent modelling. Then, it outlines a step-by-step strategy to calibrate model components separately and then in increasingly more integrated software setups.

The following three sections 7.2-7.4 summarize the parameterization and describe the calibration of the three basic model components MP-MAS, WASIM-ETH and EdIC as standalone modules. This was performed by project partners (MP-MAS, WASIM-ETH) and within this PhD project (EdIC). Then, Section 7.5 focuses on a single interaction process, the distribution of water from irrigation sectors to individual farmers under structural uncertainty, and assesses the impact of canal conductive efficiency improvements (in response to Research Question 4). Section 7.6 elaborates the challenge and solutions to conceptualize and calibrate the multi-agent model MP-MAS with dynamic environmental boundary conditions, especially with variable water supply (estimated using water rights, river flow data and non-attributed water) and crop irrigation demand (estimated from cropped area, crop data and precipitation measurements). Finally, all model components were fully coupled hierarchically, and preliminary results using the latest input parameter sets of disciplinary modules are presented and also discussed here.

7.1 Introduction And Calibration Strategy

Calibration is the variation of one or more uncertain model parameters, the ‘calibration parameters’, with the objective of minimizing the deviation between model outputs and empirical data. To describe this deviation, several distance measures exist (the distance measure is also called calibration index or calibration criterion). In order to minimize the calibration index, the calibration strategy then prescribes how to vary the calibration parameters systematically.
The validity of any single calibration strategy or even calibration index remains disputed. For hydrological models, Krause et al. (2005) compared nine different criteria applied to three models and conclude that no single one is robust in all applications. Moriasi et al. (2007) systematically compare criteria and recommend the use of three: the Nash-Sutcliffe efficiency, the percent bias, and the ratio of the root mean square error to the standard deviation of measured data.

Generally, the more variables of a complex model that behave realistically, the more likely it is that the model is an adequate representation of the real-world system.

When using a complex model to simulate a real-world system, then more than one (and often many) parameters are uncertain. If the model has many degrees of freedom (the number of uncertain parameters with respect to data points to parameterize these), then many combinations of parameters exist that reproduce calibration data well. The number of parameter combinations with reasonable values may form a huge set of system descriptions that are potentially true (equifinality). The calibration strategy can only derive a subset from this parameter space of equally true system representations.

In such models with many uncertain parameters, a strategy to improve calibration is to inspect as many model variables as possible. For example, a runoff model can be calibrated to a single time-series of downstream flow measurements. If several flow stations, which are distributed over the study area are used, the calibration improves. In addition, other processes – irrigation methods, soil condition, crop growth or crop yields – can be added for calibration and validation. In other words, if more processes are included in the calibration criteria, then the degrees of freedom of the model are constrained. Calibration is more difficult but the final product is probably more robust.

However, how can a complex model with several sub modules be calibrated, if the number of uncertain parameters and the uncertain parameter space is very large. Especially if each software component is managed by a different person, with knowledge from another discipline embedded in that module, and if these persons are physically not in the same location?

In this context of a large integration project and a high-dimensional model, calibration is not only a technical parameter sampling rule and model runtime, but it also requires a procedure that is compatible with the integration architecture and knowledge resources.

### 7.1.1 Calibration In Agent-Based Modelling

In agent-based economic modeling, a number of authors have addressed the challenge of calibrating a complex model. This section schemes the calibration approach taken by our research group within the context of this debate.

A calibration strategy must always take into account the model objective and how the modelling team must deal with quality assurance. For the integrated analysis of human–natural systems that use agent-based simulations, Robinson et al. (2007) identify a range of these objectives: knowledge bridging, training, concept building and theory selection, but also qualitative and quantitative analysis based on future scenarios.

**Dynamics and calibration.** The term ‘estimation’ usually refers to a procedure in which statistical techniques are used to identify the best parameter so that model results match observed
data. In the typical situation where more parameters exist than data (an under-identified model), Hansen and Heckman (1996) recognize the potential for linking insights from micro-level modelling to handle the problem of under-identification of macro-level models with large parameter sets.

If models are recursively coupled to each other or to additional processes, then the difficulties that Hansen and Heckman describe for static models multiply. In addition to the quantity of each variable, its direction of change must be estimated as well (first and higher-order derivatives). This not only increases the unknown parameter space, but also introduces sensitivity to initial and boundary conditions. Within earth sciences that deal with such dynamically described systems, the term ‘calibration’ usually refers to the process of varying unknown parameters within an acceptable range of uncertainty until model results match observations.

Mathematical Programming (MP) models are usually more sensitive to the relation between variable (e.g. price ratios, asset ratios) than to the absolute values of variables. If MP models are used recursively, this recursion can feed back on these sensitive ratios and cause exponential divergence of model results.

A simplified example illustrates this. Let two variables that are functionally related (e.g. costs $C$ and revenue $R$) be of similar magnitude and influence the derivative of a third variable (e.g. the annual accumulation rate of equity $\frac{E_{t+1} - E_t}{E_t}$). Model processes that are triggered by this accumulation rate, such as new investments, then feed back on the relationship between the former two and thus on itself. The sensitivity of this accumulation rate, and its heterogeneity across a population of economic enterprises (farms) induces re-distributional dynamics across a population of farmers.

In our model, the accumulation of equity changes with (net) income minus consumption. We define a typical (average, effective) Rates of Return $rr = \frac{\Delta E}{E}$. This rate $rr$ can be expressed in the form of an exponential growth function that describes the development of equity distribution over time. With a rest $\Theta$, this equation becomes

$$\Delta E_t = R(E) - C(E)$$

$$E_{t+1} = E_t + \Delta E_t \pm \Theta \approx (1 + rr) \cdot E_t \pm \Theta$$

The effect of a drift of the accumulation rate $rr$ increases over time and diverges, because of the exponential characteristic of this difference equation. Such equations are also used to model bacterial growth, plankton and predator-pray-relations in population ecology (Begon, Mortimer and Thompson 1997). Only if an additional term with higher order counter-acts this exponential development, for example a quadratic predation term, then the difference equation can stabilize and converge. Otherwise, asset distribution of a farmer population diverges over time.

In addition to the complexity of dynamic systems, there are theoretical limitations to the calibration of dynamic models with measurement data, especially if no continuous time series are available for all relevant variables (compare definition of equifinality on page 8 and Figure 2.1):

- ‘True’ equifinal system developments occurs if two system developments start at equal (or equally appearing) situation and end in equal situations (Beven 2001). However, the transition from one to the other state might differ. While truely equifinal development paths should not occur fully deterministic systems, a random component would allow it. Data may be missing to distinguish which transition paths between this transition, so modellers cannot identify which path (and model parameterization) is true.
7.1. INTRODUCTION AND CALIBRATION STRATEGY

- **Equi-projected developments** are two different development paths of two systems that differ at micro-level. However, observable variables only describe macro variables and aggregates from micro variables. Thus, both system descriptions cannot be distinguished by observing macro variables. Especially the inconsistent use of effective variables and the use of macro-level parameters to calibrate micro processes can result in such equi-projected systems. Within economics, possible methods for linking micro and macro data are much disputed (see e.g. Hansen and Heckman 1996).

- **Temporal divergence.** The modeled system reaches the correct state after a wrong time interval because the dynamic speed was miss-estimated, even if the process is well-captured structurally and conceptually.

In system dynamics, model realizations that are either equifinal or equi-projected developments are called ‘behavioral’: model outputs will be accepted by any statistical validation test, even if completely false if analyzed at a different scale or from a different perspective. On the other hand, structurally ‘true’ but temporally divergent (e.g. time-lagged) model realizations will fail statistical validation tests. In other words, the model conceptually performs fine but processes are either too slow or too quick – but at any time slice, observations do not match model results. For dynamic calibration, structural validity and the qualitative reproduction of patterns and the reproduction of empirical data are thus two different calibration measures.

**Calibration in empirical ABM.** For empirical agent-based modelling, Windrum et al. (2007) suggested a taxonomy for calibration and validation. They differentiate the nature of a model, the goals of analysis, model assumptions and methods for uncertainty/SA. When formulating a model, the scientist first identifies macro-level stylized facts that should be logically explained by a model. Then, he describes the micro-level ‘as close to empirical evidence as possible’ and ‘not-too-unrealistic’. Windrum then differentiates three approaches to calibration and validation.

If using the *Indirect Calibration method*, a set of facts is first identified that a model should describe and reproduce. Second, the model is formulated by gathering all possible evidence about the underlying principles that inform real-world behaviors and by including all ‘relevant’ micro-scale theories (‘not-too-unrealistic’). Then, all combinations of micro-parameter and initial conditions are chosen so that the model reproduces the facts at macro-scale. Each of these parameter combinations represent a model formulation that is ‘behavioral’. Finally, the modeller should investigate further into causal mechanisms within this parameter sub space.

The *Werker-Brenner approach* is somewhat similar: After model formulation, empirical evidence is used to define initial conditions. For all relevant model parameter data is used to define minimum and maximum values, with wider ranges if uncertainty is large. Then, the model is run and outputs are either accepted as ‘behavioral’ or rejected. Sub spaces for unknown parameters are specified, and the calibration is repeated. Bayesian inference then gives robustness indications on model outputs. Within the set of behavioral models, the model identifies structural similarities which the modeller can discuss with experts (‘abduction’).

The *History-friendly approach* takes a path of trial-end error. Malerba (1999) used a body of verbal appreciative theorizing, developed a formal representation of that theory, and found that the formal version of that theory is consistent and capable
of generating the stylized facts the appreciative theory purports to explain. Going through this analytic exercise has significantly sharpened the theoretical understanding of the key factors behind salient aspects’ (page 1, Malerba 1999).

In other words, a single historical trace was reproduced by subsequently adding theoretic processes, until the stylized facts and data were satisfactorily reproduced.

All three approaches are theory-based and require detailed knowledge about the system. From the scientific and epistemic perspectives, Windrum, Fagiolo and Moneta favour the Werker-Brenner approach as most satisfying. However, this approach is also most demanding on data and runtime.

The history-friendly approach is susceptible to equifinality errors and path-dependent model mis-specifications. On the other hand, it is the simplest approach and in line with the Ockham’s Razor. Also, it is least demanding with regards to runtime and most adequate within a project setting.

Within the history-friendly approach, theory selection is based on observations and expert judgement. If alternative theories exist to explain the same phenomena and these theories have similar levels of complexity, then both should be implemented as alternative model branches. Otherwise, according to Ockham’s Razor, the simpler theory is chosen.

The calibration process first addresses the central model elements. In the case of MP-MAS, this core element is the decision model (the MILP matrix). Then, additional model features (investment cycles, innovation and its diffusion, water scarcity and drought conditions) can be added and analyzed one at a time, and/or in combination. With each step, the model behavior converges towards the real system. From the modeller’s viewpoint, the model evolves in a step-by-step process, starting as an explorative model that may have few empirical components, toward a fully empirical model. A challenge (which is not unique to this approach) is that only the final, fully empirical model can be validated against real-world data.

7.1.2 Calibration Of A Multi-Component Model As A Conceptual Challenge

In this study, the history-friendly approach (see definition on p. 125) was used to calibrate a high-dimensional model with many degrees of freedom and large runtime. System conceptualization, as the selection of adequate theories, is usually not based on ‘objective’ criteria but on subjective selection by experts. These experts define which processes are relevant and which ones are not to be included in the model.

Conceptual model selection and model calibration are two processes that are directly related. If an additional model component is linked to an existing model, then this new module could either reduce the degrees of freedom of the combined model (and thus reduce the number of uncertain parameters that can be used for calibration), or it increase the degrees of freedom to the model. In the latter case, the model can be calibrated better without enhancing the model’s predictive quality\(^1\). In a complex, multi-disciplinary model that was build by more than one person, it is difficult to assess whether new model components increase the model’s degrees of freedom or reduce them.

\(^1\)For example, if a 2nd degree polynomial (a parabola) is fitted to five points, some calibration error is expected. With each additional degree, the polynomial fit will improve until a model is found that calibrates ‘perfectly’.
For the conceptual selection of models, formal methods exist to evaluate this trade-off between model simplicity and calibration accuracy. Here, the costs from the addition of new parameter is compared against the benefit obtained in improved fit (Forster 2000). One example is the Akaike’s Information Criterion (AIC), which punishes every non-zero parameter in addition to the calibration error.

For the integration of disciplinary modules, the widely accepted use of ‘effective’ variables across disciplines poses a challenge. ‘Effective’ variables are defined as variables for an artificial system that represent a more complex, but unknown process. For example, modellers use ‘effective soil conductivity’ to describe groundwater flows in a homogeneous grid cell, knowing that the conductivity within the real soils can vary by orders of magnitude (spatial homogenisation with effective variables). Also, irrigation models with monthly time steps use ‘effective’ river flow values, usually the median. Here, the effective variable ‘river flow’ disregards runoff events because this water carries too much sand for irrigation (temporal aggregation with effective variables). Agricultural crop planning models use ‘effective yields expectations’, which are long-term averages where positive and negative deviations from it may even be weighted differently, resulting from asymmetric utility functions (conceptual aggregation with effective variables). Surface runoff models use ‘effective precipitation’ as the share of precipitation that reaches creeks as runoff, while other processes (infiltration, evaporation, transpiration, . . . ) are disregarded (filtering of one sub process by using effective variables).

In all these examples, the effective variables are simplifications that are legitimate in modelling. Integration may re-interpret these variables that were ‘external’ boundary conditions and become ‘internal’ interactions. For effective variables that are spatial or temporal aggregates, a change of resolution may require re-specification. If effective variables are conceptual simplifications, then it is necessary to revisit these if the extended model describes related processes in more detail.

Scale-transitions may also necessitate the use of ‘effective’ variables, as exemplified by the variable ‘irrigation efficiency’ (see Section 5.3.2). Even if this variable is perfectly known at the field scale, but the model equations use the farm scale, then model parameterization requires that one scale is transformed into the other. In this case, the field data can only be used to calibrate a farm-level model if a factor ‘within-farm reuse’ is known. This correction factor is statistically distributed. The need for such rescaling creates additional free parameters.

The parameters within scale corrections and ‘effective’ variables are often used for calibration, because they accumulate (and hide) a great number of processes that are not relevant for the description of a mono-causal cause-effect chain. Examples for uses of ‘effective’ variables along disciplinary boundaries or scale boundaries are abundant: hydro-geologists use ‘effective’ porosity, ‘effective’ aquifer storativity and ‘effective’ soil conductivity to describe groundwater flow at model resolution beyond soil scale; economists use a correction factor to account for risk-aversive behavior, and also as ‘effective’ prices within the decision process that take into account ‘effective’ marketing opportunities.

If ‘effective’ variables are used to describe interactions between system components, then much of the uncertainty can be ‘externalized’ with simple regression models, by defining a transformation rule from ‘real’ data to the effective variable (e.g. a correction factor or polynomial). Ultimately, this approach cannot elucidate processes embedded in such interactions,
and feedbacks between sub systems remain unknown.

If multiple cause-effect chains are evaluated simultaneously, then those processes hidden within ‘effective’ variables become relevant for other lines of reasoning and must be described explicitly. Integrated models with multiple cause-effect chains and feedbacks have the advantage of offering a more detailed description of a system and a more comprehensive analysis. Unfortunately, this comes at the expense of more parameters that require empirical data and must eventually be calibrated.

### 7.1.3 Step-By-Step Calibration Strategy

for the Coupled MP-MAS/Ed1c/WASIM-ETH Model

The last two section discussed the conceptual challenge selecting and calibrating a complex, integrated model, and three approaches to calibrating a complex and empirical agent-based model. Both sections neither addressed the procedural challenge that arises from the use of multiple software components that are used for hierarchical coupling. In our project setting, these software components are managed by different individuals that belong to different disciplines. Each scientist moves along the line of integration and gathers new information about that part of the real-world system that he models; he obtains knowledge of the software package he uses, and an understanding about the dataset used to calibrate that software component. However, for an *in vitro* analysis as an analysis at field conditions, such disciplinary focus on one sub system is usually possible only through the use of simplifying assumptions, for example effective variables along the boundary of the sub system (as discussed in Section 7.1.2).

It is the objective of an integrated model to learn about system feedbacks across these disciplines. Once all sub systems were analyzed within disciplines, then the products, which are pieces of model software, are combined. At this point, all assumptions along disciplinary boundaries have to be re-visited and the model components must be re-calibrated along each interaction ‘boundary’, because boundary conditions are now internalized into the model. From now on, I call these ‘internal boundaries’, because these boundaries are still reflected in the software itself, in the knowledge and specialization of modellers, in responsibilities for software components and in the understanding that modellers have of input and output data.

Modelling is iterative by nature. However, if it is not a single but multiple scientists working on sub systems, then knowledge barriers must be taken into account. These barriers include conceptual boundaries between disciplines, technical boundaries between multiple software platforms and further boundaries with regards to data and empirical details. Furthermore, it is not feasible to feed all data into one large, overarching supermodel and the number of uncertain parameters would be too large for any reasonable re-calibration, it is difficult to locate errors and to manage uncertainty across modules from different individuals.

The idea of step-by-step calibration is that each integration step can only address the internalization of one boundary condition at a time, as modelling of each internal boundary will require fine tuning. Thus, all model components must first be parameterized and tested as standalone models and then sequentially integrated into the coupled model system. With this aim, a modular architecture of model integration was chosen and implemented, as described in Section 6.5. This chapter describes how step-by-step calibration utilizes this modular architecture in a way that transaction costs between researchers remain viable.
For the model system that is created and calibrated in this project, the model components CropWAT, MP-MAS, EDIC and WASIM-ETH were used both as standalone models and in different levels of coupling. Several combinations of model setups were created to facilitate the calibration of the fully coupled modelling system in the project setting, which is given as the boundary condition for this model integration process (see Section 6.5 and overview in Figure 7.1). The fully coupled model system operates at four spatial scales:

1. The homogeneous agricultural field (or plot), which is based on a CropWAT-type model embedded within the MP-MAS software. Within the WASIM-ETH model software, the homogeneous gridcells represent the same plot scale. However, the spatial size of a grid cell is fixed and usually substantially larger than the fields managed by individual farm agents. Also, different processes were selected in both plot/grid cell-level models: the CropWAT module focuses on yields and uses the water demand satisfaction as a decision variable of a farm agent, while the grid cell computes within-soil processes such as infiltration, evaporation and transpiration, surface runoff and groundwater recharge. Both models use crop parameters as input data, which were gathered from and with local experts (Uribe 2007, internal project report).

2. The population of farm agents, as modeled within the MP-MAS modelling software. The core of this model is the three-step farming decision process outlined in Section 4.3.2. The model can be viewed in a succession of complexity levels. The simplest form is a single farm agent. Then, a population of farm agents should be interpreted as a parameter variation of this single agent. As the model has no interactions yet, it should not qualify as ‘true’ multi-agent model. In the third complexity level, farmers are allowed to interact – for example by exchanging knowledge on farming technologies (diffusion of innovation) or through a shared market that coordinates demand and supply of resources and goods.

The model calibration began with a single-agent model (Schilling 2007b). For this single-agent model, the characteristics of the farm agent was varied and validated interactively with stakeholders (ibid). Then, the full population of farmers was parameterized (ibid), while interactions were ignored.

3. Irrigation sectors and water routing are represented by the EDIC model. This model describes how water is distributed from rivers to individual sectors and how several inefficiencies that add to a pool of non-attributed water are either distributed to irrigators within the same sector, are lost to groundwater or are available in other downstream irrigation sectors. Boundary conditions are precipitation data, river flow data, the distribution of river water to irrigation sectors, and plant water requirements. The model allows for the computation of irrigation security by crop, by crop group, and individually for each irrigation sector (see Section 7.4). To avoid the MP-MAS software- and data overhead, the EDIC model was re-implemented in MatLab®.

4. The watershed is modeled within the WASIM-ETH runoff model. Using the original software, this model was first calibrated by Koenig (2004) using the topmodel approach, and later by Leemhuis (2006) using the Richards equation, which also allows for the use of the original WASIM-ETH irrigation module.
The calibration of the coupled model starts with each of these model scales. The plot scale and the watershed scale was calibrated within the hydrological project group. The farm decision model was calibrated within the economic project group. The irrigation sector model was calibrated within the interaction group, in close collaboration with the hydrological partners.

After all standalone model components were calibrated, the first level of interactions can be calibrated. Three model setups with interaction components were calibrated as a cooperative effort between two project partners each:

5. The bio-economic model MP-MAS/CropWAT was first initiated as single-agent model and later as a multi-agent model. The calibration of the bio-economic model incorporated the plot-level data such as crop water requirements, which was gathered and validated by the hydrological group. At this point in time, static (or representative or ‘effective’) hydrological and meteorological conditions were assumed and the full population of farm agents was then parameterized (Schilling 2007, Troost 2009 and a summary in Section 7.2). For this calibration step, abundant water was given to all farmers, so that the behavior of the agricultural economics model was unconstrained by hydrological model components.

6. The EDIC sector model was also implemented as a standalone model using the MP-MAS software. In this parameterization, MP-MAS simulates a single agent that owns all land of an irrigation sector. Land use is read from file as boundary condition, which was empirically determined. Conceptually and numerically, this model is identical to the MatLab-based implementation (Point 3.). However, it uses the MP-MAS software and the same input data as the multi-agent version, with a few data manipulations that invoke this sim-
7.1. INTRODUCTION AND CALIBRATION STRATEGY

Plified mode.
This technical model setup was generated in a collaboration between the integration group who calibrated the standalone EdIC model and the economic group that champion the parameterization and calibration of MP-MAS farm agents (Latynskiy 2009).

7. The runoff model WASIM-ETH++ was extended with a new irrigation module, to account for relevant processes that the original WASIM-ETH model does not represent. Calibration and debugging were done as collaboration between the integration group and the hydrological group (for details, see Uribe, Arnold, Arumí, Berger and Rivera 2009).

Integration steps one to seven maintain their sequencing within the original modelling software. The bio-economic model is fully controlled by the MP-MAS sequencer and models WASIM-ETH and EdIC also use their own sequencing.

The following integration steps represent a second level of coupling, where data is exchanged between model scales or sub modules. Except for step eight, timing is controlled by an external sequencer using the hierarchical coupling scheme.

8. On the bio-economic side, the multi-agent model MP-MAS was economically calibrated and integrated with a plot-level crop growth model in Step 5. The next logical extension is the integration with a sector-scale EdIC model, as was first implemented by Berger (2001) and conceptually improved within this thesis (see Sections 5.3.1 and 6.2.2). This step allows for the calibration of water scarcity under static, as well as dynamic meteorological conditions, in order to analyse the impact of fluctuating water availability on farmers (see Section 7.6). This step exemplifies how the complexity of the MP-MAS model evolves as soon as the assumption of a static (or ‘effective’) hydrological year is dropped (see Section 7.6). Technically, the MP-MAS-EdIC model setup within the MP-MAS software is used, with all extensions described in Chapter 6.

9. The first mode that uses the full hierarchical coupling framework is WASIM-ETH++/CouplTest (see page 119). It is only used for technical debugging of the sequencer and all data manipulations of the coupling scheme. In future applications, it may serve to evaluate the impact of dynamically changing land use and irrigation scenarios on the hydrosphere.

10. The next integration step from WASIM-ETH++/CouplTest is the coupling of WASIM-ETH++ with the EdIC/EXTLU setup, which also has a runtime of seconds per year. Again, land use data is read externally as a specification of the EdIC model. However, landuse is not defined as a spatially explicit map, but as a table that defines an area per sector for each cropping activity. The extended MP-MAS software distributes these crops spatially, assuming one agent that owns all fields of one irrigation sector, estimates within-sector reuse and return flows between sectors. Finally, the WASIM-ETH++ model then estimates the impact of irrigation on the larger hydrological cycle at watershed level. As in the previous calibration (step nine), this step does not create new dynamics because the EdIC model is memoryless. Both models, EdIC and WASIM-ETH, could be equally driven with external data. However, this setup uses the main MP-MAS modules and is thus useful for source code verification.

11. Finally, the fully coupled MP-MAS/EdIC/WASIM-ETH model setup can be calibrated. It requires that agents plan, decide and act properly under dynamic environmental conditions (both at the crop- or plot level, and at larger scales, responding to precipitation...
and river flow fluctuations), that those relevant agent-agent interactions which are fully information-based (e.g. diffusion of technology) are understood and quantified. Furthermore, interactions through the shared use of water resources must be properly calibrated, both within an irrigation sector, such as the use of non-attributed water, and between irrigation sectors through return flows. Then, the fully integrated model can add insight about feedbacks between the hydrosphere and the anthroposphere.

The rest of this chapter highlights the calibration of standalone modules and also of interaction processes. Finally, a preliminary evaluation of model performance of the fully coupled model (Step 10) is presented.

7.2 MP-MAS: Economic Land Use Modelling For A Population Of Farmers

7.2.1 History-Friendly Calibration Of MP-MAS

Within the project ‘Integrating Governance and Modelling’, the history-friendly approach was used to calibrate the MP-MAS model.

Parameter estimation for internal variables (land use, asset endowments) used census data for two time horizons: the year 1996/7, and the year 2005/6. For dynamic calibration, time series for external forcing variables (boundary conditions) describe the economic and hydrological framework. Census data from 1996 was used to derive initial conditions. Expert knowledge was collected as prior information, to test structural validity (see also Section 1.2 of the Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’). Dynamic calibration combined this structural information with census data from 2006.

The researcher’s knowledge on local details improved with time and the conceptual model was thus iteratively adjusted. The history-friendly approach is consistent with this learning process of researchers.

Another important reason are runtime restriction of the Indirect Calibration approach or the Werker-Brenner approach. The runtime of the MP-MAS model (≈ 2 hours) and the computer resources available restricts the number of model experiments to ≈ 200, which – with a high number of parameters – makes the Indirect Calibration approach or the Werker-Brenner approach infeasible.

7.2.2 Parameterization and Data Sources

The economic model builds on the parameterization of (1) agricultural activities, with inputs required, costs of these inputs, a specification of adequate conditions, and yields under these conditions; (2) a population of farm agents that is statistically consistent with the real population of farmers; (3) the availability of production activities to different farm types, and the distribution of productive assets ownership over population segments. Furthermore, interaction processes between farm agent can be parameterized (diffusion of innovation).

Agricultural production technologies and prices. Agricultural production technologies are defined by all input requirements, production constraints and outcomes of a homogeneous
cropping activity. For example, a specific crop variety (rice) is planted with a certain irrigation method (terracing) on a defined soil – with inputs that range from labor, pesticides and insecticides, fertilizers, skill, labor input and the machinery needed for it, water and energy. By definition, if implemented in the way planned, such production technology always leads the same outcome with regards to yields, impact on soils etc. (see Hazell and Norton 1986). Variations in soil and input intensity result in other production technologies and require separate parameterization.

The socioeconomic model of the IGM project combines data on agricultural production technologies from various sources. Those technologies already used in 1996 were extended from Berger 2000. As additional data sources, a household survey\(^2\) and the Chilean Agricultural Census from 1997 was available.

Within the project, data on input costs and prices was collected and processed (Schilling 2007b). Specific data for the crop prices are obtained from national and international statistics offices (FAO, ODEPA). To correct monthly price fluctuations, prices were averaged over the months around harvest (Schilling 2007a). Then, prices were translated to the study region by subtracting transport costs and marketing margins.

Fertilizer costs were gathered and analyzed (ibid.). Real cost for urea and ammonia phosphate was lower around 2000 and re-gained the original level. Increases by 20-35% are reported for Sodium nitrate, potassium sulphate and for potassium nitrate.

Data for labor costs was obtained by ODEPA and fine-tuned with local experts (Schilling 2007a). Three labor inputs are differentiated with different costs: permanent labor (e.g. family), permanently hired labor and demand in peak season (harvesting, planting). With an annual increase in 1.5%, the rise of real labor costs is nearly constant.

Capital costs are specified in real interest rates, which fall from 10% (1996) to 5% (2005). Interests for short-term savings are about 3% lower.

Production assets (constraints) are financial assets (liquidity, savings and credits; differentiated for the production and the investment decision); labor (permanent, hired, peak and specialist labor demand); standing investment into perennial crops (fruit plantations, berries, forest, and miscellaneous such as green houses). Further production assets are land at its soil suitability classes, water and machinery (Berger 2000).

Miscellaneous constraints are production abilities, access to certain markets (especially export), contract farming, crop rotational constraints and minimum area constraints for certain cropping technologies.

All technologies require a specification of earliest availability. Within the project, 1996 and 2005 technologies are distinguished. The former were already available in 1996, and all others were observed in 2005. For the latter, the earliest date of availability thus falls into this period. The actual spread in 2005 results from introduction and the diffusion process.

The population of farmers. The reference data to parameterize the population of farmers is the Chilean Agricultural Census of 1997. Spatially, farmers are referenced to districts which have similar size as irrigation sectors, but different extent. The large censu contain data on assets endowment, on production by crop and specifying the production methods, including machinery and broad categorization of irrigation methods.

\(^2\)Chile: Household Survey Maule region (Version 2006_08-03), available on project website http://www.igm.uni-hohenheim.de_publications.
The population of farmers was categorized in two dimensions (Troost 2009): by defining four ‘sub regions’ within the study region, and based on land endowment (the ‘stratum’). As sub regions, the districts were aggregated into Colbu’un, Linares, Longaví I (North of River Liguay) and Longaví II (South of River Liguay). This regional categorization aims to avoid aggregation errors when parameterizing the distribution of production assets in response to location-specific soil and climate characteristics.

According to the same national census, the study area host around 5,000 land owners. Using locally accepted categorization into strata, these farmers were divided into small farmers with less than 3.5 ha (2.0 hrb), into the most innovative and ultimately dominating class are small and medium-size farmers (5-25 and 25-60 ha). Both groups are highly competitive producers of export crops (plantations of small and large fruit trees, berries, rice, wheat and maize). As fourth and least tangible group, SEREMI staff describes large farmers with more 60 hectares (usually even more than 200 ha), which often own various holdings under different names, and are difficult to characterize (SEREMI, personal communication).

According to SEREMI experts, very small farms (<3.5 ha) can be categorized further into subsistence producers, into vegetable farmers that produce traditionally and for local markets, and producers of high-value crops (berries) for export markets.

For modelling purposes, four strata are defined (for details, see Troost 2009):

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Land endowment</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n/a)</td>
<td>&lt; 3.5</td>
<td>not modelled*</td>
</tr>
<tr>
<td>0</td>
<td>3.5 – 5</td>
<td>Specialized small farms</td>
</tr>
<tr>
<td>1</td>
<td>5 – 25</td>
<td>Small farms</td>
</tr>
<tr>
<td>2</td>
<td>25 – 60</td>
<td>Medium farms</td>
</tr>
<tr>
<td>3</td>
<td>60 - 200</td>
<td>Large farms</td>
</tr>
</tbody>
</table>

* mostly home gardens (Berger 2000)

In average, the model population contains 93% of the census area, but 108% of the farm agents (probably because some owners were divided into more than one agent, see Section 2.8 in the Technical Report ‘Background and description of cross-disciplinary data’). Analysis by sub area shows that the overestimation is concentrated in medium-sized farms, while only 77% of small farmers and 74% of the area owned by small farms are considered in the model (69% large farmers, 51% area by large farmers respectively). For detailed description and analysis as well as fine tuning, see Troost (2009).

Asset endowment across the farming population. The distribution of assets over the population of farm agents uses a two-step heuristic (Berger and Schreinemachers 2006). First, for each population segment, descriptive statistics and cumulative distribution functions are created from data for each segment, and assets are randomly distributed. If population segments are well-defined, then correlation between assets are such that the CDF creates asset combinations that are consistent with reality. However, data is seldom available at that level of detail. In a second step, rules are applied to correct for inconsistent asset combinations that are not observed and dysfunctional (e.g. dairy houses plus green houses).

A total of 43 innovation groups were defined, as different combinations of 8 irrigation methods, 15 perennial crops and four levels production machinery. For each segment, the CDF is
defined for each innovation group. Other characteristics include the composition of the household, access to credits and production technologies, farming ability (vegetables, seeds, flowers, forest, contract farming) and dairy (see Troost 2009).

7.2.3 Calibration of the Cropping Decisions

In a market economy, farmers face a complex decision of what to crop and how to do that every year. This decision must take into account their individual endowment of productive assets: their tools and machinery, their water, land and labor resources and their financial situation. This decision is modeled in a multi-step decision process that is broken down conceptually into an investment decision with outreach of several years, an annual production decision and an irrigation decisions for each month\(^3\) (see Berger, Schreinemachers and Arnold 2007b). The tactical irrigation decision is modeled with a heuristic rule which prioritizes the irrigation of perennial and high-value crops first, and low-value crops are sacrificed during water shortage. The investment and the production decisions is modeled with a linear programming (LP) optimization model (Berger 2001). This LP defines a set of options, which are cropping activities and other asset uses, each characterized with a set of inputs that must be provided. These activities contribute to some objective function, typically farm income. The optimization algorithm allocates assets to that the objective function is maximized, and the solution suggests a bundle of activities that does so.

A set of statistically representative agents was selected, each characterized with an individual asset endowment and other characteristics parameterize. Technically, the same Mixed Integer LP (MILP) model in re-used and re-parameterized for each agent. Thus, the identical MILP model can be used to characterize the behavior of all agents.

As a first step, the calibration of the economic model used best-estimate but constant values for hydrological-economic interaction variables. For ten selected agents, the sensitivity of their decisions to water scarcity was then tested and validated interactively with farmers (Schilling 2007b). Then, the population of agents was calibrated with 1996 data, so that land use and irrigation reproduced census data and the distribution of productive assets is realistic. Here, a ‘typical’ hydrological year is assumed. Furthermore, this model was extended to reproduce 2005 data with 2005 boundary conditions. As next step, the investment model was parameterized and the transition from 1996 to 2005 was modeled, still with a constant hydrological year (Troost 2009).

Especially during dryer years, access to irrigation water is an absolute constraint to agriculture in the study region. The typical-year approach is a first step, but it does not yet allow in-depth dynamic interpretation regarding the impact of water shortage, because in the Chilean context, droughts are partly expected and path dependent investments into irrigation technologies occur. Also, the expectation- and learning model assumes ‘typical’ (or ‘fully relaxed’) conditions. In further steps, water shortage must calibrated – proceeding from single drought events, to fully dynamic hydrological data.

The 1996 production decision. To calibrate the MP-MAS production decision, the model was initiated with a pre-determined endowment of production assets (investment goods etc), which are not aging (constant). The investment model was thus deactivated.

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\(^3\)In other settings, MP-MAS offers to specify complex consumption decisions that are especially relevant for contexts with subsistence farming (Schreinemachers 2005).
The resolution of the calibration data, a farm census for 1996, exists at district level. It was further aggregated into four sub areas (Colbún, Linares, Longaví I (North of River Liguay) to create consistency with model sectorization (Troost 2009). Also, several farm size strata were defined (see p. 133). Together with the census sub areas, this gives a total of 16 population strata that were endowed and calibrated separately, with cumulative distribution functions for the endowment of each asset.

The calibration aimed to represent the characteristics of agents, while also reproducing water use and water balances. To level out inconsistencies in data resolution (spatial boundaries, the resolution of small and large agents, land endowments), three rules were applied:

1. the aggregate land use in the region should match census data,
2. within one population strata, the relative distribution of activities should match census data,
3. matching the total land use at sub region level has higher priority than the relation between strata in that area, because some inconsistencies is expected when using land ownership data, because land is rented out to others.

The distribution of assets (machinery and perennials) takes into account the land- and water endowment of individuals, so that the combination of asset bundles that this individual owns is consistent and the distribution of assets between sectors matches data (Troost 2009). ‘Shared data’ on crops and river flows was cross-validated across disciplines so that it meets hydrological balances at sector level. Water assets and land was given to agents, based on water and land registries. The multi-agent model was parameterized with these data and calibrated with 1996 census data, so that 1996 land use and the distribution of irrigation activities was reproduced with boundary conditions for 1996 (prices and hydrological conditions).

Once agents have sufficient water to irrigate something, then other factors determine which crop, irrigation method and machinery level a farmer uses, such as labor endowment and other production assets. Ultimately, the combination of water assets and other assets determines the cropping pattern at watershed level. For this calibration step, a constant ‘typical’ hydrological year was used (Section 7.4.2), and the production- and investment decisions were calibrated at population level (Section ), including a diffusion of innovation model. To increase access to water from non-right holders, the conceptual model on access to water from individuals, both with and without legalized rights, was re-implemented (see Section 5.4.2).

The benchmark for calibration was taken from Census data (see Table 2.5 in Technical Report ‘Background and description of cross-disciplinary data’; Troost 2009). Sensitive assets are liquidity, machinery endowment, machinery hiring access, production contracts. The resulting decision LP is sensitive especially to price- and yield ratios between crops. Here, corrections were needed for yield security equivalents (especially tomatoes, peas, beans and choclo maize) and for pastures. Other special treatment was needed for transport cost of sugar beets (which are locally processed), lowered farm-gate prices for raspberries, minimum household consumption and also rainfed wheat. With regards to vegetables, gross margins are over-estimated if based on transport costs to Santiago (see Section 7.2.2, or Schilling 2007a for detail ). For typical conditions, this lead to an over-estimation for tomatoes, melons, choclo and peas. Either these products are perishable or labor requirement is delicate, products are mainly marketed locally, or marketing to large-scale wholesalers and distributors has high entry barriers. In the model, these entry barriers are subsumed under a constrained called ‘vegetable farming ability’ (Troost 2009).
7.2. MP-MAS: ECONOMIC LAND USE MODELLING FOR A POPULATION OF FARMERS

The 2005 production decisions with new production technologies. In the year 2005, new production technologies emerged that increased the cost-effectiveness of production and also allowed farmers to produce on soils that were not suitable for earlier technologies. Efficient irrigation methods spread widely, especially among export-oriented farmers and for perennial plantations, but also for maize and other products. Irrigation-based fertilization now enables farmers to produce fruits on more constrained soils (suitability classes III and also IV). With new export markets such as the United States and the European Union, new quality standards are becoming more and more important, and require modifying production standards and processes and thus input costs.

To account for these new technologies, the initial 1996 decision LP was extended considerably, now using ten irrigation methods, 63 crops and over 1000 production and investment activities, as variations of these basic crops (Schilling 2007b).

For ten selected farm agents that were selected as ‘typical’ from local experts (under the lead of Diego Varras), the 1-agent decision model was intensively tested and analysed with regards to choice of activities and water sensitivity (water shadow prices).

Each of these farmers was confronted with a decision problem (fluctuations of product prices and water), and the predicted behavior was discussed and validated for plausibility (see Schilling 2007b, Diego Varras). This interaction process was helpful to identify and eradicate data errors and generally enhanced our understanding of relevant processes. As outcome, water sensitivity and water shadow prices were found reasonable (and convincing), while improvement was needed for other data (especially labor requirements). In the follow-up process, these improvements were incorporated so that model results are now reasonable also for these variations.

The investment decision. Many production activities make use of machinery tools, perennial plantations and other equipment with lifetimes that range from few to twenty years. Before every production decision, the total amount of such equipment and standing capital is updated, and the agent carries out an investment decision, also implemented as MILP optimization problem.

To estimate the returns to an investment, the activity matrix is re-parameterized internally with values that are averaged over the full lifetime of each activity. The objective function value of the activity is the annualized expected cost of the activity. This way, MP-MAS investment decisions avoid large multi-period LPs. If returns to an investment are then negative during the first years (e.g. when planting an apple plantations or vineyards), agents can easily run into shortage of liquidity and eventually go bankrupt. Two tricks prevent this: a special constraint maintains a minimum liquidity to cover the equity share of the investment. Also, the total area that can be invested during each time step is bounded.

The share to be financed by own capital is 25%, at an interest rate for long-term credits of 7.53%. Liquidity that is neither consumed nor invested is saved at an assumed interest rate of 5.85%.

A detailed description of the investment decision is given in Troost 2009.

Diffusion of innovation. After the third period (season 1998/9) ‘2005 activities’ and ‘T3 technologies’ become available. From the sixth period onward (season 2001/2), fruit trees can also be grown on Soil Class III. All other activities are available over the full model period, or were deactivated.
7.3 WASIM-ETH: Modelling of surface irrigation at watershed level

7.3.1 Overview

The WASIM-ETH model was first calibrated using the TOPMODEL approach (Koenig 2005). The soil model was extended and an unsaturated zone model based on the Richards 1-D equation (Leemhuis 2006). In both approaches, potential evapotranspiration is computed within the evapotranspiration module, in our case using the Penman-Monteith equation. The Richards-based soil module then computes real evapotranspiration, by estimating evaporation from the leaf interception layer and the soil surface, and by computing plant water uptake (transpiration) from the soil water content. The soil component takes into account the root profile of plants, soil moisture and movements of water within soil layers, actual capillary pressure (suction) as given by the Van Genuchten parameters and infiltration using the Green-Ampt equation.

The study region was subdivided into 21 sub watersheds, based on one downstream flow station, two further flow stations located within the study region (3 and 9) and other research objectives, especially the location of water takings. Also, flow station data existed for all rivers flowing into the study area. Evapotranspiration, precipitation, other climatic data and fluvimetric data was obtained from the Dirección General de Aguas (DGA) and data was processed (Uribe, Arnold, Arumí, Berger and Rivera 2009). Calibration was performed in several steps: first, irrigation water was abstracted from rivers but not re-applied to the fields, assuming 100% use efficiency. Then, the original WASIM-ETH irrigation module (Schulla and Jasper 2006) was used and later an extended irrigation module (Uribe, Arnold, Arumí, Berger and Rivera 2009), which is described in this section.

7.3.2 Parameterization Of Inefficient Surface Irrigation

Division into sub watersheds

The study area corresponds to the watersheds of the rivers Putagán, Ancoa, Achibueno and Longaví, in the Maule Region of Chile and has a total area of 5300 km². The highest elevations are located in the east, in the mountain range of the Andes, with altitudes around 3000 amsl. From the east to the west the land declines to 100 amsl. Half of the area is located in a plain, with altitudes between 100 and 200 m. This plain corresponds to the agricultural zone. The water flows of interest for this study include the rivers Putagán, Ancoa, Achibueno and Longaví, and smaller tributaries. These rivers originate in head watersheds located in the Andes mountains and mouth into the Loncomilla river, which flows from the south to the north (Figure 1). In the eastern part of the study region, the Melado River (located outside the study region) contributes water resources to the study region through the Melado Canal, thus influencing the hydrology of the study region. In the main rivers, flows measurements pertaining to the Water Direction (DGA) have daily information for the period of this study.

The spatial resolution was of 2000 × 2000 m² and the temporal resolution was daily. The pre-processing used TANALYS (Schulla and Jasper 2007). The 90 × 90 m² DEM was analyzed (NASA, 2005), calculating secondary grids as slope, aspect, flow direction, flow accumulation and rivers network. For the modelling with WASIM-ETH, the area was divided in 21 watersheds, defined from important points in the rivers that are flows stations, water intake points or external inflows (Figure 7.3(a)). The study region is part of a larger river basin that is not considered in its totality. To capture inflows from these areas outside the study region, the artificial
sub watershed 8 was generated but inflows are treated as external and not modeled explicitly, to incorporate inflows from a larger basin size. Two further head watersheds 10 and 11 were treated as external because they are located in mountainous zones with insufficient data.

Parameterizing irrigation abstractions and water rights

The incorporation of human redistribution of water is essential for hydrological modelling of an area with heavy irrigation. In the study region, the use of surface water and its distribution across space is regulated through Water Rights that is legally based on the Codigo de Agua and operated by local water user organizations (see Section 7.5.1, page 165).

Technically, the distribution of water from one intake structures (Spanish ‘bocatoma’) into major and minor canals and finally to the field is modeled within WASIM-ETH by parameterizing ‘abstractions’ (minimum river flow, the percentage of river water above this level that is abstracted, and the maximum canal capacity. See Appendix C for details), and then by returning the water into the receiving catchment at the pour point, using the ‘inflow’ option (Figure 7.2). Irrigation water is taken from these pour points and applied to the fields, where it evapotranspires, creates runoff or percolates to ground water. There are between 10 and 30 intake structures on each of the main rivers. An extensive canal network, covering most of the agricultural area, allows for the distribution of water. This has a major impact on the natural hydrological regime of the rivers. Each farmer can use the water from an intake point according to the amount of Water Rights that he owns or rents. The distribution of the water resources is complex and the water extracted from a watershed can be used in several different watersheds down stream. The distribution of water across space, the crops irrigated and the irrigation methods was parameterized from data that is consistent to the MP-MAS model (Chile data set 60, Dec 2007).

A farmer can have Water Rights from several different sources of water. Water Management Organizations provided information on water rights, which was processed using GIS to aggregate water rights for each sub watershed. In such form, it was possible to incorporate the flows for irrigation into WASIM-ETH (Uribe, Arnold, Arumí, Berger and Rivera 2009). The surface water sources were classified as either ‘internal’ if abstractions from rivers occur within the study region and as ‘external’ if outside. External sources are those which are not affected by the local hydrology, and normally routed through concrete structures. They are modeled as inflows to the pour point of their usage. Thus, only river abstractions are dynamic variables of the model. Furthermore, even if water rights are abstracted within the same subcatchment they are used in, both an inflow and an abstraction is defined for consistency. The full routing graph is given in Figure 7.3.2, with data listed in Table C.1.

Although groundwater resources exist, to this point in time their use is minimal, compared to the quantity of surface water use. However, irrigation based on groundwater is rapidly expanding, partly for water quality reasons (Hammel and Arnold 2008).
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(a) Topographic map and sub watersheds

(b) Conceptual routing graph

Figure 7.3 — Sub watersheds and basic routing
Figure 7.4 — WASIM-ETH Routing graph with rivers (black lines) and irrigation water abstractions (green lines) and external inflows (red lines). Sub watersheds are depicted as ellipse (headwater) or as rhombus; those watersheds that are incorporated as external inflows because data is insufficient are marked as red rhombi.
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Figure 7.5 — Calibration of evapotranspiration

Potential Evapotranspiration using the CropWAT approach

The original WASIM-ETH irrigation module parameterizes each land use separately, requiring large amounts of data on each plant that is usually not measured by irrigation engineers. In most countries, engineers rely on data for some reference crop that is corrected with an empirical crop factor to estimate $ET_{pot}$ for any other irrigated crops.

In the modified irrigation module, such computation was implemented using the reference crop approach that parameterizes $ET_{pot}^c = k_c \cdot ET_{pot}^0$. To use this feature, each irrigation land use must be marked as an irrigation activity and the ID of the $k_c$ value table. The $ET_{pot}^0$ is then computed with reference surface parameters for the Penman-Monteith equation, and corrected with crop-specific (and often locally available) $k_c$-factors. Later, evaporation and plant water uptake (transpiration) is computed within the unsaturated zone model. This module is parameterized with soil characteristics, soil moisture and root parameters and is upward bound by $ET_{pot}^c$. For details, see Uribe, Arnold, Arumí, Berger and Rivera (2009).

Cyclic flows and effective irrigation efficiency

This section was published as ASABE conference paper (Arnold, Uribe and Berger 2008a).

The cyclic reuse of water within an irrigation basin limits the adequacy of the on-field irrigation efficiency concept for basin-scale water management (Molden 1997). However, maintaining the on-field perspective is helpful, because this is the scale in which farmers and farm organizations operate and think (Lankford 2006). But, the basin-scale assessment is blurred by the compensation of data errors between on-field efficiency and cyclic reuse. Water users can exploit this problematic to avoid efficiency improvements (ibid.) and modellers are limited by this typical case of equifinality (Beven 2001).

For models that balance at the ‘sub basin’ level, it is useful to separate water reused within a sub basin (‘internal re-use’) from water reused in downstream sub basins (‘return flows’). Three efficiency concepts thus emerge: on-field irrigation efficiency is the ratio of beneficial evapotranspiration and the total water applied, basin-level efficiency the ratio of and gross irrigation
7.3. WASIM-ETH: MODELLING OF SURFACE IRRIGATION AT WATERSHED LEVEL

Figure 7.6 — (a) Scale-dependency of irrigation efficiency and (b) Effective irrigation efficiency at sub watershed level

water depleted from the rivers (Perry 2007), and sub-basin-level efficiency the ratio of beneficial evapotranspiration to the total irrigation water that was applied less the internal re-use share. Within the family of hydrological models that balance water flows at the level of a sub-basin, empirical parameterization of cyclic water use below the sub-basin level is limited. Validation through field-level measurements is not feasible, because field efficiency measurement uncertainty and cyclic reuse uncertainty mutually cancel each other out (Lankford 2006).

To model irrigation water use and reuse, micro-level data needs are excessive, requiring field-level measurements on soil characteristics, irrigation methods, drainage and the canal system, on irrigation scheduling (Gosain et al. 2005). Such data needs restrict the usefulness of physical-based modelling approaches. As avoidance strategy, some authors use random or rotational initialization, but the problem of micro-level heterogeneity has not been resolved (Hansen, Refsgaard and Ernstsen 2007).

For modelling, three options remain:

1. In the absence of any data, core irrigation parameters are left loose and then calibrated. Internal reuse and return flows become calibration parameters. However, a set of different equifinal parameterizations can describe the system equally well.

2. All irrigation parameters are estimated from other models, e.g. from an agricultural bio-economic model. If the same parameters are consistent in both models, they are assumed to be a true representation of the system. Though not fully empirically verifiable, this approach allows exploring hydrological consequences of human actions and feedbacks on the human sphere. At a minimum, model scenarios will capture all endogenously modeled interactions.

3. Use two separate modelling studies of the same area, on at large scale and one at micro scale. If empirical data exists, the fine model can first be calibrated with these. Then, a translation function is estimated that converts parameters from the micro scale (measurement data) into the coarse scale. The coarse-scale model is then theory-consistent.

Even though the third option is scientifically aspired, the second option was chosen, taking into account the available research resources and data. In order to assess economic returns from
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

water usage from an individual, farm-level perspective, while maintaining a watershed-level perspective on the cumulative hydrological impacts, the model must capture processes at field, farm, sector and sub watershed level.

Regarding return flows, farm (or field) level measurements exist and were incorporated. Also, secondary data from the EdIC model study are used, and the EdIC model is used to estimate sector-level reuse. Together, effective efficiency at sector (and sub watershed) level can be roughly estimated even without measurements, using a linear translation function (Figure 7.6). However, we stress that uncertainty related to cyclic flows is structural and therefore empirically irresolvable.

The WAsIM-ETH irrigation module was modified so that ‘effective’ irrigation efficiency can be parameterized at sub watershed level. The original model applied all irrigation water as precipitation above the leaf layer, and all modules are used – the model resembles a sprinkler that permanently operates, or as specified in the irrigation table.

In reality, small patches of an area may be irrigated for relatively short time, and this area frequently rotates so that all fields receive water. However, for watershed level models with spatial resolution of 1km² or more, it is not possible to capture these rotational schemes. Also, the proper parameterization would require significant input data for which empirical data is not available. These rotational schemes are especially important for inefficient methods, such as gravitational flooding.

To avoid the parameterization of complex rotational scheduling and other sub-resolution processes, surface runoff and deep percolation can be separately parameterized with ‘effective’ data on irrigation efficiency at the appropriate model scale, with constant and daily water tables.

The model now allows applying irrigation water directly to the following compartments of a cell, and to overwriting some of the soil processes: as precipitation, directly to the soil surface (thus bypassing the interception model and evaporation from the interception storage), as surface runoff (ignoring the former plus infiltration), and as deep percolation (bypassing all processes). For example, drip irrigation would bypass interception and evaporation. Runoff, evapotranspiration and percolation can still be calibrated to field measurement data.

**Restriction to river abstractions for irrigation**

During modelling, the original restriction to take irrigation water from rivers was found problematic and caused numerical artefacts. This section first explains the original small-area approximation which restricts irrigation water uptake from rivers. Furthermore, two alternative methods were implemented and tested to limit irrigation abstractions: a large-area approximation and a second one that uses iteration.

1. **Small-area approximation.**

   The WAsIM-ETH irrigation model computes the irrigation restriction by using the river flow from the previous time step. As irrigation restriction, it uses the river flow $Q$ in the pour point plus upstream irrigation water $Q_{IRR}$. This assumes a rapid variation of infrequent irrigation events upstream $Q_{IRR}$, for example when using a many but small sub watersheds.

   The formula used in the original irrigation module is

   $$\text{MAXIRRRIG}_{t+1,\text{this}} = Q_{\text{river, before}}^{t} + \sum_{j \in UP} Q_{t,j}^{IRR}$$
where UP is the set of all upstream sub watersheds, and \( Q_{t,\text{this}}^{IRR} \) is the irrigation water applied in the current sub watershed, and \( Q_{t,\text{river,before}}^{\text{river}} \) is the river flow after inflows from upstream riparians from external were added and after abstractions were served, but before irrigation water was diverted from the river. We call it ‘small area approximation’ because it uses the assumption that the irrigated area (‘field’) is large in comparison to the sub watershed and discontinuous. If the field is irrigated for one day, then the river is emptied during that period and less water is available downstream. The next day, the field is still wet and the irrigation can be discontinued so more water is available downstream.

2. **Large-area approximation.**

In large sub watersheds, the discontinuous daily irrigation for many fields even out. The total amount of water required for that sub watersheds is fairly constant. For the estimation of downstream availability of irrigation water, the semi-continuous upstream water abstractions can be considered as constant for the next day. However, the change of irrigation water uptakes during two days is also computed, to account for changing irrigation because of monthly parameterization.

This large-area approximation of the irrigation restriction considers changes of irrigation in upstream sub watershed \( j \), as \( \Delta Q_{t,j}^{IRR} = Q_{t,j}^{IRR} - Q_{t-1,j}^{IRR} \), to avoid double accounting. Furthermore, for numerical stability, an environmental flow is left inside the river, so only a maximum share \( f \) of river water can be diverted for irrigation.

\[
\text{MAXIRRIG}_{t+1,\text{this}} = f \cdot Q_{t,\text{river,before}}^{\text{river}} + \sum_{j \in \text{UP}} (Q_{t,j}^{IRR} - Q_{t-1,j}^{IRR})
\]  

(7.1)

3. **Irrigation water abstraction with iteration.**

A third and most exact manner to compute downstream irrigation water availability uses an iterative approach, where upstream abstractions (and return flows) use data from previous model runs.

Abstractions are defined as river flow share according to water right endowments. The first model run abstracts irrigation water from the system. During the second and further iteration steps, the model reads these actual abstractions and uses the actual river flow as irrigation restrictions. A third (and forth) iteration is used to account for return flows from upstream to downstream sub watersheds.

In both the small-area and the large-area method, the irrigation restriction is computed after irrigation water is diverted at the pour point, so that the river flow exported to the output files is

\[
Q_{t,j}^{\text{river,final}} = Q_{t,\text{river,before}}^{\text{river}} - Q_{t,j}^{IRR}.
\]

Furthermore, negative river flows are temporarily allowed in approach 2. (large-area approximation) and approach 3. (iteration). The original model does not permit such negative river flows, and sets flows to zero after abstraction of irrigation water. We experienced artificial creation of water: If irrigation water was abstracted in a large sub watershed and significant return flows exists, than the river is fully emptied (e.g. from 5 \( \text{m}^3/\text{sec} \) river flow 8 \( \text{m}^3/\text{sec} \) – 3 \( \text{m}^3/\text{sec} \). With 4 \( \text{m}^3/\text{sec} \) return flows, this leaves 1 \( \text{m}^3/\text{sec} \) in the river. If negative flows are not permitted and are artificially forced to zero, then the river falsely carries 4 \( \text{m}^3/\text{sec} \). This negative flow time problem occurs in the small and the large-area approximation, but is not relevant for the iterated scheme.
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7.3.3 Model Calibration

River flows

The model was calibrated for three measurement stations from 1995-1999, at daily intervals (Figure 7.7). Calibration proceeded from winter flows to evapotranspiration, grid-level effective irrigation and abstractions, and return flows. Results are satisfactory for winter months and for months with supplementary irrigation (Nov-Dec). During the main irrigation periods (Jan-Mar), irrigation flows are approximately $200 \text{m}^3/\text{s}$ per 140,000 ha, which is significantly larger than actual river flows ($20 - 40 \text{m}^3/\text{s}$). While measured data on $ET_{pot}$ was used to estimate irrigation water requirements during irrigation season, during the ripening and drying season irrigation had to be stopped, and all further evapotranspiration was only from moisture stored in soils. However, if the abstraction of irrigation water from rivers was discontinued, then calibration quality decreased significantly – especially during late January and February. The systematic over-estimation of flows hinted to the fact that, after wheat harvest in late December, farmers use remaining water to irrigate pastures.

Irrigation with inefficient surface methods

This section gives an overview on model results from the WASIM-ETH model. Implementation was done as part of integration, as summarized in Section 6.1. Calibration and validation was done under the lead of the hydrological working group. Results were published in conference articles and journal articles, see Arnold et al. 2008a, Uribe et al. 2008b, Uribe and Arnold 2008 and Uribe et al. 2009.

For irrigation columns used at field scale, return flow quantities were estimated for the river watershed. 16% of the applied irrigation water returns as surface flows, and 19% as base flow. Calibration is best if deep aquifer losses of 5% are added (see Uribe, Arnold, Arumí, Berger and Rivera 2009).

The full area is assumed to be irrigated with a single efficiency level that is parameterized with the following flow components:
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<table>
<thead>
<tr>
<th>General irrigation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain 0%</td>
</tr>
<tr>
<td>Topsoil 60%</td>
</tr>
<tr>
<td>Direct runoff 15%</td>
</tr>
<tr>
<td>Percolation 15%</td>
</tr>
<tr>
<td>Losses 5%</td>
</tr>
</tbody>
</table>

Losses of 5% are removed from the system, partly because of deep percolation to aquifers, or because evapo(transpi)ration. In this mode, some of the fraction that is applied at topsoil level and infiltrates further adds to percolation, giving the above stated absolute flow shares.

7.3.4 Results And Discussion From Disciplinary Calibration

The hydrological objective of applying the WASIM-ETH model to the study region was to quantify water flows within a catchment that is heavily influenced by agriculture with inefficient surface irrigation methods. This model application should be consistent with all knowledge obtained through other the models of this project, including land use, irrigation efficiency and the abstraction of irrigation water from rivers with water registries.

The model WASIM-ETH v2.1 had to be modified in several ways to represent these processes: the handling of several special cases that the original irrigation module did not permit; the parameterization of evapotranspiration with crop factors; the routing model that incorporates water rights registries into river abstraction; and the restriction of irrigation water abstraction from rivers was specified with two alternative assumptions to circumvent errors that the original small-area assumption produced.

The extended model functions well for larger sub watersheds of the study region, while smaller sub watersheds (<50,000 ha) continued to perform poor during calibration. Especially in irrigation season, natural river flows are at the same magnitude as irrigation water flows. Here, the poor performance can be attributed to high uncertainty in the specific localization of input data rather than in a faulty conceptual model: the proper location of irrigation water use from water right registries, uncertainty around artificial canals, natural creeks and the drainage system, etc.

The Nash-Sutcliffe criterion of calibration efficiency (Nash and Sutcliffe 1970) at the exit of the watersheds 1 and 12 were good, with values of 0.95 and 0.85 respectively. For smaller watersheds 3 and 9, these values were poor (<0.7).

It is worth noting that these calibration quality indicators did not improve significantly with the described model modifications. In earlier versions of the model, similar calibration quality was obtained by extensively using calibration parameters such as base flow, for which no empirical data was available. However, we are confident that the modified model is a conceptually more consistent representation of the system and the good calibration performance of earlier model versions is mainly a result of insufficient access to calibration data, resulting in equifinality (compare Beven 2001).

Finally, the use of integrated data hinted toward an inconsistency between empirical data and model data and revealed that the irrigation of pastures is relevant for the hydrological cycle. Empirical results were published or are being published under the lead of disciplinary scientists (e.g. Uribe, Arnold, Arumí, Berger and Rivera 2008a, Uribe, Arnold, Arumí, Berger and Rivera 2009), who are responsible for model calibration and verification.
7.3.5 Outlook: Irrigation With Conjunctive Ground- And Surface Water Use

This concluding section demonstrates the potential of the modelling system, especially for the analysis of conjunctive use of groundwater and surface water for irrigation. All results shown in this section are qualitative only. Model experiments use the standalone WASItM-ETH version with the modified irrigation module. Exogenous land use and irrigation scenarios were used as boundary condition.

To test and demonstrate the interaction between surface- and ground water irrigation as well the efficiency module, a simple combination of scenarios is demonstrated.

In eleven scenarios GW 1...GW 11, the agricultural area under surface irrigation is gradually transformed into ground water irrigation. Also, four different irrigation efficiency scenarios are tested: the first scenario, the Reference scenario, was determined with the general irrigation method (see previous section). From this reference scenario, three variations are tested:

1. no return flows (Direct runoff = 0 %, Percolation = 15 %)
2. no percolation (Direct runoff 15%, Percolation = 0 %)
3. both zero (Direct runoff 0%, Percolation = 0 %)

For demonstration purposes, the water balance is not closed in these variations, so that water is actually lost. The same amount of water is requested from the river in all scenarios, and surface irrigation water abstractions are bound as a percentage of the river with an upper limit, the canal capacity.

First, the transformation of surface irrigation area into ground water irrigation caused the internal WASItM-ETH ground water limit (MAXPUMP) to cut supply. The attempt to increase the quantity of water abstracted from groundwater linearly through area expansion resulted in an under-proportional and nonlinear behavior. Giving more detail, the internal WASItM-ETH ground water restriction is currently estimated using a simple heuristic: 

$$\text{MAXPUMP} = 1000 \cdot \sum z d_z \cdot (\theta_z - \theta_{3.45})$$

where $z$ are soil layers, $d_z$ is the thickness of soil layer $z$ and $\theta_z$ the suction in layer $z$. The (in this respect unchanged) WASItM-ETH code assumes the suction as in 3.45 m to coincide with field capacity (Schulla and Jasper 2007).

Second, in the reference scenario, surface irrigation is limited through water rights. Thus, an increase of ground water irrigation upstream and thus a reduction of abstractions from the river causes river flows to increase. During a wet year, the median outflow from sub catchment 1 thus increases from 48$m^3$/s to 86$m^3$/s.

Table 7.1 shows exemplary modelling results. For all variables, the daily median was computed over a two-month interval of a wet irrigation season (Dec 97 – Jan 98). From left to right, increasingly more irrigation area is converted to ground water irrigation. For downstream sub catchment 1, the variables shown are the averaged irrigation from ground water and from surface water [mm/day], river flows [m$^3$/s], base flow, direct runoff, for the four irrigation efficiency scenarios that are shown.

For the first conversion scenario with river-constrained deficit irrigation, the actual irrigation water abstracted from rivers remains constant or even increases. Only if significant areas of staple are converted from surface- to ground water irrigation, then the increase in ground water irrigation reduces surface water abstractions.
### Table 7.1 — Impact of ground water irrigation and surface irrigation efficiency. A gradual transition from surface water irrigation to ground water irrigation (left to right) is tested against four different irrigation efficiency scenario.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Content</th>
<th>Efficiency</th>
<th>GW 1</th>
<th>GW 2</th>
<th>GW 5</th>
<th>GW 9</th>
<th>GW 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Irrigation from ground water [mm/day]</td>
<td>Reference</td>
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<td>0.07</td>
<td>0.15</td>
<td>0.47</td>
<td>0.71</td>
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<tr>
<td></td>
<td></td>
<td>Zero Return flows</td>
<td>0.00</td>
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<td>0.15</td>
<td>0.47</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zero Percol</td>
<td>0.00</td>
<td>0.07</td>
<td>0.16</td>
<td>0.47</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zero both</td>
<td>0.00</td>
<td>0.07</td>
<td>0.16</td>
<td>0.47</td>
<td>0.72</td>
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<tr>
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<td>18.19</td>
<td>14.86</td>
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<tr>
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<td>14.50</td>
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<td>66.50</td>
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<td>1.60</td>
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<td>0.70</td>
<td>0.84</td>
<td>0.57</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Discussion of indicative results.** These results are qualitative, and should not be over-interpreted. The (unchanged) ground water irrigation restriction $MAXPUMP$ still creates spurious model behavior. Also, each cell (grid size 4 km$^2$) can only use surface or ground water irrigation, which is not realistic and causes unrealistic gradients of ground water levels, and possibly numerical artefacts. Furthermore, the ground water model that was used in the Chilean case study is not process-based but uses the overly simplistic regression equation.

It is the objective of this little experiment to demonstrate the potential for combined surface- & groundwater modelling, in a system that has strong and relevant feed backs. The implementation of further details could greatly improve its usefulness: an improved pumping restriction and the conjoint use of ground water and surface irrigation within the same grid. The latter requires one additional raster file as input and the expansion of the data container array by one element.
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

7.4 **EDIC: Calibration Of The Routing Model**

### 7.4.1 Objective

The objective of the parameterization of EDIC is to match water supply of irrigation sectors with measured data and with expert knowledge, as pre-condition to calibrate the water supply to individual farmers within the MP-MAS model using water right registries and dynamic meteorological-hydrological conditions.

Farm agents are supplied with irrigation water from various sources: rivers and river-like canals, such as the Melado canal that brings water the reservoir of another catchment, are regular sources that get distributed to farmers through water rights. Also, return flows of spillover from upstream to downstream sectors additionally supplies water to sectors.

Furthermore, re-distributive processes within a sector, such as the use of surplus water from neighboring agents (Section 6.3.2), are a relevant source to individual farmers. For the calibration of EDIC at sector level, all re-distributive processes within a sector can be ignored, because water availability is only assessed at the broader sector scale.

The model parameterization suggested here combines five data sources:

1. Land use data obtained from an agricultural census, and processes for the MP-MAS model (see Technical Reportootnote{Arnold 2009: Irrigation in Chile, Region VII: Background and description of cross-disciplinary data}). Land use was averaged with data for 1996 and for 2006. This land use is assumed as constant over the time horizon 1944-1986.

2. Crop water requirement data gathered within the project (Uribe, internal technical report), and assigned to land use classes within the MP-MAS group. Each land use is thus defined as very specific cropping activity, identical to the MP-MAS use. Such data not only defines the area cropped, but also the plant water demand for each month and the irrigation methods.

3. Topography-driven lateral flows, estimated with topographic analysis for WAS1M-ETH, are included as ‘near-surface’ routing parameters $e_{jk}$.

4. Canal return flows, estimated within the study done by EDIC-CEDEC consortium for DOH, are included as ‘surface runoff’ routing parameters $d_{jk}$.

5. For calibration, data on irrigation security was compared with model results so that consistency with the Ancoa feasibility study (DOH/SMI 2004) was maintained. For fine-tuning of within-sector water supply and losses, parameters $b_j$ and $g_j$ were used.

The IGM data gathered for the MP-MAS calibration and the three hydrological studies capture the best local expert knowledge available, with various thematic foci. By joining the main finding of these studies, we ensure robustness of EDIC results to a wide range of assumptions.

### 7.4.2 Data And Strategy For Calibration

**Irrigation priority groups**

One assumptions of the EDIC model is the that crops are grouped by irrigation priority.
Following locally accepted farming rules, MOP (1992) and Berger (2001) define the order by which plants are irrigated by grouping crops. If less water is available than needed, then first those crops belonging to the highest irrigation priority group (IPG) are watered, until all water is used. Thus, even under conditions of severe droughts, negative effects on high-value crops and perennial crops can be avoided, while crops with low priority (wheat, pastures) frequently don’t receive sufficient water. To account for this prioritization criterion, the following heuristic is used in the Ancoa Dam feasibility study (DOH/SMI 2004, Tomo IV, Cap 2).

First, plant irrigation demand is computed from measured plant water demand data \( ET_{pot}^{crop} \), after correction with effective rain fall. Then, crop-specific land use maps was generated using the CENSUS Agropecuaria (1996) and for each irrigation activity and sector, an area with assigned. Land use is then categorized into five irrigation priority groups \( IPG \):

<table>
<thead>
<tr>
<th>IPG</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fruit plantations, as perennial investments with high economic value, export vegetables and contract farming</td>
</tr>
<tr>
<td>2</td>
<td>Vegetables</td>
</tr>
<tr>
<td>3</td>
<td>Other annual crops, especially staple crops</td>
</tr>
<tr>
<td>4</td>
<td>Artificial pastures (alfalfa, clover) and winter wheat</td>
</tr>
<tr>
<td>5</td>
<td>Natural pastures</td>
</tr>
</tbody>
</table>

Using this data, irrigation water \( IRR_{IPG} \) is first supplied to the classes with highest priority to meet plant irrigation demand. For each sector and \( IPG \), the total plant irrigation demand is computed. For the computation of IPG-specific irrigation security, it is reasonable to maintain a low number of groups. If irrigation security is used to calibrate water losses in an irrigation sector, and thus water availability to farmers, then it is self-evident that irrigation security differs among irrigation priority groups. Because the monthly plant water demand varies for each crop, the resulting irrigation security differs among crops with the same irrigation priority.

**Irrigation Security: Definition, data and computation rules**

As indicator for water scarcity and its fluctuation, the concept of irrigation security (IS) is used by several institutions in the study region.

Using land use and crop parameters from MP-MAS, the model was calibrated to fluctuating meteorological conditions, so that modeled IS conforms with the empirical studies. This way, the dynamic model properly recreates the risk of crop failure over the years.

In this section, we first define computation rules for irrigation security as calibration index. Then, the implementation of an improved Edic model to compute irrigation security in MatLab® is summarized, with scripts that facilitate calibration and parameter variations. With such computationally slim Edic model code, input data errors were eliminated and sector-level parameters were fine-tuned. Third, irrigation security was computed for ‘irrigation priority groups’ and also for individual crops, assuming that priorization rules are applied at sector level. Finally, model sensitivity to variations of selected parameters was assessed.

Irrigation security must be defined for a specific area cropped under a specific plant (or plant mix). For such a cropped area, irrigation water demand is calculated, and the plant water satisfaction factor (the share of plant water demand that can be satisfied) is computed for each monthly time step, and later aggregated annually. The frequency distribution of this annual satisfaction level, over a span of at least 15 years, is then called irrigation security.
Analogously, for a specific irrigation security level, e.g. 85%, for a known crop mix and assuming an irrigation efficiency and reuse, the maximum area that can be irrigated can also be computed.

Various irrigation security criteria co-exist, and two definitions were used:

The CNR Irrigation Security index (Source: Codigo de agua)
To define irrigation security, the National Irrigation Commission (CNR) distinguishes "failed" and "served" years. Irrigation security is the percentage of years where the planned water quantity is "served". More precisely, years are defined as "failed" if one of these conditions holds true:

- during one month, less than 85% of irrigation demand (based on water rights) was available to farmers
- during two months, less than 90% of irrigation demand was available.

Otherwise, years are considered as "served". The percentage of "served" years to total years is the irrigation security. This criterion is either computed for the total land use, for each individual crop or for a crop group (IPG).

Factor of Satisfaction
(Source: Ancoa Dam feasib. study, DOH/SMI 2004, Tomo IV, Cap 2)
Within the Ancoa feasibility study, a similar definition for irrigation security was applied. The annual factor of satisfaction for each irrigation group, $FoS_{IPG}^y$, is defined as the mean monthly factor of satisfaction, averaged over all irrigation months $n$ that are relevant for each specific crop. It takes average of the monthly ration of actual irrigation water applied to each crop group, $IRR_{IPG}^{m,y}$, and the plant water demand $PID_{IPG}$ needed to grow the defined maximum yield, also aggregated for each crop group:

$$FoS_{IPG,crop}^y = \frac{1}{n_{crop}} \sum_{m=1,...,n} \min\left(1, \frac{IRR_{IPG}^{m,y}}{PID_{IPG}}\right)$$

The ratio is limited to full satisfaction (or 1). This rule resembles the computation of the $k_r$-factor within the crop yield model to compute water deficit (Section 4.3.4).

Area with irrigation security $IS = 85\%$. According to the Ministry of Agriculture, a core challenge is to mainstream consistent use to define irrigation security, in order to obtain statistics on the area with irrigation security $S = 85\%$ at national level (Ministerio de Agricultura 2005).

For our use, we define this area using river flow data over a period of $N = 50$ years. The maximum irrigable area with $IS = 85\%$ for a specific $IPG$ is computed from water that remains for each priority group. Thus, this definition requires first to subtract water for other crops with higher priority.

---

5 Spanish: ‘factor de satisfaccion’
Irrigation security at crop level. The aggregation of several crops into an irrigation priority group causes significant bias if IS is computed at such level. If two crops are pooled into one IPG, then information at IPG level blurs the actual risk of crop failure. For example, winter wheat is most water sensitive in November and then harvested, while peak water demand of Maize in January. If both fall within the same IS called ‘staple crops’, a water shortage in January and February would falsely indicate low irrigation security for wheat. Thus, while irrigation priority groups are used to allocate water, outputs must be re-transformed into crop-specific irrigation security indices.

A two-level approach was taken. First, the allocation of irrigation water to plants is based on the IPG rule. Irrigation security is then computed separately for each crop using its specific irrigation months.

Input Data

Empirical data on irrigation security exists, but computation rules for these data are mostly inconsistent, or the spatial resolution of this data is inconsistent with the sectors used within our project.

The first-best estimate was taken from DOH/SMI 2004, Tomo IV, Cap 2. Data on irrigation security was compiled within this comprehensive feasibility study for the Ancoa dam project. For the calibration of the EDIC model within the IGM project, river flow measurements (usually daily time series) were first aggregated into monthly average flows, either using a mean (total) or a median rule.

Irrigation security is computed using the official CNR criterion, for the full area of the Ancoa reservoir study, corresponding approximately to sectors 04-g,h,k and parts of l, n, o. Here, IS was computed separately for land use groups and for water sources (Ancoa, Melado, Achibueno) for a time horizon of 50 years and for a fixed land use. By comparing monthly plant irrigation demand with (effective) monthly river flow data, the frequency with which an irrigation security threshold is exceeded was computed then, with the following results:

<table>
<thead>
<tr>
<th>Land use group</th>
<th>Security [%]</th>
<th>Area [ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit plantations</td>
<td>85</td>
<td>9.71</td>
</tr>
<tr>
<td>Annual crops</td>
<td>75</td>
<td>8.77</td>
</tr>
<tr>
<td>Wheat</td>
<td>85</td>
<td>6.15</td>
</tr>
<tr>
<td>Fodder crops</td>
<td>40</td>
<td>2.09</td>
</tr>
</tbody>
</table>

Further assumption. ‘Extremely dry years’ do not enter the statistics, as these are considered seldom and thus irrelevant for general assessment. A cut-off value is defined and eventually modified so that no more than 5% of the years have a lower annual factor of fulfillment (2 in the case of \(N = 50\)). Years are classified as extreme drought years, if the annual factor of fulfillment is below a cutoff \(f_{\text{sat}}\), which is 0.5 for \(S = 85\)% and 0.3 for \(S \leq 70\)%.

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6The median rule filters out peak flows from infrequent rainfall events, so that heavy flows with high sediment loads are not considered. Such flows are not suitable for most irrigation equipment.
Runtime improvement and re-implementation of the EDIC model in MatLab®

General model and data structure. In order to make parameter variation experiments, the EDIC model was re-implemented under MatLab® (notated as ML-EDIC). The fully equivalent model uses the same data set developed for MP-MAS and results for this model are equal if all agents in one sector are ‘pooled’ into a single sector agent, and no constraints exist. To facilitate I/O routines, MP-MAS input data was hyper linked into a separate Excel file (‘RegionKey.xls’), containing all relevant sheets. Input format was slightly modified in order to use a generic read-function.

All equations are identical, and the full data on cropping activities is also used. Irrigation demand was first taken from ‘expected irrigation demand’, and was extended to account for sector-level variations of precipitation. Also, sector-level canal efficiency is computed, which defines sector-level irrigation efficiency and thus irrigation water demand.\(^7\)

Levels of analysis. At post processing level, the evaluation of model results is automated and FoS and CNR criteria are computed for all crops and at sector level. Irrigation sectors can either be endowed with water separately, or water can be pooled and all sectors are treated as a single entity. The latter is equivalent to the assumption that total water entitlements in the study region were optimally re-distributed among all sectors so that the irrigation security is constant for each IPG across the full study region. In comparison with the sectorized model, potential benefits of optimal between-sector re-allocation can be assessed.

Model implementation. The model was implemented in MatLab®. The STRAHLER stream order of sectors is automatically determined, using the between-sector routing matrix (d + e, see Technical Report Arnold 2007).

The model is implemented in matrix notation so that the dimensions of input matrices (number of sectors J, number of rivers R and number of months M) automatically determine all further computations. Each model run covers one year, and multi-year runs require repeated call to the function ‘computeEdicModel’.

The function ‘computeFullTimePeriod’ calls this function for all 50 years, evaluates results and computes irrigation security, for irrigation priority groups and at crop level.

Runtime for each model year is 0.6 second with a 2.4 GHz processor, thus one full 50-year run takes less than 45 seconds (including post processing and outputs to the screen).

---

\(^7\) The ‘original’ EDIC canal model is used, in parameter specification Canal 10 (see Table 7.5).

\(^8\) Strahler stream order is a classification system based on stream/tributary relationships (Strahler 1952). The uppermost sub watersheds or canals in a routing network (i.e., headwater sub watersheds without tributaries) are designated as having order 1. A sub watershed (or sector) has an order that is one higher than its highest tributary (Strahler 1952).
Further scripts were implemented to automatize calibration and analysis. These include

- **SCRIPT_Edic_AutomaticCalib_bg** automatically returns \( b_{\text{max}} \) and \( g_{\text{max}} \) so that eq. (1.30) (see Technical Report Arnold 2007, Section 1.4 Calibration parameters and strategy) is fulfilled as equality, by first varying \( b_j \) and \( g_j \) at sector level\(^9\). Eventually, if important parameters (irrigation methods, land use, etc.) change significantly, this calibration needs to be repeated.

- **SCRIPT_ParameterSensitivity** automatically varies a single parameter over a defined range (either in linear or geometric intervals), and estimates irrigation security as function of that parameter. The script requires the name of the parameter, the range and the number of full runs; Furthermore, only a single parameter or a full matrix may be varied;

### 7.4.3 Model Calibration And Analysis

The aim of fine calibration is to reproduce irrigation security data at realistic ranges. Calibration parameters were adjusted so that the model becomes sensitive to core parameters, in accordance to expert opinion.

Perfect calibration of irrigation security is not feasible, because the definition of irrigation security is scale-dependent and also dependent on the mix of crops, and at the level to which crops are aggregated (see Fig. 7.11 for detail). Furthermore, irrigation security requires to assume a specific irrigated area. Especially in small sectors, such land use data often has poor quality.

Taking into account these constraints imposed by model structure and data availability, irrigation security was assessed for all sectors using both the CNR criterion and the average level of satisfaction, by varying two parameters that were identified as most relevant with parameter experiments:

1. Canal efficiency both through scaling of water rights, and using sector-specific canal efficiency\(^{10}\);

2. The scaling of the sector loss parameter \( \bar{b} = f \cdot b_{\text{max}} \), with \( f \in [0, 1] \).

Then, parameter combinations for the scaling of precipitation and internal reuse \( b \) were identified where the model reacts sensitive and irrigation security is realistic. Values are given in Table 7.2.

#### Calibration results

Various water sources contribute to irrigation security: rivers, the Melado canal and within-sector reuse. The relevance of each source varies for each month, and also over years, as shown Figure 7.8 for selected sectors. The anti-cyclic nature of the Melado canal flow gives it highest relevance during months with lowest water flow, e.g. for sectors 05-e and 04-l.

The share that cyclic reuse contributes to irrigation water is constant for each sector by construction of the EDIC model, with contributions varying between 5 and 15%, as shown for the

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\(^9\)We note that there is strong ambiguity because multiple combinations of \( b_{\text{max}} \) and \( g_{\text{max}} \) can be obtained, as function of land use or irrigation methods.

\(^{10}\)After changing from constant to sector-specific canal efficiency, automated computation of \( b_{\text{max}} \) was repeated.
### Table 7.2 — Final parameters for EDIC model.

<table>
<thead>
<tr>
<th>Sector name</th>
<th>Canal Efficiency</th>
<th>$b_{j,max}$</th>
<th>$g_{j,max}$</th>
<th>$b_j$</th>
<th>$g_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>05a</td>
<td>0.67</td>
<td>0.44</td>
<td>0.19</td>
<td>0.308</td>
<td>0.1387</td>
</tr>
<tr>
<td>05b</td>
<td>0.66</td>
<td>1</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>05c</td>
<td>0.50</td>
<td>0.375</td>
<td>0.1</td>
<td>0.679</td>
<td>0.19</td>
</tr>
<tr>
<td>05d</td>
<td>0.70</td>
<td>0.92</td>
<td>0.19</td>
<td>0.644</td>
<td>0.175</td>
</tr>
<tr>
<td>05e</td>
<td>0.90</td>
<td>0.6</td>
<td>0.7</td>
<td>0.07</td>
<td>0.45</td>
</tr>
<tr>
<td>04b</td>
<td>0.55</td>
<td>0.1</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>04c</td>
<td>0.55</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.3075</td>
</tr>
<tr>
<td>04e</td>
<td>0.55</td>
<td>0.92</td>
<td>0.2</td>
<td>0.644</td>
<td>0.175</td>
</tr>
<tr>
<td>04i</td>
<td>0.55</td>
<td>0.12</td>
<td>0.15</td>
<td>0.084</td>
<td>0.15</td>
</tr>
<tr>
<td>04k</td>
<td>0.60</td>
<td>0.49</td>
<td>0.5</td>
<td>0.343</td>
<td>0.5</td>
</tr>
<tr>
<td>04m</td>
<td>0.87</td>
<td>0.1</td>
<td>0.2</td>
<td>0.07</td>
<td>0.2</td>
</tr>
<tr>
<td>04n</td>
<td>0.60</td>
<td>0.46</td>
<td>0.5</td>
<td>0.322</td>
<td>0.5</td>
</tr>
<tr>
<td>04a</td>
<td>0.55</td>
<td>0.1</td>
<td>0.2</td>
<td>0.07</td>
<td>0.2</td>
</tr>
<tr>
<td>04h</td>
<td>0.61</td>
<td>1</td>
<td>0.175</td>
<td>0.7</td>
<td>0.15</td>
</tr>
<tr>
<td>04o</td>
<td>1.00</td>
<td>0.74</td>
<td>0.4</td>
<td>0.518</td>
<td>0.4</td>
</tr>
<tr>
<td>04d</td>
<td>0.59</td>
<td>0.8</td>
<td>0.175</td>
<td>0.56</td>
<td>0.19</td>
</tr>
<tr>
<td>04i</td>
<td>0.75</td>
<td>0.4</td>
<td>0.7</td>
<td>0.28</td>
<td>0.7</td>
</tr>
<tr>
<td>04j</td>
<td>0.60</td>
<td>0.48</td>
<td>0.5</td>
<td>0.336</td>
<td>0.19</td>
</tr>
<tr>
<td>04g</td>
<td>0.60</td>
<td>1</td>
<td>0.3075</td>
<td>0.5</td>
<td>0.19</td>
</tr>
<tr>
<td>04f</td>
<td>0.59</td>
<td>0.69</td>
<td>0.45</td>
<td>0.483</td>
<td>0.375</td>
</tr>
</tbody>
</table>

Indicator month January (Figure 7.9). The sectors where return flows from other sectors add to water availability most significantly are 04-j, which receives canal flows from the large sector 04-l, and the tail-end sector 04-f.
Figure 7.8 — Sources of water during one cropping cycle, for four selected sectors.
Figure 7.9 — For January, comparison of relevance of water sources (in percentage), for all sectors.
Proportional scaling of water rights values was used to verify the post processing routine technically and also to evaluate sensitivity to water for each sector. Figure 7.10 shows results of this stepwise reduction, for an exemplary sector 05-d. On the left, the graphs show irrigation security, ordered by irrigation priority group, but computed for individual crops. The right shows the average factor of satisfaction, which describes the percentage of crop water demand satisfied, either by precipitation or by irrigation. As expected, IS is zero if water rights are reduced to zero, with the exception of some horticultures that grow during winter (broad beans, pies). If some water is provided, irrigation security increases first for high-value crops because of the IPG rule. Resulting from the aggregation at sector level and the high priority of fruits, fruit plantations are hardly ever water-constrained and irrigation security is mostly 100% for all sectors that receive water. For some horticultures that are harvested before water gets scarce, the irrigation security is also very high.

If actual water quantities are provided (factor 1), both horticultures and fruits are fully irrigated in sector 05-d, IS for annuals is below the CNR threshold of 85%, and the other IPGs remain at 10-15%. In this sector, the actual FoS, which is also used to estimate crop yields, is 0.75 for wheat, and 0.6 for irrigated pastures.

The calibration of the EDIC model to irrigation security data revealed that neither the canal flow component (1) nor the topographic flow component (2) were, on its own, sufficient to reproduce a behavioral model with regards to irrigation security data (3.). Instead, the combination of both components gave good results.
Further observations:

- The large sectors 04-l and 05-e can fully satisfy irrigation demand through water rights, especially from Achibueno river.

- Sectors that significantly rely on return flows from other sectors are
  - 04-j, which receives surface/canal return flows from 04-l and is water-restricted;
  - 04-g, which satisfies water demands with both Melado and river shares,
  - 04-f, as bottom sector that gathers return flows from all other areas.

- There are difficulties with obtaining robust data for very small sectors, because water rights registries and land use data do not match at this level of detail. This becomes specifically relevant for sectors 04-a and 04-o, and to a lesser extend for sectors 04-c, 04-m and 04-n.
Table 7.3 — **EDIC Base Run** — Model results for calibration land use, the mean of 1996 and 2006 land use ($\frac{LU_{1996} + LU_{2006}}{2}$), during a relatively dry year. All units in [liter/s].

<table>
<thead>
<tr>
<th>Sector Name</th>
<th>Net uptake (lateral)</th>
<th>Net uptake (surface)</th>
<th>Max. irrigation restriction</th>
<th>Irrigation demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>05a</td>
<td>1056.4</td>
<td>1203.6</td>
<td>2180.3</td>
<td></td>
</tr>
<tr>
<td>05b</td>
<td>1455.0</td>
<td>0.0</td>
<td>1900.9</td>
<td></td>
</tr>
<tr>
<td>05c</td>
<td>1680.5</td>
<td>109.0</td>
<td>3223.5</td>
<td></td>
</tr>
<tr>
<td>05d</td>
<td>3117.3</td>
<td>92.0</td>
<td>3124.7</td>
<td></td>
</tr>
<tr>
<td>05e</td>
<td>2162.1</td>
<td>0.0</td>
<td>1637.5</td>
<td></td>
</tr>
<tr>
<td>04b</td>
<td>60.6</td>
<td>63.0</td>
<td>66.2</td>
<td></td>
</tr>
<tr>
<td>04c</td>
<td>61.8</td>
<td>77.0</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>04e</td>
<td>718.9</td>
<td>819.5</td>
<td>615.0</td>
<td></td>
</tr>
<tr>
<td>04f</td>
<td>88.7</td>
<td>91.9</td>
<td>170.1</td>
<td></td>
</tr>
<tr>
<td>04g</td>
<td>169.1</td>
<td>191.6</td>
<td>326.6</td>
<td></td>
</tr>
<tr>
<td>04h</td>
<td>180.6</td>
<td>201.3</td>
<td>120.6</td>
<td></td>
</tr>
<tr>
<td>04i</td>
<td>138.7</td>
<td>148.4</td>
<td>197.4</td>
<td></td>
</tr>
<tr>
<td>04j</td>
<td>42.8</td>
<td>44.3</td>
<td>941.8</td>
<td></td>
</tr>
<tr>
<td>04k</td>
<td>1205.2</td>
<td>1396.7</td>
<td>1668.9</td>
<td></td>
</tr>
<tr>
<td>04l</td>
<td>113.1</td>
<td>153.6</td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>04m</td>
<td>967.3</td>
<td>1118.0</td>
<td>1422.8</td>
<td></td>
</tr>
<tr>
<td>04n</td>
<td>5296.1</td>
<td>5858.6</td>
<td>5452.7</td>
<td></td>
</tr>
<tr>
<td>04o</td>
<td>204.4</td>
<td>229.0</td>
<td>354.7</td>
<td></td>
</tr>
<tr>
<td>04p</td>
<td>5100.8</td>
<td>5728.2</td>
<td>6517.2</td>
<td></td>
</tr>
<tr>
<td>04q</td>
<td>2834.9</td>
<td>3133.4</td>
<td>3290.4</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.12 — *Total scaled sensitivity of all sectors to routing factor $e$ (return flow). Sectors are grouped according to their position within the study area.*
Table 7.4 — EDIC Base run – Relevance of water sources during relatively dry year

<table>
<thead>
<tr>
<th>Sector</th>
<th>Rivers</th>
<th>Melado</th>
<th>Internal reuse</th>
<th>Return flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>05a</td>
<td>87.2%</td>
<td>0.5%</td>
<td>12.2%</td>
<td>0.0%</td>
</tr>
<tr>
<td>05b</td>
<td>14.9%</td>
<td>48.1%</td>
<td>14.5%</td>
<td>22.4%</td>
</tr>
<tr>
<td>05c</td>
<td>3.3%</td>
<td>69.9%</td>
<td>14.9%</td>
<td>11.9%</td>
</tr>
<tr>
<td>05d</td>
<td>54.7%</td>
<td>21.6%</td>
<td>11.4%</td>
<td>12.3%</td>
</tr>
<tr>
<td>05e</td>
<td>25.6%</td>
<td>49.7%</td>
<td>14.8%</td>
<td>9.9%</td>
</tr>
<tr>
<td>04h</td>
<td>96.3%</td>
<td>0.0%</td>
<td>3.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04c</td>
<td>80.3%</td>
<td>0.0%</td>
<td>19.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04e</td>
<td>61.1%</td>
<td>0.0%</td>
<td>26.6%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04i</td>
<td>35.3%</td>
<td>61.2%</td>
<td>3.5%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04k</td>
<td>4.7%</td>
<td>83.6%</td>
<td>11.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04m</td>
<td>75.2%</td>
<td>14.5%</td>
<td>10.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04n</td>
<td>42.7%</td>
<td>50.8%</td>
<td>6.5%</td>
<td>0.0%</td>
</tr>
<tr>
<td>04d</td>
<td>10.4%</td>
<td>43.8%</td>
<td>26.4%</td>
<td>19.4%</td>
</tr>
<tr>
<td>04g</td>
<td>45.9%</td>
<td>37.3%</td>
<td>13.5%</td>
<td>3.4%</td>
</tr>
<tr>
<td>04l</td>
<td>72.1%</td>
<td>18.1%</td>
<td>9.6%</td>
<td>0.3%</td>
</tr>
<tr>
<td>04j</td>
<td>20.6%</td>
<td>28.6%</td>
<td>10.8%</td>
<td>40.0%</td>
</tr>
<tr>
<td>04b</td>
<td>38.2%</td>
<td>37.1%</td>
<td>11.0%</td>
<td>13.8%</td>
</tr>
<tr>
<td>04f</td>
<td>58.1%</td>
<td>1.1%</td>
<td>9.5%</td>
<td>32.3%</td>
</tr>
</tbody>
</table>

Sensitivity of sectors to \( b_j \) and \( g_j \) Results of data sensitivity analysis are summarized in a routing graph (Figure 7.13)\(^{11}\), as colors of sector nodes. Surface (or canal) flows are depicted with blue arrows, and lateral (or topographic) flows with brown arrows. The share of total inter-sectoral return flows are written to the arrows.

As extreme test scenarios, calibration parameters \( b_j \) and \( g_j \) were varied between extreme values \( b_j^{\text{max}} \) and 0, respectively \( g_j^{\text{max}} \) and 0. The analysis is based on 4-year drought river flows, so that slight over planning is likely for those sectors that fully make use of their water.

- Blue sectors are, under 1996/7 land use, not water restricted even if \( b_j = g_j = 0 \).
- For yellow sectors, land use (and plant irrigation requirement) cannot be met with irrigation water delivered, even if assuming no further losses of internal reuse water \( b_j = b_j^{\text{max}} \) and \( g_j = g_j^{\text{max}} \). During a 4-year dry year, over-committed occurs by factors 1.1 to 1.5.
- Light green sectors become water-sensitive if setting all \( b_j \) to zero, where both internal reuse and surface return flows become zero.
- Dark green sectors become sensitive to water-scarcity only if all \( b_j \) and additionally all \( g_j \) are 0, thus also lateral return flows are switched off.

In summary, this rough analysis already indicates levels of water scarcity and importance of interaction. For green sectors, within-sector and between sector interactions matter. Dark green sectors can only be served if considering between-sector interaction.

To summarize how parameter sensitivity impacts on different sectors, the scaled sensitivity \( SS(p) = \frac{IS(p_{\text{base}}) - IS(p_{\text{scen}})}{(p_{\text{base}} - p_{\text{scen}})} \) was computed and averaged over the tested parameter range. Sectors were grouped into upstream, central and downstream sectors, and results were plotted (see \( ^{11} \)The graph was created with dot, a public domain product from GraphViz (www.graphviz.org). Arrangements of nodes and arrows do not represent topographic relations, rather than rules to structure the graph.)
Figure 7.13 — Routing graph with sensitivity of sector-level irrigation security to calibration parameters $b_j$ and $g_j$.

Figure 7.12 for the sensitivity to return flows). The water-scarce and small upstream sector pre-Andean sector 04a depends heavily on return flows, from sector 04-b (see also routing diagram, 7.13).

**Parameter scenarios** A set of parameters scenarios was identified as 'behavioral' (Beven 2001), meaning that the model fulfills calibration requirements and also validates for all parameter combinations: irrigation security for IPGs and/or crops is in a reasonable range with Ancoa feasibility study and other studies (Longaví study), and local parameter sensitivity is in line with expert opinion. Thus, it is not reasonable to prioritize or even select one parameter scenario as optimal. To maintain this calibration uncertainty within further analysis, three scenarios are identified that are both typical representatives of the set, and also have interpretative meaning:

1. *For the reference scenario*, the relevance of actual precipitation at sector level is proportionally scaled down by a factor 0.85. Internal sector losses $b$ was computed as $b = 0.7 \cdot b_{\text{max}}$ for average and small sectors, and for larger sectors (05-d, 05-e, 04-f, 04-g and 04-l) as $b = 0.5 \cdot b_{\text{max}}$. 
For this combination of parameters, the model is sensitive to all relevant parameters (b, g, d, e, canal efficiency, precipitation). Irrigation security was computed for each crop and sector, classified by irrigation priority group and plotted at sector-level (7.11). For a relatively dry historical year that is water constrained, model results are further shown in table 7.3

2. *In the Precipitation scenario*, the relevance of precipitation is assumed as higher than in the reference scenario. Actual precipitation enters the effective precipitation correction at full volume (factor 1.25). Instead, water rights are scaled down (factor 0.8). This scenario shows similar irrigation security for central sectors, higher dependence on water rights and lower security for downstream sectors, and higher security for Pre-Andean sectors.

3. *The return flow scenario* reduces in-sector losses by maintaining in-sector loss parameter \( b = 0.85 \cdot b_{\text{max}} \) (for large sectors, 0.7 respectively). Instead, water rights are scaled down by a factor 0.87, while precipitation correction remains as in the reference scenario (factor 0.75). This scenario assumes high relevance of irrigation reuse at similar overall irrigation security.
7.5 The MP-MAS/EDIC Interface: Farmer’s Access To Water And Canal Efficiency

One interaction process was found to have grand impact on model calibration, between the individual farm level (as modelled within the multi-agent component and with mixed-integer linear programming) and the level of irrigation sectors (as modelled within EDIC). This interaction is related to the distribution of water to individual farmers, and the existence of a pool of non-attributed (or informally managed) water.

To analyze this interaction process, a model use case was elaborated. First, the models were calibrated with a pool of non-attributed water and formal and informal access to water. Then, it was tested how an improvement of canal conductive efficiency would impact the population of farmers, to assess the benefits of such improvements on individual farmers.

7.5.1 Introduction

Farmers’ Access to water

With improved and more detailed registry data for both land and water (Uribe, Arnold, Arumí, Berger and Rivera 2009), we were confronted with a paradox: only 2301 out of the 3594 agents own water rights, and several of these own far less water than required to crop their land. For January of a representative and a dry year, the average water endowment was computed per hectare and farmers are counted for each farm size stratum (Table 5.1). Assuming a typical crop irrigation requirement for one hectare of 0.5 - 1 liters/second, only about 29% of all farmers have an adequate endowment of water rights in a normal year (23% in a moderately dry year). How do those without adequate water rights operate their farms? Observing this phenomena, Donoso (2006) mentions spillover or ‘surplus’ water that is abandoned by their owners after having been abstracted from the original water system.

The extended MP-MAS/EDIC model is used to simulate the non-attributed water and its use by farmers quantitatively (see Section 6.3.2).

The impact of sector-level projects on farmers’ access to water and structural uncertainty

The CNR Use Case ‘Investment into canal conductive efficiency’ estimates how meso-level irrigation infrastructure improvements trickle through to a heterogeneous population of farmers and ultimately impact their access to water.

The model use case builds on the farm- and field-level use case ‘Impacts of CNR policies on farm-level investments into irrigation methods’ (Troost 2009), a farm-level economic cost-benefit analysis of a policy program that supports farmers to acquire improved on-farm irrigation equipment. The aggregate impact of such farm-level technological change also revealed meso-level impacts, e.g. a changed quantity of surplus water or return flows.

This use case ‘Impact of CNR support to canal infrastructure improvements’ investigates changes in meso-level canal infrastructure, and assesses its impacts on individual farmers. Mandated by their individual members, water user organizations can present projects to CNR and apply for support to improve the infrastructure of the water conduction system. Such works include the maintenance, repair and extension of canals, aqueducts, distribution devices and inlets, water gages etc. As with on-farm projects and depending on the wealth structure of the members of
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

Figure 7.14 — Approximation of canal efficiency after infrastructure investments, in percent (Source: Diego Varras, Hamil Uribe)

The organization, a graded system for reimbursement through subsidies was established. In practice, many sector-level infrastructure projects receive considerable support, because many small producers benefit. All projects that were commissioned after 2001 received subsidies (‘bonificación’) of between 65% and 75%; earlier projects received between 25% and 35% (CNR data12).

The intermediate processes ‘effective canal conductive efficiency’ combines both the impact of the water management institutions and of the physical infrastructure. From the farmer’s perspective, it is not possible to decide if the (in)efficiency of distribution from rivers through sectors to the farm is actually caused by the physical infrastructure alone, or by the ability of the water user organization to manage this physical infrastructure. Several local experts pointed out that irrigation infrastructure is only partially responsible for improved access and that ultimately this access requires both functioning canals and functioning institutions. Thus, WUA members are more optimistic about investing into infrastructure, if they believe that their WUA is capable of handing down the benefits from these improvements.

Data on canal conductive efficiency. To assess ‘effective’ canal conductive efficiency, a consultant was contracted (Diego Varras, internal project report). At canal level, he interviewed farmers what proportion of their water rights equivalents were actually delivered to the farm. This percentage measures losses when sector-level water delivery is passed on to farms. Such status quo analysis can only measure the impact of all projects combined, and no ‘without-

12 see also Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’
scenario’ can be assessed. Furthermore, the impact of small but necessary maintenance works (e.g. repairing a defect gage or simply exchanging a fuse) are difficult to value against more costly improvements (e.g. the re-lining of the canal with concrete). Data on effective efficiency (the percentage of water rights actually served) is shown in Fig. 7.14.

Data about the interplay of meso-level institutions and infrastructure is shallow – partially it is most difficult to quantify this meso scale and partly because it was not possible to differentiate between institutional and physical efficiency empirically.

7.5.2 Experimental Design

CNR is interested how canal improvements actually improve the economic situation of farmers, as a proxy if public funds are effectively used with the current legislative rule. However, CNR data on canal infrastructure projects only provides information on the type and cost of projects, and also on those farmers that are affected by these improvements (see Technical Report ‘Background and description of cross-disciplinary data’, Section 1.6). Neither the impacts of the infrastructure on canal conductive efficiency is known, nor how these improvements actually translated into changes in access to water for farmers. Also, simple maintenance and repair jobs and long-term improvement projects are mixed, but effects are difficult to compare. For these reasons, it is not possible to relate investment costs with benefits to farmers directly. Instead, the problem is divided into two sub-problems: a) the impact of capital investments on the physical canal conductive efficiency, and b) the impact of canal conductive efficiency on the outcomes for farmers. Only the second part of this problem is analyzed further; sub-problem a) requires further empirical research. For this model experiment, we assume an improvement of 10%.

MP-MAS/EDIC is used to describe how water that is delivered to sector-level organizations from the watershed level ultimately benefits end users. To do so, sector-level processes were implemented and parameters were varied over a large but feasible range. We demonstrates how MP-MAS is used to elucidate structural uncertainty at sector level and the scope of impacts on farmers. In the face of data scarcity and structural uncertainty, core cause-effect patterns are identified, parameterized and their impacts on different segments of the farming population assessed.

The redistribution model deals with delivery of legalized water rights from the sector to farms, and also with non-attributed water. From a large range of parameter variations, five parameter scenarios were identified as sufficient representation of this structural uncertainty.

Reference scenarios under structural uncertainty

A ‘without policy’ reference scenario is constructed. Here, canal conductive efficiency is assumed to be 10% less than assessed by Diego Varras, as theoretical baseline or reference scenario. The reference scenario uses the MP-MAS model that was calibrated to depict farmer behavior and farm economics (Troost 2009).

Instead of a single reference scenario, a set of different parameterizations of the canal model are used to describe a range of system responses from canal losses on farmers. The following experimental design was chosen to capture those processes relevant to describe the impacts of canal conductive efficiency:
### Abbreviation Mode Description Parameters

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Mode</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆</td>
<td>X</td>
<td>Half institutionalized/on-farm reuse, half redistributed to smaller farms proportionally, some return flows (15%).</td>
<td>$\beta_c = 0.15, \lambda_c = 1.0$</td>
</tr>
<tr>
<td>C₇</td>
<td>X</td>
<td>Half institutionalized/on-farm reuse, half redistributed to smaller farms over-proportionally, some return flows (15%).</td>
<td>$\beta_c = 0.15, \lambda_c = 2.0$</td>
</tr>
<tr>
<td>C₈</td>
<td>X</td>
<td>Half institutionalized/on-farm reuse, half redistributed to smaller farms over-proportionally, medium return flows (40%).</td>
<td>$\beta_c = 0.4, \lambda_c = 2.0$</td>
</tr>
<tr>
<td>C₉</td>
<td>A</td>
<td>Institutionalized reuse, mostly within sector. Canal flows lost totally.</td>
<td>$\beta_c = 0.0$</td>
</tr>
<tr>
<td>C₁₀</td>
<td>A</td>
<td>Institutionalized reuse with losses and return flows (the original MP-MAS model)</td>
<td>$\beta_c = 0.5$</td>
</tr>
</tbody>
</table>

**Table 7.5 — Canal models**

- Price changes are not the focus of analysis. When assessing the impact of canal conductive efficiency, only slow price trends (4-year running mean) are considered and adaptive expectations are used ($\lambda_{prod,P} \equiv \lambda_{invest,P} \equiv 0.5$).

- Investment is required in order to compare the impact from planning modes. As investment mode, the expert-based reference scenario is used. Also, typical shares of capital/equity (25%) and typical credit rates (7.53%) are used (Policy scenario S1, see Troost 2009).

- Regarding water delivery, the measured hydrological data was used as non-constant (‘dynamic’) boundary conditions. Farmers have access to a portion of non-attributed water as available, and this ratio is modeled at three levels: 30%, 60% and 90%.

- The default planning model for investment and production planning was used, an adaptive expectation model with an adaptivity parameter $\lambda_{prod,W} = \lambda_{invest,W} = 0.5$.

- From a large quantity of canal scenarios tested, five were used for close analysis, $C₆ \ldots C₁₀$ (see description in Table 7.5). These scenarios use the modes elaborated in Section 5.4.2.

For the reference scenario, all five canal scenarios were run, Combined with the three ratios of non-attributed water use, the number of parameter combinations that represent the reference scenario under structural uncertainty is $3 \times 5 = 15$ model runs.

**The policy scenario and scenario evaluation**

All reference scenarios were re-evaluated under improved canal conductive efficiency, as stated in the following table:

<table>
<thead>
<tr>
<th>Sector</th>
<th>Canal efficiency</th>
<th>Without investment</th>
<th>With investment</th>
<th>Sector</th>
<th>Canal efficiency</th>
<th>Without investment</th>
<th>With investment</th>
</tr>
</thead>
</table>
All scenarios were run for both policy scenarios, and outcomes were compared between corresponding scenarios. Model outputs were evaluated at agent, stratum and sector level and for the complete study area. However, over the run of the model, around a quarter of the farm agents stopped farming, while no new agents were allowed to migrate into the area. Thus, model data was systematically biased towards more successful farm agents, and incomes and all other indicators gradually improved through this selection process. To cancel out this effect, only those agents were evaluated that farmed over the full study period (1996-2006), and in all scenarios. Mathematically, the set of agents was created by intersecting the vectors of surviving agentIDs for all scenarios, giving 2585 of an initial number of 3394 agents. Then, all other data (landuse, incomes, etc) was filtered for this set of remaining agents.

The evaluation of these remaining agents systematically biases the model outcome towards those farms that endure. The advantage of such filter is that interpretation of evolving variables is unbiased.

Evaluation was first done for the original farm size strata. Then, agents with and others without water rights were evaluated at farm size stratum level, at sector level and for the full study area. As third grouping, agents were grouped according to the percentage of irrigation water demand that they could satisfy through river deliveries (entitlements through water rights), because many of those agents that own water rights own less than sufficient with respect to their land and remain water constrained.

Data was imported into high-dimensional arrays, with dimensions policy scenario, water scenario, canal scenario, variable, year, sector, stratum. For selected variables, descriptive statistics (mean, median, standard deviation, sum) as well as the distributional indicator (Income Gini coefficient) were computed.

Summary of scenarios and evaluation

Policy scenario: 10 % increase of canal conduction efficiency.

Reference scenario(s): Price trends, expert-based investments, no INDAP credit program, and

- Actual data for river flows.
- Five canal models $C_6 - C_{10}$
- Three levels of non-attributed water use (30%, 60%, 90%)

Evaluation: of canal conductive efficiency

- By agent and sector
- By ownership of water rights (with/without/all)
- By access to water rights (% of water delivery through non-attributed water)

Dynamic coupling with the WaSiM-ETH model is not needed in this use case, because the dynamics of river flows and implications of these are not objectives of this model use case.

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13For the definition of farm population strata, see p. 133.
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7.5.3 Results

Perhaps the most important result is that farming becomes economically viable for most farm agents only when non-attributed water is taken into consideration. Then, only 322-356 quit farming over the study period (1996-2006), depending on which canal conduction scenario is used. Without considering this water and while using the best water right registry data, about 2100 agents immediately quit farming. While this result is not proof of the correctness of the non-attributed water model, it does hint toward its relevance.

Flow quantities for all agents

The rather typical and largest irrigation sector of the study region, 04-1, demonstrates model behavior (Figure 7.15). It is located centrally within the study region, has access to almost all water sources, represent all farm size strata and also spans a wide range of soil conditions.

The graphs in the left column of Figure 7.15 show the development of absolute flow quantities for a selection of three canal specifications (6, 8, 10). Two cropping seasons are represented: the season 1997/8 with sufficient water and the season 1998/9 after a very dry winter, with a minimum of snow accumulation and strongly reduced river flows. Each variable is shown for three variation of the percentage of non-attributed water use, with 30% (full lines), 60% (dashed lines) and 90% (dotted lines).

Different flow variables are shown over the time of two cropping seasons. Total plant irrigation demand (purple) starts in October, then rises and peaks in December. It falls through autumn (March) and becomes zero end of April.
Direct water delivery from rivers (blue line) and irrigation water taken from non-attributed water (including return flows, green line) and sum of these as total delivery (red line). Quantities are largest during winter, where water is of little use to farmers. Finally, the cyan-colored line shows the sum of expected total delivery, added over all farmers. If actual delivery falls below these expectations, than planning errors and unplanned irrigation deficit may occur. This is not the case during the season 97/8, but very relevant during the drought year 1998/9. In the following year 1999/2000, the water expectations of farmers are considerably lower than in the previous years. This simulates the adaptive behavior of farmers and reflects the learning model that is used for all scenarios.

The graphs in the right column of Figure 7.15 show relative values, around 100% (cyano lines, scaled between 0% and 150%). For the wet 1997/8 cropping season, the share of plant water demand that is satisfied is generally 100%, so water deficit does not impact on the economic performance of farmers at all. In the dry year 1998/9, the share of the plant water demand that farmers can satisfy is 100% in the early irrigation month October, but then drops to 38% in the core summer months December and January. At this aggregate level, the differences between scenario for non-attributed water use are relatively small, both regarding the canal model and the percentage of non-attributed water use.

The delivery from river water (blue line) and through non-attributed water (‘Wsurplus’, green line) is scaled to the total expected delivery. During wet years, the quantity of river water is sufficient to meet all water expectations. However under dry conditions, expectations can not even be met with a combination of non-attributed and river water – the economic relevance of non-attributed water thus increases during these dry conditions, even at this aggregated perspective. Also, the total quantity of non-attributed water is significantly reduced in drought conditions: the share of non-attributed water of the total delivery (red line), especially surplus water, significantly decreases during summer, and drops to zero during the decisive months of a drought year when all deliveries from rivers are used. Farmers without secure water rights, who mainly must rely on non-attributed water for irrigation, will thus not receive any water at all. The deliveries from rivers to those farmers with access to these irrigation sources remain, at a level that is lower than originally planned with.

**Flow quantities for agents without legalized water rights**

To investigate further the economic relevance of the type of access to water, Figure 7.5.3 shows the same variable, now aggregated for only those agents without legalized water rights, who fully rely on non-attributed water for irrigation. By definition, the irrigation water ‘from legalized sources’ is always zero (blue line in right graphs), and the share of the total water delivery from non-attributed water sources is always one (‘Wsurplus’, red line in graphs on left side).

The total expected delivery (cyan) is far more sensitive to the usage level of non-attributed water (30%, 60%, 90%, in full/dashed/dotted lines respectively). The model behavior for all three canal models remains fairly similar, but the quantities of non-attributed water and total water delivery deviate, as can be seen especially in some of the peaks.

In the wet year 1997/8, expected water quantities and actual delivery matched fairly well. As depicted in the right graphs, the share of water demand satisfied is exactly 100% for a 60% ratio of usage. The share of water demand satisfied is a little higher for the lower use ration of 30% (full line), and lower for 90% usage (dotted line). For the drought summer 1998/9, these shares change radically, with a pronounced minimum supply in December of only 10-15%, depending
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Figure 7.16 — Flows in largest sector 04-1, only agents without legalized water entitlements. Full lines represent a scenario with 30% use of non-attributed water; dashed and dotted lines 60% and 90% respectively.

on the use ratio. While differences between the canal models are reflected in slightly different temporal behavior, this aggregate analysis does not allow further conclusions.

Finally, for agents with access only to non-attributed water resources, the monthly supply also fluctuates much stronger over the year, and very little water is available during the core irrigation months (Dec-Feb) even under typical meteorological conditions.

The impact of water scarcity over time

To estimate the impact of water scarcity over the study period, the percentage of agents that cannot meet plant irrigation demands is computed for all years and selected sectors (Figure 7.17, top graph). Years during which water demand was usually met are years 1997/8, 1999/2000, 2000/1 and 2002/3. Severe water scarcity is experienced in 1998/9, 2003/4, 2004/5. Interestingly, the number of agents that face water deficit is larger in 2003/4 than in the much dryer year 1998/9: after the preceding wet years, water expectations had adapted to a high level so that even a moderate drought impacted on significant parts of the farmer population.

Over the study period, average incomes increase from 264 to 337 thousand pesos, and the standard deviation of incomes from increases from 198 to 419 thousand pesos respectively (Figure 7.17). During the drought year 1998/9, incomes decreased in average by 13% compared to the previous and the following year. If analyzed at sector level for this year, changes of average income range from -32% (Sector 05a) to an increase of 12% (Sector 05c). Here, access to
the Melado canal and its anticyclic supply is the most relevant factor\textsuperscript{14}. The season 2004/3, a moderately dry summer during which few agents can irrigate the full quantity planned, shows an average decrease of incomes of only -0.2\%. Those sectors that were hardest hit during 1998/9 now performed much better: Incomes in sector 05a increased by 9.6 percent in comparison to season 2002/3. Total income in sector 05c decreased by 11.2 percent.

\textsuperscript{14}Compare Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’
Figure 7.17 — Water deficit and income development. (a) Percentage of agents that meet plant irrigation demand, (b) Development of average income and (c) Standard deviation of income.
The Income Gini coefficient was computed as indicator for overall income disparity. Over the full period, the Gini increases from 0.39 to 0.44. This upwards trend is accentuated in drought years 1998/9 and 2003/4, with values of 0.51 and 0.46 respectively. This increase in income disparity is most notable for the two Longaví sectors 05a and 05b, while the adjacent sector 05c maintains a lower income disparity.

Figure 7.18 — The relevance of non-attributed water for all agents and over the full year. Three levels of non-attributed water usage are shown: 30%, 60% and 90% (blue, green, red). Furthermore, the share is averaged over 10 years (full line) and shown for a single dry year (1998/9, dashed line).

Non-attributed water

Non-attributed water use across the full population. Averaged over all farmers, the share that non-attributed water contributes to total irrigation water use was computed and compared for all canal models. It is defined as the water that, in average $\mu$, each agent receives from non-attributed water $Q_{ij,\text{non-attributed}}$ in relation to the total water that is available, including both river sources $N_{ij}$ and the pool of non-attributed water $Q_{ij,\text{non-attributed}}$:

$$r_{\text{non-attributed}} = \mu \left( \sum_{m=Dec,Jan,Feb} \frac{Q_{ij,\text{non-attributed}}^m}{Q_{ij,\text{non-attributed}}^m + N_{ij}^m} \right)_{i=1,...} = \mu \left( r_{\text{non-attributed},i} \right)_{i=1,...}$$

The share of non-attributed water varies from month to month. In winter months during which no irrigation occurs, all river water is also accessible as (non-attributed) surplus water and $r_{\text{non-attributed}}$ is 0.5, as shown in Figure 7.18. As expected, $r_{\text{non-attributed}}$ is lowest during the irrigation period, especially in Nov-Jan (full line). Also, $r_{\text{non-attributed}}$ drops even lower during dry years (dotted line), because those agents that usually have more water endowments than they use will leave less surplus water in the canals.

The canal models qualitatively behave very similar, but the level of non-attributed water creation varies, especially if comparing the two extremer scenarios $C_8$ and $C_9$. The former scenario allows moderate reuse of canal losses (30%) and re-distribution of water especially to small farms, with the latter scenario $C_9$ that all canal inefficiencies are totally lost. During dry years,
the average share of reused water $r_{\text{non-attributed}}$ varies between 10% for canal scenario $C_9$ and 16% for scenario $C_8$. At aggregated scale, neither the impact of canal efficiency nor of dry years reveals strong heterogeneity, which was also the case in many other graphs and evaluations tested.

**Heterogeneity across years and sectors.** A multi-agent model allows to look at impact in aggregate and disaggregate manner. For a disaggregated analysis, scatter plots was created that allow for the comparison of all agents in all sectors. A similar index looks at the share of water that is served through legalized water entitlements, by computing the share served from rivers in a year $y$ for a single agent $i$ in a sector $j$:

$$r_{\text{rivers},i,y} = \sum_{m=\text{Dec},\text{Jan},\text{Feb}} \frac{N_{ij}^{m,y}}{QM_{ij}}$$

The x-axis of the first plot (Figure 7.19(a)) uses the yearly access to legalized water rights $r_{\text{rivers},i,y}$, as ratio of water use from rivers with respect to total irrigation water use during the irrigation months December to February, as index that captures the legal security of an agent’s access to water. On the right are those agents that can fully serve plant water demand from rivers ($r_{\text{rivers},i,y} = 1$). On the left are those agents which mostly rely on non-attributed water, with $r_{\text{rivers},i,y} = 0$. On the y-axis, it shows the share of plant irrigation demand that can actually be satisfied, an index that describes the impact of water scarcity on yield losses caused by water deficit (which has economic implications). Using colors, the outcomes are separated for different hydrological years (see color bar in Fig. 7.19(b)). With markers, agents that belong to four indicative sectors (05a, 05b, 04l, 04j and 04j) can be distinguished. Marker size indicates the quantity of total water demand on a logarithmic scale.

All agents that can fully satisfy irrigation demands appear lumped together at the top of the page. In many years, the access security index $r_{\text{rivers},i,y}$ is relevant for the overall yield, because water demands cannot be completely satisfied – in seasons 1996/7 (dark blue), 1998/9 (light blue), 2001/2 (yellow), and 2003/4 (light red), 2004/5 (brown). Usually, the agents that belong to a single sector fall on a pronounced line, suggesting a proportional relation between access security and drought-induced yield deficit. However, some agents scatter around these lines, suggesting another influence on yield deficits, which could not be attributed to specific conditions. As expected, the year with the lowest share of plant irrigation demand satisfied is the drought year 1998/9, especially for sectors 04l (circle) and sector 05a (plus). An interesting curiosity is the reversed relation in year 1996/7 for sectors 04f and 04l. This specific relation could be a calibration artefact, because both sectors strongly depend on the anti-cyclic inflow of the Melado canal. During wet years, the water influx from this canal is significantly reduced and used for hydropower generation, and agents in both sectors own a larger proportion of water rights to this canal.

In downstream sector 04f (‘×’), significant shares of irrigation water demand are covered through return flows from upstream sectors, as parameterized in the routing model. This sector is significantly affected by water shortage – especially in years 2004/5 (brown), 2001/2 (yellow) and 1998/9 (cyan). It is noticeable that shortage is stronger in later years, which reflects improvements in irrigation efficiency upstream. Similarly, agents in Sector 04j (‘⊓’) are water deprived at a constant relation ($y=0.47$), because this small sector receives significant return flows from upstream sector 04l. In other years, this otherwise pronounced linear relation is less developed for Sector 04j.
(a) The relevance of irrigation sectors with respect to water demand covered from river and from non-attributed water. Colors encode for years (see color bar), markers for selected sectors 05a, 05b, 04l, 04f.


Figure 7.19 — *The relevance of irrigation sectors*
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

(a) Total water quantity available for irrigation

(b) Average income

Figure 7.20 — Impact by farm size stratum (‘cluster’), for reference sector 04l.

In a second scatter plot in Figure 7.19(b), the same relative water deficit, formerly used as y-axis, is used as x-axis. It now related with the economic performance of each agent. As indicator on the y-axis, an index was defined that specifies how well an agent performs, compared to the average income over all years

\[ i_y = \frac{I_y}{\mu (I_y)_{y=1995,\ldots,2004}} \]

For each year, the relative water deficit is now related with this economic performance index\(^{15}\). The relation between water deficit and relative economic performance in one year is far less pronounced, though it is clearly not random. All years that have sufficient water supplies now lump together on the far right. While all sectors are negatively impacted by the 1998/9 drought for water deficit and also for relative incomes, this relation is not clear for 2003/4. Here, even though a comparably low satisfaction level is reached, incomes remain above the 10-year average, especially for the large sector 04l. This observation decouples the incomes of farm agents from water delivery within the economic model. One explanation is the general increase of incomes over the study period. Another is that farmers increasingly specialize and derive their main income from few crops with high irrigation priority, such as fruit plantations. Occasional water deficit leads to losses on less economically relevant crops, which are only irrigated and harvested in good years and abandoned if water becomes scarce. Examples may be wheat, corn or pasture. With such strategy, income from high priority crops is maintained, and losses from low-priority crops are less relevant for overall farm income. Further model analysis is needed to elaborate why such low shares of water demand satisfied can actually increase incomes

Impact by population stratum

Descriptive statistics by farm size strata (‘cluster’) give further insight into the role of non-attributed water (Figure 7.20). On the x-axis, the relative abundance of water was computed by dividing the total irrigation water abstractions from rivers during January, the most relevant

\(^{15}\)For visual purposes, only a random sub sample of 20% of all agents were plotted.
7.5. THE MP-MAS/EDIC INTERFACE

irrigation month, with the flow of the year 2002, when most was water available. All years thus score between 0.0 and 1.0.

For each sector and stratum, average water delivery and income were computed for each cropping season. On the y-axis, Figure 7.20(a) shows the amount of water that is available for an average farmer of each farm size stratum, against the relative water abundance on the x-axis. As expected, those population groups representing larger farms also have access to more land also receive more water. Sub figure 7.20(b) shows average farm income per stratum. With only 10 model years, the number of data points are not sufficient for rigorous statistical testing.

However, the annual variation of incomes as function of water abundance shows decreasing incomes for all strata. Only for the large commercial farm stratum (cluster 3), incomes actually become negative. For strata with small land (clusters 0, 1), incomes change relatively less than for commercial farms (clusters 2, 3), mostly because agents that represent small farms partially rely on incomes from off-farm labor and can thus balance out the negative impacts of droughts.

Further analysis on how the economic model translates water scarcity into income is recommended. Question that should be addressed range from the role of specific high-return crops (perennials such as fruit plantations), and how non-farm sources of income (off-farm labor, returns from financial assets or from renting out machinery or land) contribute to the total incomes. A model assumption becomes relevant: during dry years, agricultural labor markets may be affected negatively and off-farm incomes may be more restricted than assumed in the model. On the other hand, much of the agricultural labor force works in high-priority products such as fruit and berry plantations and vegetable gardens, which are usually less affected by droughts than staple goods.

Impact of structural uncertainty of the canal model

After evaluating the general impact of non-attributed water – the availability and its use – in the previous sub section, the impact of two policy scenarios with variations of canal conductive efficiency is now evaluated (see p. 169). From the total pool of non-attributed water that is generated, only 30% are re-distributed to farm agents for irrigation in all scenarios regarded here. For simplicity, only three of the five canal model parameterizations are depicted.

The difference of these two different model scenarios are summarized in Figure 7.21. As part of post-processing, all 734 agents that quit farming during the model run in either one of the parameter scenarios were filtered out, to avoid a systematic drift of population statistics over time. For all those 2860 agents that remained, the difference of total water delivery between the scenario with 10% improved canal conductive efficiency and the scenario without improvements. Total water delivery includes both river and non-attributed water sources for irrigation, as delivered to farms.

Farmers were grouped along two dimensions: First, by farm size strata, then by the share of water from secure entitlements (rivers) divided by the total water used (actual water demand). Five categories were thus created: those who only have secure entitlements to 0-30% of their actual use (blue line), with 30-70% (green), with 70-100% (red), 100-200% (cyan) and more (magenta). The number of agents per group are as follows. The last row shows the number of farm agents at the beginning of the MP-MAS model:

---

16 In each scenario, between 329 and 358 agents stopped farming.
17 Input data Version Chile270, October 25, 2008.
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

<table>
<thead>
<tr>
<th>Category: Access from river average in</th>
<th>Farm size stratum</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30%</td>
<td>185 884 41 5</td>
<td>1115</td>
</tr>
<tr>
<td>30-70%</td>
<td>6 161 24 5</td>
<td>196</td>
</tr>
<tr>
<td>70-100%</td>
<td>34 913 146 15</td>
<td>1108</td>
</tr>
<tr>
<td>100-200%</td>
<td>38 295 40 7</td>
<td>380</td>
</tr>
<tr>
<td>&gt;200%</td>
<td>17 42 2 0</td>
<td>61</td>
</tr>
<tr>
<td><strong>Total (start of study period)</strong></td>
<td>281 2564 593 156</td>
<td>3594</td>
</tr>
<tr>
<td><strong>Total (end of study period)</strong></td>
<td>280 2295 253 32</td>
<td>2860</td>
</tr>
<tr>
<td><strong>Farmers that quit agriculture</strong></td>
<td>1 269 340 24</td>
<td>734</td>
</tr>
</tbody>
</table>

To depict the vast number of agents in one comprehensive graph (Figure 7.21), a Gaussian distribution function $P_{\text{cat}}$ was fitted for each category and stratum. These distribution functions were then normalized so that the resulting $P_{\text{cat}}$ for each farm size stratum add to one$^{18}$:

\[
\sum_{\text{cat}=1,\ldots,5} \int_{-\infty}^{+\infty} P_{\text{cat}} \equiv 1.0
\]

Also note the different y-axis.

The relative change of total water availability is further shown for two years: the average of dry years 1998/9 and 2003/4 (solid lines) and for typical hydrological years (dotted line). As index for water supply from rivers and non-attributed water, the sums over those months where water supply constraints plant growth (Nov-Jan) are used.

The model shows that most farmers that belong to the commercial strata (and continued farming over the complete study period) own sufficient secure water rights to cover plant irrigation demand. The categories which supply at least 70% from secure water rights are further called ‘mostly supplied from rivers’.

With canal improvements, those farmers that are mostly supplied from rivers consistently receive more water in normal years and also in dry years. For canal models $C_6 - C_8$, it is the absolute delivery of water that increases for these farmers. For the MP-MAS/EDIC realization $C_{10}$ (the original Berger 2001 model), the absolute supply with water remains constant while plant irrigation water demand decreases, as a result of higher irrigation efficiency with reduced canal conductive losses. In both cases, a larger area can be irrigated, or irrigation security for the same area effectively improves – and farmers always benefit.

For those categories that mainly receive water from non-attributed water, especially the 0 – 30% category, the impacts from canal efficiency improvements are more complex. For some canal models, total availability of water increases, for other canal model realizations it decreases. Especially if most canal inefficiencies are lost from the system ($C_6, C_7, C_9$), then the reduction of these losses consistently increases both river delivery and – as a result – also the amount of non-attributed water.

$^{18}$To do so, each $P$ was weighted with the number of agents in each category and stratum, and divided by the total number in the stratum.
Figure 7.21 — Impact of canal efficiency improvements on water supply, by farm size stratum
For other canal models (e.g. $C_8$ with 50% reuse of canal losses and non-attributed water), the outcome reverses direction for most small farmers from stratum 0 and nearly half of those belonging to stratum 1. Especially during dry years, when access to water is highly important to maintain high-value crops, canal improvements induce that the amount of non-attributed water decreases drastically and the average amount that farmers of stratum 0 receive by a significant 8%.

### 7.5.4 Discussion Of Results

The overall impact on water availability $\Delta W^i$ on an individual agent $i$ can thus be decomposed into three components: the increased delivery of river water $\Delta W^i_{\text{river}}$ because of improved conductive efficiency; the increased overall availability of non-attributed water because those agents that already received more than enough water leave even more surplus water $\Delta Q^i_{\text{surplus}}(\Delta \text{river})$ in the canals once these were improved, and third the decrease of non-attributed water because canal losses that originally produced non-attributed water are now properly delivered.

$$\Delta W^i = \Delta W^i_{\text{river}} + \Delta Q^i_{\text{surplus}}(\Delta \text{river}) - Q^i_{\text{non-attributed}}(\Delta \text{reuse from canal losses})$$

The impact on individual agents thus varies with how these three components relate to each other. For agents that have plenty of water rights and already produced non-attributed water (Group a), the benefits from canal efficiency are only relevant during very dry years when water is scarce. For agents that own sufficient water rights during ‘typical’ years but suffer from deficit even during moderate droughts, canal improvement give largest benefits (Group b). For agents that are constrained in production because of a deficit of water endowments, especially for those that over-proportionally benefit from non-attributed water (Group c), the impact of canal improvements is even more complicated: if canal improvements cause the overall amount of non-attributed water to increase, they benefit (canal models $C_6$, $C_7$). Otherwise they loose ($C_8$). The impact on this Group c even depends on location-specific, within-sector factors that may be hard to measure empirically.

Further analysis must clarify why so many of the commercial farm agents quit farming in one or the other scenario (465 out of 749 or 62.5% of all farmers that quit). This percentage is much higher than if only typical hydrological years are used (<20%, depending on canal model and non-attributed share). Eventually, the quality of the planning model (for example the dealing with fluctuating water supply) must be improved, before further interpretation is reasonable.

Many commercial farms belonging to strata 2 and 3 owned more land than they could supply with secure water rights, even though plenty of non-attributed water is available to them. Many of these agents are not taken into account within this analysis, because they went bankrupt over the model period. A comparison with Figure 7.20 shows that commercial farm agents – even those whose enterprises survived the model period – combine higher incomes in good years with negative incomes during drought years, while agents that represent small farms usually have low but mostly positive incomes, and the risk of bankruptcy is thus lower. The relevance of fluctuating non-attributed water supply for commercial farms that operate ‘at the economic margin’ should be analyzed in more detail.

In summary, the economic multi-agent model was extended with simple meso-level heuristics to demonstrate re-distributional impacts of policy measures to capture location-specific processes at this interaction scale. Canal efficiency improvements intuitively are beneficial to all farmers.
However, a mechanism is demonstrated why especially those most vulnerable to drought conditions can even be marginalized more by such measure if they previously made a living on these canal inefficiencies – even if most parts of the population benefits.

It is the heterogeneity of production assets that determines these outcomes, especially the area cropped against secure water endowments. Many small farmers have little access to secure water but benefit from non-attributed water, and canal efficiency improvements can exclude them from their access to water. Three effects must be regarded if looking at how canal efficiency improvements impact on farmers: direct benefits from higher delivery, behavior changes of those with even plenty supplies, and the fact that many have benefited from utilization of ‘inefficient losses’ that are now reduced.

For policy makers, the most relevant factor is that water supply for the economically most relevant group, the farm size strata 2 and 3, significantly improves. However, it may not be justifiable to finance these canal improvements with funds that are reserved for poverty alleviation: the canal restructuring might even marginalize this target group further. Thus, the use of general economic development funds is fully justifiable, while poverty alleviation funds should be used to mitigate negative impact on farmers that get by on water niches.

An economic cost-benefit analysis of canal impacts would require additional, detailed data how the canal infrastructure improvement projects actually change water availability for farmers. Such research is also required to determine the relevance of this poverty-related impact as was demonstrated through modelling. Core processes that determine this feedback are the distribution of water rights within the farming population, the current usage of this water especially from those with more water rights than actually used, the way that WUA operate and distribute water to those that have no water rights and those that have more than they actually use, and the state of the physical canal infrastructure.

7.5.5 Conclusion

Empirically, this section underlines that the Chilean model of privatized water rights is complex and must be assessed within its local context, in this case the Maule region. Informal arrangements may be as important as the legally prescribed water rights and management regime, especially for small, traditional farmers as the rural poor. Water access related to these informal arrangements may be an important reason why farmers support the improvement of canal infrastructure, which can benefit those with legalized water more than those without.

Methodologically, the integrated analysis elucidated an agent-to-agent feedback mechanism by extending assessment across a long chain of causes and effects. The interactions ‘between disciplines’ were especially relevant for poorer segments of the population that benefit over proportionally from a niche of informal arrangements. This only became apparent with a disaggregated analysis, combining a multi-agent model with detailed data on water endowments.
7.6 Calibrating MP-MAS To Dynamic Weather Conditions

7.6.1 The Calibration Strategy

The objective of MP-MAS calibration

To calibrate the interaction of transient hydrological conditions and a recursive farm economics model MP-MAS, the transfer of water from rivers to farmers must be understood. For individual farmers, weather variability results in the economic risk of loosing yields and thus income.

All existing MP-MAS model calibrations used constant meteorological conditions as boundary parameters (examples are Berger 2001, Schreinemachers and Berger 2006). For such conditions, a representative or typical year was estimated from time series, and calibration parameters were adjusted in a manner that land use data was reproduced. With more than one unknown or uncertain parameter used for calibration, such method is open of equifinality errors (see page 8).

For a single year, water availability of each farmer could be determined and parameterized based on tedious measurements. For a long-term and integrated analysis of the impact of irrigation water use, a more complex calibration index is needed, which captures the uncertainty of fluctuating irrigation water supply. Measurement data for individual farmers at catchment scale is not available.

Hence, to calibrate a model to varying hydrological conditions over multiple years, the water distribution model EDIC was used to simulate and calibrate the fluctuations of water supply to each irrigation sector and total reuse within these sectors, using sector-level irrigation security as calibration index.

Equifinality errors that occur when calibrating a model to effective boundary variables are normal for modelling (Beven 2001). They are also irrelevant as long as impacts on model results can be neglected. However, if a static model is extended to a transient model, then new processes become relevant; for example yield expectations are now dependent on long-term averages of crop yields rather than on the ‘maximum representative’ yield; expected yield losses are a complex aggregate that take into account gains in good years and losses in bad years. The learning model must be re-evaluated under such dynamically fluctuating conditions. Finally, new natural processes be relevant that were not noticed during a static assessment and farmers might engage in behavioral strategies when dealing with these fluctuations.

This section documents some of the challenges encountered when extending the static multi-agent model to dynamically fluctuating meteorological boundary conditions. It also demonstrates how some of them were dealt with or can be dealt with in future.

Summary of relevant processes

Before elaborating the calibration strategy, a brief summary is given of those processes that are most important for the calibration of MP-MAS under dynamic hydro-meteorological boundary conditions: the planning objective function, which controls the cropping decision of farmers and the crop yield response function to water deficit that depends on plant water deficit which again depends on the ratio of water that can be actually evaporated with respect to maximum or potential evapotranspiration.

The simplified planning objective function for the planning decision of an agent (see eq. 4.3)
7.6. **CALIBRATING MP-MAS TO DYNAMIC WEATHER CONDITIONS**

is

\[ \bar{I} = \hat{p} \cdot \bar{Y} - \text{costs} \]

Here, the expected income \( \bar{I} \) depends on expected marketing prices \( \hat{p} \), expected yields \( \bar{Y} \) and production costs. This function also determines land use and all inputs, because the vector of total yields is composed of the area cropped with each production activity, the inputs needed for each activity and the per-hectare yield of each activity – dependent on the availability of these inputs (see Section 4.3.2).

The plant water demand of each production activity is measured as potential evapotranspiration (see Section 4.3.4). Correcting for effective precipitation and for data on field-level irrigation efficiency, the resulting irrigation water demand and the crop yields were computed as follows:

The linear equation to estimate crop yield under water stress is (see eq. 4.15 on page 67)

\[
Y = \begin{cases} 
Y_{\text{max}} \cdot \bar{k}_r & \text{for } \bar{k}_r \geq 0.5 \\
0 & \text{for } \bar{k}_r < 0.5 
\end{cases}
\]

with the annual yearly linear reduction factor \( \bar{k}_r \) and a threshold of \( \bar{k}_r < 0.5 \) where a harvest is considered a complete loss (see Berger 2000). The linear reduction factor \( \bar{k}_r \) is:

\[ \bar{k}_r = 1 - K^a_y \cdot \left( 1 - \frac{\sum_m ET_{\text{real},m}}{\sum_m ET_{\text{pot},m}} \right) \]

(7.2)

with the annual crop-specific water stress sensitivity factor \( K^a_y \). Contributing factors to real evapotranspiration are potential evapotranspiration (the energy potential) and water availability (effective precipitation, irrigation IRR and irrigation efficiency \( \eta \)).

\[
ET_{\text{real},m} = P_{m}^{\text{eff}} + IRR_m/(1 + \eta)
\]

Within the project, soil-specific yield data was obtained from local experts that work as extension workers and have close relationship to farmers in the study area (Uribe, internal report). To parameterize the impact of different cropping technologies with the same plant species, the economic model uses field data to estimate the maximum yield that a crop can give with each combination of inputs (for detail, see Berger 2000 or Troost 2009). Thus, the same physiological plant uses different parameters for crop water demand and maximum yield, dependent on the production technology and the yields associated with it. Also, the water stress function differs for each activity, because the threshold value for total yield loss, \( \bar{k}_r = 0.5 \), is relative to the maximum yield (see Figure 7.22). Hence, if the same physiological plant is cropped with a different technology, then the maximum yield parameter and also the total loss threshold parameter shift.

**The challenge**

During early calibration steps with the EDIC model and real crop parameters, we assumed that the irrigation demand of all irrigated crops are fully met. At that stage, the model used only one agent per each sector and all resources were pooled, so that the distribution of water amongst farmers was irrelevant (see Section 7.4.2). However, the model produced a shortage of water if ‘full’ irrigation of plants was assumed, by a factor 1.2 to 2.5 (depending on the year and month). Even for a ‘representative’ year (medium monthly river flows), the total plant water demands,
under given irrigation efficiency, exceeded water supply by 1.5. At the same time, yields for
many cash crops, for example wheat or corn, are below the theoretical maximum yield.

The most probable explanation is that in the study region, only a portion of the plant water
demand was met and farmers irrigated less than needed for this maximum yield. This hypothesis
is also supported by empirical survey data, as shown later in this section on page 188). However,
there are several chains of reason that can explain this water deficit.

Following the history-friendly calibration approach, micro-level parameterization of cropping
activities was re-visited. Some theoretical arguments used to modify the model and its
input data so that the resulting total water demand at sector level is consistent with both theory
and empirical data on water delivery and land use.

Using the assumption that farmers are rational in their production decision, the yield gap was
explained within economic theory.

As mentioned earlier, the MP-MAS decision model was parameterized with ‘typical’ meteo-
rological and hydrological conditions that were estimated from time series data, for example by
using monthly median values for river flow and precipitation. Crop yields and plant water de-
mand was estimated using these ‘typical’ conditions and were thus ‘effective’ values that are not
purely based on observations, but rather adapted to the artificial yet ‘representative’ boundary
condition.

When extending the MP-MAS model from such constant hydro-meteorological boundary
conditions to dynamic ones, the ‘effective’ parameterization of irrigation-based cropping activi-
ties must be was revisited.

‘Rational’ deficit irrigation. If constant, ‘representative’ hydro-meteorological boundary con-
ditions are assumed, then the rational farmer should not have erroneous expectations on water
availability. Expectations used for planning and ‘real’ conditions should match ‘perfectly’, at
least if no other processes change water availability. However, even under perfect knowledge,
there are two general cases where agents choose to supply less water to crops than needed for
optimal yields – ‘anticipated deficit irrigation’.

The first type of deficit irrigation that is frequently discussed in the literature is deficit irriga-
7.6. **CALIBRATING MP-MAS TO DYNAMIC WEATHER CONDITIONS**

...tion because of a non-linear and convex crop water response function. Here, additional units of water have diminishing yield returns. If water is associated with constant costs, then an optimal irrigation level is where the marginal costs of water equals its marginal return in yield (Allen, Pereira, Raes and Smith 1998). This has also been shown empirically (Sarwar and Perry 2002). For a review, see Conradie and Hoag (2004). However, in the Chilean region, no indications were found for deficit irrigation related to the diminishing yield returns of water.

The second potentially relevant process is anticipated deficit irrigation because of non-water production constraints. Here, inputs other than water are not available or have opportunity costs that do not economically justify irrigation, such as the labor needed for irrigation with some inconvenient irrigation methods.

For example, a farmer has the option to use one of two irrigation methods for the same cash crop: A fully automated ‘pigote’ that requires significant investments in equipment, and a simpler water gun on a tripod, which is cheaper in acquisition but has to be moved manually every other day. Empirical studies show that average yields of those farmers that use tripods is effectively 18% lower than with the pigote (Uribe, internal report).

This yield deficit can be at least partially attributed to additional labor inputs needed for moving this tripod, even if the farmer has sufficient water available. Reasons are many: during peak season, the returns to labor might be higher in other activities. Expressed economically, during peak season the opportunity costs of labor may be too large to irrigate.

In this example, a rational farmer who uses labor-intensive irrigation methods would already anticipate this irrigation deficit caused by high economic costs of labor. He would take into account yield deficit as well as water requirements in planning and expectation building. For such an activity, he would not plan with maximum yield expectations and related inputs, but he implicitly plans with a lower labor- and water requirement. Furthermore, the rational farmer also makes use of this water ‘savings’ and attributes it to other cropping activities that have better returns to labor.

Such rational ‘anticipated deficit irrigation’ occurs under constant and under dynamic meteorological boundary conditions.

More technically and assuming identical soil, the difference between the watershed maximum yield $Y_{\text{max}}$ and the smaller actual yield can be decomposed into a yield deficit related to water supply $k^*_w$ and a deficit resulting from under-supply of other inputs $k^*_\text{input}$ (soil conditioning, agrochemicals, ...).

$$Y_{\text{real}} = Y_{\text{max}} \cdot k^*_w \cdot k^*_\text{input}$$

If $k^*_\text{input} < 1$, then the maximum effective yield (taking into account non-water related yield deficit) is $\hat{Y}_{\text{max}} = Y_{\text{max}} \cdot k^*_\text{input}$, even with full irrigation.

With fluctuating meteorological conditions, new processes emerge in the economic farm irrigation model that were not relevant when modelling a constant, ‘representative’ or ‘typical’ year. Risk considerations $r^{IS}$ of farmers because of fluctuating water supply and low irrigation security should also be internalized into yield expectations, under ‘representative’ conditions:

$$\hat{Y} = Y_{\text{real}} \cdot (1 - r^{IS}) = Y_{\text{max}} \cdot k^*_w \cdot k^*_\text{input} \cdot (1 - r^{IS})$$

Finally, the technical parameterization of the decision LP and the yield model (see Figure 7.22) is the source of logical inconsistency. The parameterization of the MP-MAS model, as
described for constant meteorological conditions, cannot be easily transferred into a dynamic model. If used with fluctuating boundary conditions and yields, then the model systematically creates errors which are asymmetric for dry and wet years. This error is described in sub section 7.6.3.

7.6.2 Model Calibration

The calibration takes occurs in two steps: First, constant ‘typical’ hydro-meteorological boundary conditions (precipitation and river flows) are assumed to constrain the MP-MAS model, and the model was extended to take into account the processes mentioned above. Data from an agronomic survey and its published analysis were combined with the above stated theoretical arguments, which are further elaborated in the next section. Using these, the observed yield gaps were reproduced with the CropWAT model while the total water supply and demand matched.

To calibrate the impact of water supply fluctuations correctly, losses of crop yields that are caused by plant water shortage (irrigation deficit) must be attributed correctly between water shortage and non-water related reasons (time constraint, energy cost, knowledge, etc).

This is first done for typical or representative conditions. In a second step, these typical conditions can be substituted with dynamic boundary conditions. However, due to limitations in data and to the technical parameterization, some tasks related to this second integration task were only conceptualized.

Parameterization of water related and non-water related irrigation deficit

Observed yields \(Y_{\text{real}}\) are usually far below the maximum basin yields on the same soil, so it is fair to assume that the yield gap \(y = \frac{Y_{\text{real}}}{Y_{\text{max}}}\) must be attributed to water and other inputs, such as irrigation investment, application of fertilizer, pesticides, machinery, labor. However, specific data is not available.

To analyze this problem, Cai et al. (2007) used data from a production survey in Region V and estimated the substitutability between inputs through a quadratic regression model\(^{19}\). They found that particularly for low-value crops, the yield-gap is multi-causal: a shortage of water for irrigation combined with a lack of other inputs. For high-value crops, yields are mainly constrained by water supply.

Economic theory of rationality postulates that inputs are applied until the marginal costs equal the marginal revenues. With diminishing yields to additional irrigation water, deficit irrigation is economically optimal, in line with common observation of local experts that observe that many farmers under-irrigate some of their crops.

Deficit irrigation because of diminishing returns was assumed and parameterized as a theoretical (unobservable) variable, which we define ‘maximum yield under deficit irrigation and unconstrained other inputs’:

\[
Y^* = k^*_T \cdot Y_{\text{max}} = \frac{\bar{Y}}{k^*_\text{input} \cdot (1 - r/\tilde{s})} = \frac{Y_{\text{real}}}{k^*_\text{input}}
\]

\(^{19}\)A generalized maximum entropy approach was used.
The share $n$ for the irrigation-related yield gap is defined\(^{20}\):

$$n \equiv \frac{Y_{\text{max}} - Y^*}{Y_{\text{max}} - Y_{\text{real}}} = \frac{1 - k^*_r}{1 - k^*_r k^*_{\text{input}}} \leq 1$$

According to Cai, for high-value, high-priority crops, water deficit fully explains the yield gap. For lower priority crops, about half of the observed yield gap that can be explained with deficit irrigation (either because water or labor is constraining). Other factors explain the remainder, which are not related to plant water deficit (pesticides, fertilizer).

For this chain of reasoning, we define the ratio $\lambda \equiv \frac{k^*_r}{k^*_{\text{input}} + k^*_r}$ between irrigation-related yield gap factors (water, energy, labor, hassle with neighbours), and other inputs that are not related to water.

The survey used by Cai classifies water, labor and energy as separate inputs for an irrigation-based cropping activity. Unfortunately, it does specifically separate irrigation-related labor from other labor, such as sowing, application of fertilizers and other agrochemicals, and harvest. According to local experts from INIA, irrigation itself is often not constrained by access to water, but by labor needs or energy costs.

Based on survey- and expert data for $Y_{\text{real}}$, and using the soil-specific, observed basin maximum yield for $Y_{\text{max}}$, Cai derived the following water deficit factors $k^*_r$ (slightly adapted to match our five irrigation priority groups):

<table>
<thead>
<tr>
<th>IPG</th>
<th>$Y_{\text{real}} / Y_{\text{max}}$</th>
<th>$1 - Y_{\text{real}} / Y_{\text{max}}$</th>
<th>Relevance of water as limiting constrain</th>
<th>Share of deficit explained with water shortage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95%</td>
<td>5%</td>
<td>100%</td>
<td>95%</td>
</tr>
<tr>
<td>2</td>
<td>80%</td>
<td>20%</td>
<td>80%</td>
<td>84%</td>
</tr>
<tr>
<td>3</td>
<td>60%</td>
<td>40%</td>
<td>60%</td>
<td>76%</td>
</tr>
<tr>
<td>4</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>75%</td>
</tr>
<tr>
<td>5</td>
<td>35%</td>
<td>65%</td>
<td>50%</td>
<td>68%</td>
</tr>
</tbody>
</table>

Cai’s estimates for the water deficit share $k^*_r$ during typical years were used to calibrate ‘planned irrigation deficit’ and to correct plant water demand parameters for rainfed and partially irrigated crops.

Other data such as evapotranspiration $ET_{\text{pot}}$ and irrigation efficiency $\eta$ were measured or generated elsewhere within the project and assumed as given. Using the land use data and the water balance for a typical year, the economically efficient level of deficit irrigation $IRR^*_{\text{m}} = \zeta \cdot IRR_{\text{max}}$ was numerically estimated by varying $\zeta$ during the driest month Jan-Mar, until $k^*_r \equiv k^*_r$. Yields were left as free variable and later compared with survey data from Uribe, as some means to validate the calibration exercise.

With an improved water balance and yield reductions that match field data, the resulting monthly irrigation deficits were used to further calibrate the model. Without being economically unreasonable, even the irrigation water deficits for high-value crops can be as large as $\zeta = 67\%$ during single months, while irrigation supply for staple crops with lower irrigation security and

\(^{20}\)For equal contributions of irrigation and all other inputs $k^*_c = k^*_{\text{input}}$, it simplifies to $n \equiv \frac{1}{1 + k^*_r}$. 
thus larger yield gaps (e.g. wheat and peas) drops to $\zeta = 40\%$, especially for sectors with higher precipitation.

Certainly, a rigorous empirical calibration of anticipated, rational deficit would require data far beyond what is available within this project, and it is not the focus of this thesis. However, for the analysis of the impact of irrigation water shortage, it is necessary to understand precisely why farmers apply less water than the plant needs for maximum yields. Rational deficit irrigation – either because of diminishing yield returns to water (as the most cited reason), or because of complex production factors such as marketing problems, long distances to the fields or labor shortage during some months (as elaborated here) – can explain many yield gaps otherwise mistaken as water shortage. From a modeller’s standpoint, these alternative explanations are degrees of freedom for the parameters effective crop water demands and effective yields, especially for those crops with larger yield gaps.

**Irrigation security during representative years**

The calibration of the MPs- MAS model started with macro-level water availability that reproduces sector-level irrigation water security adequately. Such parameterization resulted in a overall shortage of water supply, even if anticipated deficit was considered – as long as 100% irrigation security is implicitly (and falsely) assumed for the LP as water requirement data.

In reality, water supply fluctuates over the years. Even during ‘representative’ hydro-meteorological year, the production plan of a rational farm agent would take into account that water supply is not fully secure. As analyzed in Section 7.4.2, irrigation insecurity increases strongly for crops with lower irrigation priority (IPG). The planning with high insecurity is equivalent to a reduced ‘effective’ water demand plus consistent expectations of ‘effective’ yield. IPG-dependent irrigation security data was obtained from the Ancoa dam feasibility study (see Section 7.4):

<table>
<thead>
<tr>
<th>Category</th>
<th>IPG</th>
<th>Irrigation security (CNR), %</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruits and fresh exports</td>
<td>1</td>
<td>95</td>
<td>9712</td>
</tr>
<tr>
<td>Vegetables for local marketing</td>
<td>2</td>
<td>90</td>
<td>8769</td>
</tr>
<tr>
<td>Staple crops</td>
<td>3</td>
<td>60</td>
<td>8769</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>4</td>
<td>85</td>
<td>6152</td>
</tr>
<tr>
<td>Fodder crops and pastures</td>
<td>5</td>
<td>30</td>
<td>2089</td>
</tr>
</tbody>
</table>

High irrigation security for winter wheat is related to early harvest before the dry period starts, while IS if far lower for summer wheat, which is harvested in January.

To account for risk-aware planning, an IPG-dependent correction factor on expected irrigation water demand was introduced that was derived from priority in irrigation (IPG). An irrigation security at 60% (CNR criterion) for a low-priority crop means that, in 60% of all years, at least two cropping month receive less than 90% of the required water. For the ‘effective’ meteorological year, we found that a reduction by 80% of plant water demand (after correction for effective precipitation and anticipated deficit because of labor) closed the water gap of the macro-level balance, so this parameterization was found ‘behavioral’ (consistent with reality, see definition on page 9) and was maintained.
7.6. CALIBRATING MP-MAS TO DYNAMIC WEATHER CONDITIONS

Within the multitude of degrees of freedom and the lack of exact measurements, parameterization remains a balancing it between different assumptions. The ones presented here use the same theoretical assumptions that were already made in other model components and are consistently based on secondary data sources.

We acknowledge and point out the re-interpretation of crop yields, which were derived from survey data and adjusted to soil specific yields by experts. At this point, we interpret these as ‘effective’ crop yields for an ‘effective’ year, as \( \tilde{Y} \).

7.6.3 Technical Parameterization Problems When Calibrating Dynamic Conditions

A technical challenge arises when planning for crops that are either rainfed or irrigated in supplement to natural precipitation, in an MP-MAS model with fluctuating meteorological conditions.

To exemplify this point, assume that a crop is purely rainfed. From natural precipitation, the plant receives 60% of the water requirement for full yield \( Y_{\text{max}}^{\text{perfect}} \) and produces only 55% of the yield that it could achieve if not constrained by water supply. No other input constrains yield.

Within conventional parameterization of the MP-MAS production decision, both water requirement and maximum yield are adjusted to the above values and entered into the LP. A new cropping activity is defined called ‘rainfed corn’, with reduced maximum yield \( Y_{\text{max}}^{\text{inferior}} = 0.55Y_{\text{max}}^{\text{perfect}} \) and adjusted crop water requirements \( PW_{D_{\text{inferior}}} = 0.6PW_{D_{\text{perfect}}} \).

What would happen in a dry year, with only 60% of the typical rainfall? The plant would receive \( 0.6 \times 0.6 = 36\% \) of the (perfect) water demand. In this case, the crop model should really give 0% yield because of the yield threshold at 50% (eq. 4.15 and Figure 7.22). However, the maximum yield parameter \( Y_{\text{max}}^{\text{inferior}} \) was adjusted to define a new crop with inferior production technology. Thus, the model would assume that 60% of plant water demand were satisfied and give

\[
0.55 \cdot Y_{\text{max}}^{\text{inferior}} = 0.55 \cdot 0.55 \cdot Y_{\text{max}}^{\text{perfect}} = 0.3025 \cdot Y_{\text{max}}^{\text{perfect}}
\]

of the full yields. Instead of 0%, the farmer harvests 30.35% of the achievable maximum - a model inconsistency that seems somewhat acceptable, but an error nevertheless.

Let’s explore how the model would respond to a wet year, with 130% rainfall, for the same plant that is cropped with inferior technology: within the model, the additional water cannot increase yields, because the crop yield equation would already be saturated at the adjusted maximum yield \( Y_{\text{max}}^{\text{inferior}} \). To consistently depict a good year, the model should increase the yield \( Y_{\text{wet}} \) according to the additional water supply, and the yields should be above the modified parameter \( Y_{\text{max}}^{\text{inferior}} \):

\[
Y_{\text{max}}^{\text{inferior}} < Y_{\text{wet}} = 0.6 \cdot 1.3 \cdot Y_{\text{max}}^{\text{perfect}} \leq Y_{\text{max}}^{\text{perfect}}
\]

In short, the use of the maximum yield parameter to calibrate rainfed crops with ‘effective’ yield and water demand parameters causes two types of errors: In cases of under-supply with water, yields are over-estimated. In cases of additional supply with water, the parameterization forces a cap to the adjusted yield level, thus under-estimating yields. In total, the error creates an asymmetric response to fluctuating water supplies, which completely ignores yield increases in wet years and over-estimates yields during dry years.

This error was not corrected because it requires structural re-organization of input data, which is not within the scope of this project.
7.6.4 Outlook On ‘Dynamic’ Calibration

Stochastic treatment of expectations

The dynamic micro-calibration of irrigation requirements and yields depends on fluctuating precipitation and on fluctuating river flows. Yield will fluctuate around some ‘typical’ value \( \mu \), with some deviation \( \sigma \):

\[
Y_\text{real} \rightarrow \mu(Y_\text{real}) + \sigma(Y_\text{real})
\]

Using the same argumentation as for effective years, fluctuating precipitation influences the water deficit that the agent has planned with. In a year with good precipitation, the actual yields will exceed the expectations. Fluctuating river flows and irrigation water supply cause a deviation from risk-corrected, expected total irrigation water supply and also result in fluctuating yields and income. In short, expectations become a stochastic variable

\[
\tilde{Y} = Y^{\text{max}} \cdot \mu(k_r) \cdot k^*_{\text{input}} \cdot (1 - r^{IS})
\]

Actual yields are computed for a specific time \( t \):

\[
Y_t = Y^{\text{max}} \cdot k_{r,t} \cdot k^*_{\text{input}}
\]

So far, potential evapotranspiration is kept constant and the yield reduction factor \( k_{r,t} \) is only a function of water availability (effective precipitation and irrigation water supply). In theory, the hierarchically coupled WASIM-ETH/EDIC/MP-MAS setup would technically allow for dynamically expressing potential evapotranspiration – with variations in temperature, wind, cloudiness, air moisture etc. However, the calibration and analysis of such setup would first require a precise understanding of the above process.

Feedbacks from dynamic meteorological conditions on other assumptions

For non-typical meteorological years, other model assumptions must be tested and eventually re-visited and refined.

For example in a dry year, vegetable prices at local farmers markets rise drastically by a factor 1.5 to 3 (expert knowledge and personal observations). However, the total production of commercial vegetable remains fairly constant (ODEPA data\(^{21}\)), which is consistent with the high irrigation priority of vegetables. In summary, the production of these high-priority products seems to remain unaffected by the drought, but local prices react strongly. On the other hand, yields for staples are strongly affected (ibid.) but show little in the way of price signals, probably because these products are traded on global markets. These observations seem to contradict the basic economic law that supply and demand determine prices!

During drought conditions in a dynamic setting, new cause-effect mechanisms may become relevant and the conceptual model assumptions may need to be re-visited. For example, local market prices for vegetables are generally lower than calibration data (processed Santiago price data from ODEPA). Santiago prices average crop production over a large supply region and are even linked to global markets. However, many vegetable farmers sell directly to local markets within the study area – to avoid the middle man premium and transport cost or other barriers to

\(^{21}\)see also Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data’
enter larger food chains. On local markets, vegetable prices fluctuate anti-cyclically to drought incidents, remaining below the prices of supermarket chains. Thus, farmers who market locally benefit from the anti-cyclic prices for their premium, high-priority crops. These extra premiums may pay the losses made with crops that have low irrigation priority.

7.6.5 Discussion

As consequence of a model extension into hydro-meteorological conditions, further details and interactions at micro level may become relevant, and may require a revisiting of assumptions in other model components. For example, the small-market assumption (the independence of local prices from local production) should be tested empirically. Especially for vegetables, which small farmers mainly market locally, the meteorological conditions have a coherent impact on all local producers and producers react in a coherent manner, which may lead to emergent market phenomena. This effect exists, but its relevance for small farmers, compared with other processes, in not clear. During drought years, farmers may rely on further compensatory mechanisms to avoid risks.
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

7.7 The Fully Coupled Model

This chapter demonstrates first results from dynamic coupling between MP-MAS and WASIM-ETH. At a technical level, it is demonstrated that coupling behaves properly. Outputs are compared between a fully coupled WASIM-ETH/MP-MAS/EDIC model run and a MP-MAS/EDIC model run with river flows as external boundary conditions. Results are analyzed and discussed, and next steps are outlined.

7.7.1 Coupled And MP-MAS Standalone Flows

The coupling was technically outlined in Chapter 6.4. The WASIM-ETH model was parameterized within the hydrological project sub group (compare Section 7.3 and Uribe, Arnold, Arumí, Berger and Rivera 2009), and the MP-MAS model within the economic sub group (Section 7.2, from Schilling 2007b, Troost 2009).

This Section summarizes insights from model coupling by comparing MP-MAS/EDIC standalone runs (input dataset Chile 270, after Section 7.5) with the fully coupled runs (Chile270, from November 2008 and WASIM-ETH parameterization from March 2008).

Figure 7.23 shows a time series graph of the total water that is received by each irrigation sector. The top graph shows this total inflow into the irrigation canals for the fully coupled model with river abstractions computed within WASIM-ETH. The middle graph shows the same variable, for a model run that uses the MP-MAS/EDIC model setup – itself an integrated...
biophysical-socioeconomic model, but river flows are read from file and irrigation water abstractions are percentages of this river flows. The bottom graph shows four lines: the sum of total irrigation water received by all sectors without coupling (blue line) and with WASiM-ETH coupling (green line). Also, it distinguishes the origin of irrigation water flows within the coupled model: the portion of irrigation water that is abstracted from within the study region (‘internal’, cyan line) and irrigation water that originates from sources external to the study region, especially the Melado canal and Canla Maule Sur (magenta line).

Most obvious, the MP-MAS/EDIC model overestimates irrigation water delivery during winter season and during early spring. This over-estimation is consistent with the fact that MP-MAS interprets water rights as percentage of river flow, which is high during the winter months and especially the spring flood. In the WASiM-ETH model, abstractions are defined with three parameters: the minimum flow that is left in the river, the percentage that is taken if this flow is exceeded, and the maximum flow that can be abstracted (the canal capacity). Hence, abstractions during high river flows are limited in the WASiM-ETH model, and irrigation water deliveries are significantly lower.

From the empirical point of view, Chilean water rights are defined as fixed flow quantity. In periods of water scarcity, water user organizations convert these rights into percentages of available water and allocate the remaining according to these percentages.

The economic model MP-MAS, which was designed to analyze the allocation of scarce goods, always uses such percentage rule, because during wet years water is economically not scarce and thus irrelevant. For this reason, the over-estimation of the MP-MAS/EDIC model can be tolerated for economic analysis, even though such flows do not occur – the MP-MAS model is ‘effectively’ giving correct outputs in this respect. If interpreting water quantities as balances, e.g. to validate the coupling with a balance model such as WASiM-ETH, the behavioral economic model is not integration-consistent.

During the peak irrigation period of the very typical irrigation season 1998/9 (December until February), the correspondence of WASiM-ETH and MP-MAS total water deliveries to the irrigation sectors is very good (Here, canal losses and other within-sector processes are considered). During the dryer season 1996/7, WASiM-ETH estimates a total delivery to sectors that is 20.5 m$^3$/s higher than the MP-MAS/EDIC. This relatively large value corresponds to delivery from an external water source: the Melado canal brings water from an Andean reservoir from the watershed of the Melado river. Eventually, the MP-MAS/EDIC calibration over-estimates the magnitude of fluctuations of water availability.

Within the WASiM-ETH model, the two origin of irrigation water (external sources: magenta line, and internal river abstractions: cyan line) contribute a flow of irrigation water that has similar magnitude. During the driest season 1998/9 (not depicted), external water plays an even more prominent role than in the two seasons that are visualized. Especially water resources from the Melado canal are important, because these are regulated to level out shortages from other rivers.

Looking at model outputs at sector level, the differences between both models are considerable (Figure 7.24). For the relatively large upstream sectors 05a and 05e and during a wet year, the WASiM-ETH model estimates flows that are 25% higher ($\frac{q_{MP-MAS} - q_{WASiM-ETH}}{0.5(q_{WASiM-ETH} + q_{MP-MAS})}$). During the year 1996/7, December flows are generally larger in MP-MAS, and February flow in average 12.4%
The overall land use area of the MP-MAS model outputs exhibits a drift. The reduction of total cropped land, and especially the reduction of irrigated area can be attributed to two causes: some farm agents quit farming because farming is not viable (e.g. because of mis-investments), and farm agents endogenously adapt their cropping pattern (and crop mix) to changing environmental conditions, especially market prices and hydrological conditions.

With input data set Chile270, 62% of the land reduction must be attributed to agents that quit farming. Currently, if such agent quits farming then his land is taken out of production and also his water endowments is not used any more. No new agents can start farming.

For model results presented earlier, a data-intensive post processing routine was used to filter out all agents that quit farming during the study period. In this manner, the temporal development of average farm income, and the income distribution amongst the farming population, is cleaned from such drift that must occur if those farmers that perform worst are permanently filtered out.

### 7.7.2 Discussion

The current parameterization of the coupled model, water flows between different model setups correspond quiet well during normal years, especially during those months relevant for irrigation. As explained above, the overestimation of irrigation water within the MP-MAS model is an artefact that is not economically relevant.

To improve model correspondence at sector level, an improved understanding why downstream sector delivery deviates between both models is needed, with regards to the conceptual model and empirical data for calibration and validation. At sector level, not only the flow at major inlets (e.g. bocatomas) are needed to validate meso-level processes, but also an estimate of alternative water sources (return flows and spillover water).

The MP-MAS drift may or may not be a numerical artefact. Empirical analysis is needed to verify how much of the reduction of cropped area, which is indeed observed in the study region, is actually related to an adaptation of cropping patterns, or by a reduction of farmers. Also, it is not clear what happens to the land and water right if farmers stop working their fields.

Numerically, the drift can be filtered out for the purpose of economic analysis. If MP-MAS is coupled with a balance model in real time, then this drift should correspond to reality though, or water balances are unrealistically altered. This drift is the most important driver of the two main coupling variables, land use and irrigation water use. At this point in time, its empirical relevance remains unclear.

WAS1M-ETH-based analysis of return flows within the study region was ongoing when this thesis was submitted. Sub catchments were delineated based on available measurement data and based on the objective of hydrological analysis. As implication from this delineation, most farming activities occur in a single downstream sub catchment ‘1’ (see Figure 7.3.2). Return flows that are created here leave the study region and are thus externalities for the model. The explicit analysis of return flows would require a far larger number of sub catchments, empirical data on river flows that support this resolution, re-coding of the current routing model and a calibration based on the iterated modelling approach for the restriction of water abstractions from rivers (see
7.7. THE FULLY COUPLED MODEL

Section 7.3.2).

The routing of irrigation water through canals within the WASIM-ETH model is embedded in the WASIM-ETH routing model, which is a node-link network that is hard-coded within the WASIM-ETH control file template. Because of the way that the balance model is structured, WASIM-ETH computes irrigation abstractions from one river pour point into another sub catchment, using an aggregation of all water transfers that move from one sub catchment to another.

The MP-MAS model uses irrigation sectors, which are not congruent with sub catchments: sectors are defined by the beginning of major irrigation canals, which follow the topography at minimum slope. Canals often are nearly parallel to contour lines. The area starts upstream in a single point and widens towards downstream, in tree-like patterns. Rivers on the other hand follow the strongest topographic gradient and creeks accumulate in a single pour point, which defines the sub watershed. Sub watersheds also have a tree-like structure, but the trunk of this tree is downstream. Thus, regardless of model resolution, one sub catchment can always contain more than one sector, and each sector will necessarily drain into several directions (or sub catchments).

Currently, irrigation water transfers from WASIM-ETH to MP-MAS were parameterized at sub catchment level. For historical reasons, these must be translated back to the sector level, where water rights of the MP-MAS/EDIC model and water enters the model world. Water flows are abstracted from the WASIM-ETH model at the location of a ‘bocatoma’ and pumped to the sub catchment where they are used, as part of the WASIM-ETH routing model.

Two possibilities exist to distribute this water to farm agents: either, each of the many abstractions are reported to MP-MAS separately, and then agents receive water according to their water rights to these abstractions. Alternatively, water from all abstractions is first aggregated for each sub basin, and this aggregate is then distributed to all agents that live in this area. While the first option is far more accurate, it requires complex data transformations of MP-MAS water rights data (re-normalization), and a total of approximately 50 ‘inflows’ are exchanged between models: one for each combination of river as source and sector as target. For calibration purposes, the second option was implemented, which reduces the number of flows to only five. However, if parts of several sectors are located in the same sub watershed and these receive water from other rivers, then information about the exact source of water is lost. Instead, water is distributed to sectors using the area ratio between the sectors.

A second reason to refrain from the tedious first option is that internal irrigation water transfers are not very relevant during dry periods. Then, water delivery from sources outside of the study region (especially the Melado canal) dominate system behavior. Especially when water is economically most relevant, then water rights-based transfers within the model system have low relevance (Figure 7.23).

If sector-level data exists to validate these flows, and if the model system is increased so that the economically most relevant flows origin from within the study region, then the first model type should be used. Technically, this requires to set a switch in the coupling scheme, and manipulation of MP-MAS input data.

Finally, the study region was chosen so that those irrigation water sources that are most relevant, especially during the decisive irrigation months of drought years, originate from outside the study region. The processes of irrigation water creation are not captured within the model, but remain as an external forcing to the coupled model.
CHAPTER 7. MODEL CALIBRATION AND ANALYSIS

If the such processes as irrigation water creation and return flow remain external to the coupling scheme, the question may be posed which extra benefits this coupling gives for practical management questions. Both processes can be internalized with relative ease but require input data.

At this point in time, the minimum of interaction variables are exchanged between models: irrigation water flows and land use. The model already allows to exchange other variables, for example soil moisture, potential and real evapotranspiration or the ratio of both. At this point in time, the WASIM-ETH model was calibrated at 4km² resolution because of runtime restrictions, and a rescaling routine is used that collects MP-MAS land use activities into one larger WASIM-ETH grid cell. Hence, soil processes are not represented at the resolution and quality that the economic components of the MP-MAS requires. However, with such improved calibration it is straightforward to use the ratio of real and potential evapotranspiration to estimate yield losses. While such model setup is feasible, it is recommended only for use cases where MP-MAS resolution and WASIM-ETH resolution correspond at reasonable runtime.

Precipitation data can also be exchanged at sector or grid level. Because it is an external boundary condition to the WASIM-ETH model as well, little is gained if the data is passed through the WASIM-ETH software.

7.7.3 Next Steps

Conceptually, model coupling requires that all components describe the system at a complementary level of detail. It is most desirable if little or no manual data handling is required to change the model setup, moving from standalone modelling to full coupling. Optimally, a single data source should be used for any model analysis.

For disciplinary partners however, it is not always feasible to calibrate a component with the full data overhead of a coupled and fully integrated model. For example, for the publication in a disciplinary journal or even for a thesis, researchers must meet the communication standards of a specific discipline. With the complex setup of a coupled model, too many details and data descriptions are needed that conflict with good modeling practices for disciplinary analysis. To simplify the model parameterizations for each individual disciplinary partners, some data transformations are done ‘by hand’ which are labor intense and also a source of error.

We recommend technical works that make the full model more consistent and flexible:

- **Automation of water rights handling and routing.** It was discussed how water rights should be handled with option two at increased resolution (Section 7.7.2). This not only requires further disaggregation of agent-level water rights data (from sub catchment to river uptake point ‘bocatoma’), but also a complete redefinition of the WASIM-ETH routing node link model that is now hard-coded. The total number of water transfers within this WASIM routing model, currently around 40 (see p. 139), would increase to more than 100. This time, the routing model was computed manually in a spreadsheet program, but an automation tool is highly recommended, especially if the number of sub watersheds should be increased, or if water right transfers should be modeled.

- **The drift of the MP-MAS land use area.** As most important interaction variable, the drift of the MP-MAS land use area that can be attributed to agents that quit farming should be corrected. While the EDIC model proportionally rescales all processes and thus the drift
is averaged out, a balance model such as WASIM-ETH requires that all water is occupied and all land uses are defined. Either, land and water rights from agents that quit should be transferred to new agents that start farming, or it should be offered to existing farmers, or a combination of both.

- **WASIM-ETH return flows** are those flows that originate from inefficient irrigation methods and then return to rivers. At the moment, the relevance of return flows within the study region is minimal, because water transfers are already abstracted far upstream, before return flows become relevant (see Figure 7.3.2). Those subcatchments with major irrigation areas, especially 3, 23, 12 and 1, are not sources of relevant irrigation water abstractions. Thus, return flows are reflected in increased outflows from the study region rather than by increased reuse.

To add return flows from these downstream sub catchments into the irrigation scheme would require to add additional routing rules. Again, it is recommended to develop and use an automated tool.

- **Internalizing external water sources** would greatly improve the usefulness of a coupled system. To capture relevant hydrological processes, the creation of snow melt, the study region must be enlarged into the Andean region. Other external sources are the Melado river and the Maule river.

The WASIM-ETH model has vast capabilities for the modelling of snow and even for runoff estimation in forested areas. Also, the model can handle reservoir management (see Research Report ‘Integrating a reservoir structure into the IMS framework’, Arnold 2006).

- **Adding ground water components** is interesting methodologically, because ground water creation and abstraction causes spatial interactions within the study region and even at the scale of irrigation sectors. Ground water is also becoming practically more and more relevant, because ground water is clean and it is easy to get certification, and it is a save and independent supply for dry periods.

The MP-MAS model can be extended so that it incorporates ground water activities with relative ease. Also, WASIM-ETH is capable of combined surface- and ground water irrigation, even though minor model extensions would improve model handling (see p. 148). Thus, surface- and ground water interactions can be estimated within a WASIM-ETH model, while MP-MAS can generate groundwater use scenarios. Eventually, changes to the ground water level can feed back to MP-MAS and cause dynamic feedbacks, for example through changes in pumping costs that depend on depth. However, if dynamic feedbacks between ground water levels and pumping technologies are not occurring at a rapid temporal scale, then a loose coupling setup with iterative improvement of boundary conditions may be probably preferable to a dynamic, hierarchical data exchange.

A detailed outlook on this Model Use case is given in Section 8.4.1.
Figure 7.24 — Comparison for relevant irrigation month (Dec - Feb)
Chapter 8

Results Of Model Integration And Outlook

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The objective of this Ph.D. thesis was to develop, implement and test a method for the integration of two complex model software codes, as a contribution to and within the project. The purpose of this method is to support an international research project ‘Integrating Governance and Modelling’ in meeting its objectives, while the research objective of this thesis is to improve knowledge about integrated modeling, as defined in Section 2.2 and specified in Section 4.4. As such, the thesis objective is only indirectly an empirical one, and directly has two aims:

1. The provision of a service that aims at improved integrated modelling, within a stakeholder-driven modelling project that aims to deliver relevant policy recommendations; and

2. to develop epistemic insights on how to integrate models across system domains that belong to scientific realms as distant as socio-economics and physical hydrology.

The method of model integration proceeded from resolving many conceptual problems, especially the precise definition of interaction processes between model domains (Chapter 5), to technical integration, especially the implementation of data exchange (Section 6.4), improvement of interaction processes within the legacy models and their data handling (Sections 6.2, 6.1 and 6.3), then to step-by-step calibration across disciplinary domains of model setups with increasing complexity, starting with standalone model components (Sections 7.2, 7.3 and 7.4), over integration of two components (Sections 7.5 and 7.6) to full coupling (Section 7.7).

Integration also contributed to results from disciplinary standalone modules. The interest reader is referred to these studies directly. Also, Chapter 7 gives an outlook on two potential use cases: (1) the modelling of combined groundwater – surface water irrigation and (2) the modelling of climate change impacts.
8.1 Summary Of Empirical Results
From Conceptual Integration And Calibration With An
Integrated Modelling System

Components of the integrated modelling system were successfully applied as modelling tool to
derive empirically relevant insights for the Chilean study region. Empirical results range from the
modelling of inefficient surface irrigation at watershed scale with and extended WASIM-ETH
model (Uribe and Arnold 2009), the modelling of improvements of irrigation technological due
to public policy in MP-MAS/EDIC (Troost 2009), the impact of an additional irrigation water
source to mitigate weather-related fluctuations of river flows, using the EDIC model (Latynskiy
2009). Because these empirical questions are not the focus of this methodological thesis, and
because the documentation of each of these questions exceeds the scope of this thesis, please
refer to the referenced reports/publications for detail.

Calibration with an integrated model system that represents full cause-effect chains across
several disciplines have significantly improved the model. As example, the relevance of non-
attributed water only was noticed when empirical data was used to parameterize the water dis-
tribution model based on water rights (see Section 7.5, also Arnold, Uribe, Troost and Berger
2010). Similarly, the calibration of the EDIC model required an integrated data set that covered
several disciplines (see Section 7.4) and improved the calibration of the MP-MAS model.

8.2 The Creation Of An Integrated Modelling System

After the modelling software was implemented conceptually, the software system was set up
to allow for step-by-step calibration of several modules and interactions, with the objective to
produce relevant answers to policy questions (Arnold, Uribe and Berger 2008b). Here, it is a
characteristic of this project that calibration of modules is not performed by one single, omni-
scient researcher that pools knowledge about all system components and also has control over the
complete software source code. Instead, calibration was performed by a group of scientists that
all have disciplinary background and only have thorough understanding of parts of the fully inte-
grated system, they have partial knowledge about relevant processes and have partial knowledge
about related theories and equations that are embedded in several modules. Furthermore, each
calibrating researcher has partial knowledge on the empirical background and on the actual data
that enter the model as well as on the data processing and handling. The description of many
feedback loops, as outlined in Section 5.1.2, require the coordinated application of consistent
knowledge from more than one individual.

Model integration by an individual is challenging because of limitations in technical and the-
oretical knowledge about a system and the disciplines needed to describe it, and by resource
constraints – especially time. In contrast, the challenge of integration in a team is mainly related
to knowledge management across multiple individuals.

To address this challenge of calibrating a set of modules across disciplines and individual
knowledge barriers, a hierarchy of modelling setups was created. Using the same data, a number

1It is not possible to state an exact number because each module may be separated into further sub modules and
so forth – just as it is not possible to state how many disciplines there are, because disciplines permanently specialize
further.
of modular setups can be used with increasing system complexity and longer feedbacks, requiring input from more disciplines. Each component can be set up as standalone model, where interactions are treated as external boundary conditions. Then, the model was integrated with one further module, so that additional processes could be integrated through the collaboration of those researchers involved, and the model boundary was pushed further (see Figure 4.4). The model components that were created as part of the hierarchical modelling system are useful products by themselves. Examples are the WASIM-ETH irrigation module (Uribe and Arnold 2009), the standalone EDIC model (Section 7.4.2), the TOY model, several model extensions of the MP-MAS model (Sections 6.2 and 6.3), and new processes that were implemented within the MP-MASEDIC software: the extension toward dynamical hydro-meteorological boundary conditions (p. 100), the crop growth module with supplemental irrigation (p. 101), a learning module with increased flexibility (p. 102), and the problem of access to non-attributed water (Section 6.3 and published as article Arnold, Uribe, Troost and Berger 2010). As side products of coupling, these model improvements are available to future researchers.

Finally, integration proceeded to a fully integrated and coupled model system (Section 6.4). Here, one or a number of variables can be exchanged dynamically between the biophysical model WASIM-ETH and the socio-economic model MP-MAS with its technical components (p. 116, File-based management of data transfer). However, in addition to those challenges that were resolved, other challenges remain. In parts, their solution must be sought within the disciplinary model components, which are beyond the scope of model integration itself.

8.3 Iterative Calibration And Hierarchical Coupling

The fully coupled model system was only tested with a minimal set of interaction variables (river flows and precipitation at sector level, see p. 116). While the data exchange technically worked, at this point in time it is not legitimate to deduct empirical lessons from the model outputs for several reasons. These are technical, organizational, related to the availability of data and other resources:

- For some coupling variables, calibration objectives of disciplinary scientists correctly focused first on the disciplinary research objectives, as part of the step-by-step calibration process. More complex integration objectives are relevant only at later integration/coupling stages, and were correctly postponed to meet immediate project and research targets. However, further integration of these components into a fully coupled modelling system requires re-visiting some simplifications. For example, the WASIM-ETH soil module was implemented at a resolution of 4 km2 and calibrated to that scale, so that infiltration, evapotranspiration and percolation reproduce flows at watershed scale while also reasonably reproducing evapotranspiration (Section 7.3). However, if the WASIM-ETH soil module was to be used as part of the MP-MAS model, neither runtime of the WASIM-ETH model is sufficient, nor is data available to calibrate at the level of detail that is required, nor are other resources available. While the coupling of WASIM-ETH soil module to the plot-level crop growth module of MP-MAS is conceptually feasible and technically implemented, other barriers that are beyond the scope of technical model integration prevail.

- The analysis of the relevance of some core model assumptions is technically difficult for the fully coupled model system. For example, much of the model behavior of the fully
coupled model depends on the division of river watersheds into sub watersheds within WASIM-ETH model, which does not resolve interactions at sub watershed scale. An analysis of how the intermediate scale (irrigation sectors in EDIC, and sub watersheds in WASIM-ETH) impacts on the micro scale (farmers, plots) and the macro scale (farm population, general policy insights and downstream water availability) would require flexibility of spatial segmentation. Currently, such analysis is technically feasible but human resources are beyond reason, because it requires significant data processing that affects the WASIM-ETH control file, the spatial data of WASIM-ETH, the transactions data of the coupling, as well as the MP-MAS input data (especially water rights and routing).

- Further data is needed to parameterize interactions at sector level. The division of labor along the boundaries of scientific disciplines resulted in a lack of depth with regards to interaction variables at sector scale. How exactly do farmers who live along one specific irrigation canal struggle for access to water? The answer to this question is not reflected in the way that data was convened: what is the actual physical condition of that canal, how much non-attributed water is actually created, and how does the water user association deal with it? How do informal institutions deal with the specificities of a canal? What types of informal institutions exist across the study area, and is the type of arrangement linked to physical characteristics? Here, further empirical research is recommended, based on a holon approach (see definition in footnote 2.2 on p. 6, and Section 3.1.2).

- The understanding of many interaction processes that are specifically related to the dynamic quality must be improved, because these would not be relevant in a simplified, static world. Two examples are stated here, both related to fluctuating weather conditions:

  - How exactly do farmers adapt to variable weather conditions, especially if these changes are not changing in a quasi-linear trend (where adaptive learning models are successfully used), but conditions are volatile and even interwoven with decadal oscillation such as the El Nino (compare Figure 5.5, p. 90).

  - Another important process seem to be local markets, which (unlike in rich Northern countries) are inferior markets that operate below the official prices. These give market access to smaller or poorer producers, and also enable especially poor consumers to purchase goods far below supermarket prices. Local data on price fluctuations, on turnover and on the economic relevance of these marketing venues for farmer strata is not available. However, expert opinions and own observations show that weather-correlated price fluctuations may be a significant venue for farmers to mitigate weather-related losses: while a drought-related harvest loss hardly causes a price increase in larger supermarket and the global market, the prices on local markets significantly increase during drought years. For farmers, having access to local markets where prices correlate to weather conditions may significantly increase resilience to weather shocks.

Iterative calibration produced empirical results of very different kind. With increasing length of cause-effect chains and with increasing complexity of feedback loops, also the step-by-step calibration cascade became longer and more complex to organize: each recalibration required interactions between different project staff and thus caused transaction costs.
Along this cascade, barriers became more and more relevant and eventually limit the empirical robustness of model results. These barriers are of manifold kinds, ranging from access to conceptual knowledge, data availability and knowledge gaps along a cause-effect chain that covers multiple disciplines, and technical resources needed for implementation, and management of data sharing with multiple modellers.

With linear increase of the number of modules \( n \), the number of (potential) interactions increases with \( n! \), leading to over-exponential growth of the complexity to describe the system, which Bellman (1961) coined the ‘curse of dimensionality’. Even if 13 processes and approximately 50 interactions were identified in Figure 5.2, it is not meaningful to count the number of processes within the model – experts from one discipline would identify more than their colleagues from other disciplines. With each additional integration level, the number of processes increases and with it, the transaction costs of integration.

The improvement one model-to-model interaction process resulted in a cascade of further improvements that were required in other model components. While each of these improvements may be relatively simple and within the existing body of knowledge, these inconsistencies only become apparent at a late project stage, after other model components were calibrated with empirical data. If integration is performed in a large research consortium, then these inconsistencies may be located within several model components and managed by multiple researchers from different disciplines and institutions. With more researchers involved, transaction costs increase and significant resources are needed for planning, communication and error management. This cascade is an organizational challenge of orchestration and of timing. The complexity of systems is mirrored in organizational complexity to assess it and related transaction costs.

With constant resources and increasingly complex system analysis, the transaction costs of organizational complexity will doubtlessly exceed the available resources at one point. The question should be posed from a different angle: How much complexity can be captured at a given level of robustness of the empirical insights that were derived from model outputs and under given resources. Lindenschmidt (2001) calls this the utility of a model (see p. 9), as compromise between the level of detail that goes into the model and requires parameterization, and the certainty of model results.

As contribution to this challenge, some general insights that are systemic and thus have value beyond this single integration study are summarized in Chapter 9.

### 8.4 Outlook On Future Modelling Studies

#### 8.4.1 Combined Groundwater – Surface Water Irrigation

Within the last years, more and more farmers rely on ground water pumping for irrigation – partly as complementary and partly as sole source. Reasons are manifold and complex: access to surface water rights, the increased technical requirements from improved technologies, with regards (a) to continuous quantity of supply and (b) to water quality (particulate matter, and suspended solids), and legal restrictions on water quality (mostly biological, but also chemical contamination) are most prominent. Furthermore, ground water access makes farmers independent from water user organizations, and establishes de-facto use rights.

Legally, the Water Code of 1981 defines groundwater as a national good of public use (Water code). To apply for a right to groundwater use, interested party must correctly apply to DGA
and provide evidence that sufficient groundwater exists and is available. Furthermore, Resolution No. 186 from 1996 provides three instruments to DGA to protect aquifers as well as water rights: temporary reduction because to protect against overexploitation, restricted areas and prohibition zones where new exploitations are banned. As speedy mechanisms in emergency (damaged well, drought), DGA may grant provisional rights (Donoso 2003).

However, ownership rights to groundwater are far less established than surface water rights and free access situations occur, and the overexploitation of the exhaustible resource may lead to socially adverse outcomes (ibid, p. 47). In addition, Donoso notes that those shares of ground water that percolate from irrigation but return to rivers are legally treated as surface waters. Thus, aquifer and groundwater depletion directly results in externalities by interfering with granted and customary water rights.

From the hydrological point of view, the ongoing shift from inefficient, surface water-based irrigation methods to highly efficient, groundwater-based methods has a two-fold negative impact on the ground water balance: percolation rates drop, while abstraction rates rise. Impacts are manifold: investments into shallow ponds may become useless; rainfed agriculture may be affected negatively if the root zone is separated by the ground water table, which is often shallow (1.5 – 3 m). On the other hand, the interplay of surface water irrigators and groundwater irrigators can be regarded as reciprocally beneficial, because percolation becomes a positive externality for shallow pond miners, who retreat from the market for surface rights. Furthermore, groundwater contamination is a negative externality.

Donoso (2003) also points out a further interaction: many groundwater rights were granted for agricultural use as permanent rights, but actual use is risk management. Because of high energy costs, groundwater is only pumped during incidents of droughts, while farmers prefer to use cheaper surface (e.g. surplus) water otherwise. If such groundwater rights are then transferred to urban, industrial or mining use, extraction occurs continuously and at full rate. This transfer from risk-buffering extraction to continuous extraction might re-raise how many extraction rights can be granted without over exploiting the aquifer.

Several coping strategies were identified that help farmers to mitigate the impact of weather variability. However, most of these options have more than one benefit. For example, supplemental irrigation with groundwater is not only a safe irrigation water source in drought years; it also guarantees that water has consistently high quality, as required for advanced irrigation methods (drip, micro sprinkler). With improved consistency of production inputs and thus harvest quality, marketing can be diversified to supermarkets and export markets. Also, groundwater gives independence from surface water management organizations and personal politics. Thus, the financial viability of one coping mechanisms must also take a broader and integrated perspective.

Several scenarios can be analyzed with the integrated modelling system, using different levels of integration:

- Inefficient surface irrigation raises the groundwater above the natural level, while groundwater abstraction lowers it. Thus, what is the natural ground water level if no irrigation is applied, how much was ground water raised by irrigation, and how much area with efficient ground water techniques until ground water falls bellow the natural level?

- A comparison of district-level data on rainfed agriculture with ground water levels suggests good correlation, while precipitation and 1996 data on rainfed irrigation show very low...
spatial correspondence. It raises the question on how vadose zone processes that connect groundwater and the root zone influence crop growth, especially if ground water levels are very shallow.

• The rapid expansion of groundwater irrigation is a crosscutting theme for water management in the 7th and 8th region of Chile. However, no prognosis exists, and expectations vary drastically. Thus, groundwater use scenarios that are based on financial scenarios are groundwork for governmental planning.

8.4.2 Climate Change Impacts On Farmers

Climate change impacts can be thought of as several components: a change in mean characteristics such as sea level, temperature and CO2 content of the atmosphere; a change in weather variability and extreme conditions; and indirect impacts because societies function differently after the climate regime has shifted. Global change science has evolved beyond the assessment of mean characteristics toward the analysis of variability and its impact. However, to understand how farming societies may react to weather with changed variability, an essential starting point is to understand how farmers deal with current weather variability, and their capacity to manage those risks imposed by their biophysical environment.

Integrated, model-based assessment has been suggested as a way to understand cause-effect-chains and feedbacks faced by individual farmers (Rivington et al. 2007, Berger et al. 2007a). To link these chains and address knowledge gaps along the interfaces of ‘hard’ and ‘soft’ sciences (Ekasingh and Letcher 2008) with complex, process-oriented and dynamic models, the project ‘Integrating Governance and Modelling’ aimed to improve the usefulness of existing models for irrigation water management, looking at both individual incentives of water users and at the watershed scale.

The chain of causes and effects starts with water availability in the natural system, its supply to irrigation sectors and then to farmers (according to water endowments), to meeting plant water demand and crop harvest. The chain of events continues with incomes generated from this harvest and ends in savings and investments into farm production assets. Along this cause-effect chain, farmers have several options to minimize the negative impact of weather variability and cope with water shortage.

Coping mechanisms were identified with farmers and extension workers. These range from improving water supply and reducing irrigation demand, the (re-)allocation of water endowments and an improved marketing of produce. Coping options range from modification of on-farm practices and technologies, over water management at the level of irrigation sector or the watershed, and finally the marketing strategy.

On-farm practices to reduce water demand range from investing into technology that improves irrigation efficiency (automated sprinklers, drip or pigote, see Troost 2009); an adjustment of the crop mix, either with drought-resistant varieties, or by buffering crops with high security demands with crops that are less sensitive to temporary water shortage. Some farmers own water rights far beyond their requirements in normal years, when they leave surplus water for the use of others. Only in dry years, their water entitlements are fully utilized (Arnold, Uribe, Troost and Berger 2010). Finally, alternative sources of water can be utilized: in recent years, the supplemental irrigation with groundwater is increasing rapidly.

Increases of water supply occur either at watershed or at sector level. In our study region, the Melado canal supplies water from a neighboring watershed. Through these additional and
anti-cyclical inflows, water shortages are alleviated. Also at watershed level, a reservoir is being build that dams the Ancoa river, thus adds a new and safe supply (Latynskiy 2009). At sector level, farmers may strengthen their engagement in water management organizations and improve the physical canal infrastructure, its maintenance and the enforcement of endowments, partly by accessing financial support through the Chilean government. Such reduction of losses increases the value of every water right (Arnold, Uribe, Troost and Berger 2010).

The improvement of allocative water use efficiency is defined as the transfer from water rights from those holders that create low economic returns to others that can create higher returns. It was one of the objectives when water rights were made tradable commodities and water rights markets were established. Within the study region, little empirical evidence was found that such transfers occur at significant quantity.

Finally, farm income not only depends on the quantity and quality of harvest, but also on the prices that farmers obtain for it. Thus, the conditions of markets and access to these markets may greatly impact the risk with respect to weather variability. Statistical data from ODEPA indicates that the harvest of fruits and especially vegetables is seldom impacted during drought years, while the harvest of wheat and rice fluctuates significantly and in a correlated manner. However, the price impact of such fluctuating production quantities is heterogeneous across market segments: global prices are not impacted by the production of a small region in Chile. National prices, especially for the supply of large supermarket chain, can partly mitigate local production gaps by buying from (slightly more expensive) international markets. In Chile, prices on local markets are usually far below supermarket prices and fully depend on supply from local farmers. These prices strongly fluctuate with weather conditions, with a maximum that is set by supermarket prices.

Especially during dry years, the anti-cyclical price response of local markets makes direct marketing an effective risk reduction strategy. Many farmers have diversified marketing strategies and sell to more than one segment, partly because quality and certification requirements can be balanced out, and partly because the lower prices on local markets are still beneficial because intermediaries are cut out. However, little studies are done the relevance of these ‘inferior’ local markets. Also, data availability is poor, because direct marketing is difficult to trace on behalf of the government.

Calibration of individual models and for model-to-model interfaces was done with the best data available, and is successful for individual processes.

Empirical data on irrigation security was used to calibrate one core model interface, the simulation of water supply to sectors and to individual farmers, as long as this is based on legalized water supply. Groundwater use, as supplemental irrigation strategy, can be implemented within the existing system (see last section).

Conceptually, interfaces between all disciplines involved can be closed in a process-oriented and dynamic integrated model. Supply-side mechanisms were already implemented into the software and successfully tested. Complex coping strategies of farmers can be described within the modelling framework in a process-oriented, theory-based manner but require further data and more location-specific conceptual understanding. For some of these, we recommend small disciplinary studies to elucidate these; others require higher levels of integration.

To meet the project objectives of improving local policy making producing measurable outcomes for the most vulnerable groups of farmers, the creation of several successful model com-
ponents is not enough. Meaningful results must build on the simulation of the full cause-effect chain across all relevant disciplines. The cycles of integration, from conceptual and technical implementation, over calibration and validation, to scenario analysis, must thus be closed – not only for individual interfaces, but for the full feedback loops.

**Modelling outline:** At farm scale, the impact of climate change is linked to the change of weather statistics, and changes of the frequency of extreme weather conditions. For farming in the Maule region that relies strongly on irrigation, the frequency and impact of droughts is of core importance.

For a rigorous modelling study that describes the impact of climate change on farmers and their response, a hierarchy of Use Cases is recommended:

1. the modelling of a single drought year and farmers’ response
2. the modelling of two consecutive drought years and farmers’ responses
3. the modelling of three consecutive drought years and farmers’ responses
4. the modelling of several El Niño cycles and an analysis of farmer’s behavior in this re-occurring drought conditions
5. the modelling of changes of these cycles

Appearing trivial, this hierarchy of use cases requires the consideration of new interactions at each stage. Single dry years occur regularly. Even if farmers do not explicitly plan for these, coping mechanisms exist. During a second and third consecutive drought, these coping mechanisms consecutively fail. The third year of drought is known as a fatal threshold because farming resilience typically collapses.

The ENSO cycles (El Nino/La Nina) are somewhat cyclical with a frequency of seven years, and a duration of two to three years (compare Technical Report ‘Irrigation in Chile, Region VII: Background and description of cross-disciplinary data”). Are farmers expecting these cycles explicitly or implicitly, and are there specific response- and coping mechanisms to deal with these?

Ultimately, the integrated system conceptually and technically offers the tools to explore the full impact of climate change, giving insights to questions such as: How are the response- and coping mechanisms of farmers to drought impacted by climate change? Does climate change trigger other changes that also impact on these response- and coping mechanisms?
Chapter 9

Discussion And Lessons On Dynamic Coupling As A Method For Model Integration

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Empirical research results were partly discussed within the five model calibration and analysis
sections in Chapter 7. This chapter discusses the model integration process itself and responds
to the lack of guidance that was identified in Section 3.2.

The research setting – the architecture of the research project and the research institution –
can be seen as an external boundary condition that defines which integration methods are ade-
quate (or optimal) to respond to a given research objective. Another viewpoint is the question
which research setting is appropriate for a given integration method, for example ‘dynamic cou-
pling of models’. In this research project, lessons were derived from a defined research setting
and a somewhat open objective to couple two given modelling softwares dynamically. Hierarchi-
cal coupling was chosen as a method, and this discussion applies to hierarchical coupling within
that setting.
9.1 Towards Process Knowledge On Integrated Modelling

To manage the complexity of food and other production systems in a local context, agricultural research projects must adopt holistic or systems-oriented approaches (p. 59, IAASTD 2008a). Many researchers believe that integration across disciplines can indeed improve the relevance and validity of modeling in solving the most urgent agricultural and natural resource problems. However, examples of successful research projects that develop and apply integrated modelling techniques successfully and in a way that can be replicated by others are rare (Donatelli and Rizzoli 2008).

In Section 3.2.4, existing process knowledge and guidelines for such model integration was reviewed. It was shown that – considering the large number of projects on integrated modelling – surprisingly few lessons on the research process itself are documented. The interplay between the institutional setting, the model integration methods, and the technical, as well as human resource requirements, is rarely discussed in the literature.

The research documented in this Ph.D. project is part of a larger research project. The methodological knowledge that can be derived from such single cases is limited. Many lessons are specific to the particular context and have no scientific value beyond the single constellation of the research problem, the institutional research context, the individual characteristics of researchers and chance. However, some generic lessons may still be valuable to other researchers that are themselves charged with the task of planning an integrated modelling study.

The objective of the project ‘Integrating Modeling and Governance’, which was the context of this case study on model integration was the development of an integrated planning support system (see Problem Statement, p. 5). This system was envisioned as complex software to address multiple Model Use Cases, ranging from quantitative hydrological research questions to questions from the realm of agricultural economics. The project setting included a larger research team, with 28 contributing researchers from eight partner institutions covering various disciplines. The project context is typical for many international research projects with a focus in water management (see Section 4.2). Disciplines include governance, agricultural economics, physical hydrology and irrigation management. Principal investigators are accomplished in their fields and experienced in interdisciplinary projects.

Insights that address the specific model integration challenge of this case study were described in chapters four to eight of this thesis: the integration of the models MP-MAS, EDIC and WASIM-ETH. Some successes and some limitations of these models and potential future work were described in previous chapters. In some cases, the micro-level complexity of cause-effect chains was beyond what researchers originally expected.

In hindsight, some challenges could have been dealt with differently, in order to save time. Those challenges ranged from conceptual knowledge gaps of individual scientists at the point of linkage between disciplines, to technical knowledge of modelling software and related tools. These challenges were aggregated by the turnover of project staff. This staff turnover was also related to other problems, for example conceptual and technical errors were sometimes identified only after a researcher had left the project. Every set of data contains errors that may be within the acceptable range. Limited familiarity of the study region meant that the identification and eradication of data- and conceptual errors was a time-consuming process. All of these challenges are common to most research projects.

1http://www.igm.uni-hohenheim.de/cms/index.php?id=6
Nevertheless, generic insights and lessons can be derived from this model integration case study regarding the model-based integration process itself, which go beyond case study-specific challenges. These insights are summarized here, as a contribution to the procedural guidelines on model integration.

On order to derive process knowledge on integrated modelling, two aspects of this process are discussed in greater detail. First, technical work tasks are defined. Second, those challenges that are generic and will probably re-appear in most model-based integration studies are summarized. Finally, insights and recommendations on how to deal with these are suggested, as a step toward a checklist that can help to simplify technical model integration.

9.2 Tasks In The Integrated Modeling Processes

Within this study, the general modelling cycle was followed: definition of research question, definition of system boundaries, conceptual analysis of causes and effects, model selection, data collection, model calibration, validation and analysis, communication of results. Furthermore, existing approaches to integrated modeling were reviewed in Section 3.1.3. The following sections will discuss and generalizes the technical model integration process in more detail.

9.2.1 Conceptual Integration

In the language of ‘Integration on Demand’, conceptual integration includes posing a set of specific research questions that shall be addressed by the modelling system, selecting a subset of research question that should have priority within the research project, and developing a detailed analysis of the information, theories, concepts and knowledge data available. The result of such ‘functional design’ is a description of those system entities, processes and interactions that are relevant to answer the set of research question. This functional design includes a specification of scales and scale transitions, cause-effect chains and feedback loops (see Section 5.1), as well as the handling of time and space (Section 5.2).

Interaction processes that link entities with each other must be conceptualized. In this model integration study, these were classified into those defining the direct environment of farmers, specifically irrigation sectors and physical processes associated to these (Section 5.3), and the way that farm agents deal with this environment (Section 5.4). The conceptualization, measurement and modelling of irrigation efficiency and the quantification of related processes required a detailed specification of scales and scale transitions (Section 5.3.2). During calibration, it was difficult to obtain sufficient data at the proper scale, because available data from measurements was too ambiguous for an exact quantification of reuse and return flows.

Another process that was initially not described at sufficient detail was the occurrence and use of non-attributed water (Section 5.3.2). Here, a calibrated MP-MAS model existed that was behavioral for its initial purpose (Berger 2001). However, with an increased level of data available on water right endowments, it became apparent that the existing randomization routine was conceptually inconsistent with a higher degree of integration. Thus, the (equifinal) original model was modified (Sections 6.3.2, p. 105) and calibrated (Section 7.5, p. 165), to represent the cause-effect chain at adequate and homogeneous levels of detail.
CHAPTER 9. DISCUSSION AND LESSONS ON DYNAMIC COUPLING

Pitfall I: Inhomogeneous detail of system descriptions.

At early project stages, a simplistic understanding of the complex system may result in an ‘aggregation’ of several separate processes under a single term. This interaction process will remain of little relevance during early stages of the project. At later stages, when disciplinary models are developed and calibrated and ready to be linked, the inconsistent conceptualization of interactions becomes apparent. At this stage, many far-reaching project decisions have already been made, leading to sub-optimal but irreversible software decisions (path dependency).

Figure 9.1 exemplifies three levels of implementing a system description. In general, more detail will bring forth new processes within specific interactions, which were formerly not revealed because of aggregation. In the top part, the graph shows an aggregated and a disaggregated conceptualization of a system, each of which remains at one level of detail. The aggregate description can be seen as a conceptual understanding at the project planning and budgeting stage. The disaggregate description is assumed to be the true system description.

The bottom graph exemplifies ‘Inhomogeneous level of detail’. Here, two system components were conceptualized with a high level of detail, while the interaction process itself remains aggregated. The robustness of a model with the full feedback loop is limited to the quality and resolution of the aggregate interaction process, regardless of disciplinary attempts to increase precision at their end. Additional feedback loops within the interaction process are falsely disregarded and may lead to false conclusions.

Methods to improve conceptual understanding at early project stages exist, but are not yet mainstreamed within NRM modelling projects. Methods range from professional facilitation techniques to qualitative group modelling to create and discuss cause-effect graphs, to identify interactions and feedback loops. However, especially in international projects, interactions between disciplines are limited by travel, distance, language as well as cultural barriers. Additionally, facilitation techniques are not yet part of the curricula of interdisciplinary education for NRM and the experience of most project participants with such methods is limited.

Pitfall II: Ambiguous use of effective parameters.

Effective parameters are widely used in modelling, for example to adjust a variable or data to match the modelled process scale (see definition in Section 4.4.1, p. 68). The definition of an ‘effective’ variable depends entirely on the assessment objective. A good example is the use of ‘effective’ precipitation that was introduced in Section 7.1.2.

Each discipline is interested in a different aspect of the same process, and other aspects are disregarded. This simplification is useful for one discipline. However, during integration, the use of a regression formula to reduce a ‘real’ variable into an ‘effective’ variable may not be sufficiently detailed. For example, the use of effective plant water demand and effective crop yields during an effective meteorological year is sufficient (and adequate) to analyse farm behavior under constant meteorological conditions. When using dynamic boundary conditions (Section 6.2.2), the model must be extended so that processes driven by the fluctuation of ‘real’ variables are adequately represented, if relevant to the system behavior. In our model system, such extensions range from explicit modeling of supplemental irrigation (Section 6.2.2) and a more detailed representation of expectation building (see Section 5.4.1). Many other variables must be re-interpreted (Section 7.6) and new processes must be implemented (Section 7.6.4).

Cause-effect graphs are also called ‘meta models’ and ‘cause-link-diagrams’.

2
9.2. TASKS IN THE INTEGRATED MODELING PROCESSES

Figure 9.1 — Interactions and the level of conceptualization is determined by the level of detail and the number of disciplines involved to describe interactions. The learning from integration is determined by how well interactions are conceptualized, not by the level of detail within disciplines.

9.2.2 Technical Integration

The technical implementation of source code can be summarized into these tasks:

1. Describe the model coupling architecture (Section 4.4.2)

2. Fill missing conceptual links within all legacy model source codes (if necessary) and update legacy models for use within the hierarchical coupling scheme. This includes tasks such as

   - eradication of preexisting model errors within the legacy source codes,
   - re-factoring of the internal model time loop (if necessary) and
   - improving modularization of legacy model (if necessary).

   As a part of these tasks, the WASiM-ETH irrigation module was implemented (Section 6.1), several extensions of MP-MAS (Section 6.2) were implemented and the embedding of the EDIC within the MP-MAS source code was improved (Section 6.3).

3. Create a system with which to share input data that is used by more than one module. Data that is used in multiple formats and by multiple modellers is a re-occurring source of model inconsistencies. Thus, data that is used by more than one person, but may be updated and improved within the modeling process must be managed with care (see Section 6.4.2).

   One option is to read such data into generic data container classes and use hard-coded functions that copy this data into module-specific data storage. This way, every model can access a single data source and data inconsistency is prevented. Corrections for ‘effective’
interpretations of variables are then explicit transformations of these input data and must be hard coded, which enhances model transparency.

4. Program the hierarchical coupling scheme
   - Program of common data container classes used by all legacy models (Section 6.4.2)
   - Ensure consistent use of input data used by more than one module
   - Program of the hierarchical data exchange itself, especially
     - the data transfer between executables (e.g. using the TDT library, Section 6.4.2),
     - the sequencing in a separate executable (Section 6.4.3), and
     - the low-level analysis tools for localizing conceptual and data errors, e.g. exporting of intermediate data

5. Program tools to analyze outputs from the coupled model. In our case, the WASIM-ETH software was called by a ‘wrapper’, which re-starts the software each month. The WASIM-ETH software creates separate output files for each program call, and at least 12 separate sets of output files each year. Outputs that were scattered across multiple files were automatically processed into formats adequate for further analysis.

6. Implement intermediate processes that are not part of any legacy code, especially rescaling transformations (Section 6.4.4) and rescaling between different spatial resolutions (see Technical Appendix D.5).

9.2.3 Calibration And Analysis Within And Across Disciplines And Working Groups

External and internal boundary conditions and shared data

To ensure model consistency, the same process must be parameterized with the same data by all modules. What is trivial in theory requires careful sharing and updating of data across all project groups. In large models with many degrees of freedom, it is simple to compensate for such data error during calibration by finding an equifinal parameter set (Section 5.1.3).

Inconsistent use of shared data leads to model inconsistency that can be difficult to spot if it is implicitly embedded within model assumptions. An example was elaborated in Section 7.6.1: for a bioeconomic planning model that assumes constant meteorological conditions, crop yields must reflect these constant or typical conditions. Such parameterization may be inconsistent with physical-based crop growth models or decision making under dynamic meteorological conditions. Thus, extra care is needed with shared data.

Validation of behavioral modules: disciplinary vs. integrated calibration

parameterization and calibration of modules proceeds from calibration of disciplinary models within their knowledge domain, to extended disciplinary models that are integration-consistent but still function as standalone software, to integrated models within a coupled framework where interactions are dynamic (see Section 7.1).

In this iterative cascade of re-calibrations, the degrees of freedom of each module are successively restricted. First, the module is tested against validation objectives commonly used
within the discipline. Many processes at the disciplinary fringes use effective parameters that are calibrated. In the second step, calibration along disciplinary fringes is re-visited and the use of effective parameters is verified for consistency across all modules. Inconsistencies are identified and corrected. An example is the model extension from randomly assigned water rights (as effective parameterization) for restricted modelling objectives, to the explicit handling of non-attributed water. A second example is the parameterization of the water balance model WASIM-ETH, which also passed conventional validation tests (Leemhuis 2006) but had to be extended to represent interactions (Uribe, Arnold et al. 2009).

In both cases, the initial model passed validation tests within their disciplines. However, with the extended modelling objectives of integration, these validation tests were insufficient.

Linking Modules

After the linkage of two modules is confirmed as integration-consistent, these modules can then be linked dynamically. Interactions in a coupled model can be such that sub modules perform at the same temporal or spatial hierarchy level, or such that one model is fully embedded within one the other. Conceptually, the MP-MAS crop module is spatially embedded within each farm parcel, while the linkage of an EDIC sector and a WASIM-ETH sub basin are at the same hierarchy level, even if models have different resolutions.

Model resolutions define runtime as well as the detail of data required. Two models that operate at the same scale can use different temporal or spatial resolutions. In this case, data that is passed from MP-MAS to WASIM-ETH must be spatially aggregated from a 1 ha grid to a 400 ha grid, and temporally disaggregated from monthly to daily time steps (see Section 6.4.4 and Electronic Appendix D.5).

On one hand, the linking of two modules reduces the degrees of freedom because it rules out some equifinal parameterizations of modules as non-behavioral within the integrated model. On the other hand, it can also increase the degrees of freedom of the model if interaction processes require additional free parameters (and further calibration). The explicit consideration of individual water rights and non-attributed water is an example of the model was further constrained, but at the same time conceptually extended along an interaction process.

Linkage strategies If more than two modules are linked, then several options exist to organise the links. For three modules A, B and C, three basic strategies (and permutations) exist:

1. All models are linked at the same time and the result (A-B-C) is analyzed.
2. First A is linked to B, resulting in (A-B). This resulting model (A-B) is then linked to C, written as ((A-B)-C).
3. First A is linked to B, resulting in (A-B). In parallel, B is linked to C, resulting in (B-C). Then, all components are linked (A-(B)-C)

Each linkage may reveal model inconsistencies and require that the linkage be re-visited. Depending on model software, each strategy may have advantages and disadvantages. However, model complexity is lowest in Strategy 3, because no more than two components are studied at any single time. On one hand, this strategy minimizes technical difficulties associated with runtime and memory problems and requires the least knowledge transfers within large and multidisciplinary project team, because the coupled model never requires more than two experts. On
The other hand, this strategy requires the most stringent degree of software modularization and data sharing, which also increases transaction costs.

The calibration of the EDIC model used the third strategy. The EDIC model was implemented as a standalone module and calibrated. Due to quick runtime, millions of model years could be executed within an automated calibration routine (Section 7.4). A strongly simplified version of MP-MAS was generated with constant landuse for each sector. This simplified model was coupled to WASiM-ETH by using hierarchical coupling. Such a setup was used to test data transfers technically. The calibrated EDIC model was used also as the hydrological module for all Chilean MP-MAS applications. Finally, the full coupling uses the full parameterization of WASiM-ETH, EDIC and MP-MAS.

9.3 Challenges

Generic challenges on model integration for natural resource management can be categorized into three groups: 1.) Characteristics stemming from the complexity of a system, with cause-effect chains and feedbacks across several disciplines; 2.) the technical integrated modelling processes, and 3.) the embedding of the integrated modelling process into a stakeholder-driven policy assessment.

Literature that generically analyses how model-based research is embedded into a stakeholder-driven policy assessment already exists (Section 3.2.4). In our case, the timely creation of models as research tools and the timely production of research results with these tools was relevant. Local stakeholders have expectations with regards to the research questions that interest them, in a time frame that is often shorter than that of modellers. The simplicity of language and graphical tools needed for stakeholder processes adds an additional challenge for the modelling team.

While stakeholder communication was not a task within this model integration study, it was an objective of the research project. Within a project, the allocation of resources and technical decisions must address multiple objectives. The needs of technical model integration and of stakeholder contact can compete. In some instances, these decisions can lead to path dependencies that add additional transaction costs.

The focus of this thesis project is model integration within the context of a larger modelling project, and the interdisciplinary analysis of the model system. Thus, the third group of challenges is not discussed further. Instead, the focus is shifted to the technical aspects of model integration.

9.3.1 The Complexity Of An Interdisciplinary System

It is difficult to describe the human-environment interactions if such description must be carried out along long cause-effect chains and the knowledge of each of these sub-systems is managed by different disciplines (see also Section 3.1.1) Reductionist methods that focus on one sub system and restrict the analysis with ceteris paribus assumptions may fail to recognize these feedback loops. Integration specifically addresses such types of interaction and thus complements the shortcomings of reductionist approaches.

The epistemic challenges of integration are related to the qualitative and conceptual cause-effect model that is the starting point of a Use Case for quantitative modelling. In an optimal situation, the conceptual phase should identify all processes that are relevant to a research question, and only those. If the system is conceptualized too simplistically and relevant processes are
initially missed, then the integrated model remains inconsistent and needs conceptual improvements later. These improvements require the re-examination of model assumptions, access to the technical knowledge embedded within models, additional programming works and ultimately the re-calibration of those components affected by any modification. If processes are analyzed that are not relevant for the feedback, then resources were wasted. In both cases, the eradication of conceptual errors can be resource intensive and increase integration time and costs.

Farmers often have many reasons for and against each cropping activity. These reasons are attributed to different academic disciplines (e.g. economics, soil sciences, cultural studies and hydrology). Only a combined analysis of multiple reasons determines which activity the farmer should or will chose. The weighting of these reasons against each other is the heart of agricultural research. In such a context, conceptual learning is likely and any integrated modelling method must be flexible enough to accommodate new insights.

9.3.2 Organizing An Integrated Modeling Process

Model integration across disciplines

The nature of integration is to re-interpret parameters that were reduced to ‘boundary conditions’ of delimited sub systems, and to embed them into a larger system as ‘interaction variables’ between sub systems. This integration can be performed by individuals or by research teams, each method leading to different types of challenges.

From individuals to teams. Many integrated models were developed by far-sighted individuals who combine interest in more than one field of expertise with high academic skills in their ‘home’ discipline and technical knowledge regarding software development. These individuals were able to program complex models and to apply them to a case study. They are so successful that their software evolves to a higher model development stage (see definition in Section 3.1.3).

Both complex softwares used in this case study, MP-MAS and WaSiM-ETH, were developed by individuals during their Ph.D. WaSiM-ETH integrates surface and groundwater water balances with advanced representation of surface processes, especially evapotranspiration. MP-MAS maintained its theoretical foundation in economics and extended it towards heterogeneity across actors and some biophysical interactions. Both models include a range of additional modules that make them particularly apt for this integration case study. However, both models are less accurate at their disciplinary fringes, due to the limited resources of the individual developers.

To improve the representation of models at disciplinary fringes, larger research teams were formed to obtain access to specialist knowledge. Tasks were then executed by multiple individuals. On one hand, the total knowledge of such a team far exceeds the knowledge of any individual. On the other hand, no single individual has complete knowledge about all aspects of the model. Knowledge barriers are transaction costs that were not relevant when a single individual was involved.

Integration by one individual was limited primarily by knowledge and resources. If integration is performed by multiple persons with a broad range of knowledge, the limits are mostly related to the transaction costs of making use of the knowledge consistently. These two research settings differ fundamentally in methods, challenges and the strategies needed to address these.
The step-by-step procedure of calibration and validation was elaborated in Section 7.1 and discussed in Section 9.2.3. Starting with disciplinary modules that are validated, it proceeds to the validation of integration-consistency of standalone models, to model extensions (if needed), and then to the dynamic coupling of models and interaction analysis.

The peer review process of disciplinary modules was established to test research results against the best disciplinary knowledge. Especially in projects with development objectives, the reviewers do not necessarily have sufficient knowledge about the specific details of a local context. Then, the review process can only identify apparent methodological shortcomings within the discipline, but an insufficient description of reality is not tested for. Assumptions about the disciplinary fringes are not the focus of most peer reviews. Thus, peer review within the disciplinary academic community is not a sufficient quality assurance mechanism for integration and it is likely that models that are not integration-consistent will pass existing review mechanisms.

In the second step of calibration and validation, integration-consistency of each disciplinary module must be tested. This test must involve explicit and implicit assumptions as well as consistent use of shared data. This step requires detailed knowledge of the local context, the model and its assumptions, software methods to check consistent use of shared data, and good documentation of the calibration procedure that was initially applied.

The third step is the correction of inconsistencies, which implies computer programming, data manipulations, re-calibration and re-validation of modules. The technical knowledge of computer software and modelling techniques is needed, as are resources needed to apply them.

There is no guarantee that an inconsistency that was identified is the only relevant one in the process. The second and third steps must be repeated until the model validates for all intended modelling objectives.

The returns to research for performing each step in the calibration sequence for coupling strongly diverge. These returns are measured in units relevant to the performing researcher: a consultant contract defines a specific output at a specific price; while in the academic setting, research projects are parts of a career and usually contribute to academic titles (master or Ph.D. thesis) or journal publications relevant to their future plans.

Integrated modelling research was classified into (1) conceptual and (2) technical integration, (3.a) the calibration of models that is behavioral within their disciplines, (3.b) the re-calibration so that each module is 'integration-consistent', and (3.c) the analysis of interactions in a linked model (see Section 9.2). Especially steps 3.a and 3.b require disciplinary expert knowledge.

Results from step 3.a (behavioral calibration of disciplinary model) can only be published if they are innovative within their specific discipline. The academic realm will thus create a bias toward such innovative methods, even if established (and academically ‘boring’) methods would be more adequate for the purpose of integration. As such, step 3.a could be contracted to an external consultants outside of the academic realm. Then, access to relevant knowledge moves outside of the project and will not be available to the integration project at later stages. This also increases transaction costs during future learning cycles.

Results from step 3.b (integration-consistency) have unclear direct scientific returns. In our project, two scientific articles were published that focused on the embedding of disciplinary models into the integrated framework. Arnold, Uribe, Troost and Berger (2010) focused on a single interaction process that is empirically relevant. Uribe, Arnold, Arumí, Berger and Rivera (2009) describe a discrepancy of an existing model and a solution to deal with it. However, many other model extensions were highly resource intensive and had no immediate research return.
Only at step 3.c, with the linkage of many modules and empirical calibration, project outputs are again publishable.

In summary, integration relies on inputs from disciplines at a quality beyond those standards established in the respective disciplines. It is not trivial to build research incentives in a manner that scientists comply to these higher integration standards, especially because model quality standards within disciplines differ.

**Scale mismatches** only become apparent at later stages of the project, when model components are already calibrated with empirical data.

One example is the mismatch between EdIC irrigation sectors along canals and topography-defined WASIM-ETH sub watersheds. Irrigation sectors follow canals that usually follow along contour lines with a minimal slope. Natural water courses follow the strongest topographic gradient of the landscape. To deal with this scale mismatch, large sub watersheds and a coarse resolution of WASIM-ETH-EdIC coupling were necessary (see Section 7.3.2 and Figure 7.3(b)). A finer resolution would exponentially increase the number of data transactions needed and require a more automated database system and additional resources.

Theoretically, both scale mismatches and inadequate conceptualization of disciplinary linkages should be identified in an early project stage, as part of conceptual integration. In practice, at the earliest project stage, team members have limited familiarity with the study region and with the models used by other project members. At this planning stage, it is difficult to assess ‘ex-ante’ which interaction processes are worth further investigation (and resources) and which ones are not.

To achieve long-term integration goals, it is necessary to test each and every decision on explicit or implicit model assumptions against conceptual inconsistencies or technical problems. However, with disciplinary researchers focused on specific deadlines, the broader perspective that takes into account the full cause-effect chain can easily have low short-term priority against pressing deliverables. In theory, this broader perspective could be re-visited after the deliverable. However, too often researcher contract then ends and much of the knowledge is lost.

**Iterative nature of learning**

A fundamental challenge results from the iterative nature of modelling. Regardless of the quality of conceptualization, only after a model has been implemented and produced unsatisfactory results can project team members learn that their previous understanding of the system was insufficient to explain the empirical processes that are to be analysed. Only then can modellers review data quality, revisit assumptions and modify them in response to the model outputs and the empirical processes. Functional and technical design are thus part of a cyclic modelling process. It is this cyclic nature of modelling that is the enabling condition for deep learning about the processes, being studied beyond what is known at the beginning of the project.

Especially for those NR systems with complex cause-effect chains, interactions and feedbacks are not understood quantitatively and/or qualitatively. Because learning is the very objective of modelling these systems, it is almost certain that – once initial model results are obtained

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3 Another approach would be to implement all assumptions, and select those system representations that do not conflict with observations.
and compared to reality in the quality assurance phase – we will realize that at least one important aspect of the system in question has been inadequately captured. This is the true moment of learning, though it is often regarded as an error or setback. The modelling team must now return to the conceptual stage, the functional and technical design stage. Changes to the source code of the model(s) may be required, as may adjustments to the data structure. Subsequently, the project will have to return to calibration. If an interaction between two disciplines was mis-estimated or neglected in the beginning, than all disciplines affected will have to 1) implement the relevant processes within their models, 2) update their data and data structure, and 3) re-calibrate their models. Then, the project can return to the quality assurance stage and test for deviation between model behavior and observations of the real system. This learning cycle ultimately leads to a refinement of theory and concepts and better understanding of human-environmental interactions. Learning cycle management must take into account how responsibilities are shared within the team.

**Error management**

For systems with long chains of reasoning where knowledge is dispersed over several individuals, the propagation of technical and conceptual errors pose an enormous procedural challenge for a modelling process. Error analysis requires the identification of an error, the identification of the source of the error, the eradication of this error source, and the eradication of the consequences of this error. If a chain of reasoning contains components that are managed in more than one discipline, then spotting this error requires an understanding of the system and the chain of reasoning in its full length. Furthermore, errors can occur within data (measurement and processing), within the data format required for model input (format), within conceptualization (structural), and within implementation (technical).

Errors can also occur outside of the realm of the project. If existing modelling software is coupled and integrated, then this model will be analyzed and validated with objectives that might have never been tested before. A new type of model use might therefore reveal errors that were not previously found in the software. The eradication of such errors will require additional knowledge, time and resources that were not accounted for in the planning stage.

In our experience, the most time-consuming type of errors combine two errors that compensate for each other: If one of these error is identified, then the output actually worsens. Unfortunately, many errors only reveal themselves in the last stage of the calibration cycle, during quality assurance of interactions. At this stage, combined errors may even originate from two disciplines and may thus require the inputs and knowledge of two individuals (perhaps employed by institutes located on two continents) in order to be resolved.

Within a Model Use Case, input errors, structural errors, technical errors and ‘outside’ errors will occur, even with the most knowledgeable and accurate project staff, because learning is the objective of scientific modelling and learning always requires that new trails be taken. A Model Use Case design must therefore take into account the nature of errors that will be encountered in an integrated system analysis. Even though the frequency of combined errors is low, the cost of such errors is so high that it is worth accounting for them when designing the project process.

**Management of knowledge**

The quality of knowledge needed to address a particular research question may be unevenly distributed across disciplines. Quantitative disciplines have focused attention on those processes
that are quantifiable – either because data already exists or it can be obtained within the project, with measurements or surveys. The abundance of quantitative knowledge in one field of knowledge can distract from the lack of knowledge in another – regardless of its relevance in the cause-effect chain.

Knowledge barriers and communication barriers occur along the lines of research divisions in a team. Integration is the process of bridging these barriers. In some respect, this is trivial and normal in any team. However, the depth of knowledge required to understand models and the interplay of assumptions between models, as well as the technical skills required to use or even modify a legacy model, creates transaction costs for overcoming these barriers that are very high. Scientific models require research staff with very highly specialized skills and a long time of initial learning. One inhibiting factor is a high turnover rate of scientific staff that is associated with a loss of knowledge. To shorten this initial learning phase, access to technical support related to computer and software technologies is paramount.

Technical programming support also helps to follow professional software standards and to create a sustainable software product. Their level of professionalism also helps to avoid tremendous costs at later project stages, if the researchers that implement software code are not trained programmers. The lack of regular face-to-face communication and language barriers in international projects are additional burdens that increase transaction costs of model integration.

Project architecture

The organizational challenge of integrated modelling for resource management can be defined as finding a research setup to meet the technical as well as epistemic challenges. If factual and technical knowledge is spread across multiple individuals in a research group, the challenge is to reconcile the system perspective, the technical (or software) perspective and the research perspective of integrated modelling within the project architecture (compare definitions on page 19).

On one hand, taking the system perspective and structuring a project accordingly can facilitate conceptual understanding of cause-effect chains, for their quantification, and ultimately for model calibration. In this case study, a holon approach (see definition in Section 3.1.2) would have allowed for the conceptualization and understanding of interactions at sector level, for data measurement, and for the calibration of models quantitatively to reproduce the specificities of these interactions in each sector. Without this conceptual understanding of interactions and calibration with data at their appropriate scale, much of model software development remains a technical exercise without sufficient data for empirical validation of interactions. However, the holon setting is difficult to realize within the organisational form of existing research institutions, which usually follows disciplinary domains rather than system entities. For example, social, economic and hydrological descriptions of the same water canal and its users usually require three departments or institutes in three faculties. Not only mental barriers may exist, but also practical barriers related to personal management and room policies.

On the other hand, taking a technical perspective and structuring a project along the hierarchy of institutions and project partner, while sharing responsibilities for software development along these, give advantage to the cross-link interface approach, or even to a pillar approach that requires even less interaction (see definitions in Section 3.1.2). Here, research sub tasks are shared among and divided between project partners – along the lines of reductionist disciplines,
research institutions and modelling software. Nevertheless, interactions in the system occur at
the level of spatial and conceptual holons.

The selection of model software often occurs at an early stage of a project, when knowledge
about the local context and the system under research is still incomplete or unevenly distributed
across project partners. This leads to a chicken-or-egg challenge of selecting both the model(s)
and the research question for a project at the same time, and poses a general challenge to inte-
grated modelling. Once models have been selected, they restrict research and analysis to those
processes that the models can represent, along with those processes that a software developer
can implement within the allotted time and budget.

Only with the choice of model software, the magnitude of technical works can be estimated
that are required for the hierarchical coupling. Only then, the final allocation of software de-
velopment budgets should occur. The most ‘appropriate’ system should be quick in runtime,
give results that are scientifically robust and must be manageable within the existing project
team. Thus, guidelines on software system selection must take into account resource availabil-
ity, project time-lines and setting, and the organizational environment.

The challenge of finding appropriate project architecture reaches far beyond the project team
itself. It also covers the structure of institutions involved in natural resource management and
integrated modeling, which were created under a reductionist paradigm. For the wider system
of academia, the challenge begins with education approaches within and beyond disciplines,
through the provision of technical facilities, staff contracting and the hierarchy of projects, and
the funding mechanisms to support these institutions.

9.4 Lessons On Model Integration

This dissertation has shown that conceptual difficulties in irrigation modelling can be solved.
The following and closing sections document and systematize lessons on model integration from
the procedural perspective, in order to stimulate further discussion on how to organize empirical
modelling for irrigation management (and NRM) at the local and regional level.

9.4.1 Meeting Integration Challenges

Knowledge management aims to combine excellence with continuity. Software based projects
make use of advanced programs that require individuals with years of experience. In addition,
specialized software developed in and for research is often intended to be flexible. This means
that a graphical user interface is usually not feasible because it would confine development and
restrict learning. Thus, the learning curve to use advanced modelling software is steep.

Continuity and technical professionalism is absolutely paramount for software development,
but professional software architecture skills are rare within NRM research settings. Often, NRM
projects are forced to cooperate with spatially or otherwise distant IT departments, so that own-
ership remains within the institute and not where NRM is performed.

Shortening the Calibration cycle. A set of tools, automation techniques and methods can
greatly shorten the duration of a cycle, but require additional resources. Such tools range from
data bases which grant access to the same data set for the full modelling team. They improve doc-
umentation (meta data), quality tests and data consistency. Sampling methods include screening,
9.4. LESSONS ON MODEL INTEGRATION

Figure 9.2 — Model evaluation, calibration and analysis — by hand or with automated techniques — is a sequence of standard methods. However, the practicality of this cycle and the cycling length is determined by the slowest or technically most error-prone step.

Figure 9.3 — The Conceptualization-Implementation Cycle

Latin hypercube and complex group sampling. Automated calibration tools exist that speed up re-calibration (e.g. PEST\(^4\)), and other tools assist the handling of large modelling experiments (e.g. SimEnv\(^5\)).

However, all automation techniques are knowledge intensive and require additional project resources. The choice of methods should thus balance practicality, existing knowledge and preferences, and ambition.

Shortening the Conceptualization-Implementation Cycle. Whenever concepts are identified as insufficient or even false to describe a system, modelling requires re-visiting of the model itself (Fig. 9.3): identification of false or missing assumptions, theory-based re-conceptualization, functional and technical design, implementation and testing. This re-visiting of concepts is a core element when studying a complex system. Under structural uncertainties, the duration of a Conceptualization-Implementation Cycle determines the adequacy of a model for studying a system. The early creation of a simplistic model that is technically fully functional is recommendable for the technical side of development. Expert involvement, qualitative and communication techniques are useful methods.

\(^4\)http://www.parameter-estimation.com/
\(^5\)http://www.pik-potsdam.de/research/research-domains/transdisciplinary-concepts-and-methods/modsimenv/simenv/index.html
Shortening the Learning cycle is the most difficult task. It requires balancing the time needed for both the calibration and the conceptualization-implementation cycles. It is at the heart of epistemic, technical and structural management, because learning is the goal of research.

The use of a central database is recommendable, which exports input data for all models. Such database must store a range of formats and meta data on data sources, as well as data manipulations. To create model input files and read model outputs, the database must be combined with scripting functions. To manage large amounts of data, pre- and post processing analysis tools should be highly automated and used by all team members. Such a database is not only a valuable tool for error management and learning cycle management, but it adds value for local project partners, and it allows for data analysis across disciplines but without explicit use of models.

A second useful product is a slim coupled model that can be easily extended with each module. Such an interface can be used by all team members, regardless of their specific modelling task. Each modeller can simplify the model and use only those data and model components required for his research task.

Side product management. Side product management deserves early consideration in planning and budgeting. The benefits from side products can glue a project team together over prolonged periods of time by producing disciplinary publications, technical improvements and learning across the boundaries of individual researcher’s disciplinary domains.

Integration of lessons from specialized modelling agencies. In empirical research projects in NRM, researchers are typically faced with uncertain, inconsistent and incomplete data, with evolving data management systems, increasingly complex models and computer numerics, with permanently evolving model software and finally with rapid turnover of project staff.

It is useful to learn from those agencies that successfully host dynamically coupled model systems over a long time period, in order to derive structural lessons on enabling factors for model coupling. For example, specialized modelling agencies for complex modelling offer the service for tidal predictions, weather forecast, economic forecasts and climate change.

Structurally, most of these institutes have reached a high level of organizational specialization. Reviewing a few organigrams of such institutes shows how they manage technical modelling challenges. For example, the German Weather Service is a permanent organization with permanent (technical) staff and specialized branches for observation, data collection, development of methods and measurement techniques, data assimilation, data quality control, numerical development of models, investigation to improve model theory, and computer system administration. Quality control of model outcomes is institutionalized as a separate department.

Within climate research, national research institutes show similar levels of specialization (see organigrams of the Australian Bureau of Meteorology Research Centre, the Canadian Centre for Climate Modelling and Analysis, the British National Centre for Atmospheric Science, or the German Bundesamt für Seeschifffahrt und Hydrographie, Potsdam Institute for Climate Impact Research or Deutsches Klimarechenzentrum GmbH with specialized scientific, as well as technical support branches). Within such agencies, the high knowledge requirements of complex models, the quantity of data that these models use, the immense cost of data collection and data management, and the very specific knowledge required to handle computational issues has led

\[\text{http://www.dwd.de/de}\]
to a high degree of specialization — both of permanent staff and of the organizations’ structures. In contrast, stakeholder-oriented, modelling guidelines for river management in hydrology (e.g. Van Waveren et al. 1999, Refsgaard and Henriksen 2004) do not address these technical and organizational issues, but assume the prevailing research structure of multi-national EU projects.

For watershed management, different organizational solutions are needed. However, the large spatial scope that climate, oceanographic and weather forecast centers cover allows for the pooling resources, which is not feasible for small single watersheds or other NR systems. On the other hand, the abundance of NRM institutions such as watershed management boards, soil centers or forestry bureaus could allow for the development of high-quality and easy-to-use tools in modelling agencies of a similar professional level.

9.4.2 Success Factors

Guidelines for a full Model Use Case modelling cycle are scarce (see Section 3.2.4). Moreover, it may be difficult to standardize a process for the diversity of study regions, data availability, project setups, research personalities and disciplines that may be involved in modelling in NRM. Nevertheless, this section attempts to describe preliminary success criteria – with the intention of stimulating discussions and warning other projects of potential pitfalls.

Modelling is knowledge-intensive and interdisciplinary integration requires knowledge management skills. Knowledge management is required for the coordination of short-term tasks (such as data collection, software engineering, and disciplinary model calibration) across the two technical project cycles (conceptualization-implementation and calibration-analysis), and over the full learning cycle.

An appropriate organizational and hierarchical structure for the project greatly facilitates an effective overview of the entire process, graceful retreats from dead-ends, timely correction of conceptual errors, definition of milestones that are feasible and compliance of all project members to these. The responsibility for this organizational and hierarchical structure extends beyond project management, but also for project funding mechanisms. Hosting organization or research institutions must create enabling conditions that minimize transaction costs of integration.

The design of an integration project will depend on the local context of the participating research organizations, the system that is to be analyzed, the research team, and the research theme. At this point, I would like to suggest a checklist of success factors and enabling conditions that can be used in the planning phase of an integration project:

**Disciplinary knowledge is available.** Knowledge on model components is needed in great detail and depth, especially related to interaction variables. Access to an experienced researcher with each model is highly beneficial. Furthermore, well-tested modelling systems decrease the probability of existing errors in the source code. However, a strategy to deal with these errors must exist.

**Interdisciplinary system knowledge is available.** If a project is interested in empirical insights, and conceptual and theoretical knowledge on interaction and feedbacks of the system, then it must obtain detailed cause-effect hypothesis on the study system, especially on interaction variables and issues of rescaling/transformation. Communication skills are most valuable during this qualitative phase, but also when the technical tools are summarized. Ultimately, during the
quality assurance of a fully integrated system, full knowledge of all conceptual and technical
details is paramount.

**Qualitative methods are combined with quantitative methods.** Qualitative methods (expert inter-
views, conceptual group modelling techniques) improve conceptualization and the targeting of
costly and focused quantitative methods. The chances that conceptual errors occur increases if
researchers are alien to the study area and its culture. Good qualitative assessment before quan-
titative methods are applied (and even chosen!) can prove valuable especially in international
projects.

**Procedural knowledge is available.** This is knowledge of the integration process itself. Commu-
ication capacities exist to reach all disciplines, and to identify and manage possible misunder-
standings. Budgeting is flexible enough to handle some re-priorization.

**Technical knowledge is available.** It is tantamount that this knowledge is available over the full
life of the project, thereby allowing for repetitions of the learning cycle. Special attention should
be given to data management, source code development and implementation, post-processing
and automatization techniques.

**The duration of a conceptualization-implementation cycle.** The duration of this cycle is most rel-
levant if system conceptualization and the identification of feedback loops are part of the research
objective. Because errors may only be revealed in a late stage of calibration with the integrated
model, it is useful to have access to the knowledge of all previous stages during that late stage.

**The duration of a calibration-analysis cycle.** The duration of this cycle is relevant as part of the
learning cycle after each re-conceptualization. In addition, it is relevant if interaction data for
interaction processes carry with them large uncertainty. Because the calibration-analysis cycle
involves modellers from many disciplines, central data management and automated calibration/-
analysis techniques are highly recommended.

**A slim integrated model** is developed and is continuously supported over the complete project
duration. It connects disciplines by representing the most relevant interactions and is extended
with new insights. It is functional and is re-calibrated as soon as shared data on interaction
processes is identified as inconsistent at any stage of the project process.

**Data management facilities** exist to (re-)connect evolving disciplinary work with the integration
level and vice versa, in order to speed up the learning cycle and to minimize data handling errors.
Also, communication of project results can rely on this interface for coherent visualization.

**The duration of an error testing cycle is manageable.** To spot errors and test their propagation
through a long chain of reasoning, one person must have oversight and technical access to test
and vary *all* assumptions/model components. The length of a testing cycle is a good indicator
on how easy it is to eradicate technical and structural errors.

**Documentation tools** facilitate standardized communication within the project team.

**Management support tools** facilitate quick oversight of all steps of the integrated modelling pro-
cess. Tools range from documentation tools to powerful visualization of the complete modelling
process. These tools help project management to assess if deliverables are met in sufficient
quality.
The orchestration of disciplines Dictionary.com defines the verb orchestrate as ‘to arrange or manipulate, esp. by means of clever or thorough planning or manoeuvring’. If the objective of sciences is the improvement of Natural Resource Management and if NRM requires system understanding across disciplines, then orchestration of research for NRM involves all actors of research: funding mechanisms, research organizations, and the incentive structure that researchers face.
Chapter 10

Conclusion

Stakeholder-oriented research projects for NRM aim to find answers to practical questions, often at local or regional levels. In this context, the use of legacy code and the reliance on existing models is a reasonable method and dynamic coupling of models across domains an important option. Within this Ph.D. thesis, we demonstrate that dynamic coupling of a process-oriented hydrological model at watershed level and an economic farm-level multi-agent model is conceptually and technically feasible. The resulting software is capable of representing heterogeneity of interactions, a range of actors and multiple scales. Side products include an improved conceptualization and coding of the multi-agent model Mp-MAS and a re-conceptualization of the WASIM-ETH irrigation module, which was improved and extended conceptually and is now more consistent with the exigencies of irrigation management and an integrated framework. However, the real challenge of model coupling for relevant NRM is to bring down transaction costs so that research resources are not diverted from empirical questions.

In this Ph.D. thesis, I identified and elaborated three integration cycles that are required for successful model coupling: the technical cycle of data handling and calibration, the conceptual cycle of improving system understanding as well as source code, and the cyclic learning of complex interactions that embraces both.

Even complex coping strategies of farmers can be described within the modelling framework in a process-oriented, theory-based manner. Supply-side mechanisms were already implemented into the software and successfully tested within the IGM project. Calibration of individual model components and of model-to-model interface processes used the best data available and is successful for single processes. This calibration revealed model inconsistencies that could be resolved (e.g. Arnold, Uribe, Troost and Berger 2010). Other interaction mechanisms require further research – for conceptual understanding, for technical solutions and regarding the collection of empirical data.

Local resource dynamics may be equally complex as processes of global change. However, the limited scope of smaller watersheds and irrigation management confines the resources that can be justified for their assessment – even though it requires knowledge that is equally dispersed across multiple disciplines.

Furthermore, cause-effect chains must be assessed within their local context, and these may vary qualitatively at each location. Currently, researchers must use ‘patience and perseverance’ (Ekasingh and Letcher 2008) to resolve the host of interfaces and data transfers between model components. In research teams, system complexity is mirrored in organizational complexity
and increases research transaction costs and research time. However, as long as the timing of a research process conflicts with the pace of the world of policy making, then integrated modelling remains confined to the academic realm. Only by reconciling these time frames, the ‘outcome gap’ (K.B. Matthews, in IMACS 2009) of research for NR management can be bridged, and the ‘yet another modelling framework - phenomenon’ of current research (Evert, Holzworth, Muetzelfeldt, Rizzoli and Villa 2005) can be overcome.

Little procedural knowledge exists on how to apply integrated modelling under a given resource constraint and a given research setting (compare Anderssen, Braddock and Newham 2009). This thesis explores this knowledge gap and offers initial insights.

Can lessons from successful global change modelling be translated to smaller systems? What would an institution look like that provides integrated, meaningful and timely support to watershed management? What organizational form would be required to use complex modelling in a local context? While scientists agree on the importance of integrated modelling and have proven its feasibility in numerous projects, the IAASTD concluded that agricultural research has failed to deliver its promises to meet development goals in praxis so far. The intergovernmental panel concludes that ‘Business as usual is not an option’ (IAASTD 2008b).
References


DOH/SMI (2004): *Construccion embalse ancoa: Estudio de factibilidad VII Region.* Feasibility study, SMI, for Dirección de Obras Hidráulicas, Chile.


REFERENCES


REFERENCES


REFERENCES


Martínez L. (2001): Manual de operación y mantención de equipos de riego presurizado. Boletín inia 65, Gobierno Regional de Atacama, Comisión Nacional de Riego e Instituto de Investigaciones Agropecuarias (Chile), Centro Regional de Investigación Intihuasi (La Serena), Centro Experimental Huasco (Vallenar).


REFERENCES


REFERENCES


