BRAMAR PROJECT

Water Scarcity Mitigation in Northeast Brazil

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Anna Abels
Marcos Airton de Sousa Freitas
Johannes Pinnekamp
Bernd Rusteberg

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BRAMAR Project – Water Scarcity Mitigation in North-East Brazil

Preface

This book was written as a culmination of the joint efforts and results of many researchers involved in BRAMAR project. BRAMAR was a research project aimed at strategies for mitigating water scarcity in North-East Brazil and was funded both by the German and the Brazilian ministries of research. As some might know, it is a long way from the first concept of an international research project until its end. Along the way, many people have helped to shape BRAMAR's results and finally also to shape this very book you are reading now.

First of all, we want to thank the German Ministry of Education and Research (BMBF) and Project Management Agency Karlsruhe (PTKA) within Karlsruhe Institute of Technology (KIT) as well as the Brazilian Ministry of Science, Technology, Innovation and Communications (MCTIC), through its Water Resources Fund (CT-HIDRO), the Funding Agency for Studies and Projects (FINEP) and the National Council for Scientific and Technological Development (CNPq). The project would not have been possible without them. The Paraíba Technological Park Foundation (PaqTc) provided the operational support for the project.

We acknowledge the CT-HIDRO's Management Committee for supporting the Project application. Among the several people who supported BRAMAR application we can mention Prof. Dr. José Almir Cirilo, Dr. José Monserrat Filho and Dr. Sanderson Leitão. Lia Santiago de Falco, FINEP analyst, was an important partner during the project execution. Additionally, we gratefully thank Dr.-Ing. Bernd Rusteberg (Rusteberg Water Consulting), Prof. Dr.-Ing. Christian Kazner (Bochum University of Applied Sciences), Prof. Dr. Janiro Costa Rêgo (UFCG), and Marcos Airton de Sousa Freitas (National Water Agency, ANA) for conceiving the project.

During the active project phase many researchers have contributed their part and we are extremely thankful for it, as well as for all the partner institutions' support. However, it was only with the help of the numerous students that carried out research in the field, that we were able to achieve these results. Besides that we highly appreciate the work of Anna Abels and Ulf Pedro Schulze-Hennings (RWTH Aachen University), who have played a crucial role as BRAMAR project managers.

Regarding this book, we are deeply indebted to all its authors and editors for the effort they put into it. Additionally, we are thankful for the huge help and support of Vera Kohlgrüber (RWTH Aachen University) who did a great job in revising and keeping all the feedback and communication together. A special thank you also goes to student assistant Cindy Ayumi Nagamine Komesu (RWTH Aachen University) who spend many hours revising the texts, too.

Now that the book is finished, we hope that it proves to be valuable not only for the scientific community, but also for interested civilians and decision-makers who have to deal with water scarcity in a comparable situation both in Brazil and other parts of the world.

Univ.-Prof. Dr.-Ing. Johannes Pinnekamp
Prof. Dr. Carlos de Oliveira Galvão
Prof. Dr. Iana Alexandra Alves Rufino

BRAMAR Project – Water Scarcity Mitigation in North-East Brazil

Foreword

Water resources managers find themselves facing a diverse array of challenges, no matter where they are based. Climate change is a mutual challenge both in Germany and Brazil, with its effects on water resources being numerous and mostly detrimental to sustainable management. Climate change also leads to a higher frequency of extreme weather events like heavy rains or the prolonged drought that has struck semi-arid North-East Brazil in the recent past. Despite North-East Brazil's continuous struggle for water, increasing pressure is also being put on the scarce water resources not only due to droughts, but also because water demand continues to grow within its cities, like it is the case in many areas of Germany as well. The demand for strategic and integrated water resources management has surely risen due to the aforementioned challenges.

The velocity of some of these changes, paired with a high uncertainty about their development and interactions, is making it increasingly difficult to decide which path to adopt in order to make sustainable choices in water resources management. To provide answers to the many open questions on hand, research naturally plays a vital role as there is a clear need for more information and management tools that enable decision-makers to do their job. The complexity of integrated water resources management problems, which touch numerous fields of study, is naturally a major challenge in itself and thus calling for multidisciplinary research collaboration across the globe.

BRAMAR project is an answer to this call as it brings together researchers from Brazil and Germany; with backgrounds in all fields of water resources and environmental studies. There was however one thing that united all of them: Their will to identify sustainable solutions to water scarcity in North-East Brazil. Together, they formed a deeper understanding of water availability in terms of location and volume as well as structural and non-structural water management measures in the project's case study areas. Collaborative research projects such as BRAMAR are a motor for sustainable development as the various angles taken by the participating researchers propel innovative thinking and solution-finding. The output can be found in this book. It is, however, more than just the mere results described in the following chapters, as personal development, capacity building and relations go far beyond the bare numbers. In light of the academic and personal value created in BRAMAR, the importance of international research cooperation does become visible once again.

Univ.-Prof. Dr.-Ing. Ernst M. Schmachtenberg
Rector of RWTH Aachen University

A SUCCESSFUL PROJECT

Foreword

This book, which I am pleased to introduce, is about the experience of a successful project: the BRAMAR PROJECT – Strategies and Technologies for Water Scarcity Mitigation in Northeast of Brazil. The outreach of this project is on the states of Paraíba, Pernambuco and Rio Grande do Norte, with Brazilian coordination by professors from the Federal University of Campina Grande – UFCG.

It is unnecessary to mention how great opportunity is a project like this, applied to the Brazilian Northeastern region. The close involvement of local, national and international institutions can attest by itself the relevance and the urgency of the actions developed: at the UFCG, the Civil Engineering Department (Water Resources group), the Agricultural Engineering Department, The Minning and Geology Department and the Center for the Sustainable Development of the Semi-Arid; at the national level, institutions such as INSA, UFC, FUNCEME, UFERSA, UFPB, IFPB, UFRPE, USP; agencies such as ANA, AESA, APAC and companies such as CAGEPA and INTRAFRUT; at the German side, two companies and three universities. This current partnership confirms a continuity of an international cooperation between the UFCG and German institutions originated in the 1970s.

This large-scale project involved approximately one hundred researchers from partners entities and institutions, working on basically three action lines: *Hydrology and Water Resources* – monitoring and modelling, groundwater exploitation, hydrological studies, water distribution, access and rationing, rainwater use, information and decision making systems, managed aquifer recharge; *Wastewater Reclamation* – reuse of wastewater in agriculture and the urban environment – including the development and improvement of technologies for those purposes; and, finally, *the dissemination of the produced knowledge* through courses, lectures and tutorials.

The dynamics of project planning and execution embraced different activities of local knowledge, research, innovation and extension, promoting a lively dialogue between the institutions and the communities involved; a two-way dialogue that research and academic extension must always achieve: getting familiar to and learning from the several institutional and community-level experiences from outside university; conveying to those environments the academic contribution that we achieve through the research process.

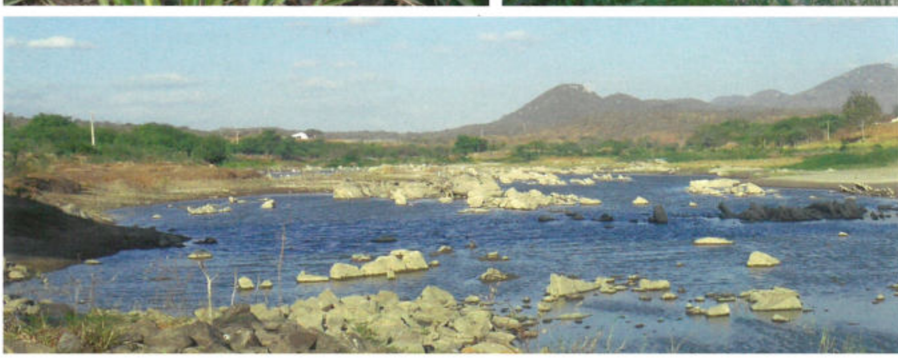
The maturity of an experience like this, now consolidated in this publication, gives us the opportunity to know better what the university does and can do in its own expertise area, which is the systematisation, production and outreach of knowledge, to the most diverse communities, entities and institutions of our society.

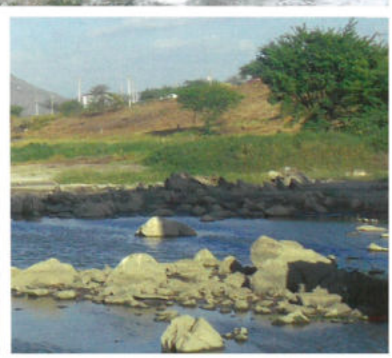
Congratulations to all the professors and researchers involved in a so large-scale project; in particular, all the centres, all the units and all the laboratories of all the institutions that contributed to the success of this project, for such a comprehensive, necessary, timely and, why not to say, generous initiative. May the success of this action stimulate equally ambitious new projects and their equally successful achievement.

Vicemário Simões
Rector of Universidade Federal de Campina Grande (UFCG)

1

Introduction





1.1 Challenges of the Study Region North-East Brazil

North-East Brazil is largely characterized by a semiarid climate and high vulnerability to droughts. Most of the nine federal states of the region present high evapotranspiration throughout the year, with rainfall being concentrated during few months. Water scarcity may be considered the major obstacle for sustainable development of the region.

During the next few decades, due to climate change impact and socio-economic development, water availability is expected to decrease, while water sector demands will increase significantly, resulting in constantly increasing water deficits. Further challenges with regards to the sustainable development of water resources relate to the huge water losses of surface water reservoirs due to high evaporation rates, the fact that large aquifer systems are restricted to the coastal region, the groundwater overexploitation during dry periods. The latter of these, result in decreasing groundwater tables and seawater intrusion as well as water pollution due to insufficient or non-existing wastewater collection and treatment.

Water deficits resulting from non-sustainable water resources development are the main reason for water-related conflicts, especially due to strong competition between the different water users.

In North-East Brazil, regulations for sustainable water resources development are still lacking, e. g. in the area of wastewater reuse and the conjunctive use of surface and groundwater resources. Water management instruments as stated in the Brazilian national and state legislation, such as water permits, water charge and water resources quality improvement are not fully implemented yet.

1.2 BRAMAR Conceptual Approach and Main Research Objectives

The BRAMAR project was conceived to help mitigate water scarcity in North-East Brazil. The collaborative German-Brazilian research and technology development project in the water sector, BRAMAR is entitled

"Strategies and Technologies for Water Scarcity Mitigation in Northeast Brazil: Water Reuse, Managed Aquifer Recharge and Integrated Water Resources Management"

The bilateral project was funded by the German Federal Ministry of Education and Research (BMBF) and the Brazilian Ministry of Science, Technology and Innovation (MCTI). It involved more than 20 project partners, consisting of universities, research centers, Brazilian national and federal Institutions, industrial partners, consulting and technology development firms as well as other stakeholders.

Main project goal was to support the implementation of Integrated Water Resources Management (IWRM) in the semiarid and coastal areas of North-East Brazil as response to the above-stated water related challenges in order to contribute to the sustainable development of the region. At the core of the IWRM concept is the integrated management of all available water resources on river-basin level within a participative planning and decision-making process. Based on the overall project goal, the main scientific and technical objectives of the project were

- to contribute to the recovery of groundwater levels, groundwater protection and quality improvement of coastal and inland aquifer systems of North-East Brazil by studying measures for controlled groundwater recharge (Managed Aquifer Recharge: MAR);

- to increase the water availability and efficiency of water use in water-scarce North-East Brazil;
- to foster water pollution control by improved wastewater infrastructure and water reuse;
- to identify opportunities for wastewater reuse in municipalities, industry and agriculture and to test and promote suitable technologies for their implementation;
- to promote water reuse in all areas, e.g. municipalities, agriculture and industries;
- to provide guidelines and methodologies and develop an expert system for water planners and decision-makers to support decisions with regards to IWRM implementation; and
- to mitigate water scarcity and avoid water-related conflicts in North-East Brazil through the joint management of all available water resources, taking climate change impacts into consideration.

The project partners also investigated how viable it is to implement new water technologies in the study region and how well these technologies and results can be transferred to similar regions. The IWRM measures and water technologies studied in BRAMAR have been evaluated based on a set of indicators, which are stored in the database of the so-called BRAMAR Information and Decision Support System (BRAMAR-IDSS) and may be filtered and accessed by water planners and decision-makers as performance matrices.

BRAMAR research activities were grouped in ten work packages (WPs). The research concept of the BRAMAR project, including all WPs and their interactions, is presented in **Figure 1.1**.

WP1 studied regional socio-economic development as well as climate change under different scenarios, quantifying their impact on sector water demands and water availability. This information served as input for the assessment of water budgets and as boundary condition for hydro(geo)logical modelling under WP2. Different hydrological and hydrogeological models have been applied in order to study the behavior and gain a deep understanding of the water resources systems in the study region. Based on this knowledge and models, the conjunctive use of surface and groundwater by Managed Aquifer Recharge was studied (WP3). WP4 and 5 focused on the treatment and reuse of wastewater in order to improve water quality and availability. In WP6, all informa-

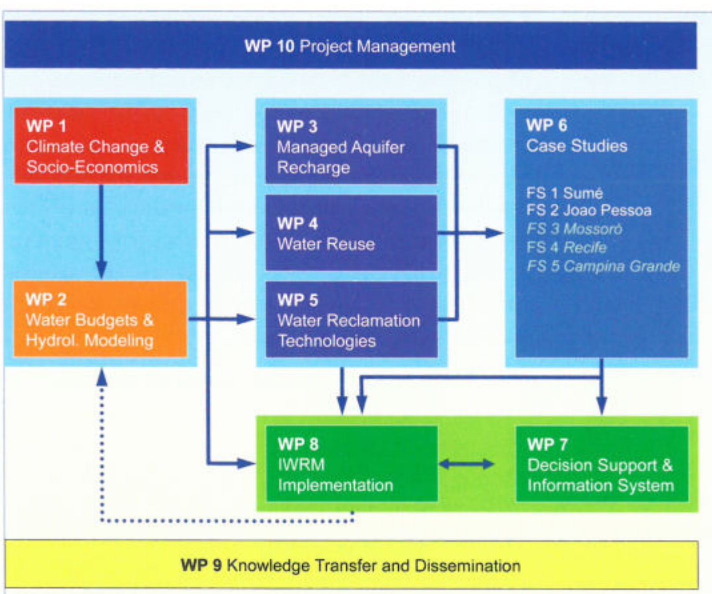


Figure 1.1: BRAMAR project structure

tion related to the characterization of the Case Study Areas (CSA), as well as the laboratory and field studies in the CSA, were collected and integrated in the project database of the BRAMAR-IDSS. WP8 focused on the development of a practical approach for IWRM implementation, taking the gained knowledge into account. Due to the technological project character, WP8 gives special attention to the evaluation of structural IWRM measures and innovative water technologies based on a set of indicators. The above-mentioned BRAMAR-IDSS was developed in WP7. Both work packages are closely linked to each other, since the expert system was designed to support decision-making with regards to IWRM implementation. To round things off, WP9 and 10 focused on the Transfer of Results and Project Management, accordingly.

1.3 BRAMAR Case Study Areas

Figure 1.2 presents North-East Brazil (in blue) as well as the BRAMAR project region with the so-called Case Study Areas (CSA). As can be seen there, five CSAs were identified to be studied in depth. The CSAs were chosen because they represented the typical conditions in both the semiarid and coastal region of North-East Brazil. This guarantees that the results can be transferred to and used in other similar areas. The activities of the German partner institutions focused on the CSA of Joao Pessoa and Sumé in the federal state of Paraiba (black dots).

Case Study Area João Pessoa – The "Technological" Site

João Pessoa is the capital of Brazilian federal state Paraíba and has about 800,000 inhabitants. The main part of the considerable annual precipitation, around 2,000 mm, is concentrated in the rainy season between March and August. During those months considerable amounts of surface water runoff is lost to the sea. The main sources of fresh water to be supplied are surface water accumulated in the watersheds of Gramame and Abiai and groundwater from the large coastal aquifer system. The aquifer system suffers from over-exploitation, especially during dry or drought periods, requiring a much better groundwater monitoring and a better control with regards to the concession of water rights. Due to insufficient sanitary infrastructure, seawater intrusion and the decreasing groundwater table, the pollution of surface- and groundwater is constantly increasing. Adequate IWRM response measures and technologies are required to attend to the increasing sector water demand and to protect the coastal water resources.

Main Research Ideas

On the one hand, the site was selected to study the applicability of conventional and advanced wastewater treatment technologies and adapted schemes for domestic, public and industrial wastewater reuse under urban conditions in the coastal region. On the other hand, CSA João Pessoa seemed to be appropriate to study the potential and viability of Managed Aquifer Recharge (MAR) implementation by using excess surface water for controlled groundwater recharge and underground water storage. Joao Pessoa and Recife were treated as "Twin" case studies since the research at both sites complemented each other towards MAR implementation.

Case Study Area Campina Grande – The "Semiarid Urban Use" Site

Campina Grande is Paraíba's second-largest city with a total of 400,000 inhabitants. It has faced a number of severe water crises during the recent past and, therefore, urgently requires adequate IWRM response measures and adaption strategies for extreme drought periods. In 2016, the collapse of the water supply was just prevented through the construction of an extra pumping system in the main surface water reservoir (Epitácio Pessoa/Boqueirão) to extract water from the dead storage.

Main Research Ideas

The ongoing water crisis is an excellent opportunity to study new water allocation schemes and emergency response measures, including the reallocation of water to different users, and to analyze the joint management of external water to be transferred from the Rio São Francisco (PISF Project) and local water resources. The performance of managers, water users, public power, press and population in the face of the water supply crisis in Campina Grande should be analyzed in this context, too.

Case Study Area Sumé – The "Rural and Semiarid Conjunctive Use" Site

The rural CSA Sumé is representative for hundreds of similar water resources systems inside semiarid North-East Brazil. The small city has some 17,000 inhabitants that rely on a small, frequently nearly depleted surface water reservoir for water supply. At the same time, a small shallow groundwater aquifer is used by farmers' private wells for agricultural irrigation. Increasing pollution due to untreated or insufficiently treated wastewater and water resources scarcity, also due to frequent drought events are the main challenges.

Main Research Idea

Conjunctive management of scarce surface-water, groundwater and wastewater resources of a typical semiarid water resources system as part of IWRM Implementation.

Case Study Area Mossoró – The "Low-Tech Water Reuse" Site

Rio Grande do Norte's capital Mossoró (around 250,000 inhabitants), as well as the regional industry, are growing rapidly due to intensive petroleum exploration. A pool of 80 industries has become established within less than two decades. Besides petroleum exploration, irrigated agriculture is a strong socio-economic factor. The main challenges to water resources management in the region are water pollution by non-treated domestic and industrial effluents and decreasing groundwater tables, which are caused by extensive groundwater use for irrigation, increasing seawater intrusion into coastal aquifers.

Main Research Idea

Develop and test low-cost wastewater reclamation schemes for water reuse in irrigated agriculture to control water pollution and contribute to conflict prevention.

Case Study Area Recife – The "Urban Managed Aquifer Recharge" Site

The water resources system in the capital of the federal state Pernambuco is Recife and very similar to the system at João Pessoa. Recife was built on the estuarine area of Capibaribe river and other small rivers that share the same estuary. Historically, water supply for Recife's 1,500,000 inhabitants has been mainly based on these surface water resources. Nevertheless, increasing water

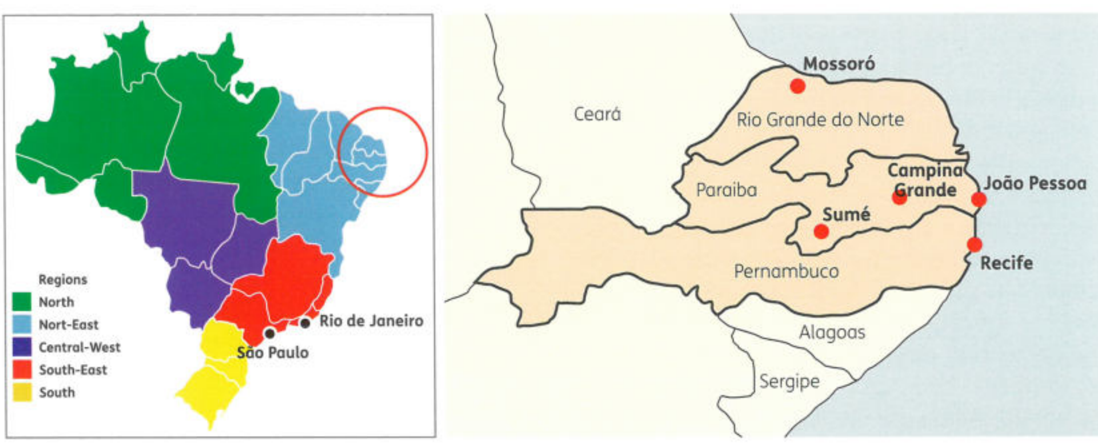


Figure 2.2: North-East Brazil and the location of the BRAMAR Case Study Areas

deficits during the past years has caused an over-exploitation of the coastal aquifer system. The over-exploitation of groundwater – regardless of difficulties in recharging the aquifers – has severely depleted the potentiometric levels and increased the vulnerability to seawater intrusion.

Main Research Idea

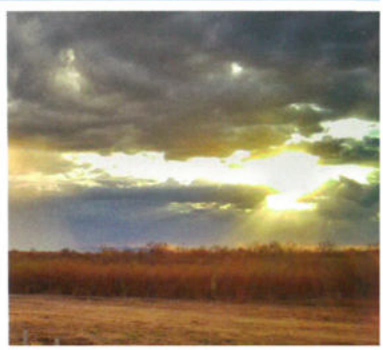
Develop response strategies based on Managed Aquifer Recharge (MAR) with surface water resources for groundwater level recovery, seawater intrusion and pollution control, based on adequate groundwater monitoring.

2

Climate Change and socio-economic Scenarios (Results from WP 1)

Cybelle F. C. Braga[a], Ana C. F. M. Braga[b], Carlos de O. Galvão[c], Márcia M. R. Ribeiro[c], Renato de O. Fernandes[d], John E. Cunha[c], Emanuella A. Figueiredo[b], Cibelle M. R. Felinto[c], Matheus D. de Araújo[c]

a IFPB, b UFPB, c UFCG, d URCA



2.1 BRAMAR Case Study Areas (CSA): Main Driving forces, Pressures, Impact, and actual Water Demand

Five representative case studies have been chosen in the semiarid and coastal region of North-East Brazil. The case studies are João Pessoa, Sumé and Campina Grande in Paraíba (PB) as well Mossoró in Rio Grande do Norte (RN) and Recife in Pernambuco (PE) (**Figure 2.1**). They feature typical situations according to the river basin area, climate, population, water users and conflicts, water resources and aquifer system, and related water problems.

In the following sections, we present a brief description of the methodology used to characterize the case studies, which focused on a diagnosis of the water issue of the case studies, by identifying the main pressures, impact, management measures and demand.

2.1.1 Methodology: DPSIR and Water Demand

DPSIR – Driving force–Pressures–State–Impact–Responses

Socio-Economic development appears as one of the main driving forces of changing natural systems and society, so it is fundamental to understand the main causal relationships, pressures, impact and responses. This knowledge allows us to analyze the scenario (current situation) and to identify – with greater clarity – the effects of new forces such as climate change. Indicators can be used to measure these relationships and elements. Originally the DPSIR (driving force–pressures–state–impact–responses) methodology was called PER (pressures–state–responses) and according to OECD (1993) it is based on a concept of causality: human activities exert pressure on the environment that changes the quality ("state"), society responds to these changes, adopting environmental, economic and sectoral policies ("social response"). These characteristics form a feedback loop and influence each other, especially through human activities. (**Figure 2.2**). DPSIR has been widely applied in the management of water resources (HAMOUDA et al., 2009; KAGALOU et al., 2012; HENRIQUES et al., 2015; PIRES et al., 2017).

Traditionally, the main response to the impact on water resources and water demand is the expansion of the supply, through an increase of supply systems, water basin transfers, or wells.

Alternatively, water resources management can be considered as the main response to the impact on water resources, in the perspective of sustainable development, seeking to guarantee water in

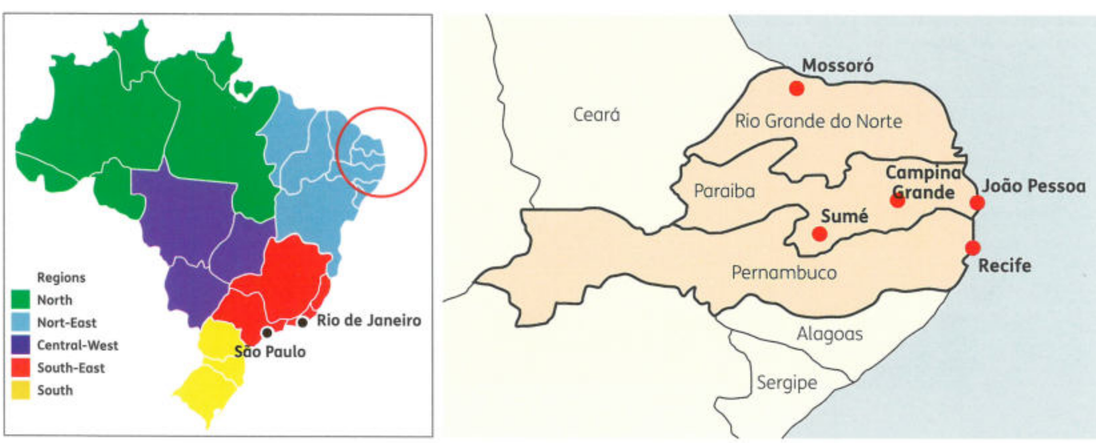


Figure 2.1: Case study areas: João Pessoa, Sumé, Campina Grande, Mossoró and Recife

quantity and quality appropriate to the uses. The Brazilian water resources management model (Water Act 9,433/1997) was designed to be implemented in a participatory and decentralized way with the participation of the government, water users and civil society. The SINGREH (National Water Resources Management System) is composed of the National Water Resource Council, State Water Resource Council (for each Brazilian state), National Water Resource Agency (ANA), Water Agencies in each state and River Basin Committees (RBC). There are five water resources management instruments to be implemented by the SINGREH: river basin plan, system for classifying bodies of water according to their quality, water rights, bulk water fees, and water-resources information system.

Water Demand

In this study, water demand was considered for urban supply (including commercial and industrial demand), livestock and irrigation purposes. For the calculation of the water demand, data from the Brazilian Institute of Geography and Statistics (IBGE) were used referring to the population, livestock and agricultural culture of each municipality. The population census (IBGE, 2010) and per capita consumption by the number of inhabitants (PERH-PB, 2006) were used to estimate the demand for urban and rural supplies. To determine the demand for livestock, the demand coefficient suggested by PLIRHINE (Integrated Water Resources Plan for the Nort-East Brazil) was applied, which takes a constant average consumption of 50 L/head/day for each BEDA (Bovine Equivalent to Water Demand) unit into consideration. To calculate the BEDA, the values of the herd were adopted according to the IBGE livestock production (2013A).

So that water demand for irrigation could be calculated, crop evapotranspiration (ETc) was considered for each type of crop and, in the end, the ETc of all crops grown in the municipality was added. The values of Kc were taken from the literature. The reference evapotranspiration adopted was the arithmetic mean between the maximum and the minimum reference evapotranspiration value empirically verified in a standard year in Paraíba. The data for calculating the demand for irrigation water were taken from the IBGE production surveys (2007 and 2013B).

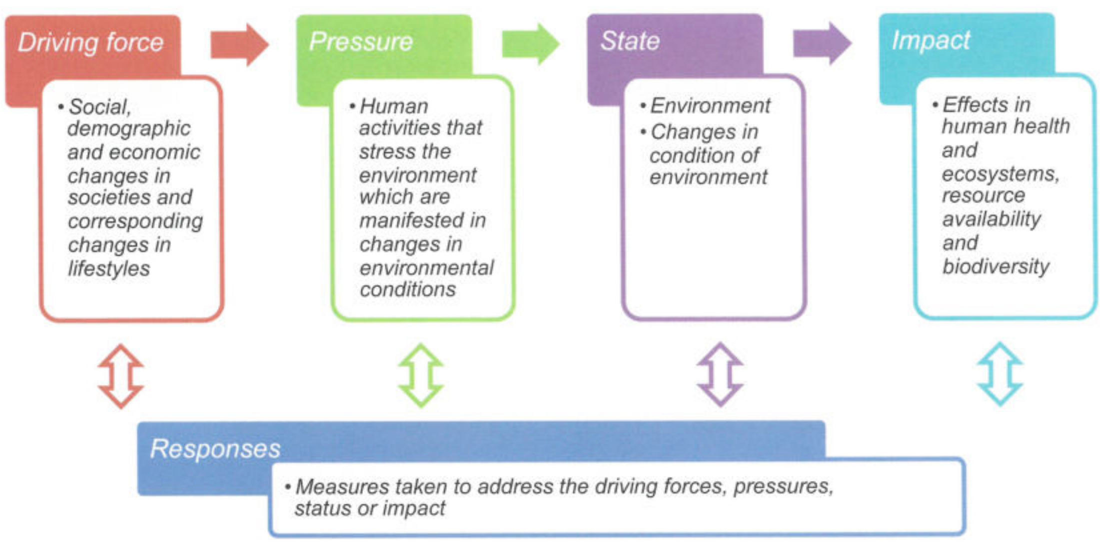


Figure 2.2: DPSIR: Driving-Force-Pressures-State-Impact-Responses

2.1.2 João Pessoa: The "Technological" Site

The city of João Pessoa, capital of the state of Paraíba, is located on the coast of Paraíba, has an area of 211.47 km², with 160.76 km² of gross area distributed in 64 neighborhoods and 49.69 km² of area with environmental preservation. In 2015, the city had an estimated population of 791.400 inhabitants (IBGE, 2010), of which less than 0.4 % is rural. The city is characterized by urban sprawl and the growth of economic activities such as tourism and services, without reducing the industrial activities concentrated in the industrial district of the city.

These characteristics impose pressures and impact on water resources and make it necessary for public managers, water users and civil society to implement structural and non-structural responses (**Figure 2.3**). While these responses increased the water supply for the population, the demand was neither questioned, nor were rational water-use practices encouraged, such as the reuse of water – the object of this study. By implementing technological alternatives for the use of water from wastewater treatment plants (WWTP), such as WWTP Mangabeira, decision makers could meet the demand for less noble uses and relieve pressure and impact on water resources.

The greatest pressures are related to population growth and socio-economic development, and consequently the increase in water demand for effluent supply and dilution. The main responses established are increased supply and management of water resources. The need for improving this management was observed, highlighting the management systems and the integration of de-

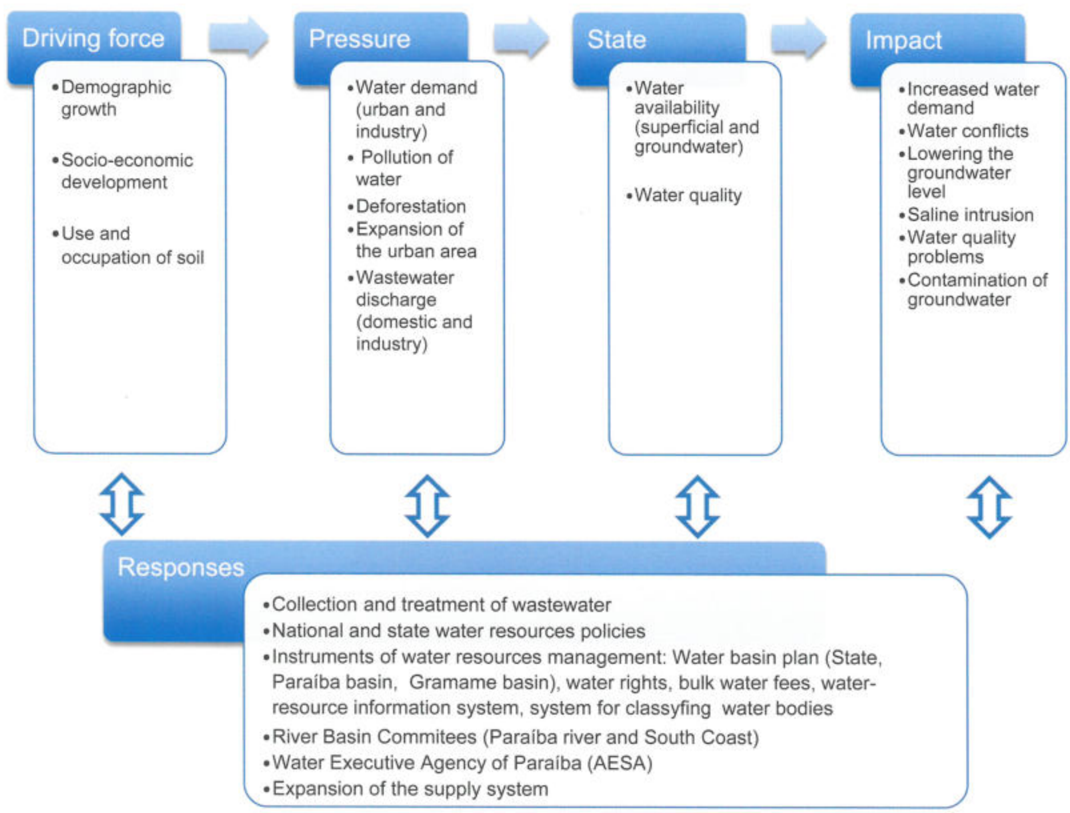


Figure 2.3: Driving-Force-Pressures-State-Impact-Responses – CSA João Pessoa

mand (reuse) and supply Managed Aquifer Recharge (MAR) alternatives.

In João Pessoa city the demand for water is 5.52 m³/s and is almost entirely for urban supply (99 %), while the remaining 1 % is for irrigation. The captations to meet these demands are distributed in the Paraíba River Basin (Gramame-Mamuaba reservoir), Abiaí-Popocas River Basin and, the Paraíba-Pernambuco Basin System (groundwater).

2.1.3 Campina Grande: The „Semiarid Urban Use" Site

The city of Campina Grande is located in semiarid Paraíba, 120 km from the capital João Pessoa. The municipality has a territorial area of 594,179 km², with approximately 96 km² of urban area. It encompasses a population of 402,912 inhabitants, of which 95.33 % comprises the urban population and 4.67 % the rural population (IBGE, 2013a). Campina Grande is one of the largest and most important cities in the interior of the North-East, as well as the second largest municipality in the state. It exerts great political and economic influence on the surrounding cities (PEREIRA and MELO, 2008).

The city has been facing serious water problems since the end of the 1990s due to two major droughts (1998 – 2000, 2012 – 2017) and the inability of the water resources management systems (federal and state) in dealing with the situation (RÊGO et al., 2015). **Figure 2.4** presents the DPSIR analysis for Campina Grande.

In Campina Grande water demand is 2.95 m³/s, divided between irrigation (62 %) and urban supply (38 %). It is worth noting that the irrigation has been "suspended" due to the great drought experienced from 2012 to 2017.

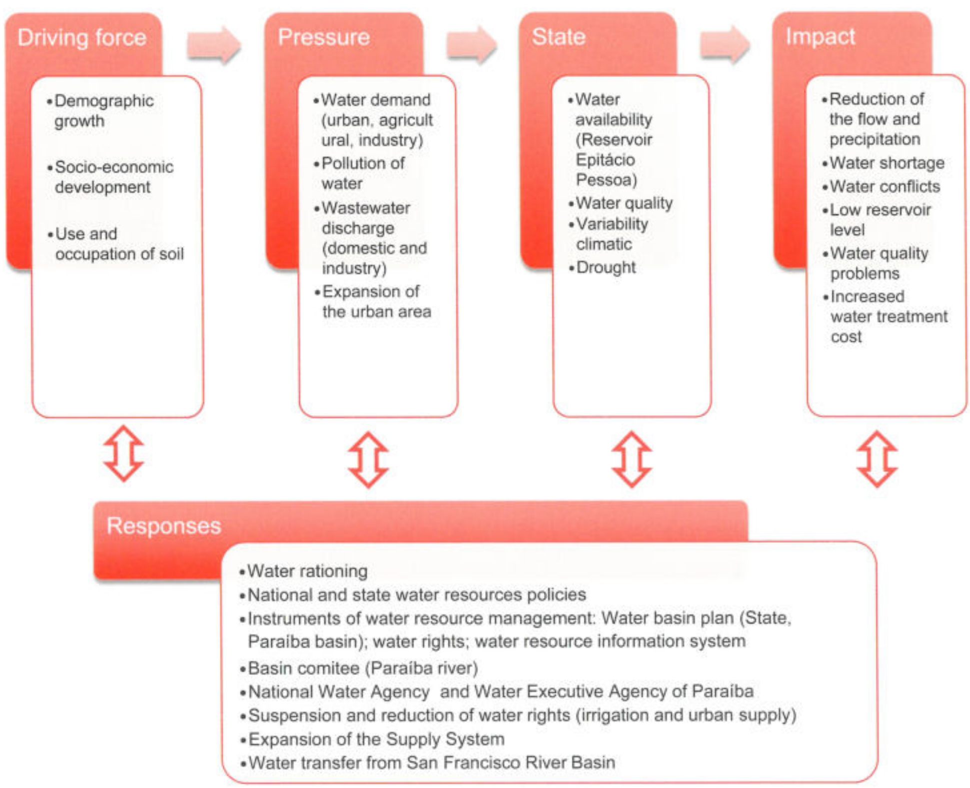


Figure 2.4: Driving-Force-Pressures-State-Impact-Responses – CSA Campina Grande

2.1.4 Sumé: The "Rural and Semiarid Conjunctive Use" Site

The municipality of Sumé is located in the semiarid region of Paraiba and has an estimated population of 16,700 inhabitants, 23.8 % in the rural area and 76.2 % in the urban area. The main economic activities are concentrated in services and agricultural sectors. These activities put pressure on the natural resources and impose a great demand for irrigation and city supply, as well as for dilution of domestic effluents (**Figure 2.5**). Thus water demand is 0.24 m^3/s, or 85 % of the demand for water serves irrigation; 11 % for human supply and 4 % for livestock farming. The main sources that supply this demand are the Sucuri River and its alluvium.

2.1.5 Mossoró: The "Low-Tech Water Reuse" Site

Mossoró is located in the interior of the state of Rio Grande do Norte, in the mesoregion of the West Potiguar and microregion of the same name. Its population was estimated at 284,300 inhabitants in 2014, rising from 259,815 inhabitants in 2010. The municipality comprises 2,099.36 km^2 with a resulting population density of 123.76 inhab/km^2. The inhabitants are concentrated in the urban portion which indicates an extensive rural area (IBGE, 2010).

The evolution of the municipality, resulting from the development of the oil industry, saline, fruit growing, among others, implies problems and impact resulting from theses processes, such as uncontrolled deforestation, irregular construction and settling, lack of basic infrastructure, environmental sanitation deficit, inequalities social, real estate speculation, vulnerability and deterioration of natural systems, problems with solid waste disposal, water supply, visual pollution, population

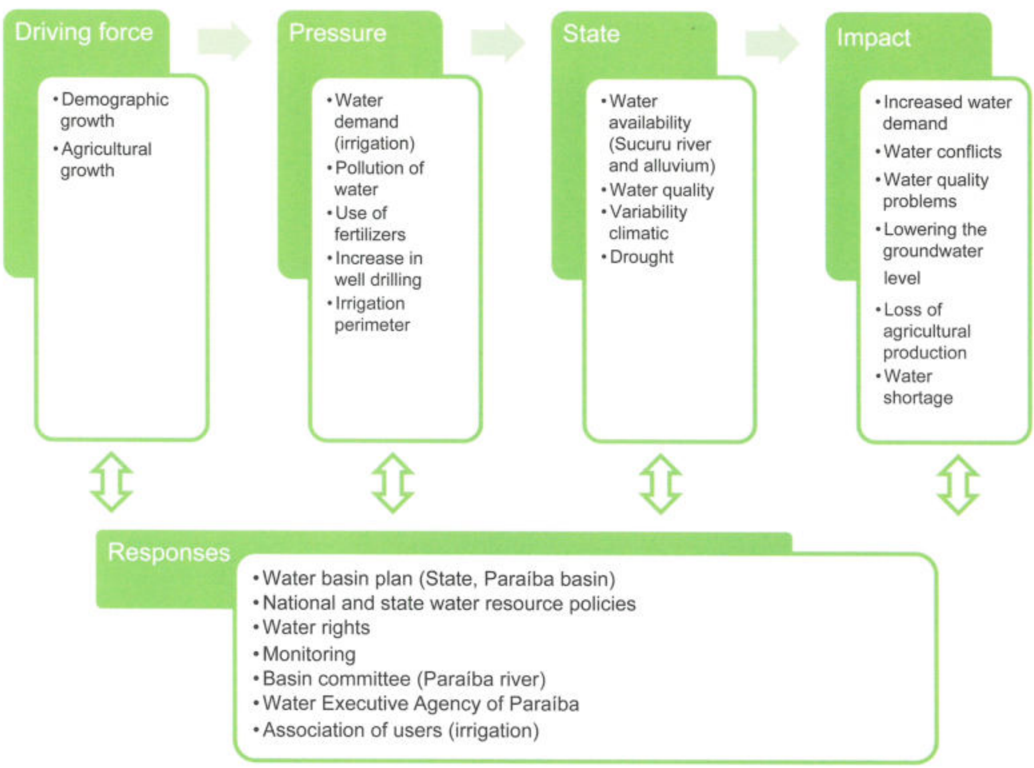


Figure 2.5: Driving-Force-Pressures-State-Impact-Responses – CSA Sumé

mobility, effluent discharge along the Apodi / Mossoró River, among others (TORQUATO, 2012). In Mossoró, water demand is 5.02 m³/s, or 94 %, almost entirely for irrigation, 5 % for urban supply and 1 % for livestock. It is worth noting that the irrigation has been "suspended" due to the great drought. **Figure 2.6** presents the DPSIR analysis for Mossoró.

2.1.6 Recife: The "Urban Managed Aquifer Recharge" Site

The city of Recife is located on the coast of the state of Pernambuco. The municipality has a territorial area of 218,435 km², and a population of 1,537,704 inhabitants, which is found entirely in the urban area (IBGE, 2010).

When the socio-economic context is taken into account, Recife is an urban cluster of great relevance from the state and regional point of view, and together with Salvador and Fortaleza, it commands a relevant part of the economic life of the North-East Brazil (FERREIRA, 2013). Since it basically has no rural population, the demand for the use of water is almost completely for urban supply, whose predominant economic activity is the provision of services. The water demand is 5.78 m³/s. The supply of water in the city, as well as in the entire Metropolitan Region of Recife, is quite complex, consisting of a series of integrated systems and complementary isolated systems. Surface water sources are the Tapacurá, Gurjaú and Botafogo dams, as well as the Capibaribe Ipojuca, Beberibe rivers, among others. Many municipalities complement their supply through underground springs and only two (Island of Itamaracá and Itapissuma) capture water exclusively in wells (ANA, 2010).

Here, it is difficult to maintain a satisfactory supply level and reduce the impact of high well drilling by users in order to guarantee water availability (**Figure 2.7**).

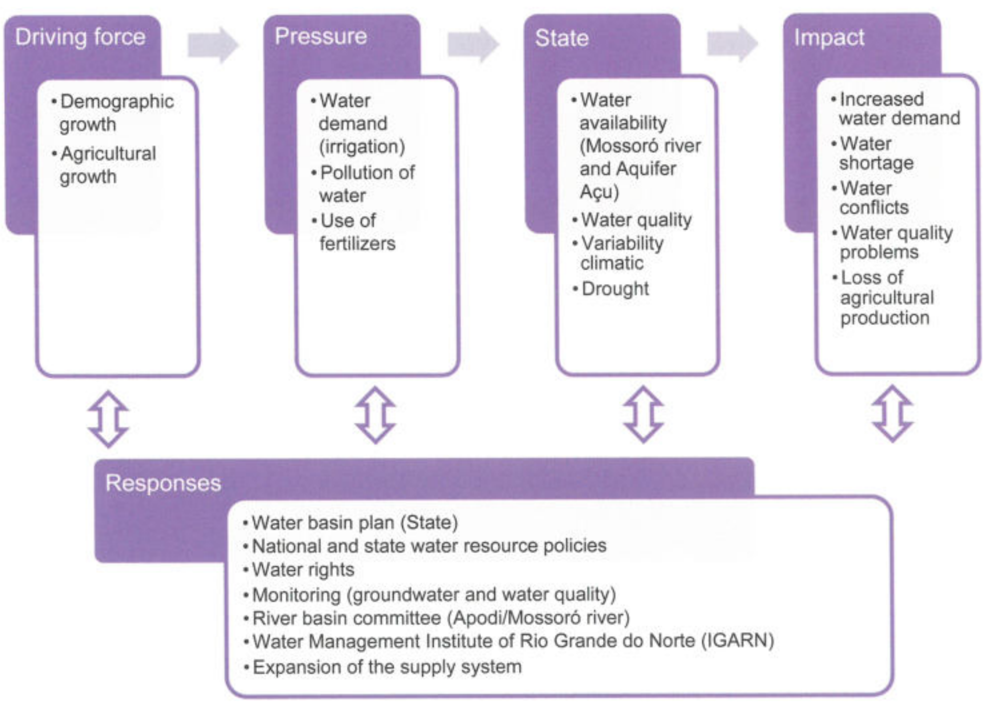


Figure 2.6: Driving-Force-Pressures-State-Impact-Responses – CSA Mossoró

2.2 Climate Change in North-East Brazil

2.2.1 General Aspects

Climate variability and change impact water resources and need to be considered in their planning and management. The changes in the climate variables that form the hydrological cycle are reflected in the river flows, in water availability of reservoirs and in water demand. Besides these, the situation of water sources can be further aggravated by changes in water quality and urbanization processes.

Impact on the economy, humans and ecosystems should be considered to ensure water security. Thus, there is a demand for information about changes in climatic variables themselves and about their impact on water systems (STAKHIV and STEWART, 2010). This is relevant information both for a small water user, who needs the information immediately, as well as for a decision-maker, who needs long-term information to plan on how to meet demands and carry out actions of climate change adaptation and mitigation. Changes in climate have direct consequences on water resources and considerably increase the degree of uncertainty in managing these resources.

Extreme events (droughts and floods) cause significant socio-economic impact and, historically, society has suffered from these events. There are records of droughts in North-East Brazil, of their

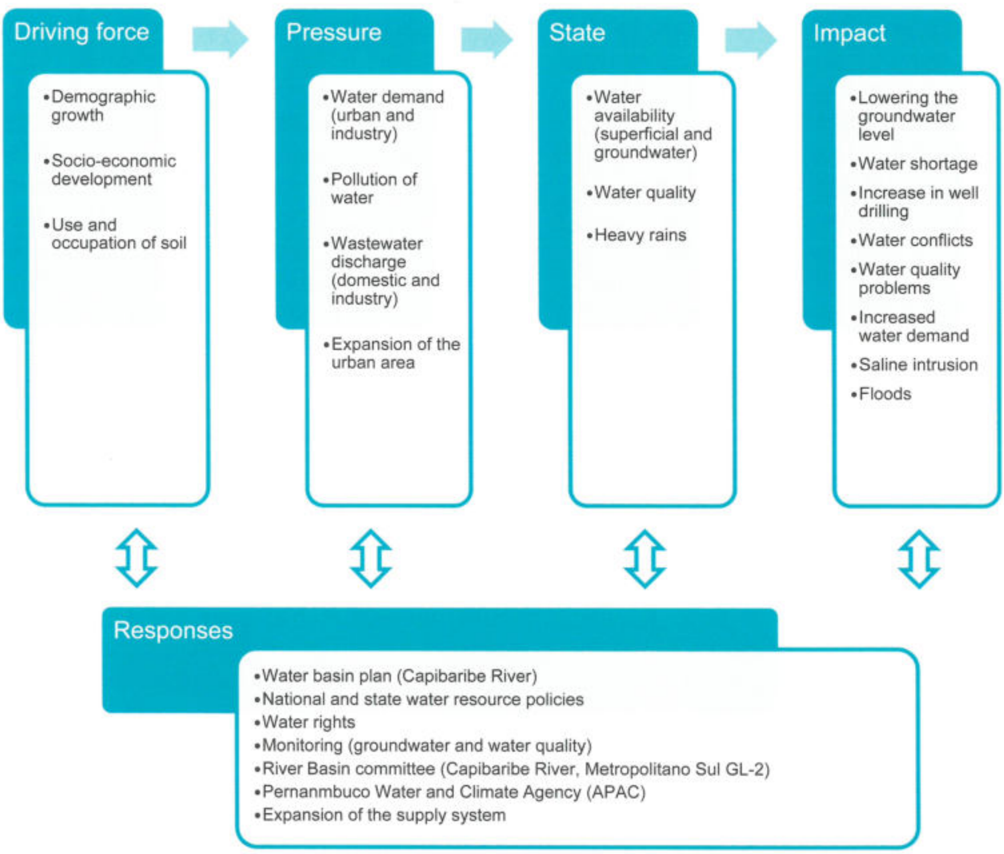


Figure 2.7: Driving-Force-Pressures-State-Impact-Responses – CSA Recife

impact and of government actions, for example, that go back to the 16th century; the droughts caused losses of agricultural productivity, migration, disease, hunger and even death (MARENGO et al., 2017). The region's vulnerability may be worse in the context of climate change.

In 1988 the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC). The IPCC was created by governments to provide technical and scientific information on climate change and to support work on climate assessments. It is an international body responsible for making available Climate Change Assessment Reports (ARs) on a regular basis with the purpose of contributing to planning and decision-making.

Depending on the vulnerability and characteristics of a region, climate change can impact various sectors deeply, and effective actions are needed to address it consequences. On the other hand, the process of modeling and studying changes in the climate of a specific region as a river basin still has uncertainties and needs to be carefully considered. Although the methodology for analyzing the impact of climate change on strategic sectors, such as water resource, is not recent (ARORA and BOER, 2001; KAY et al., 2006), the involved models, scenarios, analyzes and vision of adaptation and mitigation were improved with the release of the 5th IPCC Assessment Report (AR5).

2.2.2 Climate Models and Climate Change Scenarios

Future climate projections are simulated by climate models that represent the climatic system through laws of physics and observations (BETTS et al., 2011). Global Climate Models (GCMs) divide the terrestrial globe into a horizontal grid on an order of 200 km and divide the atmosphere into vertical layers, which allows a user to process and calculate the climatic variables. However, the horizontal resolution in which these models are simulated does not allow the necessary details for impact assessment, for example in river basins. This can be done by Regional Climate Models (RCMs), which are simulated with the boundary conditions of GCMs, but on a more refined scale (~50 km). The RCMs perform a downscaling process, which is a reduction of scale, in which the results can be applied in hydrological modeling or in climatic impact analyzes.

These models are simulated in large climatic centers of the world that compile the necessary data and have high computing power for data processing. To facilitate access to data, documentation, scenarios, validations and comparisons, the Working Group on Coupled Modeling (WGCM), under the World Climate Research Program (WCRP), established the Coupled Model Intercomparison Project[1] (CMIP), which is a standard protocol for studying the simulations performed by coupled Atmosphere-Ocean General Circulation Models (AOGCMs, a more complete type of GCM). The CMIP is in its 5th phase and offers simulations of global models performed by different institutions. The CMIP5 disseminated great deal of knowledge and make information accessible, both of which can be used by academia and society. With the same purpose, the Coordinated Regional Climate Downscaling Experiment – CORDEX[2] provides data from RCMs at different timescales of various climatic variables.

Future scenarios are generated by simulations of climate models. According to IPCC (2000), scenarios are appropriate tools with which users can analyze how the driving forces influence the future results of greenhouse gas emissions, evaluate the associated uncertainties and thus improve the understanding of the complex interactions between the climate system, ecosystems and human activities. Future emissions of greenhouse gases are the result of a number of factors such as demographic, socio-economic and technologi-

1 https://cmip.llnl.gov/cmip5/; https://esgf-node.llnl.gov/projects/cmip5/
2 https://esg-dn1.nsc.liu.se/search/cordex/

cal changes that influence the climate system. How strongly these elements impact the environment depends on changes in climate and ecosystems, as well as on the ability of society and the economy to adapt to them.

In the IPCC 5th Assessment Report (AR5), Representative Concentration Pathways (RCPs) (VAN VUUREN et al., 2011; KRIEGLER et al., 2014) were used to consider the emission of greenhouse gases, emission of atmospheric pollutants and of soil use patterns in a more dynamic perspective because the socio-economic and vulnerability scenarios are considered in parallel and integrated into climate modeling. RCPs have a broader coverage than previous IPCC emission scenarios because they represent scenarios with climate policy and land use. The RCPs are composed of four scenarios identified by their radiative forcing target level for year 2100: RCP2.6 (2.6 Wm^{-2}), RCP4.5 (4.5 Wm^{-2}), RCP6.0 (6.0 Wm^{-2}) and RCP8.5 (8.5 Wm^{-2}). Thus, RCPs include a rigorous mitigation scenario (RCP2.6), two intermediaries (RCP4.5 and RCP6.0) and a scenario of high carbon emissions (RCP8.5). These RCPs were developed using Integrated Assessment Models (IAMs), which include economic, demographic, energy and climate components. Emission scenarios are used in models to produce series of carbon dioxide concentrations in global atmosphere-ocean circulation models.

2.2.3 Uncertainties

Generating future climate projections involves the use of models that simulate complex systems and processes of the atmosphere. It needs data and monitoring information crucial to their performance (as well as timing and scale issues). The knowledge of the model by the user is important since this is for an adequate analysis of the results. However, this set of factors is not always within an optimal range of conditions for the analyses to reach their maximum performance and/or accuracy. Additionally, involved in this whole process are the uncertainties in the projections of climate change.

However, the process of analyzing the impact on water resources does not end there. The results of climate models are used as input data for impact models, which introduce their own uncertainties in the project (ENGELAND et al., 2016). Therefore, there is propagation of uncertaities because of the errors/bias (SHRESTHA et al., 2016). **Figure 2.8** shows the uncertainties involved in the whole process.

As the public slowly becomes more aware of the topic, several studies have addressed these uncertainties (TENG et al., 2011; CHEN et al., 2011; BEVEN, 2016; KUNDZEWICZ et al., 2018). However, what can be highlighted in the whole process is the inability of atmospheric models to predict precipitation. Although they often agree with the increase/decrease of temperature, the same does not occur with the precipitation signal (SILVEIRA et al., 2016), which makes the prognosis, adapta-

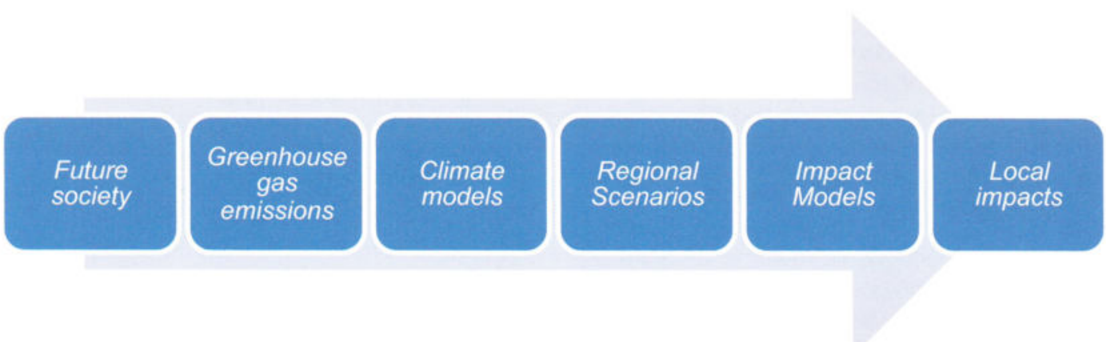


Figure 2.8: Uncertainties in climate change processes of modelling (adapted from ANA, 2016)

tion and mitigation measures more difficult. Since precipitation is the main input into impact models, how can this information be used?

The correction applied to the rainfall data (TEUTSCHBEIN and SEIBERT, 2012; MUERTH et al., 2013), although it lessens the uncertainties, does not completely eliminate them, nor does it eliminate the differences between the models. One way to better use the data could be using the atmospheric model to evaluate the simulation of the current climate since it could accurately indicate the performance of the model in a region. However, one cannot be sure if the climate will continue to change with the same seasonality of the current climate, which exposes the risk of excluding some models from the analysis and reinforces the necessity to consider the models that are equally probable (CHEN et al., 2017). In this sense, Shen et al. (2018) emphasizes the importance of using multiple climate models for the impact of climate change in hydrology, because a range of possible futures can be considered by decision-makers in this way. Despite the uncertainties, future projections are important to providing decision-makers with plausible future scenarios (KUNDZEWICZ et al., 2017). According to Kundzewicz et al. (2018), who are in agreement with this whole context (especially the differences between models), it is necessary to develop adaptation measures that do not need precise or quantitative projections of changes in hydrological variables, but rather a range of projected values. Within this, the authors indicate which precautionary principles and adaptive management are needed in case uncertainty is irreversible.

2.2.4 Climate Change Impact

In 2008, Brazil´s National Plan for Climate Change was drawn up, which included commitments, mitigation opportunities, research, training, identified impact, among other items, which provided a pathway for Brazilian society to deal with the topic. In the following year, 2009, the National Policy on Climate Change was promulgated (Law 12187/2009), which contains guidelines and instruments that formalize Brazil's commitment to the United Nations Framework Convention on Climate Change to reduce emissions of greenhouse gases [3].

These were important initiatives to deal with climate change in Brazil. Another one was the Brasil 2040 Project: Scenarios and Alternatives for Adapting to Climate Change (SAE-PR, 2015), whose objective was to estimate climate change's impact on different economic sectors and to suggest strategies for prevention and adaptation of different systems: water resources, agriculture, energy, urban infrastructure, coastal infrastructure and transport.

Studies have identified increases in temperature and relative disagreement between rainfall projections in the RCP4.5 and RCP8.5 scenarios for South America (CHOU et al., 2014) and North-East Brazil (GUIMARÃES et al., 2016), which may hinder and/or make harder the ability to directly conclude from impact models how the future flow and other variables will develop (HIPT et al., 2018). These results can further accentuate the vulnerability characteristics of a region such as North-East Brazil. In this way, BRAMAR focused on rainfall and temperature projections for the five case studies (João Pessoa, Campina Grande, Sumé, Mossoró and Recife). Three RCMs were used to assess the impact of climate change (**Table 2.1**). These models have daily simulations with horizontal resolution of 0.44°x0.44° and had the precipitation seasonality tested by Silveira et al. (2014). The historical data covered the period between 1951 and 2005 and allowed an evaluation of the accurancy of these models in simulating the present climate and the involved uncertainties.

In general, the three models underestimated the average monthly temperatures, but they represented the seasonality of this variable well. Regarding precipitation, although the frequency of distribution of the simulated daily data is compatible with that of the observed data, a more de-

3 http://www.mma.gov.br/clima/politica-nacional-sobre-mudanca-do-clima

tailed analysis by range of values showed that the models have a bias in underestimating the rainfall in the range between 0 to 5 mm and in overestimating increasing rainfall in precipitation ranges of up to 200 mm. Regarding annual totals, all models overestimate rainfall significantly. When the spatial distribution of rainfall is analyzed, no pattern can be detected: There are locations in which the models represent the seasonality well, while others do not. Thus, for evaluation of future trends, the results were analysed in a relative way, that is, with a comparison between future and current climates simulated by the models. The scenarios RCP4.5 and RCP8.5 were selected (one intermediate and another with more intense emissions) in the periods 2006 to 2037 (Δt1), 2038 to 2069 (Δt2) and 2070 to 2100 (Δt3) to analyse future climate. All models show increases in temperature, here expressed by the anomaly[4] throughout the time periods and intensified in RCP8.5. The average increase simulated by the models in RCP4.5 is 0.85 °C (Δt1), 1.49 °C (Δt2) and 1.84 °C (Δt3) and for RCP8.5, the average anomalies reach values of 0.89 °C (Δt1), 2.01 °C (Δt2) and 3.54 °C (Δt3). **Figure 2.9** shows anomalies for Campina Grande and Recife case study areas. There are no huge diferences between the increases simulated by the models in both locations.

4 The anomalies express the difference between the variable in the future scenario and the variable simulated in the historical mode of the climate models.

Table 2.1: Description of the regional models used in Project BRAMAR

Models	Institute
ICHEC-EC-EARTH_SMHI-RCA4	GCM: ICHEC-EC-EARTH/Irish Center for High-End Computing (ICHEC), EC-EARTH Consortium
	RCM: SMHI-RCA4/Swedish Meteorological and Hydrological Institute, Rossby Centre
MPI-M-MPI-ESM-LR_MPI-CSC-REMO2009	GCM: MPI-M-MPI-ESM-LR/Max Planck Institute for Meteorology
	RCM: MPI-CSC-REMO2009/Climate Service Center, Helmholtz-Zentrum Geesthacht
MPI-M-MPI-ESM-LR_SMHI-RCA4	GCM: MPI-M-MPI-ESM-LR/Max Planck Institute for Meteorology
	RCM: SMHI-RCA4/Swedish Meteorological and Hydrological Institute, Rossby Centre

Obs.: In this chapter, the names of the models were abbreviated to ICHEC-RCA4, MPI-REMO2009, MPI-RCA4.

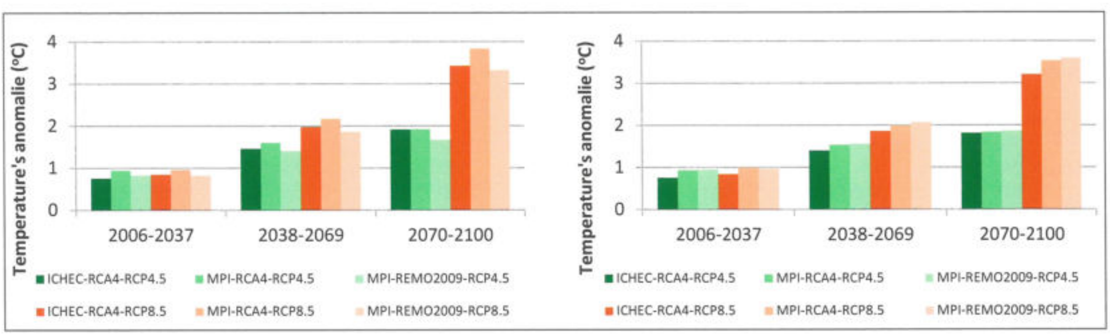


Figure 2.9: Temperature increase in two study cases: (a) Campina Grande, (b) Recife

For simulated precipitation, the models do not agree with an increase or decrease in the case studies (**Table 2.2**). In general, the ICHEC-RCA4 and MPI-RCA4 regional models indicate that rainfall will increase between 0.9% and 34.9%, while the MPI-REMO2009 model indicates that rainfall will decrease between -1.3% and -35.3%. It is interesting to note that climate models indicate different trends between the case studies, such as the MPI-REMO2009 model for the Sumé locality, in which in only one period/scenario the model indicated a percentage of rainfall increase, and in João Pessoa, the model indicated that twice.

The monthly mean values show a range of possibilities for changes in rainfall from -47.7% to +64.4%, depending on the scenario and model for the case study of João Pessoa (**Figure 2.10**). The months with the lowest variations are July to December. The case studies presented different percentages of increase/decrease over the months of the year.

When the same scenario and time period (RCP4.5, between 2038 and 2069, see **Figure 2.11**) are compared for all case studies, the models keep the seasonality for the five locations, although

Table 2.2: Percentual changes in precipitation for Case Study Areas' cases of BRAMAR project

Models	2006–2037		2038–2069		2070–2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
João Pessoa						
ICHEC-RCA4	8.6%	4.6%	17.1%	14.0%	8.9%	17.7%
MPI-REMO2009	-1.3%	-2.9%	0.3%	7.1%	-1.3%	-4.6%
MPI-RCA4	-1.0%	-1.8%	3.4%	4.6%	2.3%	4.4%
Campina Grande						
ICHEC-RCA4	8.5%	8.5%	16.9%	21.7%	14.2%	24.7%
MPI-REMO2009	-4.0%	-4.6%	-3.8%	-4.5%	-1.8%	-7.5%
MPI-RCA4	2.7%	2.5%	7.7%	10.1%	7.4%	19.8%
Sumé						
ICHEC-RCA4	9.3%	9.5%	21.8%	30.9%	19.8%	34.9%
MPI-REMO2009	1.9%	3.4%	-2.9%	4.4%	0.7%	1.4%
MPI-RCA4	6.4%	6.1%	13.0%	17.7%	13.7%	26.4%
Mossoró						
ICHEC-RCA4	2.1%	3.6%	12.3%	12.9%	10.0%	22.3%
MPI-REMO2009	-7.8%	-10.3%	-12.6%	-13.6%	-19.0%	-14.7%
MPI-RCA4	6.9%	3.2%	9.0%	11.9%	10.9%	22.3%
Recife						
ICHEC-RCA4	7.0%	5.1%	16.9%	15.8%	10.1%	23.8%
MPI-REMO2009	-10.7%	-16.8%	-17.9%	-18.1%	-23.9%	-35.3%
MPI-RCA4	0.9%	2.9%	6.4%	10.0%	7.7%	13.1%

with different percentage values. This means that little difference can be observed between the case studies over the months, but the models indicate differences between themselves that should be considered in decision-making.

The effects of climate change on water resources can impact the magnitude and frequency of extreme events affecting water systems in terms of water quantity and quality, and some other effects may be highlighted, including changes in land use, consumption patterns, production (agriculture, industry), population growth, economic growth, demands for water, energy and food, increased pollution, among others. **Table 2.3** summarizes the main impact of climate change on water resources, which must be considered in water resources planning and management for climate change adaptation and mitigation.

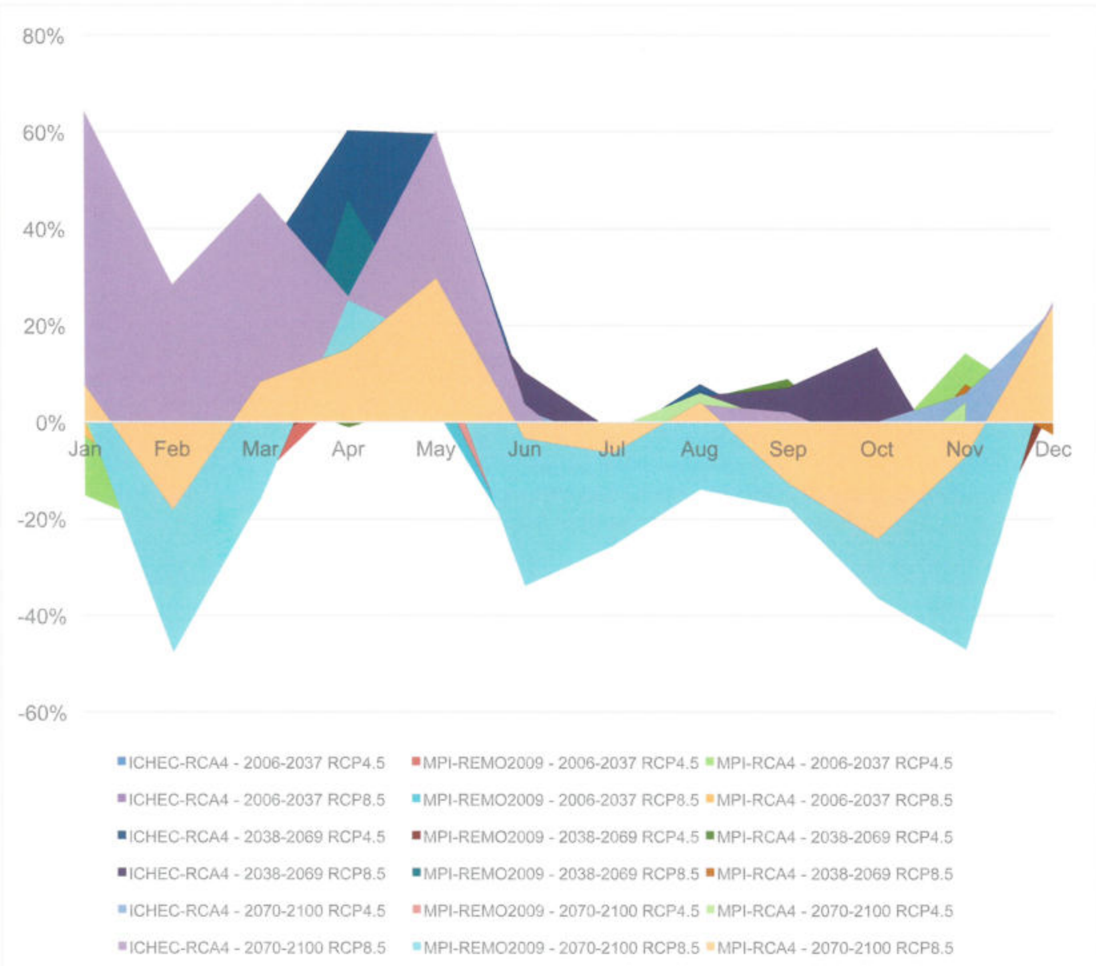


Figure 2.10: Percentual changes of the anomalies (related to historical simulations) of the models, in different scenarios, for João Pessoa

Table 2.3: Climate change impact in water resources.

Climate change	Impacts
Temperature increase	• Changes in physico-chemical and biological processes in water bodies • Changes in eutrophization processes • Increase in evapotranspiration • Changes in water demand • Reduction in water availability • Difficulties for dilution of wastewater • Interference in water and wastewater treatment systems • Difficulty in reaching water potability and effluent discharge standards.
Rainfall decrease	• Reduction in runoff • More intense droughts • Changes in water availability, with interference with the volumes accumulated and regularized flows of the reservoirs • Problems in meeting water demands • Reduction of reliability in water abstraction
Rainfall increase and more frequent heavy rainfalls	• Increase in sediment loading • Increase in flood frequency • Turbidity and pollution problems • Possibility of suspending the operation of water systems • Damage to water infrastructure • Damage to physical installations of systems • Interruption of water services
Changes in rainfall and in hydrological regime	• More consecutive dry years (years with droughts) • Dry reservoirs for longer time • More droughts • Water rationing • Inability to recover water levels in reservoirs • Rationing • Instability in electricity supply • Failure in meeting all demands • Suspension of the operation of systems • Water system insecurity • Increased competition among users and conflicts

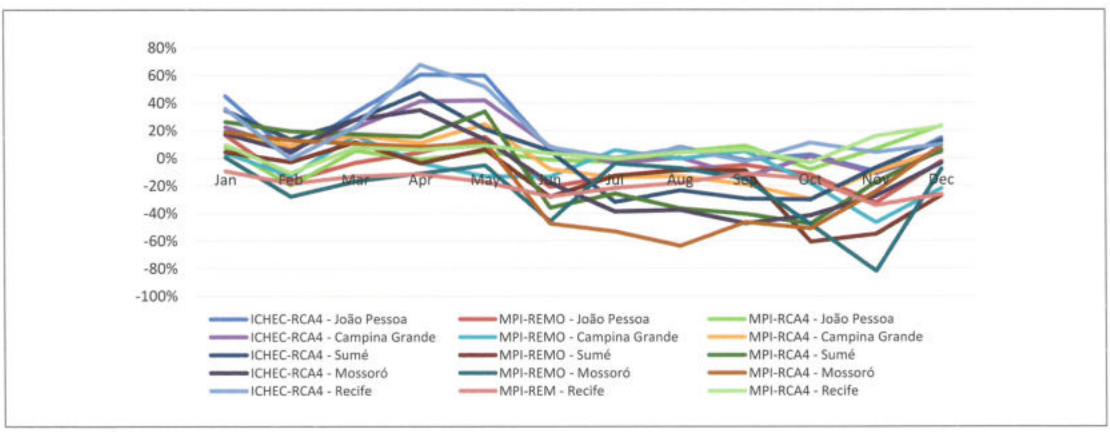


Figure 2.11: Percentual anomalies changes (related to historical simulations) of the models, in all CSAs for scenario RCP4.5 between 2038-2069

2.3 Future Water Use

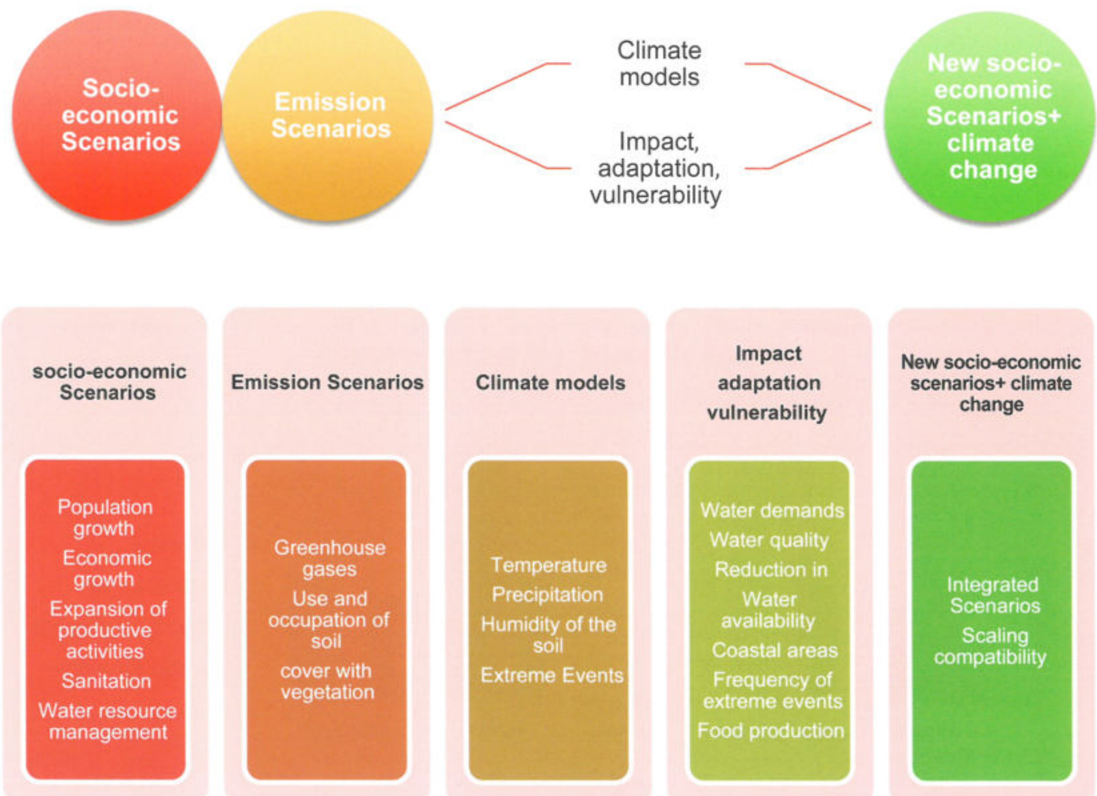
Water resources are essential for the socio-economic development of any region. Water demand evolves over time and requires planning by water users and water resource managers. Forecasting the use of water in the future (short, medium and long term) should mainly take into account the driving forces and pressures in the present and prospects for investments, public policies for water users and climate change (**Figure 2.12**).

Three scenarios were considered, based on the National Water Resources Plan (PNRH, 2006). Population and socio-economic growth projections, based on water agencies' reports and plans, were included, as were the impact of climate change on irrigation as a function of an increase in temperature for the climate change scenarios RCP4.5 and 8.5 (**Table 2.4** and **Figure 2.13**).

Table 2.4: Scenarios of future water use

Scenarios		Socio-economic (water demand)			
		Present	Future (2050)		
		Reference (2014/15)	Water for all	Water for some	Water for few
Climate Change (RCP)	4.5	+	+++	++	+
	8.5	+	++++	+++	++

It is worth emphasizing the uncertainty associated with this projected water demand for the



Source: Based on Moss et al. (2012).

Figure 2.12: Assumptions and relationships for socio-economic scenarios on climate change

future as a result of, among other factors, changes in public policies that induce a specific sector to use more water, negative impact caused by extreme events (droughts and floods), new technologies and user behaviour inducing rational use of water, which can strongly alter these demand values. For example, the evolution of water demand in the Piranhas-Açu Basin reflects this sensitivity of water uses well (ANA, 2004; PRH PIANCÓ-PIRANHAS-AÇU, 2016; ANA, 2017):

- Water demand from shrimp farming showed strong positive and negative fluctuations due to the problems caused by extreme events (2008 flood and 2012 - 2017 drought), market variations due to the dollar exchange rate, change in cultivation (increased use of sea water).
- The pisciculture presented a great increase in the demand induced by a public policy of the sector.
- The drought (2012 - 2017) had a very strong impact on agriculture due to the reduction of water availability, suspension of grants and priority of water for human and livestock supply.

On the other hand, we can also observe several data sources for the projection of demand in socio-economic scenarios, which bring a significant dispersion and consequently aggregate uncertainty to the projection. When one considers different rates of socio-economic growth in the RCPs (**Table 2.4**) and climate change forcing (increasing demand according to a trend of increasing temperature) for long-term scenarios (2050), it can be observed that water demand is more sensitive to the impact of socio-economic forcing than climate change (**Figure 2.14**).

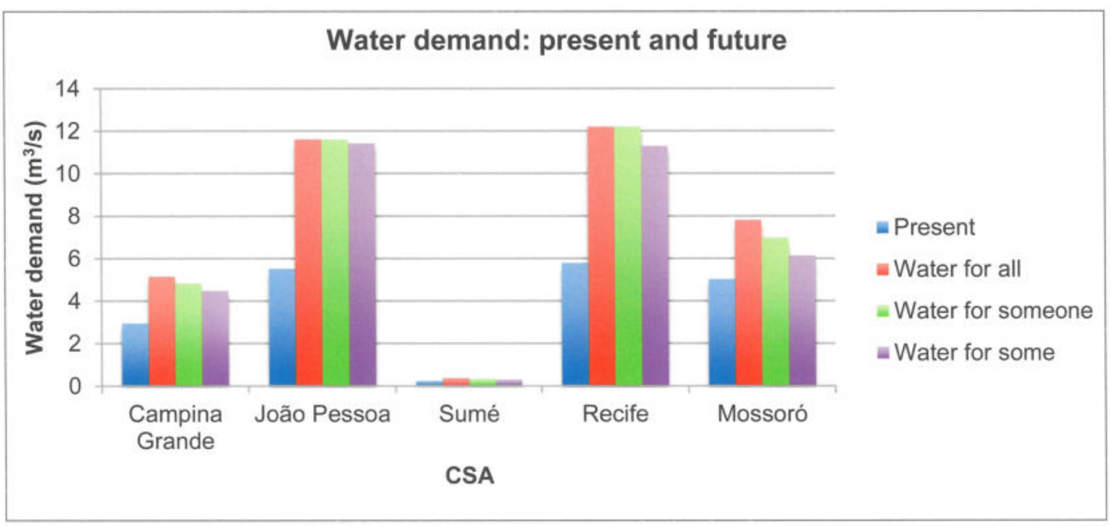


Figure 2.13: Scenarios Water demand for CSA: present and future with socio-economic growth

2.4 Conclusions and Lessons learned

Projections and scenarios, both climatic and socio-economic, are subject to very high uncertainties in the North-East Brazil. In the past 20 years, the region has experienced two drought periods (1998 - 2003 and 2012 - 2017) and one regular-to-rainy period (2004 - 2011). These two decades also saw cycles of economic crises and development, mostly unforeseen. Large-scale minimum-income and other social programs were implemented and later reduced. Institutional changes followed and suffered from these cycles, making evident that planning for medium- to long-term is difficult to develop and implement. For example, demand projections are very dependent on both climate and socio-economic projections. Accordingly, scenario development for planning is severely impaired by these high uncertainties.

However, the methods and procedures presented here for diagnosis, e. g. DPSIR, and scenario planning, are still valid and useful. They constitute baselines for developing IWRM strategies for dealing with water scarcity. On the other hand, to be effective and useful, they must comply with the principles of Adaptive Water Ressources Management (WRM), which calls for advances in the policies and management practices, through systematic learning by the stakeholders (FERNANDES, 2017; PAHL-WOSTL et al., 2010). Thus, it is recommended that the management practices should change in response to new knowledge on the climatic and socio-economic contexts. This implies continuously updating and talking with agencies and stakeholders so that the scenarios can be kept valid and useful. This strategy depends upon assessment cycles of available resources and management outcomes, as well as upon decision-making adjustments along the way. This process requires tools and models to characterise and simulate the water resource systems. BRAMAR has developed a set of models for simulating the water systems (chapter on WP2), measures and strategies to cope with water scarcity (chapters on WP3 and WP4, 5 & 6), and information systems and tools (chapter on WP7), to help with the task of IWRM strategy formulation, implementation and adaptation. Examples and case studies can be found in chapter on WP8.

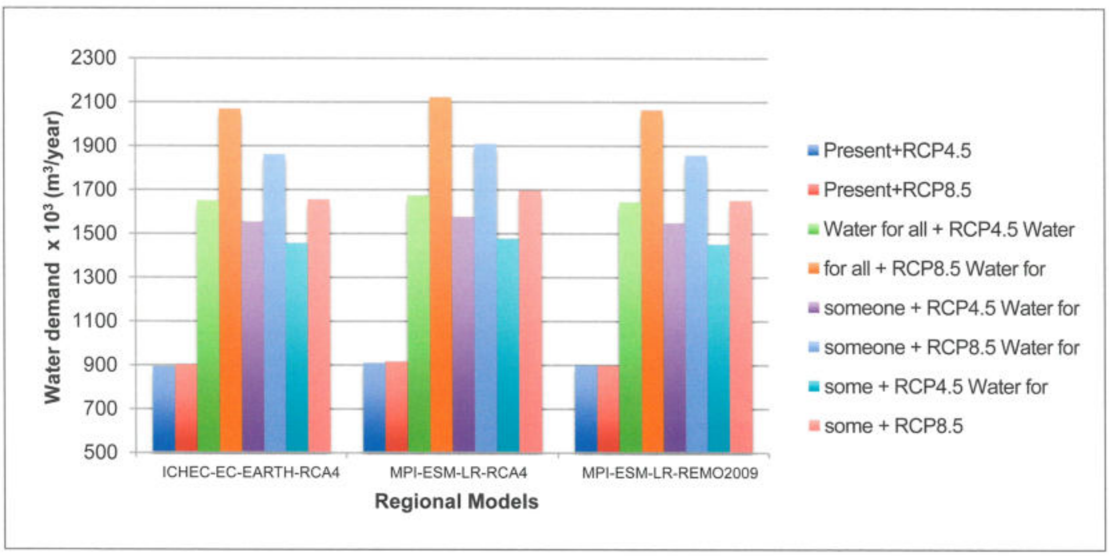


Figure 2.14: Scenarios water demand for sugar cane – CSA João Pessoa: present and future with socio-economic and climate change

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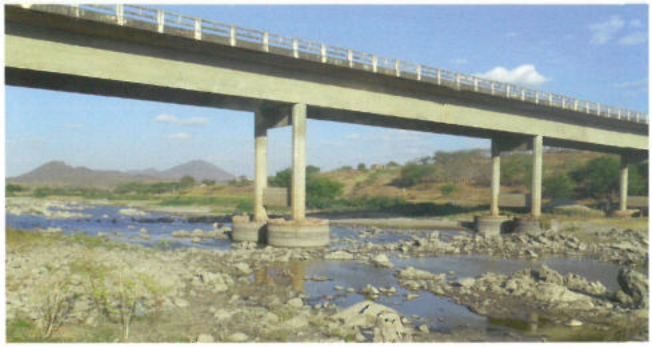
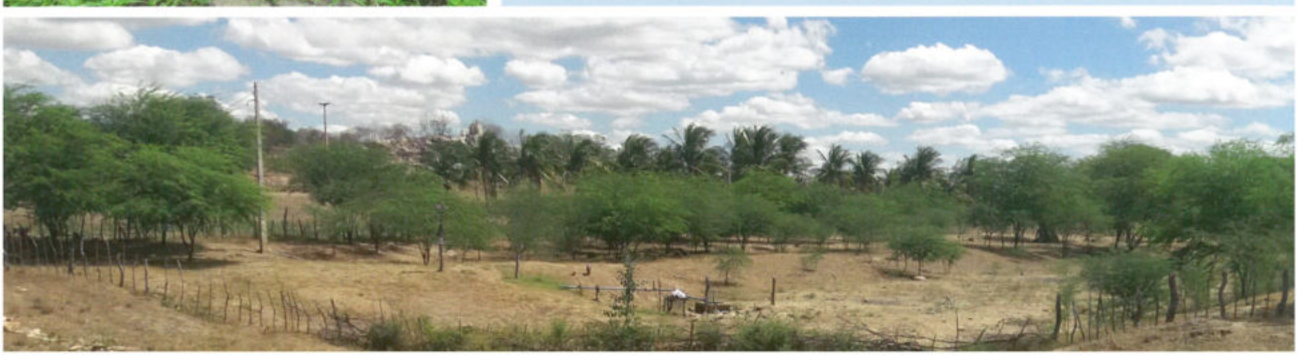


3

Hydro(geo)logical Modelling (Results from WP 2)

Saskia Schimmelpfennig[a], Günter Meon[a], Matthias Schöniger[a], Duy P. Ta[a], Bárbara B. Tsuyuguchi[b], Armando C. R. Braga[b], João D. de A. Pontes Filho[b], Francisco M. S. Nunes[b], Janiro C. Rêgo[b], Carlos de O. Galvão[b], Hugo M. de Alcântara[b], Vajapeyam S. Srinivasan[b], Ricardo de Aragão[b], Cristiano das N. Almeida[c], Nelson L. Caicedo[c], Luís R. Barbosa[c], Lucila de A. Fernandes[c], Geraldo M. Ramos Filho[c], André N. Gadelha[c], Euler N. Gonçalves[c], Matheus S. da Cruz[c], Suzana M. G. L. Montenegro[d], Victor H. R. Coelho[d], Anderson L. R. Paiva[d], Guillaume F. Bertrand[d]

a TU Braunschweig, b UFCG, c UFPB, d UFPE



3.1 Hydro(geo)logical Modelling in Water Resources Planning and Management

3.1.1 Role and Importance of Hydrological Modelling

Optimization of water management strategies requires a proper understanding of the water resource system and the flow paths within it in surface water and groundwater bodies. The maintenance and expansion of monitoring systems, as well as the parameterization, calibration and validation of environmental models that simulate aspects of quantity and quality of water are fundamental for adequate management of water resources. Monitoring and models can significantly help to improve the processes of sustainable water use (HIRATA and CONICELLI, 2012). Such models can simulate future scenarios, such as land use modifications or climate changes, or different technical options with the aim to indicate the best options for management strategies under changing hydrological and land-use conditions.

For example, when sanitary risks from water contaminated by effluents are reduced, communes can be benefited with a higher quality of life. During the BRAMAR project, efforts were taken to consider and improve both steps, monitoring and modelling in different case study areas. Some significant results are presented in the following sub-chapters.

3.1.2 Lessons Learned from Earlier Research Projects

The Research Network on Semi-Arid Hydrology (REHISA - Rede de Hidrologia do Semiárido) was established in 2001 as a consortium of hydrology research groups of Brazilian universities. Some of these groups are BRAMAR members: UFPE (Federal University of Pernambuco), UFRPE (Federal Rural University of Pernambuco), UFPB (Federal University of Paraiba), UFCG (Federal University of Campina Grande) and INSA (National Institute of Semiarid). A network of more than ten representative and experimental basins was implemented in the region, including two of BRAMAR's CSA (João Pessoa and Sumé). REHISA resumes the experience of SUDENE's (Superintendence of Northeast Development) network on these basins in the 1970s and 1980s. The monitoring data collected in these basins supported the development and validation of several modelling approaches, while it also took the climate, soils, geology, surface reservoirs and land use of the region into account. The main lessons from REHISA can be summarized as 1) unstable funding for monitoring is always a threat for the continuity of the studies; 2) long-term collaboration among the research groups is fundamental for overcoming the funding obstacles; 3) collaboration is also fundamental for fostering hydrological understanding and modelling, testing and development of instrumentation adapted to the region's conditions; 4) a range of new or emerging hydrological-related research fields have been attached to the REHISA network since its establishment, increasing interdisciplinary hydrological research: limnology, ecology, remote sensing, climate change, rainwater harvesting, wastewater reuse, social, economic, institutional and policy aspects, community-based monitoring and research, among others.

3.1.3 Main Challenges

The development and operation of a model-based sustainable water management system require reliable hydrometeorological data with high spatial and temporal resolution. The accuracy and quality of modelling results mainly depend on the available data base. Experiences gained during earlier projects emphasize the importance of hydrometric data and groundwater related data over meteorological input data, as the problematic key fields in North-East Brazil. Unfortunately, one single discharge station often covers an area of more than 5,000 km², which precludes a clear identification and quantification of discharge processes in this specific area. Highly unknown anthropogenic influences, e.g. high number of small to large reservoirs and uncertain water extraction rates, exacerbate calibration and validation processes and complicate parametrization of models. Considering modelling as the main working area, therefore, includes an assessment study for gaps and structural deficits of the existing monitoring networks and, in conclusion, the rehabilitation and implementation of additional stations in selected areas according to their priority and the financial budget. In BRAMAR it was necessary to establish a new monitoring system for groundwater measurements operated by the universities UFCG, UFPB and UFPE based on manual and automatic measurements. Historical time series were almost unavailable.

The model calibration with most up-to-date short-term data is a great challenge which raises high amounts of uncertainties. To make the monitoring system sustainable after the project ends and to avoid data scarcity, water agencies and universities need to cooperate closely and communicate clearly, which is a complex and time-consuming task.

3.2 Modelling Objectives and Methodological Approach

3.2.1 Main Modelling Objectives

The processing strategy of WP2 follows the modelling approach by using hydrological conceptual, deterministic water budget models in combination with numerical groundwater-simulations.

Starting with a hydrological model has two reasons: first, the objective is to check if the existing data base – data for the topography, soil, land use, river cross section, hydraulic structures etc. as well as hydrometeorological data – is sufficient to build up and run a planning model. The second reason is to get familiar with the hydrological behavior, in particular with the water balance at any location of the catchment.

Modelling implies 4 main steps: 1 Building a conceptual scheme, 2 implement this conceptual scheme in a numerical model, 3 calibrate the numerical model from historical hydro(geo)logical data and 4 perform simulations by changing bound conditions (e.g. recharge, discharge by pumping, land use, etc.).

The conceptual groundwater model synthesizes how, where and in which way the flow happens. It is built from existing field data and local characteristics and examines the potential impacts of the above-mentionned parameters. ANDERSON, WOESSNER and HUNT (2015) state that a conceptual model must use, in this perspective, nine data sources: geomorphology, geology, geophysics, weather, vegetation, soil, hydrology, hydrochemistry and anthropogenic aspects.

After successful calibration and validation with long-term historical data, the coupled hydrological and groundwater models can directly be used to estimate future water balance by considering further climate change analysis. Main modelling results determine the usable water resources and the water budget of the catchment or groundwater system, including, among others, trends of groundwater recharge, river discharge and groundwater level. Groundwater potential and aquifer recharge, which are some of the main results of modelling work, are highly important information for groundwater management, since they are closely related to exploitation volume limits over which aquifer depletion would occur (RÊGO, 2012; KEBEDE, 2013). The results of modelling can then be used as key indicators and evaluation parameters for decision support in the perspective of water management strategies **(Table 3.1)**.

3.2.2 Methodological Approach

Methodological modelling approaches must be dynamic as emphasized by the flowchart reported in **Figure 3.1**. A first diagnosis of a case study area – based on previous projects, studies and recognition surveys – supports the definition of its conceptual model, which describes the main in- and outputs of the water system and helps to understand the water flow behavior.

Due to the complexity of the principles and equations that govern the water cycle, numerical modelling is recommended for quantification of water availability. In addition, numerical modelling requires refinement of geological, hydrological, meteorological and land use information, leading to deeper investigations and monitoring. Boundary conditions, limits, number and thickness of layers, initial estimations of hydraulic conductivity, transmissivity, specific yield and recharge and discharge sources are defined in the conceptual groundwater model.

Modelling is a continuous process that depends on data quality and quantity (long-term time-series with high resolution) for parametrization, calibration and validation. It allows better estimation of environmental responses for present and future scenarios due to the impact of natural or anthropic events.

3.3 Hydrological Modelling

3.3.1 Model Selection

In the project, different hydrological approaches and models were applied in order to comprehensively understand surface water availability, water balance and groundwater recharge. Modelling was based on the models PANTA RHEI and SWAT.

PANTA RHEI is a deterministic, conceptual hydrological modelling system that simulates rainfall-runoff-processes and the water balance at any location within a river basin. The model allows simulations with high spatial-temporal resolutions which are based on natural catchment zones (KREYE et al., 2012; ELEY et al., 2017). The preparation of catchment data is supported by a GIS interface. The model was developed and is continuously maintained at the Leichtweiß Institute for Hydraulic Engineering and Water Resources (LWI), University of Braunschweig (TU-BS), in collaboration with the Institute for Water Management IfW GmbH, Braunschweig (LWI-HYWAG & IfW, 2012). It is used for flow forecast (e.g. in

Table 3.1: Modelling Results for Water Resources Planning

Modelling Results for Water Resources Planning	
From Hydrological Modelling	**From Ground Water Modelling**
Areal precipitation	Ground water levels
Areal evapotranspiration	Depth-to-ground watertable
River discharge	Water budget
Areal ground water recharge	Groundwater extraction
Drought index	Flow direction and travel time
Extraction from reservoirs	

the German Federal State of Lower Saxony), for planning purposes (in Germany and worldwide, e.g. for flood protection measures, reservoir planning), and – in a more sophisticated version – for research of climate change impact on water resources (Germany, Vietnam). Within the framework of the project, the groundwater recharge is one important output of the PANTA RHEI model, which allows the coupling with a numerical groundwater model. Therefore, PANTA RHEI includes different (physically-based or empirical) approaches to calculate the soil water content/ infiltration and the groundwater recharge as an important source of water storage. The spatially distributed groundwater recharge calculated with PANTA RHEI is one input for the groundwater model in João Pessoa which was developed with FEFLOW (see 3.4.2).

The Model SWAT – Soil Water Assessment Tool – has a great deal of applications all over the world because it is open access and has detailed documentation. It is a physical, semi-distributed model that was developed to be applied in large ungauged basins. The model divides the catchments in sub-basins, and later, in Hydrologic Response Units (HRU) that have the same physical attributes. SWAT is also a deterministic model that can be used to isolate the hydrologic response of a single variable, helping users to forecast management decisions (FRANCESCONI et al., 2016). For simulation, the model needs data on digital elevation, land use and land cover, soil map, daily rainfall, maximum and minimum temperature and wind speed. In response to those inputs the model provides runoff, sediment yield, groundwater recharge, pollutant load and other relevant hydrologic components. The results provided by the model can be used by planners and regional development authorities to conduct adequate regional planning.

In addition to hydrological modelling, the project considered the use of orbital remote sensing products and the Water Table Fluctuation (WTF) method for verification of modelling results, especially in the case study area of João Pessoa. The use of orbital remote sensing products and Geo-

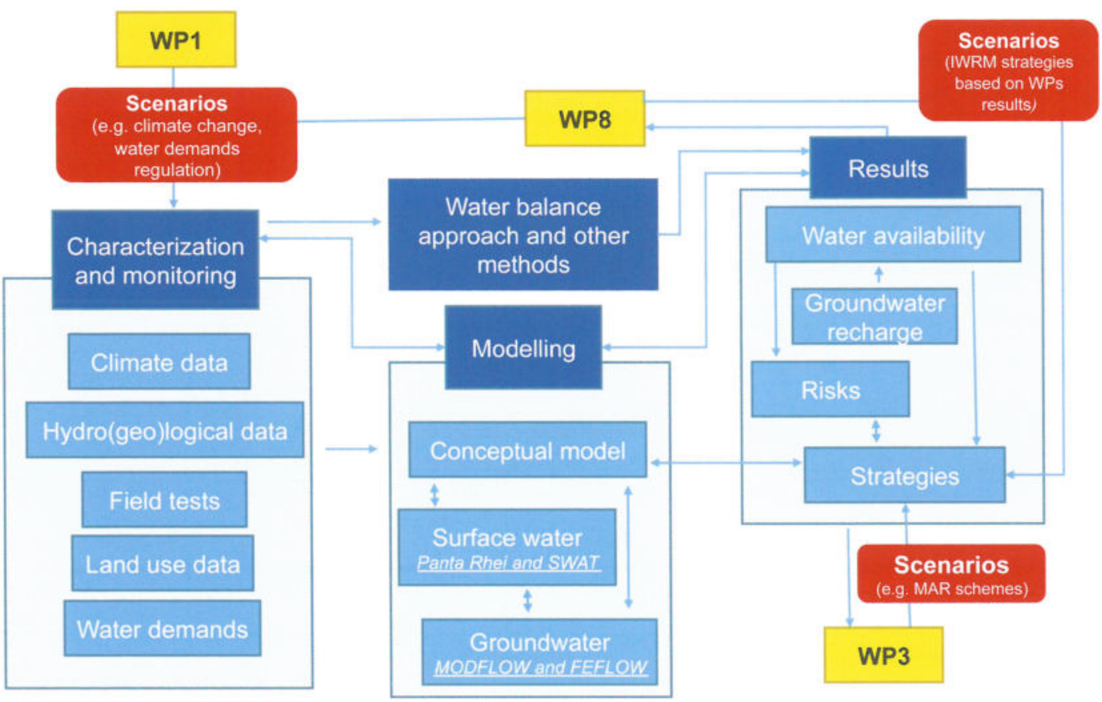


Figure 3.1: Flowchart of modelling process for Water Resources Planning and Management and relationships between WP2 and other work packages within the BRAMAR project

graphic Information Systems (GIS) plays a key role for providing global and regional distributed information about the environmental processes as a whole. The use of these advanced technologies provides many contributions for hydrological science, as it helps to understand the spatial behavior of hydrological variables. Nevertheless, using the aforementioned techniques for groundwater recharge estimation is still a challenge as it is mostly based on indirect methods (BRUNNER et al., 2007). In the project, different components of water balance – such as precipitation, soil moisture, evapotranspiration and surface runoff – were investigated using satellite data. Accordingly, implementing hydrological models in a GIS environment with satellite information may be an alternative to providing high-resolution distributed estimations of groundwater recharge in high-scale areas through a water balance approach (COELHO et al., 2017). For such an application, the remote sensing patterns are translated into distributed deterministic input data, based on pixel-by-pixel or zonal databases, which provides two-dimensional groundwater recharge maps. Moreover, downscaling algorithms may be applied in order to adjust the spatial resolution of the input data to the watershed scale due to the coarse spatial resolution of some remotely sensed products. In this perspective, the BRAMAR project has used remote sensing and reanalysis products (GPM – Global Precipitation Measurement, MODIS – Moderate Resolution Imaging Spectroradiometer, and GLDAS – Land Data Assimilation System) in the water balance equation to calculate the distributed recharge rates at João Pessoa CSA. For the groundwater recharge estimation based on ground-monitored datasets, the Water Table Fluctuation (WTF) method provides a deterministic point-scale approximation of the groundwater recharge by taking into account the water-level oscillation in observation wells as well as aquifer specific yield coefficient data. The WTF method is based on the premise that the elevation of water levels in unconfined aquifers is the result of rainfall that reaches the free surface by infiltration, which characterizes the recharge process (SCANLON et al., 2002). This method was also applied at João Pessoa CSA in order to estimate the annual groundwater recharge rate (FERNANDES, 2017). The results were interpolated in the GIS environment to provide an overview of the spatially distributed groundwater behavior.

3.3.2 Paraiba River Basin & Gramame River Basin (João Pessoa Case Study Area)

Responsible Institution for Modelling: TU-BS

In the focus of the overall regional hydrological analysis are the watersheds Paraíba (20,000 km²) and Gramame (590 km²), which cover in total about 45 % of the state of Paraíba, including 91 municipalities and two large cities: João Pessoa (811,598 inhabitants, IBGE, 2017) and Campina Grande (410,332 inhabitants, IBGE, 2017).

Meteorological parameters such as precipitation, global radiation, relative humidity etc. are the main governing factors for a hydrological model. Data are provided by AESA and INMET, which maintain a dense meteorological network including about 100 pluviometers and 10 climate stations in the region. Locally the meteorological monitoring is also supported by the universities UFPB (region of Gramame) and UFCG (region of Sumé and Sucuru). The regional climate is characterized by an uneven spatial-temporal distribution of rainfall and high evaporation rates. Precipitation values range from 380 mm/a in the semiarid inland to 1900 mm/a at the coast (**Figure 3.2**). First estimations by modelling assume that over 80 % of precipitation in the semiarid inland and 50 % of precipitation at the coast is lost due to evapotranspiration. From a temporal point of view, the hydrological year is divided in a dry season and a rainy season. The rainy season (January to June in the semiarid-inland; April to August at the coast) constitutes more than 85 % of the total annual precipitation at the coast and up to 90 % in the semiarid inland. Since 2012 the region has been suffering from a huge water crisis with precipitation rates lower than 50 % of the long-term annual average in semiarid regions.

For about 90 % of the basins, surface water is the most important fresh water resource. A typical feature for many regions in NE Brazil is the high number (thousands) of ungauged small reservoirs, which are used for small-scale irrigation and livestock supply, as well as for domestic water supply. State Executive Water Management Agency (AESA) monitors about 40 reservoirs for water level and storage capacity in the watershed of Paraíba and Gramame and the volume of these reservoirs sends a clear warning signal about water scarcity: in 2016 the storage volume of about 85% reservoirs in the Paraíba state fell below 50% of their total volume, and the storage volume of about 41% of all reservoirs reached a minimum of less than 5% of their capacity (AESA, 2016). Calibration and validation of a hydrological modelling system with regards to surface water is a complex process which greatly depends on the availability of reliable discharge data. Currently, the hydrometric monitoring program of the region contains huge gaps with only seven gauges operated by AESA and UFPB. In the perspective of an integrated management system, it was of top priority to expand the monitoring system locally. First steps were taken during the project.The model was calibrated and validated for the time periods 2004 to 2008 and 2009 to 2014 using reservoir storage, discharge time series and partly groundwater level as calibration parameters. The model represents the surface water availability and the water balance sufficiently and is suitable for scenario calculation.

The simulated groundwater recharge is one important modelling result as it serves as direct input parameters (boundary) for groundwater modelling and supports the planning of MAR strategies. The long-term groundwater recharge ranges from 11 mm/a in the semiarid inland to 360 mm/a at the coast.

3.3.3 Sucuru River Basin (Sumé Case Study Area)

Responsible Institution for Modelling: UFCG

The basin of the Sucuru River has an area of about 1680 km². The Sucuru River is a tributary of the Paraíba River and is an important source of surface water for a large portion of the semiarid interior of the State of Paraíba, a region known as Cariri of Paraiba. In this region, rainfall is highly irregular, and typically is concentrated in a rainy season of about three months, which occurs between January and June (the mean annual pre-

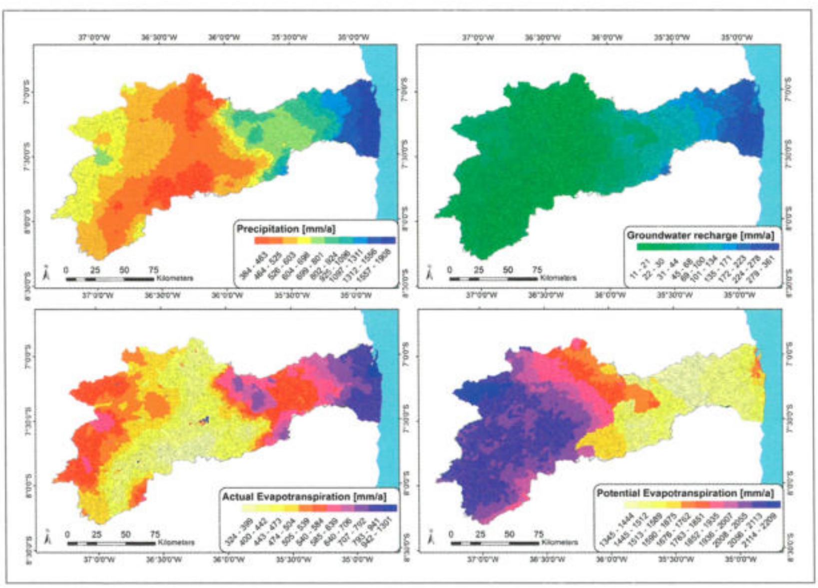


Figure 3.2: Long-term average annual simulation results for the Paraíba and Gramame basins for the simulation period (2000–2014)

cipitation registered at the Sumé rain gauge is 590 mm), with the rest of the year being marked by a dry season. Basin geological formations consist in crystalline bedrocks overlain by a thin soil cover of less than 2 m except in the alluvial deposits in the flood plains adjacent to river channels, in which thickness can reach more than 10 meters. These alluvial deposits represent the most significant aquifer in the region.

The surface water reservoir of Sumé, is the most important storage facility in the basin, with a capacity of more than $40 \times 10^6\,m^3$. Agricultural activities are carried out during the rainy season, using mostly the rainfall supply and the water stored in reservoirs when needed. It is also usual to drill wells along the alluvial deposits along the Sucuru River to use groundwater. In this context, it is of primary importance to store as much water as possible along the rainy season to use it over the dry period. In order to achieve this objective, hydrologists face an important challenge: estimating runoff and erosion without relevant data, even in adjacent basins.

There are many reservoirs located upstream of the Sumé reservoir, and most of them do not have available data about their storage capacity, operation, inflows and outflows. As a result, hydrologic modelling of the entire basin of Sucuru is not straightforward. However, the downstream area of the Sumé Dam is mostly free from interventions and, even though data are not available about historical river flows, other data like soil and land cover maps, precipitation and tank evaporation data are.

The basin area downstream the Sumé Dam is about 938 km^2 and has been subject to hydro-sedimentological modelling with the SWAT model to estimate the basin runoff, soil erosion and sediment yield as well as the groundwater recharge potential/percolation processes (NUNES, 2018). Due to the absence of flow data, the model was parameterized through a trial and error method after the most influential parameters governing the different processes were identified. Previous studies in the region, that indicate an average annual runoff between 5 % to 10 % of the annual precipitation, were used as the guiding criteria to obtain parameter values for modelling, utilizing the land cover and soil use map generated from the satellite images of 1990.

The historic period of hydro-sedimentological simulation was 1994 to 2015. The results are highly consistent with the past experience in the region and may be considered as probable good estimates of runoff considering its spatial and temporal variation. The impact of climate chang-

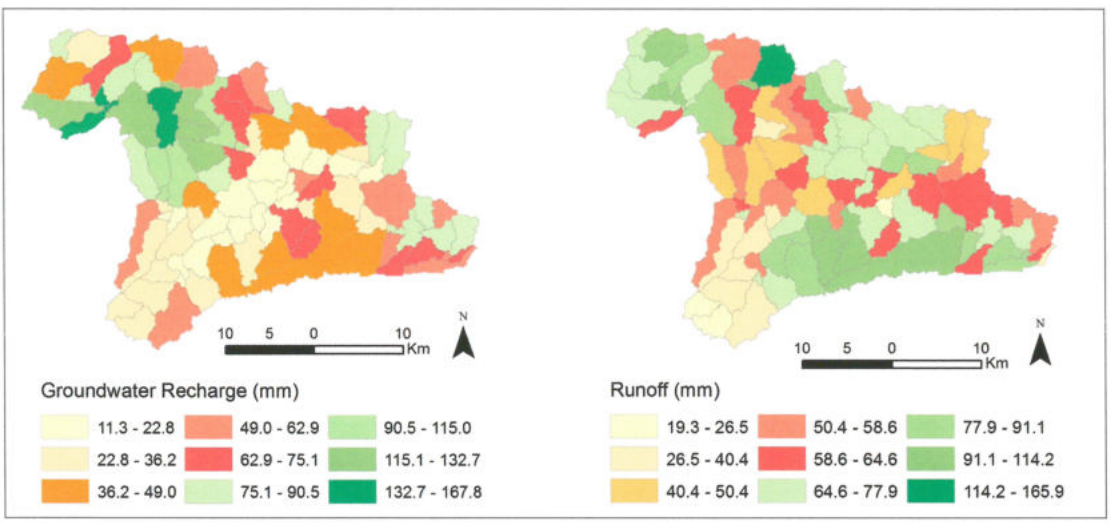


Figure 3.3: Distribution of GW recharge potential and runoff in the Sumé basin. Adapted from (NUNES, 2018)

es on the runoff and percolating/groundwater recharge was also assessed through simulations that took several variations of the historic precipitation series into account. Thus, different precipitation series were generated, altering the historic series uniformly with percentages ranging from -10% to +10% of the observed values in the series. The outputs showed a substantial reduction of overland flow and percolation as the reduction in daily precipitation was close to -10%. Even though the potential for groundwater recharge is quite high as shown in **Figure 3.3**, its average value corresponds to about 60 mm/a, of which most gets lost in a re-evaporation process through the upper layers of soil.

Although the recharge and runoff are a small fraction of the precipitation over the year, representing about 60 to 67 mm/a, the present study showed that runoff and alluvial recharge are appreciable and could be used as water supply for the population of the area.

3.4 Groundwater Modelling

3.4.1 Model Selection

Numerical models are used to solve the equations that rule groundwater flow. Generally, one of the following two methods are applied: Finite-differences or finite-elements. In the finite-differences method, the groundwater potentiometric heads are calculated in nodes using an index that indicates its position in a rectangular grid. In the finite elements method, the position of the nodes is determined by the geographic coordinates in a mesh (ANDERSON; WOESSNER; HUNT, 2015). The main practical difference between both methods is the spatial discretization of the area under investigation. The finite-difference method has the advantage of allowing an easier discretization and simple understanding. Whereas, the finite-element method allows a better discretization, so it is possible to represent irregular geometry at the border, aquifer heterogeneity, fractures or faults in a more realistic way.

The mathematical models dedicated to groundwater flow are largely applied using numerical methods through a Graphical User Interface (GUI). MODFLOW, based on finite-differences, is the industry's standard model, since it is free and requires less data for setting up, allowing a faster configuration. However, it might present some limitations, e. g. it may not be able to simulate dry cells. FEFLOW is a state-of-the-art computational model that uses finite-element methods and can use an unstructured mesh to reconstruct complex geological settings or hydrogeological features e.g. fault lines or rivers, and simulates solute and heat transport (DIERSCH, 2014). FEFLOW is developed and distributed by the company DHI Wasy.

Sumé study area has a small alluvial aquifer with irregular delimitation and high heterogeneity due the presence of clay lenses in its sandier geological composition. On the other hand, the study area in João Pessoa is a sedimentary coastal basin with three overlapped formations and a geological fault. Both models were used in the study areas. MODFLOW was applied during the investigations, and afterward the acquired knowledge was transferred to FEFLOW for more robust tasks.

3.4.2 João Pessoa Case Study Area

Responsible Institution for Modelling: TU-BS (regional unconfined model; João Pessoa & surroundings), UFCG (confined aquifer, urban area of João Pessoa)

Although surface water serves as the main source for fresh water in the whole Paraíba state, groundwater is a potential water source for urban water supply and agricultural irrigation, especially at the coast; therefore, it could constitute a key component for a sustainable, integrated management system. The area studied (1,032 km²) consists of the municipality of João Pessoa and its surroundings, including the whole river basin Gramame and parts of the Paraíba drainage system. A loose coupling between hydrological and groundwater was created using the groundwater recharge as an interface.

Hydrogeological and geological environment defines the framework and the influences on water budget, storage capacity and flow dynamics and is, thus, a crucial component in model development. The study area is part of the sedimentary coastal plain of the north-east coast of Brazil, which is limited to the west (end of Gramame catchment) by crystalline formation outcrops. From a stratigraphical point of view, two aquifers compose the aquifer system: Barreiras (upper unconfined aquifer) and Beberibe (deeper confined aquifer) with different hydrogeological characteristics. The transition between the formations is gradual and still not conclusively clarified. The upper unconfined aquifer comprises sandstone with varying ratios of alluvial sands and clay. The aquifers are divided by an aquitard represented by the Gramame formation, composed of clayey limestone. The Beberibe formation consists of various sandstones (ROSSETTI et al., 2011 and 2012).

The reconstruction of the subsurface is based on the digitalization and analysis of 83 representative bore profiles (AESA, CAGEPA, SIAGAS/RIMAS). A limiting aspect is that all geological information is concentrated on the urban area of João Pessoa and its close surroundings. The average thickness of the upper formations is found to be 45 m (Barreiras) and 55 m (Gramame). The thickness of the lower aquifer is more uncertain as only sparse information is available. The western and the eastern part of the study area are divided by a fault, which corresponds to a graben formed during the tectonic processes that led to the Atlantic Ocean aperture (Cretaceous). At the western part of the study area, the Gramame formation vanishes leaving only one unconfined aquifer based on Barreiras/Beberibe.

The analysis of the groundwater flow is based on the numerical system FEFLOW. For the study area, a three-dimensional model was built up with three layers for the main aquifer systems and a mesh-geometry of about 600,500 elements. The spatial discretization takes into account the implementation of structures, e.g. river streams or faults and follows bore profiles and topographic information for the surface. For the surface information, a digital elevation model based on Shuttle Radar Topography Mission (SRTM) data from the U.S. Geological Survey with a grid resolution of 30 × 30 m is available.

In addition to the subsurface information, the availability and plausibility of groundwater level time series are crucial factors for groundwater analysis. It was an innovative step to establish and maintain a rough regional groundwater monitoring system in this area. Efforts have been made to support the monthly manual measurement by UFPB in a total of 36 wells with the installation of 14 automatic measuring devices for water level, water temperature and electrical conductivity. Despite the (estimated) increasing extraction of groundwater, especially from the upper aquifer by private users (e. g. hotels, apartment units, educational centers, car wash, filling stations), a decreasing trend of groundwater level due to overexploitation cannot be confirmed by data so far. According to AESA as a main institution for groundwater management, about 600 wells are registered within the study area from which 63 % are officially used for water extraction. The number of private wells is expected to be much higher. For sustainability of groundwater management, an equilibrium of groundwater extraction and groundwater recharge is the key challenge. Monitoring as well as modelling helps to characterize the regional hydrodynamics, the drainage of the study area and the water budget. The first step includes the set-up of a steady flow model, developed by TU-BS, considering average annual values for the year 2015/2016 (**Figure 3.4**). The program PEST was used to support the estimation of hydrogeological parameters, like hydraulic conductivity, effective porosity and transfer rates. Pumping tests, infiltration tests and grain size analysis of soil samples were conducted to verify simulation results of hydrogeological parameters. First results are summarized in the following:

The highest groundwater levels of about 177 m a.s.l. are expected in the southwest of the catchment (**Figure 3.4**). Hence, the main flow direction of the model domain is from southwest to northeast toward the coast. The groundwater level RMSE (root mean square deviation, number of wells: 36) is equal to 3.5 m, and checking the water balance provides an equal annual balance (2015/16) when the Dirichlet-boundary (sea level) and the Cauchy boundary for the river network are applied. Monitoring data indicate water level fluctuation due to seasonal variation of groundwater recharge with increasing water levels during rainy season. Maximum amplitudes of 4 m are reached. The regional hydrodynamic is dominated by strong interaction of aquifer and rivers as a consequence of high topographic slopes. An average flow velocity of 0.1 m/d is expected. Further investigations will include simulations of the dynamics using a transient model for the year 2016/17 as well as simulations of management scenarios including changes of land use and climate.

In addition to water quantity, the quality of available water resources has to be taken into account in the framework of sustainable water management. The project focused on the indicator electrical conductivity in order to analyze the initial impact of saltwater intrusion due to overexploitation of groundwater resources in urban areas at the coast. At nine wells at the coast the electrical conductivity has been measured automatically since 2016. Moderately saline values up to 3.64 mS/cm were found. Additional investigations are required, however, to understand pathways and causes for the measured values and to clearly isolate effects of salinization on effects of agricultural use or urban wastewater discharge. A two-dimensional density-driven model was built up and calibrated at a cross-section at the coast.

Numerical modelling was used as a tool for water resources management through the application of another groundwater numerical model in a portion of the study area (BRAGA; GALVÃO; REGO,

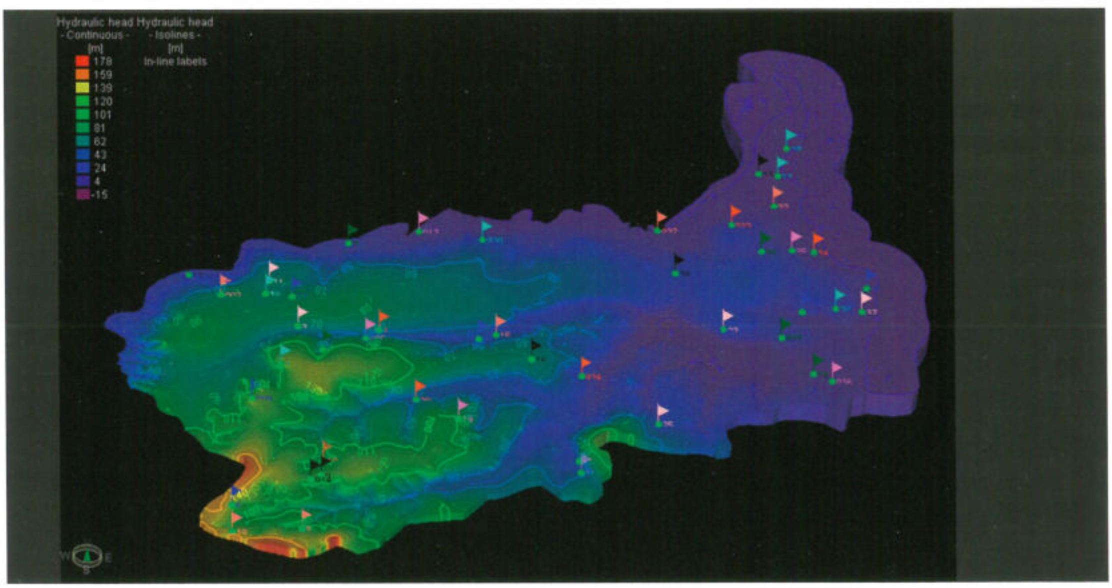


Figure 3.4: Distribution of simulated hydraulic head (steady state flow FE-model -period 2015/16, unconfined) of the João Pessoa groundwater basin (1,032 km²) with a domain direction to the coastal zone. Flags represent observation points for modelling as well as monitoring points for groundwater level. At 36 wells the water level is measured manually, at 14 wells automatic measuring devices for water level and water temperature have also been installed. At the coast the electrical conductivity is measured automatically at nine wells.

2015). The local aquifer potential was quantified and the current methodology for groundwater pumping rights permits evaluated. Although only few data were available, satisfactory calibration results were obtained using MODFLOW. The groundwater availability was compared with data relative to the amount of withdrawal allowed by the water permits. Locally, an over-exploitation was determined, since the withdrawal allowed is superior to the aquifer availability. This occurs because the current methodology does not consider the combination of the aquifer's recharge criteria and the well's yield criteria, but only the latter has been used for concession of water permits. On that way, the intra-seasonal variation has not been considered. The importance of these results shows the need for an approach that considers the spatial temporal characteristics of groundwater flow.

The confined aquifer is of high interest for water supply as it is assumed that it has better water quality. For this reason, a refinement was made in the confined aquifer through the construction of a numerical model, built up by the UFCG, dedicated only to this system. Thirty geological bore profiles and one geological section were used for aquifer reconstruction (SIAGAS, AESA and previous studies). An average thickness of 230 meters was found with a variation between 130 and 450 meters for the Beberibe formation. The closest area to the geological fault is the beginning of confined system.

An additional monitoring network was established with three automatic monitoring wells (RIMAS) and nine wells measured monthly. The current monitoring network shows a high concentration of wells in the João Pessoa metropolitan

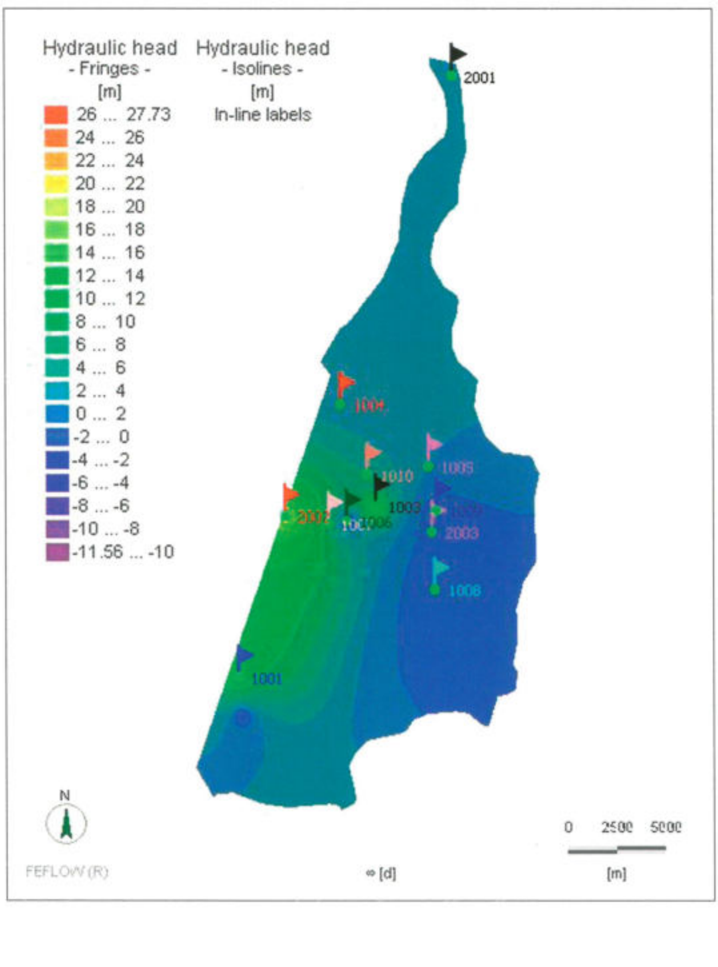


Figure 3.5:
Distribution of hydraulic head within the study area for the time period (2017)
(steady state, confined aquifer)

area, where there is a higher concentration in groundwater pumping. The Gramame River basin has large areas with native vegetation or polycultures, which have low impact on the withdrawal of the confined aquifer. However, the extension of the monitoring network is under development. The data collected for the one-year period confirms that, negative static levels, in reference to the sea level, appear in 30% of the monitoring network. The recharge of the confined aquifer occurs trhough the phreatic aquifer system, which has a positive piezometric level; as a consequence, negative static levels might represent over-explotation.

The southern region presents no-flow boundary condition because it was assumed to be a natural groundwater flow divisor. In other regions, boundary conditions with specified hydraulic head were adopted. Simulation for the steady state is presented in **Figure 3.5**. In the eastern part, negative heads occur at a distance of 5 km to the coast. In the western part, the obtained potentiometric values are similar to the hydraulic head at the border between the confined and the free aquifer, but lower than expected.

3.4.3 Sumé Case Study Area

Responsible Institution for Modelling: UFCG

In the Sucuru River Basin, small alluvial aquifers are exploited for irrigation, and more intensively in the so called "Irrigated Perimeter" area (**Figure 3.6**). This area was previously supplied by the neighboring upstream reservoir until 1987, when an interruption occurred in order to ensure water supply for urban and rural population in the region.

The Sumé case study is representative of water resources systems commonly present in the Semiarid Brazilian Region, composed of the following three main elements: surface water reservoir, small city and alluvial aquifers. Despite of its small size, the latter represents a critical source of water. In addition to the fact that Sumé city is one of the areas that benefit from the São Francisco River Integration Project (PISF), the described scheme highlights the importance of modelling future strategy scenarios to manage surface and groundwater more properly and mitigate conflicts between users. The studied portion of the above-mentioned alluvial system, which extends to approximately 12 kilometers downstream of the Sumé Reservoir, has a width varying from 100 to 400 meters and a depth between 0.45 and 11 meters. Geological profiles were obtained, with 117 boreholes, by percussion drilling (some executed during BRAMAR Project). Not only did they verify the aquifer dimensions, but also the great lithological variability, which features predominantly sandy layers interspersed by silt and clay discontinuous lenses. Furthermore, geophysical surveys using ground penetration radar (GPR) have been used to better delimit the base of the aquifer.

A monitoring network installed through the BRAMAR project, initiated at the beginning of 2015, highly improved the observation of the natural and artificial water balance components required for modelling and understanding/estimating the recharge process. The behavior of ground and surface water, precipitation and climate, as well as wastewater disposal/recharge, were monitored by automatic and/or manual gauges at regular time steps. **Figure 3.6** (zoom in the Irrigated Perimeter area) presents the groundwater level monitoring network, which has been continuously extended.

The tributaries of the Sucuru River can greatly influence the lateral recharge of the aquifer, and precipitation events contribute in various proportions from upstream to downstream (**Figure 3.7**). During the rainy season, the water table level can reach the surface, while over the dry period, which predominates throughout the year, the water depth drawdowns significantly; this, in turn, indicates that the recharge and the discharge of the aquifer occur intensively over a short period of time. Such a reactivity is explained by the combination of aquifer small dimensions and the hydrodynamic parameters of the system, featuring relatively high specific yield and hydraulic con-

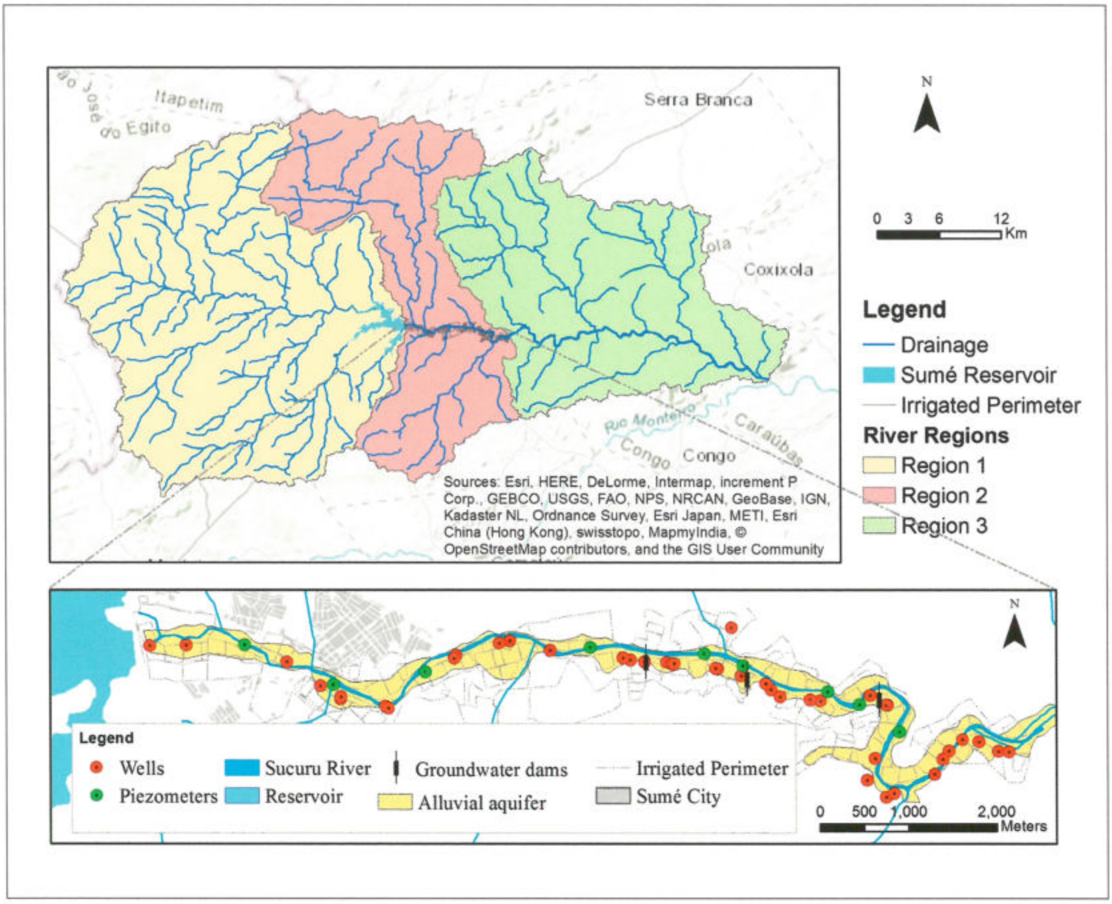


Figure 3.6: Sumé CSA

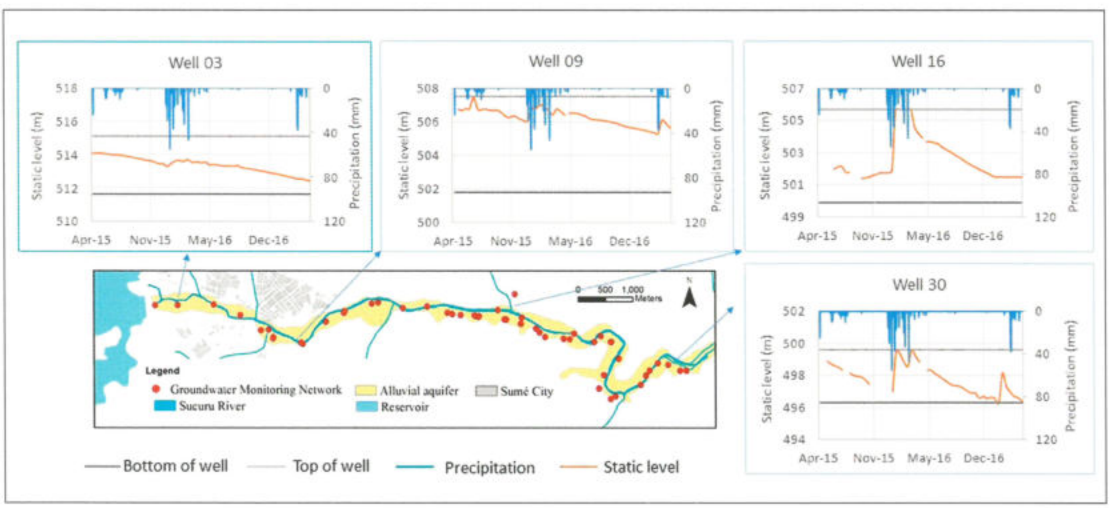


Figure 3.7: Precipitation and groundwater level monitoring along the Sucuru river

ductivity. These parameters were subject to the modelling effort presented in the following.

For this case study, hydrogeological modelling was used both investigating the hydrodynamic parameters, understanding the groundwater flow and potential (water discharge, recharge and circulation processes), and for developing and evaluating management alternatives, according to permanent conceptual model (re)construction.

The small size and high lithological variability of the aquifers' and the rivers' intermittency are aspects that imply complexity for modelling, requiring more detailed information. In this framework, both MODFLOW and FEFLOW models were applied. The latter was preferred due to its ability to better define the model boundary conditions.

The primary hydrodynamic parameters used were obtained through a pumping test (VIEIRA, 2002): 7.87×10^{-4} m/s for hydraulic conductivity and 10 % of effective porosity. Using MODFLOW, the maximum storage capacity was estimated to be near 1.1 million cubic meters, which corresponds to 3 % of the capacity of the Sumé dam. **Figure 3.8** provides an estimation of one-year water availability behavior.

The FEFLOW model was applied to investigate the influence of vertical lithological variability on the behavior of the groundwater flow by identifying different hydraulic conductivity values according to the level reached by the water table (TSUYUGUCHI et al., 2017), as illustrated in **Figure 3.9a.** The variability was also analyzed throughout the aquifer; six different zones were mapped (**Figure 3.9b**). The steady state flow simulations on different dates allowed the evaluation of the raised dynamic, which can be explained by the small aquifer dimensions and great lithological variability, and well as by the high variation of the water level differences in relation to the aquifer thickness.

Alves (2016) used MODFLOW to simulate exploitation regimes in different scenarios of well and groundwater dam allocation and discharge rates, in order to evaluate alternatives of water use management. The influence of underground dams on increasing water availability in the upstream region was observed, which, in turn, requires management of the demands to allow groundwater flow to the downstream aquifer (**Figure 3.10**). This analysis can support farmers and decision makers on discussions over agreements and legislation to allow the most efficient and fair water use.

The river flow intermittency described indicates a strong need for models to have sustainable management, while implying special difficulties for modelling, requiring that the calibration and validation process to be continuous as long as the data is acquired.

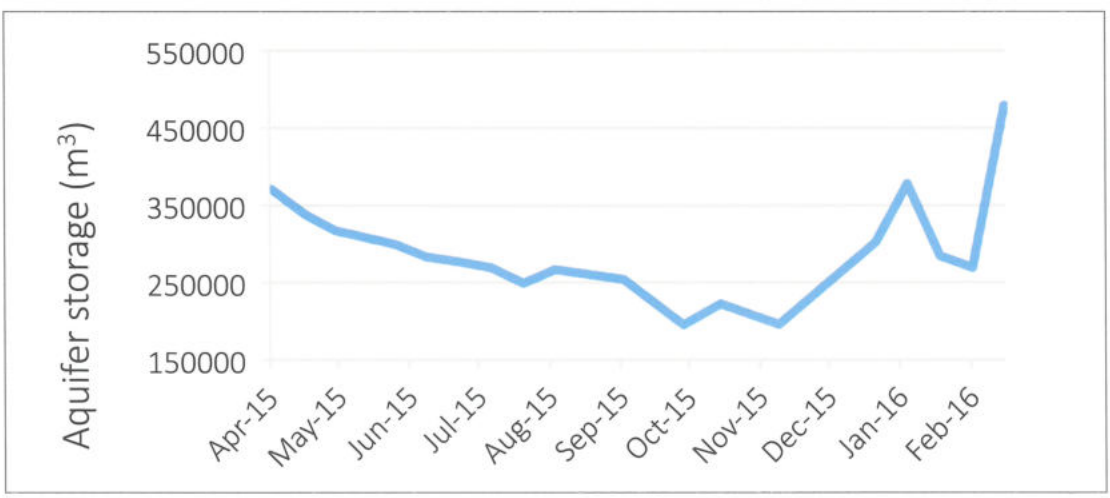


Figure 3.8: Annual groundwater storage variation estimated using MODFLOW (VIEIRA; REGO, 2016)

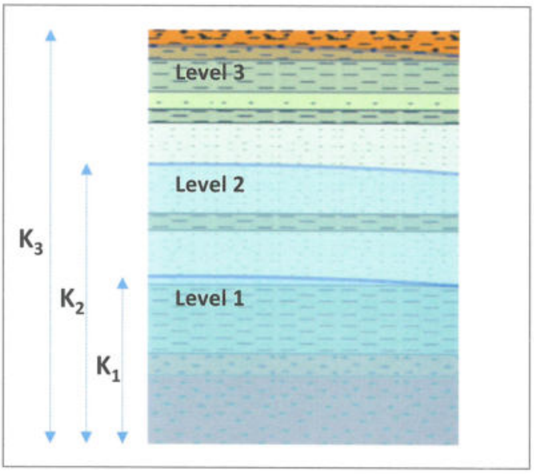


Figure 3.9a: Illustrative scheme (TSUYUGUCHI et al., 2017)

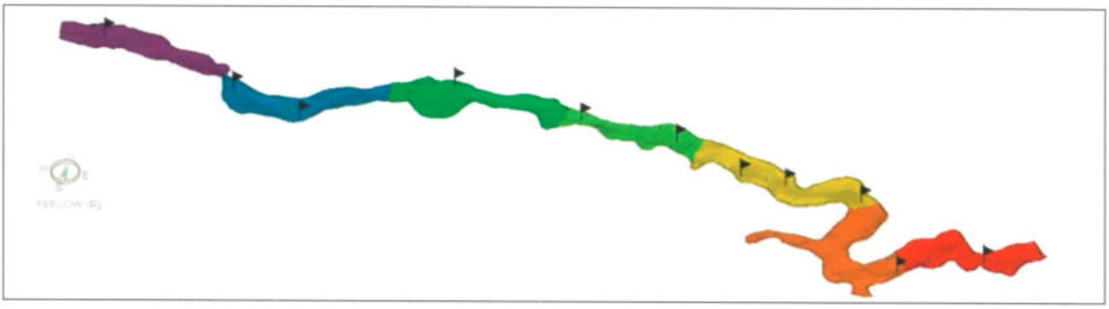


Figure 3.9b: Homogeneous areas and observed hydraulic heads scheme (TSUYUGUCHI et al., 2017)

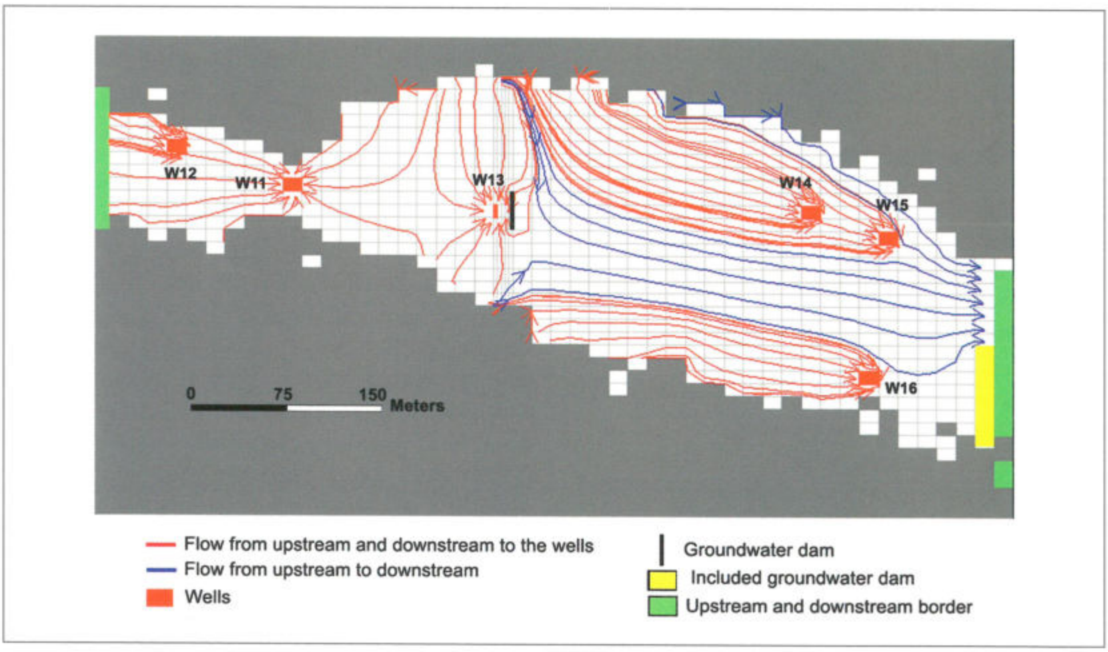


Figure 3.10: Groundwater flow simulation (wells and groundwater dams allocation) (ALVES, 2016)

3.5 Conclusions

3.5.1 Lessons Learned

Dealing with the lack of data was the main challenge of the BRAMAR project and of earlier projects in the same region in the field of modelling. This context, which is typical for the North-East and even for other parts of Brazil, means that in advance of modelling the implementation of a suitable monitoring system and a very first analysis of observations is an important task. Extensive work related to monitoring, field tests and surveys provided - besides better situation of input data and understanding of the water system - interesting knowledge on planning, developing and adapting conditions according to case study particularities. Remote sensing products, which have been globally changing conditions of data availability, have been used to fill in data gaps. The understanding of water balance, flow path and their influencing factors highly depends on the adaption of the conceptual model as close to reality as possible. The discussion over inconsistent results can indicate how to improve the conceptual model, expand monitoring network and extend surveys, applying an approach similar to trial and error methodology. Continuous feedback from monitoring network and surveys to the model, and vice versa, are necessary to overcome the lack of data.

The developed modelling systems have proved to produce - in total - reasonable results and sufficient overall models fitting for calibration with respect to the available spatial input data and available time series. The structural hydrological models show good adaptation to the real topography of the river stream (slope, altitude of catchment, flow direction) and, therefore, represent the geographical conditions of the catchments well. However, during the hydrologic simulations, it was observed that land use and soil data obviously needed to be improved, which was further investigated during BRAMAR. The existing data base with respect to meteorology time series proved to be sufficient to build up first hydrological, models for the catchment areas although several time series contain temporal and spatial data gaps. Nevertheless, the number of climate stations should be increased. The density of gauges for the catchments is very low, which leads to high uncertainties in hydrological modelling results. The accuracy of the modelling results can be improved if several tributaries as well as the inflow to the reservoirs and the outlet of the basins are gauged in the future. The catchment behavior is strongly influenced by artificial impact such as water extraction. Unfortunately, management data for reservoir operation like water extraction reservoirs, overflow and exchange between reservoirs are urgently required, but could not be made available during BRAMAR. In the field of groundwater modelling the geological data situation based on lithological profiles is critical and needs to be investigated further. Groundwater level data are essential for calibration of subsurface flow models. Only few groundwater level measurements have been made in the past within the case study areas. Some observation wells have been installed during this project to characterize the water budget. During BRAMAR, various numerical models were developed in the region which show sufficient results considering the data availability and the complexity of the study areas. The river flow intermittency in semiarid regions, as also alluvial aquifer local emptying, leads to modelling complexity on transient simulations, specially related to constant dry/rewetting cell occurrences and problem convergence issues that have been investigated along BRAMAR Project. The research highlighted the importance of doing efficient and detailed water management, considering surface, ground and wastewater sources. Modelling has a critical role in its development as a tool to support decision makers to govern waters, given the high variability of flow conditions and great seasonal and year-on-year variations of the alluvial aquifer water table and storage volume. By better understanding groundwater systems and dynamics, through quantity and quality analysis, we can support Managed Aquifer Recharge strategy choices and regulation advances. The potential of transferring technologies and strategies is great given the fact that these small systems repeatedly,occur all over the Semiarid Brazilian Region. The most important modelling results are integrated in the decision support system developed under WP8. The development of the monitoring systems was time-consuming and highly limited by its financial budget. It is highly recommended to include the new monitoring network in the framework of the monitoring systems of the water agencies to create a sustainable water management system.

3.5.2 Further Research Needs

The lack of data demanded great efforts on monitoring and field tests, which improved the knowledge of the case study systems substantially. Also, interesting results were obtained on surface and groundwater simulations, and some of the investigations are supposed to be extended. The research on saltwater intrusion and water quality are continuing.

A deeper investigation of groundwater recharge and flow in the alluvial aquifer is essential for optimizing the alluvial aquifer exploitation by development and implementation of MAR mechanisms and water use/reuse strategies. Better understanding of wastewater recharge, which is quantitatively and qualitatively relevant to the alluvial aquifer, given its small dimensions, is important for developing integrated water resource management in the semiarid region. Simulations of solute transport will provide better information of wastewater disposal impact. Conservative tracers, as chloride and bromide, can help us better understand the recharge water sources.

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4

Managed Aquifer Recharge (Results from WP3)

Florian Walter[a], Gerhard Gerold[a], Cristiano das N. Almeida[b], Gilson B. Athayde Jr.[b], Jaqueline V. Coutinho[b], Armando C. R. Braga[c], João D. de A. Pontes Filho[c], Bárbara B. Tsuyuguchi[c], Janiro C. Rêgo[c], Carlos de O. Galvão[c], Hugo M. de Alcântara[c], Suzana M. G. L. Montenegro[d], Victor, H. R. Coelho[d], Anderson L. R. Paiva[d], Guillaume F. Bertrand[d]

a Uni Göttingen, b UFPB, c UFCG, d UFPE

4.1 Managed Aquifer Recharge (MAR) in Water Resources Planning and Management

4.1.1 Role and Importance of Managed Aquifer Recharge

Managed Aquifer Recharge (MAR) is a measure to store water in areas with high evaporation rates by artificially recharging a suitable aquifer and using it as underground storage, thus reducing evaporation losses to a minimum.

The MAR technique has a broad field of application. It does not only aim at increasing water availability for households, agriculture or industry, but it may also be used for environmental issues, such as stabilizing or increasing the local groundwater level to maintain groundwater dependent ecosystems, or to prevent salt water intrusion by introducing a fresh water plume to an aquifer and thus prevent further salinization (ARDUINO et al., 2008). These aspects are of special importance for overexploited aquifers and make groundwater extraction more sustainable. Another beneficial aspect of MAR is the Soil Aquifer Treatment (SAT) effect, used for treatment purposes, e.g. for wastewater (GHANEM et al., 2007). Here, the vadose zone is used as a filter, which treats the infiltrated effluent to a point that the aquifer will not be contaminated.

The main purpose of groundwater management is to expand water resources, generate higher water quality in times of surplus, and improve better distribution in times of shortage (ASCE, 2001). MAR often provides the cheapest form of new safe water supply for towns and small communities in rural areas. With training and demonstration projects, MAR has the potential to be a major contributor to the UN Millennium Goal for Water Supply, especially for village supplies in semiarid and arid areas (DILLON, 2002). For a long time, managed recharge has provided a means to mitigate depletion of groundwater levels, to protect coastal aquifers from saltwater intrusion, and to store surface water for future use (BOUWER, 2000).

In the context of IWRM, MAR has to be understood as an optional measure, competing with other water resources planning and management solutions (RUSTEBERG et al., 2012). Implementing MAR measures is highly dependent on site-specific parameters. The quality and quantity of the water source, hydrogeology of the study area, operation and implementation costs and the availability and comparative feasibility of alternatives are of major importance (BOUWER, 1996).

4.1.2 Main Challenges of MAR Implementation in North-East Brazil

The North-East of Brazil has the common challenges faced by any MAR system throughout the world, such as risks related to health and environment or constrains in the hydrogeological or regulatory aspects. In semiarid regions, MAR could be carried out with surface water to reduce evapotranspiration and runoff losses, as also with treated wastewater to increase groundwater potential. Regarding wastewater recharge in that region, there is a current state of Un-Managed Aquifer Recharge at alluvial aquifers by wastewater that needs to be managed. However, the small alluvial aquifers present low depth and high inter-seasonal variation of saturated zone thickness, all of which limit the potential of vadose zone treatment and require, therefore, further investigation in order to optimize the possibilities of using SAT techniques. Injection of available surface water stored at dams may result in increased supply by diluting wastewater impact. A possible challenge is related to public acceptance of the use of wastewater, although, as Unmanaged Aquifer Recharge of this source already exists and as other water sources are scarce, it may not be a great concern as may be in other regions with greater availability. On top of that, there is a restrictive regulation combined with the incipient reuse legislation, limited knowledge from users and stakeholders (which may result in small acceptance) and low availability of hydrogeological data, required for modeling purposes and strategies development.

4.1.3 Overall Objectives and MAR Planning Approach

The main objective of the MAR studies in BRAMAR was to define the most promising MAR planning schemes for each case study. To achieve this, potential water sources for MAR had first to be identified and characterized. Recommendations for infiltration technologies and locations should be given, and necessary pre-treatment measures and operation schemes defined. Laboratory and field experiments should be conducted to support the analyses. The results of all case studies have been combined with regards to a set of general recommendations as well for the case study itself, as wells as for a general guideline towards MAR feasibility studies in similar regions.

Introducing the MAR concept is site specific and very challenging from a planning perspective. Depending on the raw water quality, the nature of the aquifer and the MAR technique, different methods of pre-treatment for the recharge water are required. The implementation of a MAR system requires careful planning in terms of achieving efficient integration into the water resources system and the overall water resources management objectives (RUSTEBERG et al., 2008).

Figure 4.1 illustrates the suggested overall MAR planning approach for the studies within the BRAMAR project. Before the development of MAR planning options, a feasibility study is required. This comprises an analysis of the local water resources system and the identification of the existing problems with these resources (e.g. droughts, high deficits covering the water demand or over-exploitation of existing groundwater resources). Once MAR has been identified as a potential response to these problems, MAR planning options

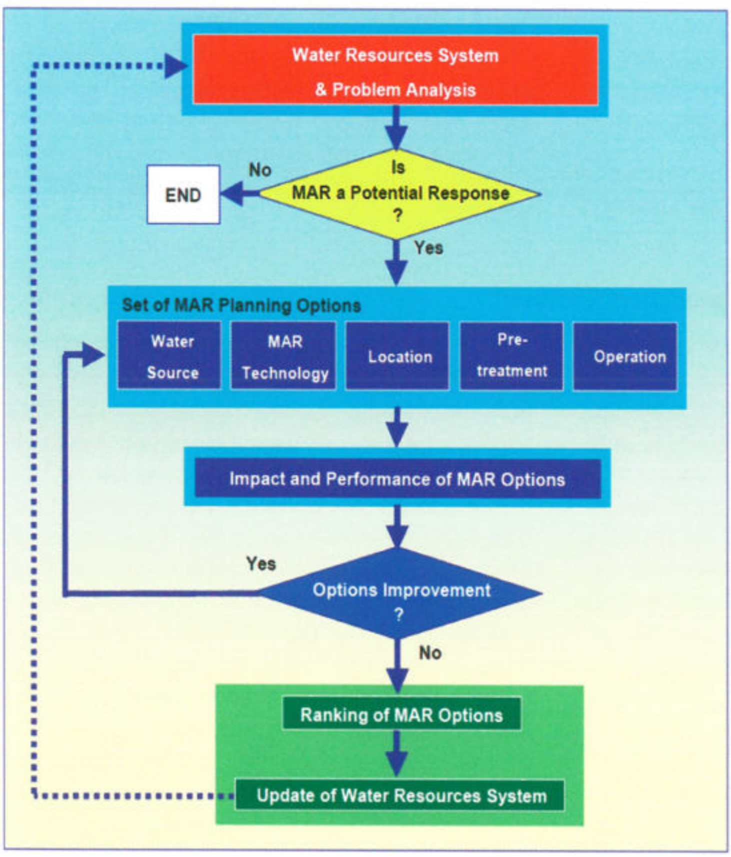


Figure 4.1:
MAR Planning Approach
(RUSTEBERG et al., 2012)

can be developed by means of water budget calculations. These need to address, following the approach of RUSTEBERG et al., (2012) five key elements: Water Source(s), MAR Technology, Location, Pre-Treatment and Operation.

As pointed out, MAR planning is very site specific. Accordingly, each case study adjusted the suggested methodological approach. The individual methodologies are introduced in the respective sub-chapters.

4.2 MAR Planning in Semiarid Region: Sumé (Editor: UFCG)

Introduction

In the case study area of Sumé, the wastewater of the city, of which only a part is treated, is disposed of over the bed of the intermittent Sucuru River, infiltrates in the alluvial aquifer and it is stablished as an Un-Managed Aquifer Recharge (UMAR). With the intensive contribution of wastewater, this recharge has potential for water reuse, but can cause contamination of the aquifer, especially in terms of salinization, as already identified (SALGADO, 2016; SILVA, 2016). Thus, the greatest challenge to MAR initiatives in environments like this is to regulate this process in order to control the quality and the volume of this recharge.

The use of MAR techniques in alluvial aquifers lying over a crystalline basement is promising, given local characteristics. Taking into account the small size and the importance of this reserve due to long annual dry period leading to water scarcity and high evapotranspiration rates, an additional and continuous recharge would be strategic to increase water security of its users and contribute to achieving United Nations Sustainable Development Goals.

This case study is representative of many other municipalities of Brazilian semiarid regions, which release their wastewater into dry alluvial river bed and are associated with dams.

Specific Challenges

North-East Brazil has the common challenges faced by any MAR system throughout the world, such as risks related to health and environment or constrains in hydrogeological or regulatory as-

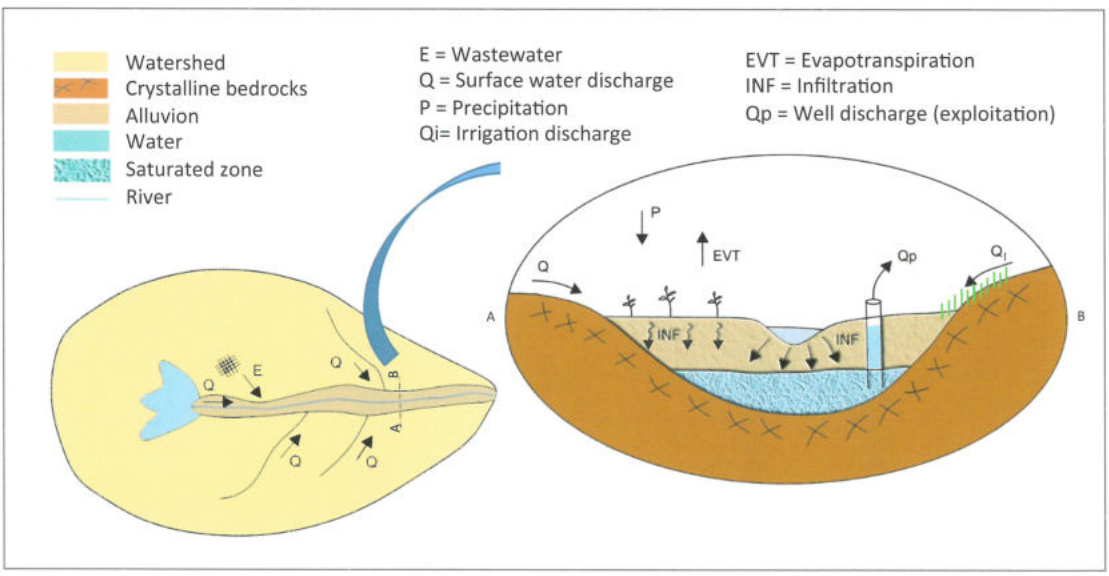


Figure 4.2: Conceptual model of Sumé CSA

pects. In semiarid regions, MAR could be carried out with surface water to reduce evapotranspiration and runoff losses as well as with treated wastewater to increase groundwater potential. In that region, there is a current state of un-managed recharge at alluvial aquifers by wastewater that needs to be managed. However, the small alluvial aquifers present low depth and high inter-seasonal variation of saturated zone thickness, which limit the potential of vadose zone treatment and require, therefore, further investigation in order to optimize the possibilities of using SAT techniques. Injection of available surface water stored at dams may result in increased supply by diluting wastewater impact. A possible challenge is related to public acceptance of the use of wastewater, although, as UMAR of this source already exists and as other water source are scarce, it may not be a great concern as may be the case in other regions with greater availability. On top of that, there is a restrictive regulation combined with the incipient reuse legislation, limited knowledge from users and stakeholders (which may result in low acceptance) and limited availability of hydrogeological data, required for modeling purposes and strategy development.

Main Objectives

The main objective is to define a conceptual model to establish MAR procedures at small alluvial aquifers combining the use of dam water release and wastewater as sources of recharge.

Methodology – MAR Planning Approach

Primary steps to consolidate a conceptual model of the area and plan MAR measures are characterizing and monitoring of water quantity and quality and analyzing hydrogeological information. More than 100 borehole profiles and geological sections, obtained by applying nondestructive geophysical method surveys (Ground Penetrating Radar – GPR), were used to understand lithology. The hydraulic head was monitored at around 40 wells, with periodicity of 15 days. Nine of these wells were chosen to be monitored in terms of water quality, as was the effluent of the wastewater treatment plant and the water from the dam. These water quality analyses are important to understand the current

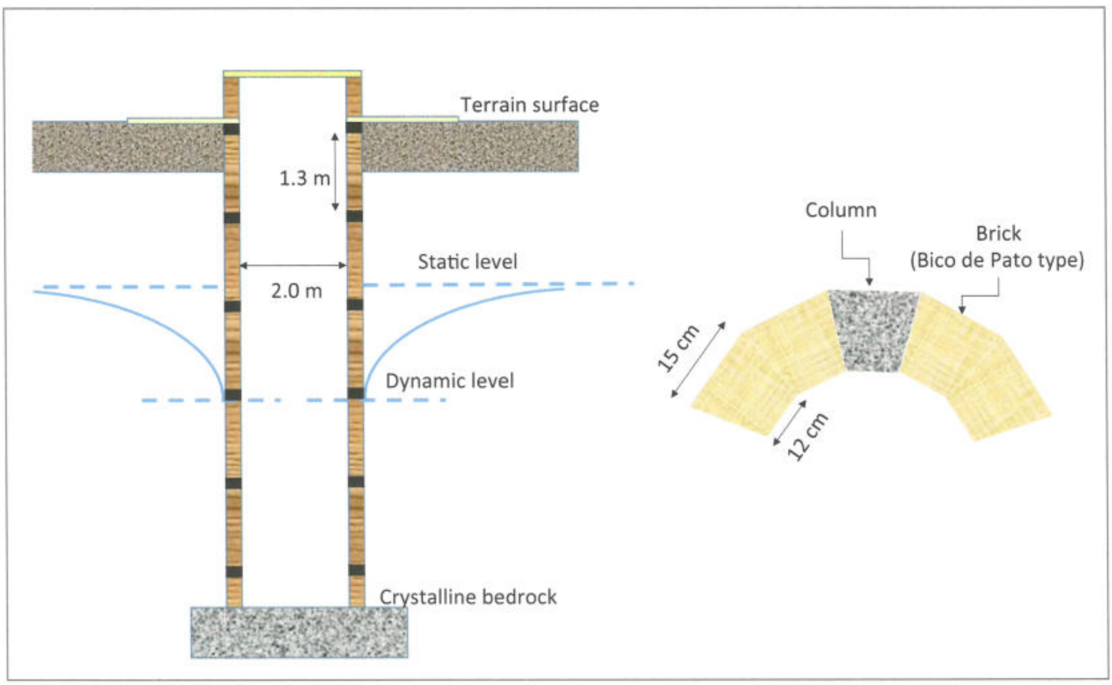


Figure 4.3: Schematics of the Bico de Pato well (adapted from REGO et al., 2014)

situation and plan MAR measures, while also considering quality issues. Chloride was chosen as a tracer to indicate relevant presence of wastewater into the aquifer.

MAR Planning at the Case Study Area

Thanks to a good understanding of current state at Sumé CSA, we could illustrate the conceptual model of the area, with natural and UMAR sources, as shown in **Figure 4.2**.

Proposed MAR procedures that suit the Brazilian semiarid region suggests operating the hydraulic infrastructure already existent in the region to recharge alluvial aquifers by dam release and treated wastewater (TWW). In Sumé, the operation of the 44 hm^3 dam and TWW flow rate of 1,460 m^3/d, to be reached at the conclusion of the wastewater drainage system of Sumé city, are considered important sources of recharge, in a quantitative point of view for MAR. This condition supplements the natural recharge that is concentrated in three or four months of the year. In order to perform its infiltration, the use of injection wells is suggested.

The well called *"Bico de Pato"* (duck beak, translated literally) was designed according to the characteristics of local aquifer and social aspects in order to enhance its production (REGO et al., 2014) and can be seen in **Figure 4.3**. Brick type and dimensions were chosen to allow the flow of water through the entire length of the well walls. As there is no grouting between bricks, every 1.2 meters structural elements are disposed along the well, as are three columns. This absence of grouting allows greater flow through its structure. This design proves to be hydraulically advantageous and is also used as an injection well. As the treated effluent has already lower suspended solids, the *Bico de Pato* injection well is proposed to infiltrate both dam release water and TWW.

Furthermore, the operation of the MAR system needs to ensure a minimum space from the soil surface to the water table to minimize evapotranspiration and to provide a large enough vadose zone to treat the injected effluent. A detailed version of this MAR strategy is presented by PONTES FILHO (2018). A summary of the MAR strategy proposed to Sumé CSA is illustrated in **Figure 4**.

Main Results

SALGADO (2016) verified the water quality variability along the groundwater flow path within the aquifer, through analysis of different parameters in nine wells distributed in the longitudinal section of the fluvial system. This diagnosis pointed out good perspectives regarding the Soil Aquifer Treatment, and so to reuse wastewater. However,

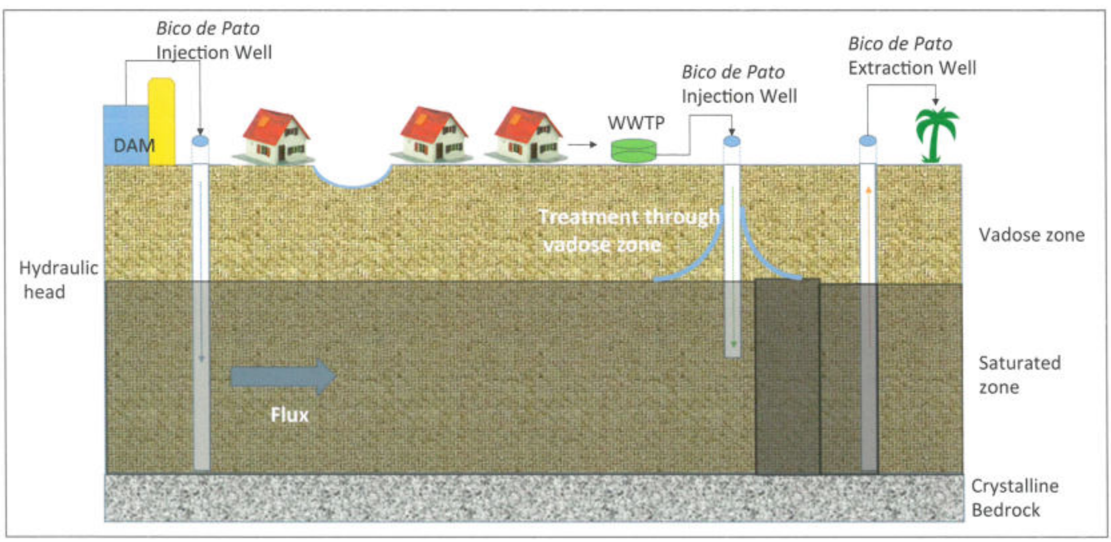


Figure 4.4: MAR strategy summarization for Sumé CSA (adapted from PONTES FILHO, 2018)

concerns about applying this technique are necessary, given the need for considering the resulting impact, such as salinization of the soil.

Based on these results, two tools can be developed to facilitate operation and simulate possible results: (i) a methodology based on water and chlorine mass balance that could be easily operated by local managers to estimate amount of water to be released and the final mean chloride concentration at the aquifer, and (ii) a flow and solute transport numerical model. The chloride ion was chosen as a tracer due to its presence in domestic wastewater and its conservative properties.

A location to install this MAR system of the TWW has to be found near the WWTP using geological surveys to identify places where soil thickness is greater than seven meters.

In governing water law instruments, legislators should properly consider the procedures presented in order to enable, in fact, their implementation and support the managers to act with the responsible entities. The medium- and short-term water plans and legislation requirements cannot be defined without the perspective of the currently situation of low-tech or no-treatment for wastewater, combined with the absence of streamflow, which is a common condition in the region. The water system peculiarities presented of this representative case should be considered on future strategies choices.

4.3 MAR Planning at Coastal Region

4.3.1 João Pessoa – Overall MAR Feasibility Study (Editor: UG & UFPB)

Introduction

The outline of the case study area João Pessoa was introduced in the chapter on WP2. The area is characterized by extreme rainfall and surface runoff during four to five months of the rainy season per year and an extensive anthropogenic use of the local aquifer system. The main sector that demands water is agriculture in the large rural area, predominantly from sugarcane plantations. Water demand and availability strongly depend on the annual precipitation falling directly over the coast, since the local aquifer system receives little to no horizontal recharge from the semiarid inland. Vertical groundwater recharge is strongly restricted in the urban area due to the impermeability of the ground. The aquifer reacts strongly to climatic variability with several meters of groundwater fluctuation in between months. Both water quantity and quality must be studied carefully with regards to risks affiliated with the intense agriculture, its consumption of irrigation water and use of pesticides. The studies also need to include the domestic water systems in the rural area, which have little to no treatment of wastewater and many cases of unmanaged aquifer recharge from cesspits and industrial wastewater. This study focusses on the quantitative aspect of a sustainable use of local water resources and the creation of a data base that is crucial to the future planning and management of the valuable resource.

Main Objectives

The case study of João Pessoa was focused on two major objectives. The first was to create a fundamental data base for MAR planning in terms of data acquisition. Since very limited data was available on local groundwater resources, it was necessary to manage these resources and overall hydrogeology and to closely cooperate with WP2 to obtain these data by means of field and laboratory tests, as well as from groundwater monitoring. The second main objective was to re-think the suggested MAR planning approach and develop a more sophisticated planning process, especially one that addressed data scarcity and dealt with limited resources. This approach should be adapted for future studies as a guideline for preliminary MAR feasibility studies, especially in North-East Brazil.

Methodology – Extended MAR Planning Approach

WALTER (2018) developed an extended MAR planning approach that should provide a guideline for initial MAR feasibility studies, lead to the implementation of test facilities and finally make recommendations for MAR implementation at any study area. **Figure 4.5** provides a simplified schematic of the approach. Within the context of the BRAMAR project, a special focus was given to the first three steps: data acquisition and analysis towards general MAR feasibility, basic MAR planning study and the definition of conceptual MAR options that should be used for groundwater simulations and be improved in an iterative process.

The individual steps and methods applied to conduct the basic MAR planning study and develop conceptual MAR options are described in the following.

Conducted Studies towards MAR Planning at the Case Study Area

Data Acquisition and Analysis towards General MAR Feasibility

There are many physical aspects to be considered for MAR implementation. In the course of the study, many assessments, field tests and laboratory experiments have been conducted.

The data sheets of 238 boreholes have been analyzed in order to outline the local hydrogeology and create a 3D image of the aquifer system.

The local hydrogeology was subject to many field investigations. Groundwater pumping tests were conducted in over a dozen wells, investigating the hydraulic properties of the unconfined aquifer that might be suited for MAR. In parallel, double-ring infiltration tests were performed to determine the natural infiltration rates allowing for percolation. The data obtained from these experiments will support the future development of groundwater models, such as under WP2, and support the current planning of actual MAR facilities. It is crucial that these experiments are extended to obtain a valuable hydrogeological model on a regional scale. In addition, the establishment of a running groundwater monitoring network in collaboration of WP2 and WP3, presented in the prior chapter, was one of the most important work packages conducted towards the creation of a data base for water management planning.

To identify the feasibility of Soil Aquifer Treatment in the region, we conducted percolation tests throughout soil columns in the laboratory. Samples from different locations were fed with

Figure 4.5: Extended MAR Planning approach (modified according to WALTER, 2018)

secondary treated wastewater from the city of João Pessoa in order to determine the natural remediation of the soil material. The studies showed promising results, but need to be extended to obtain usable data.

Some of the results were compiled in order to support the BRAMAR-IDSS developed under WP7. It includes a tool for spatial, multi-criteria analysis that helps identify suitable locations for MAR implementation. The tool operates on spatial data such as land use, topography and groundwater level. Although first results on a pre-selection of suitable MAR locations could be achieved within the project, a much more sophisticated data base is required.

It was concluded that the study area in general is suited for the installation of an MAR system.

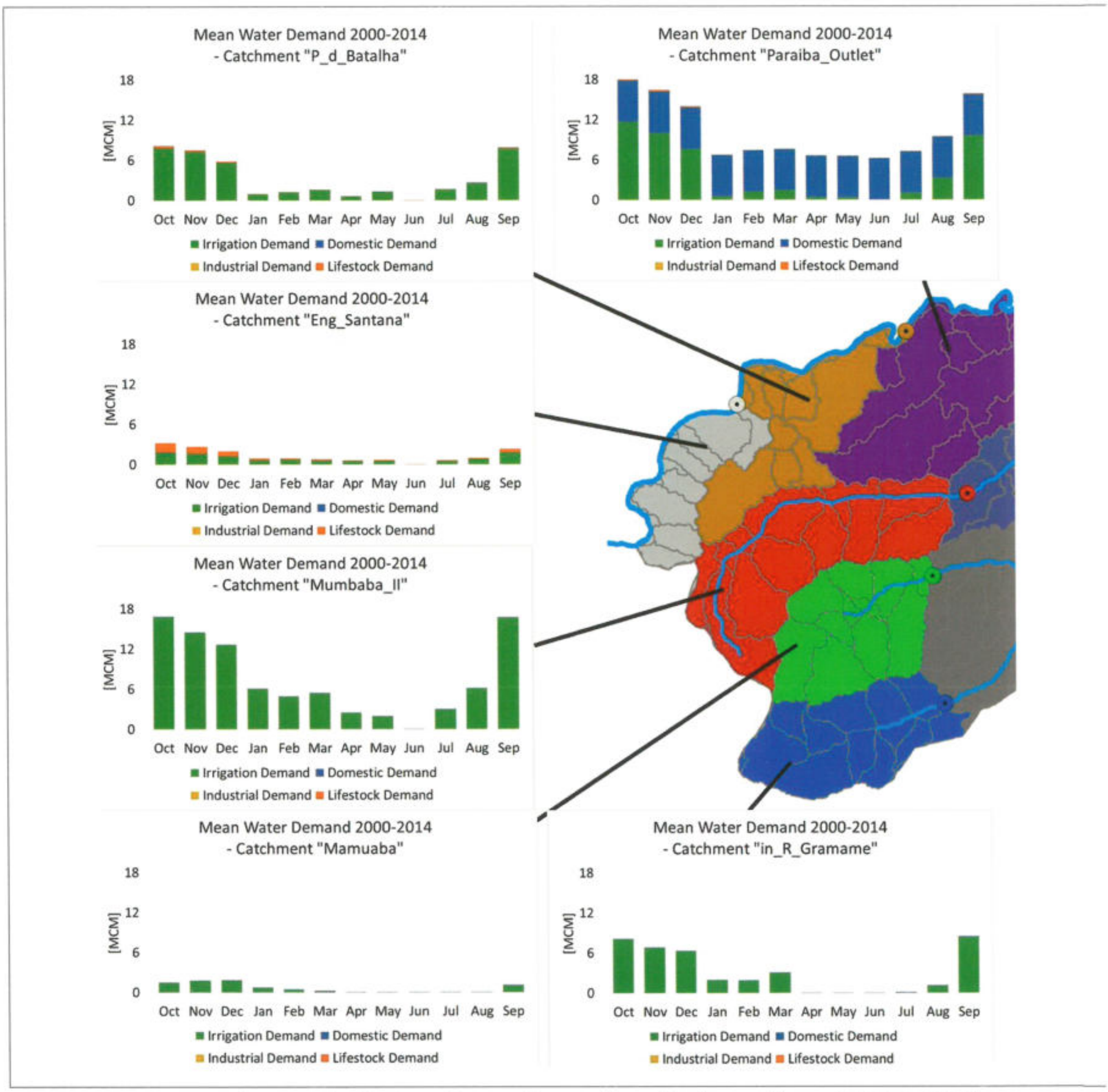
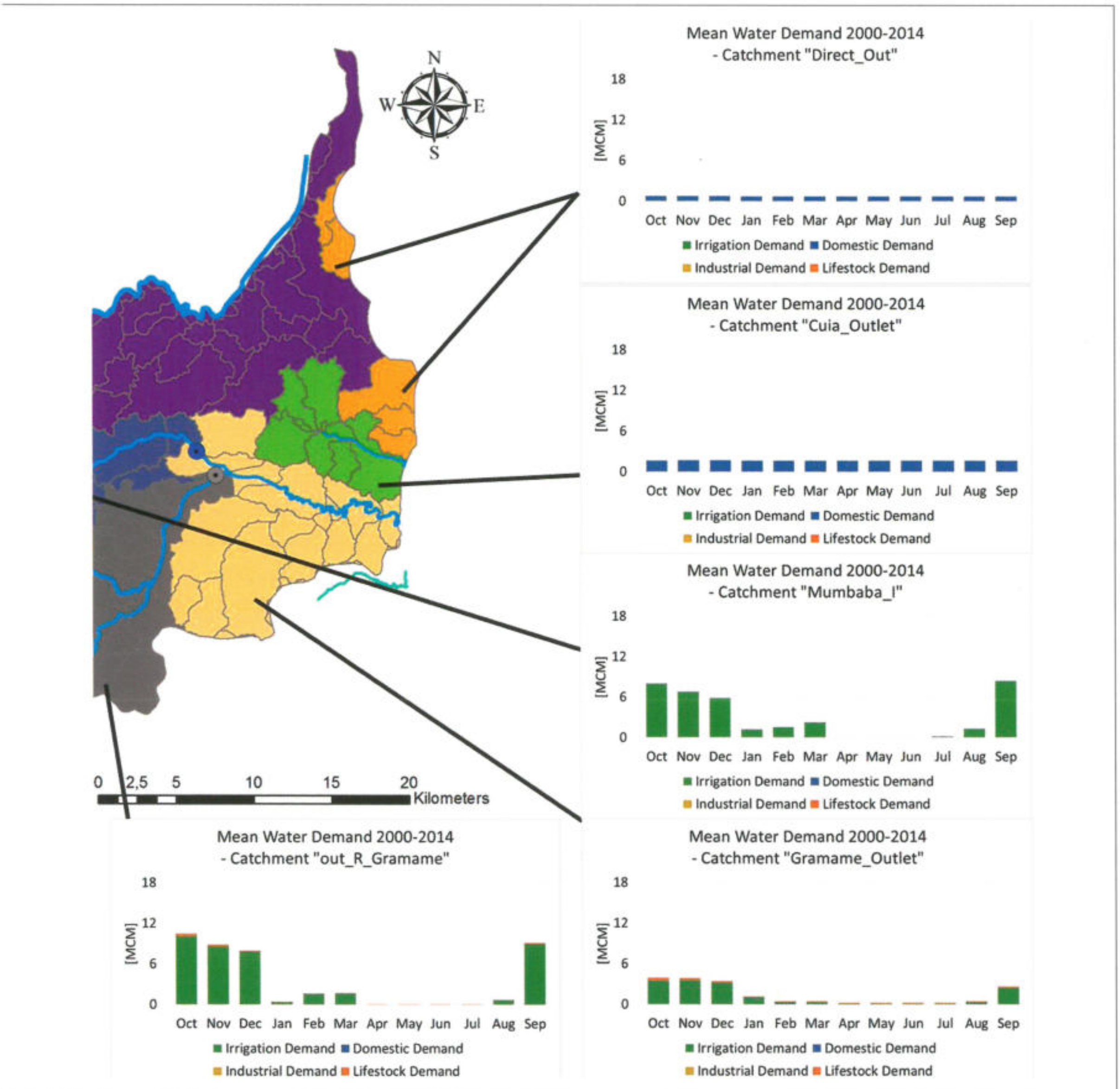


Figure 4.6: Spatial imbalance – distribution of water demand (modified according to WALTER, 2018).

Water Resources System Analysis

The identification of water surpluses and deficits is a basic step when it comes to MAR planning. For this purpose, water demands and availability must be known on a spatial and temporal level. With this information, very basic groundwater budget calculations can be performed that reveal when and where MAR might be a solution to limit groundwater depletion and increase the systems' resilience against increased water stress. Due to vast data scarcity in the study area, main source of data were the results of the hydrological model developed under WP2, presented in the prior chapter. The study is based on a meteorological data set of 14 years from 2000 to 2014 with monthly resolution. Special attention has been given to the agricultural water demand. Existing data has been updated by means of field



investigations and satellite image evaluation to create an up-to-date land use map. Together with climate data supplied by WP2, irrigation demand has been calculated according to FAO standards.

Figure 4.6 illustrates the calculated water demands on the scale of so called "Management Units". They show a great spatial imbalance of water demand due to high irrigation in the western part and high domestic water demand in the eastern part of the study area.

Figure 4.7 shows aggregated results on a mean monthly basis for groundwater withdrawal and recharge for the entire study area. The temporal imbalance of recharge and groundwater exploitation is obvious. The dashed surface represents potential additional groundwater recharge via MAR.

Results show a clear imbalance in spatial and temporal distribution of water demand and availability. This gap must be overcome by means of water storage. MAR is a valid solution to improve the water management system.

Groundwater Budgets

Based on these water budget calculations, the potential impact of MAR measures has been analyzed. These calculations have been conducted for the current situation, as well as for several scenarios of climate change, demographic development and change in agricultural land use. Figure 4.8 shows the calculated potential effect of MAR implementation on the water resources system. The graph shows a baseline scenario without any change in current land use patterns or average precipitation, assuming a conservative development of the region. The black line represents the accumulated groundwater budget calculated over the course of 15 years as an average for the entire study area. The top figure shows the scenario calculated without any additional recharge, while the lower figure represents the same scenario with an additional implementation of a set of suggested decentralized MAR facilities. The analysis has been conducted with more than a dozen different combinations of scenarios and corresponding options for MAR implementation in order to identify the best strategies for MAR.

Results show that MAR can improve the groundwater system's resilience towards dry periods. The study was also conducted with a high variation of future scenarios in relation to climate change, land use change and demographic development of the region.

Main Results

Water budget analyses show there is a strong spatial and temporal imbalance between water demand and availability in the case study area. Vast surpluses and floods during the rainy season stand in contrast to highly increasing water demand during the dry season. When scenarios of

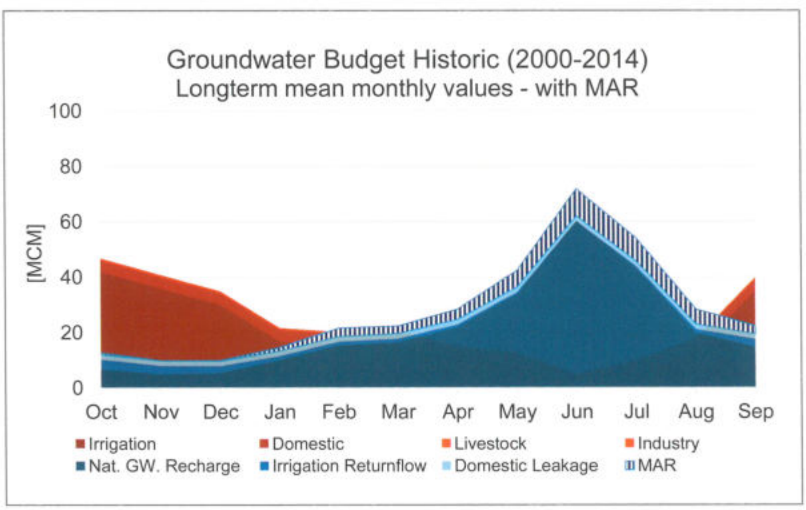


Figure 4.7: Temporal imbalance – mean groundwater withdrawal and recharge (with recommendation for MAR; modified according to WALTER, 2018)

agricultural extension, land use change and climate change are analyzed, the system shows extreme high sensitivity towards rainfall quantities. The creation of additional water storage will, in any case, increase the water resources system resilience.

Local aquifers are the most important storage facilities and sources of water to close the gap between the rainy and dry season. They are under enormous stress owing to high fluctuations of the water table and need to be protected in order to preserve a sustainable water supply for the entire study area. MAR might be a suitable and feasible instrument to achieve this goal. The analyzed time series showed an immense improvement of the systems' resilience towards dry periods.

The high spatial heterogeneity in water demand and availability lead to the conclusion that MAR should be installed in a decentralized manner. Recharge facilities must be distributed according to local water extraction rates from the aquifer within the rural area. The main source for MAR should be surface runoff during the rainy season. A sufficient distance to rivers must be considered in order not to directly lose the recharged water to the streams.

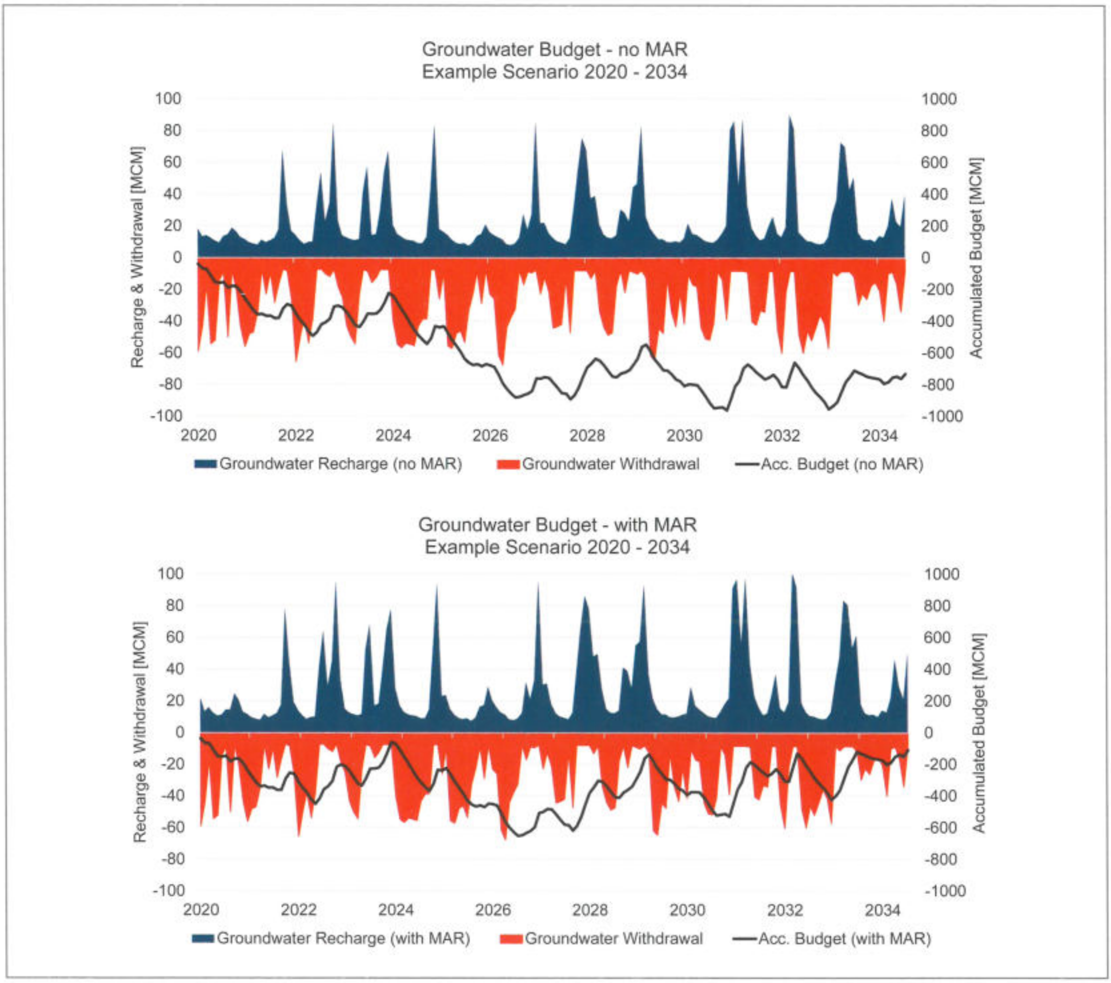


Figure 4.8: Calculated Groundwater Budget without MAR (upper) and with suggested MA implementation (lower) - example for a budget scenario 2020-2035 (modified according to WALTER, 2018)

Effective water retention methods in the rural area are recommended to increase local recharge. Rain water harvesting solutions such as those analyzed in the Recife case study can be beneficial for the study area. In addition, minor SAT facilities might support local groundwater balances.

Future studies must set a stronger focus on groundwater quality analyzes and the socio-economic feasibility of MAR implementation, following the suggested MAR planning approach by WALTER (2018). In order to plan actual MAR pilot plants, further field investigations and a continuing monitoring of the groundwater resources are crucial. Without a proper data basis, most analyses must rely too much on estimations and assumptions. Authorities are urgently recommended to support the exploration of these resources by means of monitoring the groundwater. A special focus should be set on the monitoring and restriction of groundwater exploitation. Data analyses showed a vast lack of knowledge in terms of actual extraction rates from the aquifer.

Without this information, no reliable water management can be established. The danger of overexploitation of the groundwater resources is highly indicated for the João Pessoa case study.

The detailed results of both, the water resources system analysis and numerical MAR feasibility study, will be published 2018 in the PhD thesis of Florian Walter at University of Göttingen.

4.3.2 João Pessoa – Specific Deep Aquifer MAR Planning (Editor: UFCG)

Beyond the analyses presented above, the BRAMAR project also focused on the confined aquifer exploitation at the João Pessoa metropolitan region. With more than 1 million inhabitants, the João Pessoa metropolitan region has the common problems faced by large urban areas in North-East Brazil: high impermeabilization, uneven distribution of infrastructure and uncontrolled expansion of the region. These factors, combined with economic growth, have been increasing the amount of localized groundwater exploitation, more specifically in the confined aquifer, which has a higher yield and better quality.

In a global analysis, over-exploitation was already identified in the confined aquifer, as seen in Chapter on. WP2, and caused mainly by the spatial concentration of withdrawals. The spatial distribution of wells has a major concentration in the metropolitan region of João Pessoa. Hence, a more dedicated MAR strategy also should be applied, which can recharge the confined aquifer and encompass the metropolitan region.

The geological configuration of the confined aquifer presents a natural recharge area that has positive (above sea level) heads; thus, the identifications of negative heads could indicate an over-exploitation. These signals were detected in the ASUB project (2010) and have been consistently identified in the monitoring network established under the BRAMAR project. From 13 monitoring points, 5 of them have presented negative heads (**Figure 4.9**).

A multilevel piezometer is currently being installed, and together with the phreatic and confined monitoring network, will allow a better understanding of the interaction between both aquifers. This interaction has great importance since the recharge area of confined aquifer is situated westbound of the fault where the two aquifers overlap. Hence, the piezometric head in phreatic aquifer, in the fault zone, direct influences the recharge and the confined aquifer's groundwater availability.

As result, two conceptual approaches for specific MAR measures and how to apply them are suggested , as a strategy, focusing on the recharge of the confined aquifer. The first approach takes advantage of the geological setting for inducing recharge. The second considers land use and land cover as an important interface for the aquifer recharge in urban areas.

Border induction to confined aquifer

The study area has a geological fault that functions as a border between the free and confined subsystems. East of the border the Gramame Formation occurs and acts as a confining layer of the

Beberibe Aquifer, and at the west the subsystem is free. The controlled increase of exploitation in the confined aquifer at the border between the subsystems would cause a drawdown in the phreatic levels, inducing flow from the free aquifer to the confined aquifer. The drawdown at the east would be only potentiometric due the confinement of the aquifer. The main source of recharge will be the free aquifer Barreiras. In addition to it, the Marés and the Gramame-Mamuaba reservoir may also influence the recharge process.

This measure would be implemented by installing exploitation wells distributed along the confined aquifer's border, positioned to avoid interferences between the influence radius. They would also prevent excessive drawdowns, but enhance the hydraulic gradient between the subsystems, direct it to the confined aquifer, with part of the flux continuing to the free aquifer.

The exploited amount will respect productive limits of the wells in accordance with its hydrodynamic characteristic; the well flow pumping regimes will also be taken into consideration, since these are fundamentals variables to the expansion of influence radius. The withdrawal could be distributed in the water supply system or for industrial use, contributing to reduction of concentrated exploitations through the increase of water availability.

Land use and land cover scenarios

When the current land use and land cover conditions are analyzed, it is possible to identify instru-

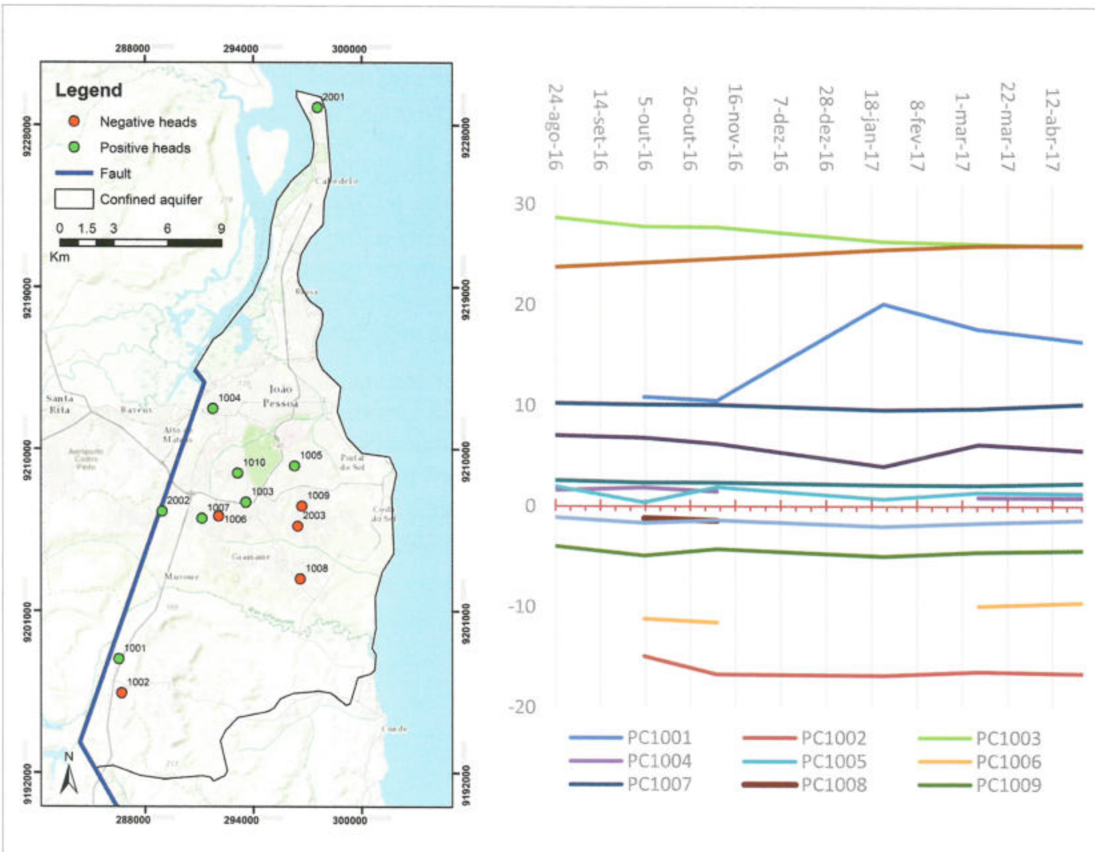


Figure 4.9: Confined aquifer monitoring network and measurements of static levels

ments that can be managed to increase groundwater recharge: (i) green areas and public open spaces, (ii) permanent preservation areas and natural landscape protection areas, and (iii) basic urban infrastructure.

Green spaces have an intersection with the public open spaces, since these could be gardens, parks or squares. Use of green spaces through decentralized urban elements, e.g. floodable parks, or the application of sustainable urban drainage systems in the already existing spaces could be implemented, aiming to increase infiltration and allow greater groundwater recharge.

The delimitation of permanent preservation areas along water bodies provides a reduction of run-off intensity and duration, allowing higher infiltration and a greater equilibrium between the hydraulic gradient of river and aquifer, which can result in lower necessity of base flow. The natural landscape protection areas can be used to establish regions with high permeability due to rural landscape characteristics, hence reducing the impact in natural hydrological cycle.

Basic infrastructure requirements include wastewater systems, urban drainage systems, access ways and water supply systems. Nowadays, there is an unmanaged aquifer recharge happening from these systems. A caution should be made to the wastewater system, which aggravates the aquifer contamination in almost every urban area (DEL CAMPO et al., 2014). Urban drainage systems and access ways could be used to ease the impact from urbanization in the hydrological cycle (GIAE, 2015). When sustainable urban drainage systems are applied proportionately the infiltration coefficient can be increased, bringing it close to natural conditions, hence also increasing recharge. The growth of cities, if planned in the correct manner, could enhance groundwater recharge.

These instruments could be applied in the metropolitan region and, specially, in the confined aquifer's recharge zone (westbound the fault). The aim is to increase the hydraulic head in the region and, as consequence, to augment the recharge towards the confined aquifer.

There is a recognized potential application of land use and land cover policies with the objective to increase groundwater recharge, using the above-mentioned instruments. This recharge will have direct influences on the phreatic aquifer; however, due to existing geological connexion, it would also enhance the recharge in the confined aquifer. Besides, an elevation in phreatic heads in the metropolitan region would cause a delay in flow, raising the opportunity to recharge the confined aquifer.

Joint application of both specific managed recharge measures

In a scenario of land use and land cover instrument application, managed to intensify groundwater recharge, there will be an increase in the phreatic levels in the João Pessoa metropolitan area and in the recharge zone of the confined aquifer during the rainy period. This increase, before the border, could be directed to the confined aquifer through the application of the mentioned induction measure. In the region after the border, the recharge of free aquifer, caused by the land use land cover instrument management, would compensate for the groundwater flow reduction induced to the confined aquifer. During the dry period, the border induction would continue to recharge the confined aquifer and reduce the phreatic levels, increasing the storage capacity of the aquifer for the rainy period. As the streamflow of rivers nearby the border is controlled by reservoir, there would be no losses due to a possible reduction of base flow.

These measures have different characteristics, when the time horizon of application, the spatial coverage and its qualitative and quantitative limits are taken into account. However, if combined, these measures could complement each other, providing an integrated strategy.

4.3.3 Recife Case Study Area (Editor: UFPE)

Introduction

The Recife Metropolitan Region (RMR, Pernambuco, NE Brazil) lies over a multilayered coastal aquifer system located in an estuarial area which has experienced some structural issues (precarious access to public water, water rationing and a poor wastewater-collection system) and repeated droughts in the last three decades. These issues have resulted in an outstanding increase of the production well number throughout the region (MONTENEGRO et al., 2010), especially in the deepest aquifers. Combined with a continuous demographic increase, these issues have led to dramatic piezometric drawdowns within the deep aquifers; the latter have increased saline intrusion risks next to the seashore as well as contamination hazards due to the hydraulic connection with the superficial aquifers (BERTRAND et al., 2016; CARY et al., 2015; MONTENEGRO et al., 2006). In addition, public services have had difficulties limiting the discharge compartment of the aquifer systems, mainly because most of wells are illegal (CARY et al., 2015).

In this context, the applicability of Managed Aquifer Recharge strategies in the RMR were discussed recently within the BRAMAR project framework. Furthermore, the region is characterized by a tropical climate featuring great amount of precipitation virtually allowing large available volumes to be used for additional recharge. Therefore, the implementation of MAR techniques could provide a sustainable way to limit the ongoing adverse effects of global and local anthropogenic pressures over the RMR.

Main Objectives

According to the above-mentioned characteristics of the RMR, the two main objectives of the Recife study case are (1) to identify relevant places and techniques for the implementation of MAR strategies in the deepest strategic aquifers featuring good-quality groundwater and (2) to develop strategies and implement experimental MAR in these systems.

Methodology – MAR Planning Approach

In order to identify the relevant places and techniques for further MAR implementation in the deep aquifer systems at an RMR scale, the researchers analyzed historical data collected during routine measurements: (1) long-term (2005–2014) spatiotemporal groundwater level variability to delineate the hydrological behavior, (2) spatiotemporal electrical conductivity (EC) changes to assess the possible origin of the groundwater flows and mixings, and (3) lithological description to identify the geological settings in which the groundwater flows (COELHO et al., 2018).

For the further implementation of experimental MAR strategies in the deep RMR aquifer systems, two multilevel piezometers shall be drilled in strategic locations where rainwater collection systems from the roofs will directly inject the rainwater into the aquifer. The treatment applied to the rainwater should be based on sandy and leaf filtration. In addition, some parameters related to the groundwater quality and quantity will be constantly monitored to evaluate the influence of the injected water. In parallel, next to the estuary area a sub-hourly monitoring program is being conducted to analyze the influence of the tides on groundwater level and EC in the Cabo aquifer from a MAR strategy point of view (PAIVA et al., 2017).

Conducted Studies towards MAR Planning at the Case Study Area

The above-mentioned data monitoring, performed for identification of places and techniques for further MAR, showed that two contrasted effects occur in the deep aquifers under similar overexploitation pressure: (1) groundwater level decrease and stable EC in the Northern and Southernmost areas of Recife, and (2) stable groundwater level and high/varying EC next to the estuarial area. These results suggest that variable hydrogeological conditions feature the RMR. Firstly, the area distant from the estuary seems to act as a closed system, i.e., where groundwater renewal is lower than exploitation rate. In contrast, in the estuarial zone, overexploitation seems to trigger groundwater flow from the estuarial complex thanks to hydraulic connections between surface and deep water. These connections occur through a process possibly favored by extended paleo-channels located between superficial and deep aquifers and characterized by higher hydraulic conductivity.

Based on these insights, two distinct MAR implementation techniques might be considered as feasible: (1) managed surface infiltration from superficial reservoirs, where connectivity between the estuary complex and the paleo-channels would allow a control of the recharge; and (2) injection systems applied to the deep vertical wells in zones more distant from the estuary (COELHO et al., 2018).

Main Results

The analyses conducted by the Recife study case to delineate MAR strategies showed that different approaches can be implemented to recharge the deep aquifers at the RMR scale. This statement was confirmed thanks to the connections found between the surface water and deep groundwater in some places next to the estuarial zone of the Capibaribe River. When the hydrological and hydrogeological similarities between the João Pessoa and Recife study cases are taken into account, analogous methodology could be applied to identify possible extended paleo-channels close to the estuarial zones of the Gramame and Paraíba Rivers. This methodology could be also suitable to spatialize possible MAR approaches in the deep aquifers at João Pessoa study case area.

In parallel to the studies conducted in the deep aquifers, a pilot experiment was carried out, using the bank filtration technique in the alluvial aquifer (superficial) of the Beberibe River flowing throughout the RMR during the BRAMAR project. The application of this technique has improved the water quality of the system along the flow path from the river course to the pumping wells: some parasites such as Cryptosporidium spp. and Giardia spp. (FREITAS et al., 2017) are filtered out and some emerging components such as pharmaceuticals attenuated (VERAS et al., 2017). Therefore, the use of this technique could potentially also be transferred to the shallow aquifers of the João Pessoa study case.

The application of the above-mentioned techniques at a larger scale in the RMR implies that strong investments are required to ensure the quality of the water to be infiltrated or injected. Special attention should be given to the water infiltration process along the estuary due to the current contamination and salinity of the surface water. The salinity of the surface water could be controlled through adapted urban drainage planning, favoring the higher gradient from inland (fresh) to littoral (salted) water, whereas investments in public water networks and wastewater treatments should be applied to attenuate the surface water contamination process mainly close to estuarial area. Moreover, it is worth highlighting that recharge tests (infiltration capacity, further water direction after infiltration/injection, effects on piezometric levels, possible upward – reverse – hydraulic connection with superficial aquifers) should be performed in the field before the proposed techniques are implemented.

Finally, this case study highlights the importance of knowing the local geology, which will constrain the injection techniques and the further biogeochemical reactivity of the groundwater system so as to mitigate possible contaminations. The next step of this work will be to implement the techniques in the selected area. Nevertheless, managers will have to take into account the implication and perception of local people regarding water resources (PETELET-GIRAUD et al., 2017) to allow best practice strategies to be performed.

4.4 Conclusions and Recommendations for MAR Planning in North-East Brazil

Three years of studying the different areas with special regards to the various aspects of Managed Aquifer Recharge planning have resulted in an increased understanding of the individual systems and their dependency on smart water management decisions. It is the hope of the researchers involved that the results of each individual case study will find attention with the local stakeholders and might contribute to a sustainable management of the groundwater resources.

The results gained and conclusions made for each individual case study can be joined and summarized to give general recommendations for MAR planning in North-East Brazil. Although all case studies focused on different aspects of MAR planning and used different approaches to reach their objectives, all of them revealed a common necessity to give special care and attention to local groundwater resources. To achieve a sustainable management of the water resources, long term planning for future development is necessary. Short-term solutions offer no sustainability.

All case studies suffered from severe lack of data. Therefore, it is highly recommended to improve and extend existing monitoring networks in all areas, both for surface and groundwater resources. This should include quantitative and qualitative evaluations.

Overall, a better understanding of the hydrogeology in all study areas has been achieved. This work must be continued with further field investigations such as pumping and infiltration tests, exploration drillings, and the prior mentioned general monitoring of water resources, the latter of which is key to all water management related decisions

Socio-economic studies must be conducted with regards to MAR implementation. There are many possible low-tech, low-budget solutions available. The existing system of water licensing is insufficient with regards to water management. Actual extraction rates must be monitored and controlled in order quantify groundwater extractions.

The results from case study of Recife with regards to rainwater harvesting can be transferred to the urban area of João Pessoa, but also to the entire semiarid region.

The results from case study of Sumé – turning unmanaged recharge of wastewater into a functioning Soil Aquifer Treatment system – can be transferred to other semiarid regions. Such regions have alluvial aquifers as an important source of water, in addition to surface reservoirs, and also receive relevant wastewater recharge from upstream city.

The methodology of MAR planning tested and extended in the João Pessoa case study may deliver a guideline for similar areas with high agricultural water demand and data uncertainty. A common guideline for MAR implementation in North-East Brazil should be developed and combine the findings of the case studies. The guideline must differentiate between urban and rural areas and between the tropical coastal climate and the semiarid region. Although there are many guidelines in existence that can serve as a basis, all require site-specific adjustments.

4.5 References

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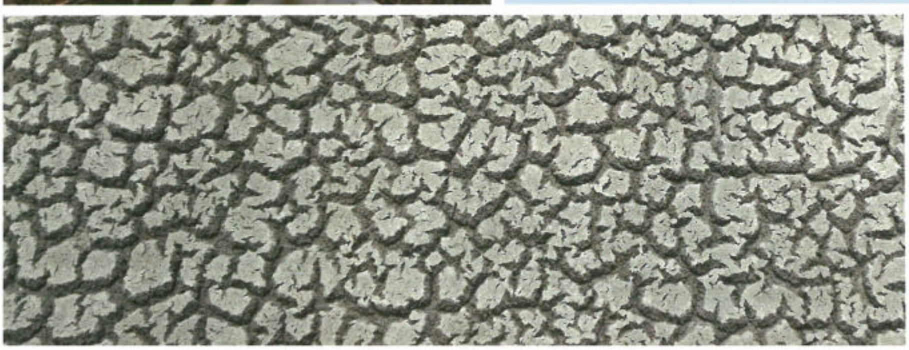
5

Wastewater Treatment and Reuse (Results from WP 4, 5 & 6)

Anna Abels[a], Gilson B. Athayde Jr.[b], Rafael O. Batista[c], Franz Bischof[d], Christoph Bohner[e], Mônica de A. Coura[f], Adrianus C. van Haandel[f], Manfred Hoyer[g], Claudio R. Itaborahy[h], Vera Kohlgrüber[a], M. César Martí Calatayud[a], Salomão de S. Medeiros[i], Johannes Pinnekamp[a], Claudia F. dos Reis[i], Jaqueline P. Salgado[f], Silvania L. dos Santos[f], Rennio F. de Sena[b], Paulo B. de M. Silveira[h], Leonardo V. Soares[b], Süleyman Yüce[a]

a RWTH Aachen University, b UFPB, c UFERSA, d HUBER SE, e EnviroChemie, f UFCG, g AP System, h ANA, i INSA



5.1 Status and Potential of Wastewater Treatment and Reuse in North-East Brazil

5.1.1 Introduction

Wastewater must be adequately treated before it is discharged for two main reasons: environmental and public health protection. In areas where water is scarce, a third reason must be taken into account: the reuse of water contained in the wastewater.

The adverse environmental effect of untreated wastewater emissions can be measured by the oxygen depletion and the eutrophication that occur in the receiving water bodies. In a low-oxygen water environment, the aquatic fauna can be severely affected, and if dissolved oxygen concentration approaches zero, nuisance conditions with odor emissions can take place in the water body. Furthermore, eutrophication can compromise water usage. Therefore, if wastewater is adequately treated before reaching the water bodies, water can be made available for supply systems.

Public health can be affected by wastewater discharges because of pathogenic microbiological content owing to fecal material in the wastewater. In this sense, the removal of such microorganisms is desired and necessary during the treatment process, especially when reuse is intended. More recently, the presence of anthropogenic micropollutants, such as pesticides, hormones among others, has come into focus due to both identified and unclarified adverse effects on the environment and human health.

In arid and semiarid areas, water scarcity can severely limit agricultural and industrial production, affecting local economy and living conditions. In this situation, the reuse of treated wastewater can help to sustain agriculture and the industries and also be used in some household applications, such as gardening, toilet flushing and floor washing, among others. As agricultural irrigation is the main source of water consumption in North-East Brazil, the reuse for this sector must be specially considered, and in this case, the nutrient content of treated wastewater can be quite advantageous.

One important premise of a wastewater reuse program is the quality of the treated wastewater, which should be correlated to the intended usage of water. Therefore, the level of treatment should be carefully chosen for each reuse option. Depending on the intended reuse, treatment options can vary from very simple to very sophisticated systems, and the corresponding costs are generally related to the degree of treatment.

In this chapter, BRAMAR studies on wastewater treatment and reuse are presented and discussed regarding their potential role in water management in North-East Brazil. As the challenges and needs of urban and rural areas in North-East Brazil differ significantly, all studies and analysis differentiate between these types of settings. In urban areas, high population levels lead to increased water consumption and wastewater production, thus calling for high treatment volumes and a stable water supply for domestic and industrial purposes. These types of areas can usually be found at or near the coastal areas of North-East Brazil.

In contrast to the situation on the urbanized coastline, the rural inland of North-East Brazil faces water scarcity mainly because of adverse climatic conditions and not high population numbers. Minimizing the effect of water scarcity on agriculture – while guaranteeing safe sanitation and drinking water is a key challenge of wastewater treatment and reuse in rural areas.

5.1.2 Status in Urban Areas of North-East Brazil

As mentioned before, the urban areas along North-East Brazil's coast face specific and comparable challenges regarding wastewater treatment and reuse. An analysis of the actual status shows that 32.2% of the urban population in the North-East region has access to the wastewater collection network, meaning that their wastewater is collected in some kind of sewer system. 78.5% of the collected wastewater volume undergoes some type of treatment before the final disposal

(SNSA/MCIDADES, 2017). **Table 5.1** presents data from the National Information System on Sanitation, from the year 2015, on the index of wastewater network service and wastewater treatment.

According to the data presented in **Table 5.1**. 76% of the urban population of the BRAMAR case study area João Pessoa is connected to a wastewater collection network. Since 93% of the wastewater is collected, the municipality of Campina Grande presents an even higher performance. Both of these highly urbanized cities have a far higher collection rate than the average in the State of Paraíba, the North-East Region and also Brazil in general. This shows that even though far more wastewater is generated in big urban areas, the collection of wastewater is also higher in absolute and relative numbers when compared to smaller urban areas.

In the Municipality of João Pessoa, the total volume of wastewater collected (about 30,000,000 m^3/a) is treated in one of the two wastewater treatment plants (WWTP) currently in operation: the Cuiá River Treatment Station, located in Mangabeira district, and the Treatment Center of Paraíba River, in Róger district. In these WWTPs, the main technology used for domestic wastewater treatment is the stabilization pond. These ponds are very common in the North-East region of Brazil due to favorable climatic conditions as well as low costs and simple operability (von SPERLING, 2002).

According to the monitoring data of the Water and Wastewater Company of Paraíba, CAGEPA, the biochemical oxygen demand (BOD_5) removal efficiency at the WWTP in Mangabeira is higher than 80%, while at the WWTP in Róger, the average annual removal of BOD_5 is 60%. Although the quality of the effluents from these WWTPs, in terms of organic matter removal, meets the standards imposed by Brazilian environmental legislation, significant amounts of nitrogen (N), phosphorus (P), total solids (TS) and thermotolerant coliforms are emitted and may impact the quality of receiving water bodies. This indicates that complementary treatment is likely needed to conserve the aquatic environment.

Post-treatment of stabilization pond effluent is also a pre-requisite for safe wastewater reuse. Implementation of wastewater reuse would make use of the wastewater volume instead of fresh water and thus reduce the demand for water supplied by the local licensee reducing the pressure on the sources that serve BRAMAR's urban case study areas, the municipalities of João Pessoa and Campina Grande. In particular, Campina Grande is located in a region that historically has had water shortages. This fact is aggravated because the management of the water resources is deficient. Therefore, the potential of using treated waste

Table 5.1: Wastewater collection and treatment indices in North-East Brazil and selected cities (SNSA/MCIDADES, 2017)

City/State/Region	Wastewater collection index [%]	Wastewater treatment index [%]
	Indicator IN_{024}	Indicator IN_{016}
João Pessoa	76.0	100
Campina Grande	92.6	74.6
Mossoró	49.2	100
Paraíba	44.2	69.2
Rio Grande do Norte	28.46	81.47
North-East	32.2	78.5
Brazil	58.0	74.0

water for non-potable purposes and for industrial supplies (approximately 15,000,000 m^3/a) is increasingly becoming necessary for this city.

While potable reuse is technically feasible, it requires very sophisticated technology and involves high costs. Therefore, potential reuse applications for non-potable purposes would be more practical and realistic in the first place. These include, for example, irrigation of parks and gardens, use for car washing, toilet flushing and floor washing in homes, commercial centers, public buildings, small industries and hotels.

5.1.3 Status in Rural Areas of North-East Brazil

Proper sanitation fundamentally promotes health and preserves the environment. In rural areas of semiarid Brazil, several conditions make it demanding to implementation sanitation efficiently. Key challenges are the widespread distribution of the rural population, the resident's lack of knowledge about the pathogenic qualities of wastewater and limited financial means to implement and improve wastewater collection and treatment.

The indices of wastewater collection and treatment in the BRAMAR case study area Mossoró amount to 49.2% and 100% (SNSA/MCIDADES, 2017), respectively, which are higher than the average in the Federal States of Paraíba, Rio Grande do Norte and the North-East Region, albeit lower than the national average and the bigger cities like João Pessoa, as described beforehand. Out of the 7,200,000 m^3/annual of wastewater collected in Mossoró, 100% are treated in five WWTPs. The principal treatment technology is the stabilization pond again, however, one of the five WWTPs uses a septic tank followed by anaerobic filters.

Rural areas around the BRAMAR case study area Mossoró are more influenced by water scarcity than Mossoró itself, because they depend on rainfall and water from reservoirs for water supply much more. At the same time, improper sanitation affects people's health and the quality of the environment in these rural areas, where there is no wastewater treatment system or only inadequate treatment in the form of rudimentary septic tanks.

These rural areas do not have collection systems for wastewater or, if existent, they are decentralized. In residences that possess an individual system for collection and treatment, blackwater (containing fecal matter) is usually discarded into rudimentary septic tanks (which are often inadequately designed and constructed and do not allow for water reuse in agriculture). Greywater is disposed without treatment in the soil, in the open, or used for agriculture and livestock production.

With the recent State Council for the Environment, COEMA Resolution 2/2017 (COEMA, 2017), which establishes rules for agricultural and forestry reuse in the semiarid region, it is possible to encourage rural producers in the vicinity of cities like Mossoró to improve the current residential wastewater system. For this, the blackwater could be treated in a complete system equipped with septic tank, anaerobic filter and infiltration ditch. For greywater, it is recommendable to use combinations of treatment components that effectively remove the pathogens, but on the other hand enable the use of nutrients present in the water, such as a grease separator, septic tank, organic filter, anaerobic filter, solar reactor and ultraviolet reactor.

All in all, in rural areas the agricultural use of treated wastewater has various advantages like the utilization of wastewater instead of freshwater as well as the reduction of mineral fertilizer usage, minimizing its polluting potential to the environment.

5.2 Technologies and Schemes for Wastewater Treatment and Reuse

5.2.1 Research Outline of BRAMAR Studies on Wastewater Treatment and Reuse

As was shown above, there is still potential for improvement of wastewater collection and treatment in both urban and rural areas in North-East Brazil since a great deal of the wastewater is not collected and treated. At the same time, wastewater reuse has hardly been implemented, thus neglecting the potential of wastewater to be used instead of fresh water.

Nevertheless, the potential role and practical implementation of wastewater treatment and reuse in North-East Brazil in the future still needs to be outlined with more clarity. There is a lack of knowledge regarding best technologies for wastewater reclamation in the context of North-East Brazil. Therefore, with the BRAMAR project we wanted to answer two essential questions: Is water reuse a promising idea to mitigate water scarcity from a technological point of view? How should it be implemented?

In order to answer these questions, several studies were carried out in the BRAMAR project that mainly focused on technological options for wastewater treatment and reclamation in different contexts. Sub-chapter 5.2 shows the results of these studies.

With our first study, presented in 5.2.2, we did, however, start by showing the detrimental effects of poor wastewater treatment in the BRAMAR case study area Sumé, where wastewater emissions were identified and quantified in the aquatic environment. In sub-chapter 5.2.3 we focused on wastewater reuse in an urban context. Our aim was to find a way of post-treating stabilization pond effluent for higher purpose reuses. Sub-chapter 5.2.4 concentrates on wastewater reuse in an industrial context. Two studies were carried out that can be used as examples for the possibilities in the industry. In contrast to the high-technology approaches used in the urban and industrial setting, mainly low-cost, low-technology solutions were applied in the studies presented in sub-chapter 5.2.5 on rural wastewater treatment and reuse.

5.2.2 Studies on Environmental Effect of Untreated Wastewater Emissions

The Sucuru's River alluvial aquifer receives a high load of both treated and untreated domestic wastewater from the urban area of Sumé village and domestic and agricultural wastewater from the rural surroundings. The discharge of these effluents represents a non-managed aquifer recharge and contaminates its water, endangering the use of safe water by the inhabitants.

To evaluate the effects that the discharge of wastewater from Sumé city had upon groundwater, we conducted physio-chemical and microbiological analysis, monthly or bimonthly, in nine of the forty wells existing in the alluvial aquifer (**Figure 5.1**). The wells were used by the population for several activities over the course of many years. We chose these wells based on the distance between them (1.5 to 2.5 km) and on the occurrence of punctual or diffuse pollution sources. The wells were monitored between May 2015 and October 2017, when precipitation was very low. The selection of parameters to be analyzed took into consideration, mainly, the organic pollution, the fecal contamination and the water salinity.

The superficial runoff and percolation of the organic matter through the soil resulted in good depuration conditions so that the BOD_5 in the aquifer varied from 0 to 6 mg/L, while the chemical oxygen demand (COD), analyzed only in 2015, varied from 0 to 332 mg/L, with the higher value found in P02 (location of the wells: see **Figure 5.1**). In the wells out of the urban area, the COD was only occasionally higher than 100 mg/L. The dissolved oxygen was found in all the wells in the range of 0.5 to 6.1 mg/L, while ammonium nitrogen varied from 0 to 8.4 mg/L, with exception of P01, where a variation between 0 and 15 mg/L was found.

Thermotolerant coliforms were found in all the wells, with *E. coli* confirmed in most of the analysis, showing the fecal contamination of the aquifer. Although the numbers of thermotolerant coliform decreases outside the urban area considerably, the water is re-contaminated by the wastewater from the rural area because the wells lack protection from it.

Elevated concentrations of chlorine – a major contributor to anthropogenic salinization – were encountered in P02 (2489–8618 mg/L). Nevertheless, these concentrations decreased substantially, as in P03 the range of chlorine was only 163 to 1156 mg/L, and in the last well, P09, the range was 7.1 to 325 mg/L. A decline like that cannot fully be attributed to filtration or other removal processes, but to elevated dispersion of this salt in the alluvial aquifer since the chlorine is highly soluble in water. The behavior of electric conductivity (EC) and total dissolved solids (TDS) was found to be the same as that of chlorine. In P02 the range of EC and TDS was 6.7 to 13.4 mS/cm and 2,703 to 9,084 mg/L, respectively, which fell to 0.8 to 4.4 mS/cm and 312 to 3,032 mg/L in P03 and reached values as small as 0.5 to 1.5 mS/cm and 277 to 1,228 mg/L in P09.

Also the values for sodium, calcium, magnesium and potassium were obtained when the alluvial aquifer was evaluated according to the criteria set by the United States Salinity laboratory, the risk of salinization is considered to be high and – in the case of P02 – extremely high.

Nitrate concentration passed 10 mg/L in three wells, which is reasonable because of the agricultural activities in the region. Nitrite varied from 0 to 5.5 mg/L and the highest value of iron was 1.2 mg/L.

According to the reference values of the National Environmental Council, Resolution n°396/2008

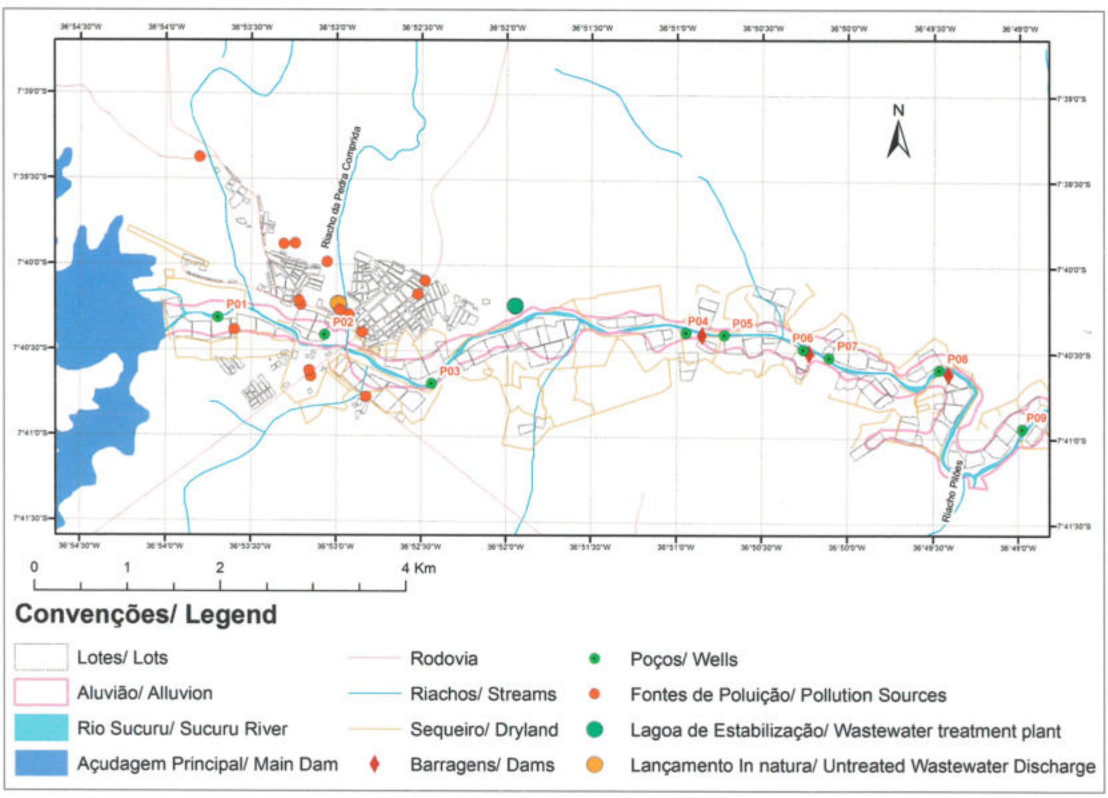


Figure 5.1: Localization of sampling wells in alluvial aquifer of the Sucuru River

(CONAMA, 2008) and Ordinance 2914/2011 of the Ministry of Health (MS, 2011), the maximum allowed values of the evaluated parameters were violated, which makes the use of the water impossible for most types of usage. Owing to the actual quality of the aquifer, using the water for irrigation is restricted to the cultivation of salt tolerant species and with special caution for soil management.

The results presented here show that the principal factor in the decrease of the aquifer's water quality is the emission of untreated wastewater. Nevertheless, other factors should not be left out of consideration, such as inadequate treatment, missing sanitary protection of the wells and absence of decentralized solutions for wastewater treatment in the rural areas.

Therefore, in the case of the alluvial Sucuru River aquifer, various measures for managing the aquifer and its recharge should be considered. Amongst them, the complete connection to wastewater collection and treatment in the urban areas, improvement of the already existing level of wastewater treatment and implementation of solutions for decentralized wastewater treatment in the rural parts. If water should be directly reused, more advanced technologies need to be implemented.

5.2.3 Municipal Wastewater Treatment and Reuse after Stabilization Pond Treatment

As stabilization ponds are the main treatment technology used in municipal wastewater treatment in North-East Brazil, it is highly desirable to make use of their effluents. Therefore, one of the studies performed as part of BRAMAR focused on reclaiming stabilization pond effluent for non-potable urban reuse purposes. For different types of non-potable urban reuse, water quality requirements are given in the Brazilian Association for Technical Standard's norm NBR 13696 (ABNT, 1997). This norm's and other guidelines' maximum values for pathogens, solids, organic and nutrient content are neither met by raw wastewater nor by the effluent of stabilization ponds. A further treatment of stabilization pond effluent is, therefore, necessary to safely make use of it. As there is a high probability of human exposure in urban water reuse, it is of special importance to choose a post-treatment process that reliably meets the elevated hygienic demands. Therefore, membrane ultrafiltration as post-treatment of stabilization pond effluent was chosen to be studied as part of BRAMAR. As ultrafiltration usually delivers an effluent quality free of pathogenic bacteria, it seemed to be an appropriate choice in this context. Consequently, an ultrafiltration pilot plant was designed and constructed in order to evaluate the treatment efficiency and operational stability of this technology as post-treatment for a facultative-anaerobic-stabilization pond system.

The investigated ultrafiltration pilot plant consists of two parallel, identical treatment trains (Train 1 and 2), each comprising several treatment steps as shown in **Figure 5.2**. Before the main process – the membrane filtration – there are two prior filtration steps: a sand filtration and a surface filtration with a filter size of 150 µm. Afterwards, there is the option of dosing acid or base to adjust the pH and flocculants like polyaluminium chloride or ferric chloride. These flocculants help to ensure a better removal of the algae which is naturally present in stabilization ponds and which also leads to unwanted membrane fouling processes. The membrane filtration step of the pilot plant follows directly after the flocculation and consists of capillary membranes by Inge AG which have a pore size of 0.02 µm. These membranes can be cleaned by backwash with the permeate, which can optionally be enriched with chemicals such as sodium hydroxide (NaOH), acids and chlorine.

The pilot plant was installed by RWTH Aachen University at the Mangabeira municipal wastewater treatment plant in João Pessoa, whose effluent was taken as influent of the pilot plant. This effluent usually has a BOD_5 of about 50 mg/L and the aforementioned elevated amount of algae. Turbidity levels are, therefore, high at about 70 NTU, and TS content lies at about 400 mg/L, of which about 60 mg/L are suspended solids from the algae and the rest dissolved solids.

Several short time test series were performed for a period of nine months with the main aim of achieving a low and stable transmembrane pressure (TMP) while at the same time using few chemicals and retaining most of the permeate for cleaning purposes. During the various test series, various factors were changed: filtration and backwash flux, filtration and backwash duration, flocculant type and dosage, pH, the treatment train currently in use and the type of chemical cleaning. At the same time, regular analytical monitoring was carried out to supervise permeate quality and evaluate its reuse options.

All in all, the short time test series came to the result that, depending on the settings, a stable operation with a TMP <0.3 bar can be achieved. Therefore, ultrafiltration of stabilization pond effluent is technically feasible when used in combination with in-line flocculation. However, the practical operation of the process is very complex and needs a high skill-level. Long-term operation has not been tested, and so there is no evidence that the process could run stably for longer periods than a couple of days. Thus, further studies and improvement of the process are needed before it can be used for water reclamation applications.

The results of the effluent quality analysis for the ultrafiltration pilot plant and the effluent of the Mangabeira WWTP are listed in **Table 5.2**. Effluent quality of the ultrafiltration pilot plant resulted in having the high hygienic level that was foreseen with no thermotolerant coliforms in most samples (mean=1.25 - TC/100 mL for Train 1; and 10 - TC/100 mL for Train 2), meeting the requirements for non-potable urban reuse which are given in ABNT NBR 13969 (thermotolerant coliforms lower 200 UFC/100 mL for water used for car washing and other applications with direct human contact and beneath 500 UFC/100 mL for applications with less human contact as e.g. irrigation or toilet flushing). Ultrafiltration effectively removes all solids bigger than 0.02 µm, which results in low BOD_5 and COD effluent values (9.0 mg/L and 39.1 mg/L respectively for Train 1 and 8.8 mg/L and 40.2 mg/L for Train 2) due to algae removal. At the same time TS levels remained quite high at a mean of 323 mg/L for Train 1 and 319 mg/L for Train 2. The reduction of TS accounts for the removal of suspended solids during the filtration process, but dissolved solids (like salts) are still present in the ultrafiltration effluent. ABNT NBR 13969 determines a maximum of 200 mg/L for TS if the water is reused for applications with direct human contact. Due to this fact the ultrafiltration effluent cannot be used for these applications, but can be reused for others like garden irrigation and toilet flushing.

Regarding the permeate quality, it was shown that requirements for some applications of non-potable urban reuse can be met with ultrafiltration post-treatment of stabilization pond effluent. However, more extensive pre-treatment, in

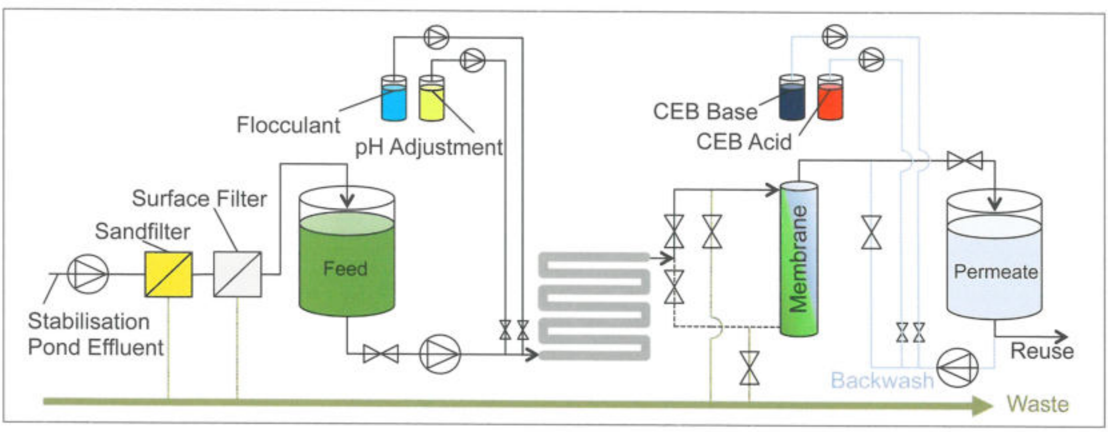


Figure 5.2: Schematic view of one train of the ultrafiltration pilot plant

addition to the stabilization ponds, would be necessary in order to ensure the ultrafiltration operates stably without the extensive use of chemicals. This prerequisite could be met with rock filters or maturation ponds. Nevertheless, other processes - such as a combination of facultative-anaerobic ponds in combination with maturation ponds, rock filters and ultraviolet (UV) disinfection - should also be tested since this technology seems to be promising and applicable to the local conditions: fewer skilled personnel are needed for operation and operating costs are considerably lower.

For now, stabilization pond post-treatment with low-technology processes such as maturation ponds or sand/rock filtration seem to be more adequate. Other ways for post-treatment that should be considered are biological processes that are easy to operate such as trickling filters.

5.2.4 Studies on Industrial Wastewater Treatment and Reuse

Combination of MBR and advanced Treatment for Wastewater from the Beverage Industry

Water stress in semiarid urban areas can be significantly reduced by decreasing the demand for freshwater resources in the industrial sector as well as by improving the quality of the industrial effluents discharged into natural watercourses. To this end it is necessary to introduce advanced wastewater treatment technologies that reduce effluent pollution levels, allow reuse schemes to be implemented in industries and minimize the intake of freshwater. In this regard, a demonstrative pilot plant was installed and tested at an industrial site in João Pessoa within the framework of the BRAMAR project. The company selected for this case study is a fruit juice producing company (Intrafrut), which is a good representative for the important food and beverage industrial sector in the city of João Pessoa. The main objective of this specific study is to prove the superior performance of the treatment plant to remove pollutants from the industrial wastewater and propose reuse options for the treated effluent.

The pilot plant was developed by the company EnviroChemie GmbH in close cooperation with RWTH Aachen University. It was operated in parallel to the already existing treatment plant at the local industry. The existing treatment plant consists of a neutralization process, an equalization tank, an aerated biological process and a secondary clarifier. So far, the treated effluent has been discharged in the natural wetlands neighboring the industrial site, which belong to the Jaguaribe river environment.

Table 5.2: Mean values of pH, temperature, BOD_5, COD, NH_3-N and thermotolerant coliforms of stabilization pond effluent prior and after membrane treatment

Characteristics	Effluent Stabilization Pond		Effluent Train 1		Effluent Train 2	
	Mean	n	Mean	n	Mean	n
pH	7.8	45	6.9	34	6.9	29
Temperature	26.2 °C	45	24.8 °C	34	24.9 °C	30
TS	409.7 mg/L	27	323.0 mg/L	28	319.4 mg/L	24
BOD_5	52.2 mg/L	26	9.0 mg/L	21	8.8 mg/L	22
COD	208.9 mg/L	46	39.1 mg/L	33	40.2 mg/L	27
NH_3-N	39.9 mg/L	45	33.9 mg/L	31	34.6 mg/L	28
Thermotolerant coliforms	5.2E+04 UFC/100 mL	3	1.25 UFC/100 mL	12	10 UFC/100 mL	9

The demonstrative pilot plant is based on a sequence of different treatments, which are shown in **Figure 5.3**. A view of the pilot plant on site is shown in **Figure 5.4**. First, the effluent undergoes a physical-chemical treatment, where it is pre-filtered and neutralized by the addition of NaOH. After neutralization, the remaining solids are removed by an electro-flotation unit. The main function of the physical-chemical pretreatment is to remove large solids and pre-condition the incoming effluent for the subsequent biological treatment. Subsequently, the dissolved organic compounds present in the effluent are treated in the membrane bioreactor (MBR).

Since wastewaters generated in the food industry contain high loads of organic matter, biological processes are the most appropriate and cost-effective treatments to degrade the pollutants. MBR technology integrates the physical separation between the treated effluent and solids present in a sludge process with the biological degradation of organic matter. As a consequence, the secondary clarifier is not necessary. This allows it to operate the MBR with biomass concentrations of around 15 g/L in the bioreactor, which is about three-fold the typical concentration in conventional activated sludge processes. Consequently, the degradation of biomass is faster, leading to a smaller reactor volume and thus less footprint of the treatment plant for the same effluent rate.

The pollutants not degraded and still present in the MBR permeate need to be removed with further treatment to achieve qualities prescribed for certain reuse options. Hardly – biodegradable organic compounds, such as pesticides, can be oxidized by means of ozonation, adsorbed in granular activated carbon (GAC) filters or separated by reverse osmosis (RO) filtration. Accordingly, the performance of these three polishing steps was also tested. In contrast to ozonation and GAC, RO entails the additional advantage of removing ions. This is particularly beneficial for specific re-

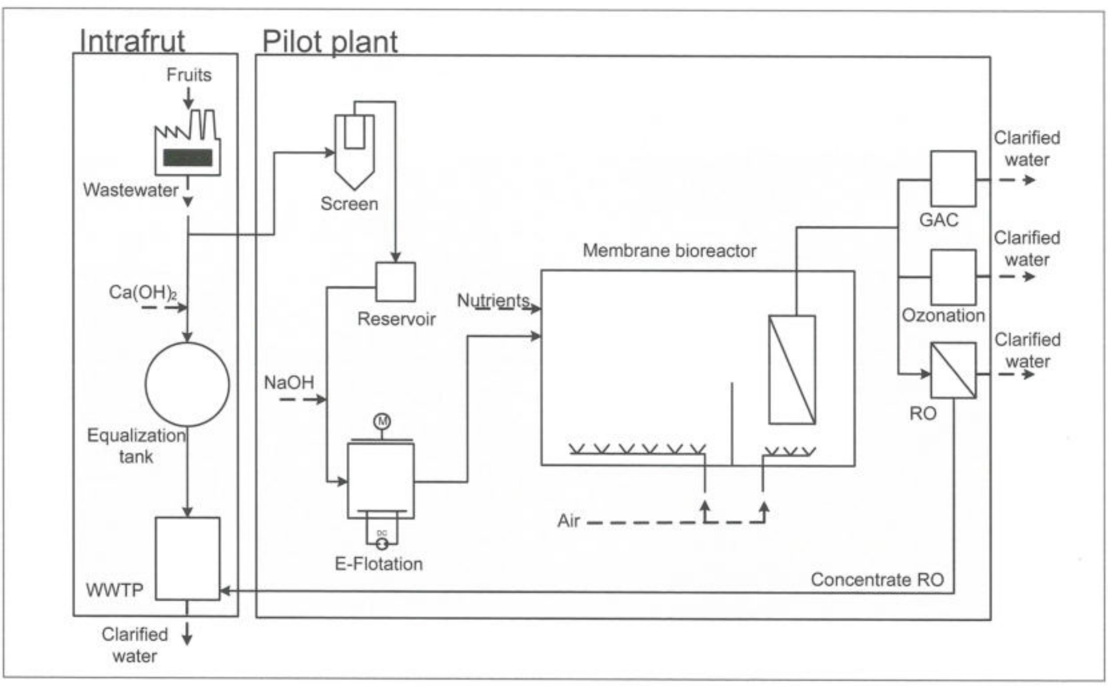


Figure 5.3: Flow diagram of the pilot plant depicting its integration into the Intrafrut WWTP. The left side shows the fruit juice production site and the conventional treatment plant. The right side shows the pilot plant based on pre-treatment steps and MBR connected with a GAC filter, an ozonation and a RO unit.

use options in the industry, which may cause corrosion in pipes or machinery.

So that the different process units described above could be better monitored, the pilot plant was operated by a Programmable Logic Controller (PLC) system. An important operational aspect to be considered when advanced water treatments are implemented is the increase in complexity of monitoring the plant and the costs associated with the plant operators. The use of automatization and remote control systems can overcome this drawback, as the local operators can receive direct assistance from EnviroChemie in Germany and their permanent presence at the treatment plant may not be needed. The pilot plant is also equipped with a touch panel and a computer-based control station, as shown in **Figure 5.5**, where process data are collected and registered during pilot operation. Furthermore, a remote access and control system has been implemented by AP System Engineering GmbH. The communication within the pilot plant employs a wide variety of different protocols. Remote access from Europe to the pilot plant is possible around the clock.

The present investigation focused on three specific aspects of the operation of the pilot plant:

1. The biological degradation of pollutants in the MBR and the desalination achieved by the RO unit in order to obtain water fit for different types of reuse.
2. The degradation of persistent pollutants, more specifically pesticides, by the different treatment steps, namely biological treatment, RO, activated carbon and ozonation. For this purpose, the concentration of atrazine in the feed of the MBR was artificially set to 1.5 µg/L, while the concentration of other three relevant pesticides used by local farmers, i.e. carbendazim, diuron and 2,4-dichlorophenoxyacetic acid (2,4-D) was set to 20 µg/L.
3. The reliability of the remote access communication system of the pilot plant.

The biological degradation of organic matter achieved in the MBR allowed it to obtain COD and BOD_5 values in the permeate below 30 and 10 mg/L, respectively. Moreover, the solid/liquid separation efficiencies ensured by the ultrafiltration mem-

Figure 5.4: View of the pilot unit installed on site (AWATER, 2017)

branes resulted in an effluent without biological flocs, suspended solids and bacteria, so that the resulting water would be already fit for reuse in low-grade applications. According to the recommendations 357/2005 of the CONAMA (CONAMA, 2005), the quality obtained in the permeate of the MBR would meet the standards required for the irrigation of trees, cereals and feedstock, for the cleaning of floor vehicles or machinery. In addition, during the high-season, where more fruits are pressed to produce juice concentrate, the MBR pilot plant still showed standards below the limits for release into surface waters. All in all, the MBR unit was able to degrade and remove more than 99 % of the total COD of the influent, which shows that this technology is suitable for the treatment of wastewater generated in the food industry. Further removal of other compounds relevant for high-grade reuses is feasible with the post-treatment units. In contrast with the other polishing treatments, when the MBR effluent was further treated by means of RO, the permeate stream reached conductivity values lower than 60 µS/cm, making its reuse as washing, cooling water or even boiler water make-up feasible.

Regarding the removal of pesticides, results confirmed that about 50 % of biological degradation of carbendazim and diuron was achieved in the MBR, whereas atrazine and 2,4-D were not degraded. On the contrary, all the remaining pesticides flowing out of the MBR were successfully removed by both activated carbon and RO, reaching concentrations in all cases below 1 µg/L. It is to be noted that RO and activated carbon filters do not degrade pesticides, but only remove them from the treated effluent. Conversely, ozonation tests oxidized the pesticides until they reached levels below 1 µg/L. These experiments proved the viability of the proposed technologies for preventing the accumulation of pesticides in the water cycle through several reuses.

Finally, the remote access from the German workstation to the pilot plant enabled to operate the plant, as well as to gather the generated data during more than one year of operation.

The results obtained at the pilot plant of Intrafrut have proven the viability of the proposed technologies and their suitability to treat industrial wastewaters generated in the local food and beverage sector. MBR technology itself can already achieve a significant degradation of organic matter. Depending on the COD levels of the wastewater generated in the industry, the quality of the effluent obtained after an MBR unit can be sufficient for low-grade types of reuse, like floor washing or irri-

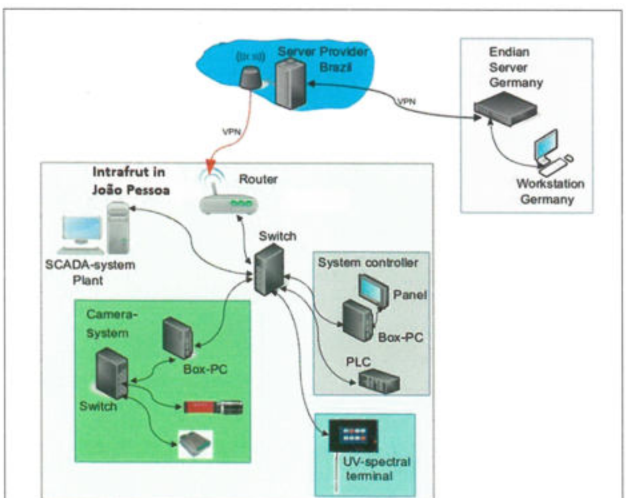


Figure 5.5:
Schematics of the remote access communication showing the pilot plant at Intrafrut with the local control system and an inline camera system for monitoring the color and turbidity of the water. Communication from the German workstation and the pilot plant is carried out via a local provider.

gation. In case that a superior effluent quality is needed for more demanding applications, the coupling of MBR technology with RO could make it possible to reach qualities comparable to the fresh water used in the factory. As an alternative to RO, in case that the concentrations of specific ions like Ca^{2+} or Cl^{-} are not a concern for the reuse of the treated water, activated carbon or ozonation are suited for removing persistent pollutants. In conclusion, MBR technology coupled with additional polishing steps may be of particular interest when implemented in areas suffering from severe water scarcity, as they allow multiple reuse of water and reduce the pressure caused by industries on the exploitation of freshwater resources. In addition to this, the present investigation has addressed the problem of reuse of treated water containing pesticides. Their up-concentration in water by introducing reuse loops in the food sector may compromise the population's health. Such issues are particularly relevant in regions like North-East Brazil, where pesticides are used extensively and the food industry is an important contributor to the local economy.

MBR for Industrial Wastewater Treatment and Reuse

Within the project another pilot plant with MBR technology for industrial wastewater reuse was built and tested by the German company HUBER. This pilot plant features the MBR as the main wastewater treatment process. It was conceived by HUBER as a compact treatment system for both industrial as well as municipal wastewater treatment that provides an effluent fit for reuse in various applications.

For this purpose, HUBER developed a compact plant for reuse of wastewater, consisting of an equalization tank with a mechanical pre-treatment and a MBR. The process scheme is shown in **Figure 5.6**. The plant is designed for the treatment of approximately 50 m³ wastewater per day. The mechanical pre-treatment features a micro strainer (type Ro9E), which is integrated in the equalization tank. This stainless steel buffer tank has a volume of approximately 50 m³. **Figure 5.7** shows the pre-treatment.

The following MBR tank is also completely made of stainless steel and has a volume of approx. 50 m³ as well. This tank features two membrane filtration units with newly developed membrane plates. Additionally, it contains an aeration unit and a surplus sludge pump. During system operation the MBR tank is filled with activated sludge for biological treatment.

One of the above-mentioned HUBER®BioMem filtration units consists of 125 membrane plates with 1 m² membrane surface each (**Figure 5.8**). The scouring box under the membrane cassettes

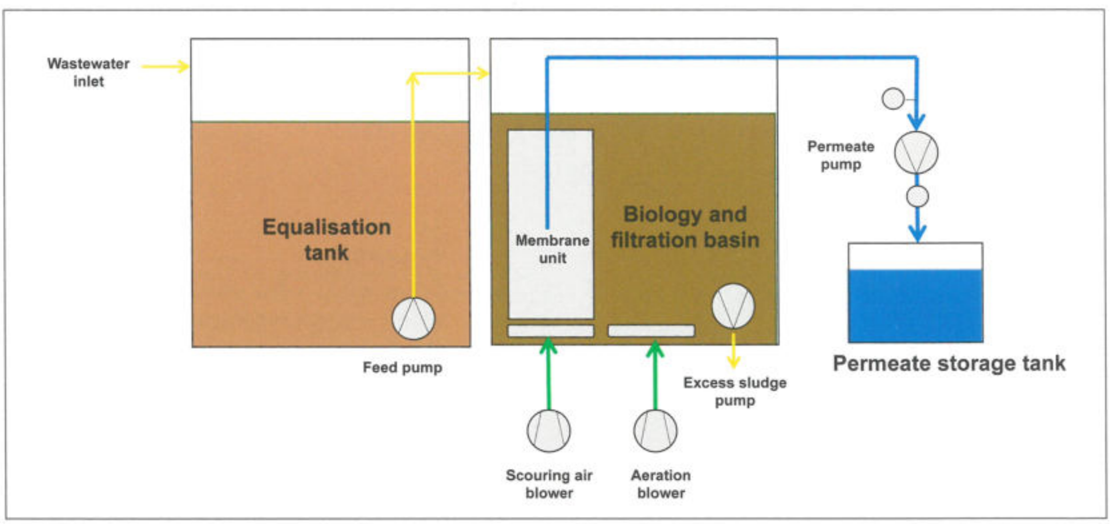


Figure 5.6: Flow diagram of the complete MBR plant

houses three pipe aerators arranged in longitudinal direction. The scouring air streams out through slots and is evenly distributed in the gaps between the membrane plates. Due to the turbulence created as the air bubbles rise upwards membrane surfaces are cleaned optimally. Each membrane unit has a set of associated equipment consisting of a blower, permeate pump and vacuum pressure gauge.

Regarding aeration, the blowers serve to scour both the air supply to the membrane unit and the oxygen supply to the bio-system. If the TMP rises above a certain value, the scouring air volume is automatically increased for a certain time to remove residuals from the membrane surface. These special cleaning and removal cycles, with an increased amount of air, repeat themselves for a certain time depending on the TMP.

For the purpose of process control, the MBR plant is equipped with sensors that allow operators to determine important process parameters such as O_2 concentration, pH value and temperature. Also the flow rate and operating pressure are measured continuously. Membrane integrity is monitored via turbidity measurement in the permeate line. The plant is equipped with a remote data transmission

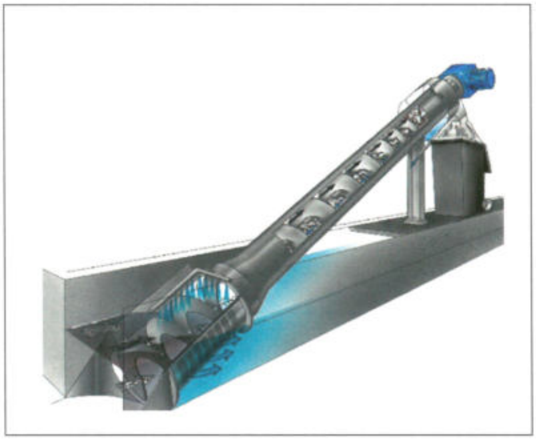


Figure 5.7: Mechanical pre-treatment system

Figure 5.8: HUBER®BioMem filtration units with innovative membrane plates

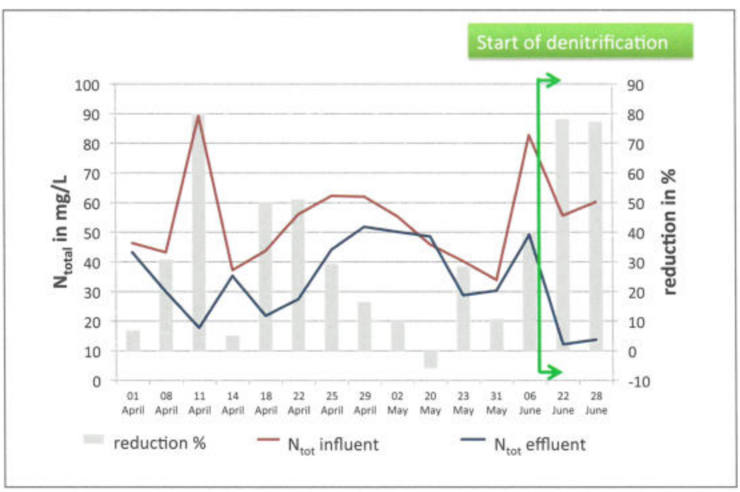


Figure 5.9: Excellent Results from HUBER®BioMem filtration for subsequent wastewater reuse

system to allow for centralized control of the complete plant from the operations control center.

The first experimental series carried out as part of BRAMAR was a test series to identify a membrane material that provides the best performance under practical conditions. Afterwards, extensive investigations were carried out with the municipal wastewater of the city of Berching to find an energy-saving operation of the MBR plant while producing a high quality wastewater effluent. As a result it was possible to reduce the required energy for the scouring air by more than 35% during the test series. This was achieved by mutual operation of the modules. At the same time, the values of COD could always be reduced by more than 95 % in stable operation. **Figure 5.9** shows that it is also possible to remove the nitrogen in the wastewater almost completely by means of a preliminary denitrification. The tests with this MBR pilot plant show that it is possible to operate a compact MBR treatment plant and save energy through special operation of the cleaning. Moreover, the quality of the effluent does not suffer. The HUBER MBR process is, therefore, a feasible option for compact wastewater reuse in small municipal or industrial applications, where water use, wastewater treatment and reuse need to be conducted on a small scale and in a single location.

5.2.5 Studies on Rural Wastewater Treatment and Reuse

Wastewater Treatment and Reuse for Agricultural Irrigation using Septic Tank and UV Radiation

Researchers at the UFERSA (Federal University of the Semiarid Region) developed and monitored two prototypes for the treatment and agricultural use of greywater under semiarid conditions, using simple and low-cost technologies, to obtain effluents that meet the standards for agricultural and forest reuse of COEMA Resolution 2/2017 (COEMA, 2017). There are many isolated or grouped rural residences and urban condominiums in the Brazilian semiarid region. The greywater has water and nutrients that can be used in fertigation of agricultural and forestry crops. In this sense, the use of greywater for irrigation is a strategic action directed to the Integrated Management of Water Resources, as it minimizes water shortage and environmental problems. How can greywater be treated and used for irrigation using simple and low-cost technologies? Will treated greywater meet the standards of COEMA Resolution 2/2017 (COEMA, 2017).

The prototypes consist of two versions of water treatment plants for agricultural and forestry purposes, one employing artificial ultraviolet radiation to inactivate pathogenic bacteria and the other using solar radiation for the same purpose. One of the prototypes was installed in a rural residence, inhabited by five people, from the municipality of Upanema and the other in an experimental area of the UFERSA in the municipality of Mossoró, Rio Grande do Norte, Brazil. In these, the

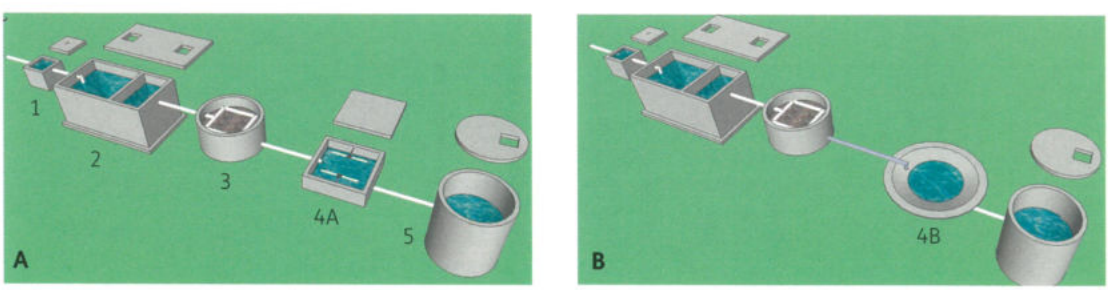


Figure 5.10: Schematic illustration of treatment systems for agricultural use of greywater with artificial ultraviolet radiation (A) or solar radiation (B) for reducing the population level of *E. coli*. Note: 1 – Passbox; 2 – Septic tank; 3 – Downflow filter; 4A – Artificial ultraviolet reactor; 4B – Solar reactor; and 5 – Reservoir

following technologies were used, as shown in **Figure 5.10**: 1) Passbox – centralizes the types of greywater generated in the residence in a single location; 2) Septic tank – removes sludge, oils and grease, sand and coarse material from greywater; 3) Downflow filter – for removal of organic particulate material and sorption of chemical elements in the 0.30 m layer of coconut fiber and carnauba straw under compression of 0.167 kgf/cm^2; 4A) Artificial ultraviolet reactor – reduces the population level of *E. coli* with ultraviolet radiation at 254 nm, emitted by two germicidal lamps, each with 30 W or 4B) Solar reactor – reduces the population level of *E. coli* after eight continuous hours of exposure to solar radiation; and 5) Reservoir – stores the treated effluent, avoiding losses by evaporation and proliferation of mosquitoes. In the experimental period from October 2014 to December 2015, the performance of the prototypes was evaluated through physical-chemical tests (pH, electrical conductivity and sodium adsorption ratio) and microbiological Helminths eggs (HE) and *Escherichia coli* analyses of the treated greywater; the results were then compared with the standards of COEMA Resolution 2/2017 (COEMA, 2017) for irrigation purposes. The prototypes operate with a greywater flow rate ranging from 0.4 to 0.8 m^3/day.

Table 5.3 lists the results of the physical, chemical and microbiological analyses of treated greywater and the respective standards for agricultural and forest reuse of COEMA Resolution 2/2017 (COEMA, 2017). In this table, it was verified that the treatment technologies of the two prototypes produced greywater with an average pH of 7.34, indicating minimum risks of acidification or alkalinization of the soil. When EC and Sodium Adsorption Ratio (SAR) are analyzed together, the effluent does not present problems of salinization and soil sodification. During the test period, HE were not found in treated greywater and both artificial ultraviolet radiation and solar radiation were able to considerably reduce the population level of *E. coli*. All the standards of COEMA Resolution 2/2017 (COEMA, 2017) for agricultural and forestry reuse, such as pH, EC, SAR,HE and *E. coli*, were met with the treatment provided by the two prototypes.

The two prototypes operated properly during the experimental period, according to the standards for agricultural and forest reuse of COEMA Resolution 2/2017 (COEMA, 2017). Nevertheless, the best performance of the prototypes was achieved when both the septic tank (removal of the sludge) and the filter (replacement of the organic filtering layer) were maintained annually, obtaining levels

Table 5.3: Mean values of physical-chemical (n=8) and microbiological (n=3 for disinfection with artificial ultraviolet and n=6 solar radiation) attributes of treated greywater and standards of COEMA Resolution 2/2017 (COEMA, 2017).

Characteristics	Treated greywater	Standards[1]
pH	7.34	6.0 < pH < 8.5
EC (dS m^{-1})	1.52	EC < 3.0
SAR (mmol$_c$ L^{-1})$^{0.5}$	5.11	SAR < 15.0
HE (egg L^{-1})	0	< 1.0
Log (*E. coli*/100 mL)*	< 3	< 3 (agricultural and forestry crops)
Log (*E. coli*/100 mL)**	< 1	< 3 (agricultural and forestry crops)

Note: EC – electrical conductivity; SAR – Sodium adsorption ratio; and HE – Helminth eggs.[1] COEMA Resolution 2/2017 (COEMA, 2017). *Population level of *E. coli* reached after 1 h exposure to artificial ultraviolet radiation at 254 nm (Figure 5.10A). **Population level of *E. coli* reached after 8 h exposure to solar radiation (Figure 5.10B).

of turbidity in treated greywater that favor disinfection with solar radiation and artificial ultraviolet light. In both prototypes, the disinfection process can be optimized by replacing the filter with an upflow anaerobic filter or constructed flood system. The technologies presented in the two prototypes have the potential to solve the environmental problems generated by the greywater of isolated or grouped rural residences and of residences in urban condominiums, leaving the treated greywater in conditions to mitigate the problems of water scarcity in Brazilian semiarid regions. After their final consolidation, these technologies can be transferred from the UFERSA to the Brazilian society through the implementation of technical training programs for teams of agrarian reform and rural extension entities (INCRA, EMATER, INSA, ONG and others); moreover, results can be disseminated through scientific articles, monographs, dissertations, theses and technical booklets. For the validation of the two prototypes, a complementary monitoring period of at least two years is necessary to improve pathogen inactivation technologies.

Rural Technological Study on Wastewater Treatment and Reuse for Agricultural Irrigation using UASB

Given the need to develop specific strategies in semiarid regions, another study aimed at developing domestic wastewater treatment technologies for the production of reusable water for agricultural, industrial and urban purposes in semiarid regions at a pilot plant scale as well as on family and community level. In addition, water reuse for agricultural purposes in semiarid conditions should be enabled and a new source of water and nutrients for irrigation of native species and forage introduced.

The promising results obtained both in the growth and development of native caatinga species and in forage palm cultivation under semiarid conditions are a justification and motivation for studies such as this.

Generally, there is a great interest in the study of technologies for water reuse by many institutions, such as the Federal University of Campina Grande (UFCG), Paraíba State University (UEPB), as well as the Program for the Application of Appropriate Technologies (Programa de Aplicação de Tecnologias Apropriadas, PATAC) and the Collective of Agriculture in Cariri, Seridó and Curimataú (Coletivo de Organização da Agricultura Familiar do Cariri, Seridó e Curimataú, COLETIVO), all of whom are partners in an cooperative initiative of technology development for water reuse in agriculture.

The cooperative initiative counts with 83 simplified treatment and reuse systems belonging to their established partners in the Cariri, Seridó and Curimataú regions of Paraíba. Three of these systems were implemented in 2010 and upgraded in 2014, 17 systems implemented in 2015, and 65 implemented in 2016. In general, key research questions of the initiative focus on the adequacy of low-cost, simplified systems guaranteeing wastewater effluent for reuse that comprises a satisfactory quantity and quality for agriculture; especially cultivation of Caatinga's native species and forage palm.

For the present study, treatment systems were designed for agricultural purposes at both family and community scales, using the Upflow Anaerobic Sludge Blanket Reactor (UASB) as a treatment principle. The systems have been implemented in the rural areas of Paraíba. In a previous study about the use of domestic wastewater in agriculture, the Instituto Nacional do Semiarido (INSA) set up its facility – a secondary anaerobic WWTP in Campina Grande – which has been used for the treatment of wastewater to produce reuse water to irrigate native species of the Caatinga region and the forage palm tree: "Orelha de elefante Mexicana".

After four years of monitoring vegetable growth, the preliminary results show an increasing growth rate for Purple Ipê tree (Hadroanthus impetiginosus), Freijó (Cordia trichotoma) and White Aroeira (Myracrodruon urundeuva). For the other species studied, Catingueira tree (Poincianella pyramidalis) and Braúna (Schinopsis brasiliensis), a decreasing growth rate was observed. Quality evaluations of the soil have been analyzed to investigate the availability of nutrients and their quality on the area in recovery process.

Regarding the forage palm studies, the results show that it could be possible to produce 49, 13 and 30 ton/day of N, P and K, respectively, with the volume of wastewater produced in semiarid North-East Brazil (14,055 L/s), comprising 14 mg/L of N; 11 mg/L of P; 25 mg/L of K. Consequently, according to the volume produced, it could be possible to cultivate 839 thousand hectares of forage palm tree, which yields 63 ton/year of raw material, and 54 million m^3 of water storage, using 528 m^3/year/hectare of domestic wastewater produced.

Regarding these aforementioned results and considering the soil and climate conditions of the semiarid region the application of that reuse water could be an excellent alternative for regions with similar characteristics.

Therefore, studies on the viability of low-cost wastewater treatment implementation are essential for the dissemination of these technologies in the semiarid region, which needs this promising alternative as strategy facilitating a life with the region's characteristics.

Rural Technological Study on Wastewater Treatment and Reuse for agricultural Irrigation using Constructed Wetlands and Sequencing Batch Reactor Technology

As mentioned in sub-chapter 5.1.3, the treatment of rural wastewater is essential to promote public health and environmental preservation. Therefore, two low-cost technologies for biological treatment of mixed household wastewater (greywater and blackwater) were implemented and tested at the Mangabeira WWTP in João Pessoa. The main aim was to test these technologies and to evaluate their technical suitability for rural wastewater treatment in North-East Brazil. Furthermore, the possibility to reuse wastewater treated with these technologies was evaluated. Each technology was set up for treating 900 L/d which corresponds to the raw wastewater of a single household consisting of six people. Especially in rural areas, the costs for implementing a centralized sewer system are quite high because the distances between the houses/settlements are large. Therefore, small treatment facilities enable safe wastewater treatment at reasonable costs.

The installed sequencing batch reactor (SBR) was manufactured by ATB Umwelttechnologien GmbH (Porta Westfalica, Germany) and put into service in March 2016 by RWTH Aachen University. The SBR consists of a sedimentation chamber where solids can settle. Through an overflow the mechanically treated wastewater flows into the bioreactor. During the treatment phase the bioreactor is aerated by the air pump and organic pollutants are removed according to the activated sludge process using floating biomass. When the water level has risen to a pre-set level, the aeration stops automatically and the biological sludge can thus settle in the bioreactor. After one hour of sedimentation, clarified water is pumped to the outlet and a new treatment cycle begins. This process is regulated by an automatic control unit and only requires yearly desludging.

The second low-cost technology that was tested by RWTH Aachen University at the Mangabeira WWTP is a constructed wetland (CW) as shown in **Figure 5.11**, which was constructed according

Figure 5.11: Picture of the constructed wetland taken in May 2017 and September 2017 (directly and four months after commissioning)

to the compact French system design (PAING et al., 2015). This specific type of CW is suitable for warm climates and can handle raw wastewater without prior sedimentation. Commissioning took place in May 2017. The wetland consists of three similar treatment beds which are each fed for 7 (or 3.5) days and then rest for 14 (or 7) days. The surface of each treatment bed was planted with reed and has an area of 2.4 m^2. The depth of the beds is 120 cm and the material used for the filling is an expanded material with high internal granular porosity, favoring biofilm growth, and gravel for support. The wastewater is applied to the surface of the beds in batches and slowly trickles through the bed before being collected in drainage pipes at the bottom of the bed. The wastewater treatment itself mostly takes place within the biofilm and is partly aerobic and anaerobic due to the batch feeding.

To monitor the performance of the pilot plants, samples were taken on a weekly basis and physical-chemical (pH, temperature, BOD_5, COD, NH_3-N, TS) and microbiological *(thermotolerant coliforms)* analyses were conducted. Both pilot plants achieve good cleaning results for BOD_5 and NH_3-N as can be seen in **Table 5.4**. In the SBR a big proportion of the TS and the COD are also removed.

The results of the microbiological analysis (thermotolerant coliforms) show that after the biological treatment in either CW or SBR relevant amounts of coliforms (4.3×10^5 and 8.3×10^5 UFC/100 mL) still remain in the wastewater so that the effluent of these treatment plants is not suitable for direct reuse. But, since both effluents have low turbidity, post disinfection using UV light or chlorine could be used to meet microbiological standards for reuse.

5.3 Water Reuse as a Measure for Water Scarcity Mitigation in North-East Brazil

5.3.1 Potential Role of Wastewater Treatment and Reuse

Research on wastewater treatment and reuse in the BRAMAR project focused on appropriate treatment solutions for different types of locations and applications. As proper wastewater treatment is required to ensure public health and to preserve the environment and the existing water bodies, individual solutions are needed to ensure this treatment in both urban and rural areas. Therefore, treatment technologies tested within BRAMAR include septic tanks and constructed wet-

Table 5.4: Mean values of physio-chemical and microbiological attributes of raw and treated wastewater

Characteristics	Raw wastewater		Effluent SBR		Effluent CW	
	Mean	n	Mean	n	Mean	n
pH	7.3	45	7.1	37	7.1	42
Temperature	26.4 °C	45	25.8 °C	37	27.5 °C	64
TS	610.5 mg/L	21	383.5 mg/L	19	701.2 mg/L	18
BOD_5	325.2 mg/L	23	16.2 mg/L	22	44.5 mg/L	17
COD	650.4 mg/L	46	70.8 mg/L	39	176.5 mg/L	43
NH_3-N	66.9 mg/L	44	14.2 mg/L	37	13.0 mg/L	41
Thermotolerant coliforms	1.1E+07 UFC/100 mL	9	4.3E+05 UFC/100 mL	7	8,3E+05 UFC/100 mL	9

land systems for wastewater treatment in decentralized rural areas and large stabilization pond systems and advanced biological treatment for urban and industrial areas.

As water scarcity plays an important role in water resource management in North-East Brazil, wastewater reclamation – meaning wastewater treatment for reuse – is a water management measure that has been discussed more and more in the last years. Therefore, the technical suitability of treatment technologies for various wastewater reuse applications was also studied during the BRAMAR project. A next step will be to evaluate the practical feasibility of implementing these technologies in real applications. For this reason, the following chapter will discuss non-technical aspects of water reuse and its implementation for water scarcity mitigation in North-East Brazil.

Concerning the implementation potential of water reuse, the report on the evaluation of water reuse potential follows the framework of the Study on the Action Plan to Establish a Wastewater Reuse Policy in Brazil (Ministério das Cidades, 2018), carried out under the Ministry of Cities coordination, with the support of Inter-American Institute for Cooperation on Agriculture (IICA). Although approximately 50% of North-East Brazilian territory is in a water stress area, the study indicates that the estimated medium-term reuse potential corresponds to 1 % of the withdrawal surface water resources since (i) the collection and treatment wastewater rates will probably continue to be low, (ii) there are alternatives for water conservation to be considered, and (iii) a significant part of the WWTP flow far from the coast must be maintained to ensure the flow within the water bodies. While there are additional approaches to meet water availability needs – including those related to the rationalization such as conservation, grey water reuse and industrial process water recycling and the use of rainwater without domestic effluent contribution – it is important to note that these alternatives are not included in the scope of this study.

Whenever the potential of water reuse in Brazil is discussed, it is necessary to consider that the infrastructure of the wastewater collection system and wastewater treatment plants is not good and, therefore, it is necessary to simultaneously improve it or, before starting to implement water reuse on a larger scale.

5.3.2 Main Drivers and Obstacles

North-East Brazil possesses great diversity of relevant aspects which are associated with the level of adoption of water reuse, such as population density, water availability, water usage, level of wastewater collection and treatment as well as legal responsibility for wastewater services and social and educational conditions of the population. As there are significant differences within the region, the most adequate level for an in-depth assessment of the reuse potential within this territory is that of sub-basin, municipality and/or project. The key issues are the availability and volume of wastewater for reuse, the need for new water sources or disposal charges associated with environmental issues, existing wastewater reuse methods and its users and also the possibility of commercialization of wastewater intended for reuse.

As mentioned before, the selection of reuse modalities and the amount of treated wastewater effluent that can be reclaimed and reused in a viable and sustainable manner are highly dependent on the local conditions, as well as the institutional framework and the reuse policy practiced at state and national levels. Although North-East Brazil has many basins and sub-basins with severe water stress situations, it is not expected that many opportunities for larger water reuse with economic and financial viability will be identified in cases of agricultural, forestall and industrial reuse. This is because there are few areas with technified and sustainable irrigated agriculture near the WWTP, and the industrial sector does not have high water consumption in the region, compared to other water use sectors. However, some opportunities can be identified for water reuse in irrigation districts and in large industrial complex-es or thermal power stations close to the WWTP, such as in the metropolitan region of Fortaleza. At the same time, there exist numerous possibilities for water reuse on small-scale projects.

An obstacle regarding to the external reuse of e.g. industrial wastewater is that neither its ownership nor who is entitled to reuse the water is legally specified. Additionally, it is not clear what competences would be necessary for institutions representing the federated entities and what possible difficulties would be observed during project development. Those issues will certainly need to be addressed in some act or guideline for water reuse in the industry, which should be elaborated within the framework of the National Water Resources Council (CNRH).

It is important to consider that specific water reuse legislation is still incipient in Brazil, even in terms of definition of the conditions and requirements and under which circumstances it shall occur. Neither the Sanitation Law (Law 11445/2007) nor the Water Law (Law 9433/1997) mention direct water reuse, neither do analogous state nor municipal laws. CNRH 54/2005 Resolution (MMA, 2014), which establishes modalities, guidelines and general criteria for the practice of non-potable water reuse, and CNRH Resolution 121/2010 (MMA, 2014), which establishes guidelines and criteria for the practice of non-potable direct water reuse in the agricultural modality and forestry, defined in CNRH Resolution 54/2005 (MMA, 2014), have not been able to leverage the practice of reuse in Brazil, even in regions where the availability of this alternative source would be of paramount importance. On the other hand, it should be observed that Brazil has environmental legislation that must be properly considered when regulating water reuse at a national level. Of particular note is the National Environmental Council – CONAMA Resolution 357/2005 (CONAMA, 2005) and its amendments, the former of which classifies water bodies and environmental guidelines and establishes conditions and standards for effluent discharge. CNRH Resolution 141/2012 (MMA, 2014) and the legal instruments of the North-Eastern States of Brazil comprise regulations on wastewater discharge into intermittent and ephemeral rivers.

In addition to domestic interests, Brazil's competitive advantages vis-à-vis the international community for protecting the environment, adopting clean technologies and focusing on sustainable development are indicative of the country's need to invest human and financial resources in a significant way to overcome obstacles in order to implement large-scale water conservation and reuse.

The population is demanding more investments in sanitation due to low coverage of wastewater collection (50 %), high inefficiency in the distribution of treated water (37 % losses) and cases of water shortage during the driest periods of the year. In addition, epidemics have increased awareness of the importance of investments in this sector since diseases such as dengue, Zika and chikungunya fever have a strong correlation with sanitation conditions.

The central axis of the respective national policy is the PLANSAB National Plan for Basic Sanitation (BRASIL, 2013), which aims to promote the national articulation of the federation entities in order to implement the guidelines of Law 11457/07 and to define goals and strategies for the government sector by the year 2033.

Another important obstacle regarding reuse implementation is that some state and municipal companies have low investment capacity and, to make things worse, many states and municipalities have debts at the federal government, which restricts access to financing lines and the receipt of transfers of non-debited resources through agreements and contracts. In addition, the overall investment capacity in the country is reduced due to the fiscal situation observed in Brazil.

A large number of Brazilian North-East WWTPs use stabilization ponds or UASB reactors. Since several of them perform poorly, this can be a barrier to reuse water in more demanding modalities because of its quality. However, even effluents treated by less sophisticated WWTPs could be applied in different water reuse modalities, and it is important that the technicians are qualified to consider this aspect and that the planning is suited to the conditions observed in the region in the formulation of actions to improve infrastructure of wastewater collection system and WWTPs.

It is known that water reuse regulation is found in an overlapping of two policies (water resources and sanitation) but worldwide it has been more under the responsibility of the first, with the support of the second. In this sense, the National Water Agency (ANA), with the direct support of the Ministry of Cities (MCidades) and the National Health Foundation (FUNASA), linked with the Ministry of Health (MS), should play the main role in Brazil. One obstacle identified is the fact that, despite legal prediction, there is still no effective articulation of the Water Resources and Sanitation Policies in Brazil, and the arrangement among listed institutions can be difficult.

ANA is the national water resources management entity and FUNASA is responsible in Brazil for implementing and expanding public water supply and sanitary wastewater systems in cities of municipalities with up to 50 thousand inhabitants. It also serves rural communities and, for this, uses resources from the General Budget of the Union (OGU) in the non-onerous financing of these actions. MCidades, in turn, serves municipalities with more than 50 thousand inhabitants usually with financial resources by CAIXA (government-owned financial institution) loans. Part of the resources to improve wastewater collection and sanitation infrastructure in Brazil may come from abroad, especially from banks and development agencies – the World Bank, for example.

ANA has introduced the PRODES Watershed Depollution Program, which aims to encourage the establishment of treatment plants to reduce pollution levels in river basins, paying for effectively treated wastewater instead of financing works or equipment.

Another obstacle regarding secure financing for the wastewater treatment and water reuse sector in the region is that many municipalities do not have a sanitation master plan. According to Decree 8629/2015 (BRASIL, 2015), after December 31, 2017, the existence of this plan, prepared by the service holder, becomes a condition for accessing budgetary resources from the Union, or to financing resources managed or administered by an agency or entity of the Federal Public Administration, to implement the infrastructure related to sanitation and water supply services.

5.3.3 Strategies and Actions for Wastewater Reuse Implementation

Despite the prediction that water reuse in agriculture and industry will be relatively low in North-East Brazil for the short and medium term, there is the tendency in large urban centers to increase reuse opportunities to supply part of the increase in water demand, supplementing the supply of non-potable or even potable water in the long run. "Barriers to salt water" could also be created by injecting treated wastewater into the aquifer, as done in several areas in California. This technology could be applied in North-East Brazilian coastal cities in whose territory saline intrusion into freshwater occurs due to groundwater overexploitation, notably in Fortaleza, Natal, Recife and Maceió.

One of the promising ways of implementing water reuse within the given conditions in North-East Brazil would be projects in larger cities, with the participation of private investors. This way, the viability of decentralized wastewater treatment systems should be specifically evaluated in urban water management, where reusing water could be a business opportunity that provides reuse of wastewater, attracting the participation of private investors, acting alone or in partnership with the public administration. The main "customers" of the reclaimed water produced from these effluents would probably be in the cities themselves, in residential or industrial areas. One issue that will certainly be evaluated in North-East Brazil is direct potable water reuse, along with the usage of desalinated water.

Another fact that can promote reuse is that the water bodies of North-East Brazil, particularly in the semiarid region, have low dilution potential for disposal of treated wastewater, which may result in a tendency to adopt wastewater treatment by "controlled disposal in the soil" to meet the objectives established by CONAMA Resolution 357/2005 and its amendments. This practice, which may impact forest and agricultural species, could be feasible in this region as small to medium-sized projects in areas under the influence of large cities, and/or projects in small and medium-sized cities in North-East Brazil with financial and operational difficulties to implement and maintain conventional wastewater treatment plants (WWTPs). However, it must not be overlooked that the reuse of wastewater in agriculture (fertigation) can lead to salinization or sodification of soils if the practice is not planned and conducted properly.

Pumping, conducting, and distributing wastewater generated in large cities for irrigation in peri-urban or agricultural areas would not normally be economically feasible, if water reuse is only intended to provide an alternative water source. Logically, the viability is more easily attained if the economic benefits of promoting fertigation are considered, which produces better results by the synergy of the simultaneous availability of water and fertilizers. On the other hand, the viability of the rural water reuse done at a more decentralized level in smaller agricultural projects, using wastewater generated in cities with fewer inhabitants, is facilitated when considering the potential of this practice in wastewater treatment. It is to be expected that a large percentage of the implementation of agricultural water reuse projects in the North-East Brazil, regardless of its size or objective, depends on some form of grant from the public power or the community.

For the issues presented earlier, water resources institutions and authorities need to be involved in developing and implementing any national water reuse policy. In addition to these, environmental and public health entities also need to play their role, noting that they act not only at the federal level, but also at the regional and local levels (basins and sub-basins, municipalities).

Regarding water resources, ANA and the National Secretariat of Water Resources and Environmental Quality (SRHQ) of the Ministry of the Environment (MMA), as well as the CNRH and the respective state councils (CERHs) are crucial, as they usually coordinate the drafting of water resources plans, in which the theme "water reuse" could be better integrated from now on. In addition to these entities, we could mention other federal or state institutions that would greatly contribute to disseminate this practice in Brazil.

As the Brazilian national water resources management entity, ANA will certainly use the instruments of the Water Law to induce and support the adoption of water reuse in the country. It is worth mentioning the recent launching of public calls for the selection of water reuse projects in the agricultural and urban modalities. In addition, ANA provides information that facilitates planning and decision-making of the expansion of water reuse in Brazil, such as (i) general data on withdrawal and consumption of water resources and on the quantitative (low flow rate) or qualitative (high levels of pollutants) critical condition of river basins (for example, National System of Information on Water Resources (SNIRH), and the Water Resources Scenario in Brazil, published every four years, with annual updates) (ANA, 2017a); (ii) specific data, such as location, flow rates, treatment levels of WWTPs (ANA/SNSA, 2017); Water in Industry: Use and Technical Coefficients (ANA 2017b); ATLAS Brazil – Urban water supply (ANA, 2010); Quantitative and Qualitative Modeling of River Excerpts in Critical Watersheds (in preparation); Study on alternatives of the industrial and agro-industrial sector, mechanisms of induction and support of the public power and of the sectoral representation of reduction of the water consumption and the generation of effluents and extension of the reuse of water (under contract). Most of the Brazilian states have specific water resource management entities or do so in conjunction with environmental management.

As an example, reference is made to Resolution COEMA 2/2017 of the State Council for the Environment (COEMA,2017), which provides standards and conditions to regulate the use of liquid effluents generated by polluting sources in Ceará State. These provisions comply with the provisions of CNRH Resolutions 54/2005 and 121/2010 (MMA, 2014). Therefore, it will be necessary to prepare legislation on the same theme for the other states of North-East Brazil and special consideration of the Wastewater Reuse Policy in Brazil to be proposed by the MCidades, mentioned previously.

In conclusion, based on the information presented, a successful water reuse policy cannot be based on the fact that the practice is only intended to mitigate situations of water crisis, but as a permanent alternative, which must be evaluated in an integrated manner with other solutions for water supply and wastewater treatment. The financing of wastewater reuse projects at the moment is advantageous in many cases. However, in order to achieve a more advanced technical, legal and institutional scenario, special concern should be given to implementing previously adequate wastewater collection and treatment.

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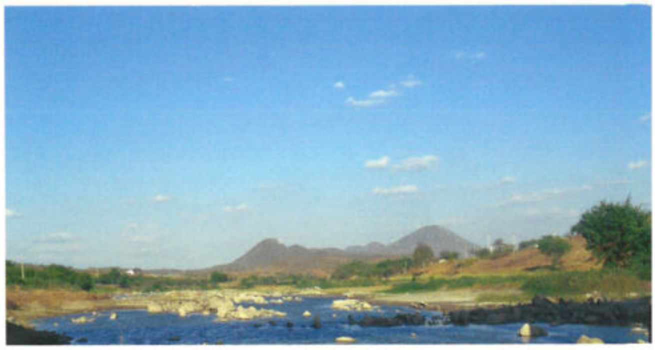
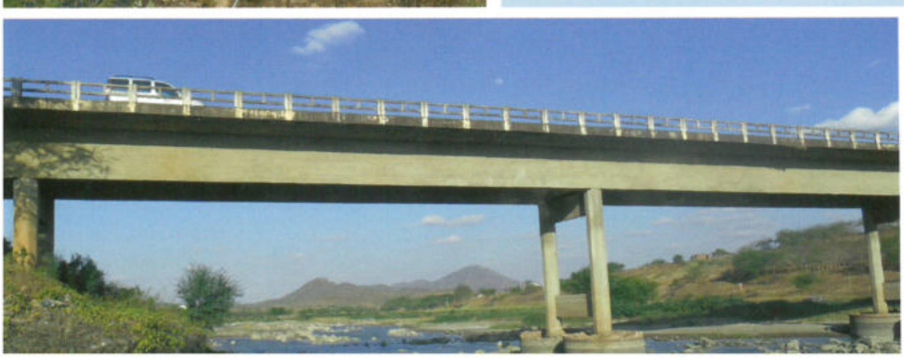


6

The BRAMAR Information and Decision Support System (Results from WP 7)

Bernd Rusteberg[a], Cecir B. de A. Farias[b], Cristiano das N. Almeida[c], Gerald N. S. da Silva[b], Iana A. A. Rufino[b]

a RWC, b UFCG, c UFPB



6.1 Decision Support towards IWRM Implementation

6.1.1 Need for Decision Support

The integrated management of all water resources is a complex and challenging task, especially in the case of regions affected by water scarcity, like in semiarid North-East Brazil. Indeed, there is a strong competition between the different water users under water scarcity conditions. This requires all stakeholders, water users and decision-makers to participate in the water-resources planning and decision-making process.

Due to the complexity of water resources systems, which commonly include man-made hydro-infrastructure, the system reaction to potential human interventions is difficult to analyze. Required are so-called Decision Support Systems (DSS) or Expert Systems, which offer special analysis and modeling tools in order to study the impact of human interventions in social, economic and environmental terms. Innumerous structural and non-structural measures may be implemented by water-resources planners to attend to the gap between decreasing water resources and increasing water demands due to climate change impact and uncertain socio-economic development, as in North-East Brazil. The chapter on WP 8 will provide an overview of potential IWRM measures, which also include innovative water technologies, e.g. related to wastewater reuse, as one of the focus areas of the BRAMAR research project. In a certain manner, all these measures compete with each other, each of them contributing to the sustainable development of water resources, but with different performance in social, environmental and economic terms. How well they can be implemented and transferred, how well they are accepted both politically and socially play an important role, too, when adequate IWRM measures are selected as response actions to specific water management challenges of a region. Innovative Decision Support Systems and planning procedures are required to support the water-resources planning process, taking all relevant aspects into account to select the most efficient response measures to guarantee sustainable development.

6.1.2 Main Challenges for System Development

A number of Information and Decision Support Systems (IDSS) have been developed in the past, attending to different water management challenges or objectives, such as water allocation, flood control or water quality management. They have proved to be powerful tools to support decisions with regards to different water-resources planning and management tasks. Thanks to DSS developments to support Water Resources Planning and Management (WRPM) tasks started in the mid-1970's, significant progress has been made in last decades. The following DSS may be mentioned: (a) Flood management: CWMS (FRITZ et al., 2002), SMS (EMRL, 2004), WMS (EMRL, 2004), (b) water allocation: AQUATOOL (ANDREU, 2004); DELFT TOOLS (DELFT HYDRAULICS, 2008); MIKE BASIN (DHI, 2008), (c) water quality: BASINS (USEPA, 2008), MODULUS (OXLEY et al., 2004), WISDOM (BMBF, 2010). (d) Managed Aquifer Recharge: GABARDINE DSS (RUSTEBERG et al., 2012). DSSWRP and MULINO are decision-support systems (EC, 2008) that specifically address the integrated management of water resources. The systems are mainly desktop solutions. Since most of the systems are directly linked or loosely coupled to hydrological models, the transferability of each DSS has to be carefully studied.

The main challenge for the development of an innovative Decision Support System within the BRAMAR project is to support water-resources planning and management decisions in a way that provides transparency in the decision-making process in order to guarantee political and social acceptance later. Thanks to automated processes, the user should be able to produce key information for water-resources planning – water-budget calculations for any partial river basin under study, budget forecasts based on different climate change and socio-economic development scenarios and identification of critical areas with regards to water scarcity. The information of the data base should be accessible to all persons and institutions involved in the decision-making process. This only can be achieved by a web-based, flexible, highly interactive and modular system structure, which guarantees that new tools and models can be easily integrated, and that different water-resources systems and boundary conditions flexibly applied. Therefore, a framework for a DSS has been developed in the present project. In order to support water-resources planning decisions and IWRM implementation, a generalized, participative and transparent approach had to be defined in the project and implemented in the DSS. Further information about this task is given under the following chapter.

Finally, when interdisciplinary demands and integration between project groups and stakeholders are considered, effective programming solutions are required in order to improve the allocation of time and to reduce the level of uncertainty in analysis, modeling and decision-making. Data organization and analysis were a key challenge of all BRAMAR research groups in order to contribute to efficient data-base management.

6.2 The BRAMAR-IDSS

6.2.1 Conceptual Structure, Data Base and Graphical User Interface

The BRAMAR Information and Decision Support System (IDSS) is a web-based modular system. **Figure 6.1** shows the Modular System Architecture. The BRAMAR IDSS is made up of four key components: Interfaces, data bases (internal/external), a tool base for analysis and a decision-support tool set for water-resources analysis and planning or comparison of technological options (SPRAGUE, 1989).

The user interface, which was developed for Internet browsers using the ArcGIS API for JavaScript (ESRI, 2017), ArcGIS for Server services (ESRI, 2015) and the DOJO/DIJIT/DOJOX JavaScript toolkit, along with other tools to enrich the user interface. The developed graphical user interface (GUI) uses an HTML site with JavaScript, which uses AJAX techniques; Ajax is a concept of asynchronous data transmission between a browser and the server (NIEDERAUER, 2013). This makes it possible to perform website requests, while the website is displayed, and allows a user to change the page without completely reloading it.

The GUI is very similar to most of the GIS platforms (BURROUGH and MCDONNELL, 1998). **Figure 6.2** presents an example of a GUI, using the Web Geographic Information System, to access water demand information, presenting the main system menu in the upper part of the screen. The main menu items are View, Water-Resources Planning, Geoprocessing, DS Tools, Analysis, Bookmarks, Water Permits and Help. Different water resources stakeholders with various knowledge levels (professionals, students, policymakers, etc.) can easily access the BRAMAR-IDSS.

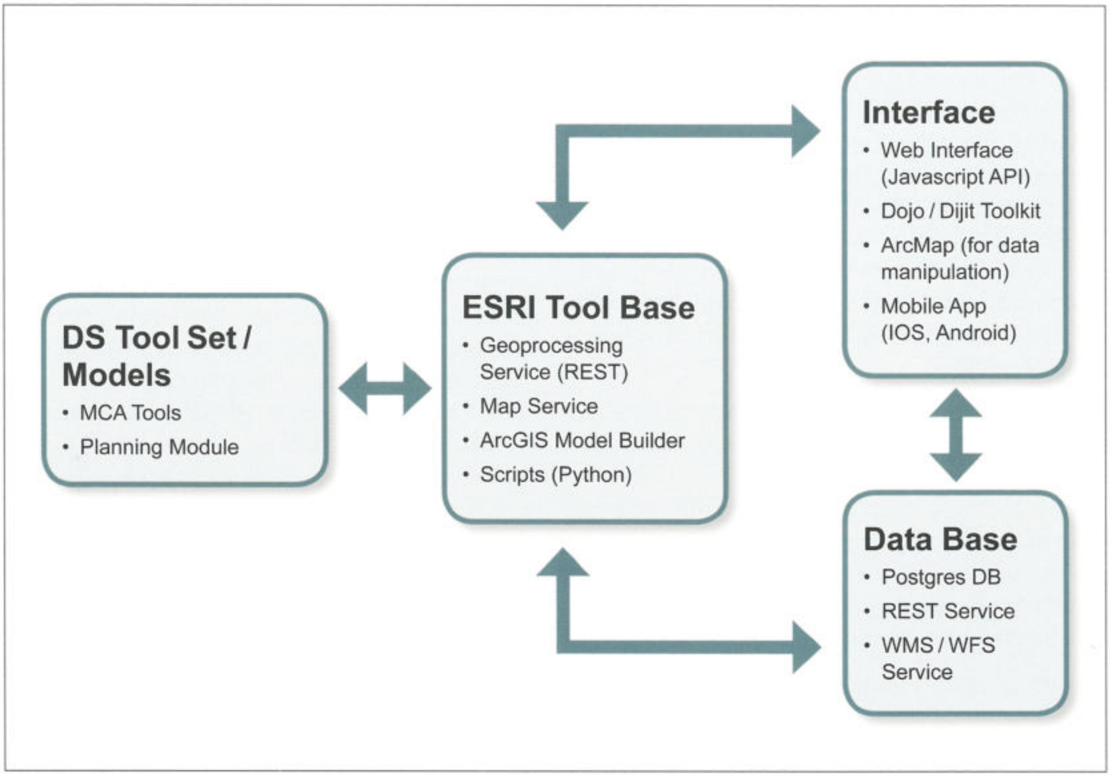


Figure 6.1: Conceptual/modular system architecture of the IDSS

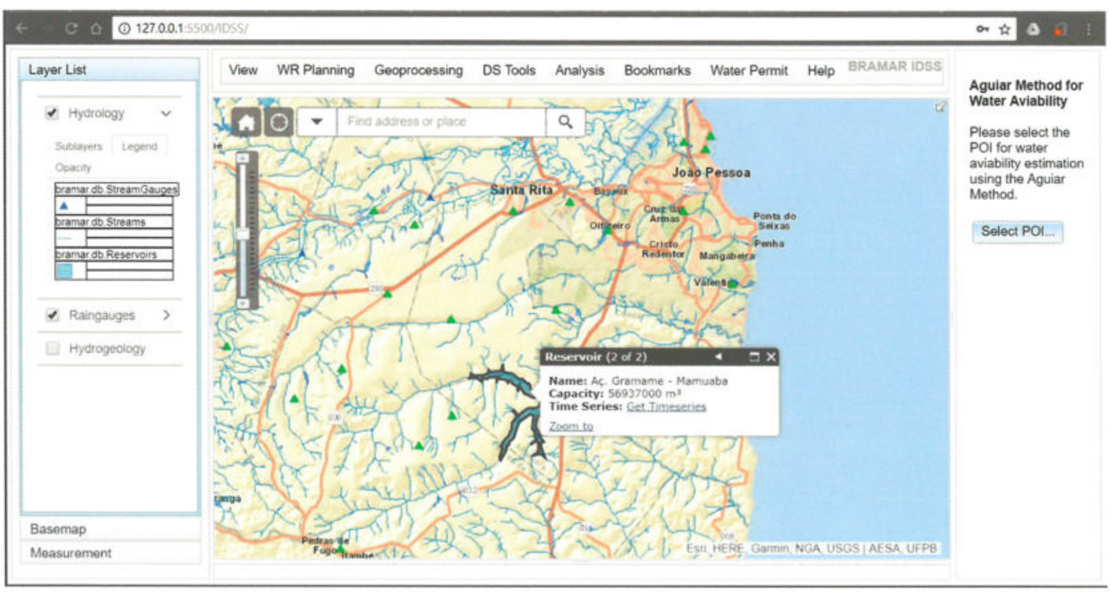


Figure 6.2: Graphical user interface BRAMAR IDSS (Esri, HERE, Garmin, NGA, USGS AESA, UFPB, edited by: G.N. Souza da Silva)

The adopted solution allows maps and geographical information to be accessed anywhere, anytime, on any device, including web browsers, smartphones and desktop applications. The target users are water-resources stakeholders (end users and/or policy makers), academic users and researchers. The IDSS provides them with access to the information in a collaborative way; users can provide some information to the system, too. **Figure 6.3** presents different system users, from different levels of knowledge and different roles in the system.

Three components are connected to the user interface: a database where every single kind of information is stored, from temporal data to spatial data; a tool base that provides general tools for data processing; and a model base where different procedures and environmental models can be linked. A hydrological regionalization model may be accessed from the model base.

Proper support for water-management decisions requires a well-modeled database. In the BRAMAR-IDSS the geo- and water-resources database is a core module, allowing spatial and temporal data management. The IDSS connects to the data base and supports the visualization of relevant water-resources management information as well as the access to source data as basis for mathematical modelling. **Figure 6.4** shows the conceptual layout - spatial data (features) and temporal data (time series) of the BRAMAR database.

ArcGIS for Server has been identified as most appropriate solution with an underlying PostgreSQL database management system (RAMAKRISHNAN and GEHRKE, 2000) for the development of the BRAMAR data base and the IDSS. The system offers a wide spectrum of capabilities, which can be easily customized for geographical and hydrological analyses within the BRAMAR project. Database/GIS features are accessible through a rich web interface including data and group management and facilitates the use of a complex database for Non-GIS professionals. The web interface makes it simple to integrate, store, share and publish data (RUBALCAVA, 2015). Advanced users can use ArcGIS for Desktop or any other API/Query interface for DB/GIS access. Furthermore, the obtained data and developed tools can be accessed

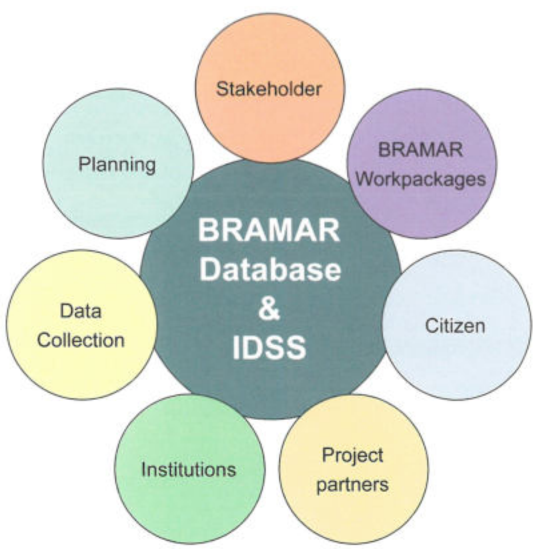


Figure 6.3: BRAMAR database and integrated concept of the system

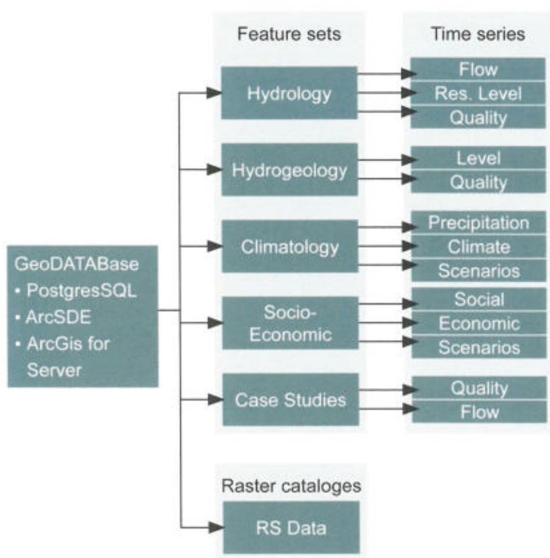


Figure 6.4: Conceptual layout - spatial data (features) and temporal data (time series)

with common web and desktop applications, like Google Earth, ArcGIS Online, SNIRH (ANA) and open source platforms. There are several Brazilian government institutions that use the same platforms to share data, such as the National Water Agency (ANA) for the National Water Resource Information System (SNIRH) , CPRM and IBGE .

The IDSS allows, for example, the editing of BRAMAR borehole data and monitoring data and provides, therefore, support to the joint monitoring and conjunctive management of surface and groundwater resources, which is one of the major challenges of the National Water Agency ANA and all state water agencies. **Figure 6.5** shows the borehole selection table and information window.

Time series can be edited by using different interfaces (beyond the IDSS), using the ArcGIS REST services connected to the BRAMAR database.

Based on aquifer characteristics, groundwater monitoring data and hydrogeological models, several groundwater related maps and information may be generated, such as on aquifer thickness, depth to groundwater, residence time in case of controlled groundwater recharge or location of pollution sources and impact.

6.2.2 BRAMAR Decision Support Tools

Introduction

The Decision Support (DS) tool base consists of Operations Research methods, especially based on Multi-Criteria-Analysis methods. They can be used for identification, rating and selection of decision alternatives, exemplification of the decision-making process, and allow the comparison of alternatives by means of performance matrices.

Water Permits

To provide support for the analysis of water demand, tools for water-permit management and technical analysis were integrated into the BRAMAR-IDSS. The system aims to provide support for the technical analysis of requested water rights and decision support and even permits to plan field visits in order to check water-permit data in

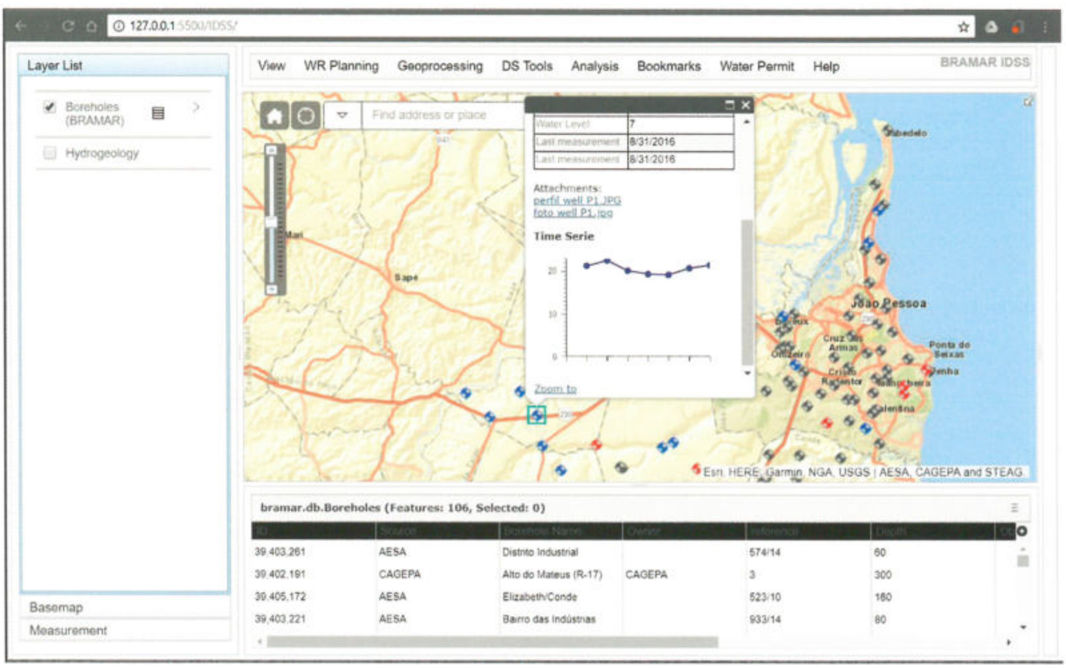


Figure 6.5: BRAMAR borehole data in the IDSS interface (Esri, HERE, Garmin, NGA, USGS, AESA, CAGEPA and STEAG, edited by: G.N. Souza da Silva)

loco. Granting water permits is a very important task, since permitting additional water use in areas with previously existing or expected water deficits may result in serious water conflicts. **Figure 6.6** shows the simplified process of the water-permit process.

The water permit support tools were integrated in the IDSS interface. **Figure 6.7** shows the interface with added SNIRH data (national water-permit web service).

Innovative tools for the filtering of water-permit data have been introduced into the BRAMAR-IDSS in order to support the work of the Environmental State Agency AESA, by making the access to the existing water permits easier and enable specific water demand assessments.

The option opens a new window which allows users to select the search field and define a value for a similarity search. The tools permit them to aggregate and analyze water permits for any partial

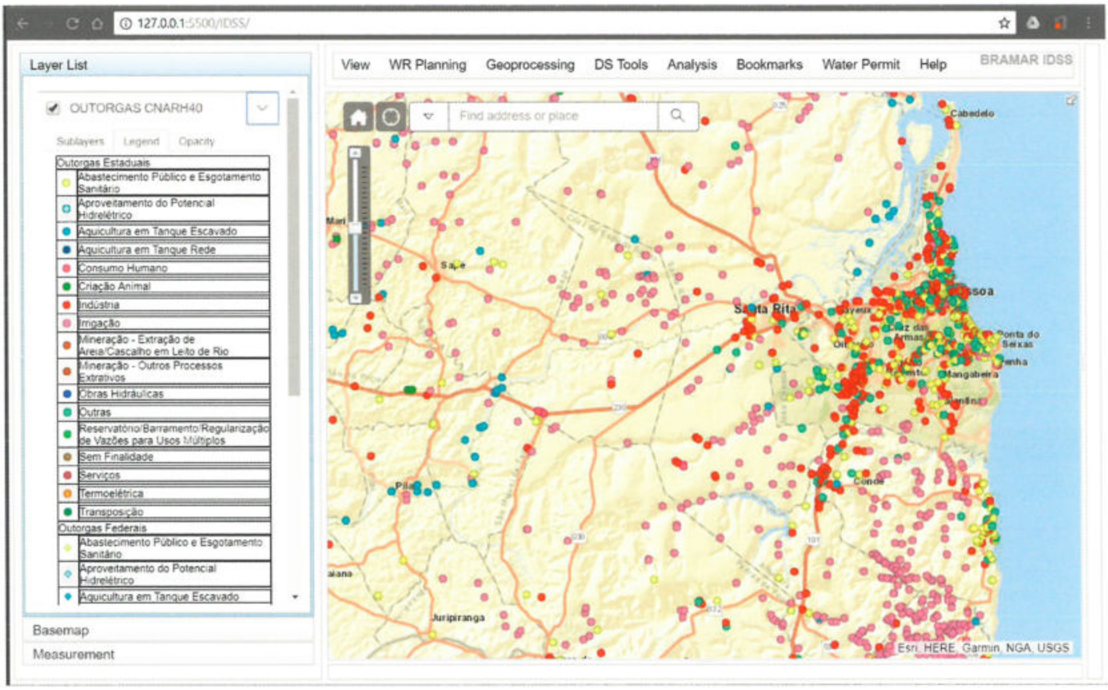


Figure 6.7: Water-permit analysis (Esri, HERE, Garmin, NGA, USGS, AESA, ANA, edited by: G.N. Souza da Silva)

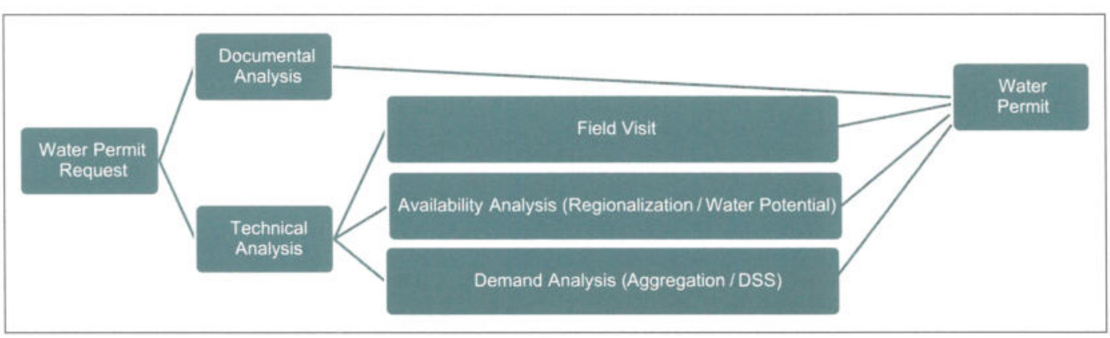


Figure 6.6: Water-permit process

area, designed by the user, or any partial watershed, which is being generated by the BRAMAR-IDSS in an automated process. **Figure 6.8** shows how selected water-permit data is being listed and how to access the filter, which permits data filtering, e.g. according to process number, type of water use, source of water, name of river, requesting party or state of licensing process.

Multi-Criteria Analysis

The BRAMAR-IDSS contains Multi-Criteria-Analysis (MCA) tools to support water-resources planning decisions. In this section, a short example is given how the system supports the selection of locations for groundwater recharge facilities in the context of Managed Aquifer Recharge (MAR) implementation. More detailed information about BRAMAR research on MAR is given in the chapter on WP 3. The planning procedure follows the approach presented by Rusteberg et al. (2012). The main steps of this procedure refer to so-called constraint and suitability mapping. First of all, the relevant decision criteria (indicators) are selected from those for constraint mapping and suitability mapping. For the selected criteria, criteria maps were developed for the project region, which represent their spatial distribution. For example, the land-use map was reclassified for the MCA site selection using eight classes. **Figure 6.9** shows the reclassified land-use map for the Gramame and Lower Paraíba region.

The interfaces for constraint and suitability mapping were developed using range sliders. Horizontal range sliders are used to define upper and lower threshold values for suitability mapping. This has the advantage that false user input is eliminated, because minimum and maximum values of the data are already defined by the sliders. Selected values are also visualized. Furthermore, a mapping window for feasible land use selection is generated.

Furthermore, all processed criteria can be reviewed to detect which ones do not meet the selected thresholds. The suitability analysis has more parameters and is more complex than the constraint mapping; therefore, a Python Script was created which calculates the suitability map-

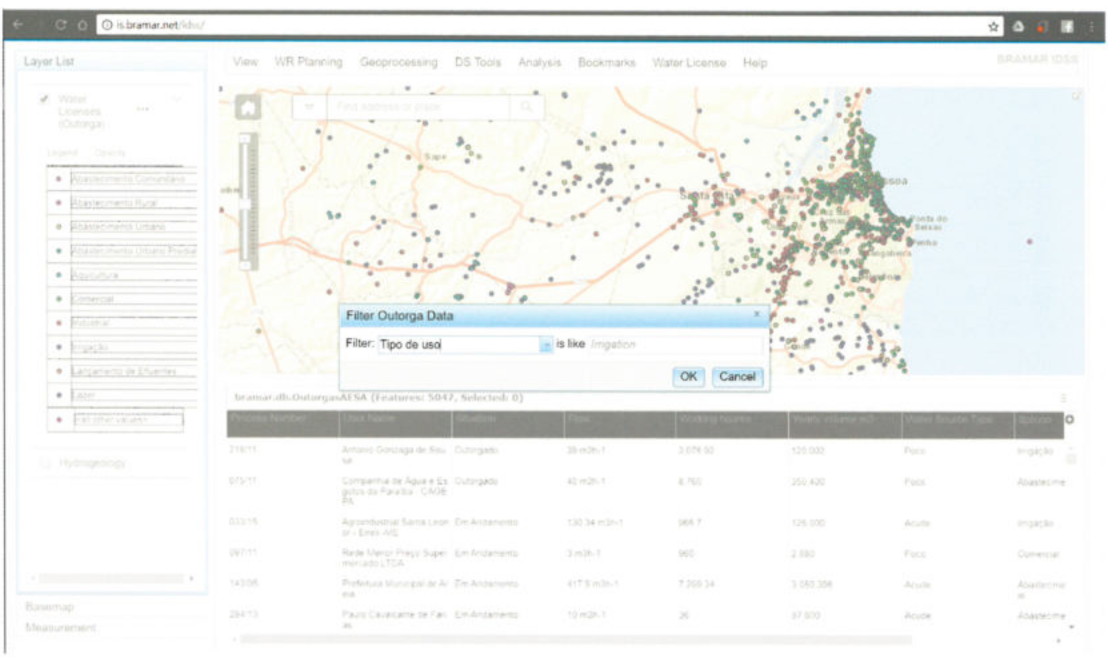


Figure 6.8: Analysis of Water-Permit Data (Esri, HERE, Garmin, NGA, USGS, AESA, edited by: G.N. Souza da Silva)

ping with the provided parameters including standardization, weighting and raster summation. **Figure 6.10** shows the user input form for Suitability Mapping. The different weighting is selected, and lower/upper bounds are chosen by the user.

Lower and upper threshold are used to linearly transform the function values to a specified evaluation scale. For suitability mapping all criteria values are transformed in a value range from 0 to 1. **Figure 6.10** provides an example of how suitability mapping results are presented. Results are classified in four ranges: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75 and 0.75 to 1. This mapping classification provides information for the best locations with regards to the implementation of groundwater recharge facilities.

Water budget

Any partial watershed can be analyzed using the tools provided in the IDSS, which are based on a point of interest and the watershed delineation of this point. Based on this delineated watershed, water demand and availability are analyzed using provided data from work packages. The water budget is key information in any water-resources planning process. Detected water deficits in the present or near future are main causes of water-related conflicts.

The calculation of the water budget for partial watersheds as automated procedure in the scope of BRAMAR-IDSS follows a step-wise approach, as presented in the below **Figure 6.11**.

The regionalization tool is especially helpful in regions with scarce river runoff data to transfer available river runoff time series to any nearby river cross section in the watershed.

The tool uses the web interface to select the point for which the regionalization will be executed (outlet of partial watershed) and nearest or most appropriate point with available runoff time series. The BRAMAR-IDSS provides a discharge duration curve based on river runoff data and the regionalization data in order to derive characteristic parameters for

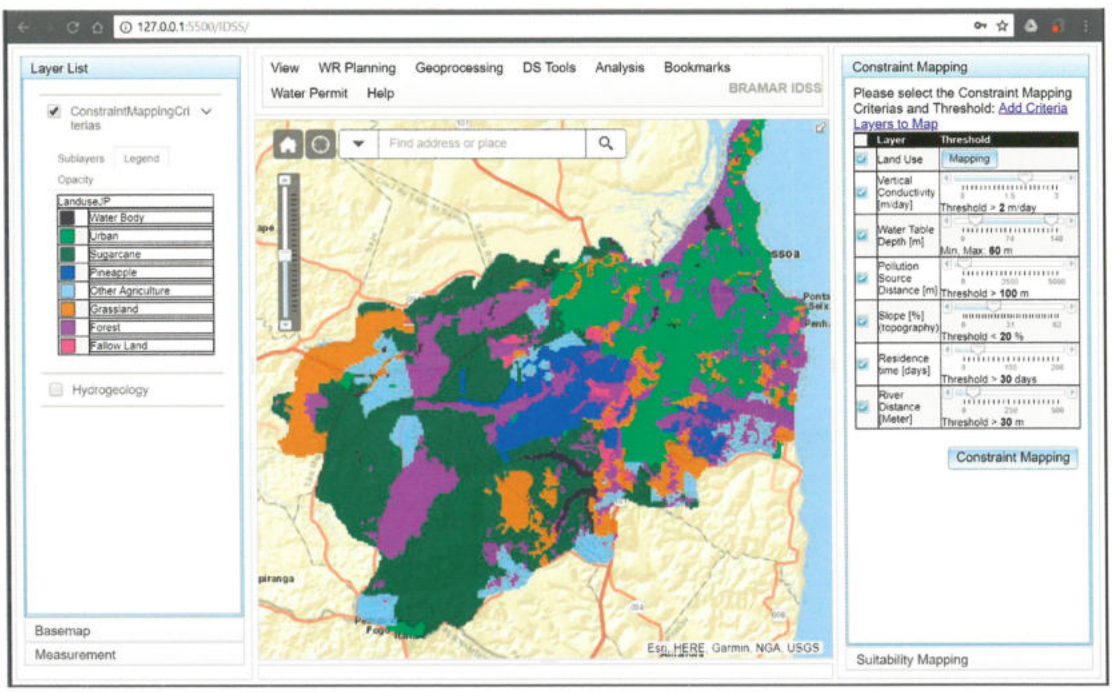


Figure 6.9: Land-use map for MCA site selection (Esri, HERE, Garmin, NGA, USGS, UFPB, edited by: G.N. Souza da Silva)

the assessment of the surface water availability at the outlet of the partial river basin (**Figure 6.12**).

Climate change data was provided in BRAMAR work package 1. Three models were used in WP1 with scenarios for RCP4.5 and RCP8.5. This data (precipitation and temperature) can be accessed for visualization in the IDSS. Rainfall runoff models are used to estimate water availability, using the rainfall distribution and temperatures. The integration of climate change scenarios uses runoff data and the developed regionalization for partial watershed availability estimation. Detailed information about the climate change studies is presented in the chapter on WP 1.

For the water budget forecast, first of all, water demand and water availability must be calculated by the BRAMAR-IDSS. The obtained data is automatically used in a water budget sub-module, which allows the comparison of the scenarios. For both, water demand as well as water availability assessment, the development and climate change scenario, respectively, must be selected. Furthermore, a time horizon for forecast calculation needs to be specified by the system user.

A key functionality of BRAMAR-IDSS is a comparison between the surface water availability of the partial watershed and the water demand, based on a water-permit data base. These are most valuable results for any water and environmental

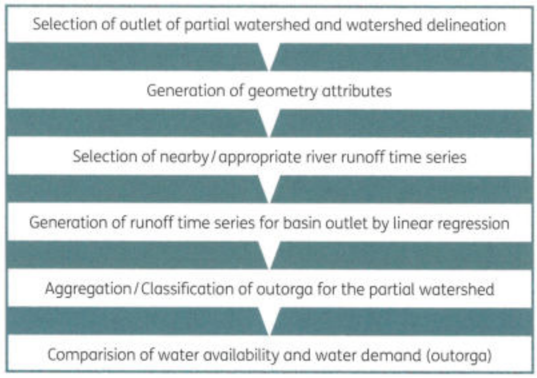


Figure 6.11: Calculation of water budgets for partial watersheds within BRAMAR-IDSS

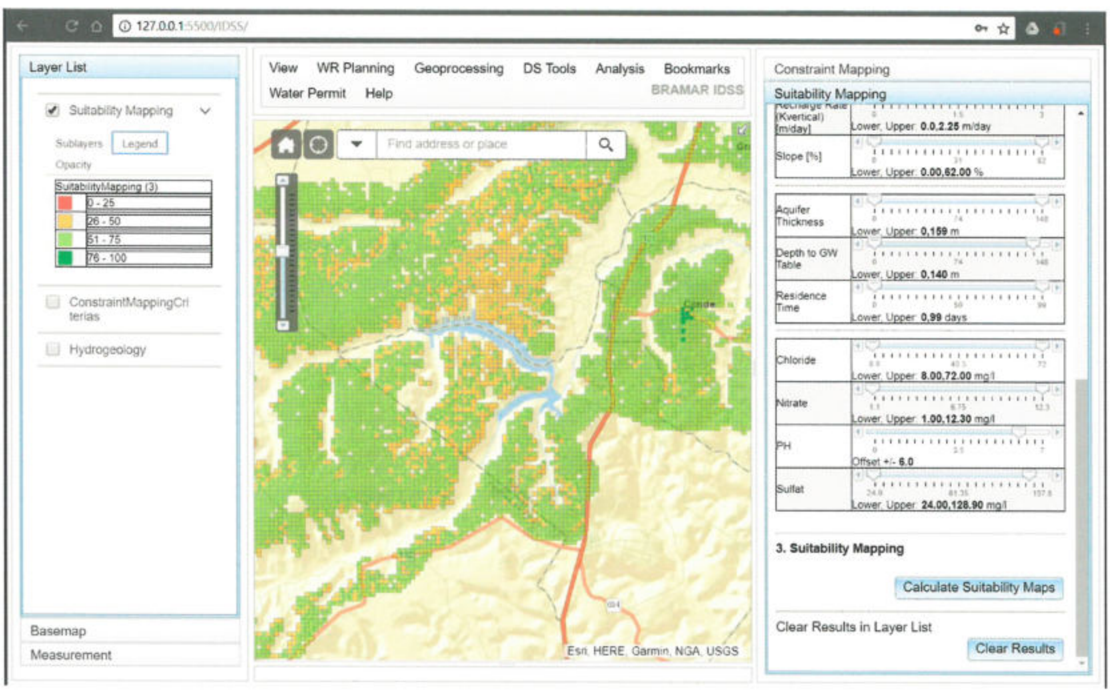


Figure 6.10: Suitability mapping result (Esri, HERE, Garmin, NGA, USGS, BRAMAR, edited by: G.N. Souza da Silva)

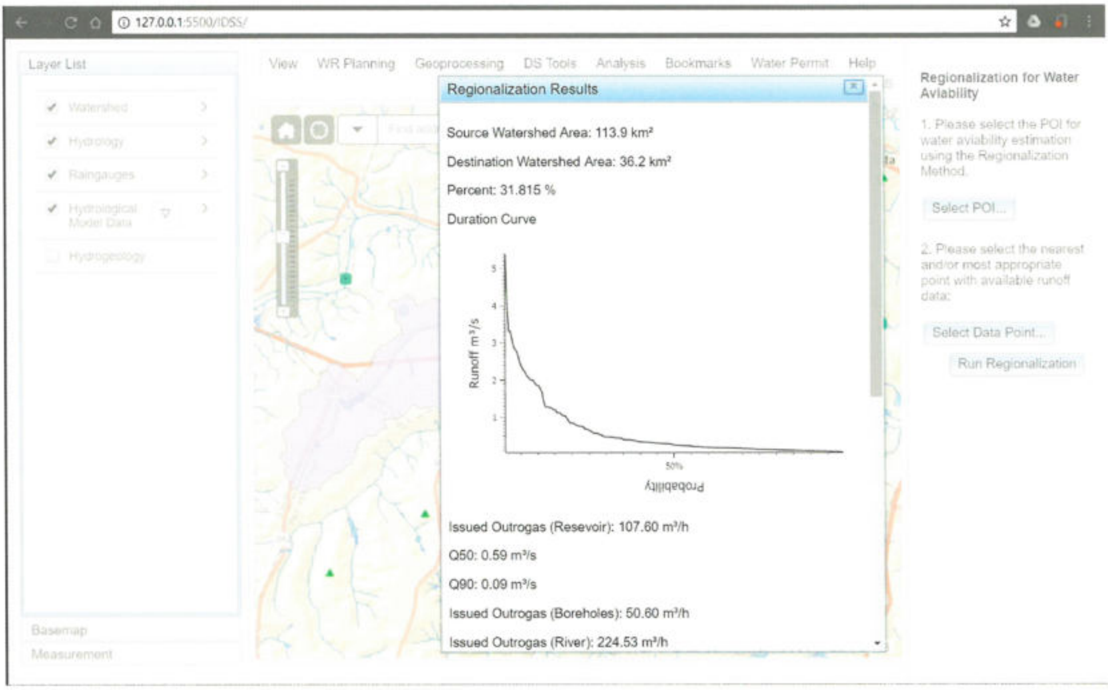


Figure 6.12: Regionalization report - duration curve and regionalization data (Esri, HERE, Garmin, NGA, USGS, AESA, UFPB, edited by: Souza da Silva, G.N.)

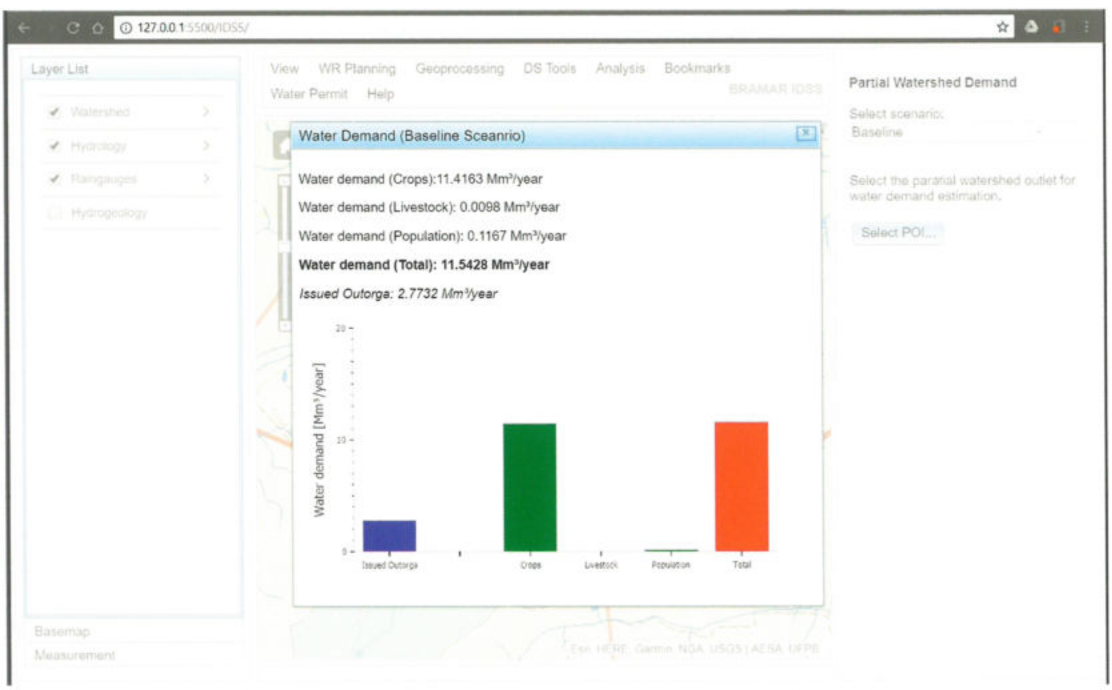


Figure 6.13: Example for water-demand assessment for partial watershed with Census data from IBGE 2010 (Mm³/year) and outorga data (Esri, HERE, Garmin, NGA, USGS, AESA, UFPB, IBGE, edited by: G.N. Souza da Silva)

agency, especially with regards to assessing water permits. **Figure 6.13** shows water demand and previously issued water permits in the partial watershed. The example shows that the actual water demand (IBGE, 2010) of the partial basin under study is much higher than the annual volume of water, related to the given water permits.

Water-Resources Planning

The IWRM planning sub-module is integrated in the BRAMAR IDSS platform and operated in an interactive manner. It guides the system user through the planning and analysis process which has been developed within the BRAMAR project. The eight-step planning procedure will be presented in the following chapter which describes the work in BRAMAR WP 8. In the system, the procedure is presented by means of a planning flow chart. **Figure 6.14** shows how to access the water-resources planning menu item in the BRAMAR-IDSS. Clicking the specific sub-items leads to the different stages of the water-resources planning procedure.

Due to the technological focus of the BRAMAR project, special attention is given to the so-called structural IWRM measures which require the implementation of hydro-infrastructure. Different structural IWRM measures, discussed in detail in chapter on WP8, have been evaluated by means of indicator sheets by the BRAMAR research groups, providing explanations with regards to the evaluation of each of the indicators. While using the BRAMAR-IDSS, researchers may add new IWRM measures and evaluate them at any time. For initial system analysis, the user may access relevant studies to numerous different methods in order to select the relevant procedures and provide a better understanding of the natural water resources, socio-economic and administrative subsystems and their interactions. Further information, together with the relevant screen of the BRAMAR-IDSS, is provided in the chapter on W P8.

Using filter, stakeholders, water-resources planners and decision makers can access this information in the BRAMAR-IDSS in order to access the

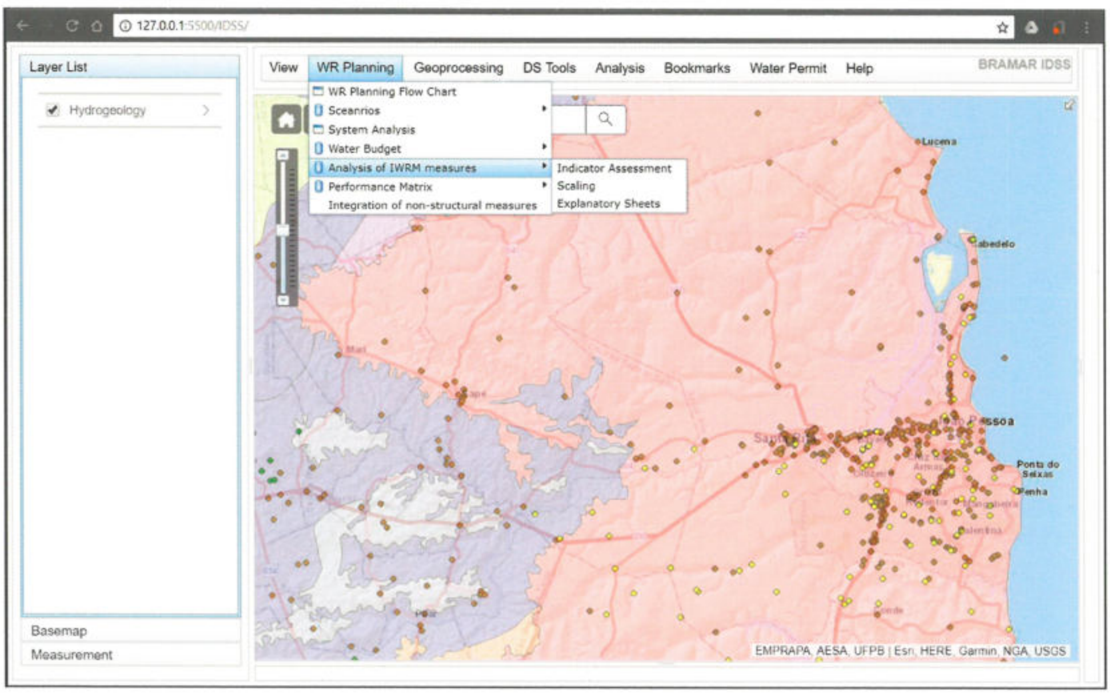


Figure 6.14: Water resources planning menu items (EMPRAPA, AESA, UFPB, Esri, HERE, Garmin, NGA, USGS, edited by: G.N. Souza da Silva)

results in a very structures objective oriented manner. **Figure 6.15** shows the analysis of structural IWRM measures, where the user can select measures, the region where the measure will be applied and minimum values for the indicators using horizontal sliders and the scale values from 0 to 10. The list of indicators is presented in more detail in the following chapter about the works of WP 8.

Based on the application of these filters, a performance matrix is created by the system which takes selected measures and minimum values for the indicators into account (**Figure 6.1**).

In order to provide an integrated approach to water-resources planning and management, the BRAMAR-IDSS offers access to a comprehensive list of non-structural IWRM measures, such as water pricing, demand management, water licensing and system operation with comprehensive studies, publications and recommendations, related to the region in North-East Brazil. All of these measures have been undertaken within the Brazilian-German BRAMAR research and development project and should be taken into consideration for IWRM implementation.

6.3 System Usage and Technology Transfer

The BRAMAR-IDSS is already being applied by the Water Agency of the State of Paraíba (AESA) and will be made fully available for decision-makers and technicians of the relevant water and environmental agencies of Paraíba, Pernambuco and Rio Grande do Norte. Version 1.0 of the BRAMAR-IDSS requires further development in a number of aspects. The need for further system validation and

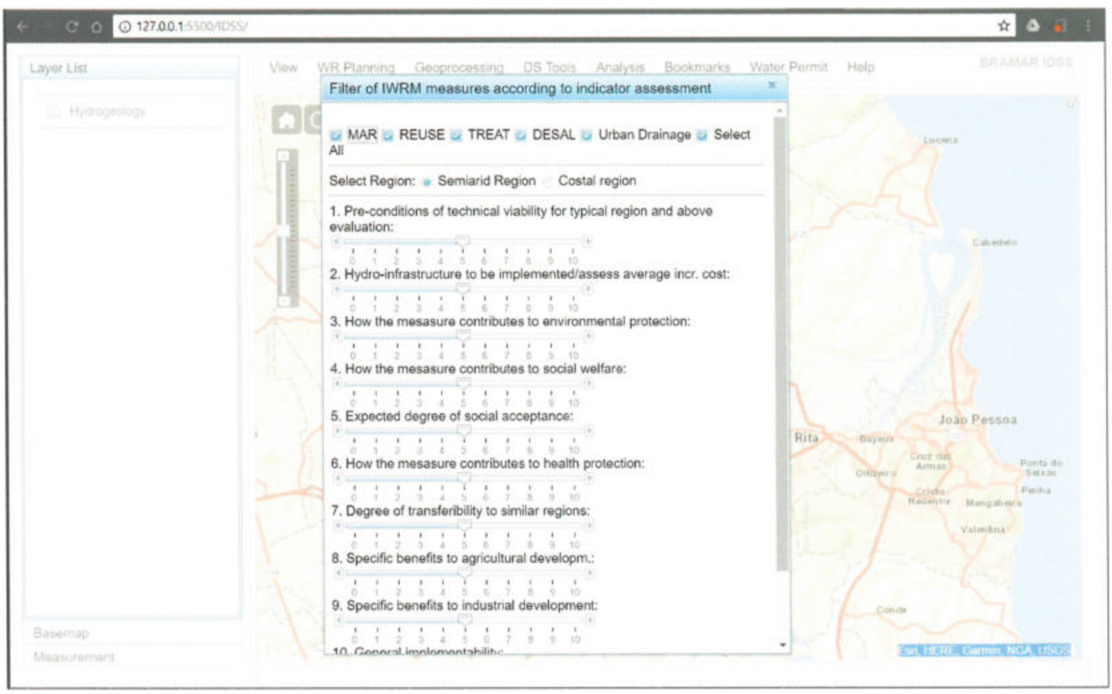


Figure 6.15: Filter/analysis of structural IWRM measures (Esri, HERE, Garmin, NGA, USGS, edited by: G.N. Souza da Silva)

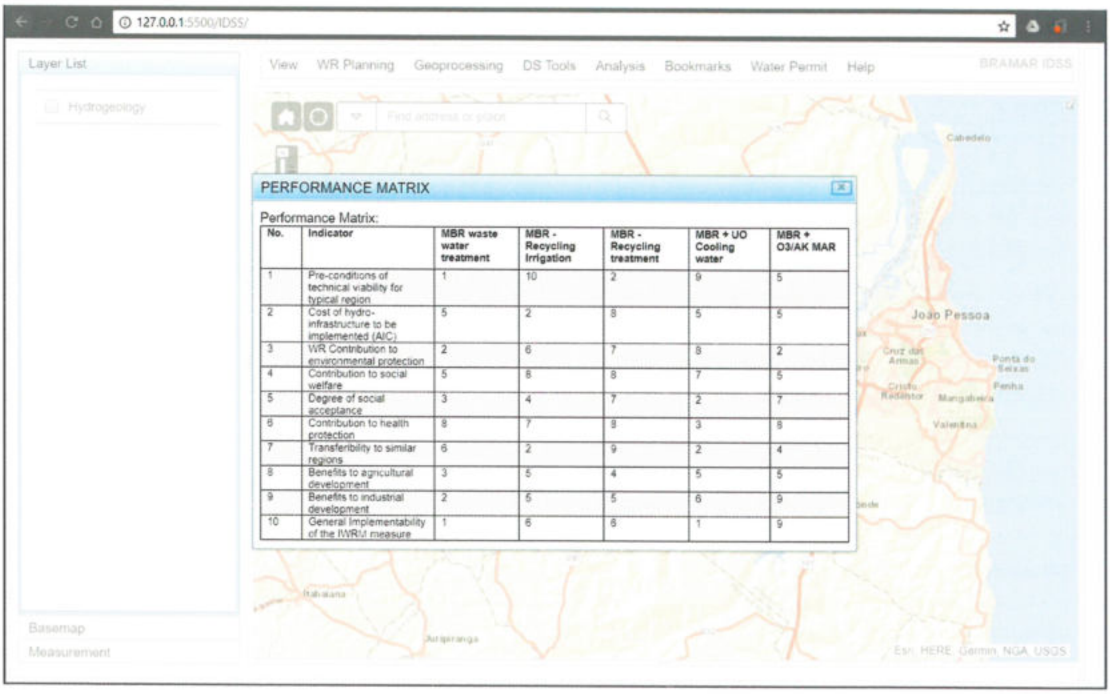
development is specified in the subsequent subchapter. It has been planned by the Brazilian IT firm I3Systems Ltda. in close cooperation with the German company Rusteberg Water Consulting to further develop the Decision Support System to attend to the demand of the state water agencies in the first place.The usage of the web-based BRAMAR-IDSS by the local water and environmental agencies in North-East Brazil will contribute to a continuous improvement of the water-resources and hydro(geo)logical data base of the system. We expect that there will be a continuously rising demand with regards to the further development of the system to include more functions and DS tools in the system. Some of the needs for further development are stated below.

6.4 Conclusions

6.4.1 Lessons Learned

The developed BRAMAR IDSS has proved to be versatile, allowing the easy integration of data and tools required for water-resources planning and management. Furthermore, the ArcGIS Rest interface allows users to integrate data and tools depending on future demands for information and decision support. However, the integration depends on how willing the different groups' are to contribute and publish available research data to the web-based BRAMAR-IDSS. Since they often use private working platforms or desktop software, they often do not share this data, thus hindering rather than helping the overall process.

As the system is developed with the ability to integrate data (services) from the SNIRH on water-resources management, compatibility with national



No.	Indicator	MBR waste water treatment	MBR - Recycling Irrigation	MBR - Recycling treatment	MBR + UO Cooling water	MBR + O3/AK MAR
1	Pre-conditions of technical viability for typical region	1	10	2	9	5
2	Cost of hydro-infrastructure to be implemented (AIC)	5	2	8	5	5
3	WR Contribution to environmental protection	2	6	7	8	2
4	Contribution to social welfare	5	8	8	7	5
5	Degree of social acceptance	3	4	7	2	7
6	Contribution to health protection	8	7	8	3	8
7	Transferibility to similar regions	6	2	9	2	4
8	Benefits to agricultural development	3	5	4	5	5
9	Benefits to industrial development	2	5	5	6	9
10	General Implementability of the IWRM measure	1	6	6	1	9

Figure 6.16: Performance matrix (Esri, HERE, Garmin, NGA, USGS, edited by: G.N. Souza da Silva)

data is guaranteed. This fact actually contributes to a high degree of acceptance and interest of the local water and environmental agencies to work with the system.

The implemented water-resources planning approach requires users to continuously add further conventional and innovative IWRM measures to the system and to evaluate them based on the indicator sheets in order to improve the data base on potential IWRM measures as part of an IWRM action plan. In this way, it can form the basis for decision-making for water-resources planners on state or national level.

6.4.2 Needs for Further System Development

The BRAMAR-IDSS, even after three years of development, may be considered as still under development. In the following, some needs for further system development are stated:

- The integration with regional or locally used systems (e.g. state water agencies) should be promoted and requires further development;
- Direct coupling of precipitation-runoff models and BRAMAR-IDSS for the direct quantification of present and future surface water availability at any partial river basin is recommended, taking the results of climate change models into consideration;
- Providing access to the IDSS and BRAMAR data base by means of mobile phones, especially during field visits, focusing on the control of water permits data, monitoring facilities and hydro-infrastructure;
- Providing full control of the water licensing process for improved decision support with regards to the concession of water rights;
- Surface water quality models may be linked to the system, too, in order to simulate the impact of pollution sources and wastewater treatment measures on the surface water quality.
- Direct coupling with groundwater simulation models would be advantageous in order to promote environmental impact assessment for groundwater resources, estimates of sustainable groundwater abstraction rates as well as the conjunctive use of surface and ground water resources, e.g. by means of Managed Aquifer Recharge;
- Integration of further Multi-Criteria-Analysis tools for option comparison and ranking, e.g. with regards to wastewater treatment and reuse;
- Integration of existing and planned hydro-infrastructure in the BRAMAR data base, including the facilities of the São Francisco water transfer project, in order to improve the assessment of present and future water budgets for partial water watersheds;
- Providing decision support with regards to the combination of different types of IWRM measures towards the definition of integrated strategies;
- Last but not least, the user management of the BRAMAR-IDSS needs to be further improved in order to permit the access of different user groups (universities, single researchers, state water and environmental agencies, secretaries of water resources, the National Water Agency) to the system and to have control on the level of access to the data base and entire system.

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7

IWRM Implementation in North-East Brazil (Results from WP 8)

Bernd Rusteberg[a], Marcos A. de S. Freitas[b]

a RWC, b ANA

7.1 Integrated Water Resources Management

7.1.1 The BRAMAR Project Initiative

The present research and cooperation project between Germany and Brazil in the water sector faced the challenge of improving Integrated Water Resources Management (IWRM) implementation in the semiarid and coastal areas of North-East Brazil, a water-scarce region that frequently suffers from drought events. Both research teams, involving a total of 22 institutions (private companies, universities, research centers and governmental agencies on the federal and state level), worked jointly together on a number of case study areas which were identified as representative for the regional conditions. The project focused, on the one hand, on analyzing structural IWRM measures and innovative water technologies as part of an integrated water resources planning process. On the other hand, new approaches, methods and tools were developed in order to support the integrated planning and management of water resources towards the sustainable development of the region. In the following subchapters, we discuss the suggested water resources planning approach as well as structural and non-structural IWRM key measures as a response to the existing water related challenges. We draw conclusions on how they can be implemented under the conditions of North-East Brazil as part of the IWRM concept as well as how well they can be transferred to similar regions.

7.1.2 Challenges

Among the challenges faced in the next century are an increasing population, unsustainable agricultural and industrial development and water quality degradation. The stress on water resources in many regions of the world is potentially great enough to spark conflict. Without mitigation, conflicts and environmental degradation may be inevitable. Minimizing water scarcity is, thus, the best mitigation and prevention strategy for possible future water conflicts that, while they may seem to be unavoidable, can be hindered with innovative water resources management response measures and technologies. These measures, as well as water and environmental technologies need to be integrated for IWRM implementation. At the core of the IWRM concept is the integrated management of all available water resources on river-basin level within a participative planning and decision-making process (RUSTEBERG et al., 2012). IWRM considers all water resources, especially in case of water scarcity mitigation, being the latter one of the main challenges in North-East Brazil. Water deficits, as a result of non-sustainable water resources development, are the main reason for water-related conflicts in water scarcity-affected regions, especially due to strong competition between the different water users. Non-conventional water resources, such as treated wastewater, brackish or imported water, need to be part of an integrated strategy for IWRM implementation.

Integration also refers to the need to take all relevant social, environmental and economic aspects into account. Acceptance from all stakeholders and public is needed, which requires transparency of the planning process and a close cooperation between state and federal water and environmental agencies. Another challenge relates to the uncertainties with regards to future climate change impact and socio-economic development, both of which need to be properly addressed. In North-East Brazil, regulations for sustainable water resources development are still lacking, e.g. in the area of wastewater reuse and the conjunctive use of surface and groundwater resources. The required participative decision-making process, involving the public, especially the so-called basin water committees, needs to be fully implemented. Also, water management instruments as stated in the Brazilian national and state legislation, such as water permits, water charge and water resources quality improvement are not fully implemented yet.

Last but not least, the poor sanitary situation in North-East Brazil requires special attention in the planning process to improve water resources and health protection.

7.1.3 Water Resources Planning and Management

Water resources management refers to both, the management of the natural water resources system as well as of the man-made hydro-infrastructure; new hydro-infrastructure is being implemented for different reasons, but mainly to make water resources available for different water users, e. vg. by means of wells, surface water reservoirs, pipelines etc. Water resources planning refers, on the one hand, to the upgrade of the water resources system by means of hydro-infrastructure, e. g. to attend to increasing water demands. On the other hand, it means to prepare for the future water related challenges to avoid water related conflicts, taking uncertainties of future conditions into account. Both the impact assessment of water resources planning decisions as well as the assessment of the external conditions, e. g. related to future climate change impacts, require the application of advanced mathematical analysis and modeling tools. Sustainable water resources planning requires actions on both "sides" of the water budget equation. Water supply has to be strengthened to increase the amount of the available water resources, on the one hand. On the other, water demand management measures are required to decrease the existing or foreseen water demand to a minimum. Each drop of water that can be spared on the demand side or in terms of water losses during water transfer and allocation does not need to be produced on the water supply side. Water resources protection may be considered a key task of the planning process to ensure sustainability. Furthermore, polluted water resources may require cost-intensive treatment before being used in the different water sectors. Another key task of water resources planning is to improve water resources system resilience and robustness against high hydrological variability or extreme events. Innovative water technologies, such as Managed Aquifer Recharge (MAR), enable the conjunctive use of water resources, minimizing surface water losses, providing additional water storage and, therefore, improving the system resilience during dry periods.

7.1.4 Decision Support

Due to the importance and need for efficient decision support to the water resources planning process, an innovative Information and Decision Support System, the BRAMAR-IDSS, has been developed in the present project and is presented in chapter on WP7.

Although the need for decision support to water resources planning and management task and related challenges has been extensively discussed in the previous chapter, some aspects should be highlighted in the context of IWRM implementation.

During the entire project, a very close cooperation between the works on "Decision Support" and "IWRM Implementation and Water Resources Planning" took place, due to their strong interaction. Specific procedures and approaches were defined under WP8 and implemented under WP7 in the BRAMAR-IDSS.

Since the BRAMAR project focused on water technologies, the BRAMAR-IDSS gives special attention to structural IWRM measures as response to the water resources challenges of the study region within the overall context of IWRM implementation. North-East Brazil needs to cope with increasing water scarcity due to climate change impact, still aggravated by drought events, and uncertain socio-economic development. Therefore, the water resources planning approach, developed under WP8 and integrated in the BRAMAR-IDSS under WP7, gives adequate importance to scenario definition, water budget assessment for any partial river basin and those IWRM response measures which are able to combat water scarcity and related water deficits.

The BRAMAR-IDSS is already being applied by the water agency AESA of the Federal State of Paraiba, but requires, in spite of all efforts during the last three years, considerable further development in order to provide full-scale support to the water resources planning process.

7.2 BRAMAR Water Resources Planning Approach

7.2.1 Methodological Procedure

The strictly participative water resources planning approach towards IWRM implementation consists of the seven-step procedure listed below. The procedure starts with the definition of the main water development goals in the river basin. These goals depend on the stakeholder and decision-makers' vision for the desired development of the river basin under study and the major water-related problems to be solved with set of water resources (IWRM) measures as a response to those challenges. Typical water development goals may refer to increasing the irrigated agricultural land to a certain extent or to strengthening the irrigation of specific crops, such as sugar cane or to collecting and treating some percentage of the total wastewater produced in the river basin. Frequently, the planning horizon is limited to 20 years, due to increasing uncertainties over time, and takes into consideration that any Water Master Plan on river basin level should be frequently updated, depending on the governing regulations on national and state level. The so-called Millennium Development Goals should be taken into consideration to guarantee sustainability.

The following sub-chapters will present and discuss each step of this water resources planning procedure, giving special attention to the structural IWRM measures as potential response to the water scarcity challenge as well as their evaluation and comparison by means of the BRAMAR-IDSS. All structural IWRM measures studied in the context of the BRAMAR project due to their competitive nature have been evaluated by the responsible research groups, who used a set of indicators, taking social, economic, environmental, health, technical or even administrative aspects into account. The results have been incorporated into the BRAMAR-IDSS. The integration of non-structural measures may be considered as obligatory for IWRM implementation. Further information on the methodological procedure is provided in the following sub-chapters.

Table 7.1: Steps of water resources planning approach

1	Water Development Goals and Scenario Definition
2	System Analysis
3	Present and Future Water Budgets
4	Structural IWRM Response Measures
5	Indicator Assessment
6	Measures Comparison
7	Integration of Non-structural Response Measures

7.2.2 Scenarios and Water Budgets

In order to cope with the considerable uncertainties related to climate change impact and socio-economic development of the river basin under study, a set of different scenarios are being defined as important step of the water resources planning procedure. Since scenario definition and the assessment of present and future water budgets are intimately linked, both are being treated together in the present sub-chapter.

Both climate change and socio-economic development have an impact on the water budget in different ways. While climate change tends to decrease precipitation rates and, therefore, surface water availability, socio-economic development increases water demand over time. Under the water scarcity and drought conditions in North-East Brazil, both driving forces together tend to increase the water deficit over time. Additionally, as climate change causes temperature to rise, evapotranspiration increases as does, therefore, irrigation water demand. In the BRAMAR project, three scenarios (water for all, water for some, and water for few) were considered, based on the National Water Resources Plan (MINISTÉRIO DO MEIO AMBIENTE, 2006). Population and socio-economic growth projections, based on water agencies' reports and plans, were included, incorporating the impact of climate change on irrigation as a function of increase in temperature for the climate change scenarios RCP 4.5 and 8.5. Detailed information about the climate change studies is presented in the chapter on WP1. Forecasts of precipitation and temperature data can be accessed and mapped by the Decision Support System. Accessing the water resources planning tool of the BRAMAR-IDSS, the system user selects the relevant scenarios and corresponding planning horizon to analyze their impact future water budgets. The integration of rainfall-runoff models to estimate future water availability for any partial watershed in an automated process is still under development.

7.2.3 System Analysis

The second step of the suggested water resources planning procedure refers to the analysis of the relevant subsystems, their interaction and their environment. **Figure 7.1** presents the subsystems and relationships in a simplified schematic way (LOUCKS et al., 2005). The total system consists of the following subsystems:

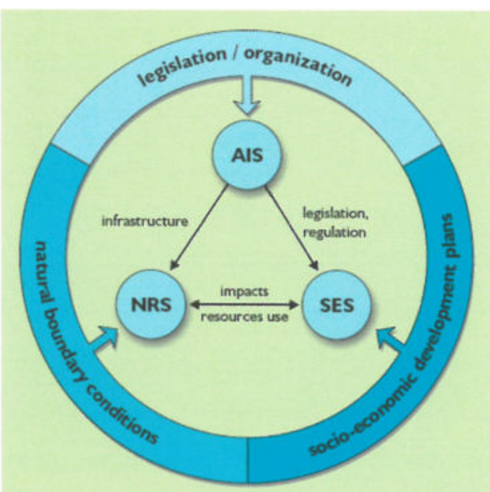

Figure 7.1: Interactions among subsystems and between them and their environment (LOUCKS et al., 2005)

a) Natural Water Resources System (NRS), where all hydrological (physical, chemical and biological) processes take place;

b) Socio-economic Subsystem (SES), which considers related human activities; and

c) Administrative and Institutional Subsystem (AIS), where the decision processes related to water resources planning and management take place, where legal constraints and regulations are be defined.

Water resources planning and management measures may impact and improve the interaction of these three subsystems. Lacking attention to one of the sub-systems can compromise any work done to improve the performance of the others.

Within the BRAMAR project, a series of studies were developed in the project region in order to study these subsystems and their interaction with different approaches. The present sub-chapter provides a short overview about these studies and procedures which may be applied to improve the system understanding and to identify potential conflicts and upcoming challenges. The latter, in turn may require specific IWRM response measures which will be later treated in this chapter.

A range of methods and theories have been studied in the context of the BRAMAR research project in the study region in order to provide decision support for a structured system analysis towards a better understanding of the system: from causal models to water justice and political ecology, urban metabolism, actor-network analysis, institutional analysis, Ostrom's institutional design principles, integrated policy analysis, social media analysis, conflict analysis, risk and crises management and negotiation theory. Public participation in the basin committees was also analyzed to provide support to IWRM implementation. Below, some key studies are listed:

The Epitácio Pessoa multi-purpose surface water reservoir is the second largest water reserve in the State of Paraíba, suffering from two major drought events during the last 15 years. The Causal Chain Analysis (ACC) has been applied, taking technical, political-managerial and socio-economic-cultural causes into consideration. It became obvious that water management strategies capable of optimizing surface reservoir operation had not been defined because the entities unfortunately did not exercise their functions in a coordinated, articulated and integrated way (SILVA, 2015).

Amorim et al. (2016) applied the Integrated Policy Analysis to the Federal Piranhas-Açu river basin, which is located in the States of Paraíba and Rio Grande do Norte. The Regulatory Framework during its ten years of existence (2004 to 2014) was analyzed, verifying aspects which led to its creation and contribution in resolving and mitigating conflicts. The study concluded that the Regulatory Framework allowed participants to discuss the challenges, but that the lack of sufficient monitoring and water uses control actions made it difficult to solve conflicts during water shortage periods. Integrated Policy Analysis has been applied by Ribeiro (2017), Guedes & Ribeiro (2017) and Brito (2017), too.

Silva et al. (2017) applied the Institutional analysis to evaluate how a combination between climate variability and water governance might affect water scarcity and increase the impact of extreme events. For this evaluation, Ostrom's framework for analyzing social-ecological systems (SES) was applied. Ostrom's framework is useful for understanding interactions between the different subsystems. The study proved that deficiencies in water management intensify droughts' impact on the water users and that the reasons are more related to water management and governance problems than to drought event magnitude or climate change.

Ribeiro et al. (2016b) studied the evolution of public participation in the committee of the river basins in the northern coastal area of Paraíba and the importance of capacity-building measures. In the context of the study, many members of basin committees and other experts in water resources have been trained to effectively implement the Water Resources Integrated Management and have had a very positive impact on the performance of the river basin committee. Further studies on public participation and performance in the study region have been done by Ribeiro et al. (2014, 2016a) and Ribeiro (2016).

Moraes and Galvão (2016) apply the method of Urban Metabolism in order to support the integrated planning and management of water resources of urban environments, here of the City of Campina Grande, which is one of the BRAMAR Case Study Areas (CSA). The method is based on the assessment of the water budget within and outside the city, including all fluxes of water into the city as well as leaving the city. The method proved to have great potential for an optimized water management. In the case study, a considerable potential for rainwater harvesting and water reuse could be identified and quantified.

Last but not least, the so-called Driver-Pressure-State-Impact-Response (DPSIR) method should be mentioned in this context, capable of identifying upcoming conflicts and main water resources related challenges. The method has been applied in the context of the BRAMAR WP1. Detailed information about the method and its application will be found in the corresponding chapter.

Figure 7.2 shows how system analysis is being accessed in the BRAMAR-IDSS. The user can select the type of analysis and retrieve more information on the specific studies, applied methods, conclusions and recommendations. In the same way, non-structural (complementary) measures are integrated the IWRM.

7.2.4 Structural IWRM Response Measures

Introduction

According to the suggested BRAMAR planning approach for IWRM implementation, structural IRWM measures compete with each other and require a specific assessment in order to compare, select and combine them, while non-structural measures may be considered as mandatory for IWRM implementation. Numerous structural IWRM response measures have been studied under BRAMAR. In the following subchapters, these measures are classified, and main project activities and studies are presented for these groups of measures, taking aspects, such as level of today's implementation in North-East Brazil, viability and importance in the context of IWRM implementation into account.

Conjunctive use of surface and groundwater resources

Due to considerable water losses by evaporation from open water storage, the conjunctive use of surface and groundwater resources is gaining special importance. A key measure is Managed Aquifer Recharge (MAR), which permits the conjunctive use of these water resources and, therefore, is an important component of IWRM. Implementing a MAR system requires careful planning

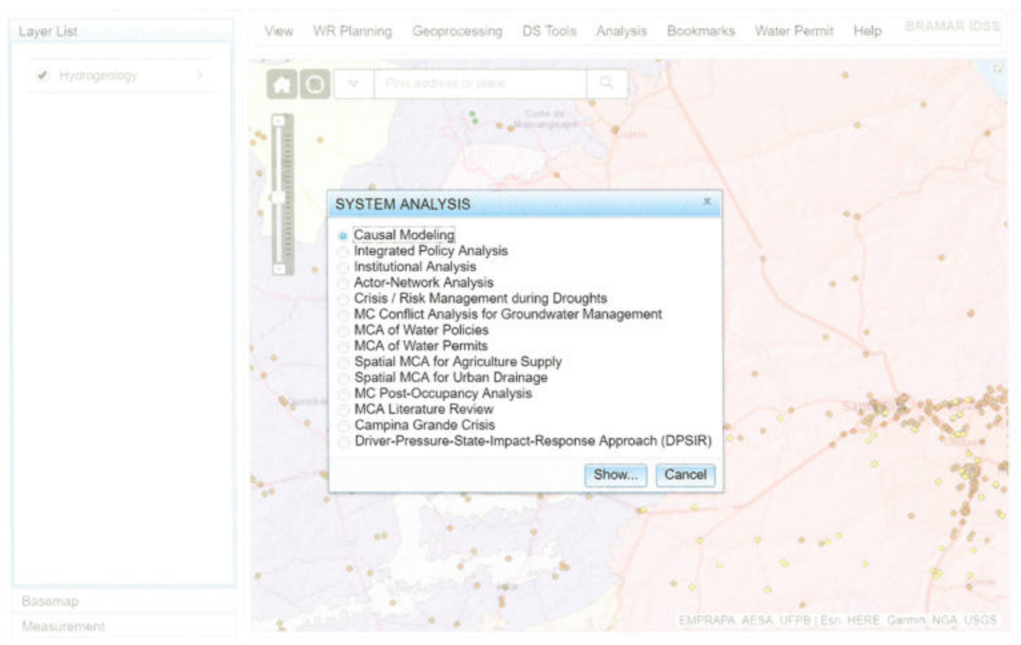

Figure 7.2: Accessing different methods for system analysis in the BRAMAR-IDSS (EMPRAPA, AESA, UFPB Esri, HERE, Garmin, NGA, USGS, edited by G. N. Souza da Silva)

in terms of achieving efficient integration into the water resources system and the overall water resources management objectives (RUSTEBERG et al., 2013). To recharge the water, different infiltration and injection technologies are available. The most common methods are infiltration basins (spreading basins), sink-pits and canals, induced recharge by bank filtration, and injection wells. Use of these methods depends upon basic planning parameters. The roles that MAR may play within the framework of a water resources system are short and long term storage for later recovery during dry seasons, recovery of groundwater level of over-exploited aquifers, provision of barriers to seawater intrusion in coastal areas, improvement of water quality, use of the aquifer as a water distribution system for individual users, and flood-prevention by deviating peak-flows (RUSTEBERG et al., 2012).

In the present book a separate chapter has been dedicated to the MAR studies undertaken in the context of the BRAMAR project. The studies at the representative case study areas of João Pessoa, Recife and Sumé show that the development of a comprehensive data base – leading to profound knowledge of the water resources system – is of crucial importance for the successful planning of MAR facilities. Clearly, implementing MAR concepts and technologies is of major importance to combat water scarcity in North-East Brazil. The studies show that its implementation is viable in general terms and highly beneficial for both the regions, the semiarid rural areas inland as well as the coastal region with its large aquifer systems. Nevertheless, further studies, including the installation of pilot plants, especially at the coastal areas, are required in order to achieve the required knowledge for the planning and operation of MAR facilities as part of IWRM implementation under the conditions found in North-East Brazil.

Wastewater Treatment and Reuse

Numerous studies have been developed within the scope of the BRAMAR project related to wastewater treatment and reuse. The chapter on WP4, 5 and 6 summarize all research work done within the collaborative BRAMAR project by the Brazilian and German Universities and technology firms in cooperation with governmental agencies in the field of wastewater treatment and water reuse. While the German partners focused on conventional and innovative, partially high-tech solutions and their transferability and implementability in North-East Brazil, including industrial water reuse, the Brazilian partners gave special attention to innovative low-cost solutions for wastewater reuse in irrigated agriculture, appropriate to local conditions.

The studies show that there is a need in the project region for further and continuous investments in basic sanitary infrastructure. In the Federal State of Paraíba just 44 % of the produced wastewater is being collected, while around 70 % of the collected wastewater is being treated. In the major urban centers, such as Campina Grande and João Pessoa, the situation is much better. For more detailed information please refer to the corresponding chapter. The responsible Brazilian Authorities on national, regional and state levels are aware of the situation. Approximately R$ 30 billion was invested in wastewater treatment from 2007 to 2015. The so-called National Sanitation Plan PLANSAB will provide approximately another R$ 180 billion for investments in sanitation infrastructure until 2033 (ANA, 2017).

The BRAMAR studies proved the general transferability of innovative wastewater treatment technologies to North-East Brazil, which includes efficient solutions mainly for non-potable reuse, including industrial wastewater reuse. Even measures for direct potable water reuse, along with the usage of desalinated water, may be of increasing interest for North-East Brazil, especially under drought conditions.

The inadequacy of wastewater systems and water shortages in semiarid North-East Brazil encourage the reuse of water in the production of agricultural crops. Costa et al. (2014) and Vasconcelos (2014) analyzed the effect of irrigation with treated domestic wastewater on the production of different crops. Especially for the rural areas, low-cost and low-tech solutions for wastewater treatment and reuse in irrigated are advantageous, taking, for example, solar radiation schemes into consideration. Cavalcante (2017) states that using solar radiation is inexpensive, easy to operate and does not need chemicals in wastewater disinfection for agricultural use. The BRAMAR researcher developed and validated a solar reactor for the disinfection of greywater from rural areas in the semiarid region, aiming at the reuse of the effluent.

As the practice promotes the improvement of effluent quality disposed in agricultural systems, it could also be feasible in this region to promote part of the wastewater treatment in small and medium cities with financial and operational difficulties to implement and maintain efficient conventional WWTPs.

The viability of low-cost water reuse solutions for agriculture, microbiological and hydraulic performance as well as fertilizing effects have been studied by several research groups in the context of the BRAMAR project; they show that there is a wide range of wastewater treatment and water reuse measures applicable in North-East Brazil (BATISTA et al., 2017; SILVA et al., 2016; COELHO et al., 2016).

All wastewater treatment and reuse measures studied under BRAMAR were evaluated by the responsible research groups based on a set of indicators, taking social, economic, environmental, health, technical or even administrative aspects, e.g. with regards to their implementability, into account. The results may be reviewed by accessing the BRAMAR-IDSS.

Rainwater Harvesting

Since 1999, the ASA (Brazilian Semiarid Articulation – Articulação Semiárido Brasileiro) has been adapting and implementing rainwater harvesting programs in the semiarid region of North-East Brazil. The main program is called P1MC – One Million Cisterns for the Semiarid Program – (Programa Um Milhão de Cisternas para o Semiárido). Thanks to an agreement with the Brazilian Ministry of the Environment (MMA), financing was secured to prepare the project and construct water catch tanks (cisterns) to supply water for 500 families in the year 2000. A second agreement signed in 2001 with the Brazilian Water Agency (ANA) financed the construction of water catch tanks for 12,400 families. By March 2018, the Program had achieved the following results: 614,442 cisterns of 16 thousand liters for capturing and storing rainwater for human consumption and 6,228 cisterns for rural schools. With the aim of increasing the water supply for families, rural communities and traditional populations to account for agricultural and animals' needs, ASA created a new, very successful action called One Land and Two Waters Program, P1 + 2 (Programa Uma Terra e Duas Águas, o P1+2) in 2007.

These so-called rainwater harvesting systems (SCAC), however, have been affected mainly by variable precipitation patterns. For this reason, it is important to evaluate them in different climatic scenarios. Within the scope of the BRAMAR project, Dantas et al. (2015) carried out simulations on the vulnerability of SCAC for three localities of Paraíba. The results showed that even under current weather vulnerabilities rainwater harvesting systems are an important IWRM measure. In spite of relevant climate change impact, adaptation measures, such as increasing rainwater harvesting area, are able to mitigate these effects.

Andrade et al. (2015) reported that in the Brazilian semiarid region, rainwater harvesting has proven to be a successful measure to mitigate the effect of the dry seasons in rural communities. Conflicts may arise when cisterns are used to store water from water tank trucks. BRAMAR researchers confirm that the cisterns are both effective tools for risk and crisis management and, therefore, an important IWRM measure.

Pereira et al. (2014), still within the scope of the BRAMAR project, analyzed a device for hydraulic tests in rainwater harvesting systems and Nóbrega et al. (2014) performed a sensitivity analysis of water balance parameters of cisterns in the semiarid region. Batista (2017) recommended guidelines for rainwater harvesting systems in open public spaces (POSs) of the CSA Campina Grande. These guidelines aim to combine the factor of the improvement of the rainwater management with the planning of public places located in the urban mesh of the city. Additionally, Souza (2015) confirmed the considerable potential for water savings from the conventional water supply system by adopting rainwater harvesting in the urban area of the municipality.

Water Allocation and Reallocation

According to Lopes & Freitas (2007) and Freitas (2009), water allocation in Brazil, historically, is characterized by a strong intervention of the public sector. Nevertheless, national and state water resources authorities implemented alternative models for water allocation based on participative processes. The analysis of different procedures shows that the water allocation process should be adapted to the specific conditions of each region, with regards to conceptual and methodological aspects as well as with regards to the definition of multiple strategic objectives.

Water allocation can be understood as an IWRM measure that aims to provide water to current and future users of the water resources system, matching water supply and demand, even meeting environmental demands and being in line with strategic management objectives. In this sense, there are several mechanisms of water allocation, which operate according to public authority guidelines, based on negotiation processes among water users or technical concepts, such as the limits of the use of water bodies, or economic ones, such as charging for water use. The evaluation of the advantages and disadvantages of each mechanism, from the point of view of objective criteria, allows a use to choose the most appropriate to each region and each situation, with a view to the sustainable use of water resources (LOPES and FREITAS, 2007).

For the so-called Negotiated Water Allocation a methodology is described in Freitas, (2003); ANA/GEF/PNUMA/OEA (2004); Freitas, (2010) and improved by Freitas (2013), Martins et al., (2013). This methodology was largely internalized in the administrative procedures of the National Water Agency, through Technical Note No. 10/2015/COMAR/SRE (ANA, 2015) and has been applied throughout the semiarid region of North-East Brazil.

For the semiarid North-East Brazil, which regularly suffers from extreme water scarcity and even droughts, water allocation may be also understood as a measure for drought management. The so-called Drought Management System (SIGES) has been validated in the context of the BRAMAR project (**Figure 7.3**). In the North-East region, 1,409 or 78.5% of the 1,794 municipalities declared an emergency or state of calamity due to the droughts between 2003 and 2017.

To optimize water allocation from surface reservoir networks, several modeling tools are available. The Information System for Water Allocation Management, or SIGA, is one of those (FUNCEME,

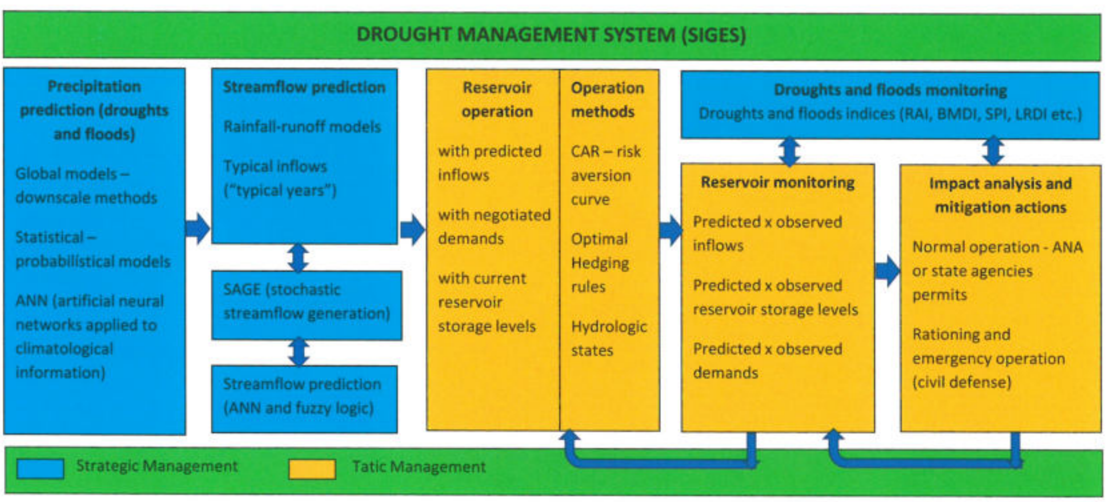

Figure 7.3: Drought Management System – SIGES (FREITAS, 2013)

2018). The water allocation software Acquanet was applied to study potential trade-offs by changing the water allocation through the adaptation of the water distribution network as well as the impact on the water budget situation (FREITAS, 2016).

The BRAMAR CSA Campina Grande suffered a serious water scarcity crisis during the project execution, which was analyzed in real-time by the project team, which also intensively participated in the crisis' discussion on potential solutions. The main reservoir storage volume was consumed by 2016, and the collapse of the water supply was barely avoided through the construction of an extra pumping system to extract water from the dead storage. Rêgo et al. (2016) studied the operation of the Epitácio Pessoa/Boqueirão reservoir during the water crisis as an opportunity to analyze the water allocation scheme and defined emergency measures, including the reallocation of water to the different users. The study shows the importance of studying and improving water allocation in order to avoid conflicts between water users and of adapting to extreme water scarcity conditions, even if hydro-infrastructural interventions are required to reallocate the water.

Water Transfer

In cases where the present or future water deficit in a river basin cannot be covered by the local water resources and local measures, as described above, external water resources, those outside the river basin may be identified, activated and transferred to the river basin under study. Then, the transfer of water from neighboring basins or even from more distant basins may be taken as additional structural IWRM measure into consideration. This is the case in the largest part of the BRAMAR project study area. In order to mitigate the water deficits of this region, the PISF project (San Francisco Inter Basin Water Transfer Project) was developed and is now in its final stage of implementation (**Figure 7.4**). According to the ANA Resolution 029/2005, a water permit has been established for a water delivery of 26.4 m^3/s at any time from the Rio São Francisco; and up to 114.3 m^3/s (daily average) and 127 m^3/s (peak), depending on water availability in the Sobradinho reservoir. The maximum water carrying capacity

Figure 7.4: Transposition Project Rio São Francisco – North and east axis for water import (MI, 2004)

on the axes is about 28 m^3/s along the so-called "East axis" and limited to 99 m^3/s along the "North axis".

To guarantee institutional sustainability of the PISF project, a specific institutional arrangement has been developed, according to the ANA Resolution 412/2005, which is presented in **Figure 7.5**. The regulation framework of the PISF Project includes a water permit, a water sustainability certificate, a commitment agreement and the Decree n. 5995, which creates the management council, the content of PGA (Annual Management Plan), and designates CODEVASF (Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba) as the federal operator. Additionally, a contract between federal and state operators is under discussion.

Rêgo et al. (2017) analyzed the water transfer from Rio São Francisco to the BRAMAR CSA of Campina Grande. They argued that the adoption of appropriate and permanent water management measures would minimize the effects of prolonged droughts. The authors stated that the inter-basin water transfer is just a "hydraulic solution" and cannot be considered as a full-scale IWRM solution for the region. Radical change in the patterns of water and effluent use (and reuse) from multiple sources must occur in order to improve the resilience of the water resources systems and water supply sustainability of the semi-arid zone. Grande et al. (2016) analyzed the perception of water users about the impact of water rationing on their household routines for the Campina Grande case study area. In the context of the BRAMAR project, the performance of managers, water users, public power, press and population in the face of the water supply crisis in Campina Grande has been analyzed by Rêgo et al. (2017), too. The BRAMAR studies show that the water transfer from – even distant – neighboring basins to water-scarcity affected areas in the project region is a viable solution if all local water resources have been already efficiently exploited in the context of IWRM implementation. The water transfer is just an additional measure to activate external water resources and as such does not substitute the implementation of the IWRM concept.

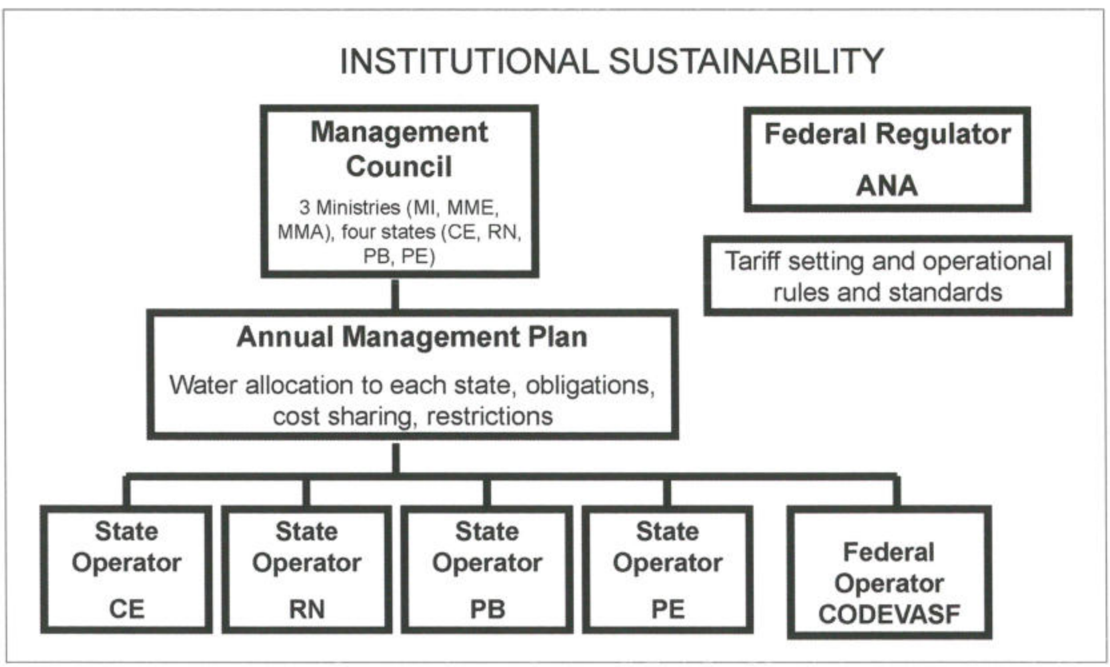

Figure 7.5: Institutional sustainability – PISF project (FREITAS, 2017)

7.2.5 Non-structural Response Measures

Introduction

Non-structural response measures are measures which do not focus or even need the implementation of hydro-infrastructure. They may consist of regulative or legal measures, like water permits or charges in order to promote the rational use of the scarce water resources, demand management measures, measures to improve the efficient operation of hydro-infrastructure, such as surface water reservoirs or pipelines, measures to improve the quality of water resources planning and management decisions, including public and stakeholder participation. These measures are essential for IWRM implementation, mitigation and even prevention of adverse impact related hydrological extreme events. A series of non-structural measures was analyzed in the context of the BRAMAR research project, which will be described in more detail below. They have to be understood as non-competitive, obligatory measures that are complementary to the structural measures in the context of IWRM implementation.

Surface Reservoir Operation

Various studies on the expected benefits of water import by means of the PISF project with regards to water availability have been developed. Initially, due to the water crisis during the long drought period between 2012 and 2017 and, finally, with the start of the operation of the PISF project, ANA had to modify the operation of the reservoirs of the receiving basins of the Eastern Axis, especially the reservoirs Epitácio Pessoa and Acauã. Several ANA resolutions were implemented and a new operation scheme for the Epitácio Pessoa reservoir had to be developed (FREITAS, 2017 / **Figure 7.6**).

BRAMAR researchers Nunes et al. (2016), using surface reservoir operation and optimization studies, developed a rule curve for reservoir operation, which permits excess water to be used in periods of large inflows without compromising water supply during dry periods. The efficient operation of the water resources system is an obligatory measure to minimize water losses and mitigate conflicts between different water users.

Demand Management

Seventeen resolutions and other normative acts were issued from 2013 to 2016 restricting or suspending water use within Brazil. Actions to control regulative or demand management measures were intensified in the semiarid region, especially in the Piancó-Piranhas-Açu River basin, due to the small volume of the reservoirs, which caused risks to the public water supply of numerous municipalities in the states of Paraíba and Rio Grande do Norte. By means of forecasting and monitoring

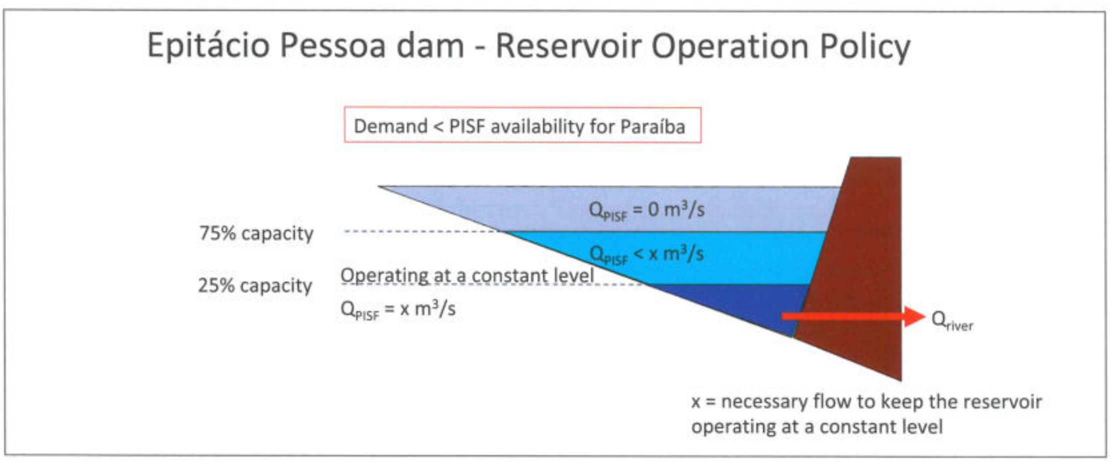

Figure 7.6: Reservoir operation policy using reservoir storage zones for Epitácio Pessoa Dam in the context of the PISF project (FREITAS, 2017)

measures during critical periods, water losses could be reduced and, therefore, water shortages mitigated.

Barros et al. (2016) evaluated the use of water saving equipment in vertical buildings, in order to minimize the increase in water demand over several years for the case study area Campina Grande. According to the study, the installation of water-saving devices in buildings considerably decreased water consumption and, therefore, is a demand management measure of first choice. The reduction of the water use caused by water savers in residential buildings was monitored and parameters for the new buildings have been established. Guedes et al. (2014) analyzed alternatives of water demand management in a city scale for the BRAMAR case study area of Campina Grande. Araujo et al. (2015) developed a new method for improved urban water management for Campina Grande. The integration of demand management measures is obligatory in the context of IWRM implementation in order to minimize investments in structural water supply measures.

Water Permits and Charges

Ribeiro et al. (2014) presented a study in the context of the BRAMAR project that considers the priority of surface water use as a criterion for the concession of water permits. The study focused on the Coastal Sedimentary basin of the Lower Course of the Paraíba River and the Gramame River basin, both in the state of Paraíba. The potentialities and availability of surface water were monitored in order to assist the responsible agencies in the concession of water permits. According to the applied criteria, the use of surface water is considered a priority, while groundwater should be considered as strategic resource and only be used if water supply from surface water resources is not viable.

In the state of Paraíba, the groundwater is abstracted in accordance with the regulation established by Decree N°19.260/1997 (AESA, 2018), which defines the well yield and the aquifer recharge capacity as criteria. BRAMAR researchers Braga et al. (2015) used numerical modelling techniques to estimate groundwater resources availability in a region of the Coastal Sedimentary Basin of the Paraíba River Basin. An over-exploitation of groundwater could be detected. It became obvious that the criteria adopted by local regulations for the concession of water rights need to be improved in order to avoid over-exploitation. The authors suggest that groundwater monitoring should be improved and present a method for defining additional criteria based on the modulated concession of water permits. Furthermore, Braga et al. (2017) presented an assessment of the water permits criteria proposed in a previous study. Among the eight criteria assessed, the criteria of aquifer vulnerability and implementation of demand management measures were identified as the most relevant.

According to Assis (2016), the raw water charge in Brazil was introduced by Law N°. 9.433 of January 8, 1997, as an economic instrument for the management of Brazilian water resources. The author presents an analysis of the raw water charge system, identifying the aspects which could be improved. The results show that it is necessary to review the values currently used in the raw water charge system. Different aspects – quantitative, qualitative and protection for emergency situations – are not sufficient to ensure water sustainability of the river basin, since environmental problems and water crises persist. Assis et al. (2018) presented a proposal for improvements to the system for raw water charges.

Hydro(geo)logical and Climatic Monitoring

The National Monitoring Network (RHN) included in 2016 more than 20 thousand monitoring stations under the responsibility of several entities. ANA directly manages 4,663 stations: 2,722 rain gauges and 1,941 fluviometric stations. There are 1,646 fluviometric stations that measure water flow (river discharge), 1,652 stations that measure water quality and 480 stations that monitor sediments in suspension (solid discharge).

According to ANA (2017), despite the availability of huge amounts of hydrological data on national level, there are still large gaps with regards to hydrological monitoring data due to the size of the country. To solve these problems, a number of actions have been undertaken, such as the National Water Quality Assessment Program (PNQA), the

National Water Quality Monitoring Network (RNQA) and the Program to Encourage Quality Data Dissemination Water (Qualiágua).

The BRAMAR project had to face an small hydrological database in the case study areas, too. Numerous groundwater, fluviometric, precipitation and climatic monitoring stations had to be installed and are now being operated by the local partner institutions in order to characterize the water resources systems and to calibrate the hydro(geo)logical models required to study the behavior of those systems.

Water quality monitoring allows the characterization and analysis of trends in river basins. There are several ways to assess the water quality of a water body. Physico-chemical and biological parameters of water samples collected from rivers and reservoirs are widely used as indicators of water quality. In Brazil, the levels and concentrations of several indicators in water are used as reference for the classification of water bodies according to water quality classes. ANA and the Federal State Units (UF), including Paraíba, Rio Grande do Norte e Pernambuco, maintain monitoring networks based on these indicators.

The classification of water bodies according to water quality classes is one of the instruments established in the Law of Water (Law No. 9.433 of 1997) (Presidência da República, 2018) to ensure water resources protection and to reduce the cost to combat water pollution through permanent preventive actions.

ANA´s so-called "Situation Room" monitors and analyzes the evolution of rains, levels and flow of the main rivers, reservoirs and river basins. All information is shared through bulletins and monitoring systems, supporting the decision of the authorities responsible for the management of critical hydrological events in the country. The National Water Agency supported the implementation of situation rooms in all federal states and currently monitors and improves their operation.

The BRAMAR Information and Decision Support Platform, presented in the chapter on WP7, has been designed to integrate all hydro(geo)logical monitoring data, including data from the National Institute for the Semi-Arid Region (INSA) about the status of hundreds of reservoirs in that region.

The Drought Monitor Action refers to regular and periodic monitoring of the drought situation in North-East Brazil. The consolidated results are disseminated by means of the so-called Drought Monitor Map. Monthly information on the drought situation is available up to the previous month, with indicators that reflect the short term (last 3, 4 and 6 months) and the long term (last 12, 18 and 24 months), providing information about the evolution of droughts in the region.

Hydro(geo)logical and climatic monitoring of the water resources system under study is an obligatory, per se, non-structural IWRM measure required for system characterization, hydr(geo)logical modeling, impact assessment and is the basis for decision-making towards the sustainable development of water resources and IWRM implementation.

Institutional Development

As discussed in the context of system analysis (Subchapter 7.2.3), the administrative and Institutional Subsystem (AIS) is where the decision processes related to water resources planning and management take place and where legal constraints and regulations are defined. Sustainable water resources management and IWRM implementation, therefore, require adequate measures for institutional development and capacity building.

In December 2011, ANA and leaders of the state bodies responsible for water resources signed the so-called National Pact for Water Management, a commitment to strengthen the State Water Resources Management Systems (SEGREHs) (ANA, 2016).

As a practical tool for the implementation of the Pact, in 2013 ANA launched the Program PROGESTAO for the Consolidation of the National Pact for Water Management, which provides for up to five annual installments in a total of 750,000 Brazilian Real for each unit of the federation when they fulfill pre-established institutional development goals. These financial resources should be applied exclusively to actions which benefit the sustainable management of water resources.

By the end of 2014, all Brazilian states, besides the Federal District, had joined the program. Paraíba was the first state to join. It is foreseen to extend the program to the year of 2019. The goals of the PROGESTAO were divided into federal cooperation goals defined by ANA and based on legal regulations on the one hand, or information sharing and water resources management goals at the state level on the other, approved by the respective State Water Resources Councils – CERHs.

7.2.6 Analysis and Comparison of IWRM Measures

Indicator Assessment

According to the suggested BRAMAR planning approach for IWRM implementation presented and explained at the beginning of the present chapter, structural IRWM measures compete with each other and require an assessment by indicators so that they can be compared, selected and combined, while non-structural measures may be considered as mandatory for IWRM implementation.

The planning approach has been implemented in the BRAMAR-IDSS. All structural measures need to be evaluated with the following list of qualitative indicators, taking social, environmental, economic and some other basic indicators into account.

1. Pre-conditions of technical viability for typical region
2. Cost of hydro-infrastructure to be implemented
3. Contribution to environmental protection
4. Contribution to social welfare
5. Degree of social acceptance
6. Contribution to health protection
7. Transferability to similar regions
8. Benefits to agricultural development
9. Benefits to industrial development
10. Benefits to drinking water supply
11. General implementability of the IWRM measure

This planning step requires the active contribution of the system user (researcher) to include the results on conventional or innovative structural IWRM measures and water technologies into the BRAMAR-IDSS. The evaluation of each measure by the above set of indicators is done separately for the semiarid and coastal region. After definition of a short synonym for the IWRM measure according to the system standard, the system user is requested to provide a short description of the IWRM measure under study and to select the study region.

The indicators are evaluated by providing a value between 0 and 10 to each of them, while the value of "0" refers to the minimum performance, the value of "10" refers to the maximum performance of the specific IWRM measure with regards to the given criteria. In terms of how viable a measure may be implemented, two indicators have been considered: the technical viability, taking the typical conditions in the semiarid and coastal region into account as well as the general implementability of the measure, analyzing additional aspects like political and social willingness as well as administrative or legal constraints. For the time being, one key economic indicator has been considered: accessing the implementation, operation and maintenance cost of hydro-infrastructure of the structural IWRM measure to be implemented. This indicator is the so-called "Average Incremental Cost," which is the present value in US dollars per m^3 of water produced or activated by the measure, including, beyond the implementation of hydro-infrastructure, all operation and maintenance costs during the planning horizon. In spite of the fact that this indicator is assessed in quantitative terms, the scientist, nevertheless, may provide a qualitative value according to a given scale; in this case, the value "10" refers to the most economic (least cost intensive) IWRM measures.

One generalized indicator to access benefits with regards to environmental protection and two indicators to access social aspects (welfare and acceptance) are being considered. A specific indicator focusing on health protection has been included, too. Finally, evaluation of benefits to water sector development is required and the general transferability of the IWRM measure to similar regions is judged by the responsible researchers of the study.

Figure 7.7 shows how the indicators are accessed by the BRAMAR-IDSS. After their qualitative assessment, it is required to insert a justification with regards to the selected indicator value by clicking on the corresponding button. A popup window opens in order to introduce the explanative text as background information for later decision support to water resources planners and decision makers.

Measures Comparison

The BRAMAR-IDSS permits the filtering and analysis of structural IWRM measures by water resources planners and decision-makers and their presentation in form of a performance matrix. The relevant screens have been presented in the chapter on WP7 chapter.

The system user, e.g. decision-maker or water resources planner, can select a type of structural measure, the region where the measure will be applied and a minimum value for each of the indicators, using horizontal sliders and the scale values from 0 to 10. Based on the application of these filters, a performance matrix is created by the system, which considers the selected measures, taking the minimum requirements of the water resources planners with regards to the performance of structural IWRM measures into consideration (Chapter on WP7: **Figures 7.15** and **7.16**).

The **Table 7.2** provides an example for a performance matrix, based on BRAMAR results for IWRM measures related to advanced wastewater treatment and water. The table shows that each of the filtered structural IWRM measures presents benefits and disadvantages with regards to the different indicators. The performance matrix, based on the set of indicators, provides basic decision support to water resources planners and decision-makers with regards to a preliminary selection of priority structural IWRM measures towards a better understanding of their performance in qualitative terms. By modifying the filters, taking new constraints and minimum requirements into account, the analysis adapts to different boundary conditions and development goals. After identification of a set of structural IWRM measures that attends to the minimum performance requirements, water resources planners are requested to

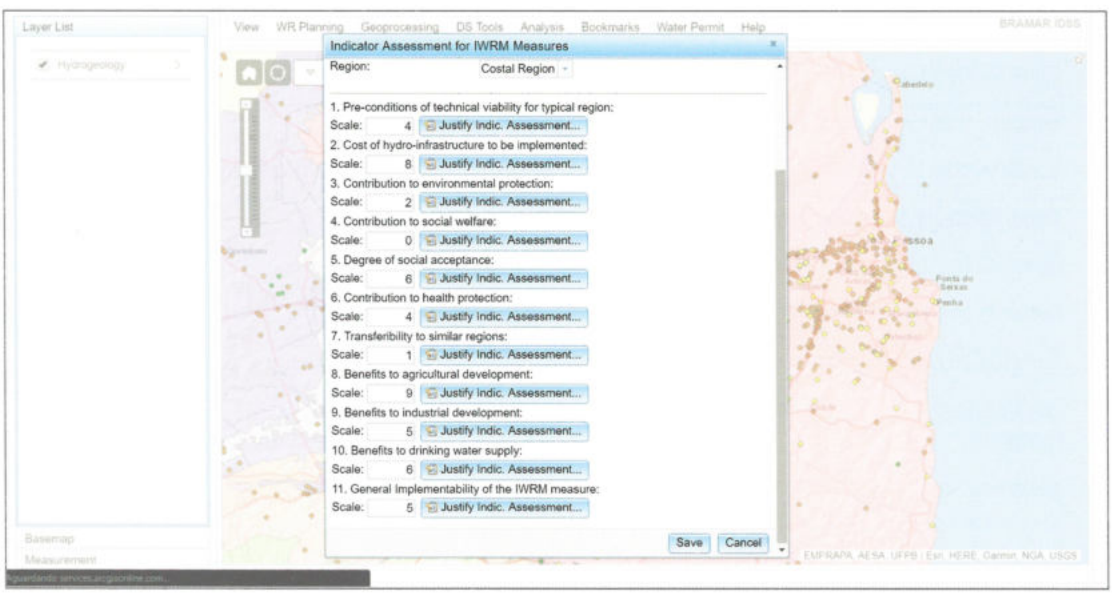

Figure 7.7: Assessment of indicators in the BRAMAR-IDSS (EMPRAPA, AESA, UFPB Esri, HERE, Garmin, NGA, USGS, edited by G. N. Souza da Silva)

rely on the corresponding in-depth research work and results for further decision support. At this stage of system development, the BRAMAR-IDSS only supports the pre-selection of structural IWRM measures according to the given set of indicators.

7.2.7 Integration of Non-structural Response Measures

In order to provide an integrated approach to water resources planning and management, the BRAMAR-IDSS offers access to a comprehensive list of non-structural IWRM measures, such as water pricing, demand management, water licensing, system operation and institucional development. Moreover, it provides access to comprehensive studies, publications and recommendations related to the region in North-East Brazil, all of them undertaken in the context of the Brazilian-German BRAMAR research and development project. These studies and their most crucial results have been presented in this chapter and should be taken into consideration for IWRM implementation. The information is accessed in the BRAMAR-IDSS by selecting the non-structural measure out of a list in a pop-up window, similar to the selection of methods for system analysis, as presented in the chapter on WP7. As mentioned before, non-structural measures, in principal, do not compete with each other. Their integration may be considered as mandatory for IWRM implementation.

Table 7.2: Example of performance matrix for IWRM measures related to advanced wastewater treatment and recycling

No.	Indicator	MBR wastewater treatment	MBR – recycling irrigation	MBR – recycling treatment	MBR + UO cooling water	MBR + O3/AK MAR
1	Pre-conditions of technical viability for typical region	1	10	2	9	5
2	Cost of hydro-infrastructure to be implemented (AIC)	5	2	8	5	5
3	WR contribution to environmental protection	2	6	7	8	2
4	Contribution to social welfare	5	8	8	7	5
5	Degree of social acceptance	3	4	7	2	7
6	Contribution to health protection	8	7	8	3	8
7	Transferability to similar regions	6	2	9	2	4
8	Benefits to agricultural development	3	5	4	5	5
9	Benefits to industrial development	2	5	5	6	9
10	Benefits to drinking water supply*	–	–	–	–	–
11	General implementability of the IWRM measure	1	6	6	1	9

* just indirect influences on drinking water supply observed

7.3 IWRM Implementation and Transfer

7.3.1 Implementation

According to the Brazilian Water Law (1997), Law No. 9433 (Presidência da República, 2018), the implementation of an Integrated Water Resources Management (IWRM) relies on the following water resources instruments:

1. Water permits
2. Water charges
3. Framework of water bodies in classes
4. Water Resources Information System (SNIRH)
5. Water resources plans on national, state and basin level

The above-listed instruments refer to non-structural IWRM measures that have been discussed in the present chapter. Numerous programs and actions, partially initiated and coordinated by the Federal Water Agency ANA, as well as by state agencies, are being conducted in order to improve the implementation of the IWRM concept. Numerous studies have been undertaken within the BRAMAR project to contribute to the process and to improve the efficiency of these non-structural measures and their implementation by means of continued programs and actions on national and regional as well as on state and basin levels.

We expect that the BRAMAR-IDSS, which is being continuously developed, may support this process since the system is fully compatible with the National Water Resources Information System (SNIRH). Furthermore, it should encourage water resources planners and decision-makers of the water and environmental agencies in North-East Brazil to apply the innovative system to support decisions in water resources planning and management. The close cooperation with the National Water Agency ANA will certainly contribute to improving the existing legislation and to implement new regulations, directives, laws in new water resources policies, based on BRAMAR results and products.

7.3.2 Knowledge and Technology Transfer

All information and knowledge about innovative water technologies, e.g. related to water reuse, methods or DS Tools acquired in the context of the bilateral research and development project BRAMAR are being properly disseminated in and outside Brazil in the context of the national and international conferences and water related events. Therefore, the present book is being published in Portuguese and English.

The project focused on characteristic case study areas of the semiarid and coastal region of the Federal States of Paraíba, Rio Grande do Norte and Pernambuco. It is foreseen to test and validate the methods and approaches developed in the project in similar regions of other states in North-East Brazil. The Brazilian team is planning to continue the work until the end of 2018. Since the selected case study areas are representative for many others, it is expected that there is a great potential for the transfer of technologies, IWRM measures and methods to neighboring states in the region which face similar conditions and challenges with regards to the sustainable development of water resources. Capacity-building measures are part of the BRAMAR research program and play an important role in the context of technology transfer. Special training activities in order to enable students, researchers, water resources planners and decision-makers to work with the BRAMAR Information and Decision Support System have been already conducted during the course of the project and will be continued.

7.4 Conclusions

7.4.1 Lessons Learned

The bilateral research project BRAMAR produced innumerous results that, certainly, will benefit not just the study region with regards to an integrated and sustainable planning and management of water resources.

In North-East Brazil, there is still a lack of regulations for sustainable water resources development, e.g. in the area of wastewater reuse and the conjunctive use of surface and groundwater resources. The required participative decision-making process, involving the public, especially the so-called basin water committees, needs to be fully implemented. Also, water management instruments as stated in the national and state Brazilian legislation, such as water permits, water charge and water resources quality improvement have not yet been fully implemented.

The poor sanitary situation in North-East Brazil requires special attention in the planning process and integrated approaches with regards to water resources development. Major efforts are required to improve the basic sanitary infrastructure for wastewater collection and treatment, before focusing on the technically, legally and organizationally more advanced water reuse. The BRAMAR studies show that "water reuse" is a most important IWRM measure and should be better integrated in the water resources plans developed by the responsible federal and state agencies.

In Brazil, the legal attribution of groundwater management belongs to the states and not to the federal government (National Water Agency - ANA). In spite of huge efforts of the National Water Agency ANA to improve the monitoring of water resources, there is still a major lack with regards to hydro(geo)logical monitoring in North-East Brazil. Although the groundwater level of the large coastal aquifer systems is continuously decreasing, causing increased seawater intrusion and groundwater pollution in many states of the region, very few monitoring data of the important coastal aquifer systems are available.

Efficient groundwater monitoring together with a reformulation of criteria and procedures for the concession of water rights is required to avoid over-exploitation, especially of the most important coastal groundwater resources in the region. New technologies, such as MAR, studied in detail in the present project, are required to improve the conjunctive and sustainable management of surface and groundwater resources, contributing to the reduction of water losses and water resources protection.

Last but not least, the Brazilian-German collaborative research and development project BRAMAR has proved that multi-disciplinary research groups, governmental experts, professionals from the private sector and the civil society are able to work successfully together, providing mutual benefits for all entities involved.

7.4.2 Further Research Needs

The following needs for continued research on the line of the BRAMAR project have been identified:

- Validation of the suggested "Water Resources Planning Approach" in North-East Brazil within a participative process together with national and state stakeholders and decision makers;
- Extension of the existing network for hydro(geo)logical monitoring in Paraíba, Pernambuco and Rio Grande do Norte in order to improve water resources planning;
- Permanent improvement of the database of the BRAMAR-IDSS, related to indicator assessment for structural IWRM measures, giving special attention to the quantitative economic assessment and based on the so-called average incremental cost in USD/m³;
- Monitoring of the short and long-term impact of structural and non-structural IWRM measures
- Continuous further development of the BRAMAR-IDSS in close cooperation with the state agencies responsible for water resources planning and environmental protection, according to their demand;
- Extension and consolidation of the suggested basic indicator list by the Brazilian research groups, taking specific aspects of sustainable development and water sector/user interests into account;
- Further decision support to the development of integrated IWRM strategies as a combination of structural and non-structural priority measures.

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8

Conclusions and Lessons Learned

8.1 Scenario Assessment and Hydro(geo)logical Modelling

8.1.1 Climate change and socio-economic Scenarios

One of BRAMAR's main goals was to identify suitable measures and strategies for water resources management under water scarcity conditions. Since solutions depend on site characteristics, five case study areas were selected and studied in depth, which are typical for the different conditions that can be found in North-East Brazil. A prerequisite to the identification of sustainable IWRM measures is a detailed knowledge of these areas as well as the future pressures on their water resources. Therefore, relevant drivers, pressures, states and impact have been identified for these areas according to the DPSIR approach. The impact of climate change and of socio-economic development were studied by means of scenarios. Climate change emission scenarios RCP 4.5 and 8.5 were combined with three Regional Climate Models. Results indicate an increase in temperatures and highly varying results for future rainfall. Socio-economic scenarios highlight the importance of taking actual drivers into account.

The climatic and socio-economic projections and scenarios are subject to high uncertainties. However, they are important in the context of water resources planning to get a better understanding about the range of potential future impacts on the water resources, helping to identify critical areas which will suffer from high pressures in the future. Therefore, the definition of scenarios and their assessment is an essential step in water resources planning in order to cope with uncertainties of the future. The results constitute baselines for the selection of adequate IWRM measures to combat water scarcity as it is shown in the context of IWRM implementation.

8.1.2 Hydro(geo)logical modelling

Hydro(geo)logical modelling tools were applied in BRAMAR to study the natural behavior of the water resources systems in the Case Study Areas (CSA) under varying climatic conditions as well as the system response to water management actions or structural interventions. The application of these models requires a deep understanding of the water resources system and its behavior. Therefore, the monitoring of the surface and groundwater bodies is of major importance in any water resources management project. Due to the scarce hydrometric and groundwater data in the BRAMAR CSA, great efforts were put into hydr(geo) logical monitoring and field tests to be able to calibrate and validate the required simulation models. Also remote sensing techniques have been applied to fill up data gaps. Continuous feedback from monitoring network and surveys to the hydro(geo)logical models, and vice versa, was necessary, to overcome the lack of data.

Based on the measured and historical data, several models were set up, focusing on the João Pessoa, Sumé and Recife case study areas. The modelling approach is based on water budget assessments, and hydrological conceptual simulation models in combination with numerical groundwater models.

Despite the scarce data, the hydro(geo)logical models were successfully applied in the representative BRAMAR CSAs and are now available to be transferred to innumerous other water resources systems with similar conditions to those in North-East Brazil. In order to decrease the high uncertainties in hydrological modeling results, the monitoring of the surface water reservoirs should be improved and the number of fluviometric and climatic monitoring stations increased in the study areas.

In particular, the geology of the large alluvial coastal aquifer needs to be investigated further to provide fully reliable groundwater simulation tools that may contribute to the sustainable management and protection of this important water resources system. Further efforts are required in this context to investigate and model the impact of seawater intrusion on the groundwater quality as well as the performance of potential response measures based on Managed Aquifer Recharge (MAR).

A deeper investigation and simulation of groundwater recharge, flow and solute transport in the alluvial aquifers at the coastal areas as well as in the small alluvial systems land inside are essential for optimizing the conjunctive management of all water resources, including wastewater. A better understanding and simulation of treated effluent recharge processes, based on the soil-aquifer treatment (SAT) concept and as part of an integrated water reuse strategy, are important to control the impact as well as to protect the most important groundwater resources. This will require the installation of MAR and SAT pilot plants to conduct field experiments.

8.2 Water Resources Management Measures

8.2.1 Managed Aquifer Recharge

Studies revealed a high demand and potential for the implementation of Managed Aquifer Recharge (MAR) as a key IWRM measure in the study areas. Even though the tropical coastal region of João Pessoa has considerable natural groundwater recharge during the rainy season, and surface runoff is abundant after heavy rainfalls, the analysis of long term groundwater budgets for different scenarios of future development revealed a need for the conjunctive management of surface and groundwater resources. According to the trend analysis, groundwater levels of the large coastal aquifer system will continue to fall due to increasing groundwater abstractions. For the urban areas this increases the risk of groundwater salinization by seawater intrusion. Studies showed that the implementation of decentralized MAR systems at the coastal areas, operating a network of infiltration sites, could potentially stop this depletion and restore sustainable conditions of the aquifer system.

These results were gained by means of groundwater budget calculations and hydrological simulation for the João Pessoa case study, but can be transferred to the very similar Recife study area, where seawater intrusion is already being monitored by a comprehensive groundwater observation network.

Studies in the semiarid study area of Sumé proved the potential, viability and necessity for MAR implementation, too. The small city suffers increasingly from water scarcity, also due to extended drought periods. Due to limited rainfall, even during the rainy season and small alluvial aquifer systems at those types of inland sites, the contribution of MAR to increase the water availability during the dry season is limited, but should be obligatory part of an integrated solution. The potential for underground storage in the narrow alluvial aquifer of Sumé has been confirmed by BRAMAR studies, being a basic requirement for MAR implementation and the conjunctive use of surface and groundwater resources. Additionally, as part of a water reuse scheme, treated effluent may be recharged to the aquifer, too. Nevertheless, due to increasing water deficits, water import options need to be studied in the near future.

It can be concluded that MAR is a highly recommended measure for these three representative case study areas, but will require more specific analysis and actual long term field experiments to validate the results obtained by the BRAMAR project.

8.2.2 Wastewater Treatment and Reuse

Wastewater treatment plays an essential role in urban water resources management as insufficient treatment can lead to severe pollution of the aquatic environment, possibly followed by serious health problems for the future users of the polluted resources. On the other hand, wastewater treatment that makes former wastewater available for reuse can help to mitigate water scarcity by providing an otherwise wasted source of water.

Therefore, various wastewater treatment technologies have been studied within BRAMAR with the aim of identifying priority technologies for the typical conditions in North-East Brazil. Several low-cost, close-to-nature technologies have been studied. These included constructed wetlands that, potentially, can be used in smaller communities, providing both wastewater treatment as well as an effluent which – depending on the scheme – is applicable for unrestricted reuse in irrigated agriculture. At the same time, high-technology treatment systems have been studied, featuring membranes and advanced treatment technology suitable for e.g. industrial settings requiring high effluent standards. The studies with pilot plants for conventional and high-tech wastewater treatment showed that viable solutions for all types of water reuse are available for the region.

And while there is room for improvement regarding the design of some of the tested treatment processes, political, financial and operational aspects of wastewater treatment and reuse pose a major challenge. At the moment, there is no nation-wide legislation that defines the conditions and requirements of water reuse. While there is some federal legislation, giving details and, of course, many guidelines from all around the world, the lack of a formal and complete legislative framework is a major impediment for decision-makers who want to play it safe. Another challenge is the overall low rate of wastewater collection and treatment in North-East Brazil, which needs to be improved as a basic requirement for water reuse, but they require considerable investments in sanitary infrastructure. Together with the lack of professionals able to run complex wastewater treatment systems, water reuse will not likely be implemented on the regional scale quickly. There is, however, undoubtedly a great potential and necessity for water reuse to combat water scarcity in North-East Brazil, especially taking the fast expansion of its cities into consideration. A better integration of water reuse solutions in the water resources plans, developed by the responsible Federal and State Agencies, is urgently required.

8.3 Decision Support and IWRM Strategy Implementation

8.3.1 Information & Decision Support System

Integrated Water Resources Management (IWRM) is a complex and challenging task, especially in the case of water-scarcity affected regions, like in the semiarid North-East Brazil. So-called Decision Support Systems (DSS) or expert systems are required to support IWRM implementation and, specifically, water resources planning and management decisions in a way which provides transparency in the decision-making process in order to guarantee later political and social acceptance.

With this purpose, an expert system – the so-called BRAMAR Information and Decision Support System (BRAMAR-IDSS) – was developed during the course of the bilateral project. The BRAMAR-IDSS is a web-based modular system made up of the following key components: graphical user interface, databases (internal/external), a tool base for analysis together with specific tools to support decisions related to water resources planning. The system is easy to handle by the user, especially because it has a number of automated processes, e.g. related to water-budget assessments for partial river basins, scenarios and water demand analysis. Thus, it helps the user easily identify critical areas, which in the near future may suffer from water scarcity and water-related conflicts.

To provide specific support to state water agencies, tools for water demand analysis and water permits management, including data aggregation and analysis for subareas and filters were integrated into the BRAMAR-IDSS. The concession of water rights (water use permit) is a very important task, since additional water uses in critical areas may result in future water crisis and water related conflicts.

The system guides the user through the planning and analysis process developed within the BRAMAR project. Due to the technological focus of the BRAMAR project, special attention was given to the so-called structural IWRM measures, which may be accessed by stakeholders, water resources planners and decision-makers by means of specific indicator filters and organized as a performance matrix.

Even after three years of development, the BRAMAR-IDSS requires further development in a number of aspects, which are stated in the corresponding chapter, in order to provide full-scale decision support to water resources planners in terms of IWRM implementation. Most important system users are the water agencies and secretaries of water resources on state level which may take advantage of the innovative system in order to guarantee sustainable water resources development.

8.3.2 IWRM Implementation in North-East Brazil

A seven-step methodological approach was developed within the scope of the project, which allows the analysis of structural measures of IWRM and innovative water technologies as part of an integrated water resources planning process. These measures, environmental technologies and water resources were grouped together, aiming on the Integrated Water Resources Management (IWRM). The suggested water resources planning procedure emphasizes the implementation of structural and non-structural IWRM measures as a potential response to the water scarcity challenge, as well as its evaluation and comparison by means of the BRAMAR information and Decision Support System (BRAMAR-IDSS).

In order to provide support to a structured system analysis, BRAMAR aimed at a better understanding of the reality of the studied region and focused on the water resources, socio-economic, administrative and institutional subsystems, numerous methods and theories, which were successfully applied and evaluated. This includes causal models, water justice, institutional analysis, social media analysis, conflict analysis, theory negotiation, among others. In addition, new approaches, methods and tools were created to support the integrated planning and management of water resources towards the sustainable development of the region.

Within the scope of the project, the following structural measures were analyzed: conjunctive use of surface and groundwater, wastewater treatment and reuse, rainwater harvesting, water allocation and reallocation as well as water transfer from external water resources. The non-structural measures of IWRM response studied were surface reservoir operation, demand management, water permits and charges, hydro(geo)logical and climatic monitoring as well as institutional development. Numerous studies have also been carried out under the BRAMAR project to contribute to improving the efficiency of non-structural measures and their implementation through ongoing programs and actions at the national and regional levels as well as at the state and basin level.

For the purpose of analysis and comparison of IWRM measures, a list of eleven qualitative indicators was established, taking into account social, environmental and economic indicators, among others. Using the BRAMAR-IDSS tool, we could test the suggested methodological procedure.

The bilateral research project BRAMAR produced innumerous results which, certainly, will benefit not only the Case Study Areas with regards to an integrated and sustainable planning and management of water resources but also may be transferred to similar areas in Northeast Brazil.

In particular, the semiarid North-East Brazil is increasingly suffering from water scarcity and droughts. In order to prevent serious water crises and water-related conflicts in the near future, the research work initiated by BRAMAR needs to be continued in several aspects. This means, e.g., that decision-support for IWRM strategy development needs to be improved by combining different kinds of structural and non-structural measures, including water reuse schemes, as well as the sustainable management and protection of the large coastal aquifer system as precious fresh water resource. Last but not least, in-depth studies are required on the allocation of those waters transferred from the Rio São Francisco (PISF) project as part of an integrated regional water management strategy towards the sustainable development of North-East Brazil.

List of Authors

Author	Institution
Adrianus Cornelius van Haandel	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Ana Cláudia Fernandes Medeiros Braga	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Anderson Luiz Ribeiro de Paiva	Department of Civil and Environmental Engineering Federal University of Pernambuco (UFPE)
André Nóbrega Gadelha	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Anna Abels	Institute of Environmental Engineering (ISA) RWTH Aachen University
Armando César Rodrigues Braga	Center for Natural Resources and Technology Federal University of Campina Grande (UFCG)
Bárbara Barbosa Tsuyuguchi	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Bernd Rusteberg	Rusteberg Water Consulting (RWC)
Carlos de Oliveira Galvão	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Cecir Barbosa de Almeida Farias	Department of Systems and Computation Federal University of Campina Grande (UFCG)
Christoph Bohner	EnviroChemie GmbH
Cibelle Mara Rezende Felinto	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Cláudia Facini dos Reis	Instituto Nacional do Semiárido (INSA)
Cláudio Ritti Itaborahy	Agência Nacional de Águas (ANA)
Cristiano das Neves Almeida	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Cybelle Frazão Costa Braga	Federal Institute of Education, Science and Technology of Paraiba (IFPB)
Duy Phuong Ta	Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI), Dept. of Hydrology, Water Management and Water Protection University of Braunschweig (TU Braunschweig)
Emanuella Almeida Figueiredo	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Euler Noiman Gonçalves	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Florian Walter	Department of Physical Geography Georg-August-University Göttingen
Francisco Miquéias Sousa Nunes	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Franz Bischof	HUBER SE
Gerald Norbert Souza da Silva	Center for Technology and Food Science Federal University of Campina Grande (UFCG)
Geraldo Moura Ramos Filho	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Gerhard Gerold	Department of Physical Geography Georg-August-University Göttingen
Gilson Barbosa Athayde Jr.	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Guillaume Francis Bertrand	Department of Civil and Environmental Engineering Federal University of Pernambuco (UFPE)
Günter Meon	Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI) Dept. of Hydrology, Water Management and Water Protection University of Braunschweig (TU Braunschweig)
Hugo Morais de Alcântara	Center for Sustainable Development of the Semi-Arid Federal University of Campina Grande (UFCG)
Iana Alexandra Alves Rufino	Department of Civil Engineering Federal University of Campina Grande (UFCG)

Author	Institution
Janiro Costa Rêgo	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Jaqueline Vigolo Coutinho	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Jacqueline Pereira Salgado	Department of Civil Engineering Federal University of Campina Grande (UFCG)
João Dehon de Araújo Pontes Filho	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Johannes Pinnekamp	Institute of Environmental Engineering (ISA) RWTH Aachen University
John Elton de Brito Leite Cunha	Center for Sustainable Development of the Semi-Arid Federal University of Campina Grande (UFCG)
Leonardo Vieira Soares	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Lucila de Araújo Fernandes	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Luis Romero Barbosa	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Manfred Hoyer	ALMAWATECH GmbH (former: AP System Engineering GmbH)
Manuel César Marti Calatayud	Aachen Chemical Engineering (AVT) RWTH Aachen University
Márcia Maria Rios Ribeiro	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Marcos Airton de Sousa Freitas	Agência Nacional de Águas (ANA)
Matheus Duarte de Araújo	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Matheus Silva da Cruz	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Matthias Schöniger	Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI), Dept. of Hydrology, Water Management and Water Protection University of Braunschweig (TU Braunschweig)
Mônica de Amorim Coura	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Nelson Oswaldo Luna Caicedo	Department of Civil and Environmental Engineering Federal University of Paraiba (UFPB)
Paulo Breno de Moraes Silveira	Agência Nacional de Águas (ANA)
Rafael Oliveira Batista	Federal University of the Semi-Arid Region (UFERSA)
Renato de Oliveira Fernandes	Civil Construction Department Regional University of Cariri (URCA)
Rennio Felix de Sena	Department of Chemical Engineering Federal University of Paraiba (UFPB)
Ricardo de Aragão	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Salomão de Sousa Medeiros	Instituto Nacional do Semiárido (INSA)
Saskia Schimmelpfennig	Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI) Dept. of Hydrology, Water Management and Water Protection University of Braunschweig (TU Braunschweig)
Silvânia Lucas dos Santos	Center for Natural Resources and Technology Federal University of Campina Grande (UFCG)
Süleyman Yüce	Aachen Chemical Engineering (AVT) RWTH Aachen University
Suzana Maria Gico Lima Montenegro	Department of Civil and Environmental Engineering Federal University of Pernambuco (UFPE)
Vajapeyam Srirangachar Srinivasan	Department of Civil Engineering Federal University of Campina Grande (UFCG)
Vera Kohlgrüber	Institute of Environmental Engineering (ISA) RWTH Aachen University
Victor Hugo Rabelo Coelho	Department of Civil and Environmental Engineering Federal University of Pernambuco (UFPE)

Notes:

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