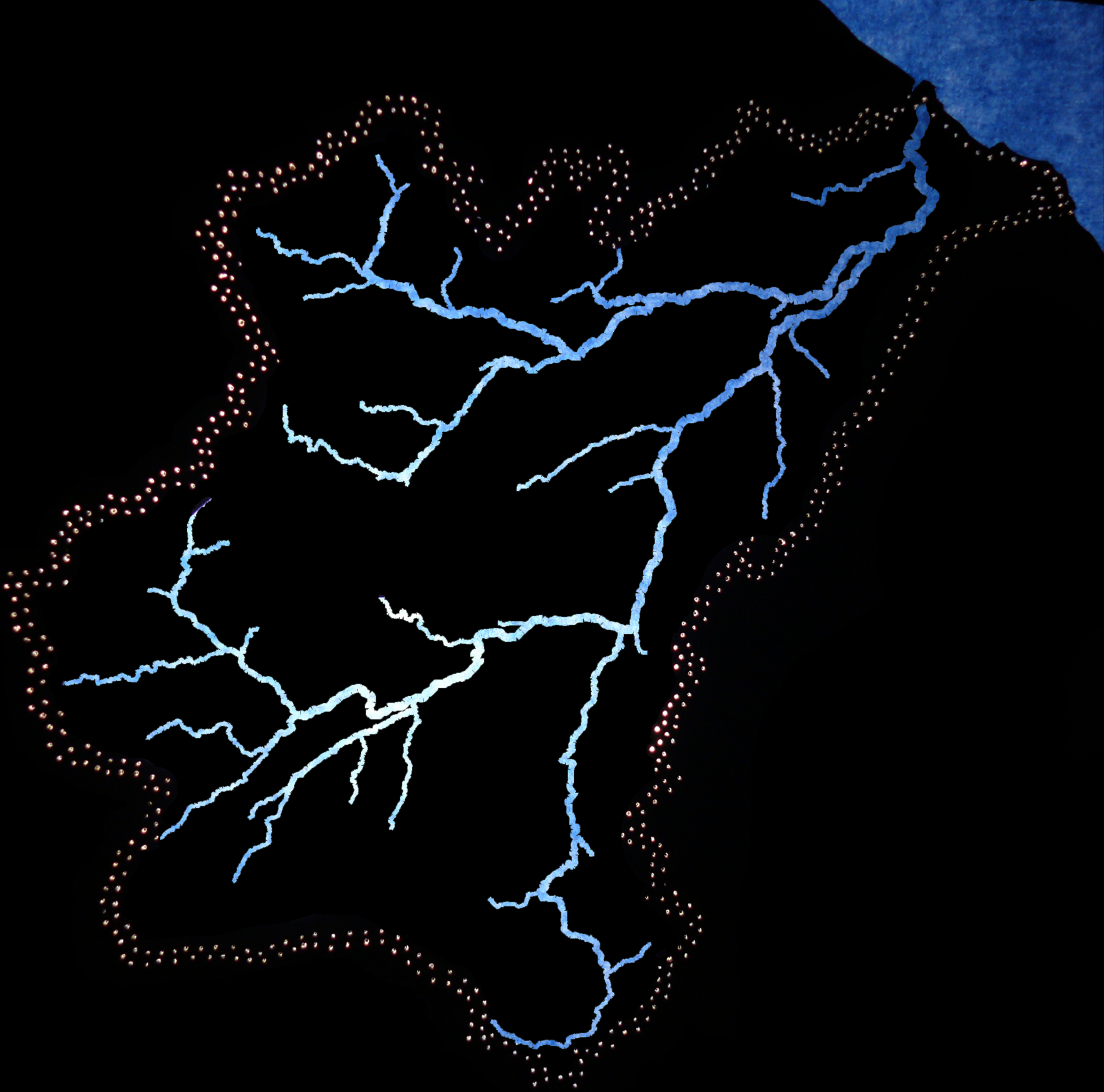


How Low Should We Go?

Water-Scarcity Patterns under Different Levels of Decentralization in Water Allocation: an Agent-Based Approach

Erwin Sterrenburg

University of Twente.

Cover: Jildou Zwamborn

How Low Should We Go?

Water-Scarcity Patterns under Different Levels of Decentralization in Water Allocation: an Agent-Based Approach

Final Report

Enschede, June 2010

Master's Thesis of:
Erwin Sterrenburg
Water Engineering & Management
University of Twente

Supervisors:
Dr. M.S. Krol
Water Engineering & Management
University of Twente

Dr. P.R. van Oel
Water Engineering & Management
University of Twente

UNIVERSITY OF TWENTE.

Tool for
Allocation
Management
Analysis
u**N**der
Decentralization
Using
Agents

All *Tamanduas* share a fascination for ants: the usual *Tamandua* (meaning "anteater" in both Tupi and Portuguese) tends to see them as a tasty snack. This *Tamandua* however, uses ants - a common metaphor for agents - to analyze a complex system. When observing natural ant colonies it can easily be seen that the complexity of each single ant is rather low. Nonetheless ant colonies exhibit complex behavior and have even been able to demonstrate the ability to solve geometric problems. Water allocation management in a river catchment is another example of such a complex system: relatively simple actions and decisions of autonomous stakeholders can lead to complex water scarcity patterns. *Tamandua* aims to increase insight in what is going on in the "ant colony of water allocation".

SUMMARY

This thesis addresses the interdependencies between water use and water availability and describes a model that has been developed to increase insight in the potential effects of different decentralization regimes in water allocation management with regard to the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin. Relevant processes include physical processes such as hydrological processes, water user responses to variations and changes in water availability and social processes between water users and water managers. The results are relevant for research on relevant initial condition, context factors and design principles for participative river basin management. Water demand, water allocation management and water availability are strongly related in semi-arid environments, where the irrigation sector is responsible for a large part of consumptive water use. Variations in water abstractions for irrigation depend on irrigated area and irrigation requirements per hectare.

Jaguaribe basin in the semi-arid northeast of Brazil, is used as case study. The agent-based Tamandua model is used to simulate water availability and water use on a river basin scale. Within Tamandua, a newly created model for the irrigated water demand is integrated with existing models from the WAVES project for water availability (WASA) and non-irrigated water demand (NoWUM). Water users and water managers are represented as agents, with their actions based on the actual activities farmers (and water managers) perform during a year. The decision-making process of the farmers is "reverse-engineered" by analyzing cropping patterns during dry, normal and wet years for representative municipios (i.e. municipality in which a single water supply source is dominant). All model parameters can be derived from physiographic information of the study area. Thus, model calibration is primarily not required. Validation against observed discharges, reservoir volumes and water footprints showed that Tamandua predicts both water availability, variation in water availability and irrigated water use reasonably well.

Three potential measures have been identified which could be included in different management strategies: prohibiting the construction of new smaller reservoirs, reallocating water towards the larger reservoirs and restricting water abstraction from strategic reservoirs in times of drought. Two scenarios have been defined: a centralized scenario in which these measures are implemented and a decentralized scenario in which the three measures are not implemented.

If water demand within the Jaguaribe basin increases with a magnitude similar to the increase in our simulation, overdevelopment will occur irrespective of the water allocation strategy used. With regard to the physical water system, refillment of strategic reservoirs is insufficient, discharge into the ocean decreases dramatically and the basin is under serious threat of (further) closure.

The more upstream located farmers are associated with high productivities and low stabilities, whereas the more downstream located farmers

are associated with low productivities yet high stabilities. Willingness to take risks increases gradually over time, based on the rationale that an occasional crop failure should not stop expansion as long as the average result over 5 years is sufficiently high. This results in vast increases in irrigated area (up to 10-fold around reservoir class 1) and in the numbers of reservoirs (up to about 50% within a sub-basin) which threatens both the productivity of the upstream farmers as well as the stability of their downstream colleagues. Meanwhile the productivity of downstream farmers (except the farmers downstream of the strategic reservoirs, but their productivities are biassed by some farmers with a large areal of banana) and, to lesser extent, the stability of the upstream farmers stay at roughly the same level. Biggest "losers" after 50 years of simulation are the farmers around the medium-sized reservoirs (competing for water with prioritized non-irrigating users and having smaller buffers than the farmers around strategic reservoirs). It is expected that the farmers around and downstream of the strategic reservoirs would follow this negative trend, if the ongoing developments continue.

Under the decentralized scenario, farmers are not restricted in their behavior; they are only limited by the natural conditions. Under the centralized scenarios, their supply is also influenced by regulations from the central government, aimed to increase the water availability for non-irrigating water users. The results of these trade-offs are visible in the reservoir volumes of the strategic reservoirs (slightly higher reservoir volumes during dry periods) and in the development of the irrigated area and production of farmers around the medium-sized reservoirs (class 4-5). These are clearly the farmers that are restricted in their growth by the administrative measures taken in order to improve the water supply for the prioritized non-irrigated demand.

In general, the effects of the implemented measures are very small compared to the effects of increased water consumption itself. This implies that the overdevelopment cannot be prevented by water allocation management alone. As long as the upstream located farmers are free to use all the water they can catch. In order to prevent the overdevelopment, an integrated approach is required including agricultural policy measures such as increasing the value added per drop (more cash crops) and restrictions on the areas to be irrigated.

I reject holism. I challenge you to tell me, for instance, how a holistic description of an ant colony sheds any more light on it than is shed by a description of the ants inside it, and their roles, and their interrelationships. Any holistic explanation of an ant colony will inevitably fall far short of explaining where the consciousness experienced by an ant colony arises from.

— Dr. Anteater in "Ant Fugue" by Douglas R. Hofstadter [1979]

PREFACE

After finishing all my courses, the time had come to lay the keystone of my master Water Engineering & Management (WEM) at the University of Twente. The large array of interesting research subjects made choosing a subject very difficult. After a long and thorough multi-criteria analysis, the choice fell on reservoir management and water allocation in the Jaguaribe basin. This subject incorporates both the technical and societal aspects of a civil engineering system and it was completely new to me, so my research project could start from scratch.

In the end, my research has resulted in this report which is made with the intention to be complete yet compact, to show a high degree of sophistication and to have the highest anteater content in the history of WEM.

Although the brochure says that "the final project is executed individually", this is certainly not true. In reality probably more people have attributed than during any course before. These people deserve an honorable mention here. At first my commitee, Pieter & Maarten: thanks for providing me with sufficient guidance while still providing the freedom to take a wrong turn every now and then. Also thanks for your doors always being open. Our meetings were always very pleasant, discussions were fruitful and your enthusiasm was really contagious. Sometimes the two of you were miles ahead, while I was trying to note down as much valuable information as possible.

Furthermore my fellow students, inhabitants of the graduation room and friends for providing opportunities to share thoughts, accompanying me during breaks and organizing social activities. A special word of thanks is reserved for three of my best friends and study mates, Bert Kort, Daniël Tollenaar & Wiebe de Boer, for their words of wisdom and help.

Mom, dad and Marnix, thanks for always being there for me yet letting me make my own mistakes. The geographical distance probably played a large role here and may have prevented some severe clashes, but nonetheless I really respect this. I hope (and think) that you can be proud of me. At least I know that I am proud of you and happy to have you!

And finally to Jildou, thanks, not only for the beatiful front page and the Tamandua, but also for taking care of me, making me smile and accepting that I could not always find as much time for you (and the household chores...) as I would have liked. Dikke krup!

Erwin Sterrenburg, Enschede, June 2010

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ABM Agent-Based Modeling

CPR Common-Pool Resource

MAS Multi-Agent System

RVE Relative Volume Error

WEM Water Engineering & Management

WFP Water Footprint

1 INTRODUCTION

Many semi-arid areas in the world suffer from water related problems such as scarcity and unsatisfactory water allocation both between and within sectors. One of such areas is the Jaguaribe basin in the Northeast of Brazil, which is seriously affected by an extreme uncertainty in the precipitation regime and long-lasting and recurrent drought periods [Kemper et al., 2007]. During drought periods, uncoordinated and unchecked individual diversions of surface water or abstraction of groundwater can result in over-commitment of water resources in a given river basin.

Large increases in reservoir capacity together with a growth in consumptive water use in upstream parts of basins have in many cases led to so-called 'basin closure' [Falkenmark & Molden, 2008, Molle et al., 2007, 2010, Smakhtin, 2008]. River basins are said to be closing when commitments with regard to societal and environmental freshwater needs cannot be met for part of the year, and to be closed when commitments cannot be met during the entire year [Molle et al., 2007]. Not only large-scale irrigation schemes, reservoirs and other infrastructure built and managed by state agencies can result in over-commitment, but it is worth mentioning that basin closure can also be compounded, and sometimes driven, by the development of diffuse individual or small-scale irrigation [Molle et al., 2010].

The growing pressure on water resources has led to a renewed emphasis on river basin management. In many people's minds, river basin management requires a unitary basin management organization. However, river basin organizations cover a wide gamut of organizations with quite varied roles and structures (Molle et al. 2007, 2010; Fig. 1). At one end of the spectrum, there are highly centralized organizations that are (or were) responsible for most water-related development and management functions in the basin. At the other end of the spectrum, there are more loosely constituted bodies that bring together stakeholders from various agencies and water use sectors. Their role is generally coordination, conflict resolution, and review of water resources allocation or management [Molle et al., 2010]. Examples include: Mexico's river basin councils [Wester et al., 2003, Wilder & Lankao, 2006], Brazil's river basin committees [Lemos & de Oliveira, 2004, Kemper et al., 2007], and most international river commissions. Although restructuring of the river basin governance may relieve the pressure on water resources, by itself it is usually insufficient. Wilder & Lankao [2006] for example conclude on the river basin councils in Mexico that without increased state support to improve water infrastructure to reduce loss and use the existing resources more efficiently, such strategies may in the end prove futile.

A common response to water scarcity and growing competition in closing basins is to capture more water, even though this is an expensive and frequently unsustainable way to respond to water stress. In closing river basins continuing the emphasis on supply-side approaches will

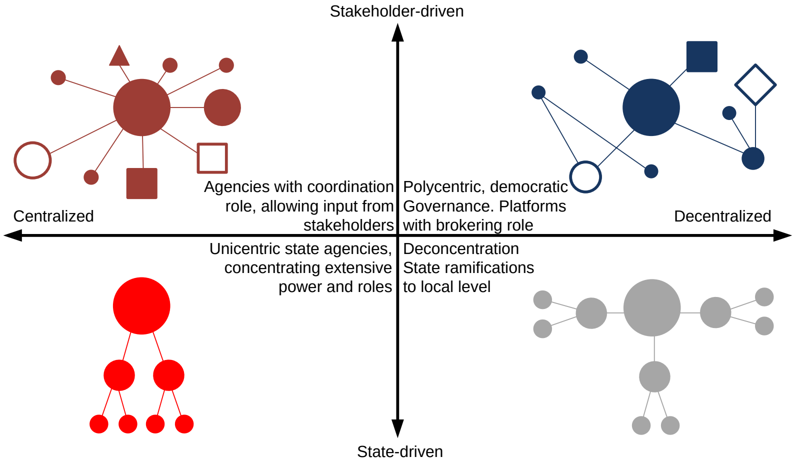


Figure 1: Typology of river basin governance [after Molle et al., 2007].

only intensify the pressure on water. The main alternative responses to water overexploitation in closed basins revolve around water demand management, but doing better with what we have has also profound implications for the choice of responses to basin closure; the allocation of scarce water resources [Molle et al., 2010].

With respect to water allocation, three modes of allocation are commonly recognized [Dinar et al., 1997]. First, the state allocates water administratively according to rules that may, or may not, be very transparent or explicit. Second, allocation can be ensured by a group of users among themselves. This case is more common in smaller systems, but users may also manage large schemes. Third, water may be allocated through water markets, as in Australia, Chile or the Jaguaribe basin. However, bulk water charges in the Jaguaribe basin are currently only levied on domestic, industrial and some irrigation water uses [Kemper et al., 2007].

Nowadays it is commonly recognized that a combination of local participation and central supervision is desirable and that success depends on finding the right balance between these forces. Some attempts have been made to identify relevant initial conditions and context factors influencing the de-centralization process, but there is still a need for additional insight into more general design principles of river basin management [Kemper et al., 2007].

Although water allocation on a river basin scale does not mirror the 'standard' characteristics of Common-Pool Resources (CPRs), river basin management research on semi-arid environments can benefit from applying elements from CPR literature. Agent-Based Modeling (ABM) is a promising approach on this matter and has already be successfully applied to model spatial-temporal variability of water availability that is influenced by water use and vice versa by Van Oel et al. [2010].

1.1 BACKGROUND

This section discusses the theoretical framework of the influence of the level of decentralization on water-scarcity patterns. This theoretical

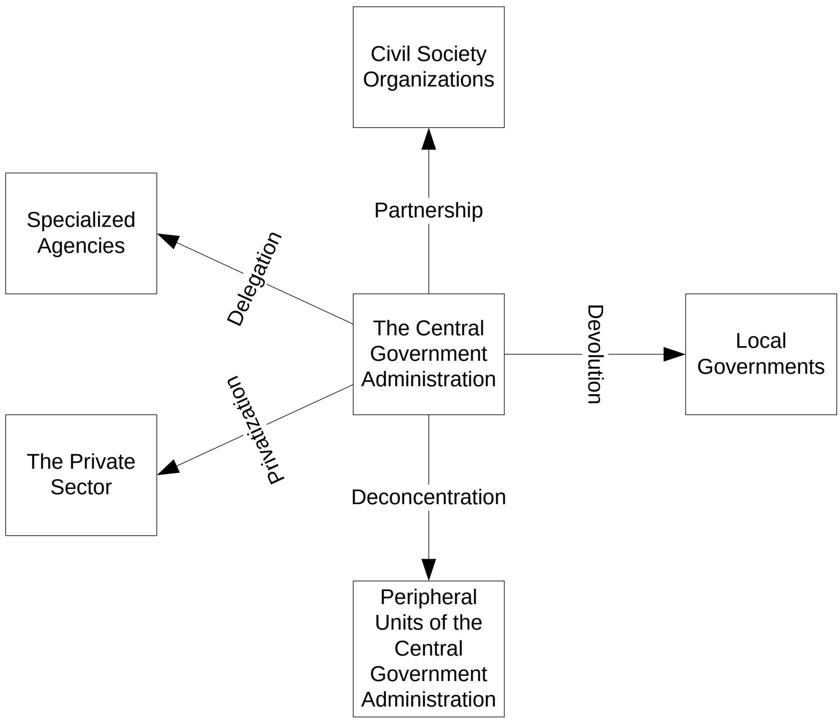


Figure 2: Five Forms of Decentralization [after Smith, 2001].

framework consists of three components: an *analysis of decentralization* in water resources management, followed by a discussion of the role of *common-pool resources* theory and a review of applications of *agent-based modeling* in water allocation research.

1.1.1 *Decentralization in Water Resources Management*

In many countries, river basin management has traditionally been the mandate of government entities, such as federal or national water resource agencies or ministries. By the end of the 1980s, it was clear that this approach often did not work well and did not produce the desired results, especially in developing countries. Analyses pointed to a need for decentralization of decision-making and the active involvement of stakeholders, the assumption being that decisions taken by and with stakeholders would be better informed and would allow negotiation among stakeholder groups in order to come to more rational and equitable solutions. Such processes might also lower resistance to sometimes difficult decisions [Kemper, 1996, Kemper et al., 2007].

Decentralization deals with possibilities for redistributing authority, responsibility and financial resources for providing public services among different levels of government in order to make the economic and political system respond more closely to people's preferences and requirements Smith [2001]. Possible forms of decentralization include delegation, devolution, deconcentration, privatization and partnership (World Bank 2009, Smith 2001, Fig. 2). By bridging the gap between suppliers and users of goods and services, decentralization measures are expected to achieve three major objectives (Smith 2001, summarized in Fig 3):

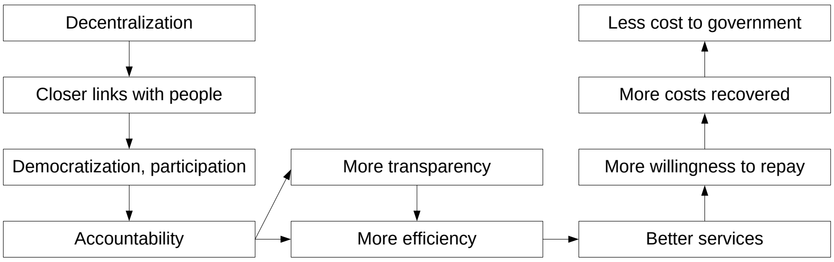


Figure 3: Paradigm of Decentralization [after Smith, 2001].

- Improved efficiency in service provision;
- More transparency of service providers;
- Better accountability to service users.

Smith [2001] concludes that in any decentralization reform process, central government needs to retain responsibility for global planning and the design of regulations and their enforcement. He distinguishes the following major considerations that justify this intervention of a central rule-making authority:

- Market imperfections which originate in the monopolistic position obtained from the control of a source of water;
- Protection of other users' rights;
- Equity issues in the allocation of the resource;
- Resource conservation issues;
- Economic priorities related to sector and spatial development policies and plans;
- The very high cost of some water resource development;
- The technical complexity and the interrelationships of resource use planning and exploitation.

Based on the considerations above, it has become increasingly acknowledged that local resources in many cases should preferably be managed by a combination of local users and authorities at the supra-local (spatial) level. Success depends on finding the right balance between these forces. The concept of co-management is often used here, specifically in cases of water resources management for which local approaches might be ineffective because of large-scale natural resource system processes and constraints [Carlsson & Berkes, 2005, Wallace et al., 2003]. This concept is expressed as follows in the second of the so-called Dublin principles [ICWE, 1992]:

"*Principle No. 2 - Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels:* The participatory approach involves raising awareness of the importance of water among policymakers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects."

While looking at this principle, the obvious question one would ask is: what are considered 'appropriate levels'? Smits et al. [2005] answer the question by saying that: "there is no recipe for the kind of institutional set-up or governance structure which is most appropriate. However, a key lesson is that the quality of interaction between a water resources management entity, national, regional and local government, the private sector and civil society groups is vital [Brannstrom, 2004]. This calls for developing governance structures in which all groups are represented and linked and for local government to engage in these institutions". Others do not directly seek for the lowest appropriate level, but try to capture the essence of 'appropriate decentralization' in water resources allocation by providing a framework [Smith, 2001] or bringing together inter-disciplinary and inter-sectoral knowledge [World Bank, 2009]. A critical success factor identified by Lemos & de Oliveira [2004] is that a strong bottom-up organization emerges independently from the state.

Kemper et al. [2007] argue that the lowest appropriate level for some water resource management functions may be a sub-basin unit, a local or regional unit of government, or a hybrid unit sometimes referred to as a "social basin" depending on various local variables. They conclude that "integrated and participatory management at river basin level cannot follow a blue print". With respect to the Jaguaribe basin, they conclude that the essence of Ceará's experience in the Jaguaribe basin may thus be that the basin scale is less relevant there for integrated water management purposes, in favor of combining state-level management with decisionmaking at smaller territorial levels than the basin, such as subbasins, regulated river valleys, and reservoirs.

Some attempts have been made to identify relevant initial condition and context factors influencing the decentralization process, but there is still a need for additional insight into more general design principles of river basin management. In the Jaguaribe basin, the quest for the optimal balance is in full swing, which makes it such an interesting study area for a case study.

1.1.2 *Common-Pool Resources in Water Resources Management*

CPRs are those natural or human-made resources which are subtractable and for which the exclusion of potential appropriators is non-trivial [Ostrom et al., 1994]. The two important characteristics of CPRs , namely non-excludability and rivalry in consumption, separates CPRs from private goods, in which exclusion from benefits is possible, and public goods, in which there is no rivalry in consumption.

With respect to water management, it is clear that small-scale water resources show the characteristics of CPRs. As a result, CPR theory has been widely used in cases of competition over water resources in irrigation systems [Baland & Platteau, 1999, Bardhan & Dayton-Johnson, 2002, Lam, 1998, Tang, 1992].

For larger-scale water resources, the link with CPR theory is not that obvious. In their analysis on the manageability of local water resources in the Jaguaribe basin, Van Oel et al. [2009] argue that: above the level of a water reservoir for irrigation, one can regard a river basin as one large water system that consists of a network of connected smaller water systems. These smaller water systems can be regarded as a 'local common-pool resource' connected through water flows from one to another. Van Oel et al. [2009] distinguish two different sorts of competition: local competition over the water within each smaller water system and competition over water between the smaller water systems, notably between upstream and downstream users. In CPR terminology, Van Oel et al. [2009] say that a river basin as a whole is an asymmetrical CPR. In symmetric CPRs externalities between users are mutual whereas in asymmetrical CPR systems, like river basins in which water flows from up- to downstream, externalities may become unidirectional.

1.1.3 *Agent-Based Modeling in Water Resources Management*

A promising approach on how to improve the human dimension in simulation models is the application of ABM, which is in accordance with the prevailing view that (eventual) large scale equilibriums should be the result of small-scale interactions, not the cause.

In this research, we use the definition of Matthews & Selman [2006]: they describe an application of ABM (also known as a Multi-Agent System or MAS) as a model that contains of a number of 'intelligent' virtual agents which: (1) have the ability to communicate and exchange information with each other; (2) can interact with their environment; (3) have the ability to change their actions as a result of these interaction; (4) and have only partial knowledge of the system as a whole (bounded rationality).

Although agent-based modeling can be considered as a very innovative new modeling approach, its advantages do not necessarily have to fulfill the requirements of one's research. Three principal advantages are claimed of agent-based over traditional top-down modeling techniques [de Smith et al., 2007]. The agent-based approach:

- Is flexible and can be used to evade limitations of traditional approaches;
- Provides a natural environment for the study of certain systems; and
- Captures emergent phenomena.

Additionally, Gunkel [2005] names the multi-disciplinary nature of agent-based modeling as another advantage.

An agent-based approach facilitates a detailed representation of the individual participants in the systems, capturing their heterogeneity and representing with realism social processes, the explicit representation of the space and the local interactions between agents. Models of agent-based nature may help to portray systems in which interdependencies between agents and their environment are essential to the proper understanding of system dynamics where the heterogeneity of agents or their environment critically impacts model outcomes and where adaptive behavior at the individual or system level are relevant for the system under study [Parker et al., 2003]. As shown by Van Oel et al. [2010], in the Jaguaribe basin these interdependencies are extremely important. They conclude that with their (multi-agent simulation) approach it is possible to validly represent spatial-temporal variability of water availability that is influenced by water use and vice versa.

With regard to policy analysis, Berger et al. [Berger et al., 2007] have shown that a MAS is a promising approach to supporting water resources management and to better understanding the complexity of water use and water users within sub-basins. Schluter & Pahl-Wostl [2007] have developed an ABM approach to compare centralized and decentralized water management regimes.

However, the spatial extent of these studies and comparable studies as provided in Appendix A on page 81 is much smaller than the extent of the entire Jaguaribe basin. Summarized, the application of ABM seems a promising approach for research on the consequences of decentralization level on water-scarcity patterns on catchment level, but no applications do yet exist on such a large spatial extent .

1.2 PROBLEM DEFINITION

There is a need for a comprehensive study on the influences of decentralization on water-scarcity patterns in a (large) semi-arid river basin. The Jaguaribe basin is used as a study area for a case study.

In the Jaguaribe basin the water related problems are targeted by a combination of physical measures (creating reservoirs) and administrative measures (decentralization). These two measure types are interrelated. Together they form the basis for designing different decentralization scenarios for the study area.

Because of the large spatial extent, together with the lack of information on the exact locations of individual farmers, a spatial aggregation of farmers is applied: the spatial resolution for the model used in this study is the municipal district. Climate change is not considered during this research. The resulting insights however, could be used for climate change impact assessments.

1.3 RESEARCH OBJECTIVE

The objective of this study is to increase insight in the potential effects of different decentralization regimes in water allocation management with regard to the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin.

This is achieved by creating an agent-based virtual laboratory in which water availability and agricultural water use are modeled under decentralization regimes. The Jaguaribe basin in the NE of Brazil is used as a case study.

1.4 RESEARCH QUESTIONS

1. How can physical water availability and agricultural water use for current water governance be modeled on a river basin scale?
    a) What physical characteristics determine water availability and what are these characteristics for the Jaguaribe basin?
    b) How can the hydrological processes determining water availability be schematized?
    c) How can industrial and domestic water use be included in this model?
    d) How can behavior of farmers and water use resulting from their actions be included in this model?
    e) What rules can be used to parameterize the decision-making process of these users?
    f) What are the possibilities for calibration, validation and verification of such a model for water availability?
    g) What are the possibilities for calibration, validation and verification of such a model for water use?
2. How can different management strategies, corresponding to different levels of decentralization be implemented in this model?
    a) What are the potential implications of different levels of decentralization for the study area?
    b) How can these implications be parameterized in our model?
3. What are the effects of different levels of decentralization in water resources management on the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin?

1.5 OUTLINE OF THIS STUDY

Chapter 2 describes the Jaguaribe basin, its physical water system and relevant human activities with regard to both water demand and water management. Chapter 3 provides an overview of the modeling concepts used and explains how these concepts are parameterized and integrated. Chapter 4 contains the simulation results and discusses the validity of these results. Finally, chapter 5 discusses the results of this study and provides the resulting conclusions and recommendations.

2 THE JAGUARIBE BASIN

The distribution of water resources in space and time is influenced by a combination of natural processes and human actions [Van Oel, 2009]. Natural processes, characterized by physical characteristics of the study area (precipitation, temperature, slope, soil type etc.), determine the actual quantity of available water and influence where and when this water will be available for consumption (Fig. 4, Arrow 1). Water demand in its turn is characterized by the human activities in the study area: domestic use, industrial use, irrigation etcetera (Fig. 4, Arrow 2).

Another type of human actions influencing both water supply and demand is related to the management of the water resources. Availability over time and space is affected by the construction of infrastructure such as reservoirs and irrigation systems and their management (Fig. 4, Arrow 3). Demand is affected by administrative measures such as regulations, taxes and subsidies (Fig. 4, Arrow 4). Mismatches between demand for water and its availability over time and space could iniate actions from responsible authorities (Fig. 4, Arrows 5 & 6). However, their chances of success depend on the location of the mismatch within the basin: Van Oel et al. [2009] show that the factors that make water better manageable vary with downstreamness. The downstreamness of a location is the ratio of its upstream catchment area to the entire basin area. Van Oel et al. [2009] argue that in the case of the Jaguaribe basin, the net result appears to be most favourable in the midstream zone because water availability appears to be most stable here.

External factors may influence the system: human actions elsewhere can lead to climate change, changes in global markets can result in other cropping patterns etc. (Fig. 4, Arrow 7). Developments within the basin will also exert influences on the external system (Fig. 4, Arrow 8). However, it seems less like that such developments will have considerable effects on the much larger spatial scales of the external

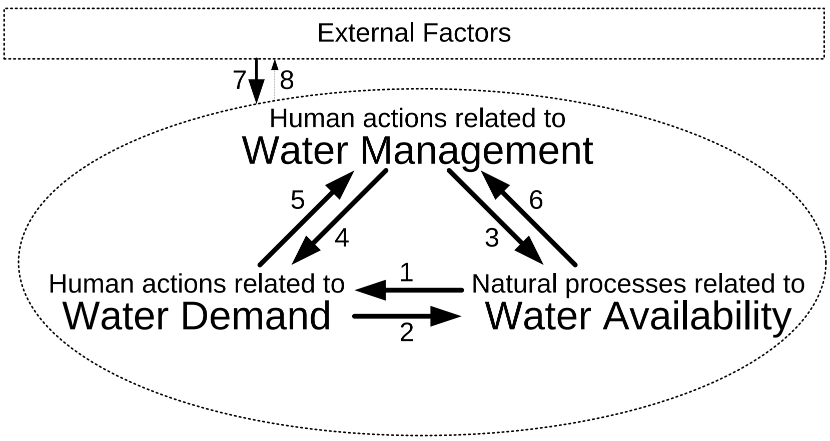


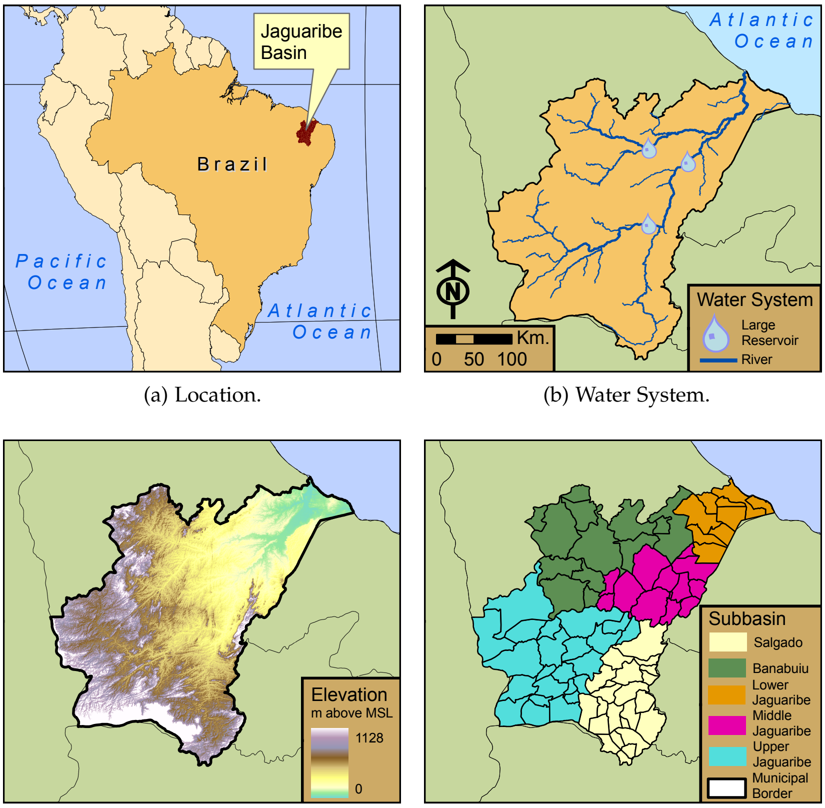
Figure 4: Scheme of the components determining the distribution of water resources and their inter-relations.

environment (varying from state level up to world level). Although such external factors are not considered under this study, it should be kept in mind that can they can play a role.

This chapter describes the three elements that affect the distribution of water resources in the Jaguaribe basin (Fig. 4): first the physical water system is described, together with the man-made infrastructure. Second, relevant human activities with regard to water demand are discussed. Finally, water resources management structure is described, with emphasis on how decentralization has already been applied.

2.1 THE PHYSICAL WATER SYSTEM

The Jaguaribe basin is located in the Federal State of Ceará in the north-east of Brazil between 4° to 8° South and 37° to 41° West (Fig. 5a). The drainage area is about 72,500 km^2. For administrative reasons, the basin is divided into 5 subbasins which together contain 80 municipalities (Fig. 5d, Appendix B on page 83). Elevation reaches up to 700-1100 m. in the mountainous areas at the western and southern border (Fig. 5c). Annual precipitation ranges from 450 to 1,150 mm. on average, with high levels of temporal and spatial variability [FUNCEME, 2010]. Rainfall is concentrated in the period January-June. Temporal rainfall variability is highly significant on a range of levels: decadal variability [Souza Filho & Porto, 2003], inter-annual variability, seasonal variability and variability on the time scale of a week [Uvo et al., 1998, Smith



(a) Location. (b) Water System.

(c) Elevation. (d) Subbasins.

Figure 5: Jaguaribe Basin.

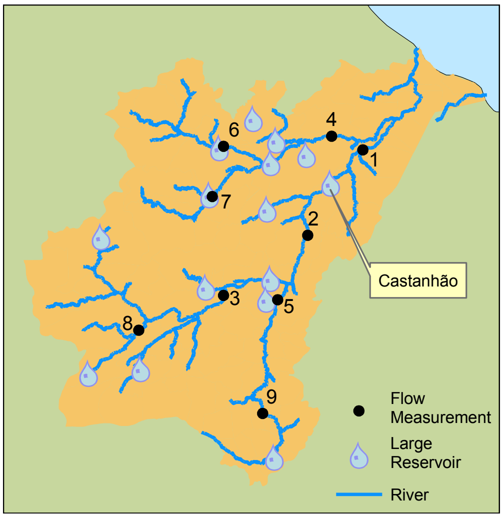


Figure 6: Locations of flow measurement stations and main reservoirs.

& Sardeshmukh, 2000, Gaiser et al., 2003]. Although total rates of rainfall are higher than in many dry regions in the world, in Ceará the combination of impermeable crystalline rocks in the soil and high temperatures produce high rates of evapotranspiration and low levels of water retention and storage. Therefore, multiyear drought events that cause much hardship for both natural and human systems are relatively common [Lemos & de Oliveira, 2004]. Since groundwater resources are considered of limited importance in most areas of the basin [Kemper et al., 2007], they are not included in our analysis.

In order to provide water for all needs during dry season, water is accumulated in surface reservoirs during the wet season: Kemper et al. [2007] provide an estimate of 4,713 reservoirs with a total storage capacity of 13,560 Mm^3. About 75% of this storage capacity is provided by three large and strategically reservoirs: Orós, Banabuiú and Castanhão (Fig. 5b). Campos et al. [1999] showed, that even with a high degree of surface control of hydrographic basin by reservoirs, a great part of the inflows over the controlled area keep on going to the sea. This paradox, high control of surface with relatively low control of mean discharges, comes from the high overyear variability (CV ~ 1.3) of the river's annual discharges.

Information on observed discharges is provided by flow measuring stations located in the basin (Fig. 6). Measuring station 1 is located downstream of the Castanhão reservoir, but during our simulation period this reservoir was not yet constructed. For our simulation period of 4018 days (1988-1998), the set of observed discharges is nearly complete for measuring stations 2 & 4. The rest of the observations show large gaps (Table 1).

Measurement Station	ID	# of days observed
1	36390000	1029
2	36320000	3964
3	36160000	3009
4	36580000	3965
5	36290000	2059
6	36520000	3181
7	36470000	2464
8	36045000	1372
9	36250000	2035

Table 1: Number of days with observed discharges per flow measurement station (1988-1998 period, ID's from ANA [2010]).

2.2 WATER DEMAND

Most farm households in Ceará produce maize and beans as the basic subsistence staples with cotton, manioc, cashew nuts, or fruits as a cash crop, and most raise a limited number of small livestock (small ruminants, swine, or fowl) [Finan & Nelson, 2001]. Some municipalities have significant levels of irrigated land; however, for the state as a whole, the percentage of irrigated area is negligible compared to rainfed area [Finan & Nelson, 2001]. Despite significant water storage capacity in reservoirs throughout the state, 92% of farm families do not have access to irrigated land and thus depend entirely on annual rainfall [IBGE, 1996].

Nonetheless, irrigation is by far the largest source of water consumption in the Jaguaribe basin (83%), followed by human consumption (12%) and industry (5%) [COGERH, 2006]. Currently there are about 26,155 ha of irrigated land in the Jaguaribe / Banabuiú valleys of which approximately 45% are planted with rice using flood irrigation. Although rice consumes close to 60% of all water earmarked for irrigation, it represents one of the lowest production values in the basin and generates fewer jobs when compared with other crops in the region [COGERH, 2006].

Associations of farmers relating to public irrigated perimeters (usually located along or downstream of large reservoirs) possess medium to high power in the water allocation process. Since many of these associations lack infrastructure (transportation, communication), they depend on support from other actors. Supporting actors include the state Water Resource Management Company (COGERH) and the Rural Extension Office for the State of Ceará (EMATERCE) [Taddei et al., In Press]. Associations related to private irrigated properties (usually located downstream of the reservoirs) also possess medium to high power. They have interests that are aligned with public irrigators (in terms of water liberation) and have good infrastructure to participate in the political process [Taddei et al., In Press]. Small farmer that work on the reservoir lands uncovered by lowering water (vazanteiros) and farmers working on small irrigated areas along small reservoirs) have little to medium power. These users tend to be poor, lack infrastructure and often do not act as a group [Taddei et al., In Press].

2.3 WATER MANAGEMENT

The current structure of water resources management in Ceará is the result of central government initiated water reforms, which were part of broader decentralization reforms which have been ongoing since the early 1990s. Kemper et al. [2007] chose the Jaguaribe basin as one of their case studies for their research on whether river basin management at the lowest appropriate level really works and what the outcomes are when it is applied. In this section, their description and conclusions regarding the Jaguaribe basin are summarized. For a more elaborate analysis on how the Jaguaribe river basin is currently managed, see Kemper et al. [2007] or Lemos & de Oliveira [2004]. Historical reviews of the administration of water in Brazil and how the issue of drought has been addressed are provided by Campos & Studart [2000, 2008].

Decentralization in the Jaguaribe basin was marked by two distinct stages: decentralization from federal to state level, including the creation of a state Water Resource Management Company (COGERH); and decentralization from state to local level, which occurred through the creation of deliberative bodies at the river basin and lower territorial levels [Kemper et al., 2007]. Responsibilities regarding planning & coordination, infrastructure operation & management, licensing water uses & allocating water supply, setting up & collecting water charges, and water quality monitoring are performed by basin scale organizations, while stakeholder involvement is organized by numerous user commissions at reservoir and valley scale and subbasin committees (Fig. 7) [Lemos & de Oliveira, 2004]. The system is funded entirely by water user charges, although those are collected by the state water management agency from users outside as well as within the basin and then reallocated to the basin [Kemper et al., 2007].

Local conditions in the Jaguaribe basin appeared to be unfavorable for decentralized water resources management. The basin is relatively poor; participatory water management ran contrary to the prevailing political culture; and Ceará state had one of the most entrenched oligarchies in the Northeast. Factors favoring reform included a national transition towards democracy, and increased promotion of integrated water resource management by the technical water resource community [Kemper et al., 2007].

The devolution of management of federal reservoirs to Ceará state (followed by delegation towards COGERH) has been effective, but devolution from state to local level (and the associated partnerships) has been more partial. Long effort to solve scarcity problems by building reservoirs was only partially successful [Kemper et al., 2007]. The creation of subbasin committees and user commissions has increased participation, but stakeholder involvement has been limited largely to negotiating water allocation and resolving conflicts. Basin committees in Ceará do not have their own executive structures (for example basin agencies) and have fewer powers than state over issues such as bulk water pricing [Kemper et al., 2007]. The financial resources of the committees and user commissions are dependent on contributions from

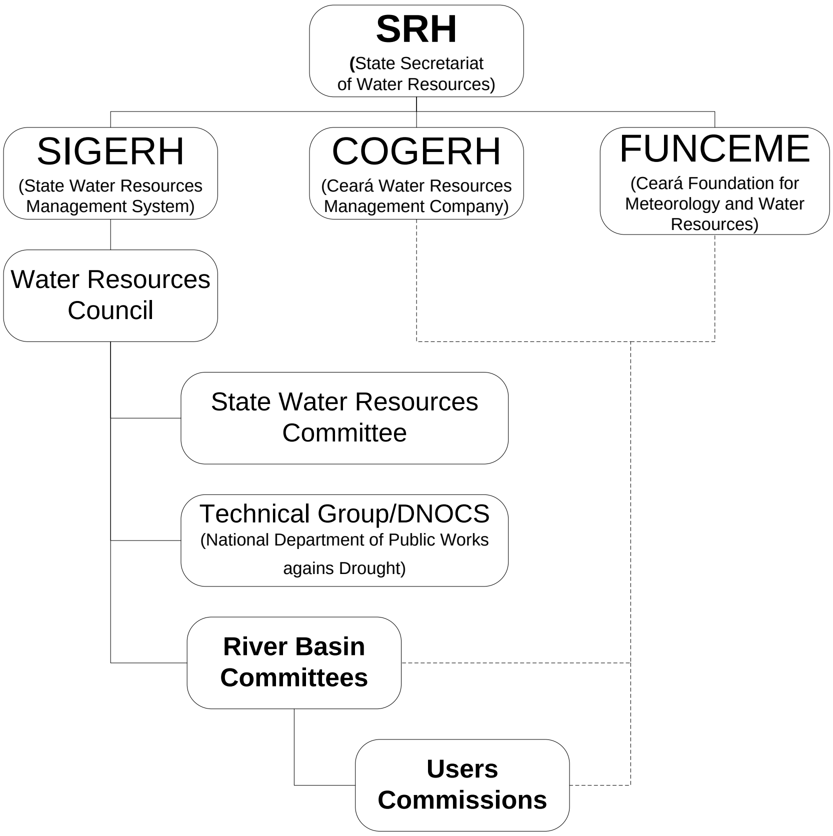


Figure 7: Simplified water resources management chart [after Lemos & de Oliveira, 2004].

state government and their members, and thus remain insecure. At the state level, though, bulk water pricing has allowed the state company to achieve financial stability for its infrastructure operations. While those state company operations bring funding into the basin, the state company also exports water from the basin for use in the Fortaleza region [Kemper et al., 2007]. The presence of large hydraulic structures throughout the state, which must be operated in close coordination if recurrent droughts are to be dealt with effectively, justifies this more centralized system. At the same time, what is particularly interesting about this approach is that although it is more centralized, local mobilization and stake-holder involvement is more intense than anywhere else in Brazil [Kemper et al., 2007].

Priority for water allocations abides by the following order: human consumption and animal consumption which is guaranteed by federal law; industry which is privileged over irrigation by state law; irrigation; fisheries [Lemos & de Oliveira, 2004, Taddei et al., In Press].

2.4 DECENTRALIZATION SCENARIOS FOR WATER MANAGEMENT

3 scenarios for water management are defined in this report representing different management strategies, corresponding to different levels of decentralization: a reference scenario, a decentralized scenario and a centralized scenario. The reference scenario consists of a continuation of the current situation as described above. Operationalization of this situation is described in Sec. 3.1, 3.2 & 3.3. The centralized and decentralized scenario share a common starting point: every farmer adjusts his area equipped for irrigation based on the ratio between his yield and his potential yield based on available water resources. They differ however in how these developments are guided by the central government. Operationalization of these two scenarios is given in Sec. 3.5. Each scenario is simulated for a 50 years period, which consists of a randomly generated sequence of years from the 1988-1998 period.

2.4.1 *Decentralized Scenario*

Under the decentralized scenario, both agricultural and water management policies are decentralized. Farmers are not restricted in their behaviour and are expected to maximize their own benefits, only being limited by the natural conditions. The only role of the central government is safeguarding the supply of water for non-irrigation demand. This scenario results in the following implications for the study area:

- Farmers will construct extra small and medium-sized reservoirs when their yields vs. potential yield ratio is low.
- No infrastructure is demolished, since there is no incentive to do so.
- Allocation of water within the system follows the reference scenario, i.e. the controlled outflow equals 0 for the small and medium reservoirs and Q_{90} for the strategic reservoirs.
- There are no restrictions on the water consumption of farmers around large reservoirs as long as their consumption does not threaten drinking water supply.

Expected large scale effects of the increase in irrigated areas around small reservoirs and in the number of small reservoirs are basically twofold: firstly, small reservoirs retain water, enabling local distributed usage, and thereby subtract it from availability to the largest and concentrated uses downstream in the river basin, e.g. facilitated through a large scale reservoir downstream in the basin, secondly, small reservoirs enhance distributed water availability.

2.4.2 *Centralized Scenario*

Under the centralized scenario, the water management policy is centralized, but the agricultural policy is not. Farmers are still expected to maximize their own benefits and are free to increase their irrigated areas and cropping patterns (which should be dealt with under agricultural policy). Supply is not only restricted by the natural conditions, but also influenced by regulations from the central government:

- No permission is given for extra small and medium-sized reservoirs.
- Priority is given to larger reservoirs: they are given the possibility to ask water from upstream.
- Use from large reservoirs is restricted if the reservoir content drops below a critical value.

These measures are aimed to stabilize water supply in the larger reservoirs in order to increase the available supply for prioritized non-irrigated demand. Although the numbers of small and medium reservoirs do not increase, increase in irrigated area for the farmers in the more upstream areas could lead to similar effects as under the decentralized scenario. However it is expected the effect on more downstream users (around and downstream of large reservoirs) is partly compensated by the possibility of water reallocation.

2.5 EVALUATION OF SCENARIOS

Based on the simulations results for the scenarios sketched above, spatio-temporal patterns in both agricultural performance and irrigation water use both over the basin and over the different types of farmers (i.e. the farmers with different sources of irrigation water) will be evaluated. How will these patterns develop over time and to what extent do the differences between the scenarios explain these developments?

3 METHOD

This chapter contains the modeling concepts used to schematize the system described in the previous chapter. The order is the same: first the physical water system and infrastructure, followed by human actions regarding water demand and water management. The final section parameterizes the decentralization scenarios sketched in the previous chapter and explains how these scenarios will be evaluated.

3.1 THE PHYSICAL WATER SYSTEM

This study focuses on the influence of human actions on the distribution of water resources. However, some natural processes need to be incorporated in order to create a useful model schematization of the natural environment. This schematization is designed to fit to the human system, consisting of water users (farmers) and water managers at different levels. Relevant processes include the generation of runoff and the distribution of this generated run-off through the network of rivers and reservoirs.

From 1994-2000, Ceará has been subject of the WAVES research project (Water Availability and Vulnerability of Ecosystems and Society in the semiarid Northeast of Brazil) [Gaiser et al., 2003]. As a result, much data on the study area has been gathered together and some models have been created and validated for the study area. The model concepts used to represent the relevant processes of the physical water system are based on the large-scale hydrological model WASA (Model of Water Availability in Semi-Arid Environments) [Güntner, 2002]. WASA is a deterministic, spatially distributed model being composed of conceptual, process-based approaches. For this study, water availability (river discharge and storage volumes in reservoirs) is determined with daily resolution and administrative units (municipalities) are chosen as spatial target units.

This section describes the main features relevant to hydrology and water resources, processes of semiarid hydrology, modelling concepts and the justification for the modelling concepts used very concisely. For a more a more elaborate version, see Güntner [2002].

3.1.1 *Climate*

This study uses the following climate characteristics of the study area:

Daily precipitation	P	Interpolated from gauging stations by Güntner [2002] [m]
Daily potential evapotranspiration	E_{pot}	Calculated using WASA [Güntner, 2002] [m]

The CROPWAT method [Allen et al., 1998], used to calculate irrigation water demand, requires daily values of precipitation and potential evapotranspiration. Although the FAO advocates the use of a standardized Pennman-Monteith method [Allen et al., 1998], Güntner [2002] uses a Shuttleworth & Wallace [1985] evapotranspiration model. The Shuttleworth-Wallace model is a two-component logical extension of the Penman-Monteith model which has been shown to perform better in a sparsely vegetated, semiarid environment [Stannard, 1993].

3.1.2 *Runoff Generation*

Whereas human actions heavily affect the discharge regimes and how water resources are distributed along the basin (Sec. 3.1.3 & 3.1.4), their influence on the actual quantity of runoff generated per municipality is negligible. Since the amount of irrigatable area per municipality is very small compared to the total area of the municipality (< 10%), alterations in the irrigating farmers' behavior will only have minor effects on the total amount of generated runoff. Therefore, we can directly use WASA [Güntner, 2002] to calculate the daily amount of runoff generated per municipality (Q_{gen} $[m^3]$) and use this as input for our model.

3.1.3 *River Network*

Municipalities are inter-connected within a dendritic river network, established by attributing to each municipality a stretch of the next major river. The routing process of river runoff through each of these units is approximated by a daily linear response function (Eq. 3.1 and Fig. 8).

$$Q_{out;j} = \sum_{i=1}^{j} Q_{in;i} * h_{j-i+1} - W_{river;j} + (P_j - E_{pot;j}) * A_{river} \quad (3.1)$$

where

$Q_{out;j}$	Daily outflow from municipality at timestep j $[m^3]$
$Q_{in;i}$	Daily inflow into municipality at timestep i $[m^3]$
h_i	Value of the response function, with $h_i > 0$ and $\sum h_i = 1$
$W_{river;j}$	Daily withdrawal from river in municipality at timestep j $[m^3/d]$
A_{river}	Surface area of river branch $[m^2]$

The response function is characterized by the parameter t_l which specifies the lag time between a runoff input to the sub-basin and the first runoff response at its outlet, and by parameter which specifies the maximum retention time in the sub-basin, i.e., the time period over which the runoff response to a given input is distributed by the routing process.

Both the structure of the network and values for t_l and t_r are obtained from Güntner [2002]. But in order to improve the spatial representation of the network, the (inter-connected) Óros and Lima Campos reservoirs have been aggregated into one large large reservoir located in the Óros municipality (Appendix B on page 83). In each municipality, direct

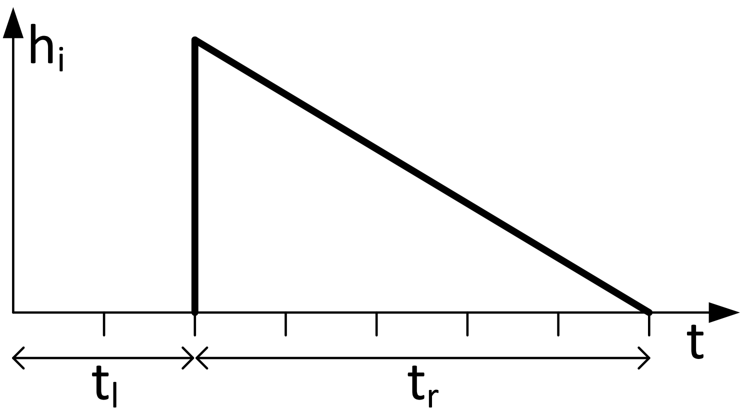


Figure 8: Scheme of the linear response function for runoff routing in the river network [after Güntner, 2002].

withdrawal from the river due to water use (Sec. 3.2.1 & 3.2.2) and evaporation losses from the river surface are subtracted from the outflow. Free water surface evaporation is assumed to equal the potential evapotranspiration (Sec. 3.1.1). Further details on the methodology for routing the river network, its parametrization and the calculation of evaporation losses are given in Güntner [2002].

3.1.4 *Reservoirs*

The natural regime of river discharge in the study area is considerably altered by human impact due to the construction of dams for water storage to supply water during the dry season. Artificial surface reservoirs have a major impact on runoff concentration and water availablity [Güntner, 2002, Güntner et al., 2004]. Krol et al. [In Press] show that small reservoirs may impact on large-scale water availability both by enhancing availability in a distributed sense and by subtracting water for large downstream user communities, e.g. served by large reservoirs.

Since they used the relatively small Benguê catchment in North-East Brazil as a case-study, Krol et al. [In Press] were able to use an explicit representation of small reservoirs. For this study however, particularly for small and medium-sized reservoirs, no detailed information on reservoir characteristics (e.g. geometry) nor on their exact location are known. Additionally, it would not be feasible to represent such a large number of individual elements explicitely in a large-scale model. This can be done only for a small number of the largest reservoirs with more detailed information (Sec. 3.1.4). Otherwise, a scheme is developed which allows to represent in an aggregate manner the effect of reservoirs on streamflow and water storage [Güntner, 2002], while pertaining some aspects of their interaction and size-dependent bevaviour (Sec. 3.1.4). For both categories, the number of reservoirs is kept constant at the most recent known levels to represent the current situation.

Small and medium-sized reservoirs

For the aggregate description of the water balance of reservoirs that cannot be represented explicitly in the model, a storage approach respecting different reservoirs size classes and their interaction via the river network is applied. In each municipio, runoff Q_{gen} enters a cascade model of reservoirs, with one-sixth of the total runoff of the municipality attributed as direct inflow to each of the five reservoir classes (classified by storage capacity). Another sixth part of the generated runoff is directly attributed to the final discharge of the municipality Q_c without retention in any reservoir class (Fig. 9). Reservoir outflow is assumed to occur only if the actual storage volume exceeds its storage capacity. This is valid particularly for small reservoirs, which are mainly simple earth dams without devices for regulated outflow. The latter may be available for some of the medium-sized dams, however, as information on operation and outflow volumes are rare, the above simplifying assumption is also applied to them [Güntner, 2002]. The water balance for reservoir class r is now calculated according to Eq. 3.2.

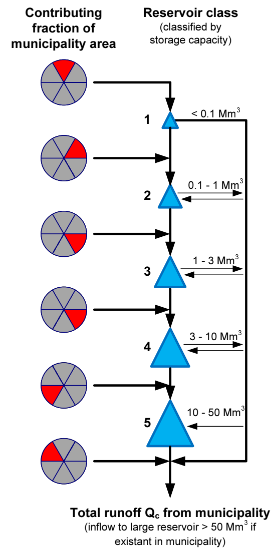


Figure 9: Cascade scheme for runoff retention and routing between small and medium-sized reservoirs in each municipality [after Güntner, 2002].

$$V_j = V_{j-1} + Q_{in;j} - Q_{out;j} - W_{r;j} + (P_j - E_{pot;j} - R_b) * A_{rm} * n_r \quad (3.2)$$

where

V_j	Total storage in reservoir class at timestep j $[m^3]$
$Q_{in;j}$	Daily inflow into reservoir class at timestep j $[m^3]$
	$= \left(\frac{Q_{gen}}{6} + \sum_{x=1}^{r-1} \frac{Q_{out;x}}{6-x} \right)$
$Q_{out;j}$	Daily outflow from reservoir class timestep j $[m^3]$
$W_{r;j}$	Daily withdrawal from reservoir class r at timestep j $[m^3]$
R_b	Daily losses to bedrock $[m]$
	$\left(R_b = \begin{cases} 0.34 * E_{pot;j} & \text{for } r \leqslant 3 \\ 0 & \text{for } r > 3 \end{cases} \right)$
A_{rm}	Water surface area of typical reservoir in class r $[m^2]$
n_r	Number of reservoirs in class r $[-]$, kept constant at the level of 1992

The total discharge from a municipality after the passage of the reservoir cascade of Fig. 9 is finally given by Eq. 3.3.

$$Q_c = \frac{Q_{gen}}{6} + \sum_{r=1}^{5} \frac{Q_{out;r}}{6-r} \quad (3.3)$$

A detailed description on the methodology for calculating the water balance and its parameterization, including a description of the volume-area relationship used, is given in Güntner [2002], Güntner et al. [2004].

Large reservoirs

For the 15 large reservoirs with a storage capacity of more than $50 \cdot 10^6$ m^3, the water balance is calculated explicitly. In our model, these reservoirs are located at larger rivers, at the most downstream location of a municipality. This approach implies that if more than one reservoir is present in a municipality, these reservoirs are modeled as a single reservoir with the combined capacity of the reservoirs present. Each large reservoir may obtain inflow Q_c from its municipality after the passage of the cascade of small and medium-sized reservoirs (Sec. 3.1.4) and inflow from upstream municipalities via the river network Q_{in} (Sec. 3.1.3). The water balance of these large reservoirs is calculated on a daily basis according to Eq. 3.4.

$$V_j = V_{j-1} + Q_c + Q_{in;j} - Q_{out;j} - W_{LR;j} + (P_j - E_{pot;j}) * A_{LR} \quad (3.4)$$

where

V_j	Reservoir volume at timestep j [m^3]
$Q_{in;j}$	Daily inflow into large reservoir (= outflow from river branch attributed to the municipality) at timestep j [m^3]
$Q_{out;j}$	Daily outflow from large reservoir timestep j [m^3]
$W_{LR;j}$	Daily withdrawal from reservoir at timestep j [m^3]
A_{LR}	Water surface area [m^2]

Reservoir outflow is composed of uncontrolled outflow over the spillway in the case that the storage capacity of the reservoir is exceeded by the actual storage volume and controlled outflow by reservoir management (Sec. 3.3.2). A detailed description on the methodology for calculating the water balance is given in Güntner [2002] and the parameter values used are listed in Appendix C on page 85.

3.2 DEMAND

Water demand is split up in irrigation demand and demand for other purposes than irrigation. These types of non-irrigated demand are quantified using the approach of Hauschild & Döll [2000] and are taken as boundary conditions for the system. Irrigation demand is calculated for each reservoir and each river branch following the method of CROPWAT [Smith, 1992]. For each supply source present in a municipio a farmer agent is created, so each municipality contains up to 8 farmers. The following types of farmers are distinguished: River Upstream (i.e. river withouth large reservoir upstream, so entirely rain dependent), small reservoir (class 1-3, storage capacity $< 3\,\mathrm{Mm}^3$), medium reservoirs (class 4-5, storage capacity $\geqslant 3\,\mathrm{Mm}^3$ and $< 50\,\mathrm{Mm}^3$), large reservoirs (storage capacity $\geqslant 50\,\mathrm{Mm}^3$) and River Downstream (with a large reservoir upstream, so controlled outflow available). Decision rules for each type of farmer are based on cropping patterns in representative municipios for years with low, normal and high water expectancy.

3.2.1 *Non-Irrigated Water Demand*

The quantification of water demand other than irrigation is based on the water use model NOWUM (Nordeste Water Use Model) [Hauschild & Döll, 2000]. They distinguish the following five water use sectors as the most important for Ceará:

- *Livestock water demand* is determined by multiplying the number of livestock and a livestock-specific water use value.
- *Domestic water demand* is calculated as a function of population number and withrawal water use per person.
- *Industrial water demand* is computed as the product of the required water volumes per production output and the industrial gross domestic product for different industry branches.
- *Touristic water demand* is determined as a function of overnight stays and withdrawal water use per tourist.
- *Irrigation water demand* is calculated following the method of CROPWAT [Smith, 1992]. It is a function of irrigated agricultural area per crop class (they distinguish 9 crop classes), climate (potential evaporation, precipitation), and a crop coefficient varying with the phenological state of the crop. In our model, 5 crop classes are differentiated and the cropping pattern depends on the decions made by the farmer agents.

The temporal resolution of water demand values varies among these four sectors as a function of the available data (e.g., monthly for touristic water demand, annual for livestock water demand). In the case that water demand data have a resolution lower than daily, they are equally distributed among all days of the given period. Actual water use per sector depends, beside of the maximum demand as explained above, on the actual water availability, i.e., withdrawal water use is reduced if available water resources area small in dry years or in the dry season (Sec. 3.3.1). Distribution of water withdrawal among different sources is controlled by global values for Ceará, given in the model SIM (about 70% from reservoirs, 20% from rivers and 10% from groundwater) [Krol et al., 2003]. Further details on the methodology for water demand calculation and its parametrization are given in Hauschild & Döll [2000]. Non-irrigated water demand is entirely attributed to the largest reservoir present in a municipality.

3.2.2 *Irrigation Water Demand*

The consumptive irrigation water demand is computed following the method of CROPWAT [Allen et al., 1998]. The total crop-water requirement (CWR $[m^3]$) for crop c in day j is the product of a growing stage dependent crop coefficient (K_c $[-]$), the potential evapotranspiration (ET_0 $[m]$) and the planted area (A $[m^2]$):

$$CWR_{c,j} = K_{c,j} * ET_{0,j} * A_{c,j} \tag{3.5}$$

The CWR can either be met through irrigation or precipitation. Using effective precipitation (P_{eff} $[m]$) instead of total precipitation (P $[m]$) takes into account that not all the rain is available to the crops. According to the USDA Soil Conservation Service Method (as given in [Smith, 1992]):

$$P_{eff} = \begin{cases} \frac{P(4.17-0.2P)}{4.17} & \text{for } P \leqslant 8.3\,\mathrm{mm/d} \\ 4.17 + 0.1P & \text{for } P > 8.3\,\mathrm{mm/d} \end{cases} \tag{3.6}$$

The irrigation water demand (D_{irr}) now equals the total crop water requirement minus the fraction supplied by effective precipitation:

$$D_{irr;c,j} = CWR_{c,j} - P_{eff} * A_{c,j} \tag{3.7}$$

Crop-specific data

Based on the IBGE [2010] database of municipal agricultural production, the crops given in Table 2 are identified to be representative for agriculture in the Jaguaribe basin. For each of these crops, data required are data like planting date, growing periods and crop coefficients per growing period. The crop-specific planting date was derived from the agricultural calender published by the Banco do Nordeste [2005] while data on crops coefficients and length of growing period are taken from CROPWAT [Smith, 1992].

Crop	Type	Water intensity
Maize	Temporary subsistence crop, 1 growing season / year	Medium
Beans	Temporary subsistence crop, 1-2 growing season / year	Low
Rice	Temporary subsistence crop, 1 growing season / year	Very high
Tomatoes	Temporary cash crop, 1 growing season / year	High
Banana	Permanent crop	High

Table 2: Representative crops for the Jaguaribe basin [IBGE, 2010].

Irrigated area

Information about the size of irrigated areas at municipal level in Ceará diverges widely. The Agricultural Census the IBGE [2006] provides information for all municipalities in Ceará. However, according to Hauschild & Döll [2000], Brazilian experts say that the total irrigated

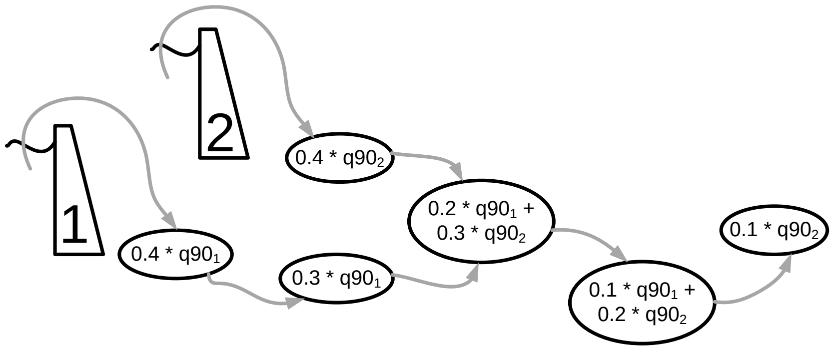


Figure 10: Distribution of Q90 for the allocation of irrigation areas in the downstream cascade of municipalities.

areas published by IBGE [2006] are strongly overestimated. Comparing IBGE [2006] data on irrigated areas and their own data on total planted area supports this conclusion: for most municipalities the irrigated area even exceeds the total area planted. Therefore, in this study the data on irrigated areas as prepared by Hauschild & Döll [2000] is used. They considered the most reliable information to come from COGERH [1998], together with downscaled IBGE data considering expert knowledge for lacking data in 23 municipalities.

The total area equiped for irrigation is allocated along the farmer types by estimating their fraction of the total water availability. The following indicators have been used to estimate the fraction of total water availability per supply source:

- *River US*: one sixth (the part that does not contribute to the recharge of small and medium reservoirs) times the area of the municipality times the mean effective daily precipitation over the 1990-2008 period [FUNCEME, 2010] times 90 days (the growing period of beans)
- *Small, medium and large reservoirs*: the storage capacity of the reservoirs in the reservoir class under consideration
- *River DS*: 90 days (the growing period of beans) * (40 % of the controlled outflow of the large reservoirs directly upstream + 30% of large reservoirs one step further upstream in the network + 20% of each large reservoir 3 branches upstream and 10% of large reservoirs 4 branches upstream (Fig. 10).

Farmer decision making

Each type of farmer is provided with a set of rules for decision making. These rules govern the area of land to be irrigated and the type of crop to grow. Water expectancy has been shown to be important in farmer decision making regarding crop choice and the area of land to irrigate. Key elements of a farmer's water expectation include rainfall expectation, quantity of stored water resources and flood risk Taddei et al. [2008]. The importance of these key elements varies with the source of water supply. In order to provide each farmer type, differentiated on its primary source of irrigation water, with an adequate set of rules, representative municipios are identified. In these municipios (locations shown in Appendix B on page 83), irrigation is dominated by a single supply source:

- *Rivers - upstream:* low water stability, no storage capacity, so water expectancy depends entirely on rainfall expectancy. Altaneira is used as representative municipality (located completely upstream, no storage capacity);
- *Small reservoirs:* limited water stability and storage capacity limited, so water expectancy depends on a combination of rainfall expectancy and the quantity of water stored. Aiuaba is used as representative municipality (considerable storage capacity, but all in reservoir class 1-3);
- *Medium reservoirs:* high water stability and storage capacity, some competition from non-irrigated demand. Tauá is used as representative municipality (high storage capacity, 67% in reservoir class 4-5);
- *Large reservoirs:* highest water stability and storage capacity, competition from non-irrigated demand. Icó is used as representative municipio (agriculture concentrated around the Óros-Lima Campos reservoir system);
- *River - downstream:* similar to large reservoirs, but supply is limited to the outflow of upstream large reservoir. The only differences with large reservoir farmers is their source of irrigation water.

For each representative municipio, cropping patterns for low, normal and high water expectancies are compared for the 1990-2008 period. Water expectancy is determined using the amount rainfall between 1 January and 31 March (the ending of the planting season), which is obtained from FUNCEME [2010]. Water expectancy is considered low if the rainfall falls in the bottom 33% of the total range and wet if it falls in the upper 33%. Normal years are neither dry, nor wet. Cropping patterns for temporary crops are obtained from the IBGE [2010] and corrected for (linear) long-term trends. Since the cropping patterns published by the IBGE [2010] include data on rainfed agriculture, they are not representative for irrigated area: especially the fraction of rice is much too low. Therefore, a correction is performed under the assumption that the complete areal of rice is irrigated, but only 8% of the all other temporal crops c (based on the IBGE [1996]: 92% of the farmers in Ceará has no access to irrigation):

$$A_{irr;temp} = \sum A_{irr;c} \text{ with } A_{irr;c} = \begin{cases} A_{IBGE;c} & \text{for } c = \text{rice} \\ 0.08 * A_{IBGE;c} & \text{for } c \neq \text{rice} \end{cases}$$

Since no reliable data on the cropping patterns specific for irrigated area are available, validating these rules remains difficult. However, cropping patterns found after these operations show similarity with known data from both COGERH [2006] (45% of the total irrigated area in the basin planted with rice) and Taddei et al. [2008] (50 - 67% of the irrigated area around the Óros-Lima Campos reservoir system planted with rice). Table 3 provides an overview of the resulting fraction of the area used for irigated agriculture and crop patterns for temporary crops as a function of irrigated area and water expectancy.

	Water Expectancy:	*Fraction of the area used for irrigated agriculture*	*Crop area as a function of irrigated area used for temporary crops (summation over crops equals 100%)*			
			Rice	Beans	Maize	Tomato
River	Dry	0.98	41%	21%	30%	8%
	Normal	1.00	42%	22%	29%	7%
	Wet	0.78	36%	18%	33%	13%
(Small) Reservoirs (class 1-3)	Dry	0.96	8%	38%	47%	7%
	Normal	0.98	9%	39%	44%	8%
	Wet	1.00	8%	40%	46%	6%
(Medium) Reservoirs (class 4-5)	Dry	0.84	3%	42%	51%	4%
	Normal	1.00	6%	41%	49%	4%
	Wet	0.96	2%	43%	52%	3%
Large Reservoirs	Dry	0.76	47%	25%	26%	2%
	Normal	0.84	51%	24%	23%	2%
	Wet	1.00	60%	20%	19%	1%

Table 3: Land use variation under different levels of water expectancy.

Figure 11 shows a flowchart of farmer decison making on land use for their available areal. Implementation of the rules from Figure 11 for the different farmer types is described in Table 4. Everyone farmer checks the area available to him for planting tempory crops: this equals the total area available for irrigation minus the area planted with banana. His following step is to determine what fraction of the total area available for temporary crops to irrigate, based on his water expectancy (according to Table 4). Finally he will plant his temporary crops according to distributions of crop choices in Table 3.

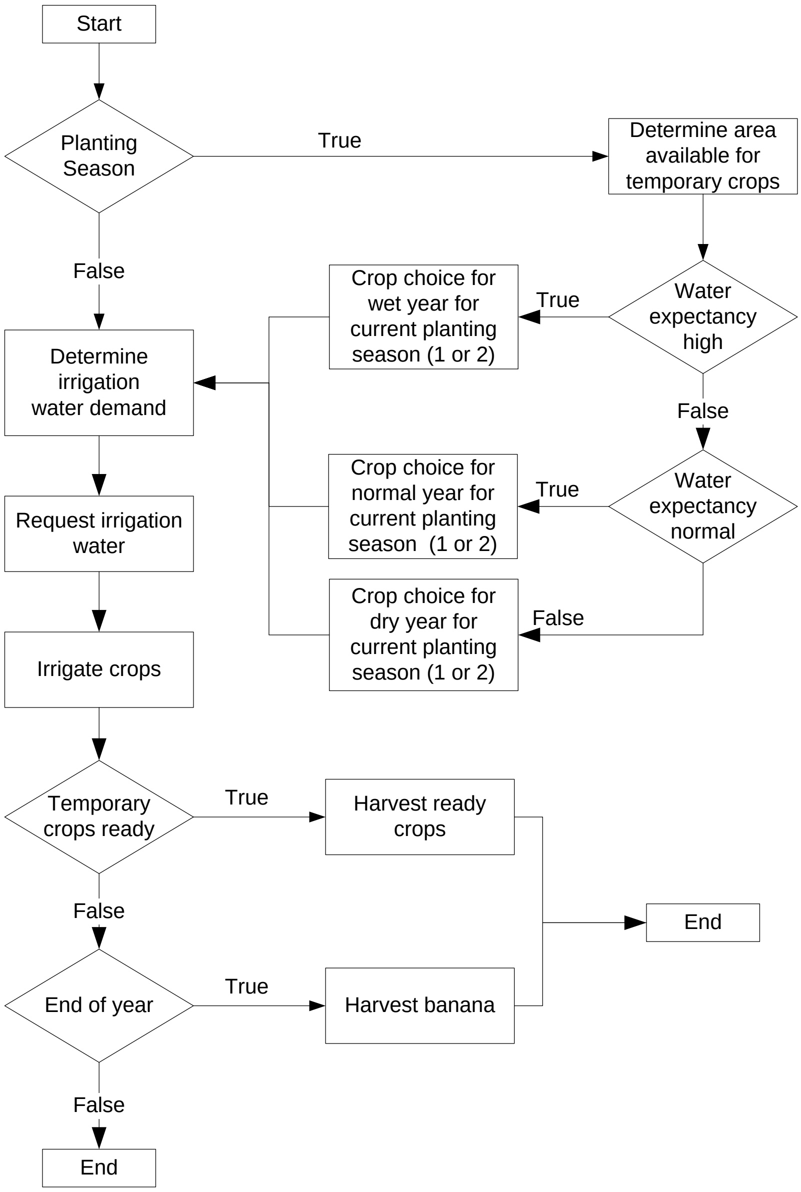


Figure 11: Land use decision making flowchart. This flowchart applies to all farmers, but the implementation of decision rules (Table 4) and crop choice (Table 3) depend on the source of irrigation water supply.

	Farmer type				
	River US	Res. 1-3	Res. 4-5	LR	River DS
1st planting season (wet season)	Rainfall > 20 mm in 10 days & date between 15 Janaury and 31 March	Rainfall > 15 mm in 10 days & date between 15 Janaury and 31 March	Rainfall > 10 mm in 10 days & date between 15 Janaury and 31 March	Date between 15 Janaury and 31 March	Date between 15 Janaury and 31 March
2nd planting season (dry season)	No 2nd planting season available	At least 30 days after harvesting the wet season crop, date < 15 August and reservoir volume at planting date > 85% of storage capacity	At least 30 days after harvesting the wet season crop and date < 15 August	At least 30 days after harvesting the wet season crop and date < 15 August	At least 30 days after harvesting the wet season crop and date < 15 August
Wet year expected	Rainfall in last 90 days > upper 33% of rainfall between 1 January and 31 March for his municipality	Rainfall in last 90 days > upper 33% of rainfall between 1 January and 31 March for his municipality	Reservoir volume at planting date > 80% of capacity	Reservoir volume at planting date > 75% of capacity	Average Qoutlake last 30 days $\geqslant 1.25 * q90$
Normal year expected	Rainfall in last 90 days > upper 67% of rainfall between 1 January and 31 March for his municipality	Rainfall in last 90 days > upper 67% of rainfall between 1 January and 31 March for his municipality	Reservoir volume at planting date > 60% of capacity	Reservoir volume at planting date > 50% of capacity	Average Qoutlake last 30 days $\geqslant q90$

Table 4: Rule implementation for farmers with different irrigation water supply sources. Rules pertain to the choices and processes of Fig. 11.

Effects of water scarcity on productivity

If the demand for irrigation water is larger than the amount of water available, water scarcity occurs. Under the reference scenario, the water available is allocated over the different crops based on the based on the demand for each crop. The part of the crop water requirement for crop c in day d that remains unfulfilled by either precipitation (P) or irrigation (IRR) is called the deficit irrigation (IRR_{def}):

$$IRR_{def;c,d} = max\left(CWR_{c,d} - P_{eff;d} - IRR_{c,d}, 0\right) \tag{3.8}$$

If there is deficit irrigation then the crop yield is reduced. The magnitude of the deficit is expressed as the quotient of the deficit irrigation and the crop water requirement ($DIRR_{c,d}/CWR_{c,d}$), which is called the K_r value. In reality it matters much in what stage of the growing period the water deficit occurs, but both Carr [2009] and Berger [2001] show that an averaged linear relation works reasonably well. The quotients of deficit irrigation and the crop water requirement are simply averaged over all months with non-zero crop water requirements:

$$K_{r,c} = \left(1/d * \sum \frac{IRR_{def;c,d}}{CWR_{c,d}} \mid CWR_{c,d} > 0 \right) \tag{3.9}$$

Following Berger [2001], it is assumed that the crop yield is lost completely if the average K_r falls below 0.5, while for K_r values greater than or equal to 0.5 the average K_r value is multiplied by the crop yield potential ($Y_{pot;c}$) obtained from Doorenbos & Kassam [1979] to simulate the actual crop yield (Y_c):

$$Y_c = \begin{cases} K_{r,c} * Y_{pot;c} & \text{for } K_{r,c} \geqslant 0.5 \\ 0 & \text{for } K_{r,c} < 0.5 \end{cases} \tag{3.10}$$

3.3 water management

3.3.1 *Prioritization of Water Use*

Priority for water allocations abides by the following order: human consumption and animal consumption which is guaranteed by federal law; industry which is privileged over irrigation by state law; irrigation; fisheries [Lemos & de Oliveira, 2004, Taddei et al., In Press]. Since drinking water, water for live stock and water for industry make up for the major amount of non-irrigated water use per municipio (> 90%), it is assumed that all non-irrigated demand comes first in the water allocating process.

In each municipality, a water manager is located who aimes to guarantee water supply for non-irrigated demand. He tries to do so by reserving the amount of water needed for non-irrigated supply until 1 january of the next year (the start of the next wet season) from the largest reservoir class present in his municipality. If there is more water present than the amount of water that is reserved, the rest is available for irrigation. If not, the farmers will get no water.

3.3.2 *Controlled Reservoir Outflow*

Following the approach of Güntner [2002], controlled outflow for the small and medium-sized reservoirs is set to zero. For the large controlled outflow is a fraction of Q90, i.e., the annual runoff from a reservoir which is provided with a probability of 90% (in 90% of all years). This fraction f_Q is set to 0.8 for so-called strategic reservoirs (i.e., reservoirs with a storage capacity greater than than 300 Mm^3, and reservoirs important for water supply of the metropolitan area of Fortaleza), and is set to 0.9 for the other large dams. If the actual storage volume of the reservoir falls below a reservoir-specific alert volume , the above outflow is reduced by a factor f_{al}, defined as:

$$f_{al} = (V_i - V_{min})/(V_{al} - V_{min}) \tag{3.11}$$

where

V_i	Reservoir volume at timestep j [m^3]
V_{min}	Dead volume of reservoir below which outflow equals 0 [m^3]
V_{al}	Reservoir-specific alert volume [m^3]

For reservoirs for which the above information was not available, V_{al} and/or V_{min} are set to respectively 20% and 5% of the reservoir capacity.

3.4 VALIDATION

3.4.1 *Water Availability*

With respect to the validation of overall water balance between observed and simulated discharges, the representation of long term discharged volumes, the commonly used Relative Volume Error (RVE) is selected. The RVE is given by Equation 3.12. The RVE is either given as a percentage or a fraction of observed discharge. A RVE of zero indicates total simulated discharge equals observed discharge. Negative and positive RVEs indicate under- and overestimation of simulated discharges respectively.

With respect to the other aspects of agreement of the discharges and for the validation of reservoir volumes, the index of agreement d is selected. The index of agreement was proposed by Willmott [1981] to overcome the insensitivity of the Nash-Sutcliffe efficiency E and the coefficient of determination r^2 to differences in the observed and predicted means and variances [Legates & McCabe Jr., 1999]. The index of agreement represents the ratio of the mean square error and the potential error Willmott [1981] and is defined as Equation 3.13. The potential error in the denominator represents the largest value that the squared difference of each pair can attain. The range of d is similar to that of r^2 and lies between 0 (no correlation) and 1 (perfect fit).

$$RVE = 1 - \frac{\sum_{i=1}^{n} (Q_{sim;i} - Q_{obs;i})}{\sum_{i=1}^{n} Q_{obs;i}} \tag{3.12}$$

$$d = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs;i} - Q_{sim;i}\right)^2}{\sum_{i=1}^{n} \left(\left|Q_{sim;i} - \overline{Q_{obs}}\right| - \left|Q_{obs;i} - \overline{Q_{obs}}\right|\right)^2} \tag{3.13}$$

where

RVE	Relative Volume Error [−]
d	Index of agreement [−]
$Q_{sim;i}$	Simulated mean discharge at timestep i [m^3/s]
$Q_{obs;i}$	Observed mean discharge at timestep i [m^3/s]

3.4.2 *Water use*

For the validation of the ration between water use and yield, the Water Footprint (WFP) concept [Hoekstra & Chapagain, 2008] is used. The WFP represents the so-called virtual water content, which is a measure for the actual volume of water used to produce a commodity and that is virtually embedded in it [Hoekstra & Chapagain, 2008]. Since in essence this corresponds to the total use divided by the yield, two characteristics tracked in Tamandua for each farmer, Tamandua provides the functionality of calculating the WFPs. Although the approach used is somewhat simplified compared to the method described in the Water Footprint manual [Hoekstra et al., 2009], we can use the WFP to check whether our ratios between water use and yield are realistic for each crop.

The following three components of the Water Footprints are distinguished [Hoekstra & Chapagain, 2008]:

- Green water is consists of evapotranspiration of rainwater and soil moisture. In Tamandua, this is the fraction of the effective precipitation that is consumed by a crop.
- Blue water is the quantity of ground and surface water used for irrigation. In Tamandua, this corresponds with the total quantity of water supplied to a farmer out of his supply source.
- Grey water is the quantity of water needed to dilute polluted ground and surface waters (for instance due to fertilizer or pesticides) until environmental norms are reached. Currently, Tamandua does not provide the functionality to determine the amount of grey water.

3.5 DECENTRALIZATION SCENARIOS FOR WATER MANAGEMENT

As initialization, the model is run using the current situation for the 1988-1998 period. Next, each scenario is simulated for a 50 years period, which consists of a random generated sequence of years from the 1988-1998 period (Table 5). A random seed is applied to ensure that all scenarios are subject to the same sequence of years.

Year 1-5:	1989	1997	1988	1994	1990
Year 6-10:	1989	1988	1989	1995	1992
Year 11-15:	1995	1997	1996	1994	1990
Year 16-20:	1998	1995	1996	1993	1992
Year 21-25:	1993	1991	1993	1997	1997
Year 26-30:	1995	1988	1996	1998	1997
Year 31-35:	1996	1995	1993	1996	1988
Year 36-40:	1993	1988	1995	1995	1988
Year 41-45:	1995	1990	1997	1994	1993
Year 46-50:	1993	1993	1989	1996	1989

Table 5: Generated sequence of simulation years

3.5.1 *Reference Scenario*

The reference scenario is a continuation of the current situation as described in Sec. 3.1, 3.2 & 3.3. No changes in parametrization are applied.

3.5.2 *Decentralization*

Under the decentralization scenario, each farmer adjusts his available area for irrigation based on his yields for the last 5 years as shown in Eq. 3.14. The area planted with banana for the farmer is multiplied with the same factor as the total area. The number of reservoirs in reservoir classes 1-5 keeps up with increasing irrigation areas following Eq. 3.15, maintaining the ratio of storage capacity and area as during the first year the number of reservoirs increases. Updates take place at the end of each year and no further adjustments are made in farmer and water manager behavior.

$$A_{i+1} = \begin{cases} 1.05 * A_i & \text{if } R > 0.85 \\ 1.00 * A_i & \text{if } R > 0.7 \\ 0.95 * A_i & \text{if } R \leqslant 0.7 \end{cases} \tag{3.14}$$

$$n_{r;i+1} = \begin{cases} \left\| \frac{n_{r;j}}{A_{r;j}} * A_{r;i+1} \right\| & \text{if } \left\| \frac{n_{r;j}}{A_{r;j}} * A_{r;i+1} \right\| > n_{r;i} \\ n_{r;i} & \text{if } \left\| \frac{n_{r;j}}{A_{r;j}} * A_{r;i+1} \right\| \leqslant n_{r;i} \end{cases} \tag{3.15}$$

where

A_i	Total irrigatable area of a farmer in year $i[ha]$
R	Result of the last 5 years

$$\left(R = \frac{\sum_{h=0}^{4} \frac{\sum_c (p_c * Y_{i-h;c})}{\sum_c (p_c * Y_{i-h;pot;c})}}{5} \right)$$

p_c	Price of crop c (Sec. 4.4.4)
$Y_{i-h;c}$	Yield of crop c in year $i - h$ [ton]
$Y_{i-h;pot;c}$	Crop yield potential of crop c in year $i - h$ [ton]
$n_{r;i}$	Number of reservoirs in class r in year i [−]
j	The first year in which $R_5 \leqslant 0.7$

3.5.3 *Centralization*

Under the centralization scenarios, farmers adjust their area the same way as they do under the decentralization scenario (Eq. 3.14). However, the numbers of reservoirs in each class stays at the same level as at the beginning. Reallocation of water in the basin is governed by the heuristics provided in Table 6. Q_{extra}equals the additional controlled outflow in case a request for water is honored. Extra condition for passing water on downstream is that it is not yet reserved for prioritized non-irrigated demand.

	Able	Ask if:	Give if:	Q_{extra}
Large reservoirs	LRs upstream Class 4/5 (the largest being present) in municipalities $\leqslant$ 1 branch upstream	$V < 0.35V_{max}$	$V > 0.6V_{max}$	$2 * Q_{90}$
Class 5	Class 4 in its own municiapility	$V < 0.3V_{max}$	$V > 0.55V_{max}$	$3\ m^3/s * n5$
Class 4	-	-	$V > 0.55V_{max}$	$1\ m^3/s * n4$

Table 6: Heuristics for water allocation between reservoirs.

3.6 EVALUATION OF SCENARIOS

To measure agricultural performance and water use in the basin three indicators are used, following Conway [1987]. This is done for all 80 municipal districts. The three indicators are:

- Productivity (P): the average annual value generated per hectare or per cubic meter irrigation water used. To unify the output of various agricultural products, their monetary value is used. This value is based on average prices for each agricultural product for the period 1994-1998 (Table 7,IBGE 2010).
- Stability (S) of productivity: the annual variation of productivity over the simulation period. Use is made of the coefficient of variation (CV). Stability is defined as: $S = 1/CV$.
- Equitability (E) of productivity both over the municipalities and over the different supply sources. Use is made of the Gini-coefficient Gini [1912], for which the agricultural income from the farmers in the basin are taken into account. Equitability is defined as: $E = 1 - Gini$ with $0 \leqslant Gini \leqslant 1$.

3.7 SENSITIVITY ANALYSIS

The model describing water availability depends heavily on the cascade scheme in which small and medium reservoirs are aggregated (Sec. 3.1.4). Güntner [2002] has shown that WASA is generally well able to represent the hydrological behaviour of the semi-arid study area in terms of discharge and reservoir storage. However, the cascade scheme used is chosen arbitrarely and models using a similar cascading scheme may function equally well. The cascade scheme of Güntner [2002] may be too favorable for the farmers around the higher reservoir classes and sensitivity of the system for the scheme used may be high.

The sensitivity for this cascade scheme is studied by defining 2 alternative schemes. Alternative A is similar to the scheme used by Guntner (Table 8a), except the coefficients corresponding to the fraction of the total inflow that flows into a certain class decrease with the reservoir class (Table 8b). In alternative B, the complete fraction of runoff entering the cascade will flow into reservoir class 1 (Table 8c). Total outflow from each reservoir class will flow into the next class. The fraction of the generated runoff that flows directly into the river is kept constant for all schemes (1/6).

	Rice	Beans	Maize	Tomato	Banana
Price R$/kg	0.52	0.59	0.58	0.78	1.28

Table 7: Average prices for each crop class for the period 1994-1998 [IBGE, 2010].

		Outflow from					
		Run-off	1	2	3	4	5
Inflow into	1	1/6	-	-	-	-	-
	2	1/6	1/5	-	-	-	-
	3	1/6	1/5	1/4	-	-	-
	4	1/6	1/5	1/4	1/3	-	-
	5	1/6	1/5	1/4	1/3	1/2	-
	River	1/6	1/5	1/4	1/3	1/2	1
	Total	1	1	1	1	1	1

(a) Original scheme by Güntner et al. [2004], coefficients resulting from Eq. 3.3.

		Outflow from					
		Run-off	1	2	3	4	5
Inflow into	1	1/6	-	-	-	-	-
	2	1/6	5/15	-	-	-	-
	3	1/6	4/15	4/10	-	-	-
	4	1/6	3/15	3/10	3/6	-	-
	5	1/6	2/15	2/10	2/6	2/3	-
	River	1/6	1/15	1/10	1/6	1/3	1
	Total	1	1	1	1	1	1

(b) Alternative A: Scheme using fractions that decrease with reservoir class.

		Outflow from					
		Run-off	1	2	3	4	5
Inflow into	1	1/6	-	-	-	-	-
	2	1/6	1	-	-	-	-
	3	1/6	0	1	-	-	-
	4	1/6	0	0	1	-	-
	5	1/6	0	0	0	1	-
	River	1/6	0	0	0	0	1
	Total	1	1	1	1	1	1

(c) Alternative A: Scheme with all inflow into reservoir class 1, all outflow from each class flows directly into the next class.

Table 8: Alternative cascade schemes for sensitivity analysis.

4 SIMULATION RESULTS & VALIDATION

This chapter contains the simulation results. First the validity of the simulated water availability and water demand is discussed. This is followed by an overview of results regarding the physical water system and the results pertaining to the human actions that determine water demand (i.e. agriculture). Finally, the sensitivity of the results for the cascade scheme used to represent small and medium reservoirs is analyzed.

4.1 VALIDATION OF WATER AVAILABILITY

4.1.1 *River Discharges*

Hydrographs showing the observed and simulated river discharges for for all nine flow measuring stations (Fig. 6 on page 11) are provided in Appendix D on page 87. Simulation of the discharge patterns is qualitively reasonable: the timing of peak flows and low flows and low flows is predicted correctly. As indicated by the indexes of agreement, given in Table 9, quantitatively the results are moderate to poor, possibly due to biased precipitation/runoff data. In general, prediction improves with downstreamness [Van Oel et al., 2009].

The RVEs show an overprediction of discharges in the Upper Jaguaribe and Banabuiú subbasins (West, Fig. 5d) and an underprediction of the discharges in the Middle Jaguaribe and Salgado subbasins (East, Fig. 5d). During peak flows, both underpredictions and overpredictions occur. This does not influence the water availability for river farmers since they have no options for storing the water. It can however negatively affect the predictions for the reservoir volumes of the large reservoirs.

Low flows during the dry season tend to be overpredicted, especially for the more upstream located measurement stations (8, 9). This implies that in our model, the amount of water available for farmers depending on the river as their main source of irrigation water is likely to be overpredicted.

Measurement Station	ID	Discharge from municipalities	RVE	d
1	36390000	São João do Jaguaribe	-12.7	0.60
2	36320000	Icó	-13.0	0.78
3	36160000	Cariús	24.9	0.70
4	36580000	Ibicuitinga + Banabuiú	32.6	0.85
5	36290000	Cedro + Lavras da Mangabeira + Umari	-55.3	0.55
6	36520000	Boa Viagem	41.0	0.62
7	36470000	Piquet Carneiro	12.8	0.60
8	36045000	Aiuaba + Antonina do Norte	80.6	0.50
9	36250000	Abaiara + Brejo Santo + Mauriti	-8.2	0.27

Table 9: RVE and index of agreement between simulated and observed discharges (ID's from ANA [2010]).

Municipalities	Reservoirs	d
Senador Pompeu	Patu	0.95
Quixeramobim	Quixeramobim & Fogareiro	0.70
Quixadá	Cedro & Pedras Brancas	0.95
Campos Sales	Poço da Pedra	0.87
Alto Santo	Castanhão	-
Tauá	Várzea do Boi	0.51
Brejo Santo	Atalho	0.18
Iguatu	Trussu	0.40
Orós	Orós & Lima Campos	0.91
Banabuiú	Banabuiú	0.40
Morada Nova	Cipoada & Poço da Barro	0.36
Solonópole	Riacho do Sangue	0.84
Assaré	Canoas	-

Table 10: Index of agreement between simulated and observed reservoir volumes.

4.1.2 *Reservoir Volumes*

Graphs showing the observed and simulated reservoir volumes for all large reservoirs are provided in Appendix E on page 93. As indicated by the indexes of agreement, given in Table 10, the quality of the simulated reservoir volumes varies widely. For the Patu, Orós + Lima Campos, Cedro + Pedras Brancas and Riacho de Sangue reservoirs, the simulated data shows good to very good agreement with observed reservoir volumes. For the Poço de Pedra, Varzea do Boi, Atalho and Trussu quantitively the simulation results are moderate to poor. The differences in gradient between observed and simulated reservoir volumes suggest presence of biasses in controlled reservoir outflow.

For the Banabuiú reservoir, the pattern in the simulated reservoir volumes corresponds with the pattern in the observed reservoir volumes. However, there is a systematic overprediction of the reservoir volume probably due to biased river discharges, since the RVEs at the flow measurement stations upstream suggest considerable overprediction in the Banabuiú subbasin (Sec. 4.1.1).

In our simulation, the Cipoada + Poço do Barro reservoir combinations remains completely full during the whole simulation period. Underlying cause is the controlled outflow of the upstream located Banabuiú reservoir, which is larger than controlled outflow + evaporation + consumption during the whole simulation period. For the Quixeramobim + Fogareiro reservoir combination, the amount of observed reservoir volumes is too small to compare. No data on observed volumes is available for the Canoas and Castanhão reservoirs, since they were not yet constructed during the simulation period.

4.2 VALIDATION OF IRRIGATION WATER USE

4.2.1 *Water Footprint*

The WFPs off all five crops show large variation, but for all crops the range is similar to the values found by Chapagain & Hoekstra [2004]. According to our simulations, the average WFPs for beans and banana are lower than the average footprints for these crops in both Brazil and the world. Tomato and maize on the other hand show higher WFPs than the averages found by Chapagain & Hoekstra [2004]. Rice is almost exactly the same as the global average, but lower than the average found for Brazil.

The large ranges can be explained by large variation in both water consumption (differences in potential evapotranspiration in time and space) and in yield (yield is reduced under water-scarce conditions). For most crops, the share of green water (especially important during the wet season) and blue water (important during the dry season) is of almost equal importance, except beans which do rely more on the green water.

	Green WFP [m3/ton]	Blue WFP [m3/ton]	Blue + Green WFP (min. / av. / max.) [m3/ton]	Blue + Green WFP [Chapagain & Hoekstra, 2004] (Brazil / global average) [m3/ton]
Rice	1220	938	1273 / 2137 / 3146	3082 / 2291
Beans	2027	1349	2128 / 3374 / 5434	3955 / 4253
Maize	928	664	887 / 1572 / 2420	1180 / 909
Tomato	140	105	145 / 242 / 366	73 / 184
Banana	369	308	583 / 671 / 950	1188 / 859

Table 11: Comparison of simulated water footprints and the study of Chapagain & Hoekstra [2004].

	Res. Class				
Storage capacity / area [m^3/m]	1	2	3	4	5
$\alpha < 1$	3	4	2	1	1
$1 \leqslant \alpha \leqslant 2.5$	3	3	1	0	0
$2.5 \leqslant \alpha \leqslant 5$	7	8	7	4	3
$5 \leqslant \alpha \leqslant 7.5$	4	5	5	2	2
$7.5 \leqslant \alpha \leqslant 10$	1	2	1	1	1
$\alpha > 10$	49	53	44	29	22

Table 12: Frequency table: α corresponds to the storage capacity in a reservoir class available to a farmer divided by his area equiped for irrigation in the initial situation.

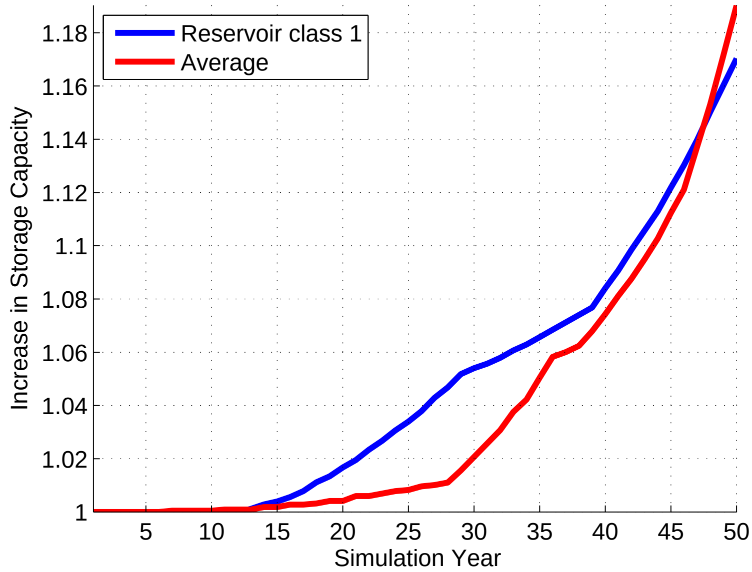
4.3 RESULTS PHYSICAL WATER SYSTEM

4.3.1 *Storage Capacity Small and Medium Reservoirs*

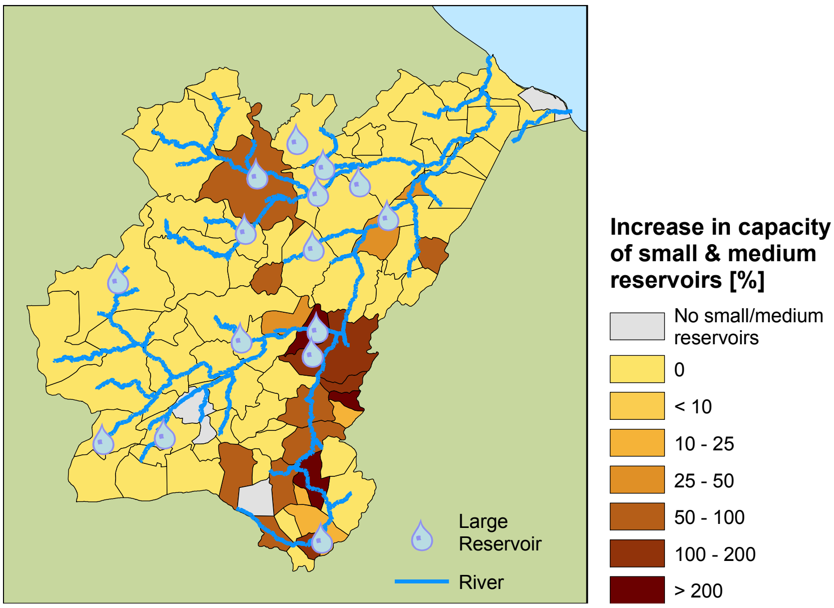
It takes some time before the number of reservoirs starts to increase. After about 10 years, the increase becomes visible for the smallest reservoirs (class 1), but it does not keep on accelerating exponentially; apparently some saturation is caused by the yield feedback. The number of reservoirs in other reservoir classes does not show a substantial increase during the first 30 years of the simulation. However, when the growth has been initiated, it catches up with the growth in class 1. After 50 years of simulation, the total storage capacity in the basin has increased by almost 20%.

Compared to the increase in irrigated areas for the farmers using these reservoirs for their water supply (from 500% for the class 5 farmers up to 1000% for the class 1 farmers; Fig. 15) this increase is very small. This could be explained by the overcapacity of the reservoirs: the vast majority of farmers has reservoirs available with a storage capacity corresponding to over 10 meters of water (Table 12)! Another major ... of importance i

While looking at the map (Fig. 12b), it can be seen that the increase is not evenly distributed over the basin. The municipalities in the Salgado subbasin (South-East, Fig. 5d) alone are responsible for almost the entire growth. In some of these municipalities, total growth equals more than 200%. In the other subbasins, most municipalities do not show an increase in storage capacity at all.

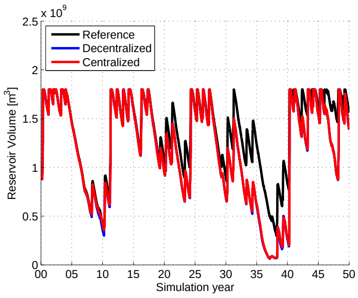


(a) Development of different reservoir classes in time.

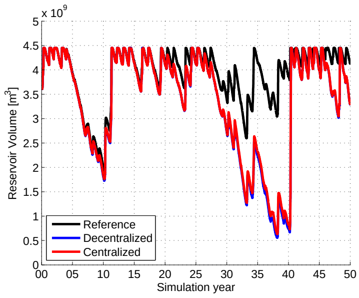


(b) Total increase in storage capacity over the basin.

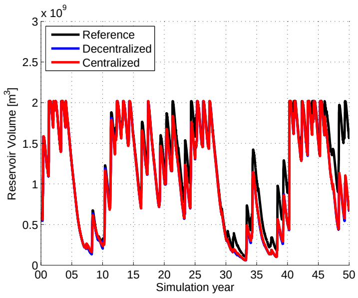
Figure 12: Storage capacity in small and medium-sized reservoirs.



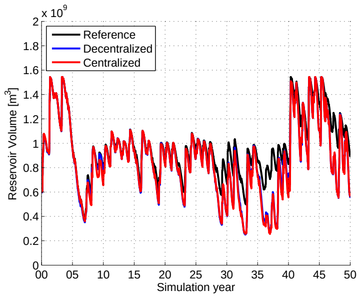
(a) Banabuiú.



(b) Castanhão.



(c) Orós.



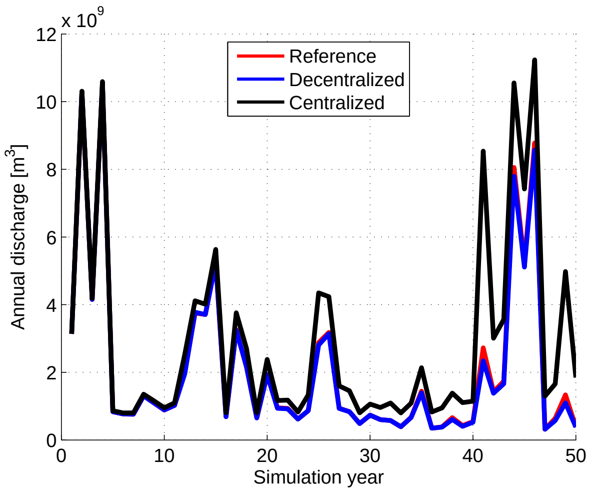
(d) Other large reservoirs summated.

Figure 13: Stored reservoir volumes in large reservoirs.

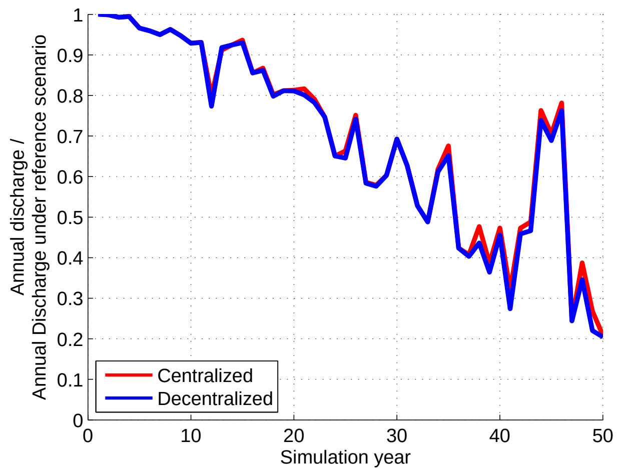
4.3.2 *Reservoir Volumes of Large Reservoirs*

During the first 25 years of the simulation, reservoir volumes show the same pattern for all scenarios (Fig. 13). During the second half however, considerable differences start to develop quite suddenly. Reservoir volumes during dry periods are much lower for the centralized and decentralized scenarios. The biggest difference can be observed in the most downstream located reservoir: Castanhão. For the Orós-Lima Campos reservoir system, it takes even longer to reach this turning point: substantial differences only occur during the last five years of the simulation.

A difference between the centralized and decentralized scenarios is hardly noticeable. Reservoir volumes tend to be slightly higher under the centralized scenario (best visible for Castanhão, Fig. 13b): possibly an effect of the reallocation of water towards the large reservoirs.



(a) Absolute.



(b) Relative to reference scenario.

Figure 14: Annual discharge into the ocean.

4.3.3 *Annual Discharge into Ocean*

Under both the centralized and the decentralized scenario, annual discharges into the ocean decreases dramatically due to increased consumption of water. As the simulation period advances, the gap with the reference scenario increases further and further. During the final year, only 20% of the discharge under the reference scenario (Fig. 14b). When looking simultaneously at Fig. 14a and 14b, it becomes visible that the relative decrease is larger during dryer periods (year 36-41 & 47-50), while during wetter periods (year 42 - 46) the relative decrease is much smaller.

The difference between the centralized scenario and the decentralized scenario is small. Annual discharges are generally a little higher under the centralized scenario (Fig. 14b). This is probably the result of the higher reservoir volumes in the Castanhão reservoir under this scenario 13b. The controlled outflow of this reservoir is the main source of discharge into the ocean during dry periods.

4.4 RESULTS DEMAND

4.4.1 *Area Equiped for Irrigation*

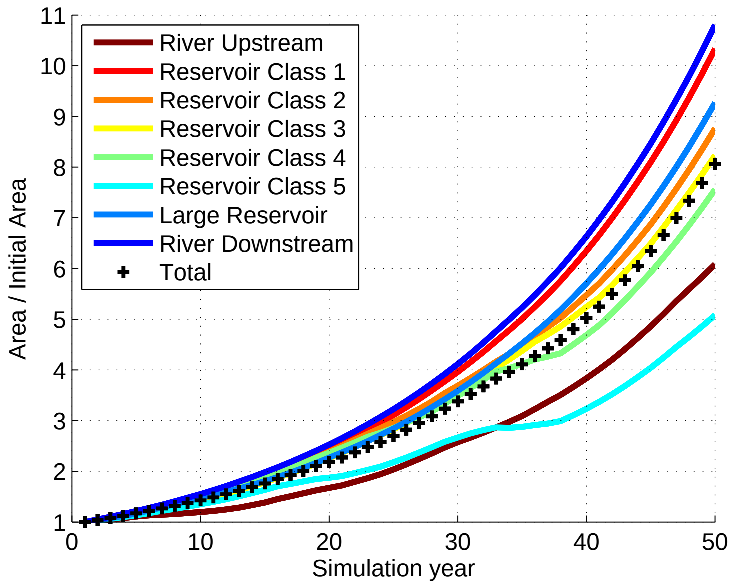
The development in area equiped for irrigation shows similar behavior for the centralized and decentralized scenario. Total area equiped for irrigation increases 8-fold during the 50 years of simulation (Fig. 15a). For most sources, the growth shows a more or less exponential pattern. Increase is largest for the area around and downstream of the large reservoirs. The area of river upstream farmers and around small reservoir show an intermediate increase. Since they are more rain-dependent, their yields are more sensitive to periods with little rain which limits their growth. Growth is slowest for the farmers around the medium reservoirs, especially reservoir class 5. Growth for these classes is strongly restricted by competition of non-irrigated demand (especially during a long dry period such as during the fourth decade).

When comparing the two scenarios (Fig 15b), we see that the increase in area around small (especially class 2 & 3) and medium reservoirs is somewhat larger under the decentralized scenario, which must be the effect of the extra storage capacity built. Remarkable is the development of the area around large reservoirs: at first this increases faster under the centralized scenario, but later on the area under the decentralized scenario catches up. Possibly at first the effect of reallocation takes the upper hand, but when the absolute area increases the restriction of consumption from large reservoirs under the centralized scenario slows down the growth. Differences for the areas for the upstream river farmers, around reservoir class 1 and downstream river farmers are negligible.

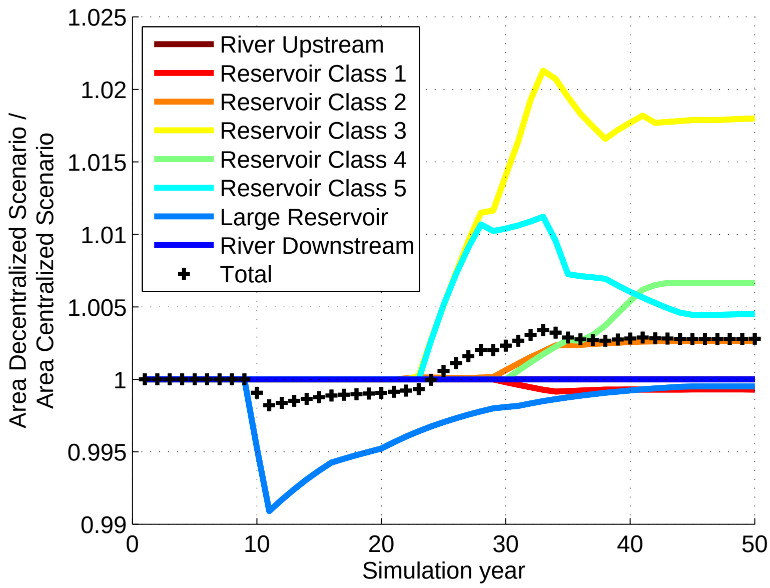
Geographically, the largest increase occurs in the Upper Jaguaribe and Middle Jaguaribe subbasins. Some upstream located municipalities in the Banabuiú and Upper Jaguaribe basin, a cluster of upstream located municipalities in the Salgado subbasin and the most downstream located municipalities in the Lower Jaguaribe basin show only a small increase in area equiped for irrigation.

In general, growth is largest in the midstream located municipalities, which would support the conclusion of Van Oel et al. [2009] that water availability appears to be most stable here. Under the rules of Tamanduá, a water supply which is *large enough and stable* leads to consequent high productivities which in its turn leads to increase in area available for the farmers experiencing these conditions.

It is interesting to note that for 3 municipalities with a large reservoir, the increase in area is larger under the supposedly unfavorable decentralized scenario. Since these are all large reservoirs which are located relatively upstream, their possibilities for receiving water from upstream are limited, while demand from downstream located large reservoirs can even have negative effects. For the most downstream located large reservoir (Castanhão), we see that increase is larger under the centralized scenario: this reservoir seems to experience positive effects of reallocation: increase here is larger under the centralized scenario.



(a) Decentralized scenario relative to thereference scenario.



(b) Differences between the decentralized and centralized scenario.

Figure 15: Area equiped for irrigation over sources.

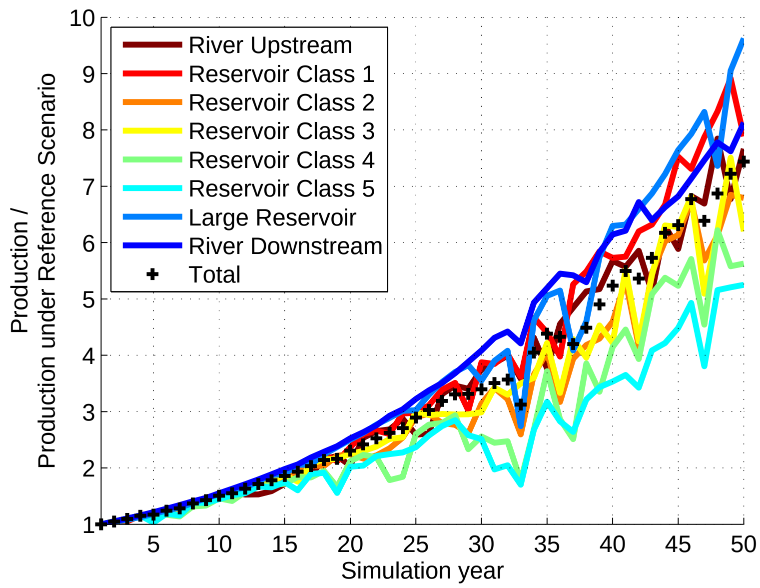
4.4.2 *Production*

As one would expect, developments in production (Fig. 16) show a pattern similar to the developments in area equiped for irrigation (Sec. 4.4.1). Total production increases about 7.5-fold during the 50 years of simulation. Since this increase is smaller than the increase in area equiped for irrigation (8-fold, Sec. 4.4.1), we can conclude that total productivity over the basin decreases. The growth rates of production show larger variation in time than the growth rates of area equiped for irrigation, since production reacts directly to variations in water availability whereas the area reacts indirectly (by the yield versus potential yield ratio) and smoothened out over time (last 5 years).

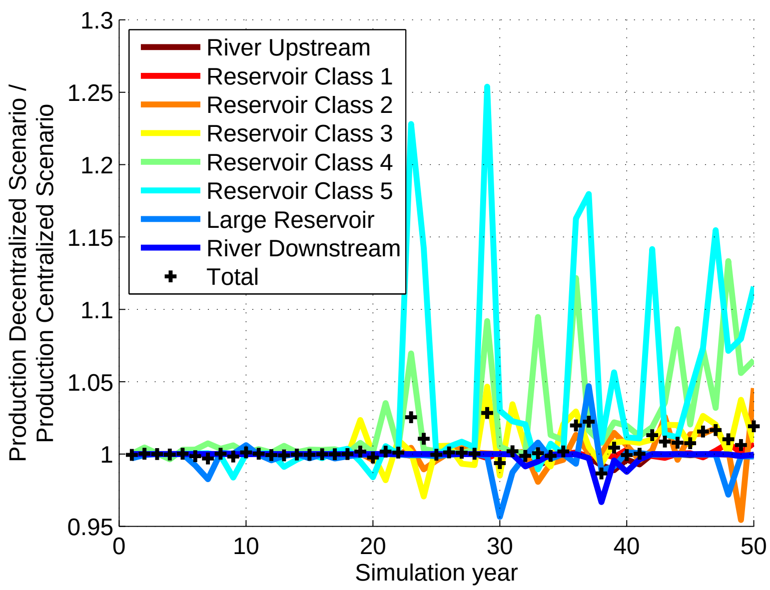
Variation in production increase over the sources is large and follows the developments in area equiped for irrigation (Fig. 15a). Underlying explanations are discussed in section 4.4.1.

When comparing the decentralized scenario with the centralized scenario (Fig. 16b), we see that the differences are much larger than for the area (Fig. 15b). During the dryer periods of the second half of the simulation, when water stress is higher, production around the medium-sized reservoirs (class 4 & 5) is up to 25% higher under the decentralized scenario. This results in higher total production under the decentralized scenario as well, since differences for the other sources are much smaller (< 5%) and not consequently in favor of one scenario.

Production is highest in the municipalities along the major rivers. Total increase in production seems somewhat higher in the western part of the basin for both scenarios, but no clear pattern is visible.



(a) Decentralized scenario relative to thereference scenario.



(b) Differences between the decentralized and centralized scenario.

Figure 16: Production over sources.

4.4.3 *Productivity (R$/m3)*

Average productivity per cubic meter irrigation water used varies from $\approx 1 - 2.25$ R$/ha (Fig. 17a), depending on the supply source. In general, productivity per cubic meter decreases with increasing downstreamness of the supply source, since the fraction of cash crops (tomato) decreases. Another reason is that for the more upstream sources a larger fraction is supplied by precipitation since not all of these farmers plant during the dry season. An exception to this rule are the river downstream farmers, probably since they occupy large areas in some municipalities with large banana fractions.

Differences between the different scenarios are negligible, due to the direct linear relationship between water consumption and production.

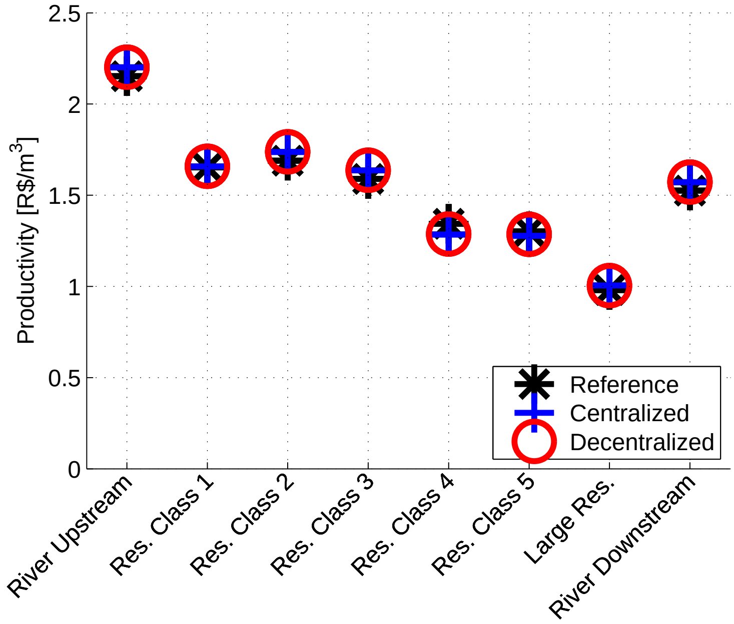
Productivity per ha. decreases in almost all municipalities during the simulation period due to increase in crop failure (Fig. 18a). There are no municipalities with large differences between the decentralized and centralized scenario.

4.4.4 *Productivity (R$/ha)*

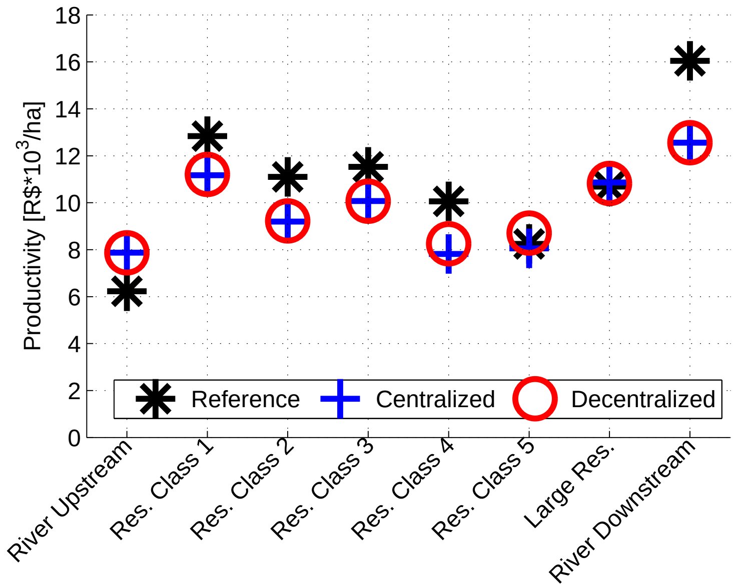
Average productivity per hectare varies from $\approx 6 - 16 * 10^3$ R$/ha (Fig. 17b), depending on the supply source. Productivity is the lowest for the river upstream farmers, since they only have one planting season available. For the reservoir 1-3 farmers, productivities are relatively high due to the higher fraction of tomatoes in their cropping patterns. Apparently their reservoirs usually provide enough buffer to ensure two planting seasons per year. The high productivity of the river downstream farmers is probably heavily influenced by some municipalities with large banana fractions.

For most supply sources (reservoir class 1-4, river downstream), productivity per ha. decreases when planted area increases heavily. Possible explanation is that water stresses result in lower yields and lower water expectancies which in their turn can result in a reduction of the fraction of the area planted (class 4, river downstream) or even complete absence of a second planting season (class 1-3). The productivity of river upstream farmers increases, probably because their area increases faster in municipalities with higher precipitation levels.

Productivity per ha. increases in almost all municipalities during the simulation period (Fig. 18b). This can be explained by differences in increase in area over the different sources: increase in area is largest for the two sources with the highest productivities: river upstream and reservoir class 1 (Fig. 15) . There are no municipalities with large differences between the decentralized and centralized scenario.

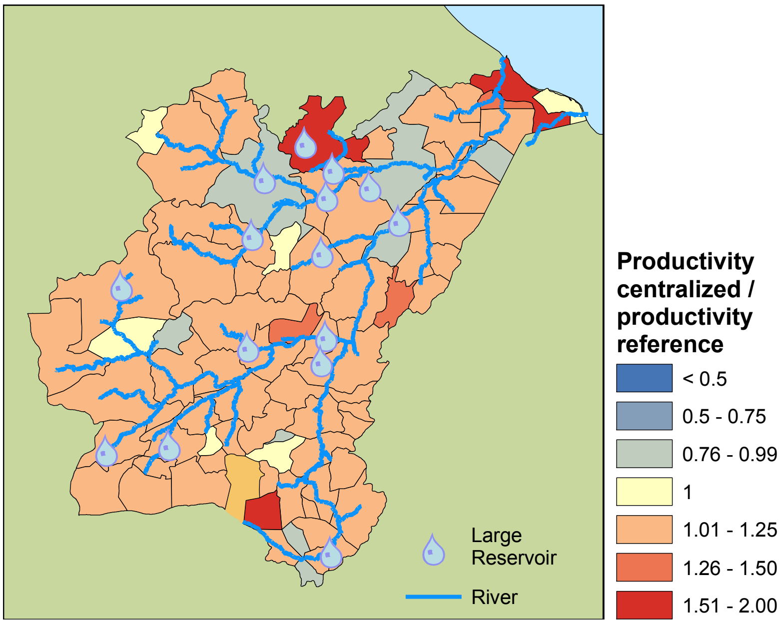


(a) Total production of source / total irrigation water use of source (averaged over simulation year 46-50).

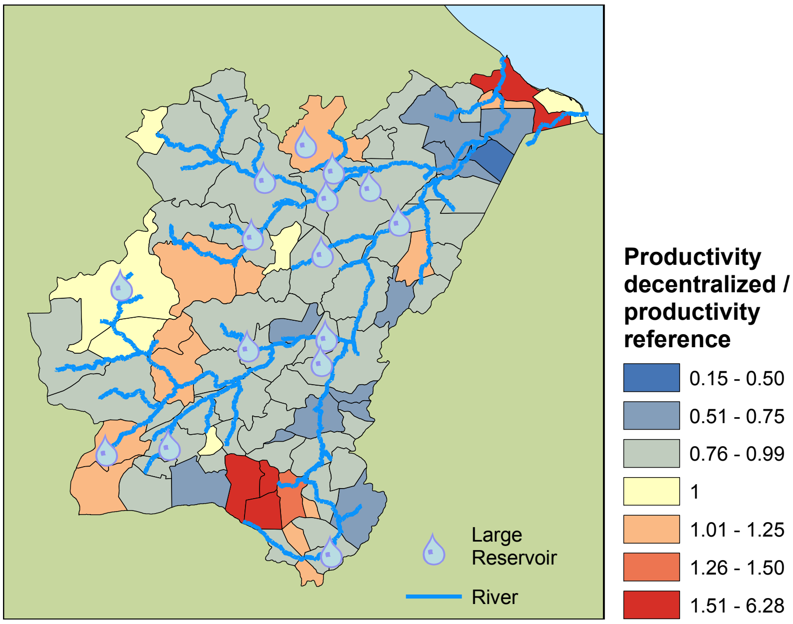


(b) Total production of source / total irrigated area of source (averaged over simulation year 46-50).

Figure 17: Productivity over sources.

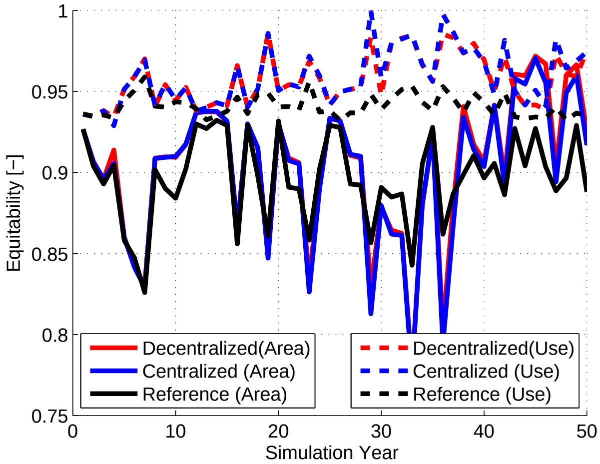


(a) Decentralized scenario relative to thereference scenario. Total production of source / total irrigation water use of source (averaged over simulation year 46-50).

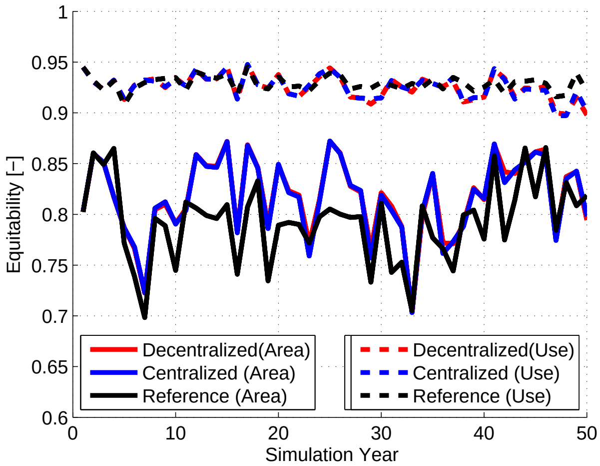


(b) Decentralized scenario relative to thereference scenario. Total production of source / total irrigated area of source (averaged over simulation year 46-50).

Figure 18: Productivity over the basin.



(a) Equitability over supply sources.



(b) Equitability over municipalities.

Figure 19: Equitability.

4.4.5 *Equitability*

Equitability in productivity per quantity of irrigation water used is higher and shows less variation than, equitability in productivity per area, both over the sources and over the municipalities.Variation in equitability over the sources is both higher for equitability in productivity quantity of irrigation water used and equitability in productivity per area. Equatibility in productivity per area over the municipalities is in general lower for the reference scenario than for the other scenarios. Over the sources, equatibility in productivity quantity of irrigation water used is lower under the reference scenario.

4.4.6 *Stability in Productivity (R$/m3)*

Stability in productivity per cubic meter irrigation water used varies widely over the different supply sources with a distinct pattern of highest stabilities for the small reservoirs, especially reservoir class 1 (Fig. 20a). Probably this is caused by the fact that cropping patterns for different water expectancies are very small for these farmers.

In both the centralized and decentralized scenario, stability in productivity per cubic meter of irrigation water used decreases for all sources except the river upstream and reservoir class 1 farmers. The increase of stability for the reservoir class 1 farmers could either be the result of the increase in storage capacity available or because the amount of farmers which only plant during 1 planting season increases.

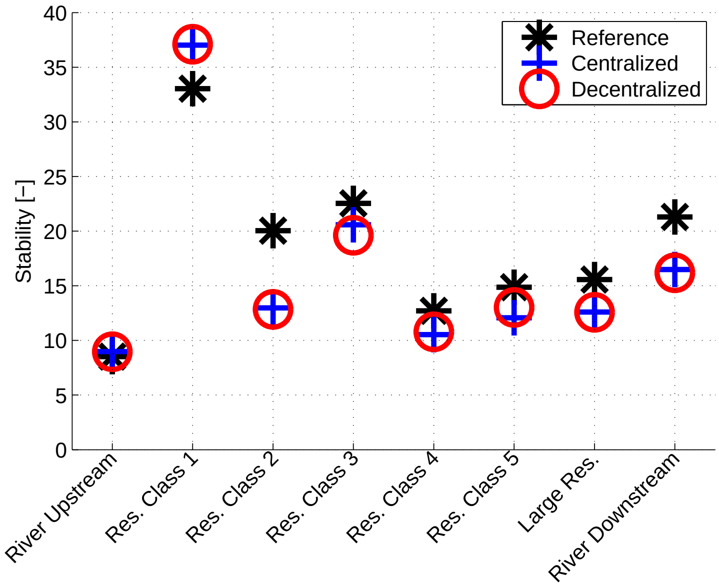
In general, municipalities with low stabilities are located upstream. Under both the decentralized and the centralized scenario, stability increases for the upstream part of the basin while stability in the downstream part decreases in both scenarios (Fig. 21a).

4.4.7 *Stability in Productivity (R$/ha)*

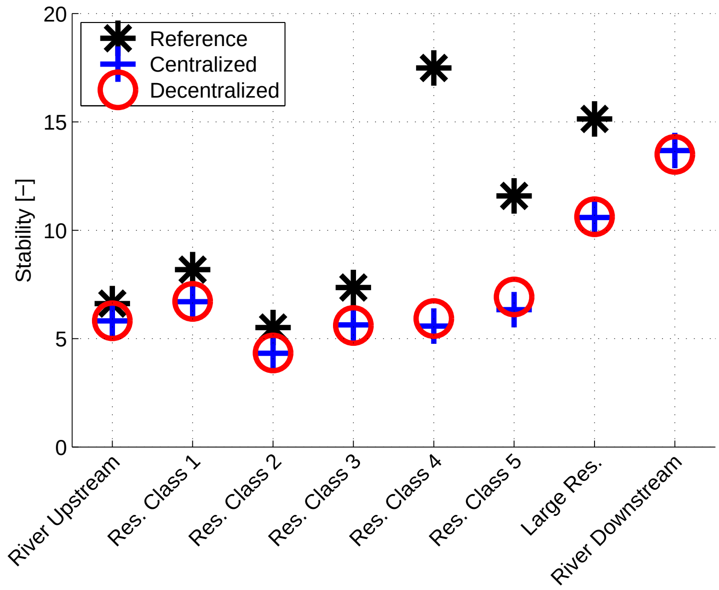
Stability in productivityper hectare varies widely over the different supply sources and increases strongly with the downstreamnes of the supply source (Fig. 20b). Apparently the increasing possibilities for buffering water and the resulting increased stability in water availability reduces yield losses due to water scarcity.

In both the centralized and decentralized scenario, stability in productivity per hectare decreases for all sources, most dramatically for the reservoir class 4 and the farmers located downstream of the strategic reservoirs.

In general, municipalities with high stabilities are located in the downstream part of the basin. Under both the decentralized and the centralized scenario, stability decreases for almost all municipalities (Fig. 21b). For most municipalities, stability is equal or higher under the decentralized scenario compared to the centralized scenario.

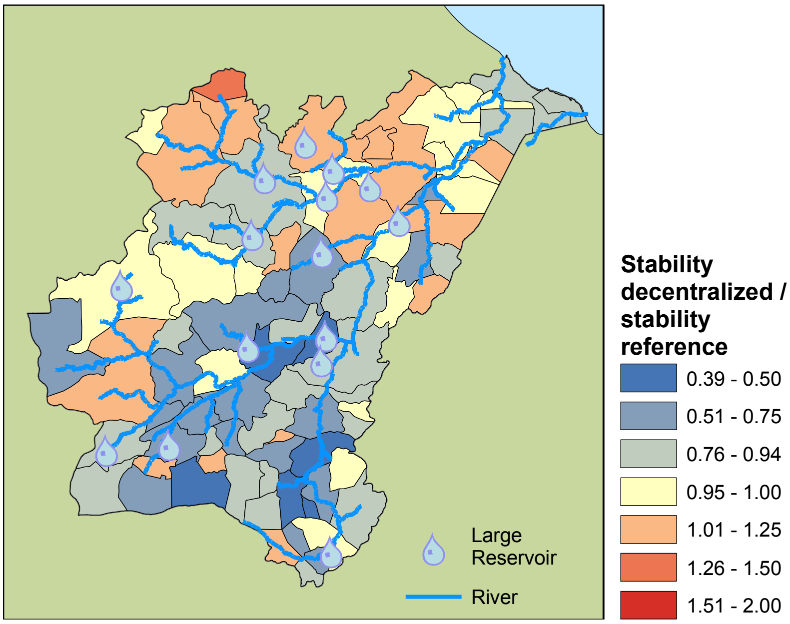


(a) Stability of productivity per cubic meter irrigation water used.

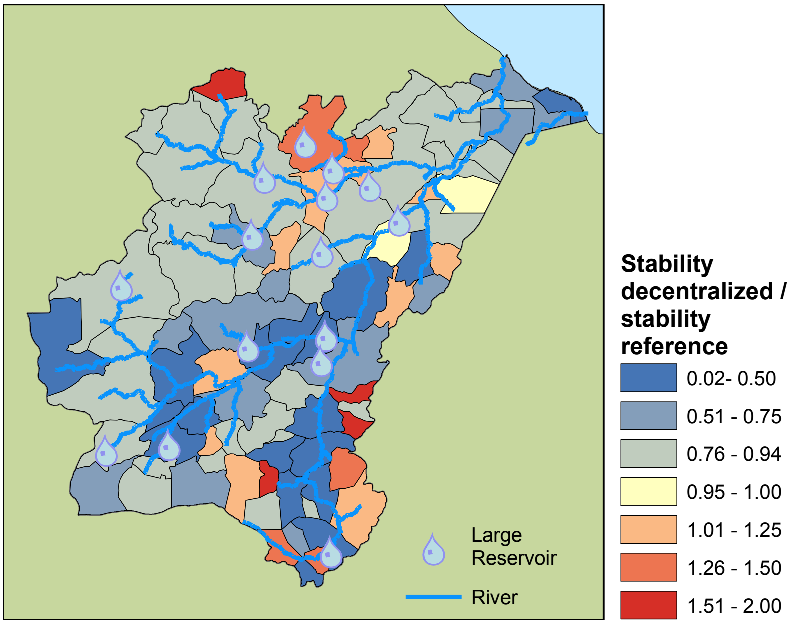


(b) Stability of productivity / hectare.

Figure 20: Stability in productivity over sources.



(a) Stability in production per cubic meter irrigation water used under the decentralized scenario relative to the reference scenario.



(b) Stability in production per hectare under the decentralized scenario relative to the reference scenario.

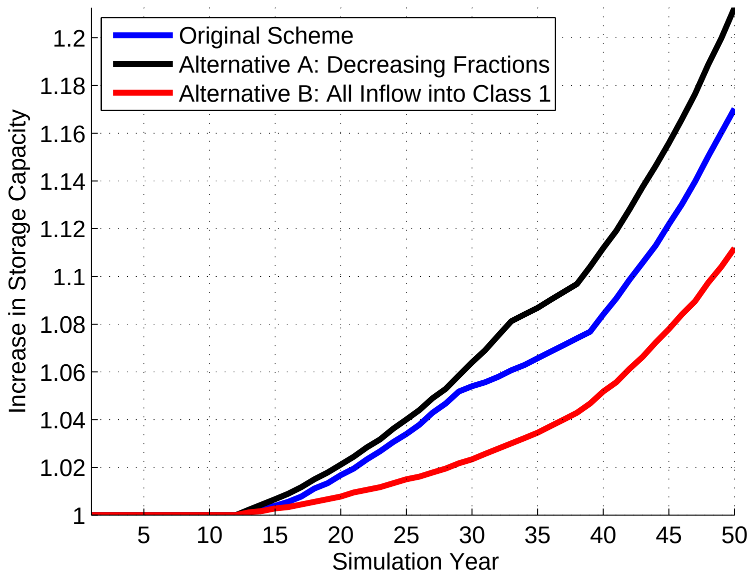
Figure 21: Stability in productivity over the basin.

4.5 Sensitivity

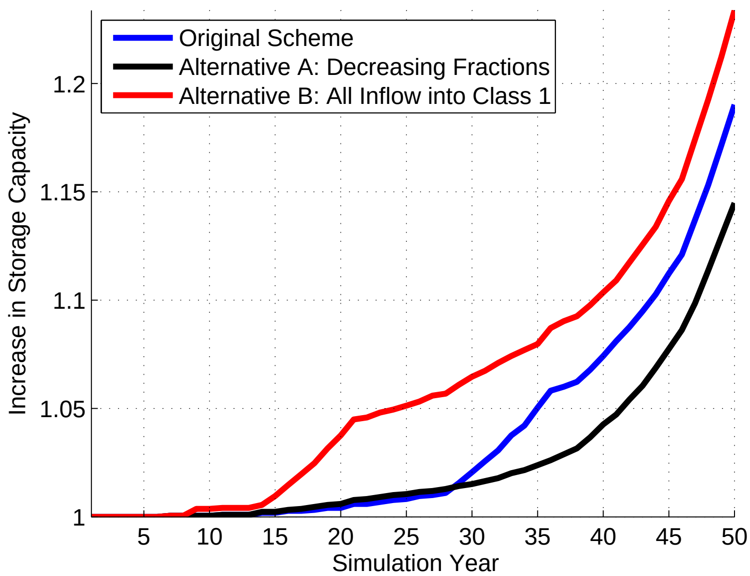
In this sensitivity analysis, only the results for the decentralized scenario are discussed. Simulation results regarding the validation of water availability will not be discussed. Due to the high storage capacities in almost every municipality, areas that drain directly on the river branches account for the major share of river discharges (and hence reservoir volumes of large reservoirs). These areas do not change. System characteristics and indicators that will be discussed are: storage capacity in small/medium reservoirs, area equiped for irrigation, production, productivity per hectare and stability in the productivity per hectare.

4.5.1 *Storage Capacity Small and Medium Reservoirs*

Changes in the development of storage capacities in the small and medium reservoirs are the result of a combination of differences in irrigated area and in water availability due to the other cascade schemes. Under the alternative B, all water flows directly into class 1. This result in a high water stability and hence in good yields, so the increase in storage capacity in this class remains small (Fig. 22a). For the other classes however, water availability is less stable, so the increase starts earlier and is larger (Fig. 22b).



(a) Class 1.



(b) Average of other classes.

Figure 22: Development of storage capacity in small and medium-sized reservoirs using alternative cascade schemes.

4.5.2 *Area Equiped for Irrigation*

As figure 23 shows, farmers around the small reservoirs reap the fruits of the increased water availability under the alternative cascade schemes. The final area of the farmers located around these reservoirs is larger than under the original scheme. This effect is strongest for the farmers around reservoir class 2, since class 1 is probably already almost at its maximum increase rate using the original scheme (suggested by Fig. 15a).

The farmers around the medium sized reservoirs have to pay the bill: at the end of the simulation period, their irrigated areas are up to a third lower (class 4, alternative B). The farmers around reservoir class 3 seem to be located at some kind of turning point: using alternative A their irrigated area at the end of the simulation is about equal, whereas under alternative B their area is considerably less (>20%) than using the original scheme.

Increase in irrigated area for the farmers located upstream along the rivers is affected as well: apparently there is a decrease in river discharges. The fact that the development of the areas of farmers located around and downstream of strategic reservoirs suggests that mainly the baseflow of the rivers is decreased. Apparently, the peak flows, after buffering in the strategic reservoirs, are still sufficient to supply these farmers with similar amounts of water as under the original scheme.

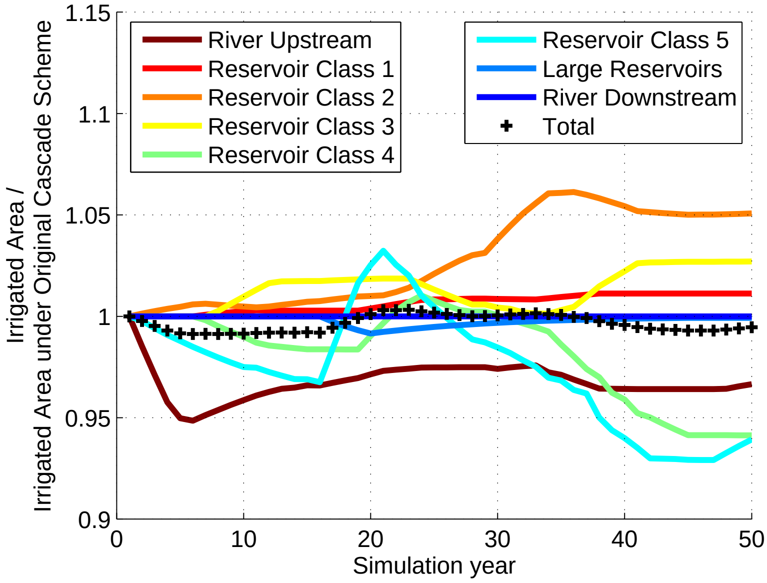
Total area equiped for irrigation at the end of the simulation period is about the same using alternative A, but more than 5% lower using alternative B.

4.5.3 *Production*

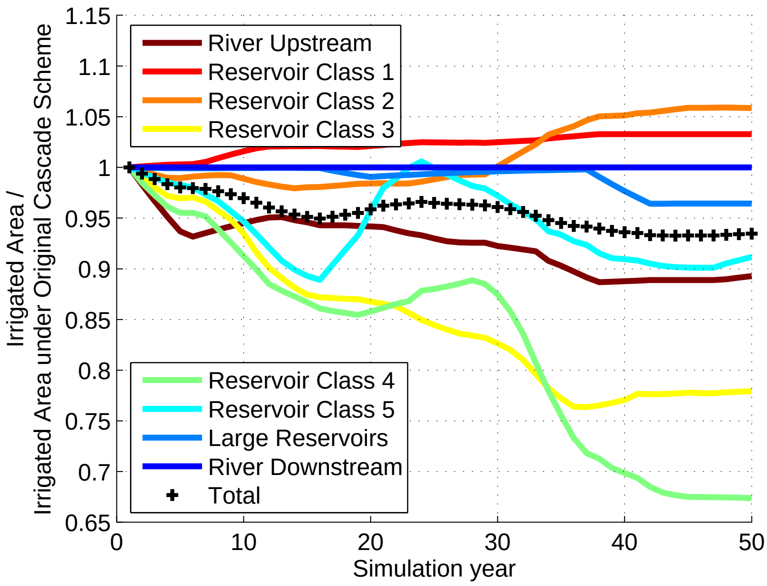
For production, differences are similar as for the areas equiped for irrigation: the farmers around small reservoirs are positively affected, all others negatively (Fig. 24). For the farmers around small reservoirs, the differences in production are much larger than the differences in area. Apparently the yield reductions due to water scarcity which took place under the original scheme are drastically reduced.

Whereas the irrigated areas of farmers around and downstream of strategic reservoirs were hardly affected by the use of different cascade schemes, in some years their production values are negatively affected.

In general, total production smaller, but the effect is less pronounced than for the area. The stable, high production of the small reservoirs partly compensates for lower productions for the other farmers.

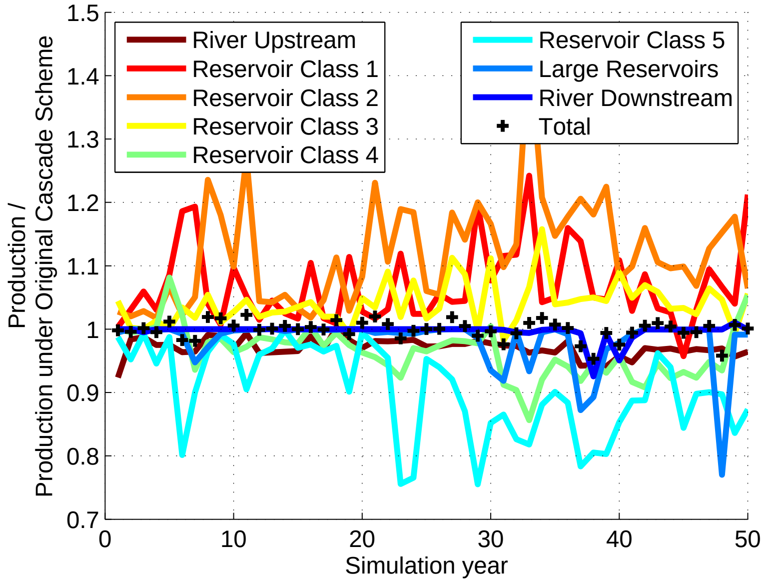


(a) Alternative A: Decreasing fractions.

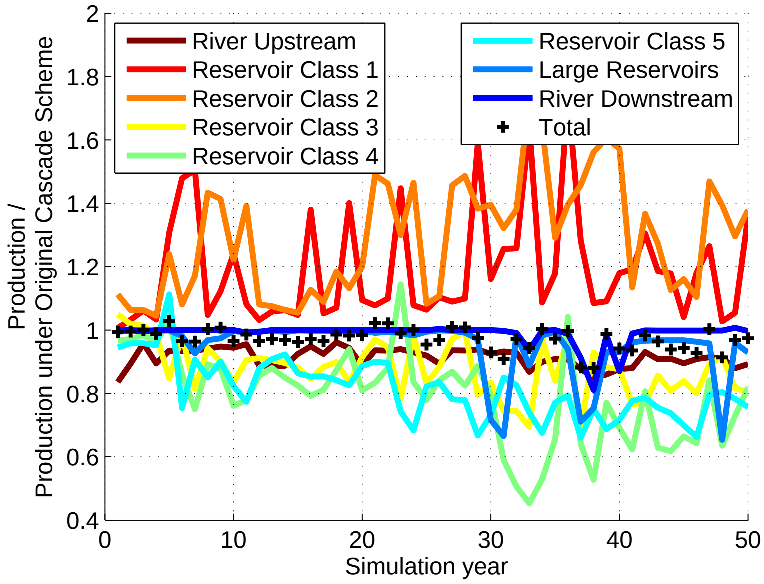


(b) Alternative B: All inflow into class 1.

Figure 23: Differences in area equiped for irrigation using different cascade schemes.



(a) Alternative A: Decreasing fractions.



(b) Alternative B: All inflow into class 1.

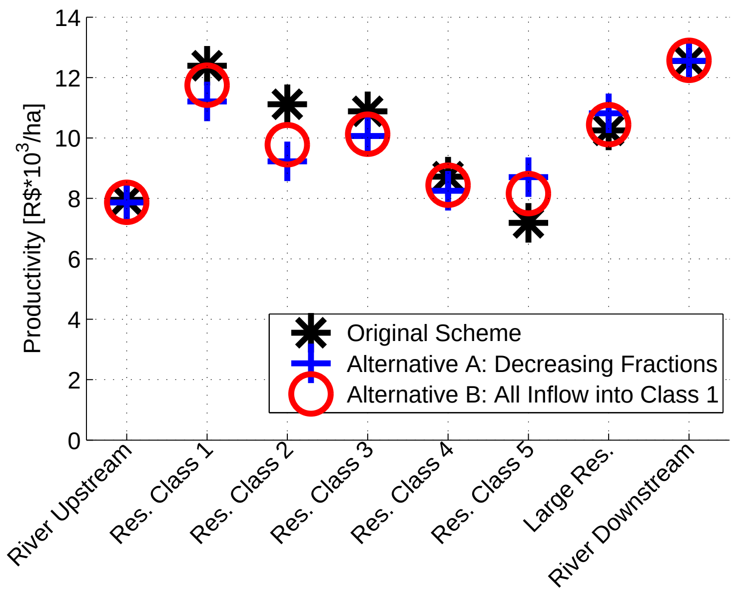
Figure 24: Differences in production using different cascade schemes.

4.5.4 *Productivity (R$/ha)*

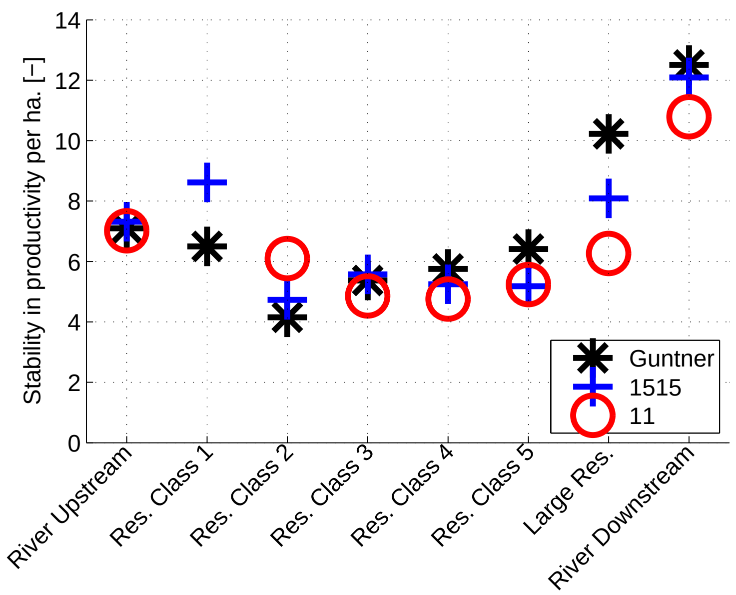
Differences in productivity per area are as one would expect: productivity increases for the small reservoirs (class 1-3) and decreases for the larger reservoirs (Fig. 25a). Productivity under alternative A is in between the original scheme and the more extreme alternative B for all reservoir classes.

4.5.5 *Stability*

Differences in stability in productivity per hectare shows a similar pattern as the differences in productivity itself: stability increases under the alternative schemes for the farmers around the smallest reservoirs classes (1-2), yet decreases for the more downstream located users (Fig. 25b). The more downstream the source, the larger the decrease. The farmers around and downstream of the strategic reservoirs are most heavily affected. Differences are similar for both alternatives, yet again more pronounced for alternative A.



(a) Productivity per hectare



(b) Stability in productivity per hectare.

Figure 25: Differences in productivity and stability using different cascade schemes.

5 CONCLUSIONS & RECOMMENDATIONS

This chapter examines the possibilities and limitations of studying the potential effects of different levels of decentralization in water resources management in a semi-arid river basin by means of the agent-based Tamandua model. This is followed by the conclusions in which the answers on the research questions, formulated in section **??**, are examined. Finally, recommendations for both water allocation management in semi-arid river basins and for further research are provided.

5.1 DISCUSSION

5.1.1 *Reflection on Research Approach*

The conceptual model provided in figure 4 has proven to be very useful in modeling the Jaguaribe basin, in fact it seems surprising that this conceptual model has not been used more commonly. Quality of modelling could be increased by improvements in the representations of some of the included actors and interactions in the conceptual model as discussed below.

In the current study, only a fraction of the agents' potential with regard to modelling complex interactions, heterogeneous populations and topological complexity [Bonabeau, 2002] is used. Communication is restricted to the managers of the larger reservoirs, while negotiating reallocation of water. This limits the possibilities for incorporating the previously identified types of decentralization forms (Fig. 2) and river basin governance (Molle et al. [2007]; Fig. 1). In this study, the decentralization scenarios are designed with the physical infrastructure as a starting point, whereas scenarios directly following from actual possible governance structures would be preferable for comparing different decentralization regimes. Improving the negotiation process between the water managers and including possibilities for negotiaton processes and information exchange between mutual farmers and between farmers and water managers could improve the representation of social processes. This could facilitate bargaining mechanism such as studied by Thoyer et al. [2003] and the incorporation of actual water resources management organizations [Molle et al., 2007] such as the sub-basin committees as present in the Jaguaribe basin [Lemos & de Oliveira, 2004].

This thesis adds an application to a river basin as a whole to the Common-Pool Resources literature. It forms an extension to the work of Van Oel [2009]in two ways: the Agent-Based Modeling approach is applied to a (much) larger spatial extent. This is achieved by defining different farmer types and aggregating these farmers at the scale of municipalities. Second, this study serves as a first attempt to extend the focus towards studying organizational, social, economic and institutional characteristics of river basin management. A promising start has been made on this matter, but there is still a lot of room for extensions and improvements.

Tamandua is the first application of an agent-based model in water allocation research that is applied on such a large spatial extent. The advantages of the agent-based approach, given by de Smith et al. [2007] and Gunkel [2005], became apparent during this study. Tamandua provides insight in the implications of activities of individual farmers and reservoir managers on a daily resolution, which can easily be accessed by inspecting individual agents or by writing their attributes to a file. Most importantly, Tamandua has shown the capability to capture emergent patterns over the basin with developments in stability (Fig. 20, 21 & 25b) as most evident example.

Omission in the current study is the water availability in the small and medium reservoirs. Including these stored volumes could help to assess the effectiveness of the centralized scenario in improving water supply for non-irrigated demand and could also be helpful in analyzing the effect of the construction of new reservoirs.

Crop decision algorithms of the farmers are distilled from annual data over municipios which include both irrigated and rain-fed production values. This has resulted in a single set of crop decision heuristics per farmer type for the whole basin and for both planting seasons. Spatially differentiated crop decision heuristics for each planting season, based on locally gathered knowledge (interviews and observations) would improve the validity of the model.

It has been assumed that current response patterns of water users and managers persist, even when production values and/or water availability change dramatically. Reservoir operation and farmer behavior will most probably be influenced by anticipatory or adaptive management and by legal, institutional and economical developments. This also applies to non-irrigated demand and to some external factors (prices on inter-regional markets, climate change, etc.; Arrow 7, Fig. 4) which could have major influences on the system.

5.1.2 *Reflection on Results*

The validation has shown that Tamandua predicts both water availability and irrigated water use reasonably well: the virtual water contents of all crops are in the same range as found by Hoekstra & Chapagain [2008], river base flows are similar to the observed values and reservoir volumes for most large reservoirs show realistic patterns in time.

The results of the actual simulation period are realistic as well. Growth rates of area equiped for irrigation that has taken place during the simulation period is in the same range as the increase of irrigation area Hauschild & Döll [2000] use in their 2 development scenarios for Ceará (respectively 200% and 440% in 25 years). Results regarding developments in production, productivities, stability and equitability could also be validated qualitively.

The differences between the decentralized and centralized scenario were smaller than expected. Water reallocation towards larger, more downstream reservoirs caused some disadvantage for the farmers around medium reservoirs. But, no clear effects of the construction of extra reservoirs could be observed. Underlying reasons could be the high ratio between the storage capacity in the different reservoir classes and the corresponding irrigated areas and the assumption that no controlled outflow occurs from the small and medium reservoirs. Another problem related to these numbers of reservoirs is the allocation of area to the different sources. The ratio between area and storage capacity is in general very high and enormous variations are observed between different municipalities. Improvement could be made by adding additional parameters to the heuristics determining growth of area and the number of reservoirs and by adding controlled outflow from some of the reservoir classes according to actual negotiating processes going on in the basin as described by Lemos & de Oliveira [2004].

The results presented are based on a single case study: the Jaguaribe basin in the semi-arid northeast of Brazil. Given the strengths of case-studies as theory-building approach, like novelty, testability, and empirical validity, and its independence from prior literature or past empirical observation, using a case study is particularly well-suited to new research areas or research areas for which existing theory seems inadequate [Eisenhardt, 1989]. Using a case-study has indeed provided the necessary starting grounds and possibilities for validation. However, it has also lead to some uncertainties in the results due to the already present infrastructure, government policies influencing crop choices and some data of questionable validity. These issues enhance the risk of both weaknesses of case-studies, as identified by Eisenhardt [1989]: yielding an overly complex theory due to the staggering volume of rich data or resulting in a narrow and idiosyncratic theory.

The system is highly sensitive for the cascade scheme used to represent small and medium-sized reservoirs. Effects found using the original cascade system still occur using alternative schemes, but the effects are much more pronounced while using a cascade scheme more favorable to the farmers around the small reservoirs. Since the original approach is likely to be too favorable for the farmers around the medium reservoirs, yet the alternative in which all water flows directly into reservoir class 1 is clearly too unfavorable. In reality, the truth lies probably somewhere in between. This implies that it is not unlikely that conditions are even more unfavorable for the farmers around medium reservoirs than found during the original simulation! In order to create a more realistic scheme, leading to more pronounced results, the reservoir cascade scheme should be dynamic. In such a system, the inflow coefficients should depend on the actual numbers of reservoirs present, preferably using a "serviceable area" per reservoir for each class as increment for the farmers' area.

It may be interesting to compare the results found using the current situation as starting condition with the results starting out from an completely empty basin in which farmers have the ability to create new reservoirs. This would provide insight in the effects of the current infrastructure and management in the basin: who are the winners and who are the losers of the state policies that have been applied over the years?

5.1.3 *Relevance to Practice*

In its current form, scientific value of Tamandua prevails over the practical value. Some practical applications could include the identification of the locations of bottlenecks within the system and to predict potential effects of water allocation measures or the resilience of the system to climate change. Another possibility could be to use this theoretical model as a learning tool for water managers and/or policy makers, so they gain more insight in what is going on in "their" system.

After some improvements and/or extensions the array of practical application widens. After the inclusion of agricultural managers for example, it could be used to predict potential long-term effects of agricultural policy measures such as subsidies and restrictions for certain crops. This would require drastic changes in the decision heuristics of the farmers and improvements in the representation of social processes as well. A possibility to overcome this difficulty is by making a serious game in which the decisions are made by the actual stakeholders themselves. This would improve insight of the stakeholders in the both long-term impacts on their own situation and the impact of their actions.

5.2 CONCLUSIONS

3. *What are the effects of different levels of decentralization in water resources management on the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin?*

If water demand within the Jaguaribe basin increases with a magnitude similar to the increase in our simulation, overdevelopment will occur irrespective of the water allocation strategy used. With regard to the physical water system, refillment of strategic reservoirs is insufficient, discharge into the ocean decreases dramatically and the basin is under serious threat of (further) closure.

The more upstream located farmers are associated with high productivities and low stabilities, whereas the more downstream located farmers are associated with low productivities yet high stabilities. Willingness to take risks increases gradually over time, based on the rationale that an occasional crop failure should not stop expansion as long the averaged result over 5 years is sufficiently high. This results in vast increases in irrigated area (up to 10-fold around reservoir class 1) and numbers of reservoirs (up to about 50% within a sub-basin) which threaten both the productivity of the upstream farmers as well as the stability of their downstream colleagues. Meanwhile the productivity of downstream farmers (except the farmers downstream of the strategic reservoirs, but their productivities are biassed by some farmers with a large areal of banana) and, to lesser extent, the stability of the upstream farmers stay at roughly the same level. Biggest "losers" after 50 years of simulation are the farmers around the medium-sized reservoirs (competition from prioritized non-irrigated demand and a smaller buffer than the strategic reservoirs), but it is expected that the farmers around and downstream of the strategic reservoirs would follow if the ongoing developments continue.

Under the decentralized scenario, farmers are not restricted in thei behavior; they are only limited by the natural conditions. Under th centralized scenarios, their supply is also influenced by regulation from the central government, aimed to increase the water availabilit for non-irrigating water users. The results of these trade-offs are visibl in the reservoir volumes of the strategic reservoirs (slightly highe reservoir volumes during dry periods) and in the development of th irrigated area and production of farmers around the medium-sized reservoirs (class 4-5). These are clearly the farmers that are restricted in their growth by the administrative measures taken in order to improve the water supply for the prioritized non-irrigated demand.

In general, the effects of the implemented measures are very small compared to the effects of increased water consumption itself. This implies that the overdevelopment cannot be prevented by water allocation management alone. As long as the upstream located farmers are free to use all the water they can catch. In order to prevent the overdevelopment, an integrated approach is required including agricultural policy measures such as increasing the value added per drop (more cash crops) and restrictions on the areas to be irrigated.

2. *How can different management strategies, corresponding to different levels of decentralization be implemented in this model?*

Three potential measures have been identified which could be included in different management strategies: prohibiting the construction of new smaller reservoirs, reallocating water towards the larger reservoirs and restricting water abstraction from strategic reservoirs in times of drought. Two scenarios have been defined: a centralized scenario in which these measures are implemented and a decentralized scenario in which they the three measures are not implemented.

1. *How can physical water availability and agricultural water use for current water governance be modeled on a river basin scale?*

Tamandua model is used to simulate water availability and water use on a river basin scale. Within Tamandua, a newly created model for the irrigated water demand is integrated with existing models from the WAVES project for water availability (WASA) and non-irrigated water demand (NoWUM). Water users and water managers are represented as agents, with their actions based on the actual activities farmers (and water managers) perform during a year. Their decision-making is "reverse-engineered" by analyzing cropping patterns for dry, normal and wet years for representative municipios (i.e. municipality in which a single water supply source is dominant). All model parameters can be derived from physiographic information of the study area. Thus, model calibration is primarily not required. Validation against observed discharges, reservoir volumes and water footprints showed that Tamandua predicts both water availability, variation in water availability and irrigated water use reasonably well.

5.3 RECOMMENDATIONS

5.3.1 *Recommendations for Water Management in Semi-arid Basins*

- Keep monitoring the development of water demand within the region. Make predictions on future developments and the potential effects of climate change, so measures can be taken before problems do occur. Measures regarding the allocation of water can be helpful, but their effects are limited. If large increases in demand (or decreases in supply) are expected, it will be necessary to use an integrated approach with the focus on managing agricultural water use.

- Try to identify the effects of individual measures, preferably after making the improvements stated in Sec. 5.3.2, in order to assist in the decision-making processes on what measures to take.
- If the desire emerges to reorganize the river governance organization, first study the potential long-term effects using a modified version of Tamandua (i.e. with improved inter-agent communication, so the social processes going on in different forms of water resources management organizations can be appropriately included).

5.3.2 *Recommendations for further research*

Interesting subjects for research, that can be performed with the model in its *current state* include:

- Analyzing the differences in the developments over the different sub-basins: what are the differences and what are the underlying reasons for these differences?
- Seeking after more quantitative relations between the indicators and the location in the basin or sub-basin (for instance using the downstreamness concept by Van Oel et al. [2009]).
- Running the simulation for longer periods: this could unveil more pronounced differences between the scenarios and emerging patterns (such as migration from water use from downstream to upstream).
- Researching influences of climate change on the system by using different values for run-off, precipitation and potential evaporation. Krol et al. [2003] could serve as a starting point for climate scenarios.
- Deeper analysis of the Water Footprints of the different crops: how do the WFPs develop in time? And how do the WFPs vary over the sources and with the location in the basin?

Another category contains subjects regarding *improvements* of some of the weaker parts of the Tamandua model:

- A critical assessment of the numbers of reservoirs and areas equiped for irrigation per municipality. Is it possible to identity a "serviceable area" per reservoir for each class?
- Improving the crop decision heuristics, preferably spatially differentiated and based on locally gathered knowledge (interviews and observations).
- Changing the reservoir cascade scheme into a dynamic system, so its coefficients will depend on the actual numbers of reservoirs present.

- Keeping track of the actual storage in the small and medium-sized reservoirs.

The final category contains subjects that are interesting for further research, but will require some major *extensions*:

- By including an agricultural manager, with the ability to regulate agricultural development, the impact of agricultural measures can be studied.
- Changing the heuristics by which irrigated area and the numbers of reservoirs are adjusted, so the system can be given the chance to develop from scratch. This could be used to study the differences between the current situation and various management strategies. who are the winners and who are the losers of the state policies that have been applied over the years?
- By improving the possibilities for communication between mutual farmers and between farmers and water managers, extra social processes can be included. This can be helpful for ex ante evaluation of different bargaining mechanisms. The study by Thoyer et al. [2003]could serve as a starting point for including bargaining mechanism in an agent-based model.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Tech. rep., FAO, Rome. (Cited on pages 18 and 22.)

ANA (2010). Hidroweb. Tech. rep., Agência Nacional de Águas, Brasilia, Brazil.
URL http://hidroweb.ana.gov.br/ (Cited on pages xii, 12, and 39.)

Baland, J. M., & Platteau, J. P. (1999). The ambiguous impact of inequality on local resource management. *World Development*, *27*, pp.773–788. (Cited on page 5.)

Banco do Nordeste (2005). Agenda do produtor rural 2006. Tech. rep., Banco do Nordeste, Fortaleza, Brazil. (Cited on page 23.)

Bardhan, P., & Dayton-Johnson, J. (2002). Unequal irrigators: Heterogeneity and commons management in large-scale multivariate research. In E. Ostrom, T. Dietz, N. Dolšak, P. Stern, S. Stonich, & E. Weber (Eds.) *The drama of the commons*. National Academy Press, Washington, DC, USA. (Cited on page 5.)

Barreteau, O., & Bousquet, F. (2000). SHADOC: a multi-agent model to tackle viability of irrigated systems. *Annals of Operations Research*, *94*, pp.139–162. (Cited on page 81.)

Becu, N., Perez, P., Walker, A., Barreteau, O., & Le Page, C. (2003). Agent based simulation of a small catchment water management in northern Thailand description of the CATCHSCAPE model. *Ecological Modelling*, *170*, pp.319–331. (Cited on page 81.)

Berger, T. (2001). Agent-based models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, *25*, pp.245–260. (Cited on pages 29 and 81.)

Berger, T., Birner, R., Diaz, J., McCarthy, N., & Wittmer, H. (2007). Capturing the complexity of water uses and water users within a multi-agent framework. *Water Resources Management*, *21*, pp.129–148. (Cited on page 6.)

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, *99*, 7280–7287. (Cited on page 65.)

Brannstrom, C. (2004). Decentralising water resource management in Brazil. *The European Journal of Development Research*, *16*, pp.214–234. (Cited on page 5.)

Campos, J. N. B., & Studart, T. M. C. (2000). An historical perspective on the administration of water in Brazil. *Water International*, *25*, pp.148–156. (Cited on page 13.)

Campos, J. N. B., Studart, T. M. C., Franco, S., & Luna, R. (1999). Liquid discharges from Jaguaribe River to Atlantic Ocean after large-scale dams construction: Variability analysis. In *International Symposium on Hydrological and Geochemical Process in Large-Scale River Basins*. Manaus, Brazil: HIBAM-Hidrologia e Geoquimica da Bacia Amazonica. (Cited on page 11.)

Campos, J. N. B., & Studart, T. M. D. (2008). Drought and water policies in Northeast Brazil: backgrounds and rationale. *Water Policy*, *10*, pp.425–438. (Cited on page 13.)

Carlsson, L., & Berkes, F. (2005). Co-management: concepts and methodological implications. *Journal of Environmental Management*, *75*. (Cited on page 4.)

Carr, M. K. V. (2009). The water relations and irrigation requirements of banana (musa spp.). *Experimental Agriculture*, *45*, pp.333–371. (Cited on page 29.)

Chapagain, A., & Hoekstra, A. (2004). Water footprints of nations. Value of Water Research Report Series 16. Tech. rep., UNESCO-IHE, Delft, the Netherlands. (Cited on pages xii and 41.)

COGERH (1998). Estudo preliminar da operação conjunta do sistema Jaguaribe e sistema Metropolitano. Tech. rep., COGERH - Companhia de Gestão dos Recursos Hídricos, Fortaleza, Brazil. (Cited on page 24.)

COGERH (2006). Il encontro regional de comitês de bacias hidrográficas. Tech. rep., COGERH - Companhia de Gestão dos Recursos Hídricos, Fortaleza, Brazil, Fortaleza, Brazil. (Cited on pages 12 and 25.)

Conway, G. (1987). The properties of agroeconomic systems. *Agricultural Systems*, *24*, pp.95–117. (Cited on page 34.)

de Smith, M. J., Goodchild, M. F., & Longley, P. A. (2007). *Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools*. Troubador Publishing. (Cited on pages 6 and 66.)

Dinar, A., Rosegrant, M. W., & Meinzen-Dick, R. (1997). Water allocation mechanisms: principles and examples. Policy Research Working Paper 1779, World Bank, Washington, D.C., United States of America. (Cited on page 2.)

Doorenbos, J., & Kassam, A. H. (1979). Yield response to water - FAO Irrigation and drainage paper 33. Tech. rep., FAO, Rome. (Cited on page 29.)

Eisenhardt, K. M. (1989). Building theories from case study research. *The Academy of Management Review*, *14*, pp.532–550.
URL http://dx.doi.org/10.2307/258557 (Cited on page 67.)

Falkenmark, M., & Molden, D. (2008). Wake up to realities of river basin closure. *International Journal of Water Resources Development*, *24*, pp.201–215. (Cited on page 1.)

Feuillette, S., Bousquet, F., & Le Goulven, P. (2003). SINUSE: a multi-agent model to negotiate water demand management on a free access water table. *Environmental Modelling & Software*, *18*, pp.413–427. (Cited on page 81.)

Finan, T. J., & Nelson, D. R. (2001). Making rain, making roads, making do: public and private adaptations to drought in Ceará, Northeast Brazil. *Climate Research*, *19*, pp.97–108. (Cited on page 12.)

FUNCEME (2010). Arquivos com dados pluviométricos. Tech. rep., FUNCEME - Fundação Cearense de Meteorologia e Recursos Hídricos, Fortaleza, Brazil. (Cited on pages 10, 24, and 25.)

Gaiser, T., Krol, M. S., Frischkorn, H., & de Araújo, J. C. (Eds.) (2003). *Global change and regional impacts : water availability and vulnerability of ecosystems and society in the semiarid northeast of Brazil*. Springer, Berlin, Germany. (Cited on pages 11 and 17.)

Gini, C. (1912). *Variabilità e mutabilità*. Rome, Italy: Reprinted in: Memorie di metodologia statistica (Ed. Pizetti, E. & Salvemini, T., 1955). (Cited on page 34.)

Güntner, A. (2002). *Large-scale Hydrological Modelling in the Semi-arid North-East of Brazil*. Ph.D. thesis, Potsdam Institute for Climate Impact Research, Potsdam, Germany. (Cited on pages xi, 17, 18, 19, 20, 21, 30, and 34.)

Güntner, A., Krol, M. S., de Araujo, J. C., & Bronstert, A. (2004). Simple water balance modelling of surface reservoir systems in a large datascarce semiarid region. *Hydrological Sciences*, *49*, pp.901–918. (Cited on pages 19, 21, and 35.)

Gunkel, A. (2005). *The Application of Multi-Agent Systems for Water Resources Research – Possibilities and Limits*. Master's thesis, Albert-Ludwigs-Universität, Freiburg, Germany. (Cited on pages 6 and 66.)

Hauschild, M., & Döll, P. (2000). Water use in semi-arid Northeastern Brazil – modeling and scenario analysis. Tech. Rep. Report A0003, Center for Environmental Systems Research, University of Kassel, Kassel, Germany. (Cited on pages 21, 22, 23, 24, and 66.)

Hoekstra, A. Y., Chapagain, A., Aldaya, M. M., & Mekonnen, M. M. (2009). Water footprint manual: State of the art 2009. Tech. rep., Water Footprint Network, Enschede, the Netherlands. (Cited on page 31.)

Hoekstra, A. Y., & Chapagain, A. K. (2008). *Globalization of WAter. Sharing the Planet's Freshwater Resources*. Oxford, United Kingdom: Blackwell Publishing. (Cited on pages 31 and 66.)

Hofstadter, D. R. (1979). *Gödel, Escher, Bach: An Eternal Golden Braid*. New York, NY, USA: Basic Books, Inc. (Cited on page vii.)

IBGE (1996). Censo agropecuário ceará de 1995-1996. Tech. rep., IBGE - Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. (Cited on pages 12 and 25.)

IBGE (2006). Censo agropecuário ceará de 2005-2006. Tech. rep., IBGE - Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. (Cited on pages 23 and 24.)

IBGE (2010). Sidra - produção agrícola municipal. Tech. rep., IBGE - Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. URL `http://www.sidra.ibge.gov.br/` (Cited on pages xii, 23, 25, and 34.)

ICWE (1992). The dublin statement and report of the conference. In *International conference on water and the environment*. Dublin, Ireland. (Cited on page 4.)

Kemper, K. E. (1996). *The cost of free water: water resources allocation and use in the Curu Valley, Ceará, Northeast Brazil*. Linköping studies in arts and science 137. Linköping, Sweden: Dept. of Water and Environmental Studies, Linköping University. (Cited on page 3.)

Kemper, K. E., Blomquist, W. A., & Dinar, A. (2007). *Integrated river basin management through decentralization*. Springer, Berlin, Germany. (Cited on pages 1, 2, 3, 5, 11, 13, and 15.)

Krol, M., de Vries, M. J., van Oel, P. R., & de Araujo, J. C. (In Press). Sustainability of small reservoirs and large scale water availability under current conditions and climate change. *Water Resources Management*. (Cited on page 19.)

Krol, M., Jaeger, A., & Bronstert, A. (2003). *Global Change and Regional Impacts - Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil*, chap. Integrated Modeling of Climate Change Impact in Northeastern Brazil, (pp. pp.43–56). Springer, Berlin, Germany. (Cited on pages 22 and 70.)

Lam, W. F. (1998). *Governing irrigation systems in Nepal: institutions, infrastructure, and collective action*. ICS Press, Oakland, CA, USA. (Cited on page 5.)

Lansing, J. S., & Kremer, J. N. (1993). Emergent properties of Balinese water temple networks - coadaptation on a rugged fitness landscape. *American Anthropologist*, *95*, pp.97–114. (Cited on page 81.)

Legates, D. R., & McCabe Jr., G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, *35*, pp.233–241. (Cited on page 30.)

Lemos, M. C., & de Oliveira, J. L. F. (2004). Can water reform survive politics? institutional change and river basin management in Ceará, Northeast Brazil. *World Development*, *32*, pp.2121–2137. (Cited on pages xi, 1, 5, 11, 13, 14, 15, 29, 65, and 67.)

Matthews, R., & Selman, P. (2006). Landscape as a focus for integrating human and environmental processes. *Journal of Agricultural Economics*, *57*, pp.199–212. (Cited on page 6.)

Molle, F., Wester, P., & Hirsch, P. (2007). *Water for Food-Water for Life. Comprehensive Assessment of Water Management in Agriculture*, chap. River basin development and management, (p. pp.585–624.). London, United Kingdom: EarthScan. (Cited on pages xi, 1, 2, and 65.)

Molle, F., Wester, P., & Hirsch, P. (2010). River basin closure: Processes, implications and responses. *Agricultural Water Management*, *97*, pp.569–577. (Cited on pages 1 and 2.)

Ostrom, E., Gardner, R., & Walker, J. (1994). *Rules, games, and common-pool resources*. University of Michigan Press, Ann Arbor, MI, USA. (Cited on page 5.)

Parker, D. C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers*, *93*, pp.314–337. (Cited on page 6.)

Schluter, M., & Pahl-Wostl, C. (2007). Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin. *Ecology and Society*, *12*. (Cited on pages 7 and 81.)

Shuttleworth, W., & Wallace, J. (1985). Evaporation from sparse crops - an energy combination theory. *Quarterly Journal of the Royal Meteorological Society*, *111*, pp.839–855. (Cited on page 18.)

Smakhtin, V. U. (2008). Basin closure and environmental flow requirements. *International Journal of Water Resources Development*, *24*, pp.227–233. (Cited on page 1.)

Smith, C. A., & Sardeshmukh, P. (2000). The effect of ENSO on the intraseasonal variance of surface temperature in winter. *International Journal of Climatology*, *20*, pp.1543–1557. (Cited on page 10.)

Smith, L. D. (2001). *Reform and decentralization of agricultural services : a policy framework*. FAO agricultural policy and economic development series,. Rome, Italy: Policy Assistance Division and Agricultural and Economic Development Analysis Division, Food and Agriculture Organization of the United Nations. (Cited on pages xi, 3, 4, and 5.)

Smith, M. (1992). CROPWAT - a computer program for irrigation planning and management - Irrigation and drainage paper 46. Tech. rep., FAO, Rome, Italy. (Cited on pages 21, 22, and 23.)

Smits, S., Bustamante, R., & Butterworth, J. (2005). Integrated water resources management at the local level: the role of local government. In *AGUA 2005, Cali, Colombia*. (Cited on page 4.)

Souza Filho, F., & Porto, R. (2003). Gerenciamento de recursos hídricos e a variabilidade climática nos semi-áridos Brasileiros. In *Anais do simpósio Brasileiro de recursos hídrico*, (pp. 1–16). Curitiba, Brazil: ABRH. (Cited on page 10.)

Stannard, D. I. (1993). Comparison of Penman-Monteith, Shuttleworth-Wallace, and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resour. Res.*, *29*, pp.1379–1392. (Cited on page 18.)

Taddei, R., Broad, K., & Pfaff, A. (In Press). *Climate, Water and Society.*, chap. Integrating Climate and Water Management in Ceará: Historical Background, Social and Legal Structures, and Implications. Palisades, NY, USA and IRI/FUNCEME, Fortaleza, Brazil. (Cited on pages 12, 13, 15, and 29.)

Taddei, R., Muller, V., Pfaff, A., Broad, K., Lall, U., & Magelhaes Cordeiro, J. H. (2008). Impact of water resource management choices in Ceará, Brazil: roles of streamflow forecasts, rainfall forecasts and participatory decision making. Tech. rep., NOAA Office of Global Programs Grant Report, New York, USA. (Cited on pages 24 and 25.)

Tang, S. Y. (1992). *Institutions and collective action : self-governance in irrigation*. ICS Press, San Francisco, CA, USA. (Cited on page 5.)

Thoyer, S., Morardet, S., Rio, P., Simon, L., Goodhue, R., & Rausser, G. (2003). A bargaining model to simulate negotiations between water users. *Journal of Artificial Societies and Social Simulation*, *4*, pp.95–120. (Cited on pages 65, 71, and 81.)

Uvo, C. B., Repelli, C. A., Zebiak, S. E., & Kushnir, Y. (1998). The relationships between tropical pacific and Aatlantic SST and Northeast Brazil monthly precipitation. *Journal of Climate*, *11*, pp.551–562. (Cited on page 10.)

Van Oel, P. R. (2009). *Water-scarcity patterns : spatiotemporal interdependencies between water use and water availability in a semi-arid river basin*. Ph.D. thesis, University of Twente, Enschede, the Netherlands. (Cited on pages 9 and 65.)

Van Oel, P. R., Krol, M. S., & Hoekstra, A. Y. (2009). A river basin as a common-pool resource: a case study for the Jaguaribe basin in the semi-arid Northeast of Brazil. *International Journal of River Basin Management*, *7*, pp.345–353. (Cited on pages 5, 6, 9, 38, 46, and 70.)

Van Oel, P. R., Krol, M. S., Hoekstra, A. Y., & Taddei, R. R. (2010). Feedback mechanisms between water availability and water use in a semi-arid river basin: A spatially explicit multi-agent simulation approach. *Environmental Modelling & Software*, *25*, pp.433–443. (Cited on pages 2, 6, and 81.)

Wallace, J. S., Acreman, M. C., & Sullivan, C. A. (2003). The sharing of water between society and ecosystems: from conflict to catchment-based co-management. *Philosophical Transactions Of The Royal Society B: Biological Sciences*, *358*, pp.2011–2026. (Cited on page 4.)

Wester, P., Merrey, D. J., & de Lange, M. (2003). Boundaries of consent: stakeholder representation in river basin management in mexico and south africa. *World Development*, *31*, pp.797–812. (Cited on page 1.)

Wilder, M., & Lankao, P. R. (2006). Paradoxes of decentralization: Water reform and social implications in Mexico. *World Development*, *34*, pp.1977–1995. (Cited on page 1.)

Willmott, C. J. (1981). On the validation of models. *Physical Geography*, *2*, pp.184–194. (Cited on page 30.)

World Bank (2009). Decentralization & subnational regional economics. URL `http://go.worldbank.org/R3M4VAP5W0`. (Cited on pages 3 and 5.)

Part I

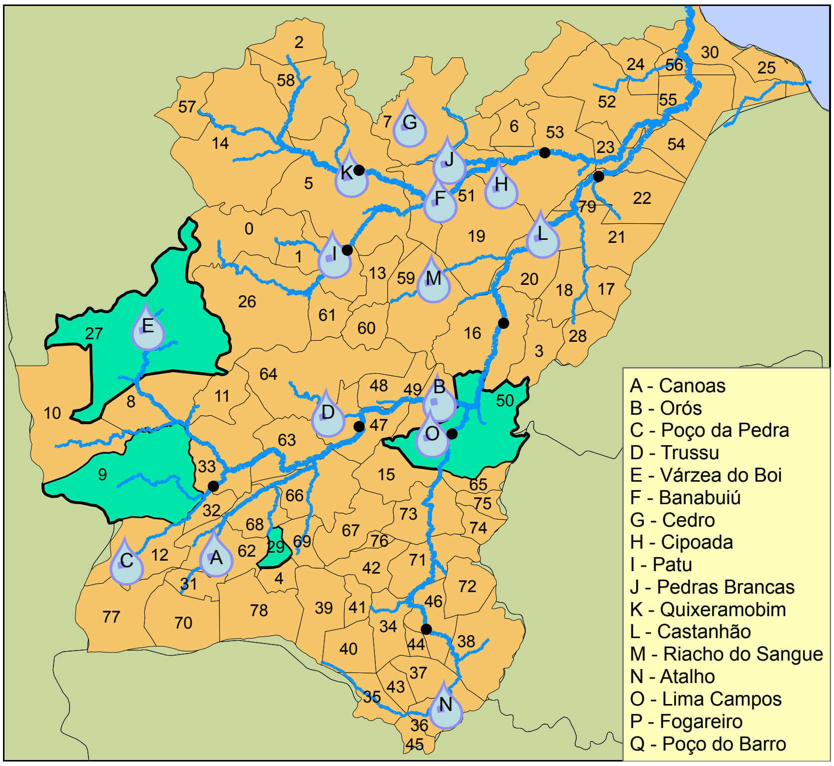
APPENDIX

A APPLICATIONS OF ABM

Objective of Study (Model Name)	Study Area	# and Types of Agents	Authors (Year)	Spatially Explicit
Impact of organization of water allocation structure on water use efficiency (Bali)	Oos River and Petanu River watersheds, Bali, Indonesia (61.4 km^2)	172 Subaks (groups of farmers), 'water temple'	Lansing & Kremer [1993]	Yes
Examine the reasons behind poor viability of the irrigated systems (SHADOC)	5 Different irrigation systems in the Senegal River valley, Senegal	40-60 Individual farmers, pumping station manager, water course manager	Barreteau & Bousquet [2000]	No
Assessment of the relevance of bargaining models as negotiation-support tools in water allocation (Adour)	Adour River basin, France (472 km^2)	3 groups of farmers aggregated by sub-basin (total 1332), 2 'environmental lobbies', 1 water manager and 1 'taxpayer'	Thoyer et al. [2003]	No
Simulate the interaction between the physical and socio-economic components of the system (SINUSE)	Kairouan water table, Tunisia (250 km^2 scaled down to 24 km^2)	2400 Individual farmers representing 1 ha.	Feuillette et al. [2003]	Yes
Impact of upstream water management on downstream farming systems (CATCHSCAPE)	Mae Uam catchment, Thailand (43.6 km^2)	327 Individual farmers, water manager	Becu et al. [2003]	Yes
Influence of organization structure of water management, information on water availability and diversity of water uses on the resilience to water scarcity (Amudarya)	Irrigation scheme in the Amudarya River delta, Central Asia	9 Farmers, national authority	Schluter & Pahl-Wostl [2007]	No
Impacts of technical change and informal rental markets on household income and water use efficiency (Maule)	4 Micro-watersheds in the Maule River basin, Chile (667 km^2)	5400 Farmer households	Berger [2001]	Yes
Inter-relation between upstream and downstream water use and availability (ABSTRACT)	Oros reservoir and 2 smaller connected reservoirs, NE Brazil (178 km^2)	2442 Individual farmers representing 1 plot of 7.39 ha.	Van Oel et al. [2010]	Yes

B

OVERVIEW MAP



ID	Name	ID	Name	ID	Name	ID	Name
0	Pedra Branca	20	Jaguaribara	40	Barbalha	60	Deputado Irapuan Pinheiro
1	Senador Pompeu	21	Alto Santo	41	Juazeiro do Norte	61	Piquet Carneiro
2	Itatira	22	Tabuleiro do Norte	42	Caririaçu	62	Assaré
3	Pereiro	23	Limoeiro do Norte	43	Porteiras	63	Jucás
4	Nova Olinda	24	Palhano	44	Abaiara	64	Acopiara
5	Quixeramobim	25	Icapuí	45	Penaforte	65	Umari
6	Ibicuitinga	26	Mombaça	46	Milagres	66	Cariús
7	Quixadá	27	Tauá	47	Iguatu	67	Várzea Alegre
8	Arneiroz	28	Ererê	48	Quixelô	68	Tarrafas
9	Aiuaba	29	Altaneira	49	Orós	69	Farias Brito
10	Parambu	30	Aracati	50	Icó	70	Araripe
11	Catarina	31	Potengi	51	Banabuiú	71	Aurora
12	Campos Sales	32	Antonina do Norte	52	Russas	72	Barro
13	Milhã	33	Saboeiro	53	Morada Nova	73	Lavras da Mangabeira
14	Boa Viagem	34	Missão Velha	54	Quixeré	74	Ipaumirim
15	Cedro	35	Jardim	55	Jaguaruana	75	Baixio
16	Jaguaribe	36	Jati	56	Itaiçaba	76	Granjeiro
17	Potiretama	37	Brejo Santo	57	Monsenhor Tabosa	77	Salitre
18	Iracema	38	Mauriti	58	Madalena	78	Santana do Cariri
19	Jaguaretama	39	Crato	59	Solonópole	79	São João do Jaguaribe

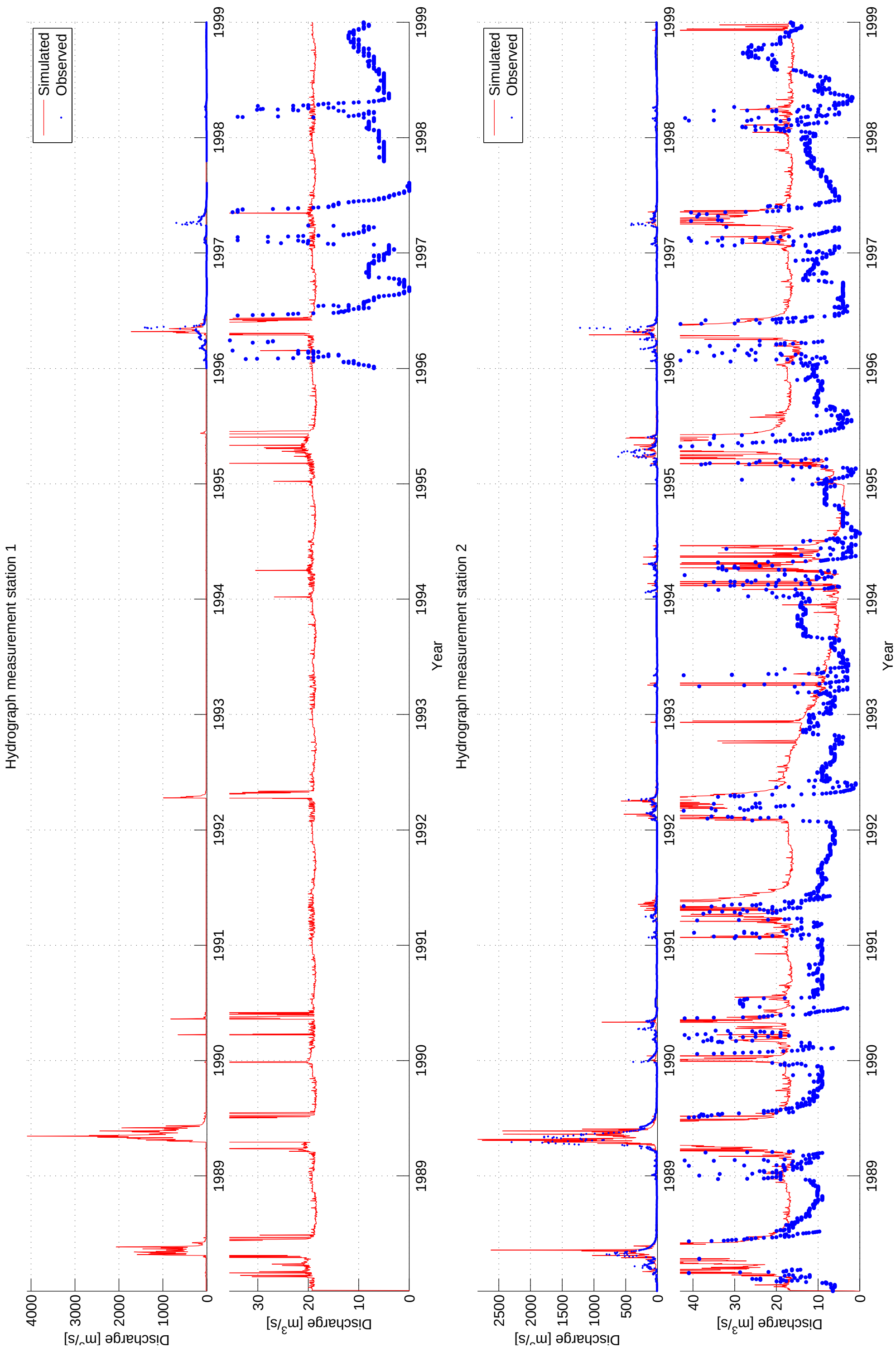
C

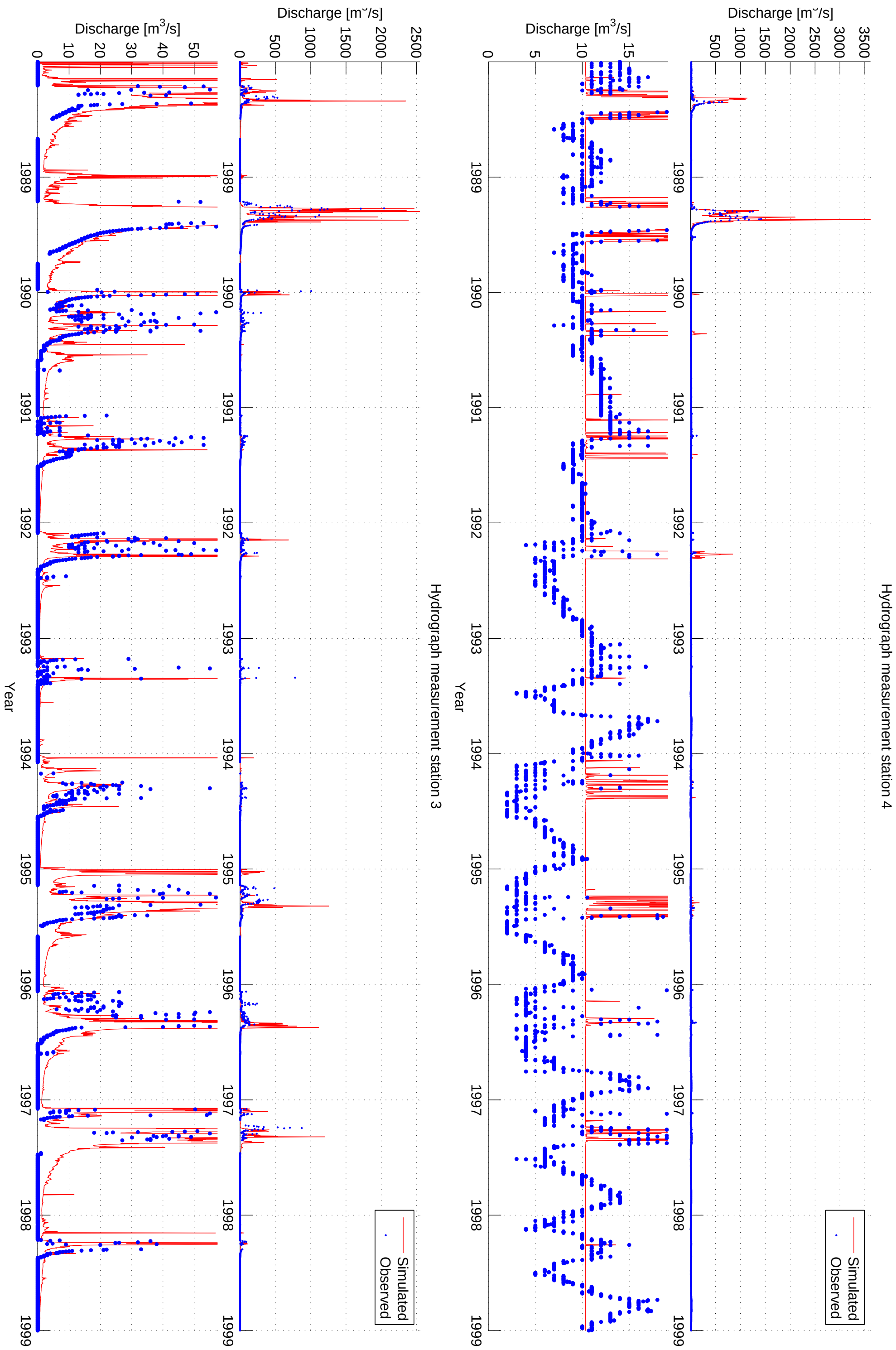
CHARACTERISTICS LARGE RESERVOIRS

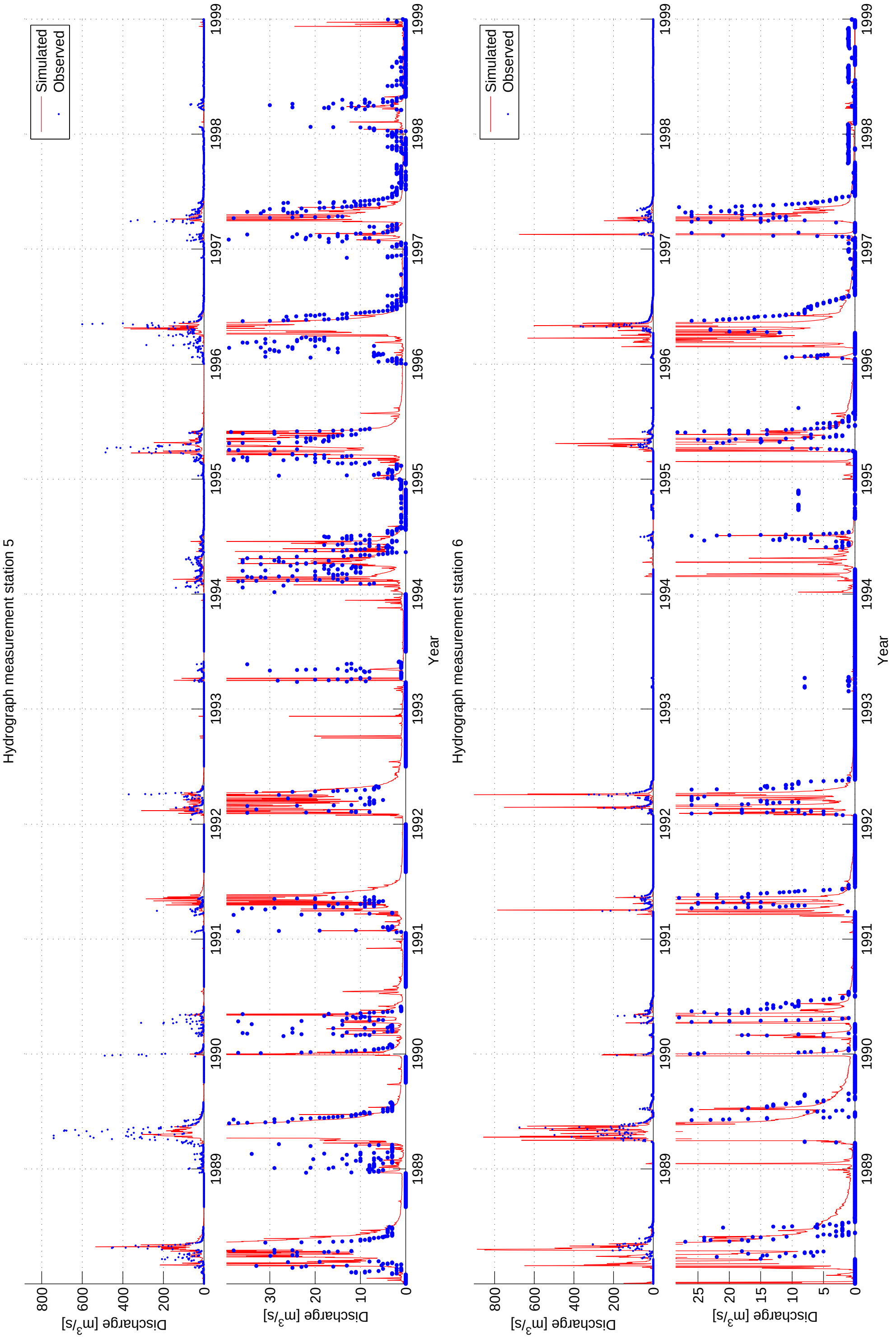
Municipality	Reservoirs	V_{max} [10^6 m^3]	V_{al} [10^6 m^3]	V_{min} [10^6 m^3]	Q_{90} [m^3/s]	f_Q [–]	c_{LR} [–]	d_{LR} [–]
Senador Pompeu	Patu	71.8	12.4	3.4	0.8	0.9	44.47	0.70
Quixeramobim	Quixeramobim & Fogareiro	172.8	11.0	0.5	2.5	0.9	63.00	0.71
Quixadá	Cedro & Pedras Brancas	560	112	28	3.7	0.9	25.00	0.86
Campos Sales	Poço da Pedra	50	8.7	2.3	0.5	0.9	60.40	0.66
Alto Santo	Castanhão	4451	890	223	21.8	0.9	74.95	0.70
Tauá	Várzea do Boi	51.9	5.9	1.2	0.2	0.9	29.35	0.91
Brejo Santo	Atalho	108	21.6	5.4	0.6	0.9	82.39	0.53
Iguatu	Trussu	260.6	52.1	13.0	1.6	0.9	74.56	0.63
Orós	Orós & Lima Campos	2020	662.8	32.5	20.82	0.8	53.96	0.79
Banabuiú	Banabuiú	1800	243.6	12.0	12.9	0.8	7.76	0.97
Morada Nova	Cipoada & Poço da Barra	138.1	27.6	6.9	0.8	0.9	73.50	0.69
Solonópole	Riacho do Sangue	61.4	21.7	5.0	0.6	0.9	53.47	0.70
Assaré	Canoas	69.3	13.8	3.5	0.2	0.9	22.06	0.62

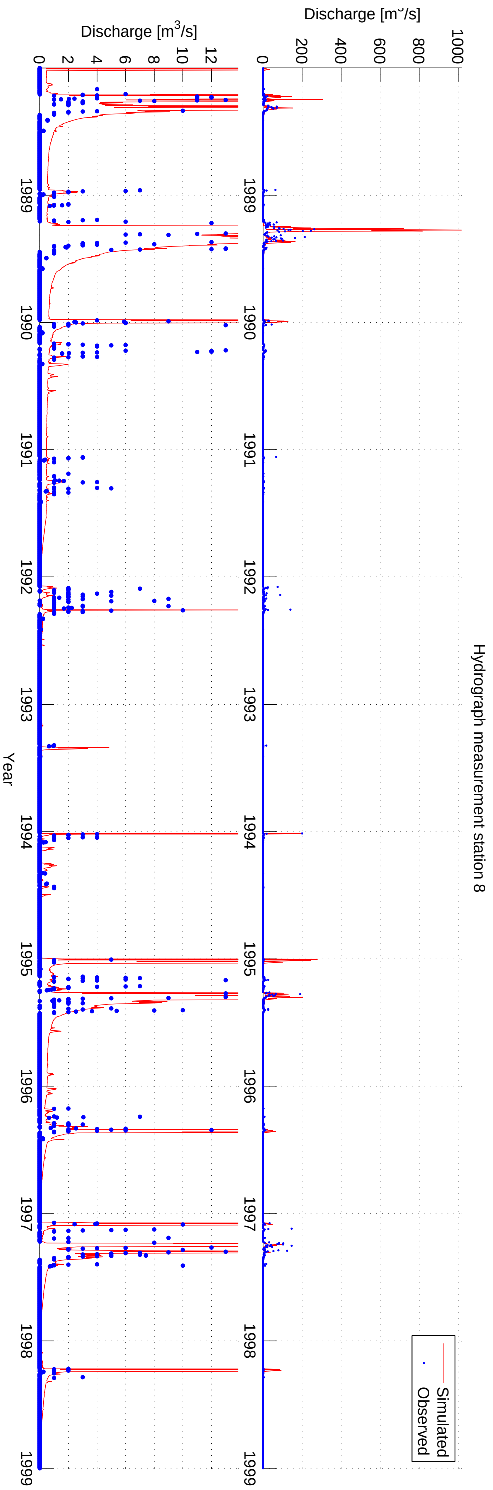
D

HYDROGRAPHS

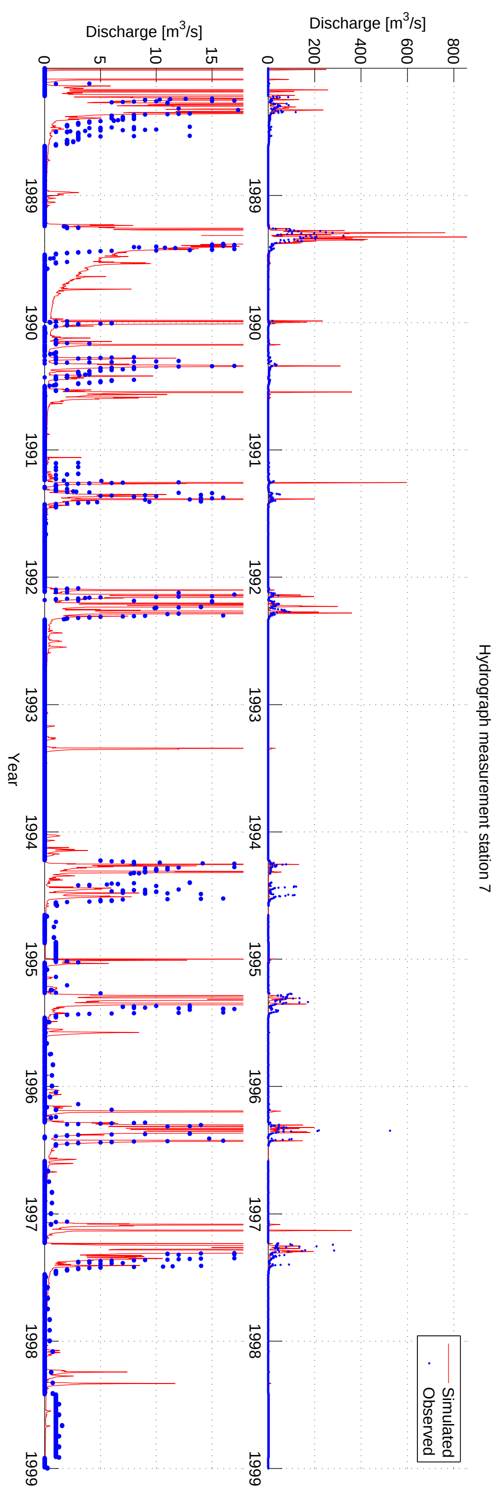



Hydrograph measurement station 4
Hydrograph measurement station 3
Discharge [m3/s]
Year
Simulated
Observed
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999

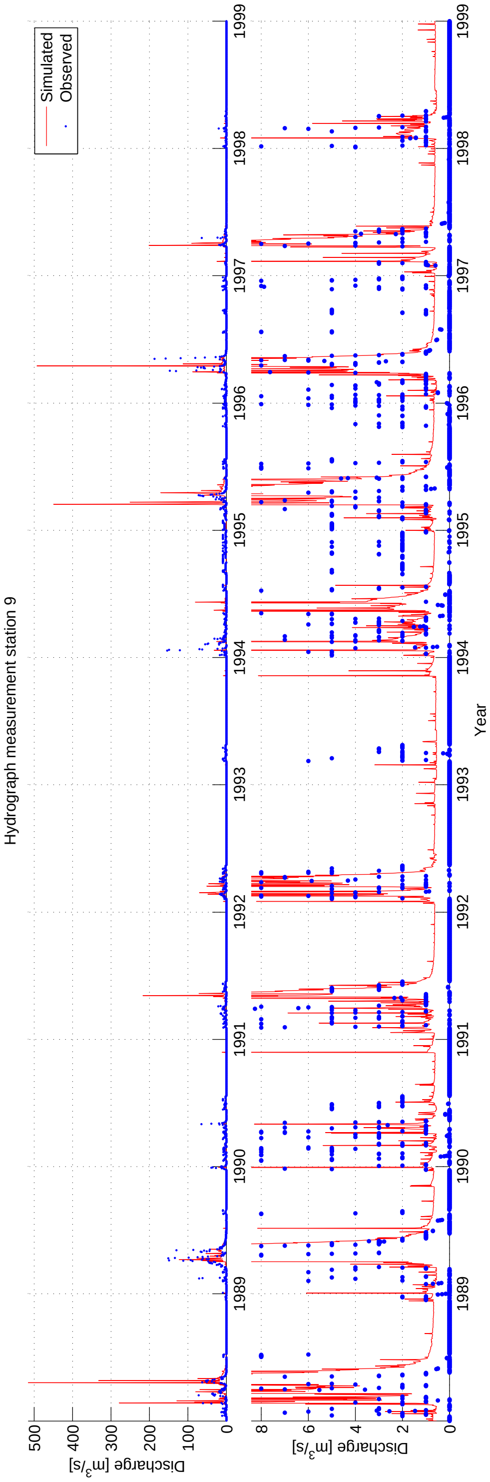

Hydrograph measurement station 5
Simulated
Observed
Discharge [m^3/s]
Year
Hydrograph measurement station 6
Simulated
Observed
Discharge [m^3/s]
Year



Hydrograph measurement station 8
Discharge [m3/s]
Year
Simulated
Observed

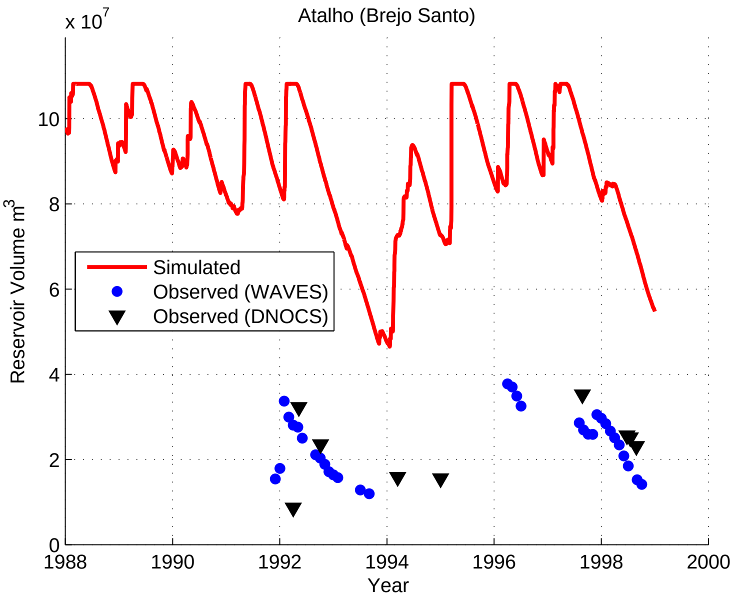


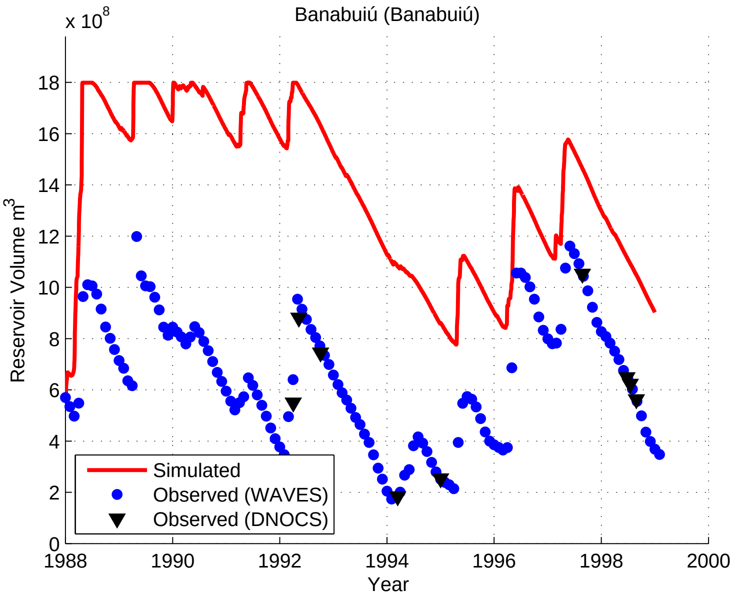
Hydrograph measurement station 7
Discharge [m3/s]
Year
Simulated
Observed

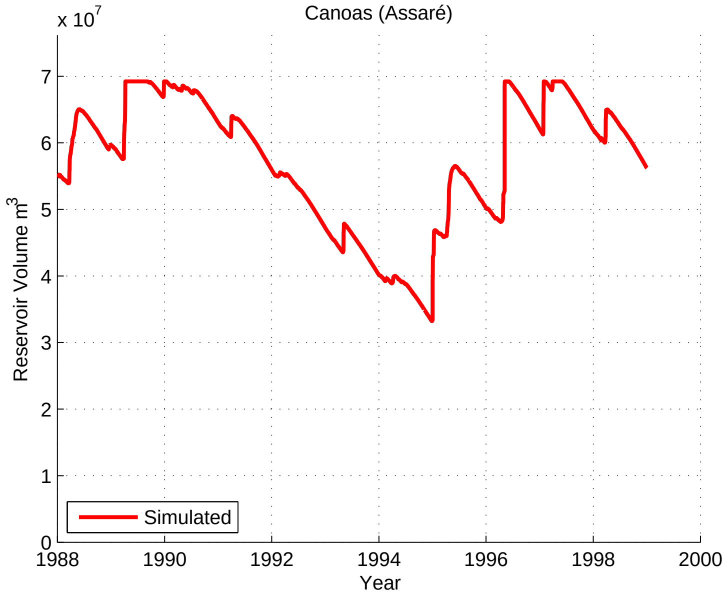

Hydrograph measurement station 9
Simulated
Observed
Discharge [m³/s]
Discharge [m³/s]
Year
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999

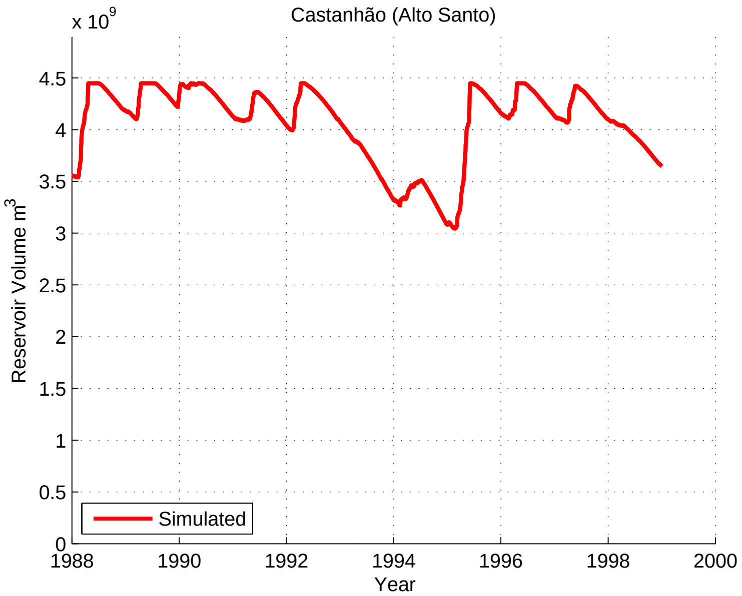
E

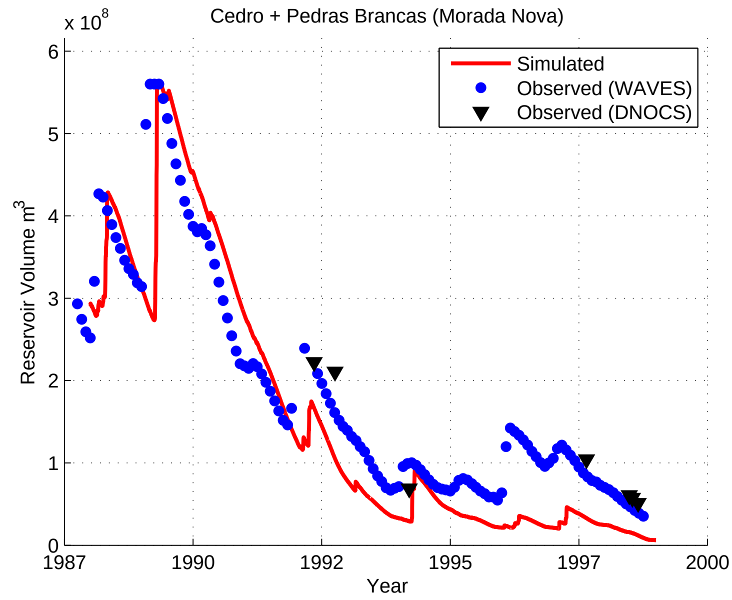
RESERVOIR VOLUMES



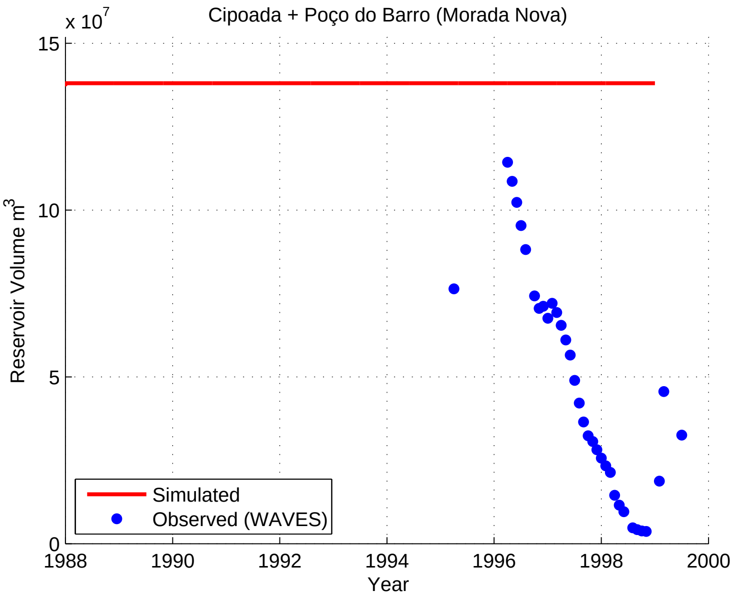



x 10^7
Canoas (Assaré)
Reservoir Volume m^3
7
6
5
4
3
2
1
0
Simulated
1988
1990
1992
1994
1996
1998
2000
Year

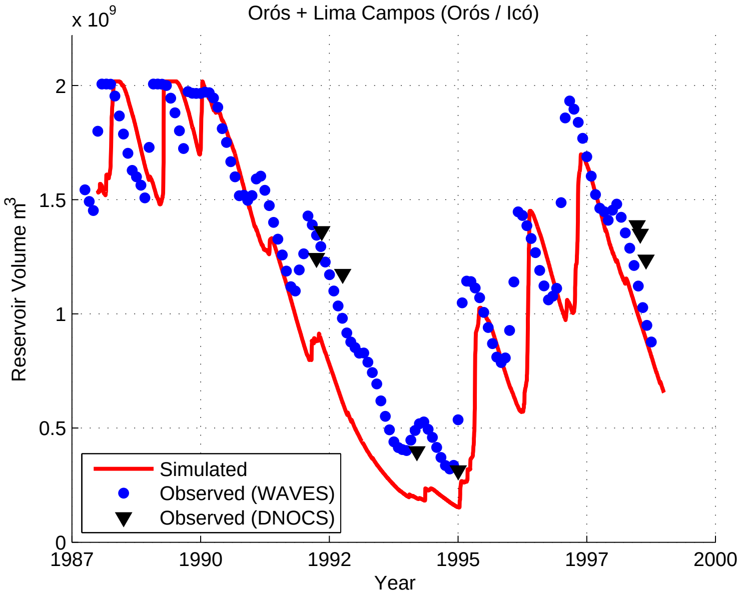

x 10^9
Castanhão (Alto Santo)
Reservoir Volume m^3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Simulated
1988
1990
1992
1994
1996
1998
2000
Year

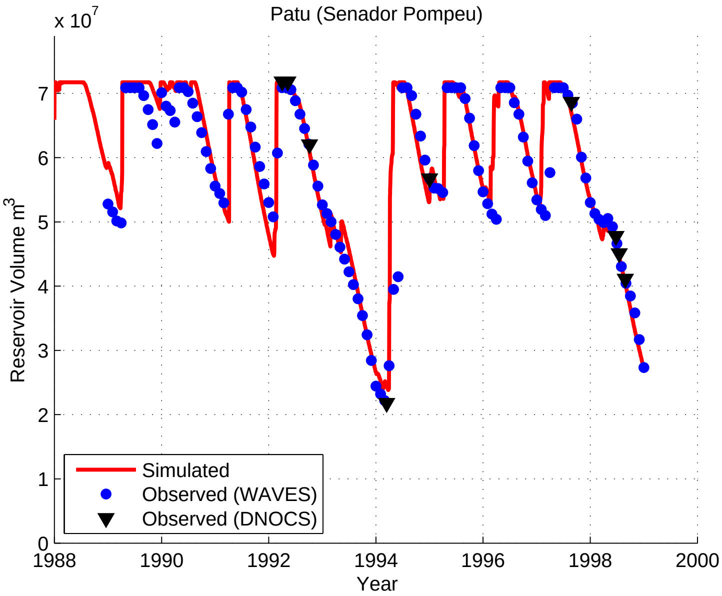


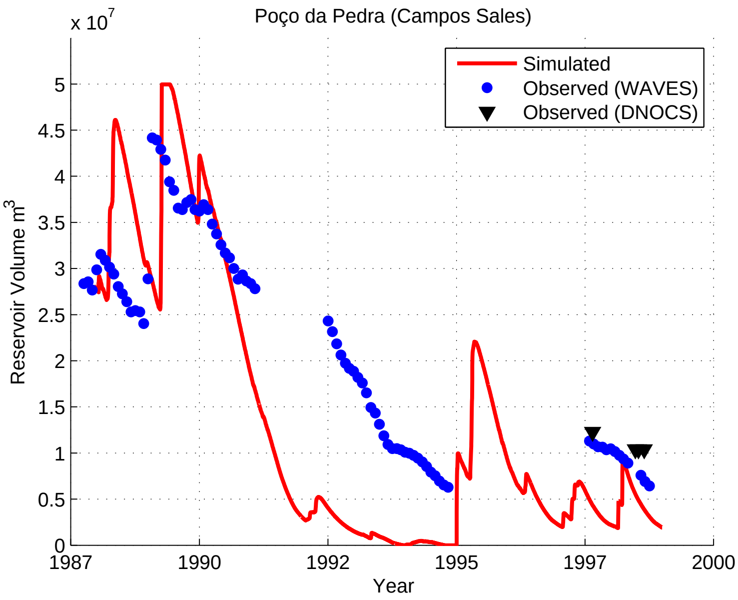
Cedro + Pedras Brancas (Morada Nova)
x 10^8
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)
0
1
2
3
4
5
6
1987
1990
1992
1995
1997
2000

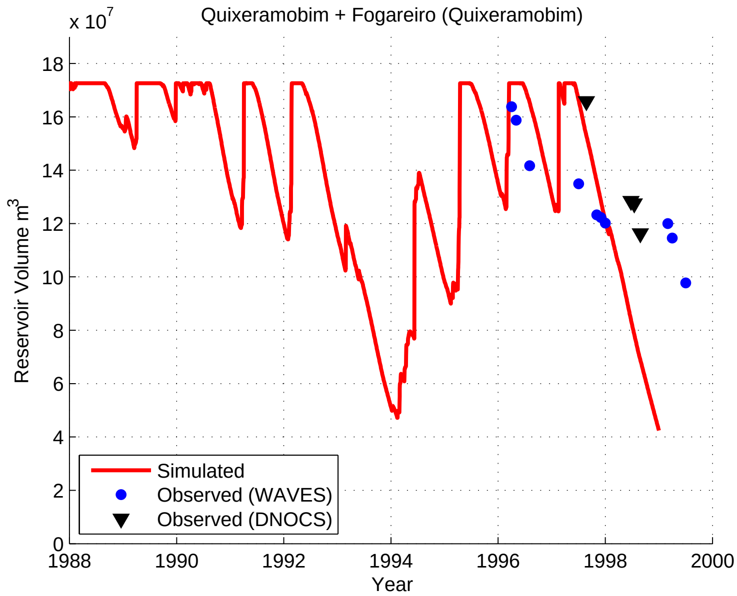


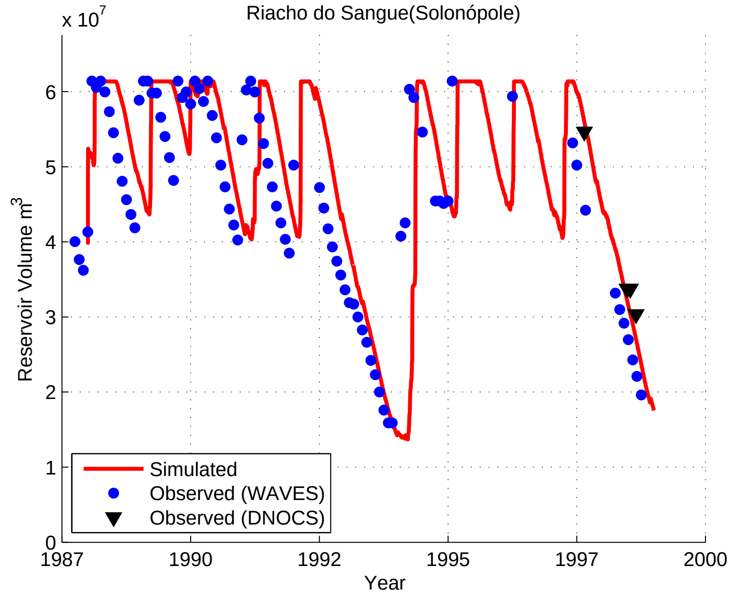
Cipoada + Poço do Barro (Morada Nova)
x 10^7
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
0
5
10
15
1988
1990
1992
1994
1996
1998
2000

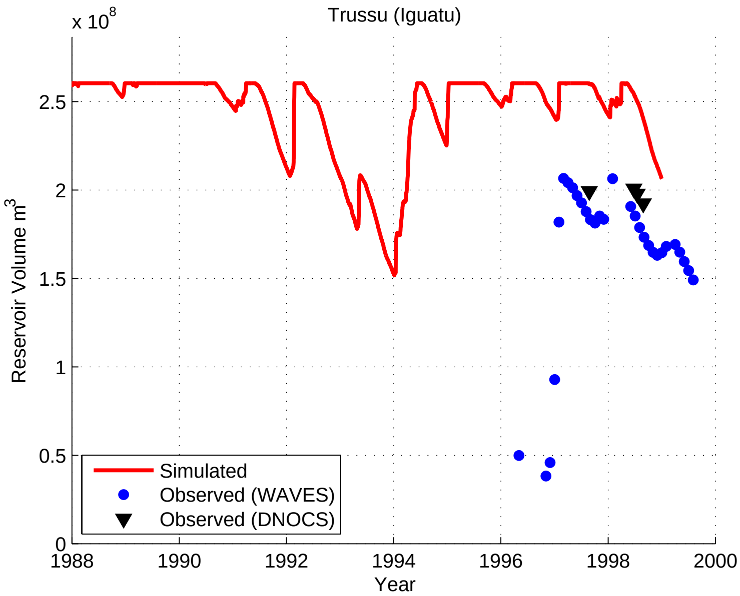

Orós + Lima Campos (Orós / Icó)
x 10^9
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)

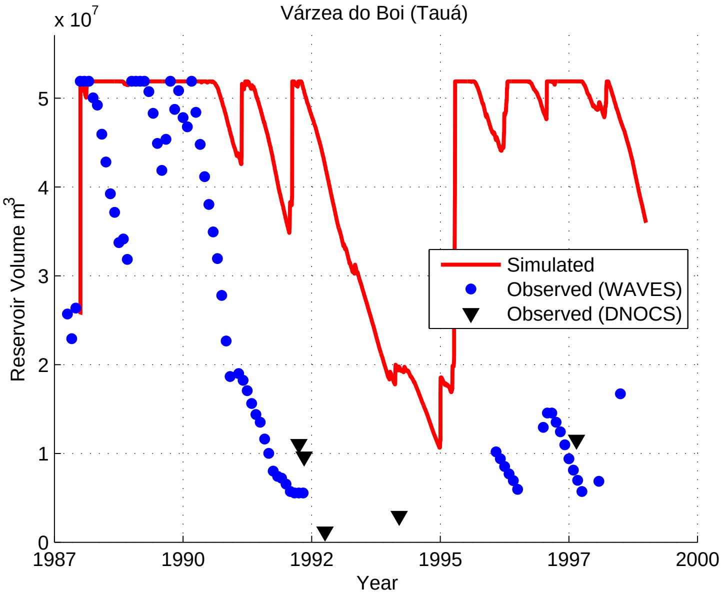

Patu (Senador Pompeu)
x 10^7
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)


Poço da Pedra (Campos Sales)
x 10^7
Reservoir Volume m^3
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1987
1990
1992
1995
1997
2000
Year
Simulated
Observed (WAVES)
Observed (DNOCS)


Quixeramobim + Fogareiro (Quixeramobim)
x 10^7
Reservoir Volume m^3
0
2
4
6
8
10
12
14
16
18
1988
1990
1992
1994
1996
1998
2000
Year
Simulated
Observed (WAVES)
Observed (DNOCS)


Riacho do Sangue(Solonópole)
x 10^7
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)
0
1
2
3
4
5
6
1987
1990
1992
1995
1997
2000


Trussu (Iguatu)
x 10^8
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)
0
0.5
1
1.5
2
2.5
1988
1990
1992
1994
1996
1998
2000


Várzea do Boi (Tauá)
x 10^7
Reservoir Volume m^3
Year
Simulated
Observed (WAVES)
Observed (DNOCS)
0
1
2
3
4
5
1987
1990
1992
1995
1997
2000