WATER-SCARCITY PATTERNS

SPATIOTEMPORAL INTERDEPENDENCIES BETWEEN WATER USE AND WATER AVAILABILITY IN A SEMI-ARID RIVER BASIN

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SPATIOTEMPORAL INTERDEPENDENCIES BETWEEN WATER USE AND WATER AVAILABILITY IN A SEMI-ARID RIVER BASIN

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
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volgens besluit van het College voor Promoties
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door

Pieter Richard van Oel
geboren op 15 januari 1980
te Meppel

Dit proefschrift is goedgekeurd door:

prof. dr. ir. A.Y. Hoekstra	promotor
dr. M.S. Krol	assistent-promotor

Contents

Preface

> *In rivers, the water that you touch is the last of what has passed and the first of that which comes; so with present time.*
>
> Leonardo da Vinci (1452-1519)

In 2003 Maarten Krol and Suzanne Hulscher gave me the opportunity at the Water Engineering and Management Department of the University of Twente to start with my research on the interdependencies between water availability and water use in the semi-arid northeast of Brazil. This thesis is the last of what has passed since then.

During model programming I lost my way many times. When it got really nasty, Nicolas Becu helped me out. Marco Huigen, you introduced me to the agent-based modelling society: thanks for your enthusiasm! I would also like to thank Chris Mannaerts for helping me in dealing with valuable remotely-sensed data and Blanca Perez for helping me a great deal with GIS-related issues.

In 2005 and 2006 I went to Ceará for fieldwork. Renzo Taddei, you were my guide to all there is to know about Ceará, its water scene, the nicest beaches and many more things: thank you so much! Zé Carlos, your help, advice and hospitality are greatly appreciated. My visits to Ceará were also special because of my friends Ana, Karen, Raimundo, Joanne, Arubio and Benjamin.

Anne Leskens and Marjella de Vries, you joined Bertien and me on our trip to Ceará in 2006, what a great time we had! The work you did helped me a lot and your working spirit motivated me greatly as well. Further, I would like to thank Alexandre, Vanda and Thereza from UFC, Paulo Miranda, Walt Disney, Margarida, Débora and Yarley from COGERH, Eduardo Sávio and Sonia from FUNCEME and Eriberto, Erivan, Douglas, João Lúcio, Elisângela, Esaú, Pedro Molinas and Tonião for helping me finding the data and information I needed.

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My supervisors Maarten Krol and Arjen Hoekstra have motivated me to look deeper and further, mostly during the meetings of the three of us. I was always strongly supported in undertaking initiatives and attending a wide variety of courses, workshops and conferences. Maarten, you have been there from the start: thank you for always being there for me.

My big brother Chris van Oel and the phenomenal Maarten Brandjes stand by my side in at the day of my defence. It is a dirty job, but someone has got to do it: thanks guys!

Paul Koopman, thank you for all your support and of course for designing the cover of this thesis.

To my parents, Adrie and Richard van Oel: bedankt voor jullie geduld, interesse en liefde.

And finally Bertien, how on earth can somebody be as fantastic as you are? You are the first in whatever comes.

Pieter van Oel

Enschede, 25 March 2009

1 Introduction

1.1 General introduction

Precipitation above land recharges the world's freshwater resources. Overland and underground water flows redistribute water availability on land. The distribution of water resources is of critical importance in the functioning of society. Water shortages are due to a mismatch between demand for water and its availability over space and time. Throughout history many communities have adapted to water shortages by transforming terrestrial water systems (L'Vovich et al., 1990). All over the world people manipulate water stocks and flows in space and time by installing and operating infrastructure. Thus the distribution of water resources is influenced by a combination of natural processes and human actions.

In many places water scarcity increases as water systems are subject to rises in pollution and exploitation (Postel, 2000; Postel et al., 1996). Water use in the agricultural sector has increased sharply since the 1960s due to investments that have led to a doubling of irrigation area worldwide (Oki and Kanae, 2006). At the beginning of the 21st century irrigation accounted for more than 90 per cent of global consumptive water use (Shiklomanov and Rodda, 2003).

With respect to climate change, changes in temperature, evaporation and precipitation influence the distribution of river flows and groundwater recharge (Kundzewicz et al., 2008; 2007). Changes in water availability vary for different regions, e.g. with respect to seasonal patterns and increased probability of extreme events (Oki and Kanae, 2006). Climate change is expected to accelerate natural water cycles and may thereby decrease the availability of renewable freshwater resources in some places and periods, while increasing it in other places and periods.

Tropical semi-arid river basins are generally subject to strong intra-annual and inter-annual rainfall variability and are among the areas most vulnerable to climate change (Alcamo and Henrichs, 2002; Arnell, 2004; Kundzewicz et al., 2007). International trade offers opportunities for economically-prosperous regions to compensate for their natural water shortage by importing virtual water (Allan, 1998; Hoekstra and Chapagain, 2008). For semi-arid basins in developing countries, however, vulnerability is exacerbated by the expectation of rapid population growth and the resulting increase in water demand (Millennium Ecosystem Assessment, 2005).

Despite rapidly improving insights, many questions relating to the impact of climate change on water availability, water use and interdependencies between these two in semi-arid river basins remain unanswered. In this thesis these questions are addressed by analysing and modelling the interaction between water use and water resources and by assessing how this interaction affects the spatial and temporal distribution of water availability and water use in a semi-arid river basin.

This introductory chapter is organised as follows. In Section 1.2 the research problem is formulated. The research objective, questions and scope that have guided this study are introduced in Section 1.3. Section 1.4 sketches the background to this study with regard to recent developments in the fields of river basin management studies, common-pool resources theory and the modelling of human-environment interactions through the use of multi-agent simulation. The outline of the thesis is described in Section 1.5.

1.2 Problem statement

There is a knowledge gap with respect to the interdependencies between water use and water availability on different temporal and spatial scales in semi-arid river basins. The relation between water users and water resources is reciprocal: human interference in hydrological processes changes water resources availability and changes and variations in the distribution of water resources over space and time induce responses by water users. Although many important studies (e.g. climate change impact assessments) recognise that one should take into account the impact of human activities on natural processes in studying water scarcity, water user responses to variations and changes in water availability are generally not taken into account. Reducing this knowledge gap is relevant to climate change impact assessments and water allocation in semi-arid environments.

1.3 Research objective, questions and scope

The objective of this thesis is to increase understanding of the influence of changes and variations in rainfall and the application of alternative reservoir operation strategies on the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin. This is achieved by analysing and modelling the interactions between water users and water resources. To guide this study the following research questions have been formulated:

1 What physical characteristics of a semi-arid river basin are critical for the manageability of water resources?

2 What is the relationship between water use and water availability in a semi-arid river basin?

3 Can the use of a multi-agent simulation approach to depicting sub-basin scale interaction between water use and water resources result in a valid representation of observed variations in the distribution of water use and water availability?

4 What are the effects of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use and water availability in a semi-arid river basin?

The research conducted aims to contribute to the literature on river basin management (RBM) with respect to water allocation in semi-arid river basins. The river basin that was used for empirical evidence in this study is the Jaguaribe basin, located in the state of Ceará in the northeast of Brazil. To answer the first research question use was made of literature on common-pool resource (CPR) management, because this field of study addresses the influence of resource system characteristics on the manageability of resource systems. To answer the second research question a standard stochastic approach was used to simulate the influence of water use in a sub-basin on the yield of a reservoir that is located downstream of that sub-basin. Variations in water use that are due to interactions between water users and local water resources are included. To answer the third research question a multi-agent simulation (MAS) model has been developed and validated. A MAS model allows the representation of interaction between water users and water resources in a spatially-explicit way. To answer the fourth research question the developed MAS model was applied.

1.4 Scientific context

This thesis is built upon three pillars of knowledge. Knowledge from the field of river basin management that relates to the subject of this thesis is described in Section 1.4.1. For analysing and interpreting processes in the Jaguaribe river basin use has been made of concepts from common-pool resources theory, which is introduced in Section 1.4.2. Relevant recent developments regarding modelling human-environment interactions using multi-agent simulation are described in Section 1.4.3.

1.4.1 River basin management research

In the literature on river basin management it is widely recognised that many human activities need and affect freshwater systems. RBM involves strategic manipulation of the interaction between natural processes, socio-economic activities and institutional arrangements that are relevant to a river basin (Mostert et al., 1999). A concept closely related to RBM is that of integrated water resources management (IWRM), which is based on the ‘Dublin principles’ (Global Water Partnership, 2000; ICWE, 1992). It has been recognised for almost a century that the river basin is the natural unit for water management and regional development (Molle, 2006; Teclaff, 1967; White, 1957). RBM emphasises the geographical dimension of water resources and the relation between water and land resources and has therefore evolved into the cornerstone of IWRM in recent decades (ICWE, 1992; Molle, 2006). It has increasingly been adopted by policy makers who have implemented institutional and organisational reforms in the water sector (MMA, 1997; United Nations, 2002; World Bank, 1993; 2003; World Water Council, 2000; 2006).

Different perspectives that are generally encountered in studies on RBM relate to natural sciences, engineering, decision making, social, legal and ethical issues, or a combination of these (Mostert, 1999). This thesis primarily concentrates on the first three perspectives rather than the latter three. An important aspect in policy reforms is a focus on the decentralisation of management to the lowest appropriate level, an approach known as the subsidiarity principle (ICWE, 1992; Kemper et al., 2007). Appropriate in this context means the involvement of stakeholders in a basin, including water users, with the aim of achieving sustainable management of water resources (World Bank, 2005).

Supported by international organisations, national governments have implemented policies that have led to impressive increases in storage capacity, as a result of the building of large dams (L'Vovich et al., 1990; Shiklomanov and Rodda, 2003). Positive and negative consequences of this increase have been intensely discussed and studied (World Commission on Dams, 2000). Brown and Casey (2006) argue that investment in infrastructure for water storage could solve (seasonal) water shortages in many countries. However, 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 and Molden, 2008; Molden, 2007; Molle, 2004; 2008; Seckler, 1996; Smakhtin, 2008; Svendsen et al., 2001). 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). When the potential effect of adding reservoir capacity begins to fail, i.e. when the negative impact of dams starts to overshadow their benefits, only water demand management offers opportunities, such as by increasing irrigation efficiency. Venot et al. (2007) argue that increasing irrigation efficiency might lead to a spatially and temporally ‘redistributed’ water availability on a local scale, rather than benefiting downstream users. Empirical evidence on the ‘basin-scale’ effects of these human-environment interactions is largely lacking.

In recent decades RBM has benefited from important improvements in the development and application of simulation and optimisation models (Loucks and Van Beek, 2005). Some of these tools enable an improved understanding of the consequences of measures at different levels and a better evaluation of water demand management alternatives. They assist authorities and local resource users by providing information useful for decision making. Few model applications take into account the effect of interactions between water users and water resources that are spatially spread over a basin. There is a lack of understanding of a potentially important feedback mechanism: water use influences water availability, which induces water user responses. In addition the variability of water use and availability in time and space creates a need for spatially-explicit model representations that allow the analysis of the effects of this feedback mechanism.

1.4.2 Common-pool resources research

Research on common-pool resources addresses the relationship between resources and human institutions designed for the use and maintenance of these resources (IASC, 2008). A CPR has been defined as a natural or man-made resource from which it is difficult to exclude users and for which the use by one user subtracts from the possibility of use by another (Ostrom, 1990). Most of the research on CPRs concentrates on natural resources such as fisheries, forests and water resources. Focus areas within the field of CPR research include adaptive systems, game theory, participatory management systems and resilience. Researchers studying CPR problems generally address solutions that move away from the tragedy of the commons (Hardin, 1968). Proposed remedies include privatisation and the establishment of a central authority responsible for managing access to resources. Much of the research focuses on local resources for which governance by local users has developed and has been found to be successful in many cases (Berkes et al., 1989; Feeny et al., 1990; Ostrom, 1990; Ostrom et al., 2002; 1994).

In relation to water resources management, CPR theory has been widely used in cases of competition over water resources in irrigation systems (Baland and Platteau, 1999; Bardhan and Dayton-Johnson, 2002; Lam, 1998; Tang, 1992). In this respect the surface or groundwater reservoir from which farmers abstract water for irrigation is regarded as a CPR. It is increasingly acknowledged that local resources in many cases should preferably be managed by a combination of local users and authorities at the supra-local level. 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 (Berkes et al., 1991; Carlsson and Berkes, 2005; De Groot and Lenders, 2006; Wallace et al., 2003).

Above the level of a water reservoir for irrigation, one can also regard the water within a river basin as a whole as a CPR. The extent is greater, but the characteristics are similar: many users have access to the water in a basin and compete for its use. To date CPR studies have typically focused on local resources, rather than on larger resource systems like river basins. For a local CPR a few physical resource system characteristics are associated with good manageability (Agrawal, 2002). But for larger (supra-local) resource systems, such as a river basin, this has not been studied in depth. A particular circumstance in this regard is that within a river basin externalities exist that are imposed by upstream water user communities on downstream water user communities. In this thesis the manageability of water resources in different parts of a river basin has been analysed and is discussed, accounting for the linkages that exist between upstream and downstream parts of a basin.

1.4.3 Modelling human-environment interaction using multi-agent simulation

Natural dynamics in semi-arid river basins include the interaction between multiple physical processes and resources at different spatial and temporal levels. The use or management of water resources directly influences water resource stocks and flows. Capturing the interaction between humans and water resources is important for understanding the distribution of water resources over space and time. There is a mismatch between dealing with issues of scale in natural sciences and in social sciences (Gibson et al., 2000). At the same time, any distinction between social and natural systems is arbitrary (Adger, 2006). The importance of dealing with issues of scale in studying 'socio-natural systems' is widely acknowledged by researchers who focus on the resilience of such systems or the vulnerability of communities to geophysical and societal changes (Adger, 2006; Adger et al., 2005; Gaiser et al., 2003; Gunderson and Holling, 2002; Holling, 2001; Turner II et al., 2003).

In modelling a multitude of processes on various scales and associated with different levels of organisation, many researchers use a multi-agent simulation approach (Wooldridge, 2001) to study natural resources management (Bousquet and Le Page, 2004; Epstein and Axtell, 1996; Hare and Deadman, 2004; Hare et al., 2001; Matthews et al., 2007; Parker et al., 2002; 2003; Schlüter and Pahl-Wostl, 2007; Verburg, 2006). Instead of modelling processes on one level or scale (i.e. by using differential equations), MAS offers the possibility of modelling processes at various levels along spatial and temporal scales (Matthews et al., 2007; Verburg, 2006). Applying a MAS approach enables the representation of local human-environment interactions that may cause the emergence of complex global system behaviour (Cariani, 1992; Hare and Deadman, 2004).

It is increasingly acknowledged that MAS is an adequate modelling technique to depict human-environment interactions (Deadman and Schlager, 2002; Gimblet, 2002; Parker et al., 2003). MAS applications generally consist of a cellular model representing a natural system and an agent-based model representing human decision making. Agents can be reactive or intentional in their behaviour. Reactive agents respond to information that is received from the environment, while intentional agents may anticipate future states of the environment (Deadman and Schlager, 2002). Only a few models have succeeded in validly representing both agents and their environment by using empirical data (Parker et al., 2003). Examples of such models related to agricultural land use include those described by Berger (2001) and Deadman et al. (2004).

Some MAS applications have been developed to analyse and support water resource management for irrigation schemes and sub-basins (Barreteau and Bousquet, 2000; Barreteau et al., 2004; 2003; Becu et al., 2003; Berger et al., 2007; Bithell and Brasington, 2009; Schlüter and Pahl-Wostl, 2007). Berger et al. (2007) show that MAS is a promising approach to supporting water resource management and to better understanding the complexity of water use and water users within sub-basins. In this thesis MAS is used to represent spatially-explicit interactions between water users and water resources and flows that are relevant to water resources management on a river basin scale and on smaller scales.

1.5 Thesis outline

The research methods that are used to address the four research questions are detailed in Chapter 2. This chapter also describes the Jaguaribe basin in the semi-arid northeast of Brazil, which was used as a case study.

In Chapter 3 concepts from the literature on common-pool resources are applied to analyse the extent to which the physical characteristics of a river basin facilitate or impede manageability of water resources in different parts of the basin. In addition the apparent manageability of water in the different parts of the basin is compared to observed agricultural performance. This chapter addresses the first research question.

Chapter 4 describes the results of an analysis of the impact of upstream water abstractions on the yield of a reservoir. For this purpose a sub-basin study area within the Jaguaribe basin was selected. A standard stochastic approach is used to simulate the influence of water use in the sub-basin on the yield of a reservoir that is located downstream of it. This chapter addresses the second research question.

The knowledge that has been obtained in answering the first two research questions is used to develop a multi-agent simulation approach. The approach, its implementation for the Jaguaribe basin and its validity are presented and discussed in Chapter 5. This chapter addresses the third research question.

In Chapter 6 the fourth research question is addressed. In this chapter the understanding gained of river basin dynamics is used to explore climate change impacts and the ability of water managers to deal with changes through the operation of reservoirs.

The results of this thesis are discussed in Chapter 7. In this chapter the answers to all four research questions are described and presented in the form of conclusions.

2 Methods

2.1 General approach

The dynamics in most river basin resource systems include both social and natural processes, and interactions between the two. To study these a framework of qualitative, quantitative and integrative research methods has been put together to analyse a case study river basin. The river basin that was chosen for empirical evidence in this study is the Jaguaribe basin, located in the state of Ceará in northeast Brazil.

This study involves analysing the system dynamics of water resources in the basin, including the mutual relationship between water availability and water use under the influence of rainfall variability and reservoir operation (Figure 2.1). Interventions in the natural course of water in one place influence water availability and water use in that place itself, as well as in other locations. Obviously, higher water demands lead to increasing abstraction and therefore reduce water availability. In turn water availability influences water demand for irrigation, because water users anticipate and respond to water availability by modifying their decisions with respect to the area of land to be irrigated and the type of crop to grow.

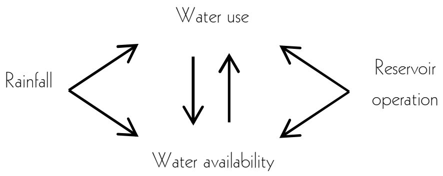

Figure 2.1 *The relationship between water use and water availability under the influence of rainfall and reservoir operation.*

A choice was made to use a single-case approach. Within the Jaguaribe study, results for different spatially-limited subsystems have been compared. A reason for focusing on the Jaguaribe basin was that it has been subject to inter-annual variations in rainfall that are reasonably well understood, while investment in infrastructure and institutional reforms have been intense (Campos and Studart, 2000; Johnsson and Kemper, 2005; Kemper et al., 2007).

The Jaguaribe basin was analysed over a period of time during which a few serious inter-annual dry spells occurred. In this sense the Jaguaribe basin was studied as a longitudinal case (Yin, 2003), in which system states and developments at several points and periods in time were compared.

The research was carried out in four stages, in analogy with the four research questions formulated in Section 1.3:

Stage 1.	Assessment of the manageability of water resources in the Jaguaribe basin (Chapter 3).
Stage 2.	Analysis of the relationship between water use for irrigation and water availability on the sub-basin scale (Chapter 4).
Stage 3.	Development and testing of a multi-agent simulation model that represents the interaction between water users and water resources (Chapter 5).
Stage 4.	Assessment of the influence of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use and water availability, by applying the model that was developed in the third stage (Chapter 6).

This chapter introduces the study area and summarises the research method used in each stage. The methods are described in more detail in the respective chapters devoted to each stage (Chapters 3 to 6). The unit of analysis has not been the same for all research stages. For stage one (Chapter 3) the Jaguaribe basin as a whole was studied (Figure 2.2). For stages 2-4 (Chapters 4-6) the Orós reservoir area was studied (Figure 2.5). In this embedded sub-basin the dynamics that are considered important for many parts of the basin take place. Data availability on the sub-basin scale was considered suitable for validation.

2.2 Study area

The northeast of Brazil has a history of recurrent water stress (Gaiser et al., 2003; Guerra and Guerra, 1980; Villa, 2000), which is related to both rainfall variability and human intervention. At the end of the nineteenth century Senator Francisco de Brito Guerra spoke about a popular desire to dam the northeast of Brazil, so that its water resources would no longer reach the ocean (Guerra and Guerra, 1980). This approach became known as the 'solução hidráulica' (hydraulic solution). Nowadays this seems to be becoming a reality for the Jaguaribe basin, as investments in infrastructure for water storage and the irrigation sector have been substantial for several decades and more are still being planned (Figures 2.3, 2.4).

The Jaguaribe basin is located within the institutional borders of the state of Ceará and covers approximately 74,000 km^2. Current annual precipitation ranges from 450 to 1,150 mm on average, with high levels of temporal and spatial variability (FUNCEME, 2008). Most rain falls in the period January-June. Temporal rainfall variability is highly significant on a range of levels: decadal variability (Souza Filho and Porto, 2003), inter-annual variability, seasonal variability and variability on the time scale of a week (Gaiser et al., 2003; Smith and Sardeshmukh, 2000; Uvo et al., 1998).

Water use is dominated by abstraction for irrigation. Water management and abstraction for irrigation are discussed intensely in Ceará, because of persistent pressure on water reserves in strategic reservoirs (COGERH, 2001a; 2003b; Döll and Krol, 2002; Johnsson and Kemper, 2005; Krol and Van Oel, 2004; Lemos, 2003; Lemos and De Oliveira, 2004). Commercial production of fruit and flowers is increasingly common in the basin (SEAGRI, 2003; 2005).

Two kinds of competition for water seem to occur. First there is competition between upstream and downstream users. User communities that are located directly upstream of reservoir dams tend to disagree with downstream user communities over water releases. Upstream users generally oppose water releases, while downstream users favour them (Broad et al., 2007; Taddei, 2005). Secondly, water users within a local user community compete, generally more or less equally, for water from the same local water resource such as a reservoir or aquifer.

The state of Ceará is Brazil's frontrunner regarding water management and legislation. Decentralisation and participation in water management are claimed to be key in its policy (COGERH, 2001a; 2003b; Kemper, 1996; Lemos and De Oliveira, 2004; Taddei, 2005). The head office of the National Department for Works Against Droughts (DNOCS) in Brazil is located in Fortaleza, the capital of Ceará. Other important organisations in relation to water resources management in the Jaguaribe basin are the Ceará State Foundation for Meteorology and Water Resources (FUNCEME), the Organisation for the Management of Water Resources (COGERH), the State Secretary for Agricultural Business (SEAGRI) and the Organisation for Technical Support for the Rural Areas of Ceará (EMATERCE).

Several earlier studies have been devoted to water scarcity and water management issues for areas within the Jaguaribe basin (Burte et al., 2005; De Araújo et al., 2006; Kemper, 1996; Pennesi, 2007; Taddei, 2005). With respect to water availability from artificially-created reservoirs, it was found that reservoir yield might reduce through decreasing storage capacity due to sedimentation (De Araújo et al., 2006). So far, little research has been done on the impact of the interaction between water users and water resources on water availability and its distribution in the basin.

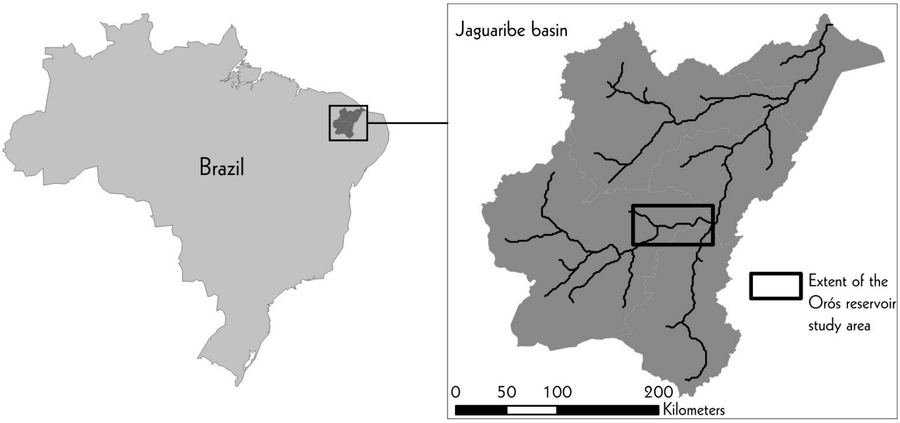

Figure 2.2 *The Jaguaribe basin in the northeast of Brazil.*

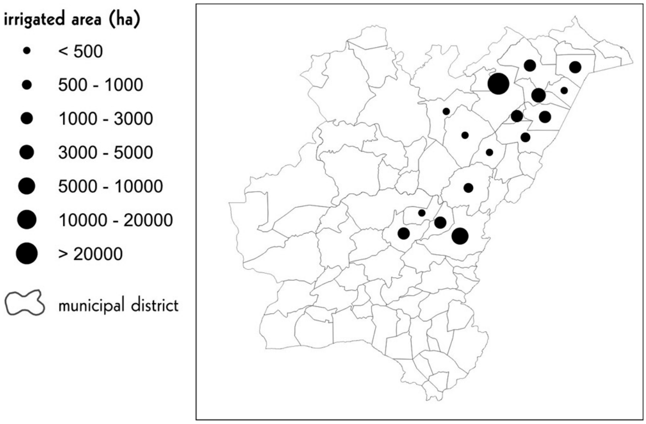

Figure 2.3 *Area equipped for irrigation in 2001-2003, within the Jaguaribe basin, as monitored by the Organisation for the Management of Water Resources in Ceará (COGERH, 2003b).*

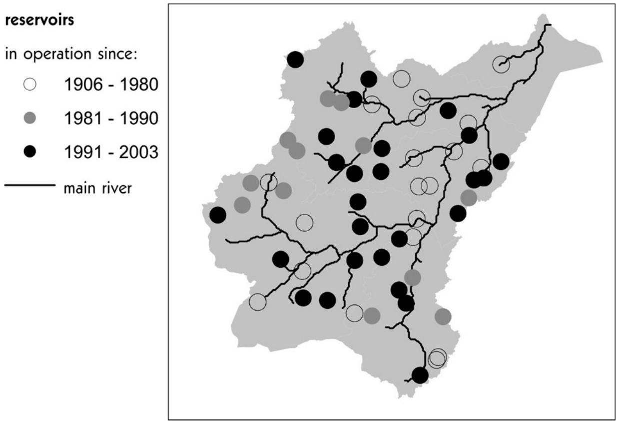

Figure 2.4 *Public reservoirs installed and operated by the National Department for Works Against Droughts (DNOCS) and the Organisation for the Management of Water Resources (COGERH, 2006).*

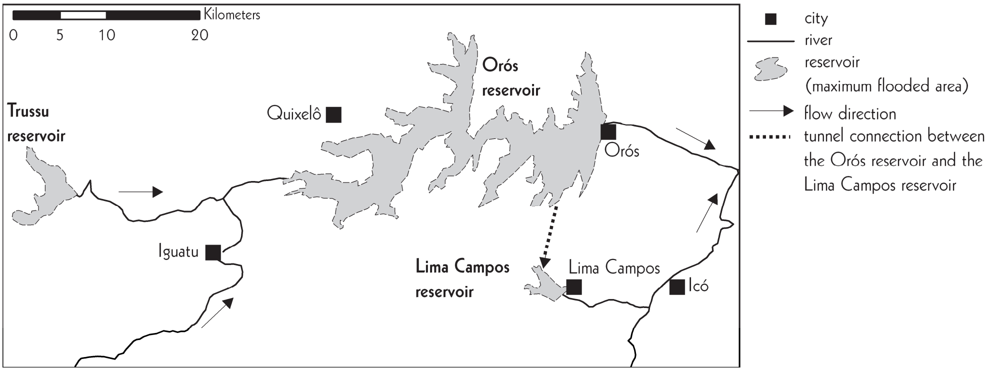

Figure 2.5 *The Orós reservoir area that is studied in stages 2-4 (Chapters 4-6).*

2.3 Stage 1: manageability of water resources in the Jaguaribe basin

To assess the manageability of water resources in the Jaguaribe basin, CPR theory is applied. According to CPR theory the following five physical resource characteristics should be regarded as critical enabling conditions for sustainable management: small spatial extent, well-defined boundaries, possibilities of storage, predictability of resource flows and low levels of mobility of the resource (Agrawal, 2002). For every topographical zone (upstream, midstream and downstream) it is estimated to what extent these conditions are met. To do this use is made of information on topographical elevation, the geographical distribution of surface water and the temporal variability of rainfall. In this way an assessment is made of the likelihood that water resources are well managed. This is then compared to actual agricultural performance in each topographical zone, which is supposed to be strongly dependent on the availability and management of water resources. Agricultural performance is measured using three indicators, following Conway (1987), which are: productivity, stability of production and equitable productivity and stability over space.

For this stage, use is made of agricultural production data (IBGE, 2006), rainfall data (FUNCEME, 2008), a digital elevation model (EMBRAPA, 2006), a database on reservoir volumes and releases from the Brazilian National Department of Works Against Droughts (DNOCS) and the Ceará State Department for Water Resources Management (COGERH, 2003a), and river flow data from the Brazilian National Water Agency (ANA, 2006).

2.4 Stage 2: relationships between water use and water availability

To analyse the relationships between water use for irrigation and water availability on a sub-basin scale, the Orós reservoir area is studied. More specifically the impact of water abstractions upstream of the Orós reservoir on its yield is assessed.

First, a relationship between rainfall and seasonal water requirements for irrigation is established. Seasonal irrigation requirements are determined using the CropWat model (FAO, 1998), based on the Penman-Monteith equation. The irrigation water requirements are taken as estimates for actual water abstraction. Secondly, relationships between water availability and irrigated area in different zones within the study area are analysed. The results obtained are used to establish a water balance for the main reservoir in the area.

For this main reservoir (the Orós reservoir), the yield is assessed at various reliability levels, influenced by upstream water abstractions for irrigation. This is done by running simulations using a synthetic 10,000-year series based on rainfall and discharge data. The method of Campos (1996), which separates reservoir water balance parameters for the dry and the wet season, is modified to include water use. Local feedbacks between water availability and water use are accounted for on a seasonal basis (6 months).

For this stage the following data are used:

- rainfall data from three rainfall stations for the period 1974-2005 (FUNCEME, 2008);
- annual agricultural production data for the period 1996–2005 (IBGE, 2006);
- seasonal agricultural production data for the period 2003–2005 from the Iguatu Office of the Agricultural Institute for the State of Ceará, EMATERCE;
- land-use classifications using remotely-sensed imagery for the dry season: Landsat TM (path–row) 217–64 (25 October 2000, 13 November 2001, 31 October 2002); CB2CCD (path–row) 150–107 (22 November 2003, 29 September 2004, 24 October 2005); and CB2CCD (path–row) 151–107 (19 November 2003, 26 September 2004, 21 October 2005);
- a volume–surface relationship for the Orós reservoir (COGERH, 2006);
- reservoir releases and river flow based on data for three reservoirs (COGERH, 2006);
- river discharge data for upstream inflow into the study area for the period 1982-2005 (ANA, 2006).

2.5 Stage 3: multi-agent simulation modelling

In this stage the ABSTRACT model (Agent-Based Simulation Tool for Resource Allocation in a CatchmenT) is designed. The ABSTRACT model is tested for the Orós reservoir area, where surface water reservoirs have been built, the irrigation sector is an important water user and there are possibilities of multi-annual water allocation. The ABSTRACT model was developed with the CORMAS platform using the VISUALWORKS environment (Bousquet et al., 1998). To represent feedback processes between water availability and water abstractions for irrigation, topographical elevation, hydrological characteristics, storage and abstraction of water resources have been included. Model output includes the spatiotemporal distribution of water availability and water use.

In the ABSTRACT model agents represent farmers who are situated at specific geographical locations and make decisions followed by actions affecting the environment. The model uses a 10-day time step. The modelling sequence is as follows: physical parameter update, biophysical dynamics, land use decisions and actions, and land availability update. In the physical parameter update rainfall and upstream inflow are calculated. This is done at the beginning of every time step.

The biophysical dynamics involve vertical and horizontal water balance calculations. A semi-distributed hydrologic modelling approach is used. The main river is represented by a network of branches. Each branch corresponds to a part of the river, including the underlying alluvial aquifer. For each branch water is withdrawn and water returns from riparian areas. Among these are irrigation areas that consist of grid cells for which the vertical water balance is simulated. Each branch receives water from its upstream river branch or branches and from riparian grid cells that provide runoff and return flows from irrigation. Water storage is arranged in alluvial aquifers and reservoirs, depending on local circumstances.

Land use decisions are made by individual farmer-agents, taking into account local conditions and preferences, and are followed by actions implementing the decisions. Harvesting takes place when crops are ready to be harvested, or harvests are lost by flooding. At every time step land availability is updated according to water levels in reservoirs and land cover changes due to harvesting. Accessibility of irrigation sources and flooding of agricultural fields are taken into account in describing farmer decision making. Both flood risk and access to water resources are related to local topography. Rules for farmer decision making with respect to the area of land to be irrigated and the type of crop to grow are based on a survey involving water users from all over the Jaguaribe valley (Taddei et al., 2008).

2.6 Stage 4: decreasing rainfall and reservoir operation strategies

In this stage the influence of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use and water availability in the Jaguaribe basin is assessed. The study area is located somewhere midstream within the Jaguaribe basin and is the same as in the previous two stages (Figure 2.5). Three scenarios for reservoir operation and spatial planning are designed. These scenarios are local interpretations of two scenarios that have previously been developed for the states of Piauí and Ceará, in which the

Jaguaribe basin is located (Döll and Krol, 2002; Döll et al., 2003). To generate a time series of upstream inflow (runoff) and meteorological parameters (rainfall and evapotranspiration), use is made of downscaled results from the ECHAM4 climate model (Roeckner et al., 1996). Downscaling for the period 2000-2050 was done during the WAVES program (Gaiser et al., 2003; Krol et al., 2003).

The distribution of water use is analysed at two spatial levels. Within the study area developments with respect to water use in upstream, midstream and downstream locations are analysed and compared. On a larger scale, the study analyses changes in the distribution of water resources that are used within the study area on the one hand and water resources that are available to users in the downstream valley through controlled yield from the main reservoir in the study area on the other (Figure 2.6).

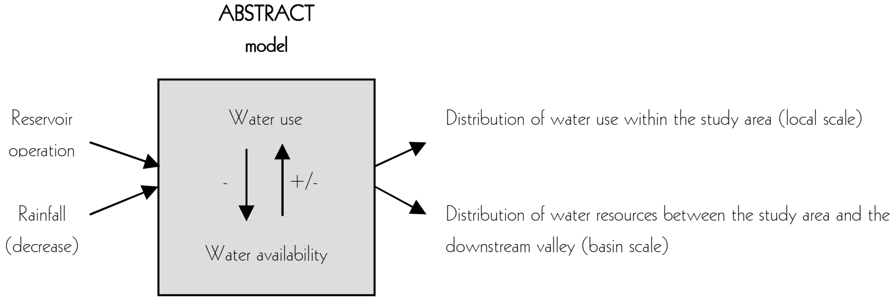

Figure 2.6 *Model input parameters and model output parameters.*

3 A river basin as a common-pool resource[1]

3.1 Introduction

This chapter addresses the first research question: *What physical characteristics of a semi-arid river basin are critical for the manageability of water resources?* To answer this question concepts from the theory on common-pool resources (CPRs) are used to analyse to what extent the physical characteristics of a river basin facilitate or impede good management of water in different parts of the basin. In addition, the actual agricultural performance in these different parts is analysed. CPR theory is grounded in game theory and has been applied in a wide variety of case studies, mostly on a local level (Ostrom, 1990; Ostrom et al., 2002; 1994). With regard to water resources management, CPR theory has been used in cases of competition over water resources in irrigation systems (Baland and Platteau, 1999; Bardhan and Dayton-Johnson, 2002; Lam, 1998; Tang, 1992). The surface or groundwater reservoir from which farmers get their irrigation water is regarded as a CPR in these studies. With most CPRs there is competition over the resource and there is generally no private ownership: various users have access to the resource at the same time. Above the level of a water reservoir for irrigation, the water within a catchment or river basin as a whole can also be regarded as a CPR. The scale is larger but the characteristics are similar: many users have access to the water in a basin and compete for it. To date, however, CPR studies have typically focused on local resources (Agrawal, 2002), rather than on large resource systems such as semi-arid river basins.

For a river basin which contains many water reservoirs one cannot speak of a single resource stock, as is the case for an irrigation scheme with one central reservoir. A river basin with multiple reservoirs is therefore fundamentally different from a canal-irrigation system and should rather be regarded as a system of nested or connected CPRs. In this study a river basin is regarded as one large water system that consists of a network of connected smaller systems. Smaller systems – characterised by a variable water stock – can be seen as a 'local common-pool resources', which are connected through water flows from one to the other. As a result it is expected that there are two different sorts of competition: local competition over the water *within* each smaller water system and competition over water *among* the smaller water systems, notably between upstream and downstream users.

In CPR terminology a river basin as a whole can be regarded as an asymmetrical CPR. In symmetrical CPRs externalities between users are mutual, whereas in asymmetrical CPR systems, like river basins in which water flows from up- to downstream, externalities

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[1] The contents of this chapter have been published in Van Oel et al. (2007; 2009).

may become unidirectional. Unidirectional externalities in river basins are, to some extent, comparable to those experienced in canal-irrigation systems. In such systems the disadvantaged users are those located at the downstream end of the system, most distant from the resource stock (Bardhan and Dayton-Johnson, 2002).

The obvious advantage for upstream water users in a river basin is that they are 'first in line'. However, the advantage to downstream water users is that in a downstream direction there is naturally more water, because water in a basin collects at its downstream outflow point. This 'funnel effect' can potentially counterbalance the negative effects of upstream use. Users in downstream parts benefit from the accumulation of water and base flow in rivers, making them less sensitive to spatial and temporal variations in rainfall compared to users located near small streams further upstream.

In the terminology of the literature on common-pool resources, CPRs are goods characterised by 'low excludability' and 'high subtractability' (Ostrom, 1990). Low excludability refers to the fact that it is difficult or costly to exclude users from using the resource. High subtractability means that the consumption by one user ('appropriator' in CPR terminology) subtracts from the possible use ('appropriation') by others. The major concern with common-pool resources is that it is easy to overexploit them, because there is a conflict between individual and group rationality. As Hardin (1968) argued, the tragedy of common-pool resources is that from the point of view of the individual user it is attractive to use more than would be best from a group perspective, often leading to overexploitation of the resource. Many studies on CPRs therefore analyse under which conditions cooperation among users does or does not occur, or under what conditions common-pool resource management can be sustainable (Agrawal, 2002; Ostrom, 1999; Ostrom et al., 2002). Agrawal synthesised findings of a large body of empirical work on common property and the commons, including the work of Ostrom (1990) and Blomquist et al. (1994). Among the factors influencing the manageability of CPRs, the following resource system conditions are associated with good manageability:

- Small spatial extent
- Well-defined boundaries
- Possibilities of storage
- Predictability of resource flows
- Low levels of mobility of the resource

Mobility of the resource is related to storage capacity: the capacity to collect and hold resource units to overcome temporal deficiencies. Increased storage capacity reduces the mobility of water resources (Schlager et al., 1994).

Based on topography and water storage capacity in the various parts of a semi-arid river basin, the extent to which in the various parts of the basin the conditions that are associated with good manageability are met is described. The Jaguaribe basin in the semi-arid northeast of Brazil is analysed as a case study.

3.2 Method

In four successive steps the following aspects are analysed: (1) the topography of the basin, (2) the observed water resources distribution, (3) the extent to which the physical characteristics of water resources in different parts of the river basin facilitate or impede good management of the water, and (4) the spatial distribution of observed agricultural performance in the basin.

Step 1: Description of topography

Topography or topographical elevation generally determines the direction of resource flow. Actual flows are influenced by rainfall rates, water use, evapotranspiration and storage. Every location x in a river basin can be characterised by the size of its upstream catchment area. If the upstream area (A_{up}) is divided by the total catchment area of the river basin (A_{tot}), a fraction is determined which is named: 'downstreamness' (D_x):

$$D_x = \frac{A_{up}}{A_{tot}} \times 100\% \qquad (3.1)$$

Water flows accumulate from up- to downstream. The direction of flow accumulation is determined using a 90 meter resolution digital elevation model of the river basin (EMBRAPA, 2006). Based on the outcome, every municipal district within the Jaguaribe basin is categorised into one of three topographical zones: upstream, midstream and downstream.

Step 2: Analysis of water resources distribution

The water resources distribution in the basin over space and time is analysed. Water resources distribution is evaluated by analysing stability of resource flows and storage in the basin. Inter-annual stability of flow at eight measurement stations in three upstream sub-basins in the Jaguaribe basin (Figure 3.1) is analysed. For each of the sub-basins up- and downstream flow characteristics is compared for the period 1990-2003.

Intra-annual stability is determined by dividing dry season flow ($\text{Jul}_{(t)}$-$\text{Oct}_{(t)}$) by wet season flow ($\text{Nov}_{(t-1)}$-$\text{Jun}_{(t)}$) for the period 1990-2003. The differences over space are evaluated.

To analyse storage capacity in the river basin the 58 largest reservoirs are taken into account. These are public reservoirs, construction of which was initiated by the national or state government. The downstreamness of the total storage capacity in the river basin (D_{SC}) is determined as follows:

$$D_{SC} = \frac{\sum_{x=1}^{n} SC_x D_x}{\sum_{x=1}^{n} SC_x} \tag{3.2}$$

where D_x represents the downstreamness of reservoir x and SC_x the storage capacity of reservoir x.

The stored volumes for the 58 largest reservoirs in the basin reservoir volumes are evaluated for the period 1996-2003. The weighted average downstreamness of the total stored water volume in the basin (D_{SV}) at the end of the wet season is determined as follows:

$$D_{SV} = \frac{\sum_{x=1}^{n} SV_x D_x}{\sum_{x=1}^{n} SV_x} \tag{3.3}$$

where D_x represents the downstreamness of reservoir x and SV_x is the stored volume in reservoir x. The downstreamness of the total stored water volume in the basin (D_{SV}) at the end of the wet season is then compared to the downstreamness of the storage capacity in the basin (D_{SC}).

Step 3: Evaluation of the five conditions for good manageability by topographical zone

The topography (Step 1) and the distribution of the water storage capacity in the basin (Step 2) determine to what extent the conditions for good management of the water in the various parts of the basin are met. In this step the subdivision of the basin into three topographical zones as ascertained in the first step is used: upstream, midstream and downstream. For each topographical zone the extent to which the five conditions for good manageability as mentioned in the introduction are met is evaluated: small spatial extent, well-defined boundaries, possibilities of water storage, predictability of water flows, and low levels of mobility of the water. It is expected that relative good manageability of water in a certain topographical zone results in a relatively good agricultural performance, which is evaluated in the last step.

Step 4: Assessment of agricultural performance

To measure agricultural performance in the basin three indicators are used, following Conway (1987). This is done for all 80 municipal districts. The three indicators of agricultural performance are:

- Productivity: the average annual value generated per hectare in a district. 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 1994-2004 (IBGE, 2006).

- Stability (*S*) of production: the variation of production over time (1990-2004). Use is made of the coefficient of variation (*CV*). Stability is defined as: $S = 1/CV$.
- Equitability (*E*) of productivity and stability over space. Use is made of the Gini-coefficient (Gini, 1912), for which the agricultural income from seasonal crops of the 80 municipal districts in the basin are taken into account. Equitability is defined as: $E = 1 - Gini$, with $0 \leq Gini \leq 1$.

The focus of the agricultural performance analysis is on the main seasonal crops cultivated in the basin (rice, maize and beans). This choice has been made because decision making with regard to cultivating these crops is done on a seasonal basis, so inter-annual dependencies for land use are limited.

Use is made of agricultural production data (IBGE, 2006), rainfall data (FUNCEME, 2008), a digital elevation model (EMBRAPA, 2006), a database on reservoir volumes and releases from the Brazilian National Department of Works Against Droughts (DNOCS) and the Ceará state department for water resources management (COGERH, 2003a), and river flow data from the Brazilian National Water Agency (ANA, 2006).

3.3 Results

3.3.1 Topography

The 'downstreamness' of locations within the river basin is shown in Figure 3.1, first at grid level (left) and then at district level (right). The downstreamness has been classified into three topographical zones: upstream, midstream and downstream. The downstreamness of a district as a whole is measured at its most downstream point.

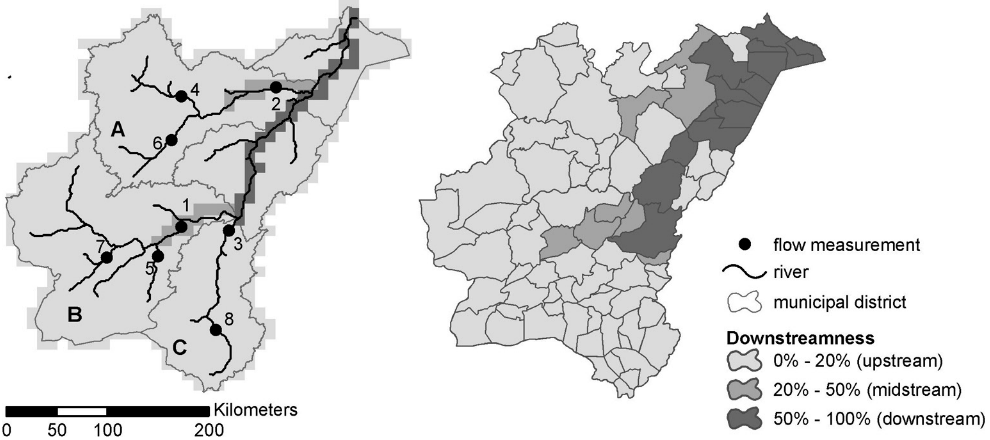

Figure 3.1 *The 'downstreamness' per grid cell (left) and per district (right). In the left map three sub-basins are shown: Banabuiú (A), Alto Jaguaribe (B) and Salgado (C). In the right map all 80 districts in the basin are categorised as either up-, mid- or downstream.*

3.3.2 Water resources distribution

Given unchanged hydrological conditions, higher yearly rainfall rates yield higher annual discharges at the outlet of a sub-basin. Deviations from this trend are explained by inter-annual effects, largely related to storage. The 1993 drought seriously affected discharges in 1994 in all three sub-basins. The amount of rain in 1994 would have resulted in a higher discharge but for the 1993 drought. In all probability saturation of natural and artificial storage bodies upstream of the measurement stations took up a large part of the 1994 rains.

In sub-basins A, B and C inter-annual stability of river discharge increases in the downstream direction (Figure 3.2). This applies most strongly to sub-basin A, where a large strategic reservoir is operated to serve the downstream community, including many farmers using the river for irrigation.

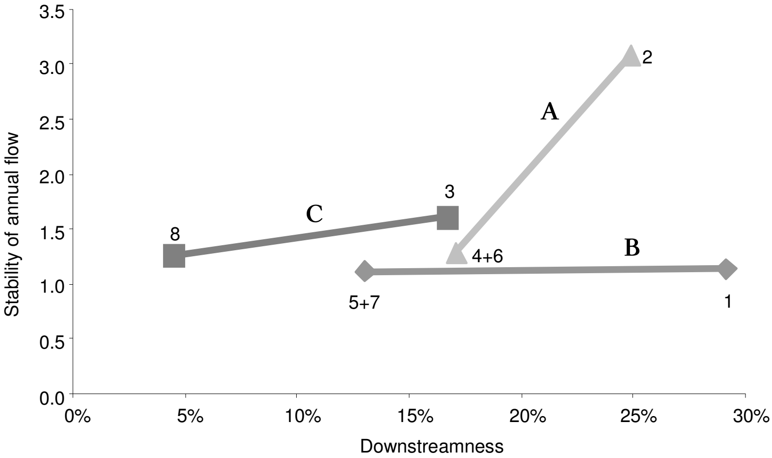

Figure 3.2 *Stability (1/CV) of flow in three upstream sub-basins: A = Banabuiú; B = Alto Jaguaribe; C = Salgado. The numbers indicate flow measurement station(s). Where there are two numbers, averages for two stations have been used.*

Compared to other sub-basins reservoir management in sub-basin A is much more successful in stabilising river flow. The average flow is however considerably lower. The characteristics of flow for the three sub-basins are summarised in Table 3.1.

Table 3.1 **Discharge characteristics of three upstream sub-basins.**

Variable	Unit	A*	B*	C*
Catchment size	km^2	17,900	21,000	12,000
Reservoir capacity	m^3/km^2	154,000	16,000	37,000
$\frac{Q(dryseason)}{Q(wetseason)}$	-	0.86	0.01	0.03
Annual variance of discharge	Coefficient of variation	0.32	0.88	0.62
Average downstream discharge	$10^6 m^3$/year	257	312	410
Average rainfall	mm/year	752	703	862

* A = Banabuiú sub-basin; B = Alto Jaguaribe sub-basin; C = Salgado sub-basin

State authorities and local communities adapt to rainfall variability by constructing dams. In the Jaguaribe basin this process of adaptation is ongoing (Figure 3.3). It decreases mobility of water resources at local levels. The building of new reservoirs brings with it the potential to create externalities for downstream users. The capacity-weighted downstreamness of the basin's storage capacity (D_{SC}) has shown a decreasing trend after the construction of a large reservoir in 1961 (Figure 3.3). This continued until the large Castanhão reservoir was built in 2003 (COGERH, 2003a).

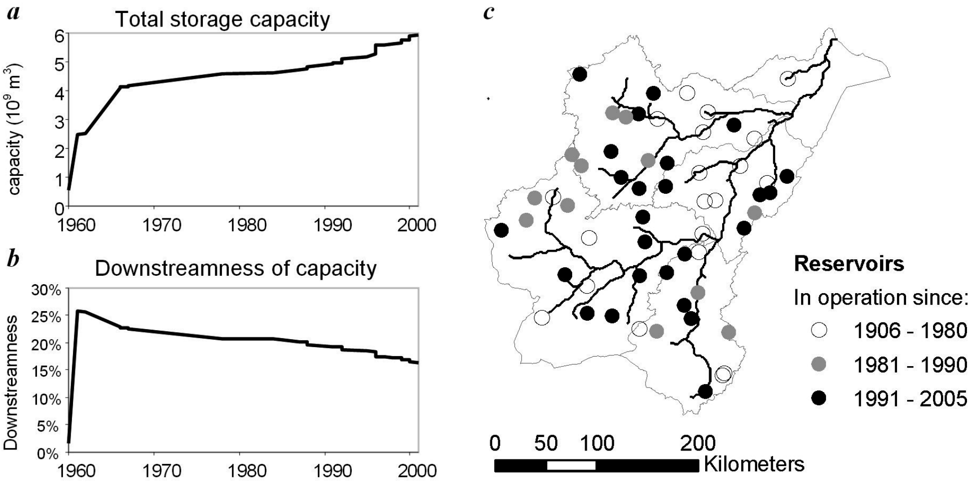

Figure 3.3 *a) Total public storage capacity in the Jaguaribe basin increases over time; b) Downstreamness (D_{SC}) of storage capacity decreases over time; and c) Locations of public reservoirs constructed in the Jaguaribe basin since 1906.*

The basin's storage capacity increased slightly in the period between 1996 and 2003, while total stored volume decreased (Figure 3.4). In Figure 3.5 the average capacity-weighted downstreamness of storage capacity (D_{SC}) and the average volume-weighted downstreamness of stored volume (D_{SV}) are shown.

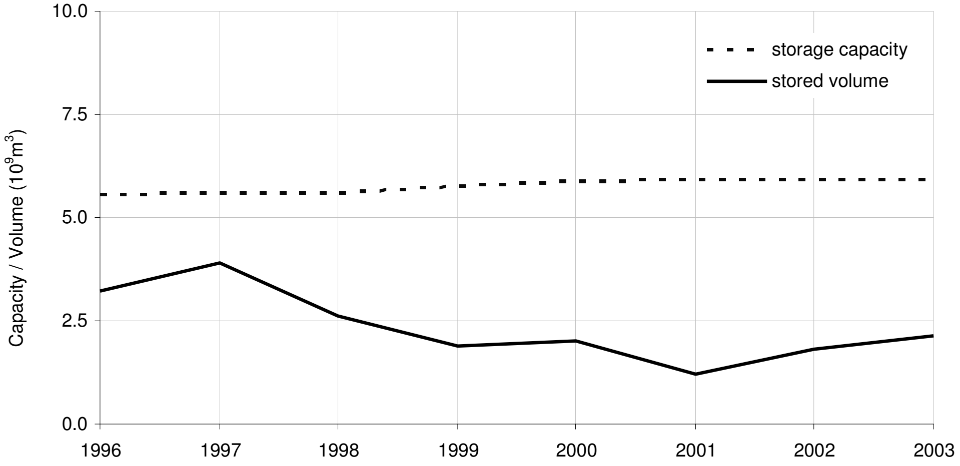

Figure 3.4 *Public storage capacity and stored volume in the Jaguaribe river basin.*

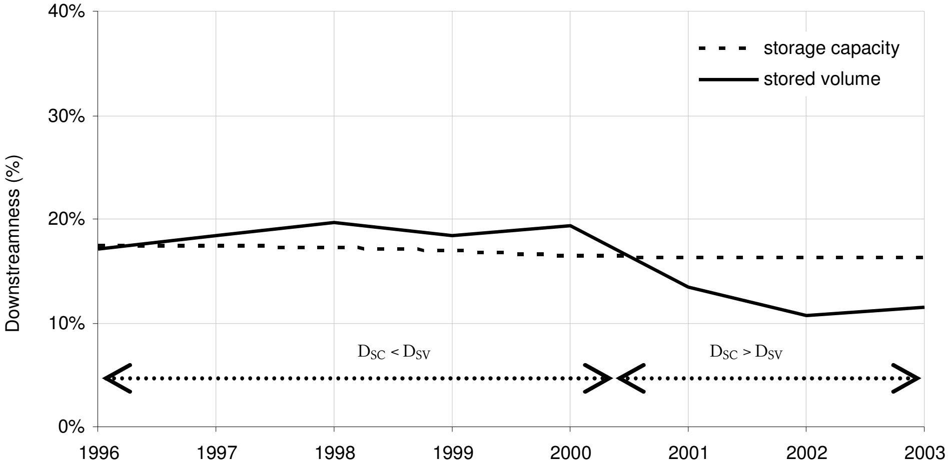

Figure 3.5 *Downstreamness of public storage capacity (D_{SC}) and stored volume (D_{SV}) at 1 July.*

In the dry period of 1997-1998 total stored volume dropped, while the downstreamness of stored volume (D_{SV}) increased. This can be explained by the fact that inter-annual storage is more easily achieved in relatively downstream parts of the river basin. However, in the dry year of 2001 downstream stored volumes decreased faster than upstream stored volumes. In the years following 2001 total stored volume rose again, while the downstreamness of stored volume (D_{SV}) decreased further and consequently the situation of $D_{SC}>D_{SV}$ remained. For a period of three years (2001-2003) a state of above-proportional upstream storage (and subsequent use) was observed. This is explained by the low saturation level of the reservoir network in this period. With an increasing part of storage capacity left unsaturated following a drought, the downstreamness of stored volume (D_{SV}) can decrease, provided that rainfall is not extremely high. This implies that upstream storage recovers faster after a drought than downstream storage. The sequence of rainfall events is very important for the spatial distribution of water quantities. Processes responsible for the effect of the sequence of rainfall events can be called the 'funnel effect' and the 'storage effect' (Table 3.2). The 'funnel effect' refers to the accumulation of flow in the downstream direction. The 'storage effect' refers to the storage of water in reservoirs and favours the water users that are first in line, i.e. the upstream users. The extent of their impact depends on the spatial distribution of reservoir capacity, the extraction of water resources, rainfall quantities and the sequence of rainfall events over time.

Table 3.2 The influence of the 'funnel effect' and the 'storage effect' over time.

Process	Impact on users	Wet following wet year	Wet following dry year	Dry following wet year	Dry following dry year
Funnel effect	Outlet advantage for downstream water users	++++	+++	++	+
Storage effect	First-in-line advantage for upstream water users	+	++	+++	++++

A '+' indicates the extent of occurrence of the effect. Both effects occur every year. However, the funnel effect is relatively large in a wet year following a wet year and the storage effect is relatively large in a dry year following a dry year.

3.3.3 Manageability of water resources

Table 3.3 shows the differences between the three topographical zones in the Jaguaribe river basin with regard to the five conditions for good manageability listed in the introduction. For the Jaguaribe basin, high downstreamness of a local CPR should generally be associated with a large spatial extent, an ill-defined boundary, good possibilities for water storage, high predictability of flows and a low level of mobility. On the other hand, low downstreamness is linked to a small spatial extent, well-defined boundaries, poor possibilities for water storage, low predictability of flows and high mobility. So for neither upstream nor downstream are the physical characteristics unequivocally associated or dissociated from good manageability.

Table 3.3 The extent to which the conditions for good manageability are met, by topographical zone.

	Conditions for good manageability of the resource system				
Topographical zone	Small spatial extent	Well-defined boundaries	Possibilities of storage	Predictability of flows	Low levels of mobility
Upstream	+	+	-	-	-
Midstream	+/-	+/-	+/-	+/-	+/-
Downstream	-	-	+	+	+

\+ means that the condition for good manageability is met;
+/- means that the condition is moderately met;
\- means that the condition is not met.

A river basin can be divided into an infinite number of sub-basins, since every geographical location in a basin has its own unique catchment area. A low downstreamness of a geographical location in a river basin is associated with a relatively small spatial extent of the relevant resource system, whereas a high downstreamness of a geographical location is associated with a relatively large spatial extent of the relevant resource system, due to the size of their respective catchment areas.

A low downstreamness of a geographical location in a river basin is associated with well-defined boundaries, because the amount of storage in the upstream catchment area is relatively low. For a geographical location with a high downstreamness it is less clear to what extent stored resources in the upstream catchment are available for use at that location. The inter-annual sequence of rainfall events is of critical importance in the distribution of water availability over the upstream catchment of the location. During drought upstream reservoir capacity remains unsaturated. Following a meteorological drought, a relatively large share of rainfall volumes is stored upstream in order to saturate upstream reservoir capacity. This process facilitates above-average use in locations with a comparatively low downstreamness. Nested upstream sub-basins can be regarded as external to the catchment of that geographical location, either temporarily or even permanently.

As supported by the results presented in Section 3.3.2, users at geographical locations with a relatively high downstreamness have the advantage of being located downstream of a larger storage capacity in the upstream catchment area than users at locations with a lower downstreamness. Due to the greater possibilities of storage in downstream locations and the merging of streams from different sub-basins, the mobility level is relatively low and predictability of flows is relatively great in downstream locations. Water resources can be released from storage reservoirs at a moment of choice. The observed increase in stability with increasing downstreamness (Figure 3.2) relates to these factors. Therefore the condition ‘possibilities of storage’ is increasingly met with increasing downstreamness.

The storage capacity and geographical location of reservoirs, together with the extent to which the reservoir capacity is saturated, play an important role in the spreading of externalities. An increase in reservoir capacity due to the construction of additional reservoirs in upstream parts of the river basin increases the risk of basin closure (Falkenmark and Molden, 2008; Seckler, 1996) and thereby the potential for producing negative externalities for downstream locations.

3.3.4 Agricultural performance

The agricultural productivity and stability of production in each of the three topographical zones in the Jaguaribe basin is shown in Table 3.4. For both productivity and stability of production the same pattern has been encountered. Districts in the midstream zone appear to have the highest productivity and the most stable production. Users there appear to have taken advantage of their relatively downstream position compared to the districts in the upstream zone. This is of great importance in order to cope with short-term intra-season rainfall variability and to be productive in the dry season. In dry periods users in the midstream zone experience the advantage over downstream users of having first access to water from large reservoirs.

Equitability of agricultural productivity in the basin is influenced by both physical processes and human activities. The spatial distribution of agricultural production over the river basin becomes clear when the Gini-coefficient of seasonal crop value for all 80 districts is compared to the actual locations in the river basin where the agricultural production is taking place. The average annual rainfall in the river basin has a significant (95%) linear positive relation to equitability (Figure 3.6). Decreasing equitability is connected with a more downstream-centred total production value.

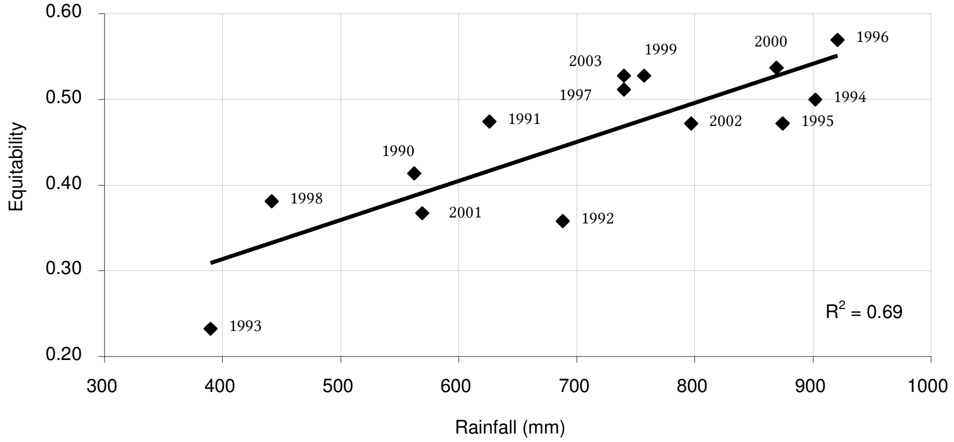

Figure 3.6 *Equitability (1 – Gini-coefficient) of production value in the Jaguaribe basin as a function of average annual rainfall.*

As has been pointed out earlier, two counter-effective processes influence spatial heterogeneity of water availability in a river basin: storage of water (natural or artificial) favours upstream water users, whereas accumulation of flow in the downstream direction favours downstream users. The result of these two processes is a relatively good agricultural performance in the midstream part of the Jaguaribe river basin. This is shown in Table 3.5, which is a qualitative interpretation of the data shown in Table 3.4. This relatively good agricultural performance in the midstream zone is achieved while all conditions for good manageability of water are moderately met (Table 3.3). As is shown in Table 3.3, some of these conditions are not met in the upstream zone, while others are not met in the downstream zone. This may play a role in the relatively worse agricultural performance in these zones.

Table 3.4 Productivity and stability of production of seasonal crops (rice, beans, maize) for the period 1990-2003.

Topographical zone	**Productivity** (Real/ha)	**Stability of production** (1/coefficient of variation)
Downstream	370	2.9
Midstream	520	4.0
Upstream	200	1.9
Basin total	240	2.4

Table 3.5 The agricultural performance by topographical zone in the Jaguaribe river basin.

Topographical zone	**Observed agricultural performance**	
	High Productivity	High Stability
Upstream	-	-
Midstream	+	+
Downstream	+/-	+/-

A '+' indicates strong correspondence between the characteristic and the location, a '+/-' indicates moderate correspondence and a '-' indicates weak correspondence between the characteristic and the location.

3.4 Discussion

The asymmetry of a river basin resource system does not fully prevent cooperation that is beneficial to both up- and downstream users. Users in downstream areas are situated downstream of storage facilities, which can make upstream users dependent on downstream production in times of meteorological drought. Governmental organisations could respond by supporting virtual water trade (Allan, 1998). Such trade can include both virtual water flows from downstream to upstream areas within the basin and virtual water flows from outside the basin into upstream areas within the basin.

Although not explicitly taken into account here, attributes of users are very important for sustainable governance (Agrawal, 2002). Among these attributes are users' dependency on the resource, their autonomy, organisational experience and differences in income. This last is likely, based on the observations in Table 3.4. In CPR literature equality of income is used to explain the success or failure of CPR management (Jones, 2004). It is argued that either very high or very low levels of inequality facilitate successful resource management. Changing inequality redistributes incentives and therefore has an ambiguous effect on the willingness of users to take steps towards conserving their resources and even towards setting up the required mechanisms (Baland and Platteau, 1999). In the case of the Jaguaribe basin income inequality can vary considerably over space and time. The results suggest that agricultural performance relates to both rainfall variability and stored water resources. This makes it very difficult to determine the influence of income inequality on governance of water resources and vice versa.

Data availability somewhat limited the scope of analysis. First, the spatial resolution of analysed data is too coarse for detailed analysis of most of the local CPRs. Finer resolutions can be achieved by using remotely-sensed imagery classification methods. Secondly, the temporal resolution of one year does not allow for the consideration of seasonal differences in use of water resources. Variations around the average agricultural calendar are possibly important in understanding the process of spreading of externalities between local CPRs in the downstream direction. Thirdly, the temporal extent of the analysis is limited. This restricts the meteorological extremes taken into account as well as the combinations of sequential meteorological events that are considered to be very important, since externalities may occur at an inter-annual level.

3.5 Conclusions

The physical characteristics of local freshwater CPRs vary, depending on their location in a basin. For none of the locations are all five conditions for good manageability favourable at the same time. The more downstream a local CPR is the more it should be associated with a large spatial extent, ill-defined boundaries, good possibilities of storage, high predictability of resource availability and low levels of resource mobility.

The sequence of rainfall events over time and the spatial distribution of reservoir capacity in a river basin influence the extent to which the merging of rivers and streams in a downstream direction can compensate for externalities due to upstream water abstractions. This principle relates to the concept of basin closure (Molle et al., 2007) and is an addition to the concept of head-end/tail-end problems encountered in irrigation schemes (Bardhan and Dayton-Johnson, 2002) on the river basin scale. The concept of downstreamness proved useful in explaining how the five conditions for good manageability improve or worsen from up- to downstream.

From a river basin perspective, storage in local CPRs in upstream parts of a basin should be associated with ‘first capture’ or ‘use it or lose it’ strategies (Blomquist et al., 1994; Schlager et al., 1994), since storage in local upstream CPRs is intended for local use. Storage in local upstream CPRs in semi-arid river basins, such as the Jaguaribe basin, should therefore be regarded as appropriation from the ‘river basin level common-pool resource’.

4 The mutual relationship between water use and water availability[2]

4.1 Introduction

This chapter addresses the second research question: *What is the relationship between water use and water availability in a semi-arid river basin?* Decreases in rainfall reduce inflow into surface water bodies, while at the same time increasing the need for irrigation water. Periods with low flows are generally also those with the highest irrigation water requirement. This could result in even lower inflows into reservoirs that are located downstream of irrigation water abstraction sites. Upstream rainfall variability and flow abstraction for irrigation are key parameters in understanding low flows in rivers (Smakhtin, 2001). Obviously, decreasing reservoir inflow may reduce reservoir yield or its associated reliability (Campos, 1996; Campos et al., 2003; Loucks and Van Beek, 2005; McMahon and Mein, 1986; Vogel and Stedinger, 1987).

Several studies address the impact of land use on low flows. Eheart & Tornil (1999) show the effect of water abstraction for irrigation in response to changes in rainfall on the occurrence of low flow in streams in Illinois and other states in the Midwest of the USA. They take into account both groundwater and river water abstraction. Wilk & Hughes (2002) studied a catchment in Southern India. They observed an increase in runoff as a result of changes in land use from indigenous forest and savannah to agriculture. This resulted in increased reservoir inflow and reservoir yield. They concluded that likely changes will have a negligible impact on reservoir yield only. Simulation results for a river basin in south central Ethiopia show an 8% decrease in discharge after the conversion of cultivated/grazing land to woodland (Legesse et al., 2003). Studies such as those by Wilk & Hughes (2002) and Legresse et al. (2003) create the impression that an increase in agricultural activities will tend to lead to increased river discharge. However, these studies did not include large-scale expansions in irrigated land use, with related abstraction.

The effects of upstream water abstraction on the inflow volume and on the variability of inflow volume in downstream reservoirs are the focus of this chapter, as are the effects of changed reservoir inflow patterns on reservoir yield and reliability of yield. It takes into account the fact that upstream water use depends on upstream water availability.

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[2] The contents of this chapter have been published in Van Oel et al. (2008).

It includes the effect of rainfall variability on water availability and on water abstraction for irrigation, and that of such abstraction on reservoir inflow, yield and reliability.

According to Campos (1996), for the purpose of deriving reservoir yield the water balance of reservoirs in a semi-arid environment is well approximated by:

$$\frac{dV}{dt} = Q_{in} - Q_{E,dry} - Q_S - Q_{out} \tag{4.1}$$

where V is the water storage volume in the reservoir, t represents time (with steps of one year), Q_{in} the inflow from the river network into the reservoir, $Q_{E,dry}$ the water loss due to evaporation in the dry season, Q_S the reservoir outflow over the spillway, and Q_{out} the regulated outflow from the reservoir in the dry season (all variables are in m^3/year). According to Campos (1996), water input through rainfall directly onto the reservoir surface, together with groundwater discharge into the reservoir, is roughly compensated for by wet season evaporation and loss due to seepage, and can therefore be neglected in deriving reservoir yield in semi-arid environments such as the Jaguaribe basin. In this study Q_{in} depends on the amount of water abstracted for irrigation. The impact of current upstream irrigation water abstraction is compared to that of decreasing reservoir capacity, enhanced irrigation efficiency and expanded irrigation area.

4.2 Study area

The Jaguaribe basin is located within the institutional borders of the state of Ceará in the semi-arid northeast of Brazil (Figure 4.1). 75% of the basin's reservoir capacity is provided by three public surface reservoirs, which have transformed about 470 kilometres of the rivers in the middle and lower part of the basin into perennial waterways. One of these reservoirs is the Orós reservoir, the subject of this study, which has been in operation since 1961 and has a capacity of 1,940 $10^6 m^3$.

Within the study area three different irrigation zones have been identified, each having a different kind of rainfall dependency: in the river zone water is pumped from the river or from the alluvial aquifer; in the natural lakes zone the irrigated area is limited by water availability and by flooding, both dependent on local rainfall; in the floodplain zone the irrigated area depends on inundation of the reservoir bed and the plains alongside the reservoir (Figure 4.1). Flooding may limit irrigation in the immediate surroundings of the reservoir.

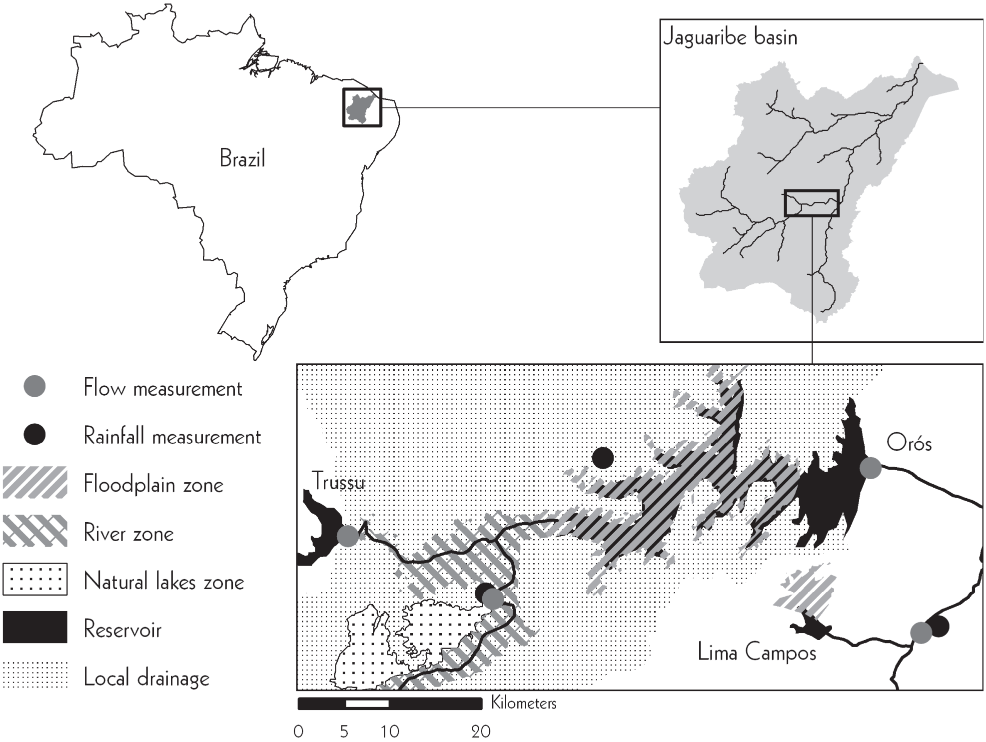

Figure 4.1 *The Orós reservoir study area within the Jaguaribe basin: the direct surroundings of the Orós reservoir, indicating irrigation zones, reservoirs, local drainage and locations of measurement stations.*

4.3 Method

The research method consists of three steps:

1. The relationship between rainfall and water abstraction for irrigation is explored, using an empirical data set for the period 1996–2005 which yielded parameterisations of irrigation area and water use.
2. The results of the first step are validated by establishing a water balance for the Orós reservoir for the same period.
3. Reservoir yield is assessed at various levels of reliability, influenced by changes in water abstraction for irrigation. This is done by running simulations using a synthetic 10,000-year series (Loucks and Van Beek, 2005) based on rainfall and discharge data.

Two assumptions are made for irrigation water abstraction:

a. The amount of abstracted water per hectare is rainfall-dependent.

b. The size of irrigated area in the vicinity of natural lakes and reservoirs is influenced by land availability, which depends on water levels in these water bodies.

Step 1: Establishment of the relationship between rainfall and water abstraction

Variations in water abstraction for irrigation are based on the following relationships, established using empirical data for the period 1996–2005:

Relationship between rainfall and irrigation (1)

Irrigation requirements by season are determined using the CropWat model (FAO, 1998), based on the Penman-Monteith equation. The model takes into account area-specific climatic parameters, including daily rainfall data from measurement stations, indicated in Figure 4.1. The model output includes irrigation requirements for each crop. Linear regression of the results yields relationships between rainfall and irrigation requirement, to be used for simulation, using a time step of one season (6 months). The irrigation water requirements are taken as estimates for water abstraction. Rice and banana are the most relevant and most water-consuming irrigated crops in the area. No other crop was taken into account.

Relationship between rainfall/river flow and irrigated area in the river zone (2a)

Whether the irrigated area in the river zone is dependent on local rainfall and river flow is tested.

Relationship between local rainfall, inundation and irrigated area in three neighbouring natural lakes, supplied through local rainfall and runoff (2b)

Tests are done for the irrigated area in the natural lakes zone to see whether it is dependent on local rainfall.

Relationship between reservoir volume and irrigated area in the floodplain zone (2c)

The surface area of the reservoir depends on the amount of rainfall upstream, on an inter-annual rather than intra-annual time scale. The relationship between reservoir volume (rather than rainfall) and irrigated area is therefore explored. The following data are used:

rainfall data for three rainfall stations (FUNCEME, 2008) (Figure 4.1)

land use based on annual agricultural production data for the period 1996–2005 (IBGE, 2006)

- seasonal agricultural production data for the period 2003–2005 from the Iguatu Office of the Agricultural Institute for the State of Ceará, EMATERCE
- land-use classifications using remotely-sensed imagery for the dry season: Landsat TM (path–row) 217–64 (25 October 2000, 13 November 2001, 31 October 2002), CB2CCD (path–row) 150–107 (22 November 2003, 29 September 2004, 24 October 2005), CB2CCD (path–row) 151–107 (19 November 2003, 26 September 2004, 21 October 2005);

- a volume–surface relationship of the Orós reservoir (COGERH, 2006).

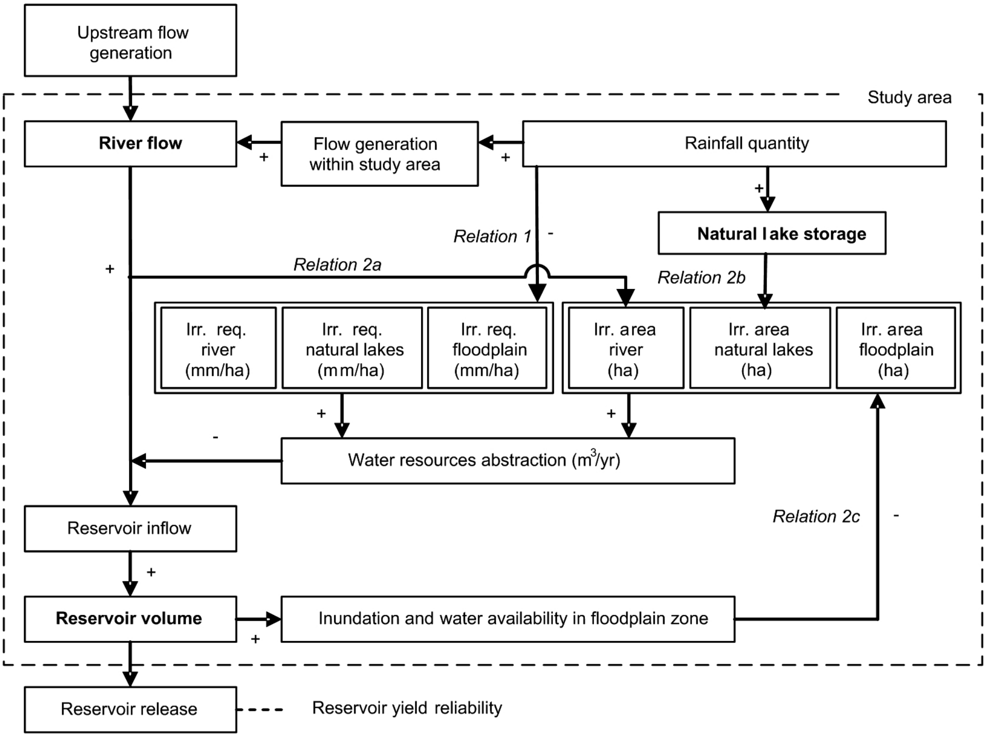

Figure 4.2 *The relationships between rainfall, irrigation requirement (Irr. req.), reservoir inflow and reservoir yield for the study area.*

Step 2: Establishment of the water balance of the Orós reservoir

The explored relationships from Step 1 are implemented in our simulation approach to calculate the season-by-season development of the volume of the Orós reservoir, using a 6-month time step. A water balance for the area around the Orós reservoir (Figure 4.1) is produced for the period 2000–2005. To determine this water balance, the following data are used in addition to those for Step 1: reservoir releases and river flow based on data for three reservoirs: Orós, Lima Campos and Trussu (COGERH, 2006), and river discharge data at Iguatu (ANA, 2006).

Equation (4.1), after the method of Campos (1996), separates reservoir water balance parameters for the dry and the wet season. When introducing water abstraction into this method, the separation is made more explicit by splitting equation (4.1) into two, one for the wet season (4.2) and one for the dry season (4.3):

$$V_{(t)wet} = V_{(t-1)_{dry}} + Q_{in} - Q_{UseWet(t)} - Q_{UseDry9(t-1)} - Q_S \tag{4.2}$$

$$V_{(t)dry} = V_{(t)wet} - Q_{E,dry} - Q_{out} \qquad (4.3)$$

where V_t (m^3) represents volume at the end of the season in year t, $V_{(t)wet}$ and $V_{(t)dry}$ for the wet and the dry seasons respectively, Q_{in} (m^3) is inflow before abstraction in the study area, $Q_{UseWet(t)}$ (m^3) is water abstraction for irrigation during the wet season, $Q_{UseDry(t-1)}$ (m^3) is water abstraction for irrigation during the previous dry season (since irrigation during the dry season is done largely by pumping water from the alluvial aquifer, reservoir inflow in the following wet season is reduced because of recharging by river water), Q_S (m^3) is the reservoir outflow over the spillway, $Q_{E,dry}$ (m^3) is the dry season evaporation from the reservoir, and Q_{out} (m^3) is the regulated water withdrawal.

The parameter Q_{in} is based on daily data from flow measurement at two inflow points, while Q_{out} is based on daily reservoir release data from measurements at the two dams in the east of the study area. Both Q_{out} and Q_{in} are converted into seasonal values. The parameters Q_{UseDry} and Q_{UseWet} are based on the land use data and irrigation requirements as described in Step 1.

Step 3: Simulation of the relationship between upstream water abstraction and downstream reservoir yield and reliability

Equations (4.2) and (4.3) are used for stochastic simulation applying a 10,000-year synthetic series of annual rainfall and discharge. This synthetic series is based on statistical characteristics of rainfall data for the period 1974–2005 (FUNCEME, 2008) and discharge data for the period 1982–2005 (ANA, 2006). It reproduces historical mean and the coefficient of variation, cross-correlations and autocorrelations of both annual rainfall and inflow, using a multivariate model with a lag of one year, as described in Loucks & Van Beek (2005).

To determine Q_{UseWet} and Q_{UseDry} in each time step the established empirical relationships from Step 1 are used. If Q_{out} is less than the target water yield, the year is considered unsuccessful. The reliability level G for that target yield is given by $G = 1 - (N_U/N)$ where N_U is the number of unsuccessful years and N is the total number of years in the simulation. The result is compared to the result of applying equation (4.1). In this way the impact of varying and changing water abstraction on reservoir yield reliability is assessed.

Finally, the effect of water abstraction is compared to the impact of decreasing reservoir capacity due to sedimentation.

4.4 Results

The dependency of net irrigation requirement on seasonal rainfall rates can be approximated by a linear relationship (Figure 4.3). Net irrigation requirement in the wet season varied between roughly 100 and 400mm for rice and 300 and 600mm for banana. In the dry season net irrigation requirement was relatively constant, since rainfall quantities in the dry season were relatively small.

Irrigated area in the river zone was found to be comparatively independent of rainfall and river flow. This is because water from the alluvial aquifer is available, originating from, but barely constrained by, river flow. Research in a nearby sub-basin within the Jaguaribe basin (Burte et al., 2005) concludes that the river is the most important source for recharging following withdrawal of water directly from the alluvial aquifer. This water is available all year round, providing a relatively stable water supply. The comparatively high coefficient of variation for irrigated area (Table 4.1) is explained by a steadily increasing area of irrigated land for fruit production, as a result of government policy (COGERH, 2001a; 2003b; SEAGRI, 2004; 2005), rather than by inter-annual variability. As this trend does not represent an effect of rainfall variability, it is not considered in the determination of reservoir yield.

The extent of irrigated area in the natural lakes zone depends on local rainfall, as this is directly responsible for both water availability and flooding of arable land by water from the lakes. The temporal extent of influence exceeds annual rainfall rates, since storage capacity is larger than what is consumed and evaporated each year. Therefore the amount of rainfall from the previous year is also taken into account. From the remotely-sensed data one can observe that flooding frequently forces farmers to change their irrigation activities. The irrigated area generally increases with increasing rainfall, but decreases when high rainfall quantities lead to inundation of a potential irrigation area. In this study a relationship representing this observed qualitative behaviour was established (Figure 4.4). This takes into account rainfall in year t and in year $t - 1$. A quadratic relationship is found to give a reasonable representation of the data for the period 2000–2005 ($R^2 = 0.73$).

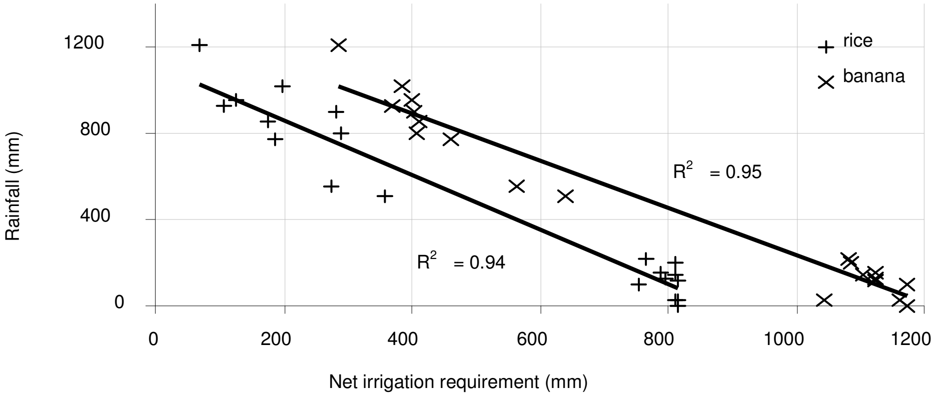

Figure 4.3 *Relationship between seasonal rainfall and irrigation requirement derived from CropWat calculations. Rainfall data for the period 1996–2005 were used.*

Table 4.1 Observed and simulated variability of land use and upstream water abstractions.

		Coefficient of variation			
		River zone	Natural lakes zone	Floodplain zone	Total
Observed 2000–2005	Irrigated area	0.28	0.65	0.12	0.19
	Water abstractions	0.28	0.59	0.16	0.19
2000–2005, simulated with land use rules	Irrigated area	0.00	0.90	0.08	0.08
	Water abstractions	0.11	0.83	0.11	0.10
Synthetic 10,000-year simulation, Q_{90}: 19.96 m^3/s	Irrigated area	0.00	0.71	0.12	0.11
	Water abstractions	0.09	0.66	0.12	0.09

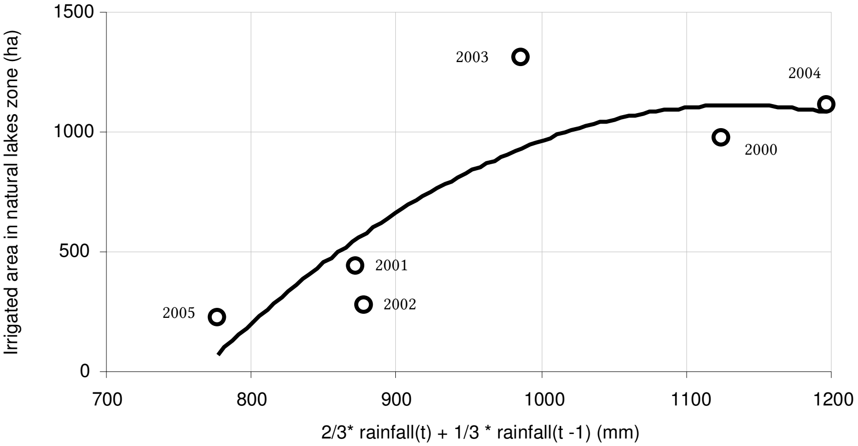

Figure 4.4 *Relationship between rainfall and area of irrigated crops in the natural lakes zone.*

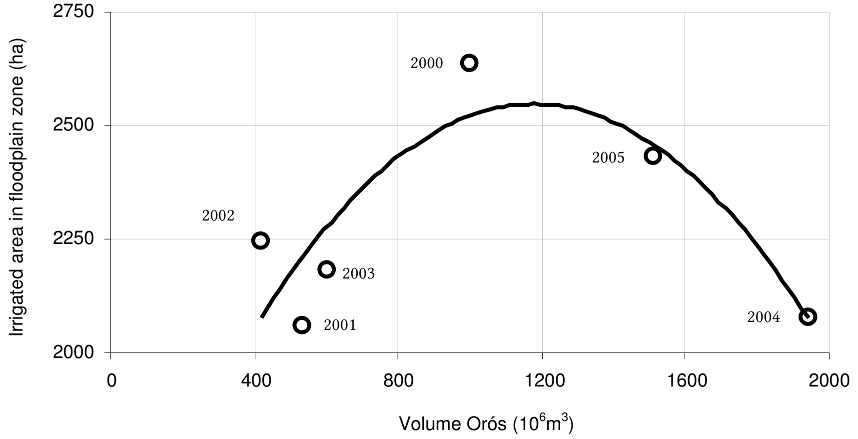

Figure 4.5 *Relationship between reservoir volume and irrigated land in the floodplain zone near the Orós reservoir.*

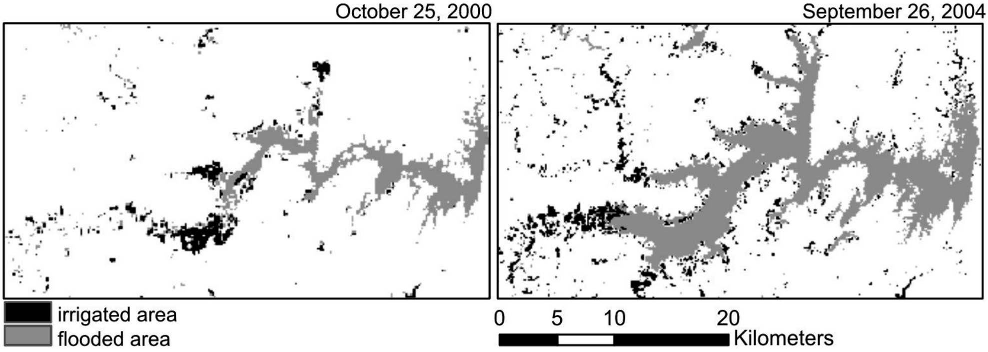

Figure 4.6 *Simplified land use classification for images from 2000 and 2004 for part of the study area.*

The extent of irrigated area in the floodplain zone appears to depend on the size of the area inundated by the Orós reservoir and the accessibility of water from local streams and groundwater. Figure 4.5 shows the empirical data and quadratic relationship between the stored volume in the Orós reservoir at the end of the wet season and the area cultivated with irrigated crops in the consecutive dry season. This relationship gives a fair representation of the data for the period 2000–2005 (R^2 = 0.70). To illustrate changes in land use, a simplified land use classification for images from 2000 and 2004 is shown for part of the study area (Figure 4.6), making clear that flooding shifts and limits irrigation.

Applying the empirical rules for the three zones in the water balance equation for the period 2000–2005 results in simulation outcomes for reservoir volume that approximate the observed data much better than the Campos method, which does not account for upstream water abstraction (Figure 4.7).

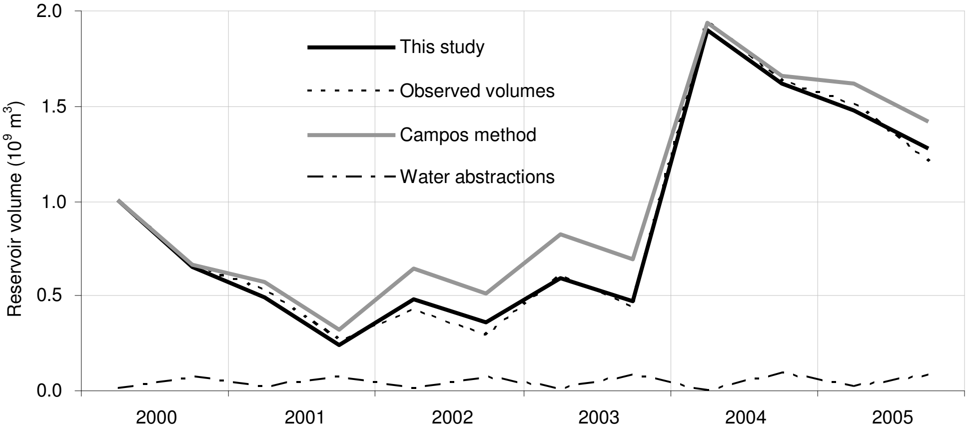

Figure 4.7 *Reservoir volume simulation taking into account upstream abstractions for irrigation.*

Therefore, this new method with empirical rules is able to represent the water balance under highly variable conditions. Applying our method to determine yield reliability simulations shows that upstream water abstraction for irrigation results in a decrease in the reservoir yield, with a reliability level of 90% (Q_{90}), from 24.4m^3/s (Campos method) to 20.0m^3/s (our approach) (Figure 4.8). According to the results of the Campos method the water-scarcity probability for a 20.0m^3/s yield, for instance, is close to 5% every year (95% annual reliability), whereas according to this study it is as high as 10%. This difference is very relevant for water allocation purposes.

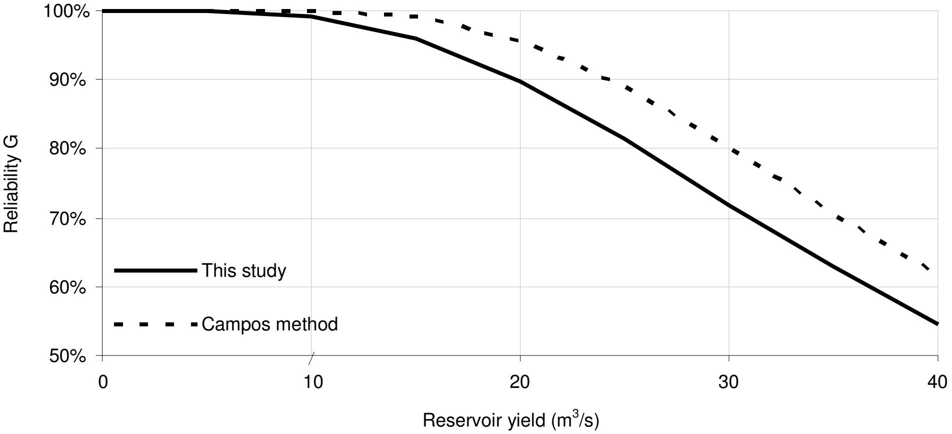

Figure 4.8 *Results of yield-reliability simulations using the Campos method (without upstream water abstraction) and using our method (with upstream abstraction).*

The results of this study show that major impacts of variations in land use on yield reliability should not be expected. Simulations which include the established relationships for land use variation in the different zones result in a yield that is 0.4% higher compared to simulations with constant land use based on the period 2000–2005.

The simulation method developed is also applied to assess the impact of possible changes on reservoir yield reliability. The current impact of upstream water abstraction for irrigation is compared to that of decreasing reservoir capacity, enhanced irrigation efficiency and an expanding irrigation area. In Figure 4.9 the impacts of 'possible' future developments are compared with the outcomes of our simulations, based on the empirical data for the period 2000–2005. Developments considered are: an increase in irrigation efficiency to 100% due to technological improvements; an increase in irrigation area for rice production to a level that was previously reached in 1993; and a 50% reduction in reservoir capacity because of long-term sedimentation.

The results show that shifts in upstream water abstraction may seriously affect reservoir yield. When water abstraction is increased to levels reached in the recent past (1993), the impact on reservoir yield is of the same order of significance as a 50% reduction in reservoir capacity due to sedimentation. However, sedimentation causes gradual changes, whereas changes in water abstraction could happen relatively fast. It would take decades for a 50% capacity reduction through sedimentation to develop. For an impact assessment of sediment deposits on reservoir yield in semi-arid Brazil, see De Araújo et al. (2006).

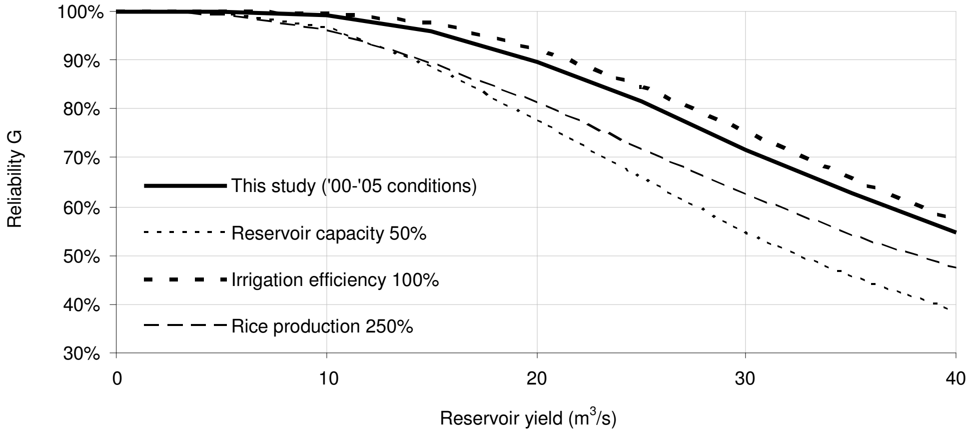

Figure 4.9 *Results of yield reliability simulations with: reservoir capacity reduced by 50%; 100% irrigation efficiency; and rice area increased by a factor of 2.5 (corresponding to the 1993 situation).*

4.5 Discussion

Some comments on the method applied in this study are justified. First, a relatively short time series of data has been used to determine variations in water abstraction. Remotely-sensed data for dry seasons in six consecutive years were used. This means that information on the variability of irrigated area is limited to the margins of events that occurred in the period 2000–2005. With regard to recent historical data on average annual rainfall in the area upstream of the reservoir, the year 2004 was relatively wet; however, 1985 and 1989 had higher rainfall. Equally, 2001 was relatively dry, yet 1983, 1993 and 1998 had lower rainfall. The effect of rainfall extremes beyond these margins is therefore uncertain. Secondly, longer series of consecutive dry or wet years that occurred historically were not represented in the empirical data set. Therefore, the effect of such series on water use could not be evaluated. Thirdly, variation in the timing of the growing season in different years was not taken into account.

The variability of irrigated land and water abstractions for the empirical data set and the simulated series do not match perfectly (Table 4.1). The rules applied do not reproduce empirical variability completely, since they are based on regression relationships. Moreover, the observed variance in the river zone is explained not so much by variability as by a trend towards more fruit production during the period 2000–2005, which is not particularly related to rainfall variability. For the natural lakes zone, it was seen that the variability of irrigated area is higher than that of water abstraction. This is explained by the observed increase in irrigated area with a lower net irrigation requirement per hectare. In the floodplain zone water use was noticed to be more variable than irrigated area. This is explained by a larger irrigated area in years of low precipitation and a smaller irrigated area in years with high rainfall over the period 2000–2005. This is probably a coincidence and is not shown as such in the simulations using a 10,000-year synthetic time series.

Inter-annual variations in water abstraction, such as were observed for the period 2000–2005, influence downstream reservoir reliability to a limited extent. The variability of water abstraction is small compared to variability of inflow. Furthermore, abstraction in the natural lakes and the floodplain zones generally decreases in times of low water availability. Applying the simulation approach that is proposed in this chapter for Q_{90} (irrigation efficiency 60% and regulated dry season release being $20 m^3/s$), the coefficient of variation for annual water abstraction is 0.09. With a fixed irrigated area (average 2000–2005) the coefficient of variation for water abstraction is 0.07. The coefficient of variation for the reservoir inflow is 1.485 when applying the proposed simulation approach and 1.484, for a fixed irrigated area. The difference in reliability levels is accordingly negligible.

The simulations in this study show that the variation in river flow upstream of the study area is of great importance to yield reliability. The variation in river flow into the area is quite large (coefficient of variation: 1.46). If all variation is fully compensated for, e.g. by upstream reservoirs, reservoir yield at Q_{90} could be increased by more than 100%. However, a significant increase in flow stability would come at a cost of increasing evaporative losses and would probably lead to an increase in upstream water abstraction as well.

Local rainfall variability affects irrigation requirement, but does not dramatically influence reservoir yield reliability. Most of the water for irrigation is abstracted during the dry season, when rainfall rates are too low to notably reduce irrigation requirement per hectare.

The volume of abstracted water due to long-term changes is more important to yield reliability than rainfall-dependent variations from year to year. This volume depends on many factors other than inflow and rainfall variability. In the early 1990s, for example, irrigation for rice production in the study area was much higher (an additional 150%) than in the period 2000–2005. Because of changes and variations in the market, and technological improvements in the irrigation sector, shifts in water abstraction are very well possible. It is hard to say what developments regarding water abstraction will occur in the future. However, it is possible to determine the effect of such developments on reservoir reliability. Our results show that these effects can be serious.

In our simulation method a fixed target yield has been coupled with a reliability level. In reality, a target yield neither is nor should be applied for reservoir operation in the semi-arid northeast of Brazil. Water demand is variable due to rainfall variations, which makes it inefficient to use a fixed release volume. Moreover, with the introduction of institutionalised participative water management in the study area, dating from late 1993, the decision making process for water allocation is no longer solely based on water engineering decisions (Johnsson and Kemper, 2005; Lemos and De Oliveira, 2004; Taddei, 2005). Besides the individual preferences of different stakeholders participating in decision making, actual reservoir reserves and increasingly also rainfall predictions are taken into account when making decisions on reservoir releases. In reality reservoir operation rules are far more complicated than represented in the reliability concept applied here. However, for the purpose of this study it served well.

Climate change was not taken into account in this study. According to Kundzewicz et al. (2007) climate change may substantially affect irrigation withdrawals. Obviously, changes in evaporation and rainfall regimes would also influence reservoir yield reliability.

4.6 Conclusions

The reliability level of reservoir yield is sensitive to upstream water abstraction for irrigation. Methods to determine reservoir yield can conveniently be adapted to account for the effect of abstraction and its variability. Yield reliability simulations for the study area show that taking into account upstream water abstraction for a reservoir yield of 20.0m^3/s results in a water-scarcity probability of 10% on an annual basis (90% reliability), while it is only 5% if upstream abstraction for irrigation is ignored. Changes in water abstraction significantly influence reservoir yield and reliability.

The results show that inter-annual variability of upstream water abstraction as a result of rainfall-dependent variability of irrigated area and irrigation water requirement is of low importance for reservoir yield and reliability. However, spatial planning regarding irrigation programmes and the construction and operation of upstream storage reservoirs strongly affects yield and reliability of reservoirs located downstream. This study shows that observed land use changes in semi-arid regions can have an impact on reservoir yield reliability that is more serious than estimated long-term effects of sedimentation.

In the case studied average upstream inflow is much higher than average water abstraction. Therefore the influence of the variability of water abstraction on reservoir inflow is small. However, if average inflow were to decrease (e.g. as a result of increasing average water abstraction), the impact of variability of water abstraction would increase accordingly. In cases where inflow is lower, relative to abstraction, the effect of variability of water abstraction could thus be greater.

In the sub-basin study area as a whole variations in irrigated area compensate for, rather than amplify, variations in irrigation water requirements. In specific parts of the sub-basin area however variations show different patterns. This implies that in other sub-basins and under other circumstances amplification rather than compensation could prevail.

5 Representing the relationship between water use and water availability in a model[3]

5.1 Introduction

This chapter addresses the third research question: *Can the use of a multi-agent simulation approach to depicting sub-basin scale interaction between water use and water resources result in a valid representation of observed variations in the distribution of water use and water availability?* To represent the dynamics of water abstractions for irrigation and the effect it has on spatial and temporal water resources distribution across a semi-arid river basin, the applicability of a spatially-explicit multi-agent simulation (MAS) approach is discussed. The geographical locations of water users and the timing of water abstractions influence temporal and geographical distribution of water availability across a basin. In this study the feedback relation between water availability and water use influenced by rainfall variability (Figure 5.1) is essential for system dynamics. Interventions in the natural course of water in one place influence water availability and water use in that place itself, as well as in other locations. Obviously, higher water demands lead to increasing abstraction and therefore reduce water availability. Conversely, water availability influences demand for irrigation water, because users anticipate and respond to water availability by modifying their decisions on the area of land to be irrigated and the type of crop to grow.

A MAS model for the spatially-explicit depiction of resource use consists of a cellular model representing geophysical aspects of a natural system and an agent-based model representing human decision making that is related or relevant to the natural environment (Parker et al., 2003). It is increasingly acknowledged that MAS is an adequate modelling technique to represent human-environment interactions (Bousquet and Le Page, 2004; Matthews et al., 2007; Parker et al., 2002; 2003; Verburg, 2006). MAS models may help to portray systems in which interdependencies between agents and their environment are essential to the proper understanding of system dynamics, the heterogeneity of agents or their environment critically impacts model outcomes and adaptive behaviour at the individual or system level is relevant for the system under study (Parker et al., 2003). According to Matthews et al. (2007) different applications of MAS models for land use are designed to serve one or more of the following five purposes: (1) policy analysis and planning; (2) participatory modelling; (3) explaining spatial patterns of land use or settlement; (4) testing social science concepts; and (5) explaining land use functions.

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[3] This chapter has been submitted for publication in the form of a paper to *Environmental Modelling & Software.*

With regard to policy analysis, Berger et al (2007) have shown that 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. Schlüter and Pahl-Wostl (2007) have developed an agent-based modelling approach to compare alternative water management regimes. It enables the resilience of a social-ecological system with respect to uncertainty and changes in water availability in central Asia to be studied. This study intends to explore the effects of water abstractions for irrigation in a semi-arid environment on water availability distribution, and vice versa. The approach aims at model outcomes that are relevant to policy analysis and spatial planning, as well as explaining spatial patterns of water use and water availability. To test the approach the Jaguaribe basin in the semi-arid northeast of Brazil was studied.

In the Jaguaribe basin there are strong dependencies between water uses and water availability at the basin level (Chapter 3 of this thesis). In the assessment of reservoir yield of a large reservoir in the basin, it was found that including upstream water abstractions for irrigation significantly improves the accuracy of predictions (Chapter 4 of this thesis). The inclusion of feedback mechanisms between water availability and water use requires new methods of model parameterisation and calibration to increase our understanding of resource system dynamics. In this chapter it is explored whether the use of MAS modelling, including agents equipped with simple decision making heuristics based on empirical survey data, is helpful in representing system dynamics that influence the distribution of water availability in a semi-arid river basin.

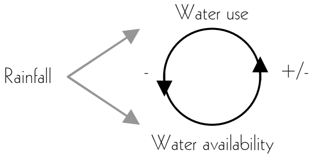

Figure 5.1 *Feedback relationship between water availability and water use influenced by rainfall variability. Water use subtracts from water availability, but the effect of water availability on water use is less straightforward.*

5.2 Method

5.2.1 Model description

The ABSTRACT model (Agent-Based Simulation Tool for Resource Allocation in a CatchmenT) is designed for a basin or sub-basin in which surface water storage reservoirs have been built and the irrigation sector is an important water user, and in which there are possibilities for multi-annual water allocation. To represent human-environment interactions a multi-agent simulation (MAS) approach is adopted. The ABSTRACT model is developed with the CORMAS platform under the VISUALWORKS environment (Bousquet et al., 1998). To represent feedback processes between water availability and water abstractions for irrigation, system components related to topography, hydrology, storage and abstraction of water resources are included. These four aspects are strongly related and representing their interaction is done in a spatially-explicit cellular model environment. Out of many possible model outputs, the main focus is on analysing the spatial distribution of water availability and water use.

Agents represent farming households that are situated at specific geographical locations and make decisions, followed by actions, affecting the environment. The modelling sequence is as follows: physical parameter update; biophysical dynamics; land use decisions and actions; and land availability update. In the physical parameter update rainfall and upstream inflow are realised. This is done at the beginning of every 10-day time step. The biophysical dynamics involve vertical and horizontal water balance calculations, including water level updates on aquifers and reservoirs. Decisions on land use are made by individual farmer-agents taking into account local conditions and preferences. These decisions are followed by actions implementing them. Harvesting takes place when crops are ready to be harvested, or harvests are lost by flooding. At every time step land availability is updated according to water levels in reservoirs and land cover changes due to harvesting.

Within the CORMAS platform several object classes are generated in which methods are implemented to represent system dynamics. A spatial entity class, represented by one grid cell, corresponds to a *Plot*. There are two agent classes: *Farmer* and *Allocation Committee*. *Farmer*-agents decide on land use and water abstractions, while *Allocation Committee*-agents decide on reservoir releases. Geographically-located object classes are: *Crop*, *River* (branch) and *Node*. *River* branches connect *Nodes* and can contain storage, through either an *Alluvial Aquifer* or a surface water storage *Reservoir*. Figure 5.2 shows the main model classes and the names of their main attributes and methods. Vertical water balance operations are modelled in the *Plot* and the *Crop* classes. The horizontal water balance is arranged in the *Node* class and its subclasses.

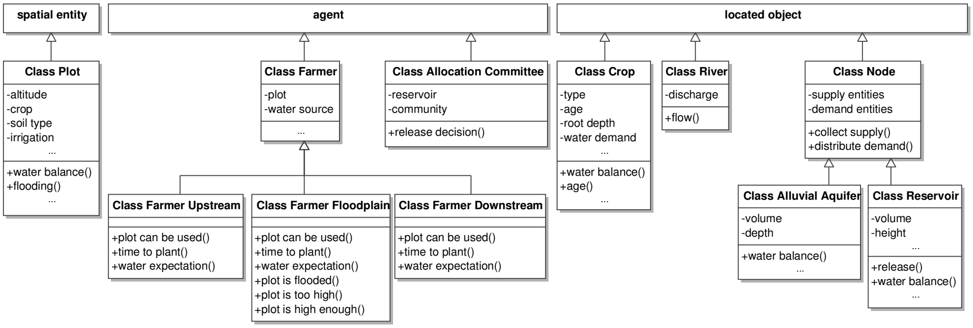

Figure 5.2 *UML class diagram of the ABSTRACT model.*

5.2.2 Water balance

A semi-distributed hydrologic modelling approach is used. The river is represented by a sequence of branches, each of which depicts a part of the river including its underlying alluvial aquifer. From each branch water is withdrawn and water returns from riparian areas. Among these are irrigation areas that consist of grid cells for which the vertical water balance is simulated. Each branch receives water from its upstream river branch or branches and from riparian grid cells that provide runoff and return flows from irrigation. Water storage is arranged in alluvial aquifers and reservoirs, depending on local circumstances. The representation of the water balance is schematised in Figure 5.3.

To determine the water demand by farmers in irrigation areas a modelling approach that is designed for a 10-day time step (Perez et al., 2002) is implemented in CORMAS, in the same way it was implemented for the CatchScape model that was developed by Becu et al. (2003). Use is made of data on soil parameters and crop parameters for all grid cells. External data are provided for rainfall (P) and potential evapotranspiration ($ET0$) values. Over each time interval the water balance of a grid cell can be expressed as a mass conservation equation (all units in m^3/s):

$$\frac{\Delta S_{cell}}{\Delta t} = P + I - R_S - R_{SS} - ET \tag{5.1}$$

where ΔS_{cell} is the change in actual soil water storage over a time interval Δt, P is rainfall, I is water used for irrigation abstracted from an irrigation source, R_S is surface runoff, R_{SS} is sub-surface runoff, and ET is actual evapotranspiration In this way grid cell-specific water demands for irrigation (I) can be determined at every time step. In the simulation a time step of 10 days is used.

The water balance of a river branch, including the underlying alluvial aquifer, can be expressed at each time step as a mass conservation equation (all units in m^3/s):

$$\frac{\Delta S_{Ri}}{\Delta t} = \sum_{x=1}^{n} Q_{u,x} + \sum_{y=1}^{m} R_y - Q_d - W \tag{5.2}$$

where ΔS_{Ri} is the change in storage in the river branch over a time interval Δt, including the underlying alluvial aquifer; $Q_{u,x}$ is discharge coming in from a directly upstream river branch x, R_y is runoff from riparian grid cell y, which is located in the local sub-catchment, Q_d is the discharge flowing into the downstream river branch and towards the next downstream node, and W is water withdrawal (minus return flows) by water users on downstream riparian lands. It is assumed that farmers try to fulfil irrigation water demands. In addition it is supposed that evaporation losses for withdrawal are 25%. Another part of irrigation withdrawals is returned to the river through return flows that are included in R_{SS} of a grid cell.

The water balance of a reservoir can be expressed as follows (all units in m^3/s):

$$\frac{\Delta S_{Re}}{\Delta t} = \sum_{x=1}^{n} Q_{u,x} + \sum_{y=1}^{m} R_y + P - E - Q_d - W \tag{5.3}$$

where ΔS_{Re} is change in storage of the storage reservoir over a time interval Δt, $Q_{u,x}$ is discharge coming in from a directly upstream river branch x, R_y is runoff from riparian grid cell y, which is located in the local sub-catchment, P is rainfall on the reservoir surface area, which is updated according to a volume-surface relationship for the reservoir and E is evaporation from the reservoir surface area. The released outflow of a reservoir is controlled by operating an outlet and consists of discharge (Q_d) and downstream withdrawal (W).

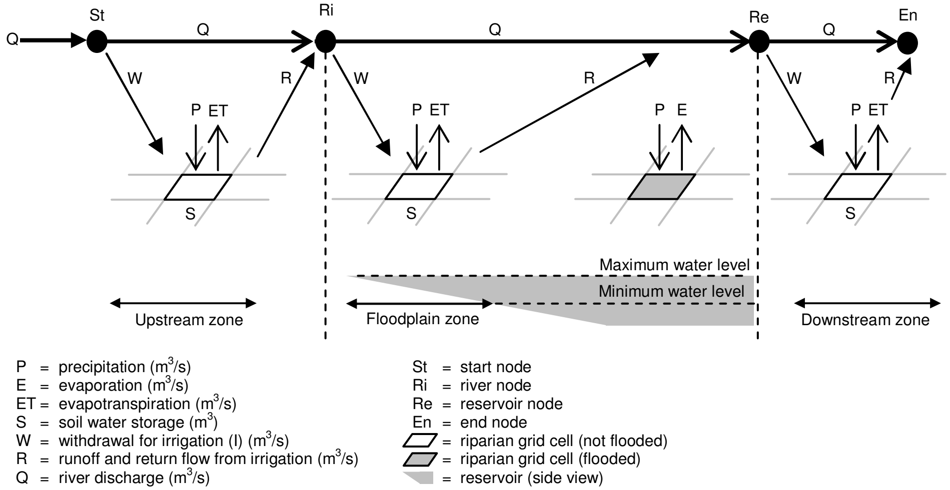

Figure 5.3 *Schematisation of the connection between the horizontal and the vertical water balance.*

5.2.3 Agent decision making

Farmers in semi-arid regions depend on an environment that in the ABSTRACT model is characterised by only a few factors. Besides rainfall, accessibility of water sources for irrigation and flooding of agricultural fields are taken into account. Both flood risk and access to water resources are related to local topography. The difference between the height of a plot and the varying water level of a local water source influences practical availability of water and thus land use decisions. Crop choice and the extent of the irrigated land are both influenced by indicators of water availability. The influence of these indicators is manipulated by using random probability generators that represent preferences of water users in a certain community. A farmer's geographical location within the basin influences his vulnerability to water abstractions by other farmers. Three different locations for access to sources of irrigation are distinguished: upstream of a reservoir, on a reservoir floodplain, and downstream of a reservoir (Table 5.1).

Decision making by an allocation committee or reservoir operator is implemented in alternative ways, i.e. to represent strategic operation or decision making by user committees.

Table 5.1 Water sources for farmers, categorised according to their location relative to reservoirs.

Relative location of a water user	primary water source for irrigation
Upstream of a reservoir	Water is pumped directly from the river or from the alluvial aquifer.
In the floodplain of a reservoir	Water is pumped from ground water that directly connects to a reservoir.
Downstream of a reservoir	Water is released from a reservoir into an irrigation scheme or channel.

5.3 Model application for the Jaguaribe basin

5.3.1 Study area and spatial representation

The study area is located around the Orós reservoir (Figure 5.4). Two other public reservoirs in the area are the Trussu and the Lima Campos reservoirs. A tunnel connects the Orós and the Lima Campos reservoirs providing the latter with additional inflow.

Farmers in the area generally cultivate riparian plots of between 5 and 10 hectares (COGERH, 2001a). The grid cell size of our model is 7.29 hectares, corresponding to nine grid cells of the digital elevation model (DEM) that is used (EMBRAPA, 2006). The DEM has a grid cell size of 90×90m^2 and a vertical resolution of 1m. For the elevation of the cells in the ABSTRACT model the value of the middle cell of squares composed of 9 DEM grid cells is taken.

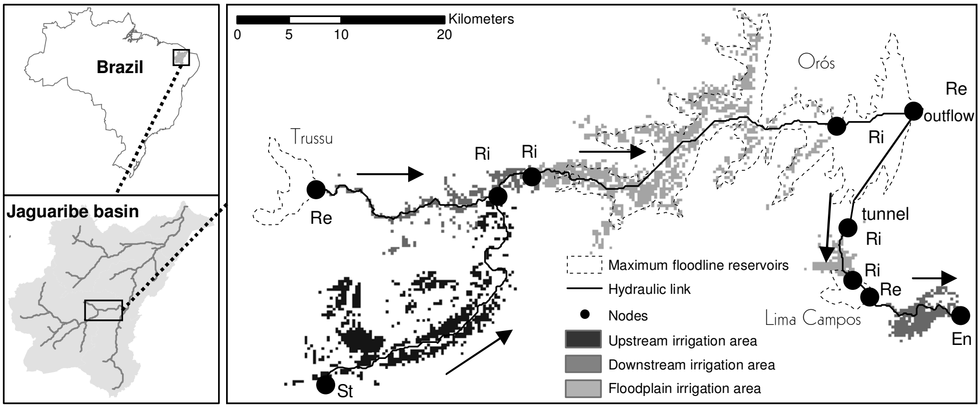

Figure 5.4 *The Orós reservoir study area, with indication of nodes and irrigation areas.*

5.3.2 Farmer decision making

Rules for farmer decision making with respect to the area of land to be irrigated and the type of crop to grow are based on a survey that was conducted in connection to a study on the impacts of water resource management choices in Ceará, Brazil (Taddei et al., 2008). During the period May to August 2006 interviews with 602 irrigation farmers in 149 localities (in 14 municipalities) in the Jaguaribe valley were conducted. A random sampling method was used. Data from 55 farmers that are located in the study area (Figure 5.5) have been used for the study described in this chapter. For the survey farmers were interviewed on their decisions regarding land use in both the wet and the dry season. Three qualitatively different situations were outlined to the respondents for the dry season: water availability that is regarded as less than sufficient, as sufficient, or as more than sufficient. The way survey respondents from different zones in the study area operate in these three situations in respect of crop choice and area of land to irrigate is presented in Table 5.2.

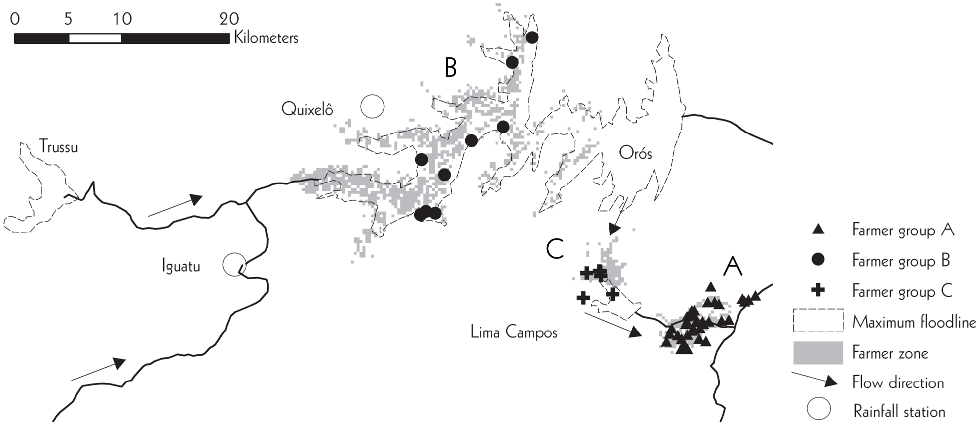

Figure 5.5 *Geographical locations of farmers in the survey of 2006 (Taddei et al., 2008).*

Table 5.2 Summary of survey results: land use variation by farmers under different water availability circumstances (Taddei et al., 2008).

		Fraction of the area used for irrigated agriculture	**Crop area as a fraction of irrigated area**			
			Rice	*Maize*	*Beans*	*Feed crops and other*
Farmers zone A	**dry season**					
	local water availability < sufficient	0.60	50%	1%	15%	34%
	local water availability = sufficient	1.00	60%	1%	14%	26%
	local water availability > sufficient	0.97	66%	1%	14%	19%
	wet season *(2006)*	0.54	41%	21%	6%	32%
Farmers zone B	**dry season**					
	local water availability < sufficient	0.79	63%	24%	10%	3%
	local water availability = sufficient	1.00	67%	17%	8%	8%
	local water availability > sufficient	0.83	67%	10%	12%	11%
	wet season *(2006)*	0.42	0%	64%	30%	6%
Farmers zone C	**dry season**					
	local water availability < sufficient	0.60	52%	0%	29%	20%
	local water availability = sufficient	0.74	56%	0%	23%	21%
	local water availability > sufficient	0.71	59%	0%	20%	22%
	wet season *(2006)*	1.00	20%	58%	10%	11%

Based on survey data and interviews with local experts in 2005 and 2006, three key elements of farmer decision making regarding crop choice and the area of land to irrigate are identified. The first is rainfall expectation, especially important for those who rely on short-term storage reservoirs and alluvial aquifers. The second key element is the quantity of stored water resources in the primary water source of the water user. The third element is flood risk, which is important to those farmers who utilise the fertile lands on the floodplains of large reservoirs. Other factors, such as individual financial resources and markets for crops are not taken into account in this thesis.

Rules for farmer decision making that take into account flood risk and limitations on the pumping capacity for individual water users involve a comparison between the altitude of the grid cell that a farmer-agent occupies and the water level in the reservoir or aquifer that is relevant to the specific location (Table 5.3). A comparison between observed water availability in the study area and survey outcomes suggests that farmers from different locations disagree on the circumstances that lead to 'less-than-sufficient', 'sufficient' and 'more-than-sufficient' water availability. Also, upstream farmers generally favour sufficient water availability over more-than-sufficient and less-than-sufficient, while downstream farmers don't mind more-than-sufficient water availability (full reservoirs).

In the ABSTRACT model three groups of farmers are differentiated according to their relative geographical location: upstream farmers, floodplain farmers (corresponding to farmer group B and C), and downstream farmers (corresponding to farmer group A). Figure 5.6 shows a flowchart of farmer decision making on land use for those of their plots that are equipped for irrigation. Implementation of the rules from Figure 5.6 for the three different farmer groups in the Jaguaribe basin are described in Table 5.3, while and Table 5.4 gives the values of rainfall that are used as thresholds on which upstream and floodplain farmers decide whether they locally expect sufficient water availability during the dry season. This deterministically shapes the cropping area. Crop choice is simulated randomly, using the distribution of crop choices in Table 5.2 (in the row corresponding to the zone in which the water user is located). Because representative survey respondent records were not available for all parts of the study area (Figure 5.5), data from respondents from farmer group A are used for farmers located downstream of both the Trussu and the Lima Campos reservoirs. For upstream farmers data for farmer group B are used.

Autonomous decision making by the allocation committee-agents is not implemented for this study. For the simulated period of 1996-2005 a time series of reservoir release quantities for all reservoirs in the Orós reservoir study area (COGERH, 2006) are taken as 'decision rule'. In this chapter, model dynamics are thus limited to those with regard to water users.

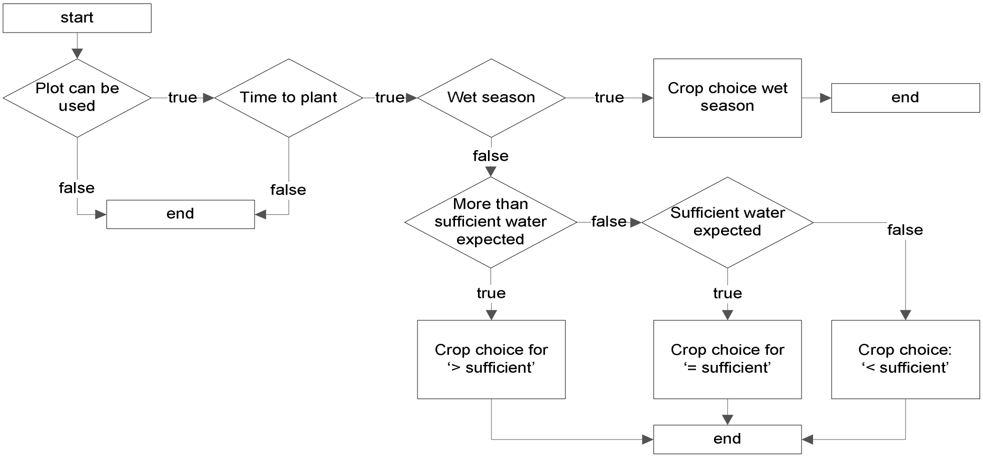

Figure 5.6 *Land use decision making flowchart. This flowchart applies to all farmers, but the implementation of decision rules differs for upstream, floodplain and downstream farmers.*

Table 5.3 Rule implementation for different farmer types.

Rule	Upstream farmer	Floodplain farmer	Downstream farmer
Plot can be used if:	there is not already a crop on the plot	there is not already a crop on the plot & for dry season: the plot is not too high (< 7m above water level) & the plot is not flooded for wet season: the plot is high enough (> 4m above water level)	there is not already a crop on the plot
Time to plant if:	rainfall > 20mm in 10 days & date between 1 January and 10 April or: date between 1 July and 1 September & at least 30 days after harvesting the wet season crop	rainfall > 20mm in 10 days & date between 1 January and 10 April or: date between 1 July and 1 September & at least 30 days after harvesting the wet season crop	date between 1 January and 10 April or: date between 1 August and 31 December
Wet season if:	1 January–30 June	1 January–30 June	1 January–30 June
Farmer expects more than sufficient water for the dry season if:	rainfall during the wet season > higher threshold	rainfall during the wet season > higher threshold	reservoir volume at 1 July > 70% of capacity
Farmer expects sufficient water for the dry season if:	rainfall during the wet season > lower threshold	rainfall during the wet season > lower threshold	reservoir volume at 1 July > 35% of capacity

Table 5.4 Rainfall (mm) during the wet season (1 January-30 June) at two locations.

	Quixelô* (1988-2005)	Iguatu* (1974-2005)
Average Jan–Jun	661	863
lower 25% (lower threshold)	< 534	< 642
Normal 50 %	534-789	642-1005
Higher 25% (higher threshold)	> 789	> 1005

* Locations of rainfall stations are shown in Figure 5.5.

5.3.3 Input data

For rainfall variability use is made of meteorological data from the meteorological research institute of Ceará (FUNCEME, 2008). Soil characteristics are obtained from the data base that was developed for the WAVES project (Gaiser et al., 2003). Discharges of upstream inflow are derived from the national Hidro data base (ANA, 2006). Reservoir volumes as well as volume–surface relationships for the reservoirs Trussu, Lima Campos and Orós are obtained from the water management authority in Ceará (COGERH, 2006). The altitude of individual grid cells in the model are determined using a 90m resolution digital elevation model from the Brazilian Agricultural Research Corporation (EMBRAPA, 2006). Runoff coefficients for runoff into the Trussu, Lima Campos and Orós are obtained from a hydrologic study for Ceará which includes our study area (Güntner, 2002). For initial land cover/use, data are used from: annual agricultural production data of IBGE for the period 1990-2005 (IBGE, 2006), seasonal agricultural production data for the period 2003-2005 of the Iguatu office of the agricultural institute for the state of Ceará, EMATERCE, and land use classifications using remotely-sensed imagery for the dry season. The following images were used: Landsat TM (path–row) 217–64 (25 October 2000, 13 November 2001, 31 October 2002); CB2CCD (path–row) 150–107 (22 November 2003, 29 September 2004, 24 October 2005); and CB2CCD (path–row) 151–107 (19 November 2003, 26 September 2004, 21 October 2005). The remotely-sensed data show which areas can potentially be irrigated because they are obtained during the dry season. These areas are considered to be equipped for irrigation during the simulated period.

In section 5.4.2 the remotely-sensed data for different years are also used to validate simulation outcomes based on survey data. Survey data are obtained from a survey conducted in 2006 among water users in the Jaguaribe valley (Taddei et al., 2008).

5.3.4 Method of validation

To test the performance of the ABSTRACT model, reservoir storage and land use are considered. Observed reservoir volumes for the Orós reservoir (COGERH, 2006) are compared to the outcomes of our simulations. This is done by determining the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) for seasonal volume changes of the reservoir. Volume changes in the wet season (1 January-30 June) are mainly caused by rainfall, while volume changes in the dry season (1 July–31 December) are mainly caused by water abstractions. Simulations of the ABSTRACT model are compared to model runs where no water is abstracted at all and to model runs where land use is coupled with the average water use over the 10 years. The observations of volume changes in the Orós reservoir are relatively reliable.

Apart from model validation in respect of the water balance of the Orós reservoir, the farmer decision making rules that are based on survey data are separately validated. To find out whether the ABSTRACT model is successful in resembling inter-annual water use variation, model outcomes should preferably be compared to empirical observations of water abstractions. These however are poorly monitored in the area. Since water abstractions for irrigation strongly relate to agricultural land use, especially during dry periods, land use data can be used for validation as well. These data are also scarce, but for the period 2000-2005 remotely-sensed imagery of the area is available. The images that are described in the previous section have been used for land use classifications in a study by Leskens (2006). The results of that study were also used for a study on reservoir yield for the Orós reservoir (Van Oel et al., 2008). Separate comparisons are made for the zones of farmer groups A, B and C (Figure 5.5) between model simulation outcomes and land use classifications from the remotely-sensed data for the same zones.

5.4 Simulation results and validation

5.4.1 Reservoir water balance

Reservoir volumes in the main reservoir in the study area, the Orós reservoir, can be predicted with reasonable accuracy by the ABSTRACT model (Figure 5.7). For seasonal volume changes the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) is 0.95 (Figure 5.8). For the dry season (1 January–30 June) alone the result is 0.98. This can be explained by the fact that uncertainties over rainfall are less dominant during the dry season. Since farmer decision making on crop choice involves randomly-generated probability procedures, three runs were done. The results presented in Figures 5.7 and 5.8 are all based on the average of these three runs. For each of three different conditions ('simulated', 'no irrigation' and 'no variations irrigation') all three runs resulted in a similar outcome for the Nash-Sutcliffe efficiency coefficient.

Figure 5.7 clearly shows that including water use significantly improves model outcomes with respect to reservoir volumes. This confirms that water abstractions for irrigation influence water availability dramatically. To analyse the effects of feedback processes between water use and water availability, the inclusion of variations in irrigation is also evaluated. Introducing variations in water abstractions for irrigation that are based on survey data regarding intended land use did not significantly influence simulation outcomes. In other words, including a feedback from water storage to water use variability does not result in significant improvements in simulated reservoir volumes for this study area.

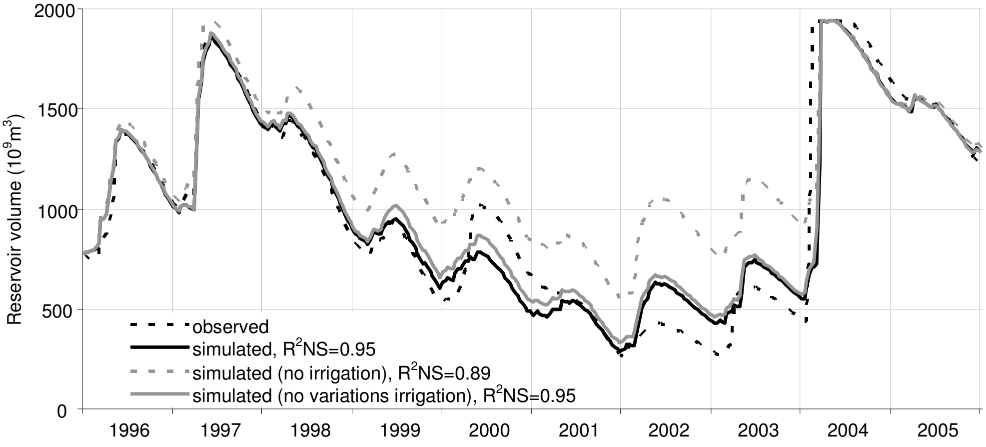

Figure 5.7 *Observed and simulated reservoir volumes for the Orós reservoir.*

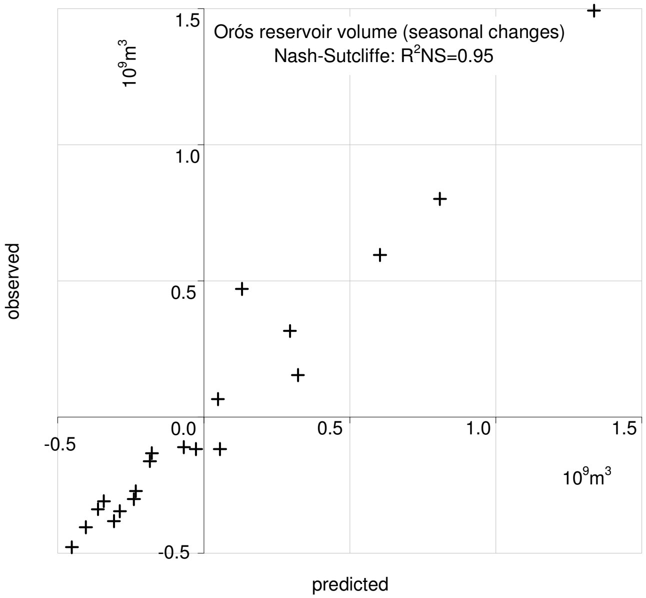

Figure 5.8 *Observations and predictions of seasonal volume changes over the period 1996-2005 for the Orós reservoir. Each year has two seasons: the wet season starts on 1 January and ends on 30 June; and the dry season starts on 1 July and ends on 31 December.*

5.4.2 Irrigated area and water abstractions

Simulation outcomes of water abstractions for the zones of farmer groups A, B and C are presented in Figure 5.9 This figure clearly shows that the ABSTRACT model enables us to analyse variations in water abstractions over time at different locations in the study area. Interestingly, the results presented in Figure 5.9, when compared to Figure 5.7, suggest that for the wet season high (low) water availability results in low (high) water use; however high (low) water availability results in high (low) water use during the dry season. Especially high water use in the wet season if there are relatively low storage levels in reservoirs increases water stress during the following dry season. As can be seen in Figure 5.9, the largest water use variations are seen in zone B. The high water use in the dry seasons of 1998 and 2005 can be explained by the relatively high water storage in the Orós reservoir in these years (Figure 5.7). The high water use in the wet season of 2001 is the result of the fact that water storage in the Orós reservoir is comparatively low (Figure 5.7), so that there is quite a lot of fertile land available for irrigated agriculture. The relatively high water use in the wet season of 2001 resulted in a further depletion of available water resources, which reduced possible water use in the dry season of 2001, especially for zone A at the downstream end of the study area.

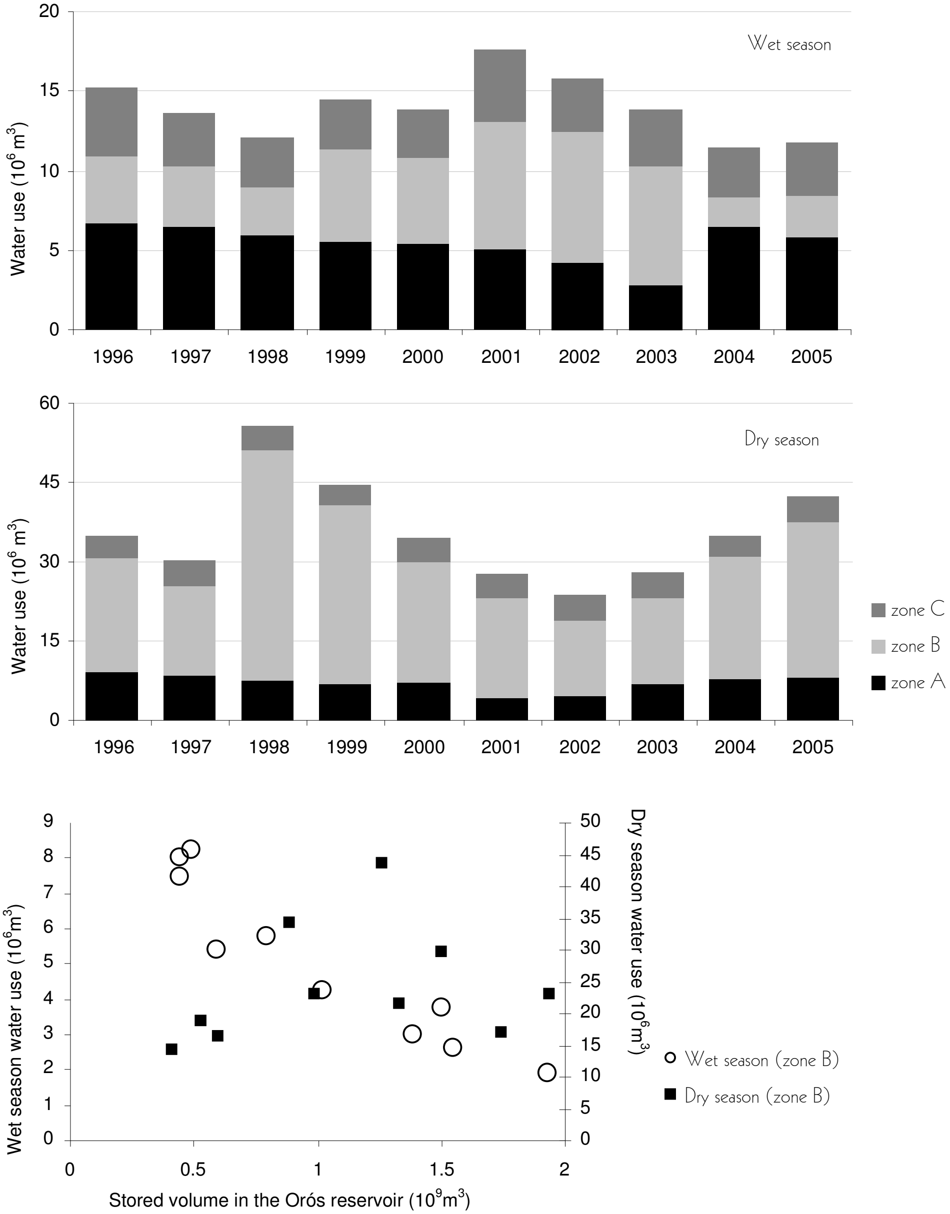

Figure 5.9 *Simulated water abstractions in the zones of farmer groups A, B and C during the wet and the dry seasons for the period 1996-2005. In the lower graph storage levels in the Orós reservoir for the wet season (10 April) and the dry season (1 July) are plotted against water use in the zone of farmer group B.*

To test the validity of the specific representation of feedback processes between water use and water availability in our modelling approach, the simulated variations for water abstractions should be compared to observations. As data on water abstractions are not available for the study area, it was decided to compare simulated land use patterns with land use classifications from remotely-sensed data. Simulation outcomes for irrigated area for the zones of farmer groups A, B and C were compared to a data series of land use classifications, one for each dry season in the period 2000-2005.

In the simulation runs that were done specifically for this analysis, farmer-agent decision making takes into account observed reservoir water levels (COGERH, 2006) rather than simulated water levels. This was done to isolate the simulated decision making procedures from uncertainties related to input data for rainfall and runoff, which could result in water levels that conflict with the observed water levels seen in Figure 5.7.

Since farmer decision making regarding crop choice involves randomly-generated probability procedures, three runs were done. The results presented in Figure 5.10 are all based on the average of these three runs.

Parts of the study area model outcomes resemble variations in irrigated area that have been observed in the land use classifications quite well. The results for the zones of farmer groups A, B and C are shown in Figure 5.10.

For the zone of farmer group A simulation outcomes show a reasonable resemblance to land use classifications. All farmers in zone A use plots within an irrigation scheme that is located downstream of a single water source: the Lima Campos reservoir. For farmers in this zone, modelled as downstream farmers, the water availability situation is directly related to the water availability in the Lima Campos reservoir that supplies the canal network of their irrigation scheme with water. Therefore heuristics of decision making are likely to be homogenous for all members of this group.

The decision making heuristics for the zone of farmer group B are likely to be quite homogenous as well. The farmers depend on one clearly-defined resource: the Orós reservoir. All farmers in this zone are modelled as floodplain farmers. Uncertainty over the representativeness of individual survey respondents in zone B might be of interest here, because the altitude at which farming activities take place influences water availability and flood risk. Although geographical locations of residence are known for all respondents, the location of the land they use for agricultural purposes is unclear. Therefore it is not possible to link the heuristics of individual survey respondents to exact locations within the zone.

For the zone of farmer group C the ABSTRACT model does not perform well. As with farmers from zone B, the exact geographical location of agricultural activities of respondents from this zone is not clear. In addition, farmers in this zone depend on different water sources for irrigation. Water from the upstream Orós reservoir is available to only some of the farmers, because of a tunnel between the Orós and the Lima Campos reservoirs. Other farmers do not have access to that water, but can pump water out of the Lima Campos reservoir and may be susceptible to flooding. It was decided to represent all individuals in this zone in the same way, treating them as downstream farmers dependent on the volume in the upstream Orós reservoir. The fact that flooding limits land availability near the Lima Campos reservoir is taken into account as well.

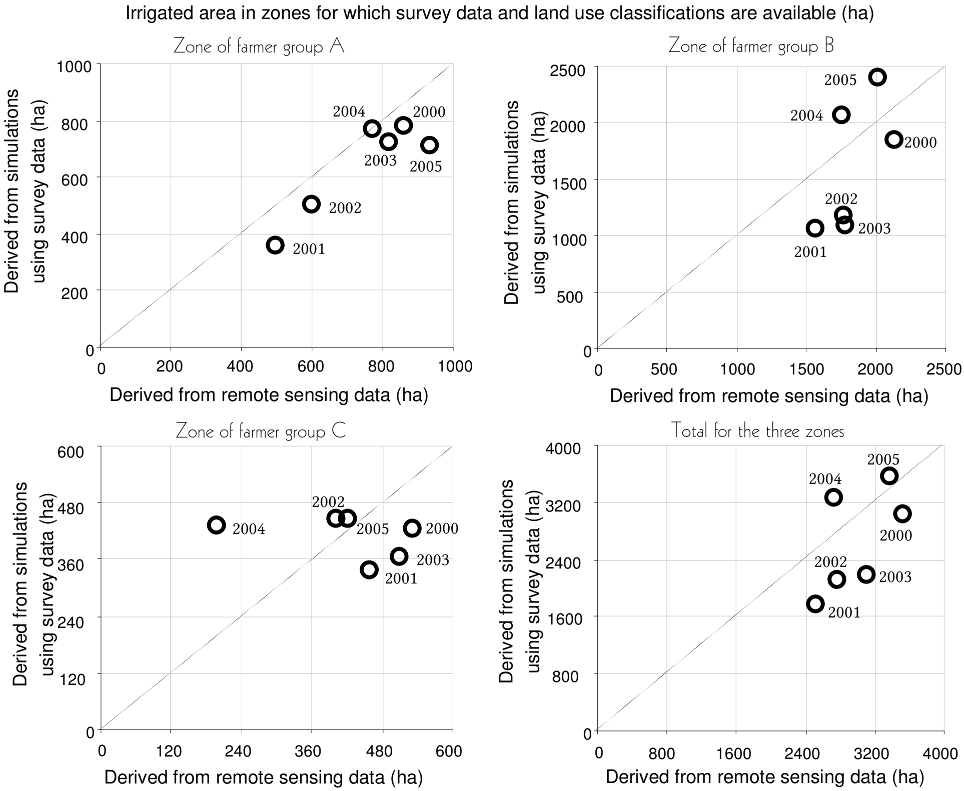

Figure 5.10 *Comparison between outcomes for irrigated area as a result of our simulation (based on survey data) and land use classification for remotely-sensed imagery. Irrigated area is shown for the three specific zones for which data were available and for the total study area.*

5.5 Conclusion and discussion

Applying a MAS approach is useful in representing feedback mechanisms between water availability and water use in the semi-arid Jaguaribe basin. It has been shown that it is possible to validly depict spatial-temporal variability of water availability influenced by water abstractions and vice versa. The ABSTRACT model outcomes resemble observed variability of water availability in the study area for the period 1996-2005.

Direct validation of the model outcomes with respect to water abstractions was not possible due to a lack of available data on water use. However, land use classifications from remotely-sensed data offered good opportunities to validate the simulation of land use, which is the main determinant for water abstraction in the ABSTRACT model. Decision making heuristics regarding crop choice and the amount of land to irrigate were implemented by equipping farmer-agents with rules based on survey data. Simulation outcomes roughly resemble land use classifications from remotely-sensed data for the study area. Resemblance is closest for farmer groups dependent on clearly identifiable water sources. Representing heterogeneity of farmer decision making based on the available survey data was not possible on a local scale, as the exact geographical location of agricultural activities was unknown.

In modelling human-environment interactions it is important to distinguish between positive and negative system feedbacks (Verburg, 2006). Interestingly, both positive and negative correlations between water availability and water abstractions have been encountered and represented. Wet season water abstractions are negatively influenced by changes in water availability, whereas dry season water abstractions are positively influenced by this. This means that wet season abstractions potentially amplify water stress during the following dry season. The character of the dynamics is determined by a combination of the agents' heuristics (especially for dry season dynamics) and the spatial distribution of agents. Representing these dynamics, including the influence of rainfall variations on water abstractions for irrigation, is essential for obtaining a more complete understanding of system dynamics in semi-arid river basins. Thus it is potentially valuable in assessing the impact of future investments in infrastructure on water availability distribution over space and time. Multi-agent simulation is especially suited to representing these dynamics.

The outcomes of this study confirm that, in the Jaguaribe basin, water availability is a major factor in farmer decision making on land use and the related water abstractions for irrigation. However, farmer decision making is known to be influenced by many factors other than the ones taken into account in the ABSTRACT model. One of these other factors is a constantly changing environment, in which the market prices of different crops and the use of technologies for irrigation can change for a variety of reasons. It is likely that developments outside the study area, such as global economic developments and national policies, also influence farmer decisions on water abstractions for irrigation. A further factor is the availability of information to farmers. In some years, for example, meteorological predictions might be more reliable than in others. The availability of information can vary and change significantly over time and among farmers in the study area. Meteorological forecasts and knowledge of agricultural practices may be available to some farmers, while not reaching others. In addition, it is possible that farming strategies change over the years, as the environmental conditions farmers experience in a given year might modify their understanding of their environment.

6 The influence of rainfall and reservoir operation on water use and water availability[4]

6.1 Introduction

This chapter addresses the fourth research question: *What are the effects of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use and water availability in a semi-arid river basin?* The effects of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use, influenced by feedback mechanisms between water use and water availability, are explored. The essential system dynamics in this study include four components: rainfall, reservoir operation, water availability and water use, and more in particular the feedback relation between water availability and water use influenced by rainfall variability and reservoir operation. Important studies engage in climate change impact assessments of freshwater without taking into account water user responses to variations and changes in water availability (Gaiser et al., 2003; Kundzewicz et al., 2008). Kundzewicz et al. (2008) argue that the impact of changes in rainfall and runoff on water users depends partly on population characteristics and the way water managers adapt to changing circumstances. This study aims to increase the understanding regarding the effect of alternative water management strategies (reservoir operation), while taking into account that water user responses to changes in water availability can amplify or lessen water stress due to decreasing rainfall and runoff.

Studying the system dynamics of water availability and water use for the study area has revealed that both positive and negative correlations are encountered (Chapter 5). For model parameterisation and calibration, use is made of a survey conducted among water users (Taddei et al., 2008) and a time series of remotely-sensed data. To represent spatial dependencies that increase the complexity of system dynamics, a spatially-explicit multi-agent simulation (MAS) approach is applied to explore the effects of possible future developments. With the ABSTRACT (Agent-Based Simulation Tool for Resource Abstraction in a CatchmenT) model the functioning of the resource system is explored by making use of a scenario approach.

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[4] This chapter has been submitted for publication in the form of a paper to the *Journal of Environmental Management.*

6.2 Method

6.2.1 Scenario approach

To explore future developments with respect to the spatial distribution of water use in a river basin, the ABSTRACT model was developed for semi-arid environments and validated for the study area (Chapter 5). Three scenarios are designed, which are local interpretations of two scenarios designed for the states of Piauí and Ceará (Döll and Krol, 2002). The three scenarios used in this study are described in Table 6.1.

For the generation of a time series of upstream inflow (runoff) and meteorological parameters (rainfall and evapotranspiration), use is made of the ECHAM4 climate model of the Max-Planck Institute, Hamburg, Germany. Downscaling of the model outcomes for the study area for the years 2000-2050 is done in the WAVES project (Gaiser et al., 2003). A summary of climate input parameters for the ABSTRACT model is given in Table 6.2.

Actual water use is the relevant part of water availability for this study. Unfulfilled water demand is not accounted for, which enables us to better analyse water availability distribution. The distribution of water use is analysed on two levels. Within the study area developments with respect to water use in upstream, midstream and downstream zones are analysed and compared. On a larger scale, on the one hand developments regarding the distribution of water resources that are used within the study area and on the other hand water resources that are available to users in the downstream valley through controlled yield from the main reservoir in the study area are analysed and compared (Figure 6.1).

Table 6.1 Description of the three scenarios for this study.

Scenario	Storylines	Study area implications	ABSTRACT parameter choices
1	- Concentration of water use for the irrigation of cash crops, tourism, and industry in the downstream valley of the Jaguaribe basin. - Water resources operated by centralised basin management.	- Target yield of main reservoir at a standard high (90% reliable), based on historic inflow statistics.	- Orós reservoir release: wet season: 5m^3/s dry season: 20m^3/s
2	- Water resources governed by local water management.	- Main reservoir is governed to serve local water users: stable dry season water level in main reservoir.	- Orós reservoir release: wet season: water storage dependent: if volume < 76% of capacity: 0m^3/s if volume > 76% of capacity: 5m^3/s if volume > 95% of capacity: 15m^3/s dry season: 0m^3/s
3	- Water resources governed by local water management. - Additional infrastructure in the study area: more storage capacity, more irrigation.	- Extra reservoir in main river upstream (capacity: 1*10^{9}m^3). - Upstream irrigation system is designed according to that yield.	- Orós reservoir release: same as for scenario 2. - New reservoir release: (local demand) * 2 + 3m^3/s - Irrigated area increases in the upstream zone by 45%.

Table 6.2 Summary of climate input parameters for the ABSTRACT model.

Climatic parameters (average for area)	2001-10	2011-20	2021-30	2031-40	2041-50
Average rainfall (mm)	877	822	911	752	594
Average ET0 (mm)	2084	2084	2046	2041	2093
Upstream inflow 1 (m^3/s)	32	22	21	12	9
Upstream inflow 2 (m^3/s)	0.9	0.4	0.6	0.2	0.1
Local runoff (m^3/s)	4.3	1.6	3.0	0.6	0.2

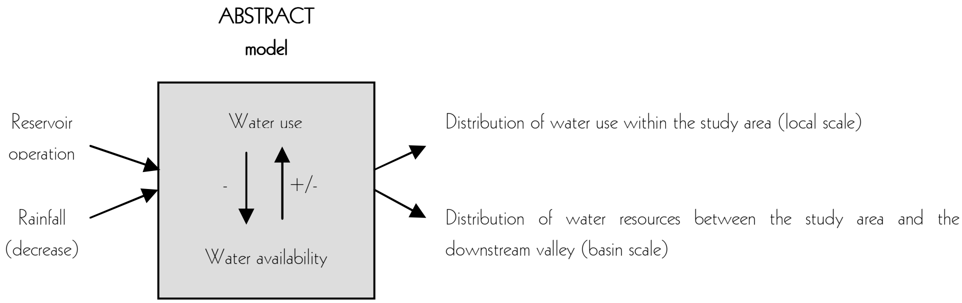

Figure 6.1 *Model input and output parameters for this study.*

6.3 Study area

Farmers in the study area generally cultivate on riparian plots with an extent of between 5 and 10 hectares (COGERH, 2001a). Conflict among water users in the Jaguaribe basin is strongly influenced by the geographical locations at which they use water. User communities located upstream of reservoir dams tend to disagree with downstream user communities over water releases (Broad et al., 2007; Taddei, 2005). Upstream users generally are inclined to oppose water releases, while downstream users favour them. Analysis of remotely-sensed data and government data on agricultural yield and production shows that there are considerable spatial and temporal differences in agricultural activity in the area under study (Leskens, 2006; Van Oel et al., 2008).

In scenario 2 dry season release from the Orós reservoir is fixed at $0 m^3/s$. Conflict among upstream and downstream users is to be expected in that case. Although this rule is not very realistic under today's circumstances and institutional developments, exploring the effect of this rule contributes to the understanding of the implications of alternative reservoir operation strategies. In scenario 3 an additional dam is constructed at the upstream end of the study area, to facilitate local development. With this new reservoir it becomes possible to retain water resources in the area. Given the extent of the upstream catchment, a reasonable capacity for such a reservoir is $1{,}000{,}000{,}000 m^3$ (about half the capacity of the Orós reservoir). Its exact location is not discussed. The same volume-surface relation as for the Orós reservoir is assumed. The unchanged inflow into the area now flows into the new reservoir. The installation of the reservoir makes it more attractive for farmers to invest in irrigation infrastructure, because of the more stable supply. Stabilisation of upstream inflow ensures permanent supply and reduces flood risk in the floodplains of downstream reservoirs, in this case the midstream irrigation zone.

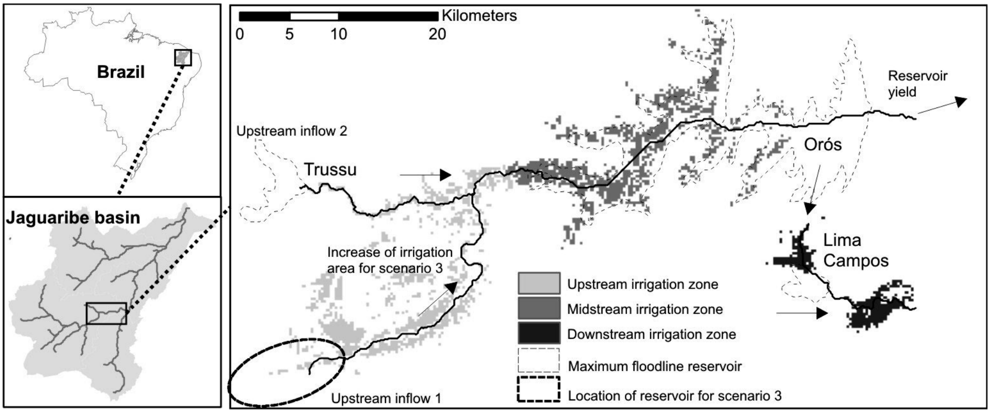

Figure 6.2 *Study area: the different irrigation zones are labelled upstream-, midstream-, and downstream.*

6.4 Results

6.4.1 Developments in the seasonal distribution of water use

During the first 30 years of simulation (2001-2030), no dramatic changes in rainfall, potential evaporation and discharges are represented in the climate input data series. Therefore no dramatic shifts in water availability and water use are expected to result from any of the three scenario simulations. Changes are expected after 2030, when meteorological pressure increases rapidly. In Figure 6.3, in which the development of reservoir volume in the main reservoir within the study area is shown, no dramatic differences between the three scenarios in reservoir volume are seen for the period 2001-2030. Between 2030 and 2050 the impact of changing meteorological parameter values becomes apparent for all three scenarios. The pattern of decline in reservoir volume is however different for each of the three scenarios (Figure 6.3).

Water use in the study area shows a modest decrease towards 2050 for scenarios 1 and 3, while it remains stable for scenario 2. The dry season and the wet season show a distinctive picture. Wet season water use increases both absolutely and relatively when compared to dry season water use, which has an absolute decrease in all three scenarios (Figures 6.4 and 6.5). Wet season increases in water use are mainly explained by growing potential evaporation and declining rainfall rates, causing higher irrigation water demands. Dry season decreases in water use are related to lessening water availability in the dry season, which is amplified by the wet season increase in water use.

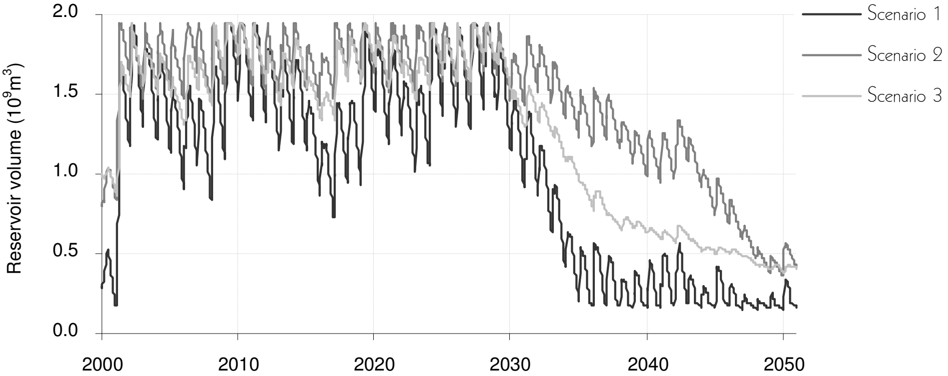

Figure 6.3 *Developments in reservoir volume in the main reservoir (Orós) for the three different scenarios.*

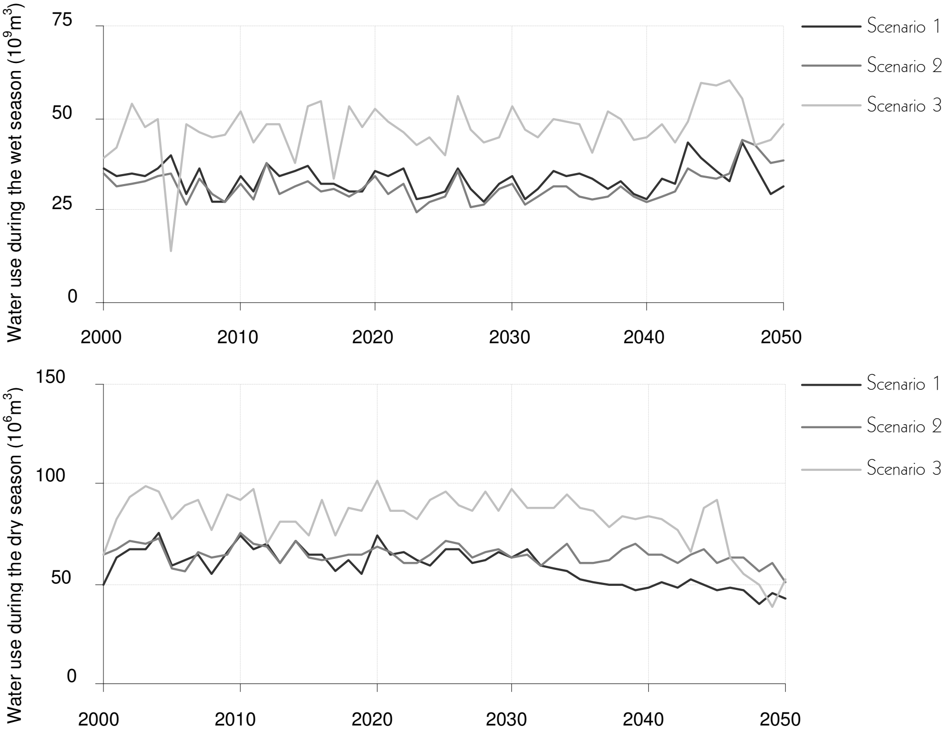

Figure 6.4 *Water use in the study area during the wet (top) and the dry (bottom) seasons for the three different scenarios.*

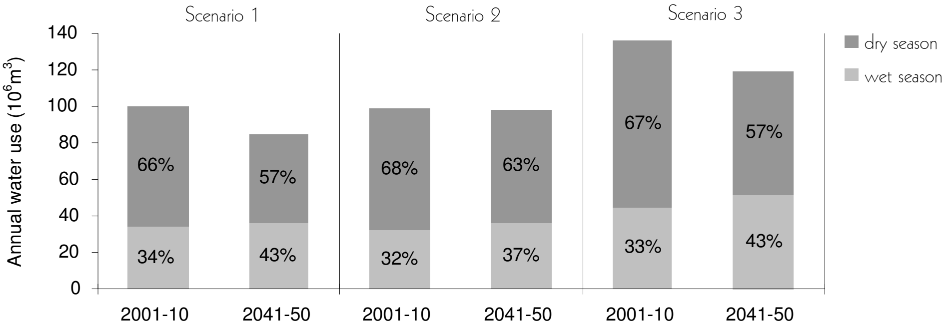

Figure 6.5 *Changes in annually-utilised water resources within the study area for the three scenarios.*

6.4.2 Spatial distribution of water use at the local level

From the simulation outcomes for scenario 1, a relative transition of water use from downstream to upstream is observed. Decreases in water use are mainly experienced at the downstream end of the study area. Although users in the midstream zone also use less water, their relative share in total water use is maintained. In scenario 2 users in the midstream and downstream zones succeed in maintaining their water use levels because of a reservoir operating strategy that directly serves their interests. In scenario 3 simulation outcomes show a relative transition of water use from upstream to downstream. Decreases in water use are mainly observed in the upstream zone, because the newly-built reservoir runs out of storage between 2041 and 2050. Water use in the downstream zone increases because of a more stable inflow from the main reservoir into the Lima Campos reservoir. Note that total water use within the study area for that period is still considerably higher in scenario 3 than in scenarios 1 and 2. This is due to the irrigation area that was added in the upstream zone. Table 6.3 shows the relative shares of total water use in the different zones for all three scenarios. Differences between the wet and the dry season are specified. Annual variation for the ten-year periods decreases for scenario 2 and increases for scenario 3. Although in both scenarios 2 and 3 local interests are served by reservoir operation, overexploitation in scenario 3 leads to increasing variability of water use when conditions become drier. This increase in variation is caused by supply failures in the upstream zone during the dry season, when water stress is highest.

Table 6.3 Relative shares of the different zones for all three scenarios

	Wet season water use		Dry season water use		Annual water use		
	2001-10	2041-50	2001-10	2041-50	2001-10	2041-50	
Scenario 1							Relative transition from down- to upstream, mainly through dry season changes (downstream supply failure)
Upstream zone	69%	61%	51%	65%	57%	62%	
Midstream zone	8%	25%	30%	20%	23%	23%	
Downstream zone	23%	14%	19%	15%	20%	15%	
coefficient of variation	0.13	0.14	0.10	0.07	0.09	0.09	
Scenario 2							
Upstream zone	72%	61%	49%	51%	56%	55%	No transition
Midstream zone	4%	18%	32%	28%	23%	24%	
Downstream zone	24%	21%	19%	21%	21%	21%	
coefficient of variation	0.09	0.14	0.09	0.08	0.08	0.06	
Scenario 3							Relative transition from up- to midstream, because of wet season changes (upstream supply failure)
Upstream zone	81%	72%	64%	63%	70%	67%	
Midstream zone	3%	13%	23%	20%	14%	16%	
Downstream zone	16%	15%	13%	17%	16%	17%	
coefficient of variation	0.25	0.14	0.08	0.27	0.12	0.19	

6.4.3 Spatial distribution of water resources at the basin level

On the scale of the river basin the decreases in rainfall and runoff lead to diminishing water supply for the downstream valley in all three scenarios (Figure 6.6), while a relative increase in upstream water use is seen.

In a situation with unchanged spatial interventions in the study area (scenarios 1 and 2), strategic reservoir operation is a powerful tool for water allocation. Under current meteorological conditions much water appears to be lost to evaporation in the case of scenario 2, while high reservoir yield in scenario 1 leads to relatively high water availability for the downstream valley. An additional advantage for users in the downstream valley in scenario 1 is the timing of water supply: most of the water is released during the dry season. In scenario 2 excess water is generally released during the wet season. Influenced by changing conditions for the period 2031-2050, relative advantages for water users in the study area become apparent. In effect a large externality is produced for the users in the downstream valley.

In a situation with increased investments in storage and irrigation infrastructure in the study area (scenario 3), water use in the area increases compared to scenarios 1 and 2. The local expansion in water use produces an additional decrease in water availability in the downstream valley. Interestingly, for the period 2031-2050 total water use for scenario 3 is higher than total water use for scenario 2.

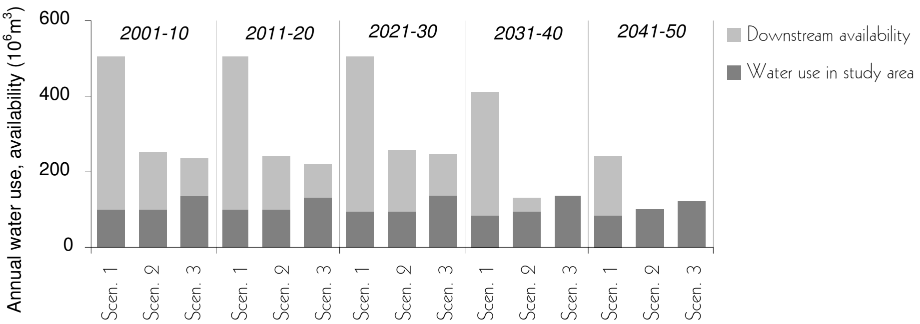

Figure 6.6 *Developments in annual water use within the study area and water available to water users in the downstream valley.*

6.5 Discussion

Modelling choices with respect to threshold values for reservoir operation, farmer decision making and the size of the infrastructural investments for scenario 3 certainly influence simulation outcomes. However, the simulated developments for the three different scenarios are not very sensitive to these choices in a qualitative sense, although the extent and timing of certain impacts obviously are.

The climatic input data that have been used have also influenced the simulation outcomes. For this study a climate scenario with a large reduction in rainfall and consequent runoff values was used. The goal of the study is to explore the impact of reducing rainfall and runoff in a realistic way, not to accurately predict future circumstances.

Empirical survey data on water user responses to variations in water availability have been used in the model. It was assumed that water users would respond in a similar way to structural decreases of rainfall and runoff as they do to the current rainfall and runoff regime.

Although the scenarios cover a period of 50 years, no developments other than climatic changes were taken into account. Important factors that potentially influence water use and water availability are demographic developments, market variations, institutional changes, governmental interventions and technological developments affecting for example pumping capacity and irrigation efficiency.

6.6 Conclusions

This study shows that a decrease in rainfall and runoff in the Jaguaribe basin leads to a transition of water use from the dry to the wet season. As a result water scarcity in the dry season increases. Because of lower rainfall and runoff values annual water use within the Orós reservoir area remains stable or decreases slightly towards 2050, depending on the reservoir operation strategy applied. For all three scenarios wet season water use within the study area shows an absolute as well as a relative increase. Water use in the dry season decreases as a result of reduced rainfall and runoff. It declines even further because of a decrease in water availability during the dry season through increased water use in the wet season.

For all scenarios, a decrease in rainfall and runoff in the Jaguaribe basin leads to a relative transition of water use from downstream to upstream on the basin scale.

This study shows that by applying alternative reservoir operation strategies and by building additional reservoir capacity water managers are able to offset the effect of lower rainfall and runoff values with regard to water use on the sub-basin level, at the cost of decreasing water availability on the basin scale. Within the study area (sub-basin scale) a relative transition of water use from downstream to upstream has only been observed for a scenario in which the reservoir operation strategy aims at producing high and stable water supply for the valley downstream of the study area (scenario 1). When the reservoir operation strategy aims to serve sub-basin interests, a situation without such a transition (scenario 2) or with the opposite transition (scenario 3) can be achieved at the sub-basin level.

7 Discussion and conclusions

7.1 Reflection on research approach

The results presented are based on a single case study: the Jaguaribe basin in the semi-arid northeast of Brazil. The results are believed to be relevant to other basins and sub-basins as well. Knowledge from the field of common-pool resources may assist in identifying water scarcity and water distribution problems in many basins other than the Jaguaribe basin. Lessons learnt from modelling interactions between water users and water resources in the Jaguaribe basin can help in analysing and modelling human-environment interactions for other basins too. More specifically, the applicability of remotely-sensed data and survey data in developing a spatially-explicit multi-agent simulation approach for the Jaguaribe basin suggests that this may be a useful approach for water scarcity studies in semi-arid basins in general. However, the kinds of feedback processes and their impact on water-scarcity patterns may vary considerably in other basins.

Data availability is critical for the extent to which relevant processes can be observed and model representations can be validated. To represent the relationships between water use and water availability in a model, data coverage should include significant variations in water availability and use and should therefore involve a multi-annual time series for both water use and water availability. To represent the relationships in a spatially-explicit model, the spatial resolution of data should be high enough to cover the diversity of the landscape as far as it is relevant to water use and water availability. To represent water users and their heterogeneity, a set of survey respondents should represent users from the various parts of the relevant area that are considered substantially different with respect to applied water use practices and the water availability situation. Data availability for the Jaguaribe and in particular the sub-basin studied is considered to be sufficient. The most important data that have been used are: a time series of remotely-sensed data on land use for the period in question (i.e. annual land use classifications for the period 2000-2005) and survey data on individual water users at relevant geographical locations (Taddei et al., 2008). For sub-basins within the Jaguaribe basin, other than the one that corresponds to the study area represented in the ABSTRACT model, the level of detail in the data that is needed to depict environmental characteristics and validate process representations were not sufficiently available. Specifically, useful time series of remotely-sensed data for relevant periods (e.g. with respect to the cropping calendar) are not available for many parts of the basin. Data on storage in small reservoirs and aquifers was not available for the study area, which limited the scale of analysis and accuracy of water balance representations and possibilities for calibration and validation at resolutions that are considered relevant to local dynamics.

In Chapter 6 the ABSTRACT model, which was validated with data from a recent period (Chapter 5), is used to explore the influence of decreasing rainfall. A development towards diminishing rainfall in the coming decades is a plausible projection for the northeast of Brazil (Kundzewicz et al., 2007). The assumption that water users and reservoir operators will respond in the same way to variations in rainfall if there is a structural decrease in water availability is perhaps less realistic. Irrigation farmers may use the same or similar heuristics in their decision making, as heuristics relate to the availability of water as the main resource restricting agricultural production. It would however be less plausible that farming plots would still be in use for production where water availability is only randomly sufficient.

Both in the standard approach of Chapter 4 and for the ABSTRACT model (with dynamic agents' response to the environment as applied in Chapters 5 and 6) it has been assumed that current response patterns of water users persist, even when water availability varies beyond observed values or when it changes dramatically. Reservoir operation will most probably be influenced by anticipatory or adaptive management and by legal, institutional and economical developments.

7.2 Relevance to river basin management research

With regard to river basin management in the semi-arid tropics where rainfall variability is generally significant, the results of this research can assist in designing tools to study and support decision making processes in water allocation. River basin management in semi-arid environments can benefit from the application of methods that explicitly address the role of water users in changes and variations in water availability and its distribution over space and time. The relevance of the role that water users play expands with reducing rainfall and with increasing consumptive water use. The benefit of applying such methods therefore grows.

River basins are generally seen as natural units for integrated water resources management, although they could just as easily be regarded as political units (Warner et al., 2008). River basins appear to be logical natural units from a supra-local perspective. However, at any geographical location within a basin one is actually at the most downstream point of its upstream catchment. Taking this observation into account, it could therefore be argued that there are an infinite number of natural units for water resources management: the (sub-)basin scale. If water resources are managed by local authorities or user communities there is not always a 'natural' need to co-operate with a downstream party. The concept of downstreamness that has been developed in this thesis can assist in analysing sub-basin points of view from a basin perspective. This perspective, which takes into account local points of view, adds to the six perspectives as distinguished by Mostert

(1999). It assists in understanding conflicts between rationalities at basin and sub-basin levels, which in a way relates to studies on common-pool resources.

Regarding the increasing amount of research devoted to basin closure (Falkenmark and Molden, 2008; Molden, 2007; Molle, 2004; 2008; Seckler, 1996; Smakhtin, 2008; Svendsen et al., 2001), the concept of downstreamness that has been developed in this thesis can be beneficial in the analysis of the distribution of water resources and water use over space and time, or the ‘waterscape’ as it is called by Venot et al. (2007). The extent to which a basin is closed, what drives closure, seasonal variations and the contribution of sub-basins to closure could be assessed more systematically if the concept of downstreamness is used.

Similar to the results of this study, Molle (2004) observed a trend of decline in dry season water availability as a result of basin closure in the Chao Phraya basin in Thailand. Molle argues that water supply and demand are not independent variables and that their relationship is often poorly understood. The findings that have been presented in this thesis show that it is possible to represent these dependent variables in a spatially-explicit model. The model may assist in making the mutual relationship between water supply and water demand more apparent.

A study on the closure of the Krishna basin (Venot et al., 2007) notes that downstream water availability depends largely on individual actions by upstream water users. The downstream part of the basin is affected by decreasing inflow from upstream and faces severe water shortages and a spatial redistribution of water during times of drought. Venot et al. (2007) reason that recent changes in the spatial redistribution of water in the lower Krishna basin are influenced by water allocation decisions and uncontrolled groundwater exploitation in both downstream and upstream areas. They argue that as a basin closes, water users, sectors and regions become increasingly interdependent. The results of the analysis of the Jaguaribe basin also suggest this. Both decreasing rainfall and expanding reservoir capacity increase the relative influence of upstream appropriation on downstream water availability. In the current situation in the Jaguaribe basin this effect is most clearly observed during dry periods (multiple years of below average rainfall), as has been demonstrated in Chapter 3.

There is growing consensus in the social sciences that there is neither an optimal scale of nor an optimal level for water management (Van der Zaag and Gupta, 2008). The suitability and acceptability of water management on a certain scale partly depends on the perspective that is chosen and partly on the political culture of a particular country or region (Molle, 2006). With regard to an appropriate spatial scale for building water storage infrastructure, Van der Zaag and Gupta (2008) discuss two distinct options: centralised storage and decentralised storage. Decentralised storage implies many small local-scale storage structures. After highlighting several possible advantages and disadvantages of both options, they stress that there is an urgent need for research into the cumulative effect of decentralised storage, in terms of both hydrology and governance. The ABSTRACT model may assist in meeting this need. In general, centralised storage may be a good measure to distribute water resources more evenly over time rather than over space, while decentralised storage could be a good measure for the distribution of water resources over space rather than over time. As has been pointed out in Chapter 3, manageability of water resources can differ considerably between upstream and downstream parts of a basin. Depending on case-specific circumstances in a basin, a balanced mix of centralised and diffused storage infrastructure may be appropriate. Case-specific conditions (e.g. the capacity and spatial distribution of storage infrastructure that is already in place and topographical elevation as shown in Chapter 3) limit possibilities for building new infrastructure from a construction engineering perspective. In cases like the Jaguaribe basin, where infrastructure is already in place (as is the case in almost all basins confronted with water stress, e.g. closed basins), one has to take into account water use patterns that have adjusted to the existing infrastructure. Dramatic changes in infrastructure can disrupt the balance between existing water supply and demand patterns. For the above reasons, it is difficult to draw generic conclusions on the appropriate spatial scale for decision making on water allocation and the scale of spatial planning with regard to infrastructure for storage and irrigation in a semi-arid basin.

This thesis has focused on supply-side management alternatives (i.e. reservoir operation strategies and investments in infrastructure for storage and irrigation), rather than on demand-side management alternatives. Such demand-side alternatives include promoting water-efficient crop varieties and irrigation techniques. Venot et al. (2007) argue that increasing irrigation efficiency might lead to a spatial and temporal redistribution of water resources that benefits upstream rather than downstream users. The ABSTRACT model could be used to explore the effect of measures aimed at increasing irrigation efficiency in specific cases.

7.3 Relevance to common-pool resources research

This thesis adds an application to a river basin as a whole to the common-pool resources (CPR) literature. Thus, CPR studies on water resources have been largely limited to local water resources such as irrigation schemes. The findings of this thesis can be used to interpret findings of local CPR studies on irrigation schemes in the context of a supra-local river basin. For a large semi-arid river basin resource system, concepts for assessing the manageability of local-scale common-pool resources (local water resources) can be linked systematically to topographical elevation. The concept of *downstreamness* is useful in explaining how physical conditions for good manageability of water resources improve or worsen from up- to downstream.

The sequence of rainfall events over time and the spatial distribution of reservoir capacity in a river basin influence the extent to which the merging of rivers and streams towards downstream can compensate for externalities due to upstream water abstractions.

This principle is an addition for the river basin scale to the concept of head-end/tail-end problems encountered in local irrigation schemes (Bardhan and Dayton-Johnson, 2002).

In Chapter 6 a scenario was formulated in which extra storage capacity was introduced in an upstream sub-basin. This additional storage capacity makes resource availability more stable. It also creates a 'first-in-line' advantage for users located relatively upstream within the study area. A possible consequence is an increase in average water demand in the area, which could eventually lead to overexploitation of locally-stored water, as suggested by simulation outcomes in Chapter 6. In this way the upstream advantage can be reduced by overexploitation, while still producing externalities for downstream water users. The case of the Jaguaribe shows that reservoir operation that only takes into account local upstream interests can undermine basin-level interests (in addition to undermining downstream interests). Among possible other reasons, this is, at least from a river basin perspective, a plea for multi-scale/multi-level management of water allocation, as is also argued in studies on co-management (De Groot and Lenders, 2006; Wallace et al., 2003).

The focus of this thesis is on the physical characteristics of and conditions in river basins. A choice was made not to engage in studying organisational, social, economic and institutional characteristics of river basin management. This means that no conclusions with respect to the legislation, rights, customs, formal and informal actions and interactions of farmers and organisations were drawn. The concept of downstreamness, introduced in this thesis, may however be useful to analyse governance by local authorities and to structure studies that compare multiple cases. One could think of an analysis of water allocation by sub-basin committees in different parts of basins, such as the ones that are active in the Jaguaribe basin (COGERH, 1994; 1995; 1998; 1999; 2000; 2001b; 2002; 2003c; Lemos, 2003; Lemos and De Oliveira, 2004).

7.4 Relevance to human-environment interaction research using MAS

It has been shown in this thesis that applying a multi-agent simulation (MAS) approach is useful in representing the mutual relationship between water availability and water use. A MAS approach can be used to depict the emergence of basin closure. The dynamics of water use, water availability and their distribution over space and time can be validly modelled by implementing a spatially-explicit multi-agent simulation approach.

Further, it was shown that remotely-sensed data are a valuable source of information and analysing a time series of such data can assist in selecting geographical locations for which deeper analysis of the relevant processes is needed. Such analysis may include surveys or interviews with local resource users. Land use classifications that are based on remotely-sensed data offer opportunities to validate simulation outcomes for land use, which is the main determinant of water abstraction for irrigation in the modelling approach that has been described in this thesis.

The MAS model that is presented here is spatially-explicit, it does not include direct social interactions and the intrinsic adaptation of agents involves multiple strategies, building on empirical data. Following a taxonomy for agent-based simulation models proposed by Hare and Deadman (2004), the ABSTRACT model should therefore conceptually be grouped with the CatchScape model (Becu et al., 2003) and the LUCITA model (Deadman et al., 2004), although its scientific objectives are rather different.

Castella and Verburg (2007) have compared and combined a pattern-oriented modelling approach and a process-oriented multi-agent modelling approach for land use change in a case study area in Vietnam. They conclude that the choice of model has important implications in terms of the specific aspects of land use changes that can be investigated and that they are complementary. They stress that a process-oriented modelling approach is better equipped to implement scenarios which include processes of change. In general, a pattern-oriented modelling approach is suitable for assessing how increases or decreases in the strength of driving forces translate into changed patterns of land use. Variations and changes in water use patterns and the emergence and consequences of basin closure are caused by processes that have been identified in this thesis. The representation of these processes in a model is preferred over a pattern-oriented approach, as they are not necessarily predicted well by pattern-oriented modelling alone. In this thesis a process- and a pattern-oriented modelling approach are combined, in order to properly simulate the consequences of decreasing rainfall and reservoir operation on water-scarcity distribution. The agent-based ABSTRACT model that was developed in Chapter 5 and applied in Chapter 6, shows some advantages over the simpler approach that was used to analyse the influence of upstream water use on reservoir yield (Chapter 4). In the ABSTRACT model patterns and processes of local changes in water use are both included, mainly building on information that was obtained from a survey. Besides spatially-explicit specifications for soil and meteorological parameters, a mass conservation water balance for alluvial aquifers is included in the ABSTRACT model, which enables the simulation of inter-annual effects of water abstractions from alluvial aquifers on downstream water availability. With the ABSTRACT model it is possible to analyse the influence of water use at one time and location within the study area on water availability at other times and locations within the area. It is thus better equipped to explore possible changes in water-scarcity patterns through changes in rainfall patterns and reservoir operation than a standard (pattern-oriented) approach.

In the ABSTRACT model agents anticipate and respond to local water availability, based on information that they obtain from their direct environment. The activities they undertake (cultivation of a certain crop on a chosen area of land) correspond to farmer behaviour at specific locations that depend on distinct but connected local water resources. The knowledge of agent behaviour was obtained from interviews with water users and survey data (Taddei et al., 2008). In a model of the Amudarya delta in central Asia (Schlüter and Pahl-Wostl, 2007) farmer-agent decision rules are also based on empirical knowledge from the field and on assumptions on bounded rationality. Agent decision rules in the model of the Amudarya delta involve the agents' past experience, knowledge of resources dynamics, expected water availability and the expected behaviour of other agents. Farmer-agents use a form of trial and error to determine their 'satisficing' harvest. In the ABSTRACT model farmer decision rules may be less complicated and perhaps less process-oriented than in the model for the Amudarya delta simulation outcomes do reasonably resemble observed patterns of water use (Chapter 5).

The system representation that is designed for the ABSTRACT model is different from the approach that has been applied by Schlüter and Pahl-Wostl (2007). In their model of water use and management in the semi-arid Amudarya basin in central Asia they portray a delta that feeds from a single source (the Tyoyamuyun reservoir), rather than a river basin with multiple reservoirs. The Amudarya study involves a large irrigation scheme, not a river basin. The Amudarya delta is modelled as a one-dimensional sequence of water users, whereas the ABSTRACT model allows for the modelling of a network of river branches and storage reservoirs from which water users can obtain water simultaneously, on the local scale. In the ABSTRACT model some water users can abstract water from alluvial aquifers and surface water reservoirs directly, so they do not depend on reservoir operation as much as users in the Amudarya delta model. In this way spatiotemporal patterns of water scarcity in a basin can be represented, rather than the one-dimensional patterns of water scarcity that emerge in the model of the Amudarya delta.

The results of this thesis support the view of Berger et al. (2007) that MAS is a promising approach to supporting water resource management and can assist in increasing the understanding of water use and water users within sub-basins. In the modelling approach of Berger et al. (2007), communication among agents plays an important role. Through communication important information can be exchanged, for instance technological innovations with regard to water-saving techniques. Such communication was not perceived to be important for the applications that are described in this thesis. However, the inclusion of model components that allow for communication between agents is believed to be valuable for further research, though its implementation for the Jaguaribe basin may require great efforts to collect data on social network structures.

Although reservoir operation strategies have been implemented in the ABSTRACT model (Chapter 6), the operating rules are purely reactive to changes in the environment (i.e. reservoir volume). In practice, reservoir operation in the Jaguaribe basin depends on decisions made by a combination of local and supra-local authorities and local users or user representatives. Although it may be possible to represent decision making at this higher level of organisation (e.g. similar to the way it was done by Schlüter and Pahl-Wostl (2007)), it is believed that models like the ABSTRACT model may be beneficial in supporting such decision making processes, rather than in representing them. Promising examples of using multi-agent simulation for decision support on a local scale have been provided by researchers who apply the so-called 'companion modelling approach' (Barreteau, 2003; Bousquet et al., 2007).

7.5 Conclusions

River basin management research on semi-arid environments can benefit from applying elements from common-pool resources literature to analyse the manageability of water resources and from applying a spatially-explicit multi-agent simulation approach to model interactions between water users and water resources.

Physical determinants for the spatial and temporal distribution of water resources and water use in a semi-arid river basin are: topographical elevation, rainfall intensity and variability (specifically over time), and water storage capacity with its spatial distribution over a basin. For a large semi-arid river basin resource system concepts for the assessment of manageability of water resources on a local scale can be linked systematically to topographical elevation. To characterise locality with respect to the topography of a basin, the concept of *downstreamness* has been introduced. This concept is useful in explaining how physical conditions for good manageability improve or worsen from up- to downstream. For the Jaguaribe basin it was found that, in general, the more a local water resource is located towards downstream, the more it should be associated with a large spatial extent, ill-defined boundaries, good possibilities of storage, high predictability of resource availability and low levels of resource mobility. The first two relate to weak manageability, the last three to good manageability. Within the Jaguaribe basin no specific location can be pointed at for which manageability is good in all respects. However, manageability may be best in the midstream zone, where a balance exists between upstream and downstream advantages.

A representation of processes that are responsible for observed variations in the distribution of water use and water availability can be made for the Jaguaribe basin by applying a spatially-explicit multi-agent simulation model approach that is implemented by using survey data on water user decision making. The model could serve as a learning tool for authorities and resource users and facilitate improved decision making on water allocation. The added value of the MAS approach that has been presented in this thesis, as compared to standard approaches (e.g. pattern-oriented, stochastic approaches), is that it allows for the evaluation of the spatiotemporal effects of the interactions between individual water users and water resources on water-scarcity patterns on different spatial and temporal scales.

For the Jaguaribe basin wet season water use grows with decreasing water availability, whereas dry season water use declines with decreasing water availability. This implies that for years with below-average rainfall the increased water use during the wet season may amplify water stress in the following dry season. Improvements in the understanding of the relationship between water use and water availability in a semi-arid river basin have been achieved by taking into account water user responses to variations in water availability. The interactions between water users and water resources are specifically important for understanding the distribution of water resources over space and time.

Decreases in rainfall and runoff influence the temporal and spatial distribution of water availability and water use. More in particular, decreasing rainfall typically leads to transitions in water use from water-scarce periods to less water-scarce periods and from downstream areas to upstream areas. To offset the effects of decreasing rainfall and runoff, water managers can apply reservoir operation strategies to manipulate temporal and spatial distribution of water resources in sub-basins. However, this can only be achieved at the cost of a decline in water availability in parts of the basin that are located further downstream.

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References

ADGER, W.N. 2006. Vulnerability. *Global Environmental Change,* 16(3): 268.

ADGER, W.N., ARNELL, N.W. and TOMPKINS, E.L. 2005. Successful adaptation to climate change across scales. *Global Environmental Change-Human and Policy Dimensions,* 15(2): 77-86.

AGRAWAL, A. 2002. Common resources and institutional sustainability. In: E. Ostrom, T. Dietz, N. Dolsak, P.C. Stern, S. Stovich and E.U. Weber (Editors), *The drama of the commons.* National Academy Press, Washington DC, USA, pp 41-85.

ALCAMO, J. and HENRICHS, T. 2002. Critical regions: A model-based estimation of world water resources sensitive to global changes. *Aquatic Sciences,* 64(4): 352-362.

ALLAN, J.A. 1998. Virtual water: a strategic resource, global solutions to regional deficits. *Ground Water,* 36(4).

ANA. 2006. *HidroWeb.* Agência Nacional de Águas, Brasilia, Brazil

ARNELL, N.W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions,* 14(1): 31-52.

BALAND, J.M. and PLATTEAU, J.P. 1999. The ambiguous impact of inequality on local resource management. *World Development,* 27(5): 773-788.

BARDHAN, P. and DAYTON-JOHNSON, J. 2002. Unequal irrigators: heterogeneity and commons management in large-scale multivariate research. In: E. Ostrom, T. Dietz, N. Dolšak, P.C. Stern, S. Stonich and E.U. Weber (Editors), *The drama of the commons.* National Academy Press, Washington, DC.

BARRETEAU, O. 2003. Our companion modelling approach. *JASSS-The Journal of Artificial Societies and Social Simulation,* 6(2).

BARRETEAU, O. and BOUSQUET, F. 2000. SHADOC: a multi-agent model to tackle viability of irrigated systems. *Annals of Operations Research,* 94: 139-167.

BARRETEAU, O., BOUSQUET, F., MILLIER, C. and WEBER, J. 2004. Suitability of multi-agent simulations to study irrigated system viability: application to case studies in the Senegal river valley. *Agricultural Systems,* 80(3): 255-275.

BARRETEAU, O., GARIN, P., DUMONTIER, A., ABRAMI, G. and CERNESSON, F. 2003. Agent-based facilitation of water allocation: case study in the Drome river valley. *Group Decision and Negotiation,* 12(5): 441-461.

BECU, N., PEREZ, P., WALKER, A., BARRETEAU, O. and PAGE, C.L. 2003. Agent based simulation of a small catchment water management in northern Thailand: description of the CATCHSCAPE model. *Ecological Modelling,* 170(2-3): 319-331.

BERGER, T. 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics,* 25(2-3): 245-260.

BERGER, T., BIRNER, R., DIAZ, J., MCCARTHY, N. and WITTMER, H. 2007. Capturing the complexity of water uses and water users within a multi-agent framework. *Water Resources Management,* 21(1): 129-148.

BERKES, F., FEENY, D., MCCAY, B.J. and ACHESON, J.M. 1989. The benefits of the commons. *Nature,* 340(6229): 91-93.

BERKES, F., GEORGE, P. and PRESTON, R. 1991. Co-management: the evolution of the theory and practice of joint administration of living resources. *Alternatives,* 18 (2): 12-18.

BITHELL, M. and BRASINGTON, J. 2009. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environmental Modelling & Software,* 24(2): 173-190.

BLOMQUIST, W., SCHLAGER, E., TANG, S.Y. and OSTROM, E. 1994. Regularities from the field and possible explanations. In: E. Ostrom, R. Gardner and A. Walker (Editors), *Rules, games & common-pool resources.* The University of Michigan Press, Ann Arbor, USA, pp 301-316.

BOUSQUET, F., BAKAM, I., PROTON, H. and LE PAGE, C. 1998. Cormas: common-pool resources and multi-agent systems, *Tasks and methods in applied artificial intelligence.* Springer, Berlin / Heidelberg, pp 826-837.

BOUSQUET, F., CASTELLA, J.C., TREBUIL, G., BARNAUD, C., BOISSAU, S. and KAM, S.P. 2007. Using multi-agent systems in a companion modelling approach for agro-ecosystem management in southeast Asia. *Outlook on Agriculture,* 36(1): 57-62.

BOUSQUET, F. and LE PAGE, C. 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling,* 176(3-4): 313.

BROAD, K., PFAFF, A., TADDEI, R., SANKARASUBRAMANIAN, A., LALL, U. and DE SOUZA, F.D. 2007. Climate, stream flow prediction and water management in Northeast Brazil: societal trends and forecast value. *Climatic Change,* 84(2): 217-239.

BROWN, C. and LALL, U. 2006. Water and economic development: The role of variability and a framework for resilience. *Natural Resources Forum,* 30(4): 306-317.

BURTE, J., COUDRAIN, A., FRISCHKORN, H., CHAFFAUT, I. and KOSUTH, P. 2005. Human impacts on components of hydrological balance in an alluvial aquifer in the semiarid Northeast, Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 50(1): 95-110.

CAMPOS, J.N.B. 1996. *Dimensionamento de Reservatórios.* UFC – Federal University of Ceará, Fortaleza, Brazil.

CAMPOS, J.N.B. and STUDART, T.M.C. 2000. An historical perspective on the administration of water in Brazil. *Water International,* 25(1): 148-156.

CAMPOS, J.N.B., STUDART, T.M.C. and CHAGAS, P.F. 2003. Reservoir yield vulnerability under global change. In: T. Gaiser, M. Krol, H. Frischkorn and J.C. De Araujo (Editors), *Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semi-arid Northeast of Brazil.* Springer, Berlin, pp 229-238.

CARIANI, P. 1992. Emergence and artificial life. In: C.G. Langton, C. Taylor, J.D. Farmer and S. Rasmussen (Editors), *Artificial Life II.* Santa Fe Institute Studies in the Sciences of Complexity Series. Addison Wesley Longman, Redwood City, USA.

CARLSSON, L. and BERKES, F. 2005. Co-management: concepts and methodological implications. *Journal of Environmental Management,* 75(1): 65.

COGERH. 1994. *I seminario dos usuarios das agua dos vales do Jaguaribe e Banabuiu.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 1995. *II seminário dos usuarios das agua dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 1998. *Relatório do V seminário de operação dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 1999. *Relatório do VI seminário de operação dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 2000. *Relatório do VII seminário de operação dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 2001a. *Plano de use racional de água para irrigação nos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Fortaleza, Brazil

COGERH. 2001b. *Relatório do VIII seminário de operação dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 2002. *IX seminário de planejamento e operação das águas dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 2003a. *Anuário do monitoramento quantitativo dos principais açudes do estado do Ceará - 2003.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Fortaleza, Brazil

COGERH. 2003b. *Relatório do plano de uso racional das águas para irrigação nos vales dos rios Jaguaribe e Banabuiú Convêncio N^0 002/2001 - SRH / COGERH.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Fortaleza, Brazil

COGERH. 2003c. *X seminário de planejamento e operação das águas dos vales do Jaguaribe e Banabuiú.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Brazil

COGERH. 2006. *Monitored reservoir releases database.* Companha de Gestão dos Recursos Hídricos (COGERH), Governo do estado do Ceará, Fortaleza, Brazil

CONWAY, G.R. 1987. The properties of agroecosystems. *Agricultural Systems,* 24(2): 95-117.

DE ARAÚJO, J.C., GUNTNER, A. and BRONSTERT, A. 2006. Loss of reservoir volume by sediment deposition and its impact on water availability in semiarid Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 51(1): 157-170.

DE GROOT, W.T. and LENDERS, H.J.R. 2006. Emergent principles for river management. *Hydrobiologia,* 565: 309-316.

DEADMAN, P., ROBINSON, D., MORAN, E. and BRONDIZIO, E. 2004. Colonist household decisionmaking and land-use change in the Amazon rainforest: an agent-based simulation. *Environment And Planning B-Planning & Design,* 31(5): 693-709.

DEADMAN, P.J. and SCHLAGER, E. 2002. Models of individual decision making in agent-based simulation of common-pool resource management institutions. In: H.R. Gimblet (Editor), *Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes.* Oxford University Press, Santa Fe, USA, pp 137-169.

DÖLL, P. and KROL, M.S. 2002. Integrated scenarios of regional development in two semi-arid states of north-eastern Brazil. *Integrated Assessment,* 3(4): 308-320.

DÖLL, P., KROL, M.S., FUHR, D., GAISER, T., HERFORT, J., HÖYNCK, S., JAEGER, A., KÜLLS, K., MENDIONDO, M., PRINTZ, A. and VOERKELIUS, S. 2003. Integrated scenarios of regional development in Ceará and Piauí. In: T. Gaiser, M.S. Krol, H. Frischkorn and J.C. De Araújo (Editors), *Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semiarid northeast of Brazil.* Springer, Berlin, Germany.

EHEART, J.W. and TORNIL, D.W. 1999. Low-flow frequency exacerbation by irrigation withdrawals in the agricultural midwest under various climate change scenarios. *Water Resources Research,* 35(7): 2237-2246.

EMBRAPA. 2006. *Brasil em Relevo.* EMBRAPA - Brazilian Agricultural Research Corporation, Brazil

EPSTEIN, J.M. and AXTELL, R.L. 1996. *Growing artificial societies: social science from the bottom up.* Brookings Institution, Washington D.C., USA.

FALKENMARK, M. and MOLDEN, D. 2008. Wake up to realities of river basin closure. *International Journal of Water Resources Development,* 24(2): 201-215.

FAO. 1998. *CropWat 4 Windows Version 4.3.* In: M. Smith (Editor). Food and Agriculture Organization (FAO), Rome, Italy.

FEENY, D., BERKES, F., MCCAY, B.J. and ACHESON, J.M. 1990. The tragedy of the commons - 22 years later. *Human Ecology,* 18(1): 1-19.

FUNCEME. 2008. *Arquivos com dados pluviométricos.* FUNCEME - Fundação Cearense de Meteorologia e Recursos Hídricos, Fortaleza, Brazil

GAISER, T., KROL, M., FRISCHKORN, H. and ARAÚJO, J.C. (Editors). 2003. *Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semi-arid northeast of Brazil.* Springer, Berlin, Germany.

GIBSON, C.C., OSTROM, E. and AHN, T.K. 2000. The concept of scale and the human dimensions of global change: a survey. *Ecological Economics,* 32(2): 217.

GIMBLET, H.R. 2002. *Integrating geographical information systems and agent-based modelling techniques for simulating social and ecological processes.* Santa Fe Institute studies in the sciences of complexity. Oxford University Press, Santa Fe, USA.

GINI, C. 1912. Variabilità e mutabilità. *Reprinted in Memorie di metodologica statistica (Ed. Pizetti E, Salvemini, T). Rome, Libreria Eredi Virgilio Veschi, 1955.*

GLOBAL WATER PARTNERSHIP. 2000. Integrated water resources management, Global Water Partnership Technical Advisory Committee.

GUERRA, P. and GUERRA, T. 1980. *Seccas contra as seccas.* Collection Mossoroense, 29, Mossoro, Brazil.

GUNDERSON, L.H. and HOLLING, C.S. 2002. *Panarchy: understanding transformations in human and natural systems.* Island Press, Washington D.C., USA.

GÜNTNER, A. 2002. *Large-scale hydrological modelling in the semi-arid northeast of Brazil*, University of Potsdam, Germany, Potsdam.

HARDIN, G. 1968. The tragedy of the commons. *Science,* 162: 1243-1248.

HARE, M. and DEADMAN, P. 2004. Further towards a taxonomy of agent-based simulation models in environmental management. *Mathematics and Computers in Simulation,* 64(1): 25-40.

HARE, M., DEADMAN, P. and LIM, K. 2001. *Towards a taxonomy of agent-based simulation models.* In: F. Ghassemi (Editor), MODSIM 10-13 December. Integrating models for natural resources management across disciplines, issues and scales, Canberra, Australia.

HOEKSTRA, A.Y. and CHAPAGAIN, A.K. 2008. *Globalization of water, sharing the planet's freshwater resources.* Blackwell Publishing, Malden, USA.

HOLLING, C.S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems,* 4(5): 390.

IASC. 2008. *Digital library of the commons.* International Association for the Study of the Commons (IASC), http://dlc.dlib.indiana.edu

IBGE. 2006. SIDRA - Produção Agrícola Municipal, Instituto Brasileiro de Geografia e Estatistica, Brasilia, Brazil.

ICWE. 1992. *The Dublin statement and report of the conference*, International conference on water and the environment, Dublin, Ireland.

JOHNSSON, R.M.F. and KEMPER, K.E. 2005. Institutional and policy analysis of river basin management, World Bank, Washington D.C., USA.

JONES, E.C. 2004. Wealth-based trust and the development of collective action. *World Development,* 32(4): 691.

KEMPER, K.E. 1996. *The cost of free water, water resources allocation and use in the Curu valley, Ceará, Brazil*, Linköping University, Linköping, Sweden.

KEMPER, K.E., BLOMQUIST, W. and DINAR, A. 2007. *Integrated riverbasin management through decentralization.* World Bank, Washigton D.C., USA.

KROL, M.S., JAEGER, A. and BRONSTERT, A. 2003. Integrated modeling of climate change impacts in northeastern Brazil. In: T. Gaiser, M.S. Krol, H. Frischkorn and J.C. De Araujo (Editors), *Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semiarid northeast of Brazil.* Springer, Berlin, Germany.

KROL, M.S. and VAN OEL, P.R. 2004. *Integrated assessment of water stress in Ceará, Brazil, under climate change forcing.* In: C. Pahl, S. Schmidt and T. Jakeman (Editors), International Congress: Complexity and Integrated Resources Management, Osnabrück, Germany.

KUNDZEWICZ, Z.W., MATA, L.J., ARNELL, N.W., DOLL, P., JIMENEZ, B., MILLER, K., OKI, T., SEN, Z. and SHIKLOMANOV, I. 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 53(1): 3-10.

KUNDZEWICZ, Z.W., MATA, L.J., ARNELL, N.W., DÖLL, P., KABAT, P., JIMÉNEZ, B., MILLER, K.A., OKI, T., SEN, Z. and SHIKLOMANOV, I.A. 2007. Freshwater resources and their management. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. Van der Linden and C.E. Hanson (Editors), *Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK, pp 173-210.

L'VOVICH, M.I., WHITE, G.F., BELYAEV, A.V., KINDLER, J., KORONKEVIC, N.I., LEE, T.R. and VOROPAEV, G.V. 1990. Use and Transformation of Terrestrial Water Systems. In: B.L. Turner II, W.C. Clarck, R.W. Kates, J.F. Richards, J.T. Mathews and W.B. Meyer (Editors), *The earth as transformed by human action: global and regional changes in the biosphere over the past 300 years.* Cambridge University Press, Cambridge, UK.

LAM, W.F. 1998. *Governing irrigation systems in Nepal: institutions, Infrastructure, and collective action.* ICS Press, San Francisco, USA.

LEGESSE, D., VALLET-COULOMB, C. and GASSE, F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology,* 275(1-2): 67.

LEMOS, M.C. 2003. A tale of two policies: the politics of climate forecasting and drought relief in Ceará, Brazil. *Policy Sciences,* 36(2): 101-123.

LEMOS, M.C. and DE OLIVEIRA, J.L.F. 2004. Can water reform survive politics? Institutional change and river basin management in Ceará, Northeast Brazil. *World Development,* 32(12): 2121-2137.

LESKENS, J.G. 2006. *Spatial dynamics in allocation of scarce water.* Master Thesis, University of Twente, Enschede, The Netherlands.

LOUCKS, D.P. and VAN BEEK, E. 2005. *Water resources systems planning and management: an introduction to methods, models and applications.* Unesco, Paris, France.

MATTHEWS, R.B., GILBERT, N.G., ROACH, A., POLHILL, J.G. and GOTTS, N.M. 2007. Agent-based land-use models: a review of applications. *Landscape Ecology,* 22(10): 1447-1459.

MCMAHON, T.A. and MEIN, R.G. 1986. *River and reservoir yield.* Water Resources Publications, Littleton, Colorado, USA.

MILLENNIUM ECOSYSTEM ASSESSMENT. 2005. *Ecosystems and Human Well-being: General Synthesis.* Island Press, Washington D.C., USA.

MMA. 1997. Law No. 9.433, Ministério do meio ambiente (MMA), Brasilia, Brazil.

MOLDEN, D. 2007. *Water for food water for life: a comphrehensive assessment of water management in agriculture.* Earthscan, London, UK.

MOLLE, F. 2004. Technical and institutional responses to basin closure in the Chao Phraya river basin, Thailand. *Water International,* 29(1): 70-80.

MOLLE, F. 2006. Planning and managing water resources at the river-basin level: Emergence and evolution of a concept. *IWMI Comprehensive Assessment Research Report,* International Water Management Institute, Colombo, Sri Lanka.

MOLLE, F. 2008. Why enough is never enough: the societal determinants of river basin closure. *International Journal Of Water Resources Development,* 24(2): 217-226.

MOLLE, F., WESTER, P., HIRSCH, P., JENSEN, J.R., MURRAY-RUST, H., PARANJPYE, V., POLLARD, S. and VAN DER ZAAG, P. 2007. River basin development and management. In: D. Molden (Editor), *Water for food, water for life: comprehensive assessment of water management in agriculture.* London: Earthscan, Colombo, Sri Lanka, pp 585-625.

MOSTERT, E. 1999. Perspectives on river basin management. *Physics And Chemistry Of The Earth Part B-Hydrology Oceans And Atmosphere,* 24(6): 563-569.

MOSTERT, E., VAN BEEK, E., BOUMAN, N.W.M., HEY, E., SAVENIJE, H.H.G. and THISSEN, W.A.H. 1999. *River basin management and planning, keynote paper for international workshop on river basin management,* The Hague, The Netherlands.

NASH, J.E. and SUTCLIFFE, J.V. 1970. River flow forecasting through conceptual models part I -- A discussion of principles. *Journal of Hydrology,* 10(3): 282.

OKI, T. and KANAE, S. 2006. Global hydrological cycles and world water resources. *Science,* 313(5790): 1068-1072.

OSTROM, E. 1990. *Governing the commons: The evolution of institutions for collective action.* Cambridge University Press, New York, USA.

OSTROM, E. 1999. *Self governance and forest resources*, Occasional Paper No. 20. Center for International Forestry Research, Bogor, Indonesia.

OSTROM, E., DIETZ, T., DOLSAK, N., STERN, P.C. and STOVICH, S. 2002. *The drama of the commons.* National Academy Press, Washington D.C., USA.

OSTROM, E., GARDNER, R. and WALKER, J.M. 1994. *Rules, games, and common-pool resources.* University of Michigan Press, Ann Arbor, USA.

PARKER, D.C., BERGER, T. and MANSON, S.M. 2002. Agent-Based Models of Land-Use/Land-Cover Change: Report and Review of an International Workshop, LUCC Focus 1, Bloomington, USA.

PARKER, D.C., MANSON, S.M., JANSSEN, M.A., HOFFMANN, M.J. and 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(2): 314-337.

PENNESI, K. 2007. Improving forecast communication - linguistic and cultural considerations. *Bulletin Of The American Meteorological Society,* 88(7): 1033-+.

PEREZ, P., ARDLIE, N., KUNEEPONG, P., DIETRICH, C. and MERRITT, W.S. 2002. CATCHCROP: modeling crop yield and water demand for integrated catchment assessment in Northern Thailand. *Environmental Modelling & Software,* 17(3): 251-259.

POSTEL, S.L. 2000. Entering an era of water scarcity: The challenges ahead. *Ecological Applications,* 10(4): 941-948.

POSTEL, S.L., DAILY, G.C. and EHRLICH, P.R. 1996. Human appropriation of renewable fresh water. *Science,* 271(5250): 785-788.

ROECKNER, E., ARPE, K., BENGTSSON, L., CHRISTOPH, M., CLAUSSEN, M., DÜMENIL, L., ESCH, M., GIORGETTA, M., SCHLEESE, U. and SCHULZWEIDA, U. 1996. The athmospheric general circulation model ECHAM-4, Max-Planck Institute for Meteorology, Hamburg, Germany.

SCHLAGER, E., BLOMQUIST, W. and TANG, S.Y. 1994. Mobile flows, storage, and self-organized institutions for governing common-pool resources. *Land Economics,* 70(3): 24.

SCHLÜTER, M. and 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(2).

SEAGRI. 2003. O agronegócio da agricultura irrigada no Ceará (1999 a 2003), Secretaria de Agricultura e Pecuaria do estado Ceará (SEAGRI), Fortaleza, Brazil.

SEAGRI. 2004. Projeto frutas do Ceará, Secretaria de Agricultura e Pecuaria do estado Ceará (SEAGRI), Fortaleza, Brazil.

SEAGRI. 2005. Fruticultura irrigada grande potencial do Ceará, Secretaria de Agricultura e Pecuaria do estado Ceará (SEAGRI), Fortaleza, Brazil.

SECKLER, D. 1996. The new era of water resources management: From "dry" to "wet" water savings. *IIMI Research Report 1*, International Irrigation Management Institute (IIMI), Colombo, Sri Lanka.

SHIKLOMANOV, I.A. and RODDA, J.C. 2003. *World water resources at the beginning of the twenty-first century.* International hydrology series. Cambridge University Press, Cambridge, UK.

SMAKHTIN, V. 2008. Basin closure and environmental flow requirements. *International Journal of Water Resources Development,* 24(2): 227-233.

SMAKHTIN, V.U. 2001. Low flow hydrology: a review. *Journal of Hydrology,* 240(3-4): 147-186.

SMITH, C.A. and SARDESHMUKH, P. 2000. The effect of ENSO on the intraseasonal variance of surface temperature in winter. *International Journal of Climatology,* 20: 1543-1557.

SOUZA FILHO, F. and PORTO, R. 2003. Gerenciamento de recursos hídricos e a variabilidade climática nos semi-áridos Brasileiros, *Anais do simpósio Brasileiro de recursos hídrico.* ABRH, Curitiba, Brazil, pp 1-16.

SVENDSEN, M., HAMMOND MURRAY-RUST, D., HARMANCIOGLU, N. and ALPASLAN, N. 2001. Governing closing basins: the case of the Gediz River in Turkey. In: C.L. Abernethy (Editor), *Intersectoral Management of River Basins.* International Water Management Institute (IWMI), Colombo, Sri Lanka, pp 183–214.

TADDEI, R., MULLER, V., PFAFF, A., BROAD, K., LALL, U. and MAGALHAES CORDEIRO, J.H. 2008. Impacts of water resource management choices in Ceará, Brazil: roles of streamflow forecasts, rainfall forecasts and participatory decision making., NOAA Office of Global Programs Grant Report., New York, USA.

TADDEI, R.R. 2005. *Of clouds and streams, prophets and profits: the political semiotics of climate and water in the Brazilian northeast*, Columbia University, New York, USA.

TANG, S.Y. 1992. *Institutions and collective action: self governance in irrigation systems.* ICS Press, San Francisco, USA.

TECLAFF, L.A. 1967. *The river basin in history and law*, The Hague, The Netherlands.

TURNER II, B.L., KASPERSON, R.E., MATSON, P.A., MCCARTHY, J.J., CORELL, R.W., CHRISTENSENE, L., ECKLEY, N., KASPERSON, J.X., LUERS, A., MARTELLO, M.L., POLSKYA, C., PULSIPHER, A. and SCHILLER, A. 2003. A framework for vulnerability analysis in sustainability science. *PNAS,* 100(14): 8074-8079.

UNITED NATIONS. 2002. Johannesburg plan of implementation of the World Summit on sustainable development, United Nations, Johannesburg, South Africa.

UVO, C.B., REPELLI, C.A., ZEBIAK, S.E. and KUSHNIR, Y. 1998. The relationships between tropical pacific and atlantic SST and Northeast Brazil monthly precipitation. *Journal of Climate,* 11: 551-562.

VAN DER ZAAG, P. and GUPTA, J. 2008. Scale issues in the governance of water storage projects. *Water Resources Research,* 44(10).

VAN OEL, P.R., KROL, M.S. and HOEKSTRA, A.Y. 2007. A river basin as a common-pool resource: a case study for the Jaguaribe basin in Brazil. *Value of water research report series*, 24, UNESCO-IHE, Delft, Netherlands.

VAN OEL, P.R., KROL, M.S. and 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(3).

VAN OEL, P.R., KROL, M.S., HOEKSTRA, A.Y. and DE ARAÚJO, J.C. 2008. The impact of upstream water abstractions on reservoir yield: the case of the Orós Reservoir in Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 53(4): 857-867.

VENOT, J.P., TURRAL, H., SAMAD, M. and MOLLE, F. 2007. *Shifting waterscapes: explaining basin closure in the lower Krishna basin, South India.* IWMI Research Report 121. International Water Management Institute, Colombo, Sri Lanka.

VERBURG, P.H. 2006. Simulating feedbacks in land use and land cover change models. *Landscape Ecology,* 21(8): 1171-1183.

VILLA, M.A. 2000. *Vida e morte no sertão.* Histório do Brasil, 74. Editora ática, São Paulo, Brazil.

VOGEL, R.M. and STEDINGER, J.R. 1987. Generalized storage reliability yield relationships. *Journal of Hydrology,* 89(3-4): 303-327.

WALLACE, J.S., ACREMAN, M.C. and 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 Of London Series B-Biological Sciences,* 358(1440): 2011-2026.

WARNER, J., WESTER, P. and BOLDING, A. 2008. Going with the flow: river basins as the natural units for water management? *Water Policy,* 10: 121-138.

WHITE, G.F. 1957. A perspective of river basin development. *Law and Contemporary Problems,* 22(2): 157.

WILK, J. and HUGHES, D.A. 2002. Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 47(1): 19-30.

WOOLDRIDGE, M.J. 2001. *Introduction to multi-agent systems.* John Wiley & Sons Limited, New York, USA.

WORLD BANK. 1993. Water resources management. *A World Bank policy paper,* World Bank, Washington, D.C., USA.

WORLD BANK. 2003. Water resources sector strategy: strategic directions for World Bank engagement Washington, D.C., USA.

WORLD BANK. 2005. Decentralization of river basin management: a global analysis. *World Bank policy research working papers*, Washington D.C., USA.

WORLD COMMISSION ON DAMS. 2000. Dams and development - a new framework for decision-making: the report of the world commission on dams.

WORLD WATER COUNCIL. 2000. A secure water world - vision for water, life and the environment, World Water Council, Marseilles, France.

WORLD WATER COUNCIL. 2006. Final report of the 4th World Water Forum, National Water Commission of Mexico, Mexico City, Mexico.

YIN, R.K. 2003. *Case study research: design and methods.* Applied social research methods series, 5. Sage, Thousand Oaks, USA.

Summary

This thesis addresses the interdependencies between water use and water availability and describes a model that has been developed to improve understanding of the processes that drive changes and variations in the spatial and temporal distribution of water resources in a semi-arid river basin. These processes include hydrological processes and water user responses to variations and changes in water availability. The results are relevant for climate change impact assessments and river basin management, in particular for water allocation in semi-arid environments.

The research approach consisted of four consecutive stages all focusing on the Jaguaribe basin in the semi-arid northeast of Brazil, which was used as a case study. In the first stage concepts from the literature on common-pool resources were applied to analyse the extent to which the physical characteristics of a river basin facilitate or impede sustainable management of water resources in different parts of the Jaguaribe basin. In the second stage the relationship between water use and water availability in a sub-basin of the Jaguaribe basin was explored. During the third stage the knowledge that was obtained as a result of the first two stages was used to design and test a multi-agent simulation approach. During the fourth stage the simulation approach was used to explore climate change impacts and the ability of water managers to deal with changes through reservoir operation strategies.

To characterise relative topographical locations within a river basin, the concept of *downstreamness* was introduced and quantitatively defined. Depending on its downstreamness, each spatially-defined unit in the basin was categorised in one of three topographical zones: upstream, midstream and downstream. For each topographical zone it was evaluated to which extent five specific ‘conditions for good manageability’ are met. These five conditions were taken from the literature on common-pool resources. It appears that three conditions are better met downstream compared to upstream, while the other two conditions are better met upstream. Factors that make water resources more manageable downstream are the better possibilities for water storage, better predictability of water flows and the lower level of mobility of water resources. Factors that make it easier to manage upstream water resources are the small spatial extent of the allocation problem and the clearly defined boundaries of the resource system. In addition, basin closure can seriously reduce water availability in downstream parts of a basin. In the case of the Jaguaribe basin the net result appears to be most favourable in the midstream zone, where the advantages and disadvantages for good water management are best in balance. As a result, the

agricultural performance, measured in terms of productivity and stability of production, is best in the midstream zone of the Jaguaribe basin.

Water demand 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. The Orós reservoir, centrally-located within the Jaguaribe basin, was specifically studied. It was shown that water abstraction for irrigation (upstream of the reservoir and from the reservoir itself) is of significant importance for reservoir yield and reliability. Yield reliability simulations for the Orós reservoir show that, taking into account upstream water abstraction, a dry season yield of $20m^3/s$ is obtained with a reliability of 90% on an annual basis. The reliability is 95% if upstream abstraction for irrigation is ignored. It was shown that observed land use changes in the study area have a significant impact on reservoir yield and reliability. The variability of upstream water abstraction was found to be of low importance for reservoir yield and reliability.

For a more detailed assessment of the influence of water use on water availability and vice versa a multi-agent simulation (MAS) approach was developed and its usefulness in representing relevant processes was discussed and tested. The purpose of the MAS approach is to explore the dynamics of water use for irrigation and its effect on spatial and temporal water resources distribution in a river basin. The MAS model represents water users which both respond to and modify the spatial and temporal distribution of water resources in the basin. Farmers' decisions on irrigated area and crop type were simulated on the basis of rules including factors such as rainfall and anticipated and observed water availability. Local water use for irrigation influences natural water flows and, in turn, the distribution of water resources over space and time influences water use. Model validity and the use of survey data to represent the studied system dynamics were discussed. It was concluded that a multi-agent simulation model offers a good opportunity for representing the mutual relationship between water availability and water use in river basin areas where irrigated agriculture is an important water user.

To further understand the system dynamics in the Jaguaribe basin and to explore the possibilities for water managers to intervene, the developed MAS model was applied to assess the influence of decreasing rainfall and alternative reservoir operation strategies on water use distribution in the Jaguaribe basin. Water use distribution was analysed both for one specific sub-basin – the Orós reservoir study area – and on the river basin scale. The influence of decreasing rainfall on water use distribution was analysed for alternative reservoir operation strategies and for a case where additional reservoir capacity and irrigation area are introduced within the study area.

One of the conclusions of this research is that river basin management research on semi-arid environments can benefit from applying elements from common-pool resources literature. The theory of common-pool resources appears helpful in analysing the manageability of water resources. Another conclusion is that a multi-agent simulation approach is instrumental in studying interactions between water users and water resources. It was shown that the concept of downstreamness is helpful in assessing the manageability of local scale-water resources.

A valid representation of processes that are responsible for observed variations in the distribution of water use and water availability can be made for the Jaguaribe basin by applying a spatially-explicit multi-agent simulation model approach, implemented by using survey data on water user decision making. For the Jaguaribe basin wet season water use increases with decreasing water availability, whereas dry season water use declines with diminishing water availability. A decrease in rainfall and runoff typically leads to a transition of irrigation water use not only from water-scarce periods to less water-scarce periods, but also from downstream areas to upstream areas. Strategic reservoir operation enables local water managers to offset the effect of decreasing rainfall and runoff with respect to irrigation water use on the sub-basin scale, at the cost of further decreasing water availability at the basin level.

Samenvatting

Dit proefschrift beschrijft de afhankelijkheden tussen watergebruik en waterbeschikbaarheid in een semi-aride stroomgebied. Hiervoor wordt gebruik gemaakt van simulatie-uitkomsten van een model dat is ontworpen voor het verbeteren van het begrip van de processen die bepalend zijn voor veranderingen en variaties in de ruimtelijke en temporele verdeling van watervoorraden. Het gaat hierbij om hydrologische processen en om watergebruikspatronen die samenhangen met veranderingen en variaties in waterbeschikbaarheid. De resultaten van dit onderzoek zijn relevant voor studies die zich richten op de gevolgen van klimaatverandering en kwantitatief waterbeheer voor waterschaarste in semi-aride stroomgebieden.

Het onderzoek dat wordt beschreven in dit proefschrift is uitgevoerd in vier opeenvolgende fasen, waarin steeds processen in het stoomgebied van de Jaguaribe rivier in het semi-aride Noordoosten van Brazilië zijn bestudeerd. Gedurende de eerste fase zijn concepten uit de 'common-pool resources' literatuur gebruikt voor het analyseren van de manier waarop de fysieke karakteristieken van het Jaguaribe stroomgebied duurzaam waterbeheer bevorderen of belemmeren. In de tweede fase is de relatie tussen watergebruik en waterbeschikbaarheid in een deelstroomgebied van de Jaguaribe bestudeerd. Tijdens de derde fase is de in de eerdere fasen opgedane kennis gebruikt voor het ontwerpen en testen van een 'multi-agent' simulatiemodel. In de vierde fase is het model gebruikt voor het verkennen van de mogelijke gevolgen van klimaatverandering en de mogelijkheden om deze gevolgen te beheersen door middel van kwantitatief waterbeheer.

Om topografische locaties in een stroomgebied te karakteriseren is het concept *downstreamness* geïntroduceerd en kwantitatief gedefinieerd. Afhankelijk van haar downstreamness, is elke ruimtelijk gedefinieerde eenheid in het stroomgebied ingedeeld in één van de volgende drie topografische zones: bovenstrooms, middenstrooms of benedenstrooms. Per zone is geëvalueerd in hoeverre daar wordt voldaan aan vijf voorwaardelijke condities voor goed waterbeheer. Deze vijf voorwaardelijke condities zijn ontleend aan de 'common-pool resources' literatuur. Aan drie van deze voorwaardelijke condities blijkt beter te worden voldaan in gebieden die relatief benedenstrooms zijn gelegen, terwijl bovenstrooms beter wordt voldaan aan de andere twee voorwaardelijke condities. Factoren die water benedenstrooms beter beheersbaar maken zijn de betere mogelijkheden voor opslag, de betere voorspelbaarheid van waterstromen en de geringe mobiliteit van het water. Factoren die water bovenstrooms beter beheersbaar maken zijn de kleine ruimtelijke omvang van het waterverdelingprobleem en de duidelijke ruimtelijke afbakening van het (locale) water systeem. Daarnaast kunnen benedenstroomse gebieden hinder ondervinden van bovenmatige opslag en bovenmatig gebruik van water in bovenstroomse gebieden. In het stroomgebied van de Jaguaribe lijkt er in het middenstroomse gedeelte de meest gunstige balans tussen voor- en nadelen van fysieke omstandigheden te bestaan. In dat gedeelte van het stroomgebied is de gemiddelde productiviteit en stabiliteit van de landbouwproductie het hoogst.

In semi-aride gebieden waar de irrigatie sector verantwoordelijk is voor een groot deel van het waterverbruik zijn watervraag en waterbeschikbaarheid sterk aan elkaar gerelateerd. Variaties in watergebruik voor irrigatie hangen samen met de hoeveelheid geïrrigeerd landoppervlak en de irrigatiebehoefte per hectare land. Het Orós stuwmeer, centraal gelegen in het stroomgebied van de Jaguaribe (middenstrooms), is specifiek bestudeerd. Watergebruik voor irrigatie bovenstrooms van het Orós stuwmeer is van significant belang voor de wateropbrengst van het stuwmeer en de betrouwbaarheid hiervan. Resultaten van opbrenst-betrouwbaarheid simulaties voor het Orós stuwmeer laten zien dat, wanneer rekening wordt gehouden met bovenstrooms watergebruik voor irrigatie, een opbrengst van $20m^3/s$ kan worden gerealiseerd gedurende het droge seizoen met een betrouwbaarheid van 90% op jaarbasis. Dat is 95% wanneer bovenstrooms watergebruik voor irrigatie wordt genegeerd. Verder is aangetoond dat geobserveerde landgebruikveranderingen in het studiegebied een significante invloed hebben op de opbrengst van het Orós stuwmeer. Variaties in bovenstrooms watergebruik als gevolg van variaties in regenval hebben slechts een geringe invloed op de wateropbrengst van het Orós stuwmeer.

Voor een meer gedetailleerde analyse van de wederzijdse relatie tussen watergebruik en waterbeschikbaarheid is een ‘multi-agent’ model ontwikkeld. De geschiktheid van het model voor het representeren van de relevante processen is bediscussieerd en getest. Het doel van de modelaanpak is het verkennen van de dynamiek van het watergebruik voor irrigatie en de gevolgen van deze dynamiek voor de ruimtelijke en temporele verdeling van watervoorraden in een stroomgebied. Het model beschrijft hoe watergebruikers de ruimtelijke en temporele verdeling van watervoorraden beïnvloeden en tegelijkertijd hoe zij op veranderingen in deze verdeling reageren. Beslissingen van watergebruikers (boeren) met betrekking tot type gewas en het te irrigeren landoppervlak zijn gemodelleerd op basis van beslisregels die rekening houden met regenval en zowel geobserveerde als geanticipeerde waterbeschikbaarheid. Lokale patronen van watergebruik beïnvloeden de natuurlijke loop van het water terwijl de verdeling van watervoorraden op haar beurt weer het watergebruik beïnvloedt. Modelvaliditeit en gebruik van enquête data voor het representeren van de geanalyseerde systeemdynamiek worden bediscussieerd. Dit onderzoek toont aan dat het mogelijk is om met behulp van een ‘multi-agent’ simulatiemodel een goede weergave van de wederzijdse relatie tussen watergebruik en waterbeschikbaarheid te geven voor stroomgebieden waar de irrigatiesector een belangrijke watergebruiker is.

Voor een beter begrip van de systeemdynamiek in het stroomgebied van de Jaguaribe en voor het verkennen van de mogelijkheden voor interventie door watermanagers is het ontwikkelde model gebruikt voor het evalueren van de invloed van verminderende regenval en alternatieve stuwmeerbeheerstrategieën op de ontwikkeling van watergebruikspatronen. Watergebruikspatronen zijn geëvalueerd voor een specifiek deelstroomgebied (het gebied rondom het Orós stuwmeer) en voor het stroomgebied van de Jaguaribe als geheel. De invloed van verminderende regenval op watergebruikspatronen is geëvalueerd voor verschillende stuwmeerbeheerstrategieën en voor een scenario waarbij extra stuwmeercapaciteit wordt toegevoegd in het studiegebied.

Eén van de conclusies van dit onderzoek is dat stroomgebiedbeheer en -onderzoek met betrekking tot semi-aride gebieden haar voordeel kan doen met het toepassen van elementen uit de 'common-pool resources' literatuur, vooral als het gaat om de analyse van de beheersbaarheid van watervoorraden in verschillende delen van een stroomgebied. Dit onderzoek heeft aangetoond dat 'multi-agent' modellering een nuttig instrument is voor het bestuderen van de interactie tussen watergebruikers en waterbronnen. Daarnaast kan het in dit onderzoek ontwikkelde *downstreamness* concept de analyse van de beheersbaarheid van locale waterbronnen vergemakkelijken.

Voor het stroomgebied van de Jaguaribe geldt dat een valide representatie van alle processen die verantwoordelijk zijn voor de geobserveerde variatie in de verdeling van watergebruik en waterbeschikbaarheid kan worden gemaakt door het toepassen van een ruimtelijk expliciet 'multi-agent' simulatiemodel. Voor het ontwikkelen van dat model kan gebruik worden gemaakt van enquête data betreffende het gedrag van watergebruikers. In het stroomgebied van de Jaguaribe neemt het watergebruik in het natte seizoen toe bij een afnemende waterbeschikbaarheid, terwijl watergebruik in het droge seizoen juist afneemt bij afnemende waterbeschikbaarheid. Een afname van de hoeveelheid regenval en afvoer leidt niet alleen tot een transitie van watergebruik voor irrigatie van waterschaarse perioden naar minder waterschaarse perioden, maar ook tot een transitie van benedenstroomse naar bovenstroomse gebieden. Strategisch stuwmeerbeheer stelt locale watermanagers in staat om de negatieve effecten van een afname van de hoeveelheid regenval en afvoer te beheersen op de locale schaal, ten koste van toenemende waterschaarste op de schaal van het stroomgebied.

Sumário

Este tese trata das interdependências entre o uso e disponibilidade da água, e descreve um modelo que foi desenvolvido para promover a melhoria da compreensão dos processos que causam mudanças e variações na distribuição espacial e temporal de recursos hídricos numa bacia hidrográfica. Estes incluem processos hidrológicos e respostas de usuários de água a variações e mudanças em disponibilidade de água. Os resultados são relevantes para a avaliação de impactos das mudanças climáticas, e para a gestão de bacias hidrográficas, em particular para a alocação de água em ambientes semi-áridos.

A abordagem usada nessa pesquisa consistiu de quatro estágios consecutivos, todos com foco na bacia do Rio Jaguaribe, no semi-árido nordestino brasileiro, que foi usado como caso de estudo. No primeiro estágio, conceitos da literatura sobre recursos de uso comum (common-pool resources) foram aplicados na análise de até onde as características físicas de uma bacia hidrográfica facilitam ou impedem a gestão sustentável de recursos hídricos em diferentes partes da bacia do rio Jaguaribe. No segundo estágio, as relações entre os usos da água e a sua disponibilidade numa sub-bacia do Jaguaribe foram exploradas. Durante o terceiro estágio, o conhecimento que foi obtido como resultado dos dois estágios anteriores foi usado para o desenho e teste de uma abordagem de simulação multi-agente. Durante o quarto estágio, a abordagem de simulação foi usada para explorar impactos das mudanças climáticas e a habilidade dos gestores de água em lidar com mudanças na operação de reservatórios.

Para efetuar uma caracterização localizações topográficas relativas dentro de uma bacia, o conceito de "downstreamness" é introduzido e definido quantitativamente. Dependendo do seu grau de downstreamness, cada unidade espacial definida na bacia é categorizada como pertencente a uma entre três zonas topográficas: upstream (montante), midstream or downstream (jusante). Para cada zona topográfica, foi avaliado até que ponto cinco condições específicas para bom gerenciamento são conseguidas. Estas cinco condições foram retiradas da literatura sobre recursos comuns. Aparentemente, três condições são obtidas mais facilmente a jusante do que a montante, enquanto as outras duas são a montante. Fatores que fazem os recursos hídricos melhor gerenciáveis a jusante são melhores possibilidades para o acúmulo de água, melhor previsibilidade de vazões e um baixo grau de mobilidade dos recursos hídricos. Fatores que facilitam a gestão a montante são pequenas extensões espaciais dos problemas de alocação, e a existência de limites claramente definidos para o sistema hídrico. Em adição a isso, fechamento da bacia pode seriamente reduzir a disponibilidade hídrica em regiões de jusante da bacia. No caso da bacia do Jaguaribe, os resultados líquidos parecem ser mais favoráveis nas regiões

intermediárias (entre as regiões de jusante e montante), onde as vantagens e desvantagens para boa gestão de água são equilibradas. Como resultado, a performance da agricultura, medida em termos de produtividade e estabilidade da produção, é melhor na zona média da bacia do Jaguaribe.

A demanda e a disponibilidade de água são fortemente correlacionadas em ambientes semi-áridos, onde o setor de irrigação é responsável por grande parte do uso da água. Variações nas abstrações de água para a irrigação dependem nas áreas irrigadas e na quantidade de água necessária por hectare. O reservatório de Orós, locado na região central da bacia do Jaguaribe, é usado como caso de estudo. É demonstrado que as abstrações de água para irrigação (a montante do reservatório e diretamente do reservatório) é de importância significativa para os rendimento e confiabilidade do reservatório. Simulações de rendimento e confiabilidade para o Orós mostram que, tomando em consideração abstrações de água de montante, uma estação seca rendimento de 20m^3/s é obtida com confiabilidade anual de 90%. Esta chega a 95% se a abstração para a irrigação for ignorada. É demonstrado que mudanças em usos da terra observados na área de estudo tem impacto significante no rendimento e confiabilidade do reservatório. Foi encontrado que a variabilidade das abstrações de água a montante foi de baixa importância para o rendimento e confiabilidade do reservatório.

Para uma avaliação mais detalhada da influência do uso da água na sua disponibilidade e vice-versa uma abordagem multi-agente (MAS) foi desenvolvida e sua utilidade na representação de processos relevantes foi discutida e testada. O objetivo da abordagem MAS é explorar as dinâmicas do uso da água para a irrigação e os efeitos que isso têm da distribuição espacial e temporal da água numa bacia. O modelo MAS representa usuários de água que ao mesmo tempo respondem à distribuição espacial e temporal de água numa bacia e a modificam. As decisões dos produtores a respeito das áreas a serem irrigadas e tipos de cultural são simuladas com base em regras que incluem fatores como precipitação de chuva e disponibilidade de água prevista e observada. O uso de água para irrigação nas localidades influencia as vazões naturais e, reversamente, a distribuição de água no espaço e no tempo influencia o uso da água. A validade do modelo e o uso de dados obtidos através de questionários na representação das dinâmicas do sistema estudado são discutidas. Conclui-se que um modelo de simulação multi-agente oferece uma boa oportunidade para a representação as relações mútuas entre a disponibilidade e o uso da água em bacias hidrográficas onde a irrigação é um uso importante.

Para uma compreensão mais aprofundada da dinâmica do sistema na bacia do Jaguaribe, e para explorar as possibilidades de intervenção por parte dos gestores do sistema, o sistema MAS desenvolvido foi aplicado de modo a acessar a influência de precipitação decrescente e de estratégias alternativas de operação de reservatórios na distribuição dos usos de água na bacia do Jaguaribe. A distribuição dos usos de água é analisada tanto para uma sub-bacia específica – a área do reservatório do Orós – e na escala da bacia. A influência de precipitações decrescentes na distribuição dos usos de água é analisada para estratégias alternativas de operação de reservatórios e para o caso em que a capacidade do reservatório aumenta e novas áreas de irrigação são introduzidas na área.

Uma das conclusões desta pesquisa é que a pesquisa de gestão de bacias hidrográficas em ambientes semi-áridos podem se beneficiar da aplicação de elementos da literatura referente a recursos de uso comum (common-pool resouces). A teoria dos recursos de uso comum parece útil para a análise do grau de gerenciamento dos recursos hídricos. Outra conclusão é que uma abordagem de simulação multi-agente é instrumental no estudo das interações entre os usos e disponibilidades hídricas. Foi demonstrado que o conceito de downstreamness é útil na avaliação do grau de gerenciamento dos recursos hídricos em escala local.

Para a bacia do Jaguaribe, uma representação válida dos processos que são responsáveis pelas variações observadas na distribuição dos usos e disponibilidade hídricos pode ser feita através da aplicação de um modelo de simulação multi-agente espacialmente explícito, implementado através do uso de dados de questionários sobre as decisões dos usuários de água. Para o Jaguaribe, o uso de água na estação chuvosa aumenta quando há decréscimo na disponibilidade de água. Um decréscimo na precipitação e vazão tipicamente leva a uma transição no uso de água para irrigação, não apenas de períodos com escassez a períodos menos escassos, mas também de áreas a jusante para áreas a montante. A operação estratégica de reservatórios permite aos gestores locais compensar of efeitos do decréscimo em precipitação e vazão com respeito à água para irrigação na escala da sub-bacia, ao custo de aumentar o decréscimo na disponibilidade de água na escala da bacia.

List of publications

International scientific journals

Van Oel, P.R., Krol, M.S. and Hoekstra, A.Y., 2008. The impact of upstream water abstractions on reservoir yield: the case of the Orós Reservoir in Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 53(4): 857-867.

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(3).

Van Oel, P.R., Krol, M.S., Hoekstra, A.Y., Taddei, R.R. Feedback mechanisms between water availability and water use in a semi-arid river basin: a geographically explicit multi-agent simulation approach. *Environmental Modelling & Software* (under review).

Van Oel, P.R., Krol, M.S., Hoekstra, A.Y. The influence of decreasing rainfall and reservoir operation strategies on the distribution of water use in the semi-arid Jaguaribe basin. *Journal of Environmental Management* (under review).

Research reports

Van Oel, P.R., Krol, M.S. and Hoekstra, A.Y., 2007. A river basin as a common-pool resource: a case study for the Jaguaribe basin in Brazil. *Value of water research report series*, 24, UNESCO-IHE, Delft, Netherlands.

Van Oel, P.R., Mekonnen, M.M., Hoekstra, A.Y., 2008. The external water footprint of the Netherlands: quantification and impact assessment. *Value of water research report series*, 33, UNESCO-IHE, Delft, Netherlands.

Conference proceedings

Van Oel, P.R., Mekonnen, M.M., 2008. The external water footprint of the Netherlands: geographically-explicit quantification and impact assessment. *Proceedings ISEE 2008: Applying ecological economics for social and environmental sustainability.* Nairobi, Kenya.

Van Oel, P.R., 2007. A river basin as a common-pool resource: a case study for the Jaguaribe basin in the semi-arid Northeast of Brazil. *Proceedings ESEE 2007: Integrating Natural and Social Sciences for Sustainability.* Leipzig, Germany.

Van Oel, P.R., 2007. Rainfall variations, agricultural performance and common-pool resource management in the semi-arid Jaguaribe river basin, Brazil. *Proceedings Framing Land Use Dynamics II.* 2007, Utrecht, The Netherlands.

Krol, M. S. and Van Oel, P.R., 2004. Integrated assessment of water stress in Ceará, Brazil, under climate change forcing. Complexity and integrated resources management. In C. Pahl, S. Scmidt & T. Jakeman (Eds.), *iEMSs 2004 International Congress: Complexity and integrated resources management.* International Environmental Modelling and Software Society, Manno, Switzerland.

About the author

Pieter van Oel was born in Meppel, the Netherlands, on 15 January 1980. After moving to the city of Groningen, he went to 'De Heerdstee' primary school and the 'Wessel Gansfort College'.

In 1997 Pieter started his academic career in Enschede, at the University of Twente. In the Civil Engineering programme he specialised in Water Engineering & Management and International Management, graduating in 2002. During an internship with Alterra Wageningen Pieter contributed to the EROAHI project, by designing and managing the construction of on-site facilities to measure discharges and sediment transport at the outlets of the Gikuuri catchment near Embu, Kenya, and the Kwalei catchment near Lushoto, Tanzania. For his Master thesis Pieter wrote a plan for improving sanitation in rural South Africa. This community-based approach to the employment-intensive construction of sanitation facilities, as part of the Mohlaletse Youth Service Programme, was designed in cooperation with the University of the Witwatersrand, Johannesburg, South Africa.

In 2003 Pieter started studying the interdependencies between water use and water availability in the semi-arid northeast of Brazil, described in this thesis. Other research activities include virtual water trade. Pieter is currently Assistant Professor at the Water Engineering & Management Department of the University of Twente. His teaching activities include data analysis, modelling and project design.