WATER MANAGEMENT ANALYSIS IN THE MAGDALENA BASIN IN COLOMBIA

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Abstract

As a water-rich country, Colombia has experienced increasing pressure on its water systems during the last decades. The population and economic growth have led to a rise in water use, un-controlled agricultural expansion, and ecosystem pollution. The Magdalena river basin, the most populated and developed region of Colombia, will be threatened by future water shortages without optimal water management strategies. Against this trend, water-economic modeling research enables new insights to cope with the future difficulties in the Magdalena watershed.

This thesis presents a research on how climate change and socio-economic development could influence water management investment and their welfare in the Magdalena region in Colombia. For this purpose, a forward-looking modeling with welfare maximization is applied to the studied area to compare optimal infrastructure investments for various scenarios.

This dissertation's primary tool is the CAMARI model to investigate optimal infrastructure investment in the Magdalena region. CAMARI model is a water management, capacity expansion, and optimization model, which maximizes water consumption's net benefits given socio-economic and water availability projections. Two simulation studies and one paper address this modeling tool's implementation in a developing country's tropical river basin, which research deficit on river management.

In the first study of this thesis, the CAMARI model is employed to detect water consumption conflicts between hydropower generation and the agricultural sector for different climate and development scenarios. Therefore, I compare irrigation patterns, water availability, and reservoir storage levels at a monthly/decadal scale. The primary outcome exhibits that under the scenarios with minor water availability (RCP2.6 and RCP6.0), water competition will arise in the Magdalena region during 2030-2040 (especially in January) when the largest irrigation values and the lowest storage level of reservoirs may occur. Furthermore, agricultural, household and industrial sectors will experience economic scarcity of water between 2020 and 2040 for the studied climate scenarios. This economic water scarcity, measured with shadow prices, reveals the necessities of infrastructure investments in the Magdalena region. Although water competition will be severe in the near future, water management investment is needed until the end of the century. Increasing optimal infrastructure investment must balance the declining existing capacity and cover future water demand for agricultural, household, and industrial sectors.

The second study identifies the impact of spatial scale variability on river infrastructure investment and total revenue for water uses in the Magdalena region. To conduct this research, I solve and calibrate the CAMARI model for four spatial resolutions (140, 34, 13, and 5 regions) for the selected scenarios. This research's relevant result shows that total optimal investment declines 80% (~ 20 billion USD) from 140-regions to 5-regions

analysis during the research time (2020-2100). On the other hand, 80-year total welfare increases circa 5% (~10 billion USD) from 140-regions to 13-regions simulations for the selected scenario combinations. Thus, the optimal investment dynamic simplifies water scarcity for coarser scale modeling, water availability is homogeneously distributed, and fewer infrastructures are required to supply water users.

In the third study, the research paper assesses the social benefits of a sophisticated planning algorithm for water infrastructure investments in the Magdalena region, Colombia. The simulations include three investment scenarios: one fully dynamic optimization and two business-as-usual. The first business-as-usual mimics a short-sighted decision-maker who decides investments assuming that current levels of water supply and demand will persist into the future. The second business-as-usual mimics a decision-maker who believes that water supply will stay constant, but demand will keep changing at the same rate as in the current decade. The results display that employing a model for optimizing investment decisions increases welfare by 120 billion USD over the next century in the Magdalena river basin.

In conclusion, my dissertation contributes to studying future global change impacts on water management in less developed countries. Considering the lack of access to historical data and scientific research, it is a high challenge to analyze Colombia's water problems. Modeling is a tool to help local authorities planning looking-forward infrastructure investments, developing scientific river management plans, and preserving water resources for future generations in the Magdalena region.

Zusammenfassung

Als wasserreiches Land hat Kolumbien in den letzten Jahrzehnten einen zunehmenden Druck auf seine Wassersysteme erfahren. Das Bevölkerungs- und Wirtschaftswachstum hat zu einem Anstieg des Wasserverbrauchs, einer unkontrollierten Ausweitung der Landwirtschaft und einer Verschmutzung des Ökosystems geführt. Das Einzugsgebiet des Magdalena-Flusses, die am stärksten bevölkerte und entwickelte Region Kolumbiens, ist ohne optimale Wassermanagementstrategien von zukünftiger Wasserknappheit bedroht. Gegen diesen Trend ermöglicht die wasserökonomische Modellierungsforschung neue Erkenntnisse, um die zukünftigen Schwierigkeiten im Magdalena-Einzugsgebiet zu bewältigen.

In dieser Arbeit wird untersucht, wie der Klimawandel und die sozioökonomische Entwicklung wasserwirtschaftliche Investitionen und deren Wohlstand in der Magdalena-Region in Kolumbien beeinflussen könnten. Zu diesem Zweck wird eine zukunftsorientierte Modellierung mit Wohlfahrtsmaximierung auf das untersuchte Gebiet angewendet, um optimale Infrastrukturinvestitionen für verschiedene Szenarien zu vergleichen.

Das Hauptwerkzeug dieser Dissertation ist das CAMARI-Modell, um optimale Infrastrukturinvestitionen in der Magdalena-Region zu untersuchen. Das CAMARI-Modell ist ein Wassermanagement-, Kapazitätserweiterungs- und Optimierungsmodell, das den Nettonutzen des Wasserverbrauchs bei gegebenen sozioökonomischen und Wasserverfügbarkeitsprognosen maximiert. Zwei Simulationsstudien und ein Aufsatz befassen sich mit der Implementierung dieses Modellierungswerkzeugs in einem tropischen Flusseinzugsgebiet eines Entwicklungslandes, das ein Forschungsdefizit beim Flussmanagement aufweist.

In der ersten Studie dieser Arbeit wird das CAMARI-Modell eingesetzt, um Wasserverbrauchskonflikte zwischen der Wasserkrafterzeugung und dem landwirtschaftlichen Sektor für verschiedene Klima- und Entwicklungsszenarien zu erkennen. Dazu wurden die Bewässerungsmuster, die Wasserverfügbarkeit und die Speicherstände der Reservoirs auf einer monatlichen/dekadischen Skala verglichen. Das Hauptergebnis zeigt, dass unter den Szenarien mit geringerer Wasserverfügbarkeit (RCP2.6 und RCP6.0) in der Region Magdalena in den Jahren 2030-2040 (besonders im Januar), wenn die größten Bewässerungswerte und der niedrigste Speicherstand der Reservoirs auftreten können, eine Wasserkonkurrenz entstehen wird. Darüber hinaus werden die Sektoren Landwirtschaft, Haushalte und Industrie zwischen 2020 und 2040 für die untersuchten Klimaszenarien wirtschaftliche Wasserknappheit erfahren. Diese ökonomische Wasserknappheit, gemessen mit Schattenpreisen, zeigt die Notwendigkeit von Infrastrukturinvestitionen in der Magdalena-Region auf. Obwohl die Wasserkonkurrenz in der nahen Zukunft stark sein wird, sind wasserwirtschaftliche Investitionen bis zum Ende des Jahrhunderts notwendig. Zunehmende optimale

Infrastrukturinvestitionen müssen die abnehmende bestehende Kapazität ausgleichen und den zukünftigen Wasserbedarf für Landwirtschaft, Haushalte und Industrie decken.

Die zweite Studie identifiziert die Auswirkungen der räumlichen Skalenvariabilität auf die Flussinfrastrukturinvestitionen und die Gesamteinnahmen für die Wassernutzung in der Magdalena-Region. Um diese Forschung durchzuführen, löse und kalibriere ich das CAMARI-Modell für vier räumliche Auflösungen (140, 34, 13 und 5 Subregionen) für die ausgewählten Szenarien. Das relevante Ergebnis dieser Forschung zeigt, dass die optimale Gesamtinvestition während des Forschungszeitraums (2020-2100) um 80% (~ 20 Mrd. USD) von der 140-Regionen- zur 5-Regionen-Analyse abnimmt. Auf der anderen Seite steigt die 80-jährige Gesamtwohlfahrt um ca. 5% (~10 Mrd. USD) von 140-Regionen zu 13-Regionen-Simulationen für die ausgewählten Szenarienkombinationen. Somit vereinfacht die optimale Investitionsdynamik die Modellierung von Wasserknappheit auf einer gröberen Skala, die Wasserverfügbarkeit ist homogen verteilt und es werden weniger Infrastrukturen zur Versorgung der Wassernutzer benötigt.

In der dritten Studie wird der soziale Nutzen eines hochentwickelten Planungsalgorithmus für Wasserinfrastrukturinvestitionen in der Region Magdalena, Kolumbien, bewertet. Die Simulationen umfassen drei Investitionsszenarien: eine vollständig dynamische Optimierung und zwei Business-as-usual-Szenarien. Das erste Business-as-usual-Szenario imitiert einen kurzsichtigen Entscheidungsträger, der Investitionen in der Annahme tätigt, dass das aktuelle Niveau von Wasserangebot und -nachfrage auch in Zukunft bestehen bleibt. Das zweite Business-as-usual-Modell ahmt einen Entscheidungsträger nach, der davon ausgeht, dass die Wasserversorgung konstant bleibt, die Nachfrage sich aber weiterhin mit der gleichen Rate wie im aktuellen Jahrzehnt ändert. Die Ergebnisse zeigen, dass der Einsatz eines Modells zur Optimierung von Investitionsentscheidungen die Wohlfahrt im Magdalena-Flusseinzugsgebiet im nächsten Jahrhundert um 120 Milliarden USD erhöht.

Zusammenfassend lässt sich sagen, dass meine Dissertation dazu beiträgt, die zukünftigen Auswirkungen des globalen Wandels auf das Wassermanagement in weniger entwickelten Ländern zu untersuchen. In Anbetracht des fehlenden Zugangs zu historischen Daten und wissenschaftlicher Forschung ist es eine große Herausforderung, die Wasserprobleme Kolumbiens zu analysieren. Die Modellierung ist ein Werkzeug, das den lokalen Behörden hilft, vorausschauende Infrastrukturinvestitionen zu planen, wissenschaftliche Flussmanagementpläne zu entwickeln und die Wasserressourcen für zukünftige Generationen in der Magdalena-Region zu bewahren.

1. General Introduction

1.1 Water management in Latin America and Colombia

Latin America is a region comprised entirely of developing nations, where it is home to 30 million people who are still lacking access to drinking water (de San Miguel, 2018). On the contrary, South America's average rainfall (1560 mm) is the highest of the continents. This continent has 26 percent of the planet's water supply but only 6 percent of the population. Water use and population tend to be concentrated in relatively low rainfall areas, where river flows are highly variable. Large freshwater reserves are located in a few large river systems far away from the population (Economic and Social Development Department Inter-American Development Bank Washington, 1984). Colombia is such an example: 70% of the population lives in the Magdalena basin, where 10% of the national water supply is available. Despite mean annual precipitation of 1840 mm/year, classifying Colombia as a water-rich country, growing population and industries led to an increase in water use, a gradual reduction of forest covers, enlargement of agricultural land, increasing erosion rates, and rising water pollution (Restrepo et al., 2006). Observed water shortages in the recent past are expected to become more frequent in the future unless adequate infrastructure investments for water management are undertaken (Domínguez et al., 2010).

Furthermore, Latin America's national water management issues are pressing concerns that have occupied public policymakers for many years. Relevant difficulties on water management regulations are coordination of supply and demand policies; policies for the quality and quantity of water; the multiple uses of resources and multipurpose projects; coordinated management of land use, vegetation cover, and water; improvements in data collection and information management; and environmental conservation policies (de San Miguel, 2018).

Water resource systems have brought benefits to people and their economy for many centuries. Nowadays, in some regions worldwide, water infrastructures cannot meet the demands for freshwater, sanitation requirements, or protecting ecosystems (Loucks et al., 2005). Inadequate water infrastructures reveal resource systems failures in planning, management, and decision-making.

Currently, planning, designing, and managing water systems involve modeling as a scientific tool for predicting the behavior of projected infrastructures and management policies (Loucks et al., 2005). Researchers have been modeling the engineering, ecological, hydrological, institutional, and political impacts of water resource structures during the last three decades. Model efforts should improve water resources

management's understanding to help planners in optimal decision-making (Loucks et al., 2005).
In Colombia's case, country legislation for water management includes various administrative, economic, and planning tools. Although Colombian environmental regulation has instruments for efficient water allocation and pollution control, these tools are not well implemented and integrated. One of the reasons for this erroneous implementation is the environmental authorities' lack of expertise to develop modeling analysis (Blanco, 2008). With my thesis, I would like to research how climate change, socio-economic development, spatial scale, and hydroelectricity generation could influence water management investment and their welfare in the Magdalena basin, the most populated and developed region of Colombia. To perform my investigation, I employ a constrained welfare maximization model called CAMARI, which maximizes the net benefits of water consumption in the studied watershed by determining the optimal times and locations for the construction of water management infrastructures.

1.2 Hydropower production and spatial scale modeling in river basins

Modeling and simulation of water demand provide a scientific basis for planning and managing the resource (Winz et al., 2009). Given the increasing impact of climate change on river basins, additional research is required to investigate water competition per sector, water scarcity, physical scale variability, infrastructure investment, and operation for different settings. Following these approaches, optimal river management has been modeled by several researchers worldwide.
The majority of river studies published in the field of major water-consumers competition focus on modeling water allocation and geographical water demand without exploring investment in water infrastructures. Some researchers usually select abstraction or operation scenarios to compare water demand for hydropower generation, irrigation, and general supply. Other river basin studies comprise geographical demand, climate change, and vulnerability analysis without optimal investment projections (see table 1-1).

Research features (Innovation)	Location	Competition outcomes	Citation
Selection of abstraction or operation scenarios to compare water demand per sector			
Water demand for hydropower generation, irrigation, and general supply under different geographical scenarios of water abstraction.	The Lweya River, Malawi	The scenario where hydropower generation was located upstream of other users is the best setting to integrate the mentioned sectors' potential use due to more water flow availability.	Phiri and Mulungu (2019)
Reservoir cascade model to evaluate water resource allocations in meeting the hydropower and irrigation water demands.	Mahaweli basin, Sri Lanka	Infrastructure limitations and spatial variability restrict the performance of agricultural systems.	De Silva and Hornberger (2019)
Impacts of increasing agricultural production, hydropower generation, and water demands under different reservoir-operation scenarios.	The Upper Niger and Bani Rivers, in West Africa.	Sustainable development should consider investments in water-saving irrigation and management practices to improve the predicted irrigation plans' feasibility instead of building a new dam.	Liersch et al. (2019)
Dynamic system model to simulate water, energy, food production, and dam operation policies.	Blue Nile River, Ethiopia	The Grand Ethiopian Renaissance Dam provides Ethiopia a greater water control for hydro-energy generation and efficient water storage/release for crop production in Egypt and Sudan.	Tan et al. (2017)
Geographical demand, climate change, and vulnerability			
Future water availability and water shortage risks in the 2050s, considering multipurpose reservoir operations, climate change, and socio-economic development.	The Durance River Basin, south-eastern France	Reservoir release-operation rules must be modified to give hydropower management more flexibility during winter-peak energy demand.	Sauquet et al. (2016)
Dynamic system model to study water management in a river basin.	Saskatchewan River Basin, western Canada	Irrigation expansion would decrease hydropower production and increase the total direct economic benefits in the studied region.	Hassanzadeh et al. (2014)
Vulnerability analysis under changing water supply and demand expansion in a river basin.	Saskatchewan River Basin, western Canada	Hydropower production is more sensitive to annual inflow volume changes than variations in either the peak flow's annual timing or the magnitude of irrigation expansion.	Hassanzadeh et al. (2016)
Impact of climate change on hydropower production and irrigation.	Kariba Dam, Zambesi river	The existing Kariba Dam should reduce the average power generation by 12% under drying climate conditions. Besides, increasing irrigation demand will also have a significant negative impact on downstream hydropower plants in Mozambique.	Spalding-Fecher et al. (2016)

Table 1-1. Selected water-consumers competition modeling grouped into categories.

During the last few decades, many models have been developed to explore relations between physical scale variations, water scarcity, and welfare for water consumption. However, they exclude optimal infrastructure investment as a management alternative (see table 1-2).

Research features (Innovation)	**Location**	**Modeling / outcomes**	**Citation**
Maximization of economic profit from water uses in various sectors.	Maipo River, Chile	The Maipo model adopted two approaches: a “bottom-up” economic structure starting from croplands and going up to the entire basin and a “top-down” water allocation structure from basin level to cropland.	Cai (2008)
Impact of spatial aggregation on agricultural water’s economic value from a farm-level to a river system-level.	Rio Grande–Rio Bravo Basin, North Mexico	The river-level model estimates better water economic value and model adaptations to new conditions and policies. The farm-level scale captured better the distribution of climate, technology, and economic scenarios.	Medellín-Azuara et al. (2008)
Water allocation responses over different temporal or spatial scales in a watershed.	Bow River Basin in southern Alberta, Canada	Modeling an allocation problem at larger scales provide more opportunities to exploit on-stream and off-stream system storages.	Cutlac et al. (2006)
Vulnerability at various scales using quantitative evaluation indexes.	Huai River Basin, China	A multiscale vulnerability research, based on political boundaries and watersheds, under a climate change background.	Xia et al. (2014) Chen et al. (2016)
Relationship between spatial patterns and scale of the data to analyze water availability, water use, and population data.	The Danube (Europe), Ganges (South Asia), and Missouri (North America) river basins.	The variability of unscaled variables (freshwater supply, water use, and population) increases with coarser scales but scaled variables (water stress/scarcity, water use/water availability) decrease with coarser scales.	Perveen and James (2010)
Comparison of climate change adaptations for three physical scales.	The Murray-Darling basin, Australia.	At wetland-scale, it is valuable to study hard and soft engineering solutions for biodiversity. At river valley-scale is relevant to balance the allocation between competing water users. At the basin scale, adaptations are useful to select actions for conservation and restoration, based on water market mechanism.	Saintilan et al. (2013)

Table 1-2. Selected spatial scale modeling in river basins.

1.3 Contributions and outline of this Thesis

1.3.1 Modeling water resources in Colombia

In Colombia, research on climate change and hydropower modeling was developed at a national and watershed scale. Arango-Aramburo et al. (2019) applied two partial equilibrium models (GCAM and TIAM-ECN) and two general equilibrium models (MEG4C and Phoenix) to detect possible pathways of power sector adaptation for Colombia under climate change. The authors found that climate change could deteriorate hydropower production by approximately 15% by 2050, under the RCP4.5 climate scenario. Ospina-Norena et al. (2011a) analyzed water resources' vulnerability to climate change/hydropower generation in the Sinú-Caribbean Basin with The Water Evaluation and Planning Model (WEAP) 2.1, a software for integrated water resources management and policy analysis. Their results showed that hydroelectricity generation has a 33.3% vulnerability, with a reduction greater than 16% in water storage, 20% in stream flows, and 22% in hydropower generation, for the analysis period 2010 to 2039. Gómez-Dueñas et al. (2018) conducted a hydropower vulnerability assessment in the Magdalena basin by applying the Collaborative Risk Informed Decision Analysis (CRIDA). Their results confirmed that climate change is the main threat to influence hydropower production in the studied river basin. Angarita et al. (2018) evaluated the current and projected impacts of hydropower expansion on the Magdalena River floodplains' environment and ecosystem processes. In the Magdalena region, hydropower plants have a total capacity of 6.89GW and supply 49% of the electricity demand in Colombia (UPME, 2015). The Colombian government has planned to increase hydropower production, taking advantage of its water availability and topographical conditions. The majority of the new hydropower projects will be located in the Magdalena basin (Gómez-Dueñas et al., 2018). In Colombia, there are some relevant studies related to water scarcity and water availability. Some research addressed the issues of water security, water availability, and water use at the watershed scale (Luijten et al., 2001), proposing a water scarcity index as an indicator of the anthropogenic pressures on limited water resources (Domínguez et al., 2010), modeling adaptation scenarios and climate change for water supply, water use and water demand in the Sinu-Caribe basin (Sieber and Purkey, 2007), and finding water management strategies to mitigate adverse effects of climate change during the critical months (February-April) for hydropower generation at the watershed scale (Ospina-Norena et al., 2011a).

My literature review shows research improvement on modeling projected water demand per sector; and spatial resolution analysis for water allocation, availability, and vulnerability. However, these studies did not include the development of forward-looking behavior for optimal infrastructure investments. My study fills the literature gap by applying a model, which can choose optimal investment under different spatial scales, water availability, and development scenarios in the Magdalena basin. I use welfare-maximization with forward-looking planning to compare infrastructure investments, water sectors' demand competition, hydropower generation, water consumption welfare, river management at multiple spatial scales, and physical/economic water scarcity. Because of the slow building and high costs of large water infrastructures, it is helpful to model optimal future investment with welfare-maximization procedures.

Research on the impact of scale variations on water resource analysis is still deficient (Perveen and James, 2010). Besides, spatial disaggregation and innovative modeling of economic data are required to represent precisely water use dynamics (Bekchanov et al., 2012). Although, temporal and spatial connections among water systems and political frontiers are still a challenge on building water-economy models (Bekchanov et al., 2017). CAMARI model is an example of water-economy modeling to compare the magnitude and pattern of spatial variation on water consumption welfare and water infrastructure investment in the Magdalena river basin. Equally important is the CAMARI model feature to extrapolate administrative data to the subbasin level at various spatial-time scales.

1.3.2 CAMARI model – water management tool for Colombian watersheds

This thesis's primary tool is the CAMARI model, a water management, capacity expansion, and optimization model, which maximizes welfare from agricultural production given socio-economic and climate projections. CAMARI is a mathematical programming model written in General Algebraic Modeling System (GAMS). CAMARI maximizes net benefits from water consumption in the Magdalena watershed. Simultaneously, CAMARI model selects the optimal times and locations to install water management infrastructures. The objective function of the CAMARI model maximizes the welfare for water uses in the Magdalena region. This objective function is constrained by several equations to depict physical resource limits, production efficiencies, technical capacity limits of investments, financial restrictions, political regulations, interregional and intertemporal relationships.

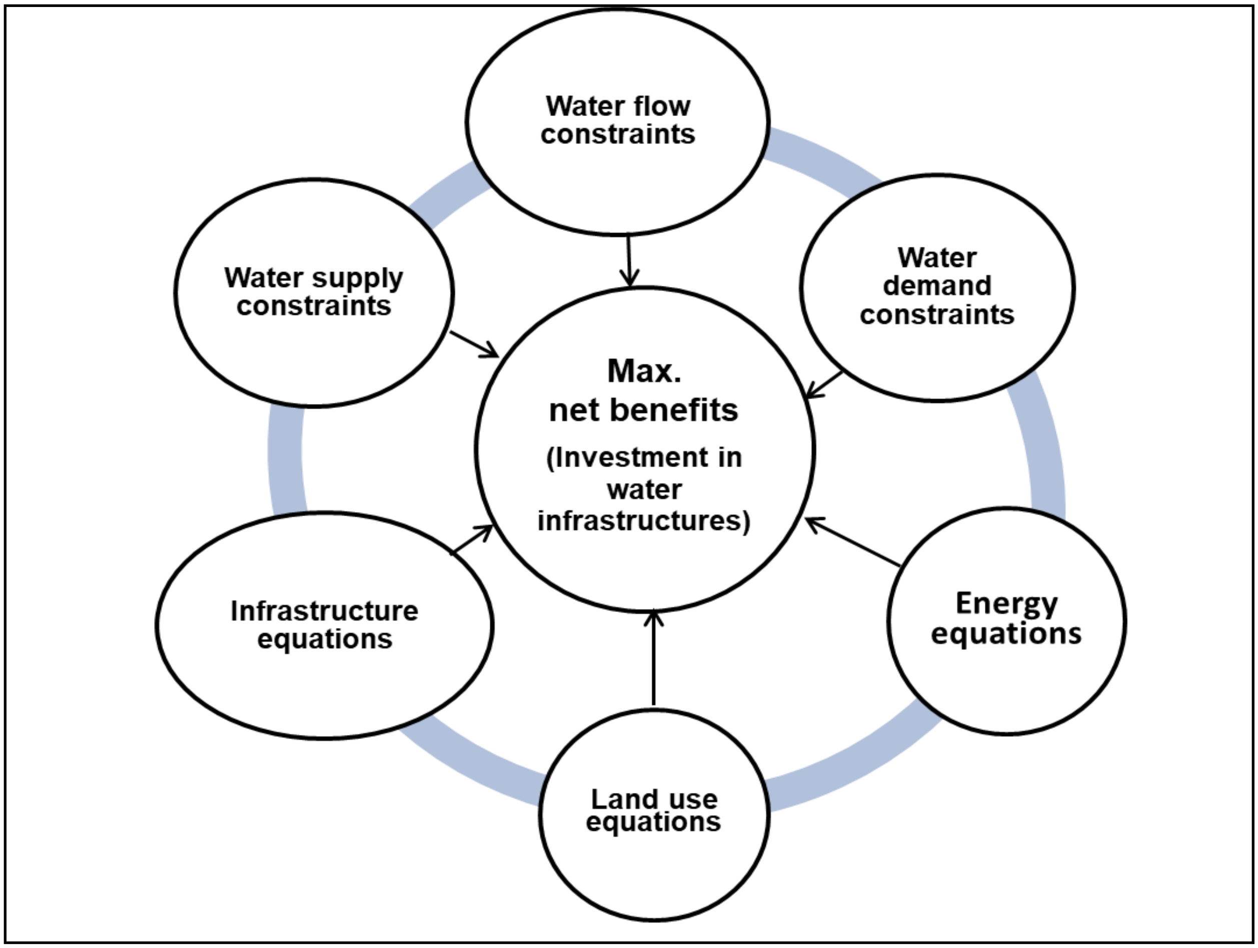


Figure 1-1. Overview of the CAMARI model

The research carried out with the CAMARI model focus on water management in the Magdalena River basin, Colombia. I chose the Magdalena region because it is the most densely populated and economically important watershed in Colombia. This large watershed covers 24% of the country's area, generates 85% of the Gross Domestic Product, provides 70% of Colombia's hydropower, and lives 32.5 million people.

1.3.3 Outline of this Thesis

In the dissertation, I present a water management analysis in the Magdalena river basin in Colombia. My investigation tool is the optimization model, CAMARI. My modeling assessment selects optimal management investment for projected water availability and development scenarios. For selected scenario combinations, the forward-looking methodology compares optimal infrastructure investments, water competition among agricultural and hydropower sectors, hydropower generation scenarios, the dynamic behavior of the agricultural water demand, the endogenous pattern of crop production, economic scarcity of water per sector, and changes of net benefits per water consumers.

My river basin investigation addresses three research questions to contribute to water management modeling in a developing country's tropical river basin, which research deficit on water issues. The first research question is: Will water competition emerge between hydropower generation and irrigation in the Magdalena watershed under various future climate and socioeconomic scenarios? The second research question is: How large is the influence of spatial resolution variations on water management investments and the welfare for water uses in the Magdalena basin?. The final research question is: How much does a sophisticated planning algorithm for water infrastructure investments improve welfare compared to simple business as usual decision-making?.

My thesis, called" Water management analysis in the Magdalena basin in Colombia," contains five main chapters.

The first chapter provides an overview of water management issues/problems in Latin America and Colombia. Furthermore, I review global, national, and regional literature about water use competition, geographical water demand, impacts of climate change on hydropower production, hydroelectricity dams vulnerabilities and operation policies, spatial scale analysis for water allocation, water availability, and vulnerability assessments.

In chapter 2 (Data and methods), I propose a methodology to investigate optimal infrastructure investments in river management, which answers my two first research questions. I introduce the forward-looking behavior with welfare-maximizationmodeling to research optimal investment in water management infrastructures. I describe and improve the constrained optimization model CAMARI, which can choose the time and location of optimal investment in the Magdalena basin. Furthermore, I depict the input data, hydroelectricity generation, and resolution analyses. I describe CAMARI model assembly, programming routines, and scale/climate/development scenario combinations for each study.

The third chapter describes the forward-looking results for optimal investments and answers my two research questions. In this chapter, detailed analyses are shown for water competition between agricultural and hydropower sectors, decadal and monthly electricity generation, projected infrastructure capacities, the economy of water scarcity per sector, detailed and general welfare of water consumption. Moreover, I propose a comparison analysis, which explores relations among spatial scale, river management, water scarcity, and net benefits.

To answer the first research question, I employ the model CAMARI to explore water demand competition among irrigation and hydroelectricity generation for selected water availability and socio-economic scenarios. By CAMARI scenario simulations, I compare projected water availability, irrigation water uses, and reservoir storage levels at monthly/decadal time scales. Furthermore, I explore optimal infrastructure investment, the economy of water scarcity, and welfare for water consumption. This hydropower analysis includes 80 years (2020-2100) of surface-runoff/development projections and a decadal/monthly time scale.

In the third chapter, I also resolve my second research question. To answer this question, I analyze connections between different spatial scales and water resources management under different future climate/socio-economic scenarios in the Magdalena region in Colombia. This research presents a method for comparing the magnitude and pattern of spatial scale variation in welfare and water infrastructure investment in the Magdalena region. I propose a methodology to compare net benefits and optimal water management alternatives for several spatial scales. To reach that aim, I analyze four spatial resolution scenarios for the Magdalena basin (5, 13, 34, and 140 regions) with the constrained optimization model “CAMARI.” This research explains how spatial scale variation would affect the results of welfare for water consumption and infrastructure investment in the Magdalena river basin, considering an 80-year time horizon.

The fourth chapter includes my first submitted version of the scientific paper called “Benefits of forward-looking water management – A case study of the Cauca-Magdalena river basin.” In this investigation, I answer the third research question. With the constrained welfare maximization model CAMARI, I study the social benefits of optimizing public/private investments into various water management infrastructures. The model simulates different scenarios of infrastructure investment decisions, compares the welfare for water uses and estimates the benefits of employing sophisticated planning methods. The last version of the mentioned paper was published in the Water Economics and Policy journal (Rasche et al., 2016).

The final chapter of my thesis summarizes the main achievements and outlines recommendations for further research. I explain how my research insights should help Colombia and the Magdalena region inside a political, economic, and environmental context. Last, I describe my research limitations and propose clear guidance on how to continue future research on water management in the Magdalena river basin.

2. Data and methodology

Part of this chapter was published in the paper: Benefits of coordinated water resource system planning in the Cauca-Magdalena river basin. Water Economics and Policy, 3, 1650037. Rasche, L., Schneider, U. A., Bolivar Lobato, M., Sos Del Diego, R. & Stacke, T. (2016).

2.1 Study area

Located in the inter-tropical converge zone with high mountains on the western part of the country (Fig. 2-1a and 2-1b), Colombia's water availability per capita is among the world's highest. The major river catchments in Colombia have yearly rainfall of more than 2000 mm each, irregularly distributed over the year, with dry seasons from December to March and June to September and wet seasons from March to May and October to November (Nakaegawa and Vergara, 2010).

The research area is the Magdalena river basin, which is South America's fifth-largest basin. The Magdalena is the river with the highest discharge and highest water withdrawal rate in Colombia. The Magdalena River originates at 3685 m.a.s.l. in the Colombian Andes, runs for about 1540 km from South to North through the Western half of the country, and terminates in the Caribbean Sea. The Magdalena catchment contains 151 subbasins, whose 109 first-order sub-basins feed 42 second-order watersheds that drain directly into the Magdalena main river. First and second-order streams consist of small tributaries that flow into larger tributaries. The Magdalena river's principal tributaries are the Cauca (the second largest river in Colombia), Sogamoso, San Jorge, and Cesar rivers. The Magdalena basin has a total area of 273,459 km2, equivalent to 24% of Colombia's territory (Restrepo et al., 2006b).

Due to the diverse topography of the Magdalena region, it is challenging to generalize rainfall patterns (Fig. 2-2a). In both watersheds, the highest rainfall (around 3000 mm/year) is received at intermediate elevations of approximately 1500 m. Regions above 3000 m height typically receive far less (~1000 mm/yr) and the Magdalena valley bottom slightly less (~1700 mm/yr) precipitation (Lopez and Howell, 1967, Restrepo et al., 2006). The Magdalena river basin experiences mean precipitations of 2050 mm/yr, and the average runoff amounts to 953 mm/yr (Alfonso et al., 2013, Kettner et al., 2010).

The Magdalena region is the economically most important but also the most environmentally vulnerable area in Colombia. It is home to 70% of the country's population (32.5 million inhabitants), which grows annually by 1.72 %. In this watershed, 95% of Colombia's thermoelectric and 70% of its hydroelectric power supply (Fig. 2-2b) are generated. Livestock and agroindustry activities in the river basin amount to 75% of the country's total production, and around 85% of the Gross Domestic Product is generated in the basin (IDEAM et al., 2007). In 2014, Employment in the agricultural sector represented 16.3% of total employment in Colombia. Even though agricultural production represents 6% of the Gross Domestic Product from Colombia (DANE, 2019) in the Magdalena region, 60% of the total water supply is consumed by the agricultural sector. Besides, 95% of permanent crops, 80% of non-permanent crops, and 90% of Colombia's coffee production are located in the Magdalena region (CORMAGDALENA, 2013). For this reason, crop production in the Magdalena watershed plays a relevant role in the water and food security of Colombia.

According to ENA (2018), total water use for Colombia was estimated at 38 billion m3/year in the year 2016. In that year, the agriculture sector was the primary water consumer in Colombia (43% of country demand), followed by the hydro-energy sector (23%) and the livestock sector (8%). Agriculture water demand includes irrigation for permanent crops (75%) and non-permanent crops (25%). The irrigated permanent crops are mainly oil palms, sugar cane, and plantains (55% of irrigation), and the non-permanent irrigated crop is rice (13%). Precipitation supplies 90% of water demand for agriculture, and only irrigation supplies 10% of agricultural water consumption (IDEAM, 2018).

Even though the water availability is circa 300.000 Million m3/ year in the Magdalena basin, water resources are under stress. Firstly, water availability is not uniformly distributed in the area. Second, this region supplies just 10% of Colombia's water demand, although it is home to 70% of the population. Third, the agricultural sector consumes a large amount of water intensively and inefficiently. Finally, large Colombian cities' location generates a high pressure on water resources due to their complex infrastructures for water supply, which implies large pipelines and several reservoirs to connect water sources inside the Magdalena region (CORMAGDALENA, 2013).

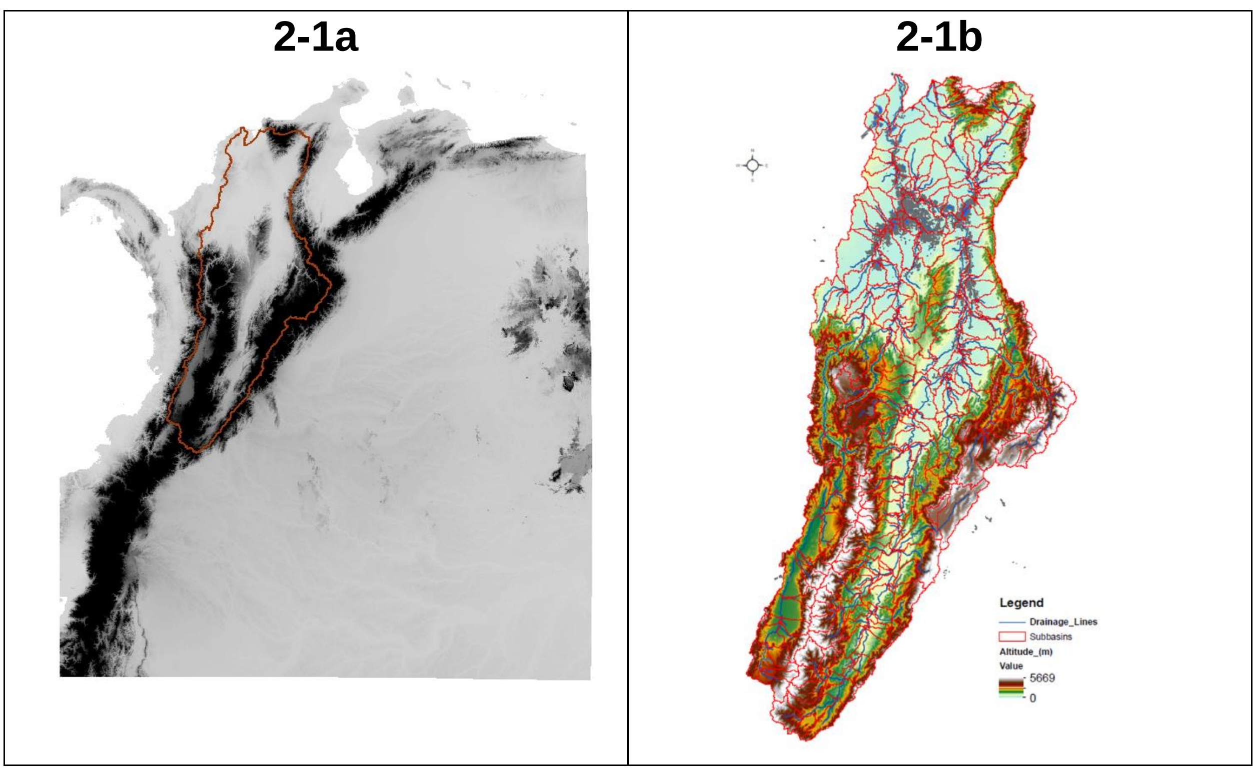


Fig. 2-1. Location of the Magdalena basin in Colombia (2-1a), water systems and topography (2-1b).

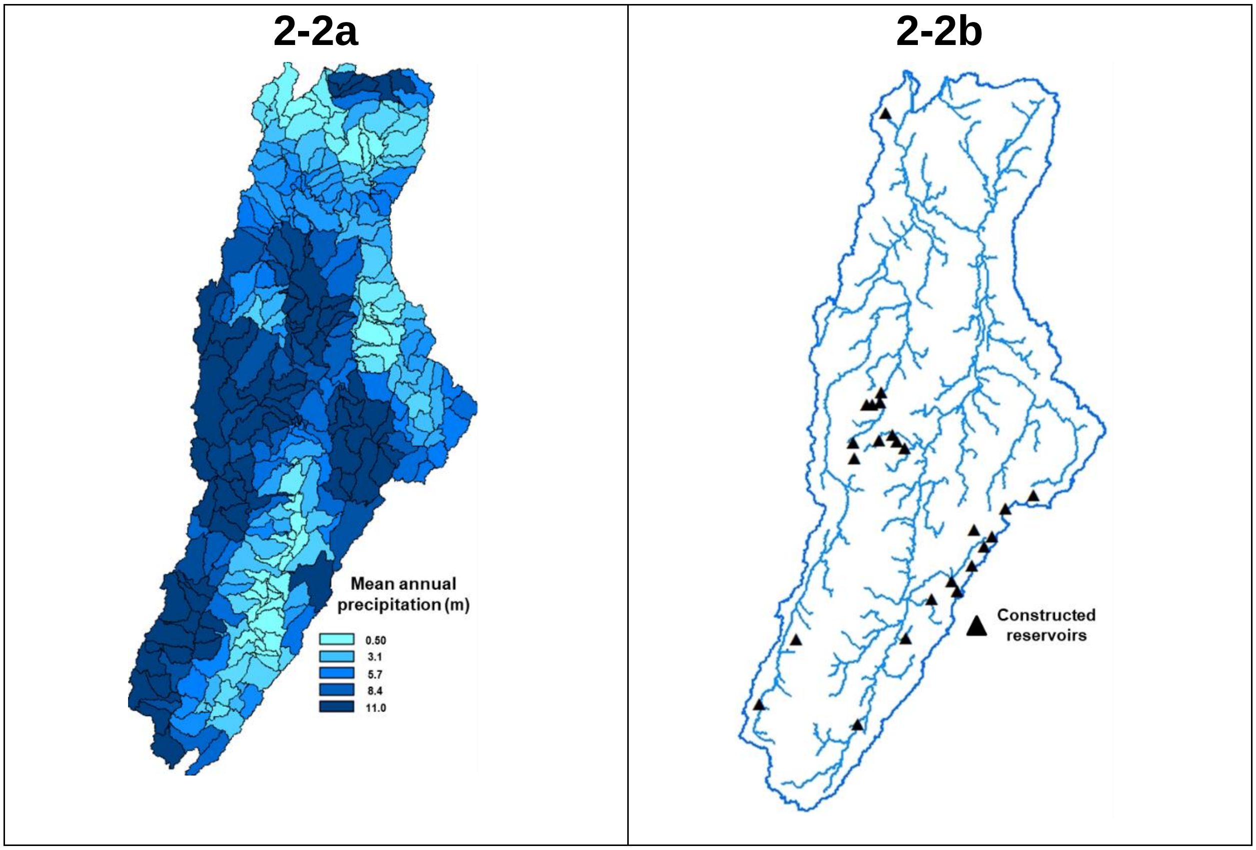


Fig. 2-2. Mean annual precipitation (2-2a) and dam-reservoirs location (2-2b) in the Magdalena region.

2.2 Relevance of water management infrastructures and hydropower generation

2.2.1 Current situation

There are three main types of infrastructures in water management, ponds, dams, and pumping stations. Ponds, an alternative for water management infrastructure to mitigate flow and supply water for irrigation (Blick et al., 2009), are being used in an artisanal way in Colombia. Documentation about existing irrigation ponds is scarce.
Pumping stations, structures that extract water directly from the source, are components of Colombian´s water supply systems. In this country, the water supply sector does not have a national database that compiles the use, quality, and quantity of water structures. For this reason, it is challenging to state checks, track efficient and safe performances concerning management and investment in water supply infrastructures. Investment failings of water systems reflect the state of abandonment of many components that never became operational or were built but not required (Ospina Zúñiga and Ramírez Arcila,

2011). Research on water supply issues in Colombia was done, describing water distribution systems and modeling in Aburra Valley (Giraldo, 2017), Barranquilla (Angulo, 2017), Manizales (Echeverri, 2017), and Santa Marta (Londono et al., 2017). Other freshwater supply investigations explore parameters optimization of water distribution systems (Mendez et al., 2013); water governance and communities(Llano-Arias, 2015); private investment in rural drinking water infrastructures (Ruiz et al., 2016), and efficiency of tariffs and subsidies in the water supply price (Ruiz, 2019).

Water availability is the primary driver of electricity production in Colombia. Almost 70% of Colombian power generation comes from the hydroelectric branch, 30% from thermoelectric power producers (Macias P.; Ana M., 2012). The hydropower sector includes several dams located in the Magdalena basin's high and middle regions. The large ones are the Betania Reservoir, located in the Magdalena river (Huila state); Salvajina reservoir, on the Cauca river (Cauca state); Hidroprado reservoir, on the Prado river (Tolima state); Tominé, Sisga und Neusa reservoirs in the Bogota river watershed (Cundinamarca state); San Carlos und el Peñol Hydroelectric stations on the Nare river (Antioquia State). The Guajáro reservoir is located inside the lower Magdalena region and supplies water for irrigation in this area. Cauca, Prado, Bogota, and Nare rivers are tributaries of the Magdalena river (Macias P.; Ana M., 2012). Dams are primarily used for electric generation and flooding control.

2.2.2 Historical development

Martínez and Castillo (2016) identified the main drivers and conflict periods during the implementation of hydropower systems in Colombia. They analyzed the facts around building thirteen Hydropower Dams between 1970 and 2010. The thirteen projects represent 83% of the national hydroelectric production. The authors have found two main drivers inside the conflicts: the political and economic context where the electricity sector was formed in Colombia and the influence and expectations of political elites in constructing mega-dams of a development model supported by Colombia's economic growth and neighboring countries. Table 2-1 lists the construction of the analyzed dams during the conflict periods in Colombia. These periods are national electricity expansion (1970-1989), privatization and decentralization (1990-1999), and violence intensification (2000-2015) (see table 2-1).

Identified periods	Name	Opening year	Generation capacity (MW)
The national electricity expansion (1970-1989)	Guatapé I	1972	280
	Chivor I	1977	500
	Guatapé II	1978	280
	Chivor II	1983	500
	San Carlos I	1984	620
	Salvajina	1985	285
	Guatrón	1985	202
	Betania	1985	540
	San Carlos II	1987	620
	Playas	1988	201
	Jaguas	1988	170
Privatization and decentralization (1990-1999)	Guavio	1990	1150
	Tasajera	1993	306
Violence intensification (2000-2015)	Urrá I	2000	340
	Porce II	2001	405
	La Miel	2002	396
	Porce III	2010	660

Table 2-1. Analyzed hydropower dams. Source. (Martínez and Castillo, 2016).

2.2.3 Competition between the hydroelectricity and agricultural sector in Colombia.

Hydropower is a renewable and price-competitive source of energy. It currently generates 3930 terawatt-hours per year, sources 16% of electricity, and produces 86% of renewable power globally. Global hydropower generation potential is 14516 terawatt-hours per year (mainly in Asia and Latin America). Although Asia and Latin America have the most significant technical hydro-energy potential, they have the most massive undeveloped resources (IPCC, 2012).

Hydroelectricity has traditionally been the primary source of power in Colombia. Power generation has increased by 13% between 2010 and 2014. In 2014, hydroelectric generation represented 69.5% (64,327.6 GWh) of the country's total energy production. Regarding Colombian energy demand, the most significant users of energy are the manufacturing industry (47%), followed by mining and quarrying (21%), and social, community, and personal services (11 %). 65% of the country's power generation is managed by the EPM, EMGESA, and ISAGEN enterprises (Procolombia, 2015).

Investment in power generation dams is one of the main political issues in Colombia. Colombian government settled the building of hydroelectric infrastructures as a national legislative priority. Therefore, this country began to be one of the main exported of hydroelectricity, ranked in place No 11 in the world in 2015. However, energy-expansion politics have increased foreign investments have also boosted social and violent conflicts throughout Colombia (Martínez and Castillo, 2016).

In the Magdalena basin, water use for hydropower generation was 33,837 million cubic meters during 2012, which corresponds to 78% of the water used for power generation for the whole country. From this volume, 95% of the water returns to the rivers (IDEAM, 2014). In the same region, agricultural water demand represents 60% of the total water consumption, and it is located more than 80% of the country's crop production (CORMAGDALENA, 2013).

However, hydropower generation is not a large consumptive water user (except for surface evaporation losses of the reservoir and located seepages); irrigation water to downstream regions may be insufficient due to inadequate reservoir operations. In other areas, reservoir capacity is not large enough to regulate downstream flows to fulfill irrigation and power demand. Besides, Zeng et al. (2017) found that 54% of global installed hydropower capacity (507 thousand Megawatt) competes with irrigated food production. This regional competition primarily occurs in the Central United States, northern Europe, India, Central Asia, and Oceania.

Considering the role of hydroelectricity generation in Colombia´s power supply and the high demand for water from the agricultural sector, I want to research possible water conflicts between agricultural and hydropower generation sectors in the Magdalena basin.

2.3 Methods

I employ the CAMARI model to study how water management investment is affected by climate change, socioeconomic development, spatial scale variations, and hydroelectricity generation in the Magdalena region. The constrained optimization model CAMARI maximizes water consumption’s net benefits in the Magdalena basin by determining the optimal times and locations to construct water management infrastructures. Several equations constrain the objective function. These constraints depict physical resource limits, production efficiencies, technical capacity limits of investments, financial restrictions, political regulations, intertemporal and interregional relationships.

CAMARI is a water management, capacity expansion, and optimization model, which maximizes welfare from agricultural production given socioeconomic and climate projections. On the supply side, the projections comprise spatially and time-resolved simulations of surface runoff. Future demand projections contain water use estimations for households, industries, and hydropower generation. Besides, it is included the endogenous dynamic representation of agricultural water use and commodities. CAMARI simultaneously optimizes investments in water management infrastructures and agricultural land-use decisions (Rasche et al., 2016).

My research includes two analyses: simulation of water use competition between agricultural and hydropower sectors and spatial scale comparison on modeling water management in the Magdalena basin.

Firstly, I explore the possibility of water competition between agricultural and hydropower sectors under global change for the Magdalena region. Using the CAMARI constrained optimization model, I propose a method to evaluate when and how climate and socioeconomic changes influence agricultural water use, hydroelectricity production, and investment in management infrastructures. Modeling is performed until the end of the century. Time is resolved in two ways (decade and month). Decadal time steps portray changes in water supply, water withdrawals, infrastructure investment, and welfare. The monthly time step simulates irrigation and water management operations. Within each decade, the model can also select between single or aggregated month resolution to show the intra-annual variability of water supply and demand. Water management simulations are driven by future projections of climate, population, and income. I do not represent individual years to keep the computational requirements manageable. A more detailed description of this simulation can be found in section 2.4.1.

Second, I explore changes in the total welfare and water management investment due to physical scale variations in the Magdalena river basin with the model CAMARI. Here, I present a method to compare the magnitude and pattern of spatial variation on welfare for water use and water infrastructure investment in the Magdalena river basin. I propose modeling output from four different resolutions with the CAMARI model. The model depicts 333 stream-linked regions at maximum resolution, which can be download to smaller resolutions (140, 34, 13, and 5 regions). A more detailed description of this simulation is found in section 2.4.1.

The following sections describe the input data, CAMARI model equations, data assembly, and simulation methods.

2.3.1 Input data

CAMARI uses input data from geospatial databases, global studies, national statistics, and model outputs.

Data from six different global geospatial databases are introduced as input to the CAMARI model: a digital elevation model, data on administrative regions, water bodies, land use type, simulation units, and existing dams (see Table 2-2 for details).

Water availability information for the years 2006-2099 was provided by the terrestrial hydrology group of the Max Planck Institute for Meteorology in Germany, using the global hydrological model MPI-HM (Stacke and Hagemann, 2012). The input data were climate data from the gfdl-esm2m global model run under the RCP2.6, RCP4.5, and RCP6.0 Representative Concentration Pathway (Thomson et al., 2011) in the Intersectoral Impact

Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013) with a resolution of 0.5°x0.5° (see fig. 2-3).

Additional water data include existing dam characteristics, provided by FAO's AQUASTAT database, and information on alternative water management structures such as irrigation ponds and pumping stations (Tarjuelo et al., 2010, Brikke and Bredero, 2003, Blick et al., 2009, Santos Pereira et al., 2009). Irrigation ponds are small constructed reservoirs with a permanent pool of water throughout the year. These ponds can be used for high flow mitigation and irrigation water supply (Blick et al., 2009). In my study, reservoirs and irrigation ponds are management structures for water storage and gradual release. In contrast, pumping stations extract water directly from the source and send it to the users without regulation management. In the model, irrigation ponds supply water to agricultural users, reservoirs, and pumping stations to all end-user groups.

Investment and operation costs for reservoirs, irrigation ponds, and pumping stations were also taken from the literature (CASQA, 2003, INEA, 1997). First, I selected investment prices for dams considering published data from previously built reservoirs in the Magdalena region. Second, I assume that investment costs for irrigation ponds and pumping stations are 70% lower than reservoir investment. Finally, operation costs for all infrastructures are assumed to equal 1.0% of their construction costs (see table 2-4).

Crop areas and technologies (irrigated/rainfed) (without time scale) were selected from the recursive dynamic partial equilibrium model GLOBIOM (Schneider et al., 2007) for Colombia. Current and projected agricultural water consumption was simulated with the EPIC model (Erosion Productivity Impact Calculator) (Vijay and Williams, 1995). EPIC was run for the Magdalena watershed, with the same climate input data as the hydrological model for the years 1990-2099, and provided monthly estimates of irrigation water use and evaporation for the 17 major crops grown in Colombia, namely: barley, cassava, coffee, maize, cotton, sorghum, lentils, beans, oil palm, plantain, groundnuts, potatoes, rice, soybeans, sugar cane, winter wheat, and yams.

Historical-monthly water prices and water quantities for the Magdalena basin were compiled from the Public Information Service in Colombia (Sistema Único de Información de Servicios Públicos -SUI) (see fig. 2-4a). The database comprises records for states, counties, water supply enterprises, sectors (household, commercial, official or industrial), and local water tariffs for urban and rural sites covering the period 2004-2012. Future projections of sectorial water demand are depicted in Fig. 2-4b. This figure displays water consumption projections per sector and per decade for the whole watershed, under two Shared Socioeconomic Pathways. In this study, I selected an SSP1 and SSP2 socioeconomic pathways following van Vuuren and Carter (2014) research.

County-level demographic data for the year 2005 and historical values of the gross domestic product were extracted from the National Administrative Department of Statistics, DANE (Departamento Administrativo Nacional de Estadísticas de Colombia). The Gross Domestic Product data were classified at the state-level and recorded between the years 2000 and 2011. Future projections of population and income growth includes also SSP1 and SSP2 socioeconomic pathways (see Fig. 2-5 and 2-6).Water incomes and water price elasticity per sector were also extracted from the literature (Rosegrant et al., 2002a, Dalhuisen et al., 2003, Krause, 2007). The elasticity of water demand measures consumed water tendency concerning increases in per capita income and prices (Rosegrant et al., 2002a).

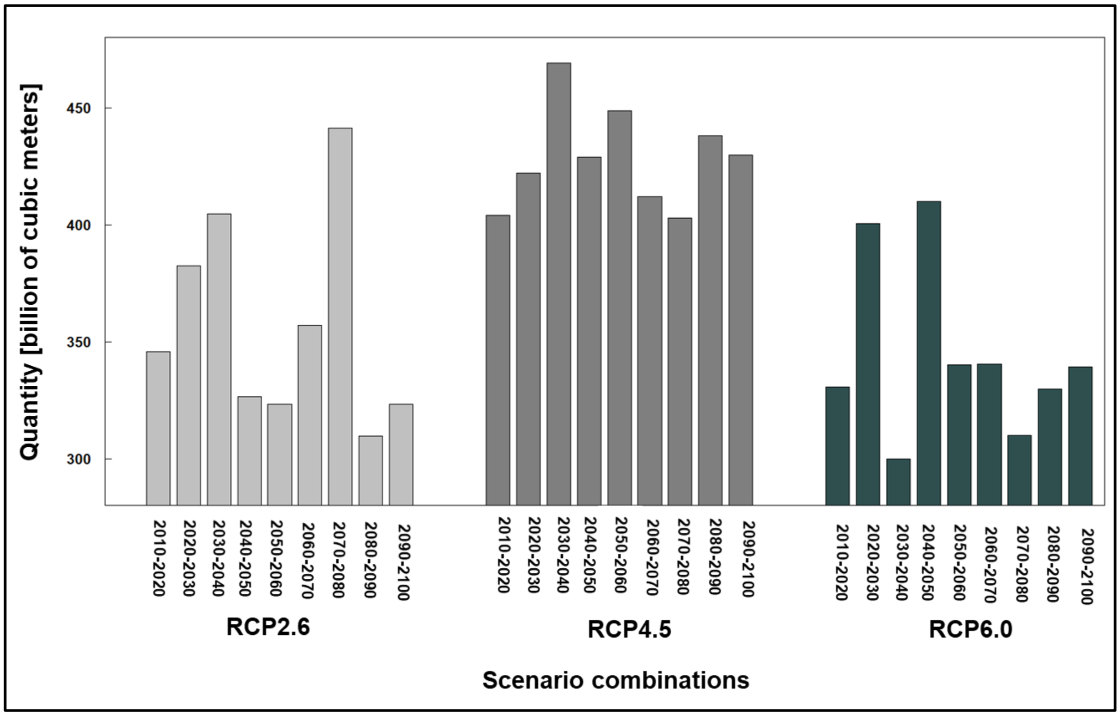
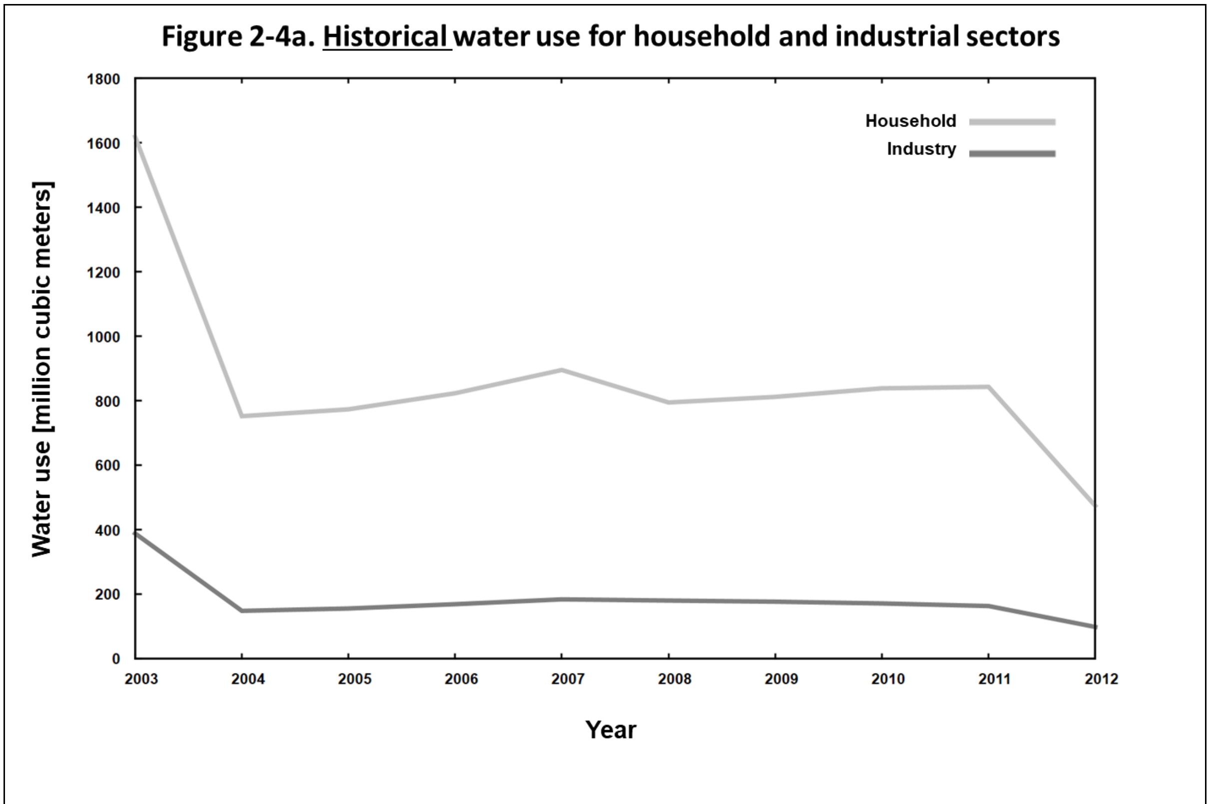


Fig. 2-3. Mean annual surface runoff in the Magdalena river basin under different climate scenarios (Representative Concentration Pathway). The variations of water availability are -RCP26- yearly average over a decade for RCP2.6, -RCP45- yearly average over a decade for RCP4.5, and –RCP60- yearly average over a decade for RCP6.0.



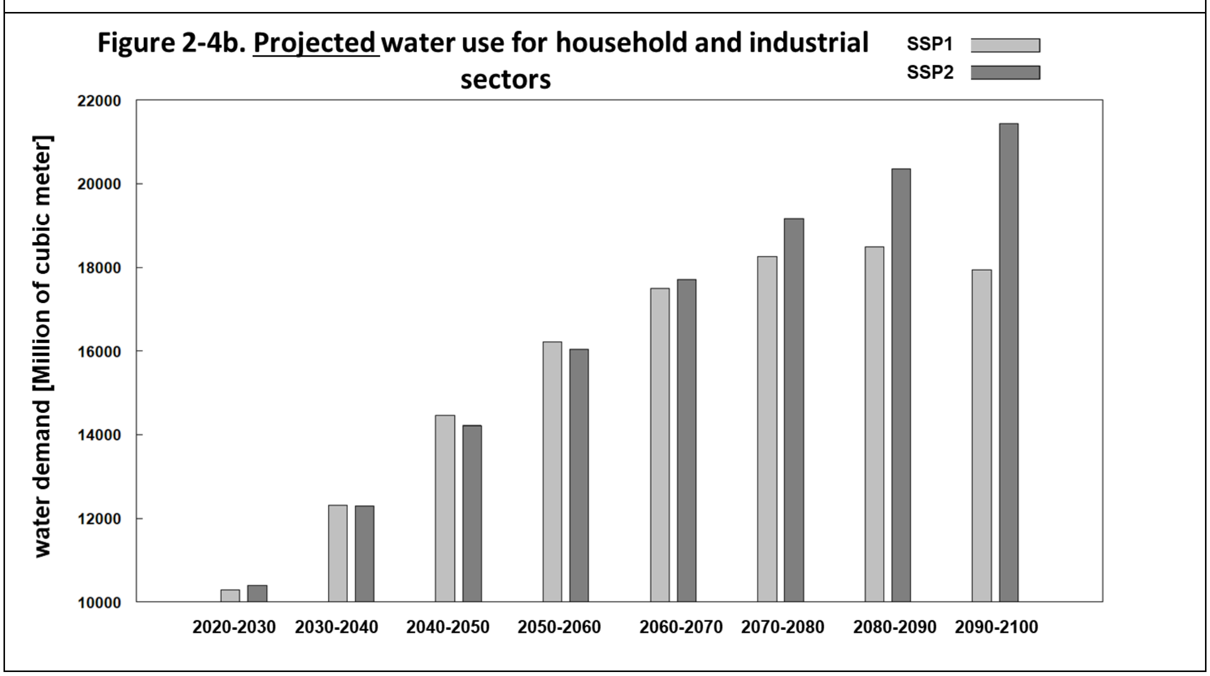


Fig. 2-4a. Historical water withdrawals for household and industrial sectors in the entire Magdalena basin. This figure displays historical water use between 2003-2012.

Fig. 2-4b. Projected water demand for household and industrial sectors in the Magdalena region under Shared Socioeconomic Pathways SSP1 and SSP2.

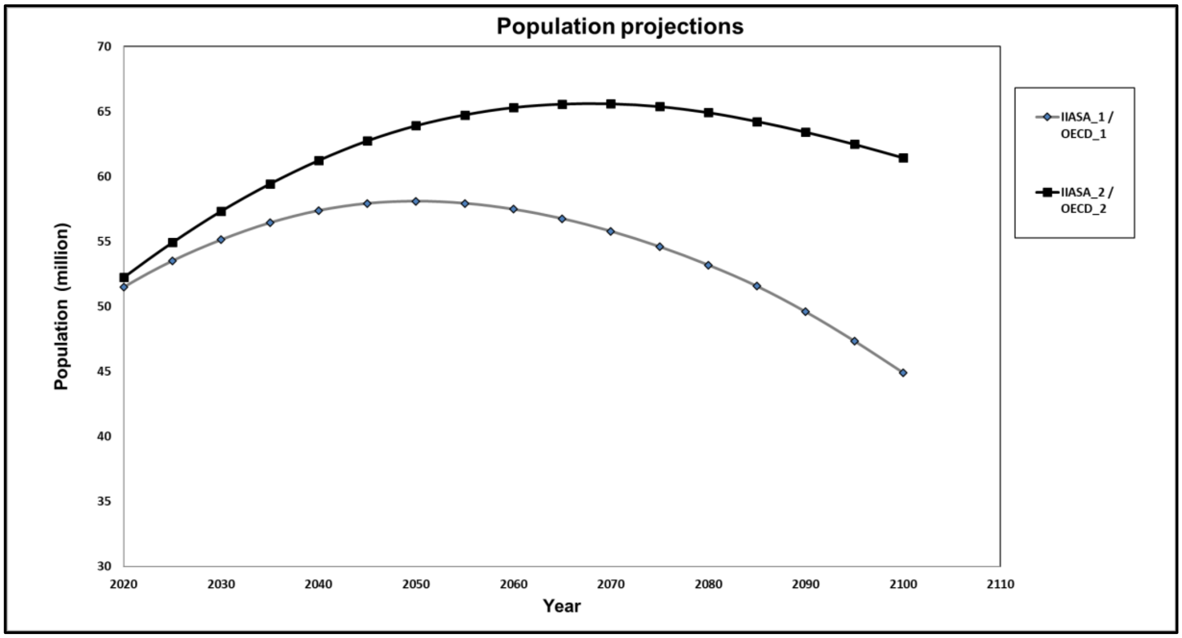


Fig. 2-5. Population Projections for Colombia. Source: SSP Database (Version 0.93). Link: https://secure.iiasa.ac.at/web-apps/ene/SspDb.

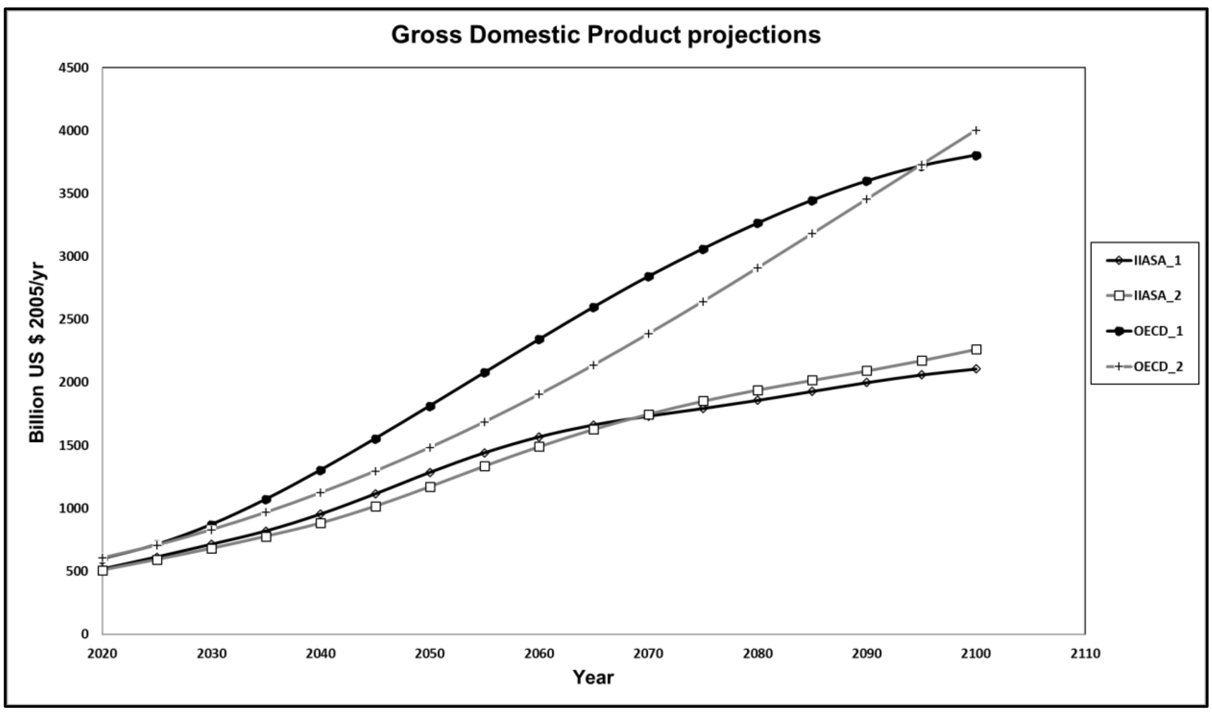


Fig. 2-6. Gross domestic product projections for Colombia. Source: SSP Database (Version 0.93). Link: https://secure.iiasa.ac.at/web-apps/ene/SspDb.

Description	Model	Source	Resolution
Agriculture			
Agricultural statistics	EPIC	Crop calendars: USDA-FAO Crop harvested area (1961-2006) Fertilizer consumption: International Fertilizer Industry Association	country subbasins country
Evapotranspiration[a] (mm/month)	CAMARI	EPIC crop model	subbasins
Irrigation volume[a] (mm/month)	CAMARI	EPIC crop model	subbasins
Yield[a] (t/ha)	CAMARI	EPIC crop model	subbasins
Climate			
Climate projections (RCP 2.6, RCP4.5 and RCP 6.0)	EPIC, MPI-HM	Global circulation model: gfdl-esm2m.	0.5° x 0.5°
Surface runoff (Million m3/month)	CAMARI, EPIC	Global hydrological model, MPI-HM. Runoff model data from 2006-2099.	0.5° x 0.5° subbasins
Geography			
Administrative division	ArcGIS, CAMARI	GADM database of Global Administrative Areas	county
Land cover	ArcGIS, EPIC	GLC2000 (Bartholomé and Belward, 2005)	1 km (subbasin)
Stream connections	CAMARI	ArcGIS stream order (Strahler method)	subbasin
Topography	ArcGIS, EPIC	Digital Elevation Model from NASA Shuttle Radar Topographic Mission	3”
Travel time between subbasins	CAMARI	Based on (NRCS, 2010)	Month
Soil data	EPIC	Digital Soil Map of the World version 3.6, ISRIC-WISE dataset (Batjes, 2012)	5’ (subbasin)
Water management structures (Capacity in Million m3 and location)	CAMARI	Dams database from AQUASTAT – FAO.	subbasin
Water systems	ArcGIS	Major river basin of the world (GRDC, 2007)	405 river basins
Socio-economic data			
Capital/operation costs reservoir (US$/m3)	CAMARI	(CASQA, 2003, INEA, 1997)	country
GDP (constant and current prices in bil. COP)	CAMARI	DANE, Departamento Administrativo Nacional de Estadísticas	
GDP and population projections (bil. US$)	CAMARI	O'Neill et al. (2012)	country
Number of water users(rural/urban)	CAMARI	SUI (2012)	county
Population (census 2005)	CAMARI	DANE, Departamento Administrativo Nacional de Estadísticas	county
Water consumption[b] 2004-2012 (Million m3/month)	CAMARI	SUI (2012)	
Water fee[c](COP/m3)	CAMARI	Congreso de Colombia (1994)	subbasins
Water prices 2004-2012 (COP/m3)	CAMARI	SUI (2012)	subbasins
Water income and water price elasticity		Data from worldwide studies (Rosegrant and Cai, 2002b, Dalhuisen et al., 2003, Krause, 2007).	country

Table 2-2. Input data. The column "Model" refers to the model or program where the input data was employed. CAMARI: Water management optimization model; EPIC: Process-based crop model; MIP-HM: Global hydrological model; COP: Colombian peso. Source (Rasche et al., 2016)

[a]For every crop and technology.

[b]For categories residential, industrial, commercial, governmental, provisory, special, non-residential, and total.

[c]For categories basic, complementary, luxury, and non-residential.

2.3.1.1 Exogenous parameters and drivers for agricultural/energy production simulations

An exogenous electricity demand was imposed to simulate power demand in the Magdalena watershed. Firstly, I calculate a historical power demand as a yearly average of total electricity consumption between 2010 and 2017 for Colombia (IEA, 2019). Afterward, I calculate the exogenous power demand as the result of the multiplication of historical electricity demand by 70% (national population who live in the study region), by 70% (Colombian electricity generation from dams), and by 60% (amount of hydropower reservoirs in the Magdalena basin).

Besides, I employ a coefficient to convert exogenous electricity demand ($P_{d,t}$) to hydropower water demand ($Q_{d,t}$). The conversion coefficient considers the calculation of a turbine power ($P_{d,t}$), for an average head (H), and a turbine efficiency (η) of 80%, over decades d and months t. I also choose an average elevation between dams and turbine stations (H) of 60 m from the Colombian dam system (see Eq. 2-0). This approximation is a suitable simplification at our level of accuracy.

$$P_{d,t} = \gamma \cdot Q_{d,t} \cdot H \cdot \eta \qquad (2\text{-}0)$$

Estimations of future energy consumption are directly correlated with population growth, income patterns, and climate scenarios. Socio-economic drivers are represented by different Shared Socioeconomic Pathways (SSPs) and climate scenarios for several greenhouse gas concentration targets (Bauer et al., 2017). Bauer et al. (2017) employed data from IEA (2012), IPCC reports, and energy IIASA database (International Institute for Applied System Analysis) to represent energy use under several SSPs and RCPs scenario combinations.

First, I select energy projections for Latin America in the IIASA database for final energy consumption by end-users (households, industry, and agriculture). After that, I compute an index that projects energy demand (decadal step) for Latin America under specific socio-economic and climate scenarios ensembles (RCP2.6-SSP1, RCP 4.5- SSP1, and RCP6.0- SSP2). Finally, I include the power index in the CAMARI simulation to project future energy demand between 2020 and 2100 for Colombia (see Fig. 2-7).

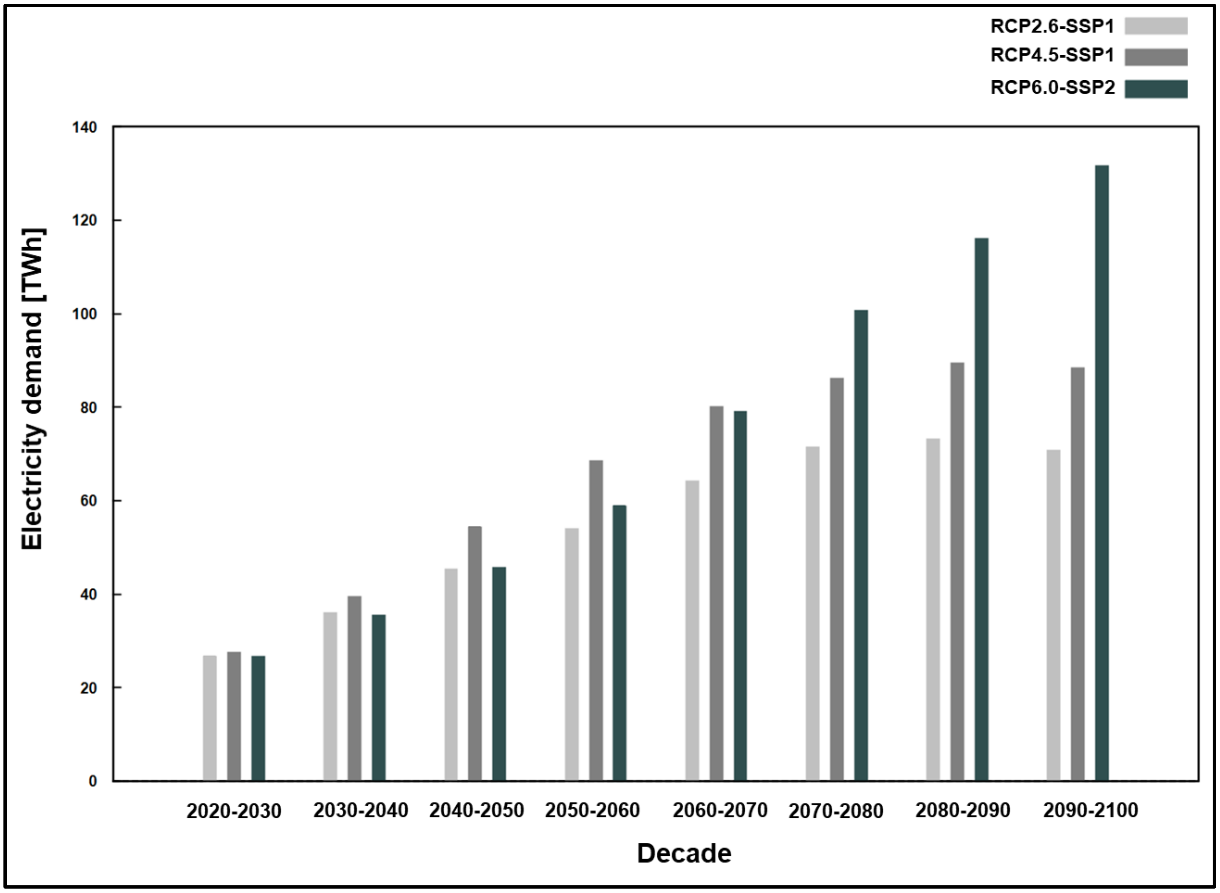


Fig. 2-7. Projected electricity demand for Colombia for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. Historical data from IEA (2012) IPCC reports and energy IIASA database (International Institute for Applied System Analysis).

The following section describes the mathematical structure of the model. All contained variables and indices are listed in Table 2-3.

2.3.2 Description of the model

The CAMARI model maximizes water consumption welfare from several sectors in the study area restricted to river management, water equilibrium, and power generation equations.
In the model, I differentiate water demand from household, industrial, agricultural, and hydroelectricity sectors. Residential and industrial water uses consist of historical and projected data. The historical data (2004 to 2012) comes from the public information service in Colombia (monthly data at the county level and detailed sub-sector information). For modeling projections (2020-2100), I estimate future water consumption following socioeconomic development for two Shared Socioeconomic Pathways (SSP1, SSP2) in Colombia (see section 2.4.1.2). The estimation of water employed for hydropower production is explained in section 2.4.1.1. The agricultural water demand is represented in an endogenous and dynamic simulation with the CAMARI model (see section 2.3.2.1).
"The important novel feature of the CAMARI model is the endogenous and dynamic representation of (i) agricultural commodity demand, (ii) spatially explicit irrigation decisions at monthly time steps, (iii) decadal investments in water management infrastructures, and (iv) results from the comparison between different spatial scales. CAMARI attempts to bridge the gap between water management planning tools and agricultural sector models, under different physical resolutions." (Rasche et al., 2016)

2.3.2.1 Objective function

The objective function of CAMARI (Eq. 2-1) maximizes the net benefits *W* of water consumption in the Magdalena river region by aggregating total benefits B_d and subtracting total costs C_d over decades *d* in consideration of a discount factor *f*:

Maximize $W = \sum_{d} \left(f_d \left(B_d^{total} - C_d^{total} \right) \right)$ (2-1)

Total benefits are the sum of agricultural and household/industry sector benefits (Eq. 2-2). Agricultural sector benefits B_d^{agr} are estimated by integrating the area underneath the demand function for agricultural commodity demand; household/industry benefits $B_d^{non-agr}$ by calculating the product of water price *p* and demand *V*. Both benefits are summed over all sub-basins/sub-regions *r*, aggregated months *t*, and, in case of the non-agricultural water demand, $B_d^{non-agr}$ over sectors *s*. The demand function for agricultural commodity demand is a parameterized function defined through a price-quantity pair and an own price elasticity for Colombia from the literature (Rosegrant et al., 2002a). I process data for eight years of water consumption and prices into monthly averages for household and industry sectors (see table 2-2). The government sets the price of the water. At a given price, I observe the willingness to pay to consume a certain quantity of water.

$$\begin{aligned}
&B_d^{total} = B_d^{agr} + B_d^{non-agr} \\
&B_d^{agr} = \int \rho_{d,y}^{agr}\left(\sum_r D_{r,d,y}^{agr}\right) d\left(\sum_r D_{r,d,y}^{agr}\right) \\
&B_d^{non-agr} = \sum_{r,t,s}\left(p_{r,d,t,s} \cdot V_{r,d,t,s}^{non-agr}\right)
\end{aligned} \tag{2-2}$$

Total costs are calculated as the sum of crop production costs, water supply, water management operations, water management investment, and hydropower generation (Eq. 2-3). Crop production costs are calculated as the product of crop production price *g* multiplied by crop production quantity *A*. Water supply costs are calculated as the sum of endogenous and constant per unit-costs, where endogenous costs of water supply are calculated as the area underneath the supply function, and constant per unit- costs as the product of water supply cost *c* and the amount of water supply *S.* Water management operation costs are calculated as the product of the cost of water management operation *o* per structure and the amount of water operated *O*. The costs of water infrastructures investment are calculated as the product of per-unit capacity *m*, the maximum capacity of the infrastructures *k* and the number of infrastructures installed *M*. Finally, the cost of hydropower generation is the product of the energy price *x,* and the amount of energy generate in a region *E*. The sub-index *m* represents the storage/level (m_1), inflow (m_2), and release (m_3) of water from a specific infrastructure (see fig. 2-8).

$$\begin{aligned}
C_d^{total} = &\sum_{r,c,j}\left(g_{r,d,c,j} \cdot A_{r,d,c,j}\right) + \sum_t\left(\int \rho_{d,t}^{agr}\left(\sum_r S_{r,d,t}^{agr}\right) d\left(\sum_r S_{r,d,t}^{agr}\right)\right) \\
&+ \sum_{r,t,s}\left(c_{r,d,t,s} \cdot S_{r,d,t,s}^{non-agr}\right) + \sum_{r,t,i,m}\left(o_{r,d,t,i,m} \cdot O_{r,d,t,i,m}\right) \\
&+ \sum_{r,i}\left(m_{r,d,i} \cdot k_{r,d,i} \cdot M_{r,d,i}\right) + \sum_{r,t}\left(x_{r,d,t} \cdot E_{r,d,t}\right)
\end{aligned} \tag{2-3}$$

Several physical restrictions constrain the objective function.

2.3.2.2 Water demand constraints

This research differentiates four kinds of water demand: agricultural, household, industrial, and hydropower generation. Eight years database of water consumption (Database of Superintendencia de Servicios Publicos de Colombia) for the household and industry sector was included in the model. This database has county-monthly level information about water supply and price rates for individual water enterprises between 2004 and 2012. For future periods, the households and industrial water demand were estimated by multiplying population and income growth rates under different shared socioeconomic pathways (SSP). The SSP scenario data were taken from van Vuuren and Carter (2014).

Water demand for household and industrial sectors has to be equal to or bigger than a reference water quantity:

$$V_{r,d,t,s}^{non-agr} \geq \sum_{g} q_{r,d,t,s,g} \qquad \text{for all } r,d,t,s \qquad (2\text{-}4)$$

For a specific region, water supply has to be bigger or equal to demand from all sectors:

$$V_{r,d,t}^{non\text{-}agr} + V_{r,d,t}^{agr} - S_{r,d,t} \leq 0 \qquad \text{for all } r,d,t \qquad (2\text{-}5)$$

Water demand from the agricultural sector is equal to crop area by irrigation water requirements:

$$V_{r,d,t}^{agr} = \sum_{c,j} i_{r,d,t,c,j} \cdot A_{r,d,c,j} \qquad \text{for all } r,d,t \qquad (2\text{-}6)$$

2.3.2.3 Water supply constraints

There is a relation between water management operations for different structures and local water supply for each sector. My research includes reservoirs, irrigation ponds, and pumping stations as water management infrastructures. The sub-index *i* represents the infrastructures: reservoir i_1, irrigation pond i_2, and pumping stations i_3. In CAMARI, irrigation ponds deliver water to agricultural users, and reservoir and pumping stations to all users. The sub-index s represents the studied economic sectors: agricultural s_1, household, and industry s_2. The first constraint (2-7 equation) restricted the water supply to all sectors (or nonagricultural sector) less than or equal to the amount of water operated by the infrastructures:

$$\sum_{s} S_{r,d,t,s} \leq \sum_{i} O_{r,d,t,i\neq i_3,m_3} + O_{r,d,t,i_3,m_1} \qquad \text{for all } r,d,t \qquad (2\text{-}7)$$

Non-agricultural water supply does not exceed the amount of water released from reservoirs and pumping stations:

$$\sum_{s=s_2} S_{r,d,t,s} \leq \sum_{i=i_1} O_{r,d,t,i,m_3} + O_{r,d,t,i_3,m_1} \qquad \text{for all } r,d,t \qquad (2\text{-}8)$$

2.3.2.4 Infrastructures constraints

The amount of water operated through specific infrastructures cannot exceed the established infrastructure maximum capacity from current and previous investments, where *d* represents the degradation rate of infrastructure capacity. It was selected a decadal degradation rate of 5%. The maximum capacity of the infrastructures includes past and future investment during the modeled time horizon:

$$O_{r,d,t,i,m=m_1} + O_{r,d,t,i\neq i_3,m=m_3} \leq \sum_{\tilde{d},a} \left(d_{r,i,a} \cdot P_{r,\tilde{d},i,a} \right) + e_{r,d,i} \qquad \text{for all } r,d,i \qquad (2\text{-}9)$$

The model represents the age of infrastructure investment over the modeled time. Transition equations for all periods ensure that the number of maintained infrastructures for all advanced age cohorts (index a>1) does not exceed the number of the corresponding (a-1) active infrastructures installed in the period before (d-1):

$$P_{r,d,i,a} \leq \left[M_{r,d,i} \right]_{a=1} + \left[P_{r,d-1,i,a-1} \right]_{d>1 \wedge a>1} \qquad \text{for all } r,d,i,a \qquad (2\text{-}10)$$

Infrastructure investment is restricted to a maximum number of infrastructures possible to be constructed:

$$M_{r,d,i} \leq r_{r,d,i} \qquad \text{for all } r,d,i \qquad (2\text{-}11)$$

For a storage structure, the quantity of water in a particular period has to be equal to the amount of water in the previous period minus the volume released plus the volume filled. For each decade, I depict the equilibrium situation, i.e., each month/aggregated months is connected to the previous month/aggregated months, and January is linked to December:

$$O_{r,d,t,i\neq i_3,m_1} + O_{r,d,t,i\neq i_3,m_3} = \sum_{t-1,t} O_{r,d,t-1,i\neq i_3,m_1} + O_{r,d,t,i\neq i_3,m_2} \quad \text{for all } r,d,t \qquad (2\text{-}12)$$

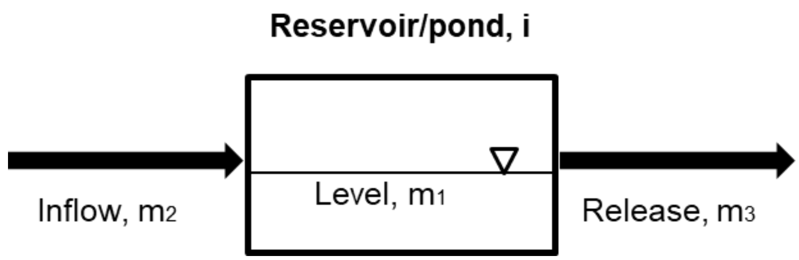


Fig. 2-8: Management operation of reservoir/wet pond

The maximum number of reservoir investment in a decade is restricted to a maximum number of historical investment of reservoirs in the Magdalena region:

$$\sum_{r} M_{r,d,i_1} \leq h_{d,i_1} \quad \text{for all } d \qquad (2\text{-}13)$$

The number of reservoirs investment is equal to the reservoir integer variable:

$$M_{r,d,i_1} = J_{r,d,i_1} \quad \text{for all } r,d \qquad (2\text{-}14)$$

2.3.2.5 Land use equations

The land use component of CAMARI is based on a short structure of the US agricultural sector model (Schneider et al., 2007). It contains 15 crops, two irrigation, and two fertilization techniques. Land areas are classified into different homogeneous response units according to altitude, soil, and topography features. Inside a global land-use project, data and modeling tools generate existing and potential cropland for each homogeneous response unit (Schneider, 2011). I simulate with EPIC: crop yields and water requirements for all combinations of crop selection, management regime, homogenous response unit, and climate projections. The CAMARI model contains three equation blocks related to land use.

The total cropland use summed over all crop management systems cannot surpass regional land endowments:

$$\sum_{c,j} A_{r,d,c,j} \leq b_r \quad \text{for all } r,d \qquad (2\text{-}15)$$

The total area allocated to individual crops is forced to a linear combination of historically observed allocations in Colombia between 1980 and 2013:

$$\sum_j A_{r,d,c,j} - \sum_h \left(a_{h,c} \cdot X_{r,h,d} \right) \leq 0$$ for all *r,d,c* (2-16)

A crop supply-demand balance restriction connects production activities to consumption levels:

$$\sum_r D^{agr}_{r,d,y} - \sum_{r,c,j} \left(y_{r,d,c,j} \cdot A_{r,d,c,j} \right) \leq n_{d,y}$$ for all *d,y* (2-17)

2.3.2.6 Water flow constraints

A group of equations describes the flow movement between the regions and connects them to different water management infrastructures.

I assume 60% as the fraction of water supply allow to be used for consumption:

$$R_{r,d,t} \leq z \cdot s_{r,d,t}$$ for all *r,d,t* (2-18)

The water balance between water operated out of the system and outflow must be less than inflow, plus return flow and water supply from runoff. The return flow is 90% of industrial water demand and around 50% of the household water demand:

$$\sum_{i \neq i_3} O_{r,d,t,i,m=m_2} + O_{r,d,t,i_3,m_1} + F_{r,d,t} \leq N_{r,d,t} + w_{s_2} \cdot \sum_{s \neq s_1} V_{r,d,t,s} + R_{r,d,t}$$

for all *r,d,t* (2-19)

Inflow has to be equal to the outflow between regions:

$$N_{r,d,t} = \sum_{\tilde{r},\Delta t} \left(u_{\tilde{r},r,\Delta t} \cdot F_{\tilde{r},d,t} \right)$$ for all *r,d,t* (2-20)

2.3.2.7 Energy generation constraints

Finally, a set of equations describes regional-hydropower production in the Magdalena region.

Water demand for hydropower production has to be greater than a maximum value of water consumption, based on the exogenous electricity demand:

$$\sum_{r} E_{r,d,t} > \sum_{r} v_{r,d,t}$$ for all d,t (2-21)

Inside a region, water released from a reservoir has to be equal to or bigger than water needed for hydropower generation:

$$E_{r,d,t} \leq O_{r,d,t,i_1,m_3}$$ for all r,d,t (2-22)

In a region, water needed for hydropower generation has to be less than the capacity of past and future (investment) reservoirs:

$$E_{r,d,t} \leq \sum_{d,a} d_{r,i_1,a} \cdot P_{r,d,i_1,a} + e_{r,d,i_1}$$ for all r,d (2-23)

Item	Description	Unit
Variables		
A	crop area	million ha/year
B	benefits	million USD
C	costs	million USD
D	commodity demand	million ton/year
E	water use for hydropower	MCM/month
F	outflow	MCM/month
J	investments in reservoir	-
M	investments in infrastructure	-
N	inflow	MCM/month
O	regional management operations	MCM
P	active infrastructures over time	-
R	the net run-off for water management	MCM/month
S	regional water supply	MCM/month
T	inflow water management operation	MCM/month
V	regional water demand	MCM/month
W	welfare	million USD
X	crop mix	-
Parameters		
a	historical crop area	million Ha/year
b	land endowments	million Ha
c	costs of water supply	USD/m3
d	declining capacity of infrastructures	MCM/unit
e	existing capacity	MCM
f	discount factor	-
g	crop production price	USD/Ha
h	maximum number of reservoirs investment	-
i	irrigation water requirements	m3/Ha/month
k	maximum capacity	MCM
m	cost of infrastructure investment	million USD/unit
n	net import	million ton/Year
o	cost of management operations	USD/m3
p	water price	USD/m3
q	water quantity	MCM/month
r	maximum number of the infrastructure installed (investment)	-
s	sub-regional water supply	MCM/month
u	travel time	month
v	energy consumption per sector	MCM/month
w	return flow coefficient per sector (industry, household)	-
x	price of water for hydropower generation	USD /m3
y	crop yields	ton /Ha/year
z	return flow coefficient	-
ε	elasticity	-
Functions		
ρ	inverse commodity demand function	-
Indices		
a	infrastructure age	decade
c	crop	-
d	decade	decade
g	sub-classifications of different household and industry demand segments	-
h	historical year of crop information	-
i	infrastructure type (1:reservoir, 2:irrigation pond, 3:pumping station)	-
j	agricultural management(2 irrigation x 2 fertilization regimes)	-
m	management operations, 1: storage/level, 2: inflow, 3: release	MCM/month
p	last decade considered	decade
r	sub-basin/sub-region	km^2
t	month	month
s	sector (1:agriculture, 2: household and industry)	-
y	agricultural commodity	-

Table 2-3. Variables and indices used in the CAMARI model.

The CAMARI model was implemented in GAMS (General Algebraic Modeling System) (GAMS, 2013b) and used the Linear Programming, Mix Integer Programing, Non-Mix Integer Programming, CPLEX, and CPLEXD solvers. CPLEX is a high-performance solver for linear, mixed-integer, and quadratic programming problems (GAMS, 2013a). I controlled the mathematical structure of the model with GAMSCHK. GAMSCHK is a system to identify generic misspecifications in GAMS models (McCarl, 1998).

2.3.3 Delineation of sub-basins and regions

The Magdalena River Basin was divided into 333 sub-basins, using threshold drainage of 500 km^2 with the ArcHydro tool from ArcGIS 10. Each sub-basin has a parameter description, including sets for states, SimuIDs, area, and land use. I also calculate the total area of the Magdalena watershed (266’948.9 km2), the total number of states (23), and counties (703). Besides, sub-basins were aggregated into regions considering water movement between them using the stream order tool from ArcGIS. Stream order is a method for identifying and classifying types of streams based on their numbers of tributaries. I employ the Strahler method to assign the number of tributaries, hereby stream order increases when a stream of the same order intersect. Finally, I obtain five spatial scales: R5, R13, R34, R140, and R333; for 5, 13, 34, 140, and 333 regions.

2.3.4 Preparation of input data and aggregation into the model

I employ diverse sources such as geospatial databases, national statistics, and model outputs for an integrated water management assessment in the Magdalena river basin.
All input data were processed in steps: first, I allocate the input data to the 333 subbasins; second, I map the input data to parameters with the inclusion one/two-time set (decade, month, or accumulative months), and finally, I aggregate the final parameters into different spatial scales (140, 34, 13 and 5 regions). The parameters, which are defined by sets, input exogenous constant to the model. Sets are the basic building blocks of a GAMS model, corresponding precisely to the indices in the models' algebraic representations.

2.3.4.1 Parameter calculations and assumptions

After converting input data into parameters (see appendix 1), I compute their initial projections and introduce new ones to run the CAMARI base model. I calculate parameter projections throughout the next assumptions:

Name	Value	Source
Initial projection to run base model. Water consumption for household and industry users, projections for 2020-2100	average of historical water consumption. Water consumption[b] 2004-2012 (Million m^3/month)	SUI (2012)
Calculation of household water price	constant fee (for the household sector) + basic fee + complementary fee + luxury fee	SUI (2012)
Calculation of Industry water price	constant fee (for industrial sector) + non-residential fee	SUI (2012)
Initial projection to run base model. The initial water price projection for household and industrial sectors, projections for 2020-2100	a weighted average of historical water prices. Water prices 2004-2012 (COP/m3)	SUI (2012)
Agricultural water price, projections for 2020-2100	0.1 dollars/m^3	DANE (2019)
Water supply price, projections for 2020-2100	household and industrial sector: 3 dollars/m^3, Agricultural sector : 6 COP/m^3	National reports.
Dams life span	100 Year	(Schmutz and Moog, 2018)
Dams standard capacity	large: 1416 MCM, medium: 290 MCM and small: 10 MCM	Analysis of Dams database from AQUASTAT – FAO.
Agricultural pond, standard capacity	12000 m3	Literature review
Pumping station, standard capacity	34000 m3 per month	Literature review
Dams investment cost	Large: 7 USD/m3, medium: 5 USD/m3, and small: 3 USD/m3	Historical investments of dams in Colombia
Dams operation cost	1.0 % of investment costs	Literature review
The maximum number of dams in a subbasin	It is the result of the balance between regional water demand and surface runoff supply	CAMARI
Projections of water supply per sector, for 2020-2100	water target for household, industrial and agricultural sectors	IDEAM (2014)
Time of concentration (the time needed for water to flow from the most remote point in a sub-basin to the sub-basin outlet)	$Tc = 0.9 \cdot A^{0.6}$ (2-24) where *A* is the drainage square area in square miles and *Tc* is the concentration-time	
Water routes	find alternative travel routes for upstream sub-basins in a region; search for the links to possible downstream sub-basins within a downstream region, and define which upstream sub-basin will link to downstream sub-basin	CAMARI
Water flow between sub-basins	Combination of concentration-time computations and travel routes	CAMARI
Return flow	90% of industrial water use 50% of household water use	Literature review
Environmental flow	40% of surface runoff	MAVDT (2004)

Table 2-4. Parameter calculation and assumption for the CAMARI model simulations

2.4 Simulations descriptions

2.4.1 Conflicts between water demand from agriculture and hydropower generation in the Magdalena river basin

I employ the constrained optimization model CAMARI to simulate demand conflicts between two primary water users for different climate and development scenarios. With CAMARI simulations, I explore relations between agriculture water demand, hydropower generation, economic scarcity of water, infrastructure investment, and general welfare for selected scenario combinations. I employ 80 years of time horizon and a decadal/monthly time scale. Population and income future projections are also included in this analysis.

2.4.1.2 Scenarios for hydropower-agriculture analysis

To explore the water competition between the Magdalena region's hydropower and agricultural sectors, I run four scenario simulations with the CAMARI model.
First, I select one spatial scale in my study. Based on the study area's digital elevation model, the Magdalena region was divided into 333 sub-basins, using threshold drainage of 500 km2 in the ArcHydro tool of ArcGIS 10. Then, the sub-basins were aggregated into 140 regions according to the water flow between sub-basins, using the stream order tool of ArcGIS (see section 2.3.3).
Second, I include three climate variations (-RCP- Representative Concentration Pathways) for water availability; based on simulations of surface runoff under RCP2.6, RCP4.5, and RCP6.0 conducted with the MPI-HM Global Hydrological Model (details see Table 2-2 and Fig. 2-3).
Third, I integrate population and income growth variation, which combine RCP radiative forcing levels (climate signals) and socioeconomic development (includes adaptation, mitigation, and climate impacts) (van Vuuren et al., 2012). These scenarios include SSPs storylines, gross domestic product (GDP), and population projections for Colombia (see Fig. 2-5 and 2-6 for details). SSPs (Shared Socioeconomic Pathways) are descriptions of plausible alternative evolutions of society at a global level to eventually be combined with suppositions about climate change and policy responses (O'Neill et al., 2014). SSP1 assumes a sustainable world, and SSP2 a continuation of current trends of economic development. The first GDP projection is based on simulations with the OECD modeling framework, in which it is assumed that income levels of different countries will converge to most developed economies (Barro and Xala-i-Martin, 2004). This methodology is applied to developed countries with a 2050 time horizon. Later, the ENV-Growth model

was included in the OECD modeling framework and used until 2100 for developing countries. The second GDP projection is the IIASA GDP model projection, based on the income per capita and educational characteristics of the population (Crespo, 2012).
Finally, I propose a baseline scenario. Data input for the base scenario corresponds to water supply projections, population, and income growth for the decade of 2000-2010. This last scenario gives us a baseline for modeling.
Overall, I simulate four scenario combinations: RCP2.6-SSP1, RCP4.5-SSP1, RCP6.0-SSP2, and 2010 baseline. To define the number of arrangements, I couple scenario parameters following van Vuuren and Carter (2014) suggestion for mapping SRES scenarios, representative concentration scenarios (RCPs), and shared socioeconomic pathways (SSPs) (see Table 2-5).

Parameter	Variations	Symbol	Characteristics
Spatial resolution (1)	140 regions	R140	Spatial scales
Water supply (Surface runoff) (4)	RCP2.6 RCP4.5 RCP6.0 Water supply for the decade 2000-2010	RCP26 RCP45 RCP6 2010	Monthly data, 2006 -2099
Population growth and Income growth (5)	IIASA_GDP_SSP1_v9_130219 IIASA_GDP_SSP2_v9_130219 OECD_Env_Growth_SSP1_v9_130325 OECD_Env_Growth_SSP2_v9_130325 Population and income for the decade 2000-2010	IIASA1(SSP1) IIASA2(SSP2) OECD1(SSP1) OECD2(SSP2) 2010	Quinquennial data projection, 2000 - 2100
Discount rate (1)	5%	DR5	

Table 2-5: Definition of scenarios for hydropower modeling

2.4.1.3 Model assembly and limitations for agricultural/power production simulations

CAMARI model includes the exogenous electricity demand and the hydropower equations to study water use conflicts between hydropower generation and agricultural water demand. I run the base model, the calibrations, and the simulations for selected scenarios for 140 region-scale.
The model CAMARI has three directories: source data, base model, and scenarios simulation. In the source data directory, I convert all input data (see table 2-2) to parameters defined by sets. In the base model directory, I load and assign the parameters to regions depending on the spatial scale; and I run the model CAMARI with all equations and restrictions. In the scenarios simulation directory, I run the model under different

scenario combinations (spatial scale -140 regions-, future water availability and population-income projections), save the model-scenarios output; and compile the intermediate results (see Fig. 2-9). Finally, I generate a final report. To avoid calibration problems, the model was solved at maximum resolution of 140 regions.

A description of the CAMARI operation chart and its directories (see Fig. 2-9) is presented below:

Input data,

- I include, organize, and convert input data to parameters in the source data directory for the highest resolution, 333 regions. This directory contains around 50 processing data files (see input data, table 2-2).

Base model,

- I download the data parameters into the base model directory.
- I aggregate the parameters from the highest scale (333 regions) to a smaller scale (140 regions) with a spatial scale map.
- I translate the yearly parameter to the average decade parameter and the monthly sets to aggregated-month sets (2, 3, 4, or 6 months) by time maps.
- Water management data were assigned to infrastructures throughout parameters. Water infrastructure parameters include investment values, operation costs, infrastructure capacities, existing capacity, and the maximum number of infrastructures. The final parameters contain the region and decade dimension set.
- I solve the CAMARI model with the objective function restricted by water demand, water supply, water infrastructures, land use, and water use equations; for one spatial resolution (140 regions). I employ the software General Algebraic Modeling System version 28.2 with the Mixed Integer Program and the CPLEXD solver.
- I calibrate the basic model, imposing constraints on the crop and water supply variables. First, the crop variable was forced to the projected crop area, and the model reference was resolved. Second, the agricultural water supply variable was forced to a minimum water demand, and the base model was resolve. Finally, CAMARI basic model was resolved without forcing constraints.
- I also calibrate CAMARI basic model, but just for the agricultural sector. First, I change the base model by restricting the current crop area and the modeled irrigation area with equations. After, I run the base model with and without the forced equations for the agricultural sector. Finally, the CAMARI model reproduces calibrated data for agricultural variables.

Scenario simulation,

- I design a scenario map, including climate simulation, discount rate, and population-income projections following van Vuuren and Carter (2014). The authors recommend the socioeconomic/climate combination of SSP1-RCP2.6, SSP1-RCP4.5, and SSP2-RCP6.0.

- I save initial values for water availability, water consumption per sector, and water supply (cost, quantity per sector, price elasticity, and maximum amount per sector).
- I include water availability parameters for each climate projection (RCP2.5, RCP4.5, and RCP6.0).
- I loop the scenario combination map, including the data for climate scenarios, loading crop data under each RCP's projections, calculating income and population projections, computing projections for supply and demand data.
- Inside the scenario-loop, I solve the basic model with Mixed Integer Program (MIP) and CPLEXD solver for each scenario combination climate/development/spatial scale). I save the partial results.
- I display the final report and figures for different scale/climate/development scenario combinations.

Even though hydropower simulations provide valuable insights into the competition of water demand between the hydropower generation and agriculture sector, this simulation analysis has its limitations. The analysis restrictions are: (a) absence of local/regional historical data for electricity demand, (b) exclusion of historical information of streamflow, turbine capacities, water discharges, and energy operating capacities, (d) absence of historical data for turbine discharge and storage level for reservoirs, (e) simplifications to simulate energy demand, (f) exclusion of spillway discharge, surface evaporation and seepage losses for reservoirs, and (g) electricity generation only by hydropower dams. Detailed technical information and historical measurements for each hydropower plant are not freely available for Colombia.

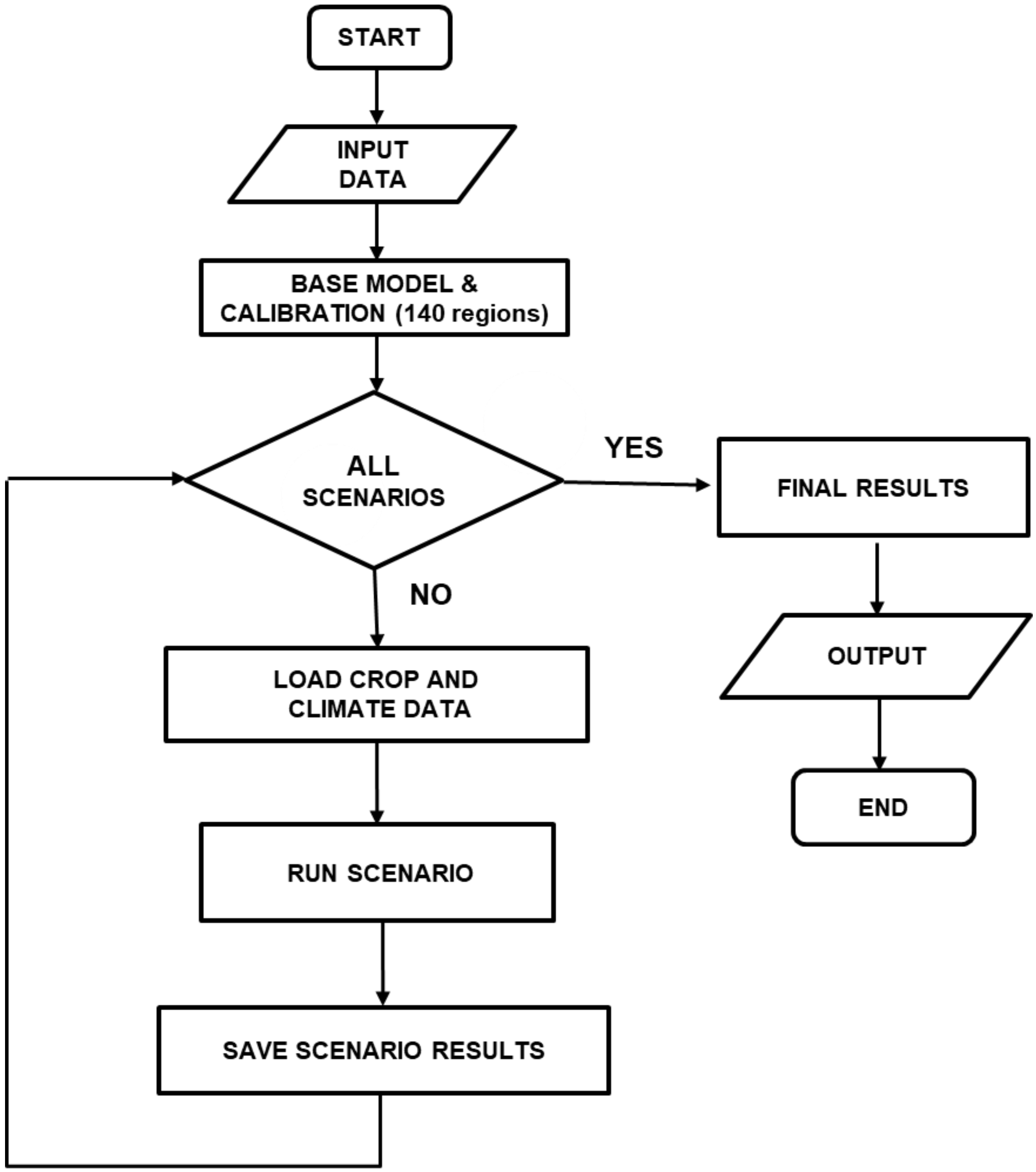


Fig. 2-9. CAMARI model. Operation Flow Chart for hydropower analysis.

2.4.2 Spatial scale effects on modeling water management in the Magdalena river basin

This section describes a methodology to compare the impact of spatial scale variation on water management decisions and water consumption welfare in the Magdalena river basin. Spatially resolved studies are helpful to approach the effects of global warming and regional water management. Because of the environmental problems' complexity, it is necessary to understand how processes operate at various spatial scales and how

strong the links are between resolutions (Perveen and James, 2010). In river basin management, the choice of a spatial scale depends on the levels at which decisions are made, stream network location, and model output accuracy (Jakeman and Letcher, 2003). Although in water management studies, not a single scale is appropriate to fulfill all environmental and economic objectives, so that the ability to aggregate and disaggregate data to various resolutions is desirable (Perveen and James, 2010).
In my study, I want to explore the relationship between different spatial scales and water resources management under different climate and development scenarios in the Magdalena basin in Colombia. This simulation aims to compare the magnitude and pattern of spatial variation on water consumption welfare and water infrastructure investment in the Magdalena river basin. To reach that aim, I present a methodology for comparing different physical scales for water management alternatives and water uses welfare. I simulate four spatial scenarios (5, 13, 34, and 140 regions) with the constrained optimization model CAMARI. This research compares how spatial scale variation would affect total benefits and water management in a tropical river basin, considering an 80-year time horizon.

2.4.2.1 Scenarios for spatial scale analysis

I propose a methodology to compare the influence of physical scale variation on water management investment and water use welfare in the Magdalena basin for different climate and development scenarios. Firstly, I delineate four spatial resolutions (140, 34, 13, and 5 regions) with the stream order tool of ArcGIS (see section 2.3.3). Second, I introduce three climate scenarios of water availability in the CAMARI model (RCP2.6, RCP4.5, and RCP6.0) (details, see Table 2-2). Third, I include socioeconomic development projections (SSPs). Finally, I define scenario-combinations and couple scenario parameters following van Vuuren and Carter (2014) suggestion for mapping SRES scenarios, representative concentration scenarios (RCPs), and shared socioeconomic pathways (SSPs) (see Table 2-6). I simulate 16 scenario combinations with the CAMARI model.

Parameter	Variations	Symbol	Characteristics
Spatial resolution (4)	140 regions 34 regions 13 regions 5 regions	R140 R34 R13 R5	Spatial scales
Water supply (Surface runoff) (4)	RCP2.6 RCP4.5 RCP6.0 Water supply for the decade 2000-2010	RCP26 RCP45 RCP6 2010	Monthly data, 2006 -2099
Population growth and Income growth (5)	IIASA_GDP_SSP1_v9_130219 IIASA_GDP_SSP2_v9_130219 OECD_Env_Growth_SSP1_v9_130325 OECD_Env_Growth_SSP2_v9_130325 Population and income for the decade 2000-2010	IIASA1 IIASA2 OECD1 OECD2 2010	Quinquennial data projection, 2000 - 2100
Discount rate (1)	5%	DR5	

Table 2-6. Definition of scenarios for spatial scale modeling

2.4.2.2 Model assembly and run structure for spatial scale analysis

The model CAMARI has the same assembly and runs structure for the spatial scale analysis as the hydropower simulations, with some differences. First, the parameters were aggregated from the highest scale (333 regions) to lower scales (140, 34, 13, and 5 regions). Second, the base model was run and calibrated for several resolutions (140, 34, 13, and 5 regions) before the scenarios simulations. Finally, the final report includes information and figures for the selected scales.

3. RESULTS

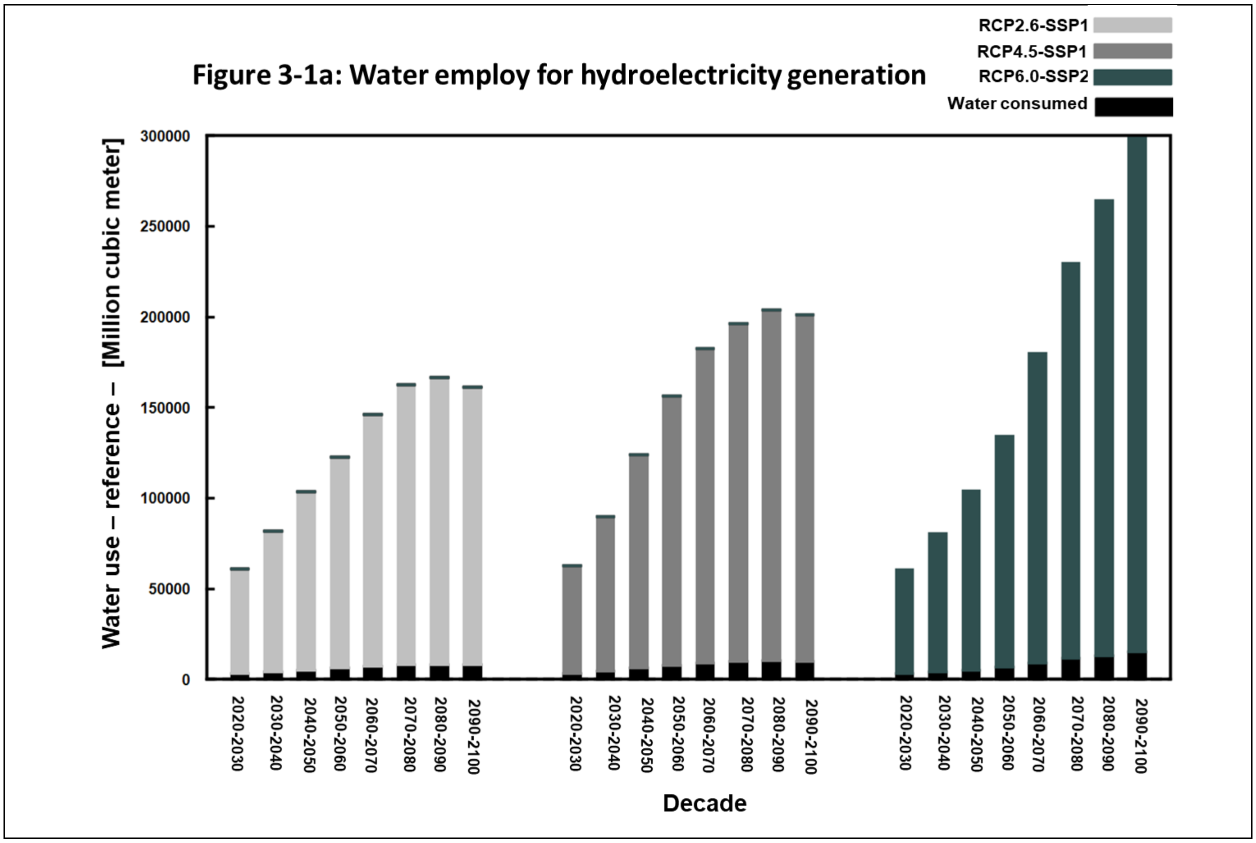
3.1. Conflicts between water demand from agriculture and hydropower generation in the Magdalena river basin

This section answers the first research question: Will water competition emerge between hydropower generation and irrigation in the Magdalena watershed under various future climate and socioeconomic scenarios?
I simulate the hydropower generation and agricultural sector water demand with the CAMARI model. These results depict possible water use behaviors and conflicts for the most relevant economic sectors in the studied region, at decadal and monthly time scales. First, I research water use conflicts between agricultural and hydropower sectors by analyzing decadal/monthly changes in irrigation demand, water availability, and reservoir storage in the Magdalena basin. Second, I study the monthly/decadal electricity generation pattern and water use for power production and decadal investment tendencies on water infrastructure. Finally, I investigate the economic scarcity of water and the net benefit of water withdrawals in the Magdalena region for the studied scenario combinations.

3.1.1 Comparison between water withdrawals per sector

I research the water use behavior for household, industrial, hydropower, and agricultural sectors for selected developments and water runoff projections, with the model CAMARI (see details in Table 2-5 chapter 2). On the one hand, water withdrawals for household, industrial, and hydropower sectors are exogenous input to the model. On the other hand, agricultural water use is an endogenous and dynamic feature of the CAMARI model. Fig.3-1a and Fig. 3-1b are input data plots that display the decadal variation of water use per sector (hydropower, household, and industry) during the century, aggregated over all regions and months. In contrast, Fig. 3-1c depicts modeling results of agricultural water consumption.
The water-withdrawals figures highlight that the most significant water user is the hydropower sector (Fig. 3-1a) following by household, agricultural and industrial users. The hydropower sector employs water resources to generate electricity. However, this economic sector seems to be the largest water consumer in the studied region; circa 95% of the water withdrawal return to the river (see Fig. 3-1a, water consumed). Hydroelectricity generation is an almost non-consumptive user of water.
Household users consume more water than industrial users in the Magdalena region (Fig 3-1b). Previous water use for the household sector is higher than the industrial sector (see chapter 2, fig. 2-4a). An explanation for the small industrial withdrawal is the

underdeveloped industrial growth in Colombia. This slow industrial development is probably the result of 1990 -1994 Colombian politics of abandonment of the industrialization and import substitution development model (Martínez and Castillo, 2016).



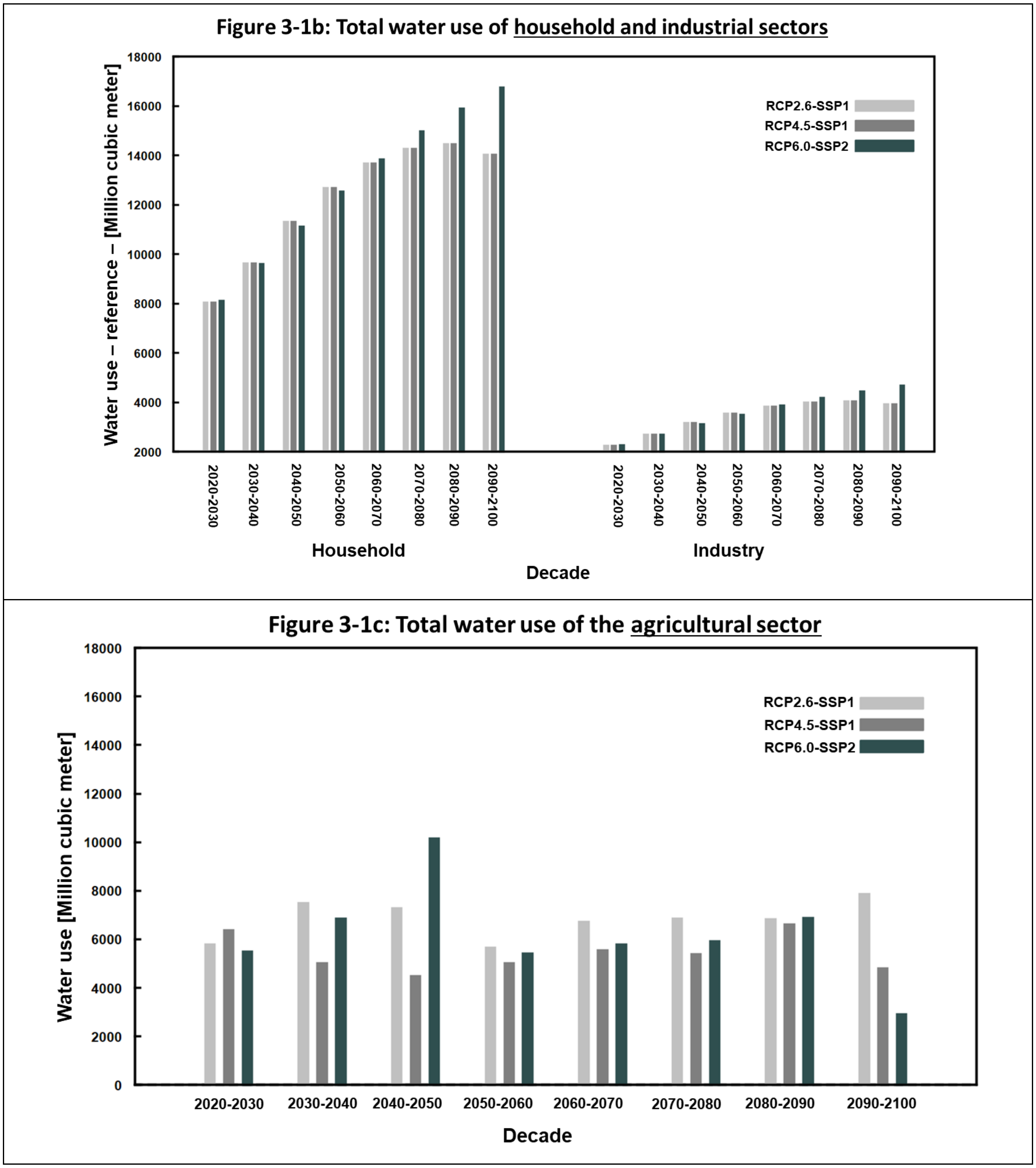


Fig. 3-1. Decadal water use for hydropower (3-1a), household and industrial (3-1b), and agricultural (3-1c) sectors in the Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. Fig. 3-1a, 3-1b, and 3-1c display decadal water withdrawals adding over all months and 140 regions for the Magdalena region.

In the agricultural sector (Fig. 3-1c), water use will be slightly higher for small water availability (RCP2.6) in almost all decades. Agricultural water withdrawals, which are determined dynamically with the land-use optimization algorithms (Rasche et al., 2016), vary over the 80-year research time without following a pattern in each scenario. For the RCP2.6 climate scenario, agricultural water use varies 40% between 6 and 8.2 billion cubic meters over 80 decades. Agricultural water withdrawals change circa 45% from 4.5 to 6.5 billion cubic meters under the RCP4.5 scenario. For the RCP6.0 climate scenario, agricultural water demand displays large fluctuations between 3 and 11 billion cubic meters. To understand agricultural water demand's dynamic behavior, I explore the decadal variation of crop area in the Magdalena river basin (Fig.3-2). Crop areas' values are around 5 Million Ha per decade, with circa 6% deviations inside each scenario combination (see Fig.3-2). Although the cultivated areas display decadal deviations from 2% to 12% between the studied scenarios, they do not follow a clear tendency. Crop extension variations do not have a direct impact on agricultural water demand. One possible explanation is that agricultural water uses change, mainly due to climate projections. As a result, more irrigation is required under the RCP2.6 and RCP6.0 climate scenario, whose water availability is minor (see Fig. 3-1c).

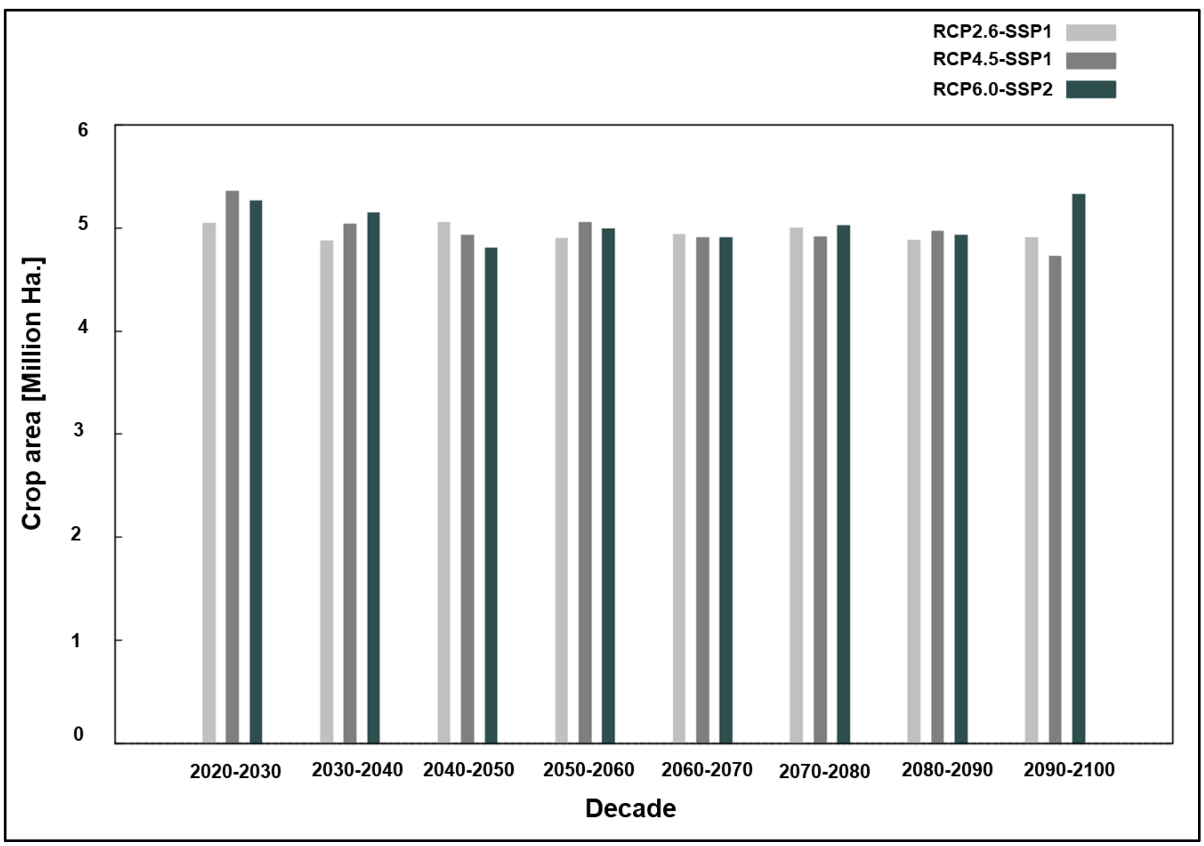


Fig. 3-2. Projections of decadal crop area in the entire Magdalena basin for three-climate change (RCP2.6, RCP4.5, and RCP6.0), two shared socioeconomic pathways (SSP1 and SSP2) scenarios, and 140 regions.

3.1.2 Electricity generation

CAMARI model includes historical electricity consumption as exogenous data (see section 2.3.1.1, chapter 2). First, I compute power demand as a yearly average of total electricity consumption (2010-2017) for Colombia. Second, monthly electricity demand is an approximation of the yearly demand. Third, future water availability (RCP2.6, RCP4.5, and RCP6.0) and development projections (SSP1, SSP2) vary this exogenous electricity demand (see section 2.3.1.1, chapter 2, fig 2-7). Finally, the total decadal and monthly average hydropower generation reflects socio-economic and climate scenarios ensembles (RCP2.6-SSP1, RCP 4.5- SSP1, and RCP6.0- SSP2) for Latin America. (see Fig. 3-3 and Fig. 3-4).
To show the monthly behavior of power generation (see Fig. 3-4), January, June, and December were selected in the Magdalena river basin due to the low variability of monthly energy demand assumptions (see section 2.3.1.1, chapter 2). The minimum scenario is the future projection of 8-year average electricity consumption.

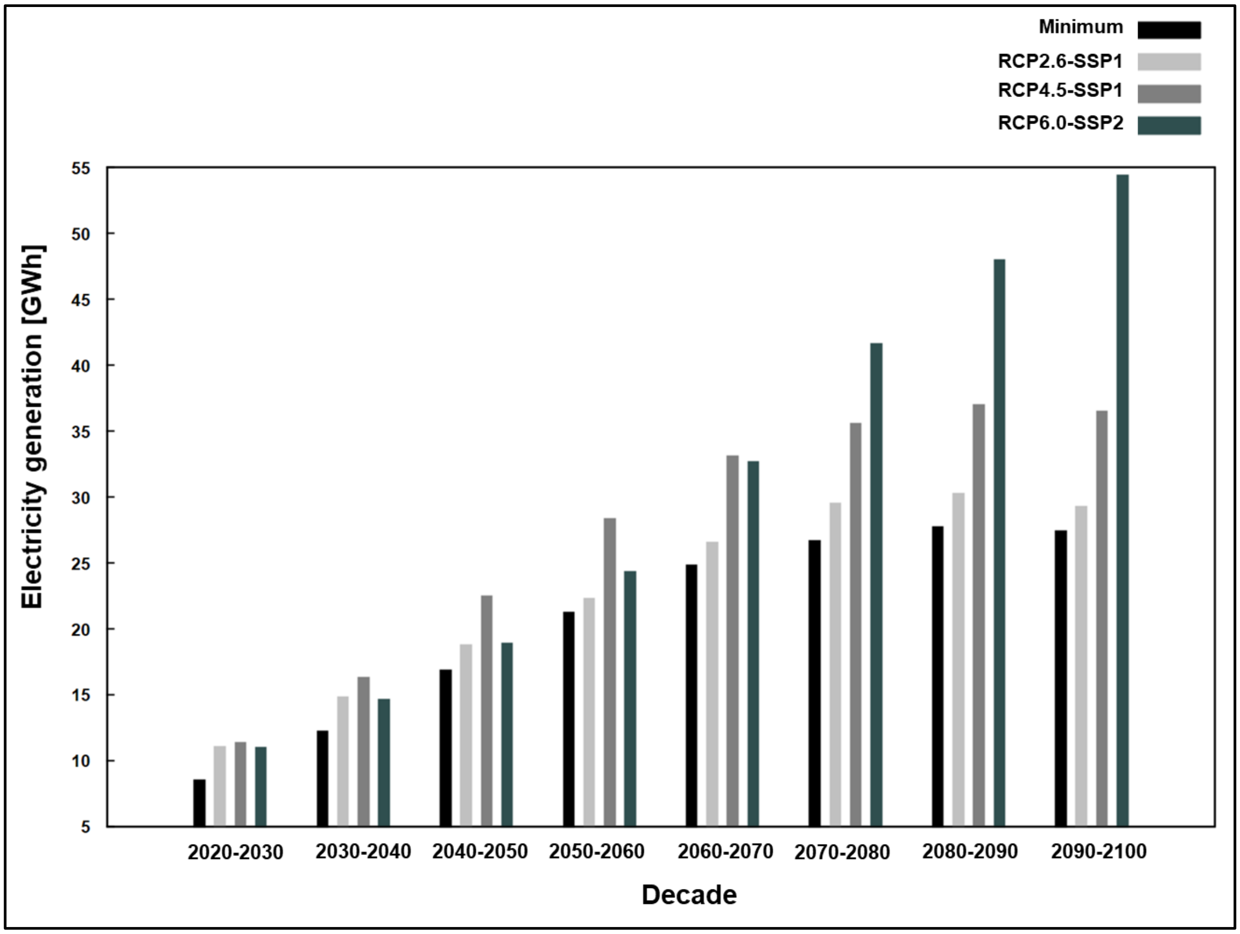


Fig. 3-3. Decadal electricity generation in the entire Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0), two shared socioeconomic pathways (SSP1 and SSP2), and the baseline-minimum scenarios. Decadal electricity generation is the result of adding monthly power generation per studied decade.

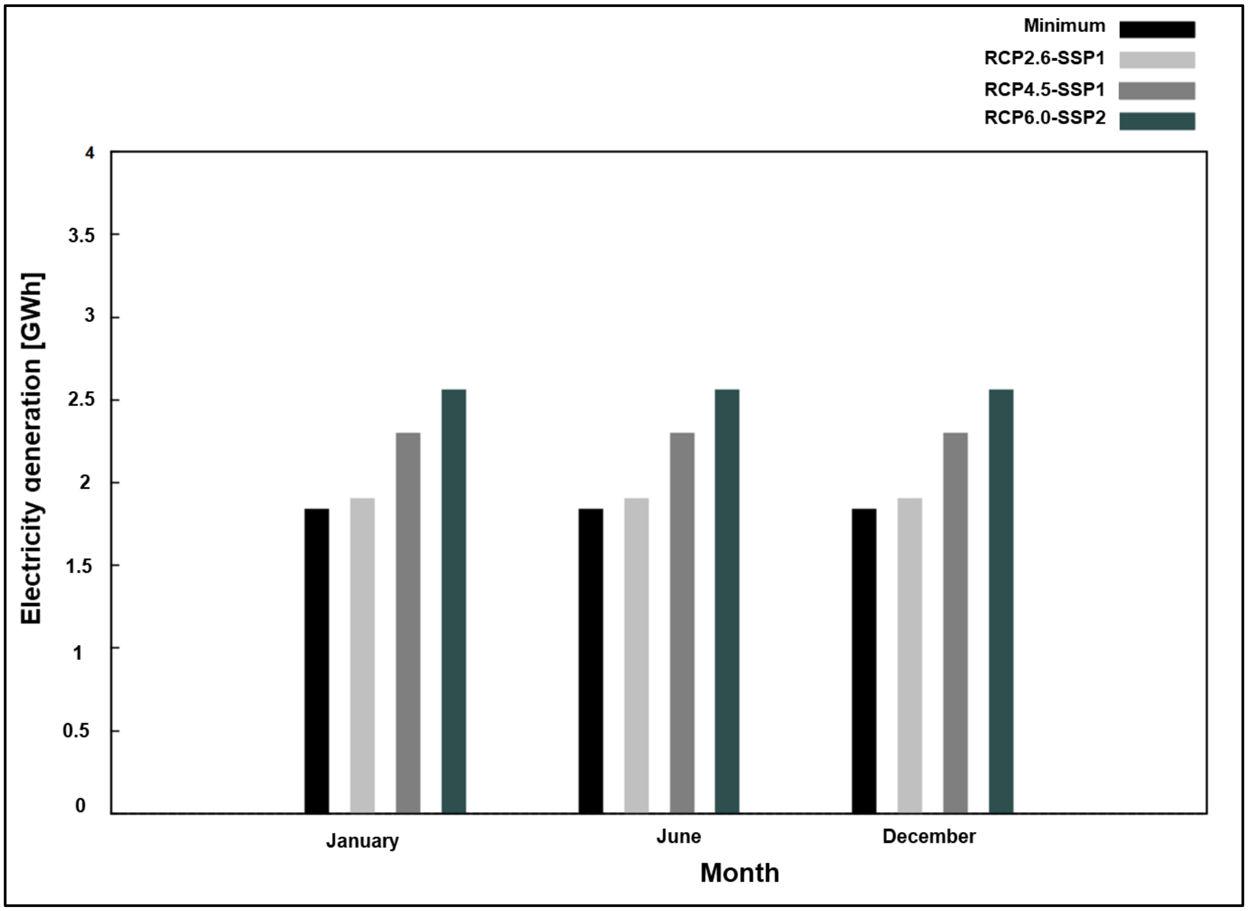


Fig. 3-4. Monthly average of electricity generation in the entire Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0), two shared socioeconomic pathways (SSP1 and SSP2), and one baseline-minimum scenarios. Monthly average of electricity generation for January, June, and December, period (2020-2100).

3.1.3 Capacity projections of water infrastructures

With the declining capacity of existing infrastructures in the Magdalena watershed, investment in new water infrastructures would gradually increase until the end of the century for all climate and development scenario combinations (see Fig. 3-5). The existing infrastructures are the constructed dams in the Magdalena river basin. The dams are geographically located inside the 140-simulated regions. Fig. 3-5 shows an interesting dynamic: when more water is available (RCP4.5), fewer infrastructures would be installed for the next 80 years. Hence, water infrastructure projections are more significant (see Fig.3-5) under minor water availability scenarios - RCP2.6 and RCP6.0 - (see fig 2-3 in chapter 2). Besides, projected water infrastructures are independent of development projections (SSP1 or SSP2).

For the next eight decades, CAMARI simulations suggest installing optimal infrastructure capacity between 15 and 35 billion cubic meters for the RCP2.6 scenario, among 10 and

17 billion cubic meters for the RCP4.5, and between 27 and 36 billion cubic meters for the RCP6.0 (see Fig. 3-5). New infrastructure investments will supply water to all user sectors in the Magdalena river basin (section 3.1.1).

The relevant feature of the CAMARI model is the forward-looking behavior with welfare-maximization modeling to compare optimal infrastructure investments. The model CAMARI chooses to build a type of water management infrastructure to supply water to various sectors. The simulations included three water infrastructures: reservoir or dams, pumping stations, and agricultural ponds. One of the CAMARI model's relevant features is the optimal decision to build or not a specific number of infrastructures in each of the 140 simulated regions for future projections of water availability, population, and income scenario combinations.

To explore the optimal infrastructure selected for the model, I present a resume of optimal capacity installed and their share during the study time. Table. 3-1 lists the type of optimal infrastructure projected between 2020 and 2100. This Table compares the decadal average of infrastructure capacity to supply water to different users for different climate-development combinations. In the model, irrigation ponds only supply water to agricultural users, reservoirs or dams, and pumping stations to all user groups (hydropower, agricultural, household, and industrial sectors). Optimal infrastructure analysis shows that dams are the most relevant projected infrastructure in the Magdalena river basin (see Table. 3-1). The CAMARI model builds more than 99% infrastructure capacity of dams per decade. CAMARI model selects DAMS or reservoirs as optimal infrastructures to supply water to the end-users and produce energy. Future reservoirs are the optimal solution to supply water to the household, industrial, and agricultural sectors and generate hydroelectricity. One logical explanation of this large number of the projected reservoirs mainly responds to the hydroelectricity generation and future climate in the Magdalena basin (see Fig. 2-3, chapter 2). For example, under climate scenarios of small water availability (RCP2.6 and RCP6.0), the optimal infrastructure's projected capacity is larger than RCP4.5, in which less water is offered.

Because of the impact of climate and socioeconomic variations in the Magdalena region, the model chooses to build almost 99% dams capacity as optimal infrastructures. Hence, dams' high capacity can compensate for water shortages between agricultural and hydroelectric sectors.

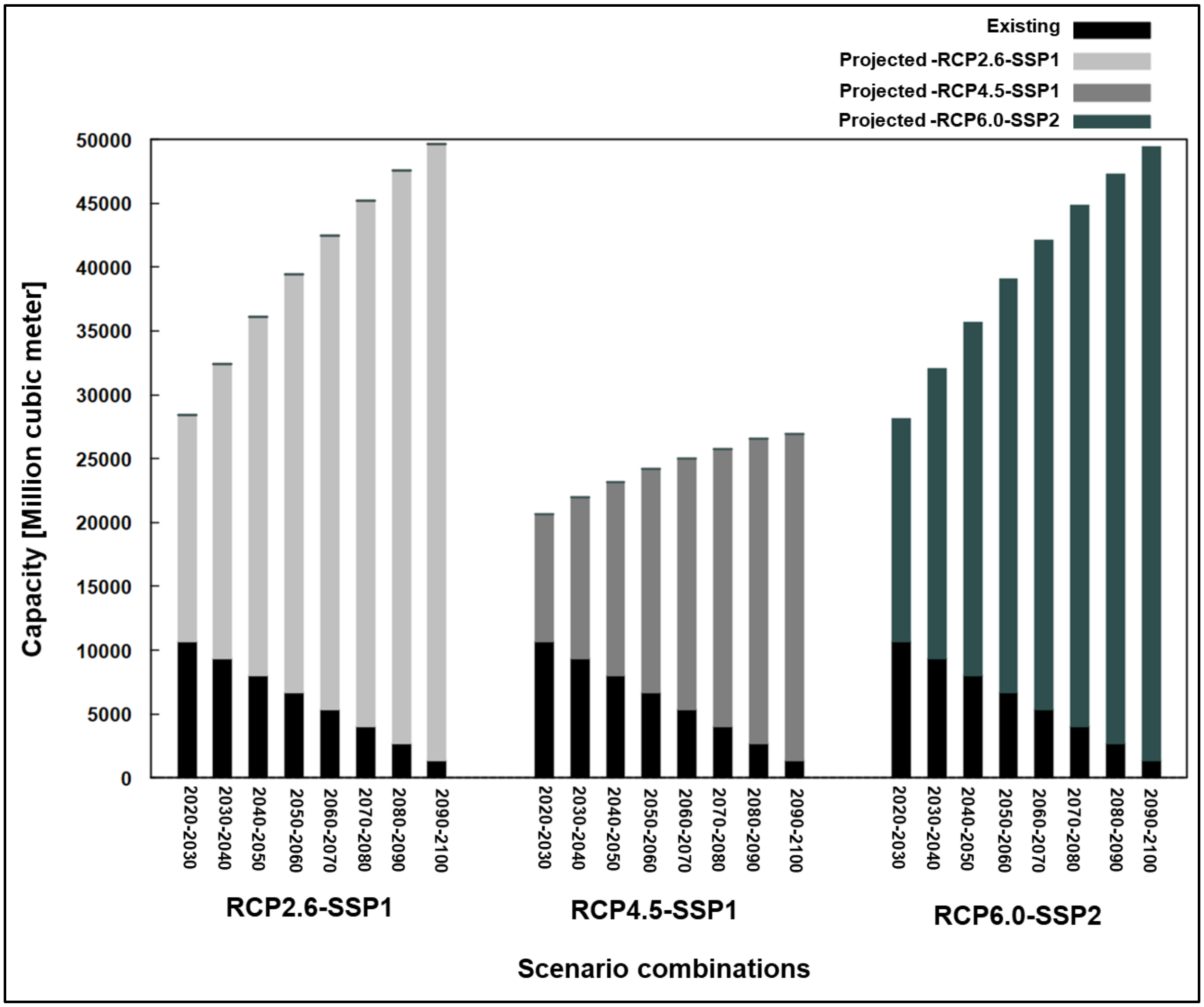


Fig.3-5. The decadal capacity of water management infrastructure in the entire Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. The decadal capacity of existing and projected water structures.

	RCP2.6-SSP1 (MCM)		RCP4.5-SSP1 (MCM)		RCP6.0-SSP2 (MCM)	
Infrastructures	**Total**	**Share**	**Total**	**Share**	**Total**	**Share**
Irrigation ponds	38	0.15 %	7	0.05 %	14	0.06 %
Pumping stations	11	0.05 %	43	0.15%	9	0.04 %
Dams	25,207	99.8 %	34,120	99.8 %	33,477	99.9 %

Table.3-1. The average decadal capacity of projected infrastructures in the Magdalena region over the research period 2020–2100 for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios.

3.1.4 Water competition between agricultural and hydropower sector

To research possible water shortages among hydropower and agricultural sectors in the Magdalena watershed, I compare agricultural water use and water storage volume in reservoirs for different climate and development scenarios (see details in Table 2-5 chapter 2). With CAMARI model simulations, I research the monthly and decadal behavior of irrigation uses and water impoundment in reservoirs.

CAMARI model simulates reservoir stream outflows to meet regional water demand and to produce power under several restrictions. Inside a region, the water released from a reservoir must be equal to or larger than the water employed for hydropower generation. Besides, minimum water storage in reservoirs is an indicator of decreased water availability and minor power generation.

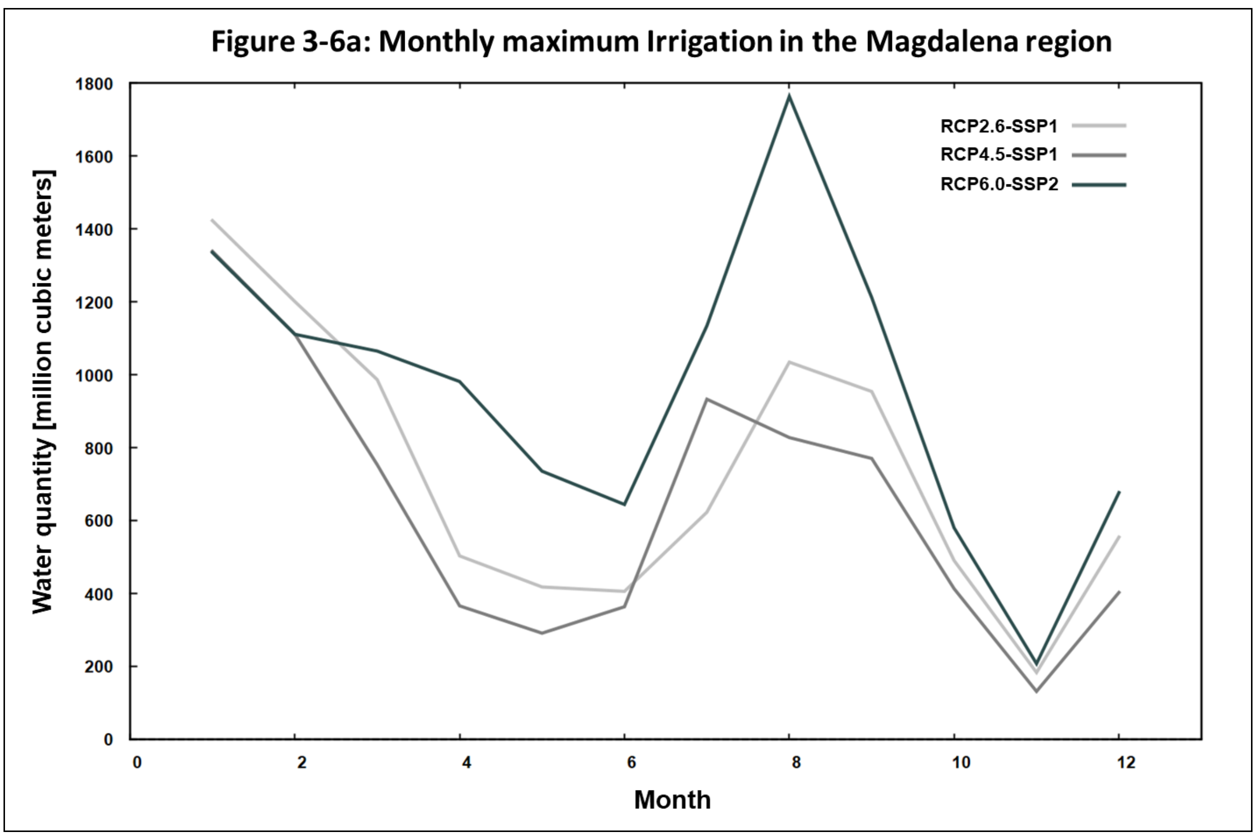
Although hydropower generation is not a large consumptive sector (except for surface evaporation losses of the reservoirs and located seepages), Zeng et al. (2017) found that 54% of global installed hydropower capacity (507 thousand Megawatt) competes with irrigation. Considering that almost 70% of Colombian power generation comes from the hydroelectric sector and the variability of water use of the agricultural sector (primary water consumer), it helps investigate possible water competition between these water consumers.

As I mentioned before, agricultural water use is an endogenous result of the CAMARI simulations. I called agricultural water use such as “irrigation water,” which is the amount of water required to irrigate crops.

Inconsistency in the timing of hydroelectricity and irrigation is one of the causes of water competing relationship between those sectors (Zeng et al., 2017). With this hydropower analysis, I research when these water conflicts appear in the Magdalena region under various climate and socioeconomic scenarios. According to the future projections of water infrastructures (see section 3.1.3), the optimal solution is the capacity installation of 99% of dam-reservoirs. Hence, I compare reservoir operations for the selected scenario combinations. Furthermore, when water is released for irrigation purposes may reduce reservoir storage, thereby reducing hydroelectricity generation, especially during dry periods, when demand for irrigation and energy might be largest (Tilmant et al., 2009).

First, I compare monthly maximum values of the decadal water withdrawal for irrigation purposes, the monthly minimum water available for consumption per decade, and the volume storage fluctuations in the Magdalena basin's reservoirs with CAMARI hydroelectricity simulations. On the one hand, Fig. 3-6 displays projected maximum values of irrigation (3-6a) and minimum water availability (3-6b,3-6c) per month during the next 80 years for three climate scenarios. On the other hand, Fig 3-7 depicts a monthly diagram containing the maximum, average, and minimum data of future storage levels of reservoirs during the research period (2020-2100). Under almost all climate-development scenarios, the first three months of the year have the maximum irrigation values, the minor water availability, and the minimum impoundment of dams, with some exceptions. Between July and September, maximum irrigation values and minimum reservoir levels would probably occur, but it does not overlap with the Magdalena region's lowest water availability.

January, February, and March are the critical months when possible water shortages will probably emerge. During these months, maximum water withdrawals for irrigation are higher in the RCP2.6 scenario, followed by RCP6.0 and RCP4.5 (Fig.3-6a). For the first quarter of a year, I can also observe that the minimum reservoir storages are lower for the climate scenario RCP6.0, following by RCP2.6 and by RCP4.5 (Fig.3-7). Climate scenarios are possibly the main drivers of the monthly behavior of irrigation and minimum storage in reservoirs. To identify possible decades when water shortages could appear, I research the decadal behavior of irrigation and reservoir storage levels during the first three months of a year.



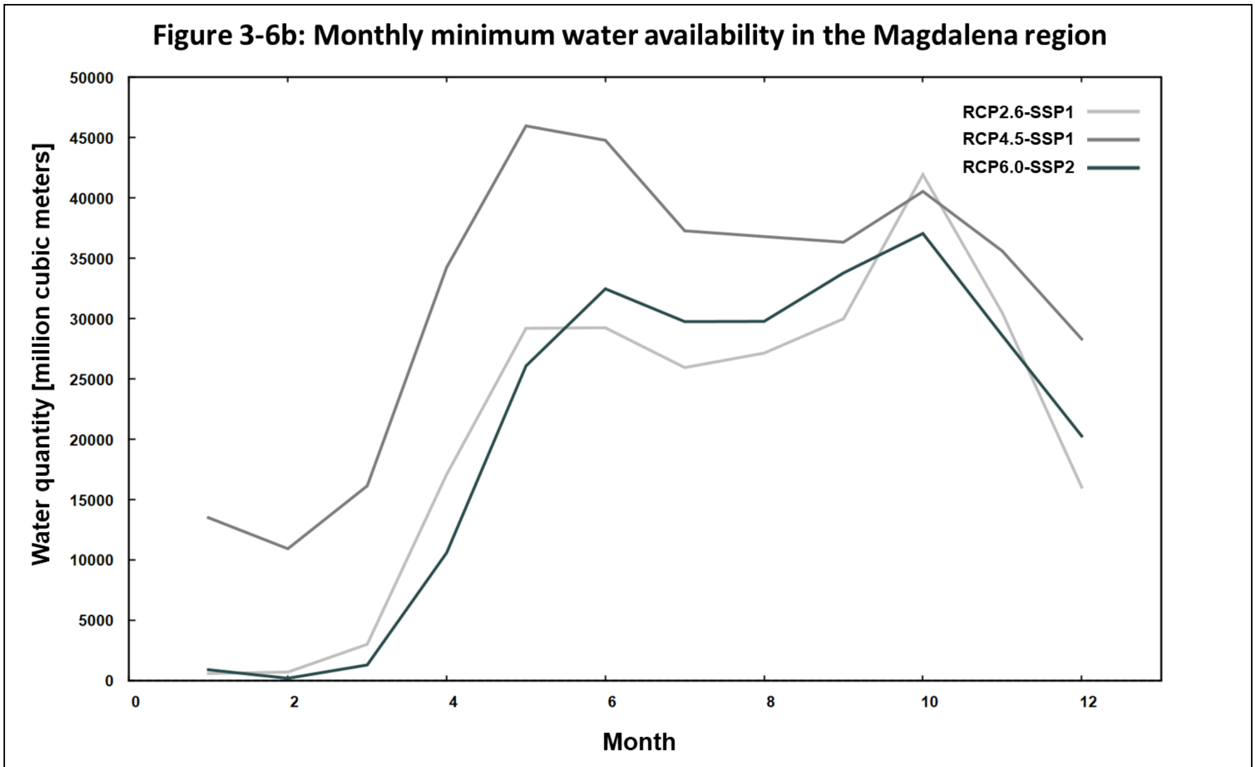


Figure 3-6b: Monthly minimum water availability in the Magdalena region

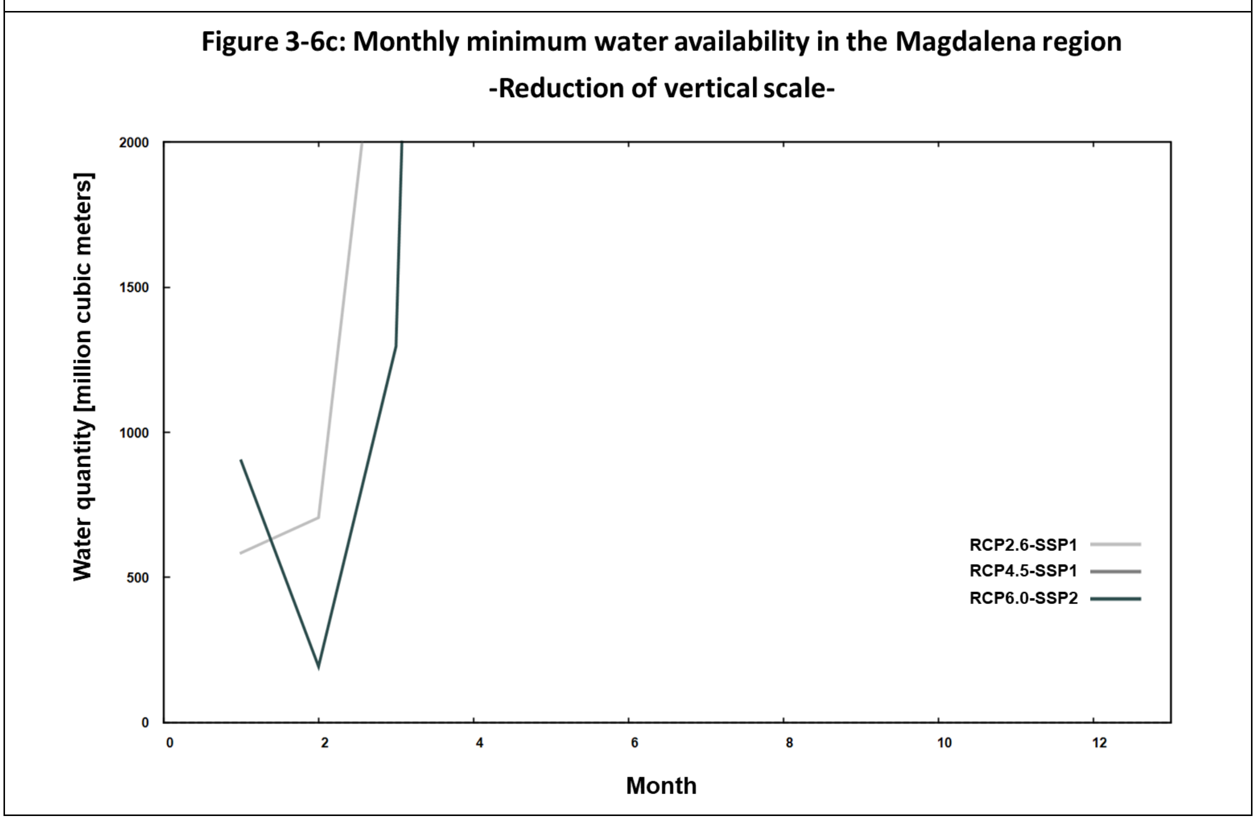


Figure 3-6c: Monthly minimum water availability in the Magdalena region
-Reduction of vertical scale-

Fig. 3-6. Maximum values of monthly irrigation (3-6a) and minimum data of monthly water availability (3-6b) (3-6c) between 2020 and 2100, for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and

SSP2) scenarios. Irrigation and water availability data are compiled for the entire Magdalena region.

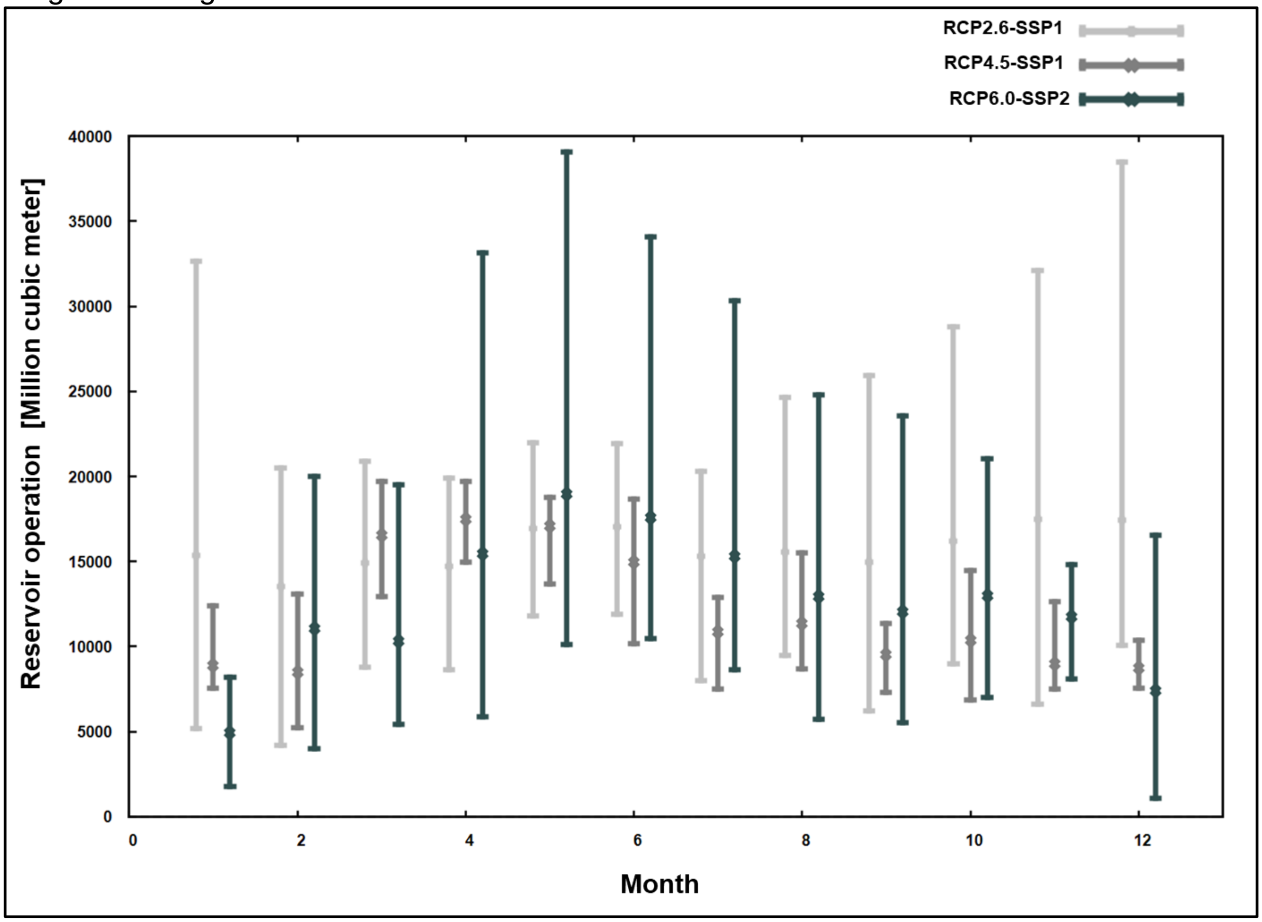


Fig. 3-7. Storage variability in reservoirs, over eight decades (2020-2100), in the entire Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios.

Second, I study the decadal irrigation pattern for the months of potential water shortages: January, February, and March. Fig 3-8a, 3-8b, and 3-8c illustrate almost the highest irrigation uses in January, following by February and March, for almost all scenario combinations and eight decades. For these months, more irrigation is also required at the beginning and the end of the century when it is less water available in the Magdalena region (See Fig. 2-3 chapter 2). In the first quarter of the year, maximum monthly irrigation would occur at the beginning and the end of the century, predominantly in the decade 2030-2040 and 2070-2080, for the RCP2.6 climate scenario (see Fig 3-8a, 3-8b, and 3-8c).

For January (See Fig 3-8a), decadal irrigation water is almost higher in the RCP2.6 than in the RCP6.0 and RCP4.5 scenarios during the research time. The exceptions are the decades 2020-2030 and 2090-2100, where irrigation water is briefly higher for the

RCP4.5 and RCP6.0 than the RCP2.6 scenario, respectively. For February and March (see Fig 3-8b and Fig 3-8c), decadal irrigation withdrawals are still higher for several decades under the RCP2.6 scenario but with an increasing number of exceptions. During the second and the third month of the year, decadal irrigation values slowly decline for all scenario combinations. From January until March, irrigation withdrawals differences among climate scenarios (RCP2.6 and RCP4.5) also decrease.

After comparing irrigation water in the first quarter of a year, I found that January presents the largest irrigation withdrawals for the decades 2030-2040 and 2070-2080, under the RCP2.6 scenario (See Fig 3-8a).

For the first quarter of a year, monthly irrigation follows a particular tendency. Decadal irrigation is major for climate scenarios with minor water availability (RCP2.6 and RCP6.0) (see Fig 3-8a, 3-8b, and 3-8c). One possible explanation of this seasonal dynamic is that monthly irrigation withdrawals are mainly influenced by water availability, similar to decadal agricultural demand (see Fig. 3-1c). More irrigation is required under low water availability scenarios -RCP2.6 and RCP6.0- than a high water availability scenario -RCP4.5- (See Fig.2-3 in chapter 2).

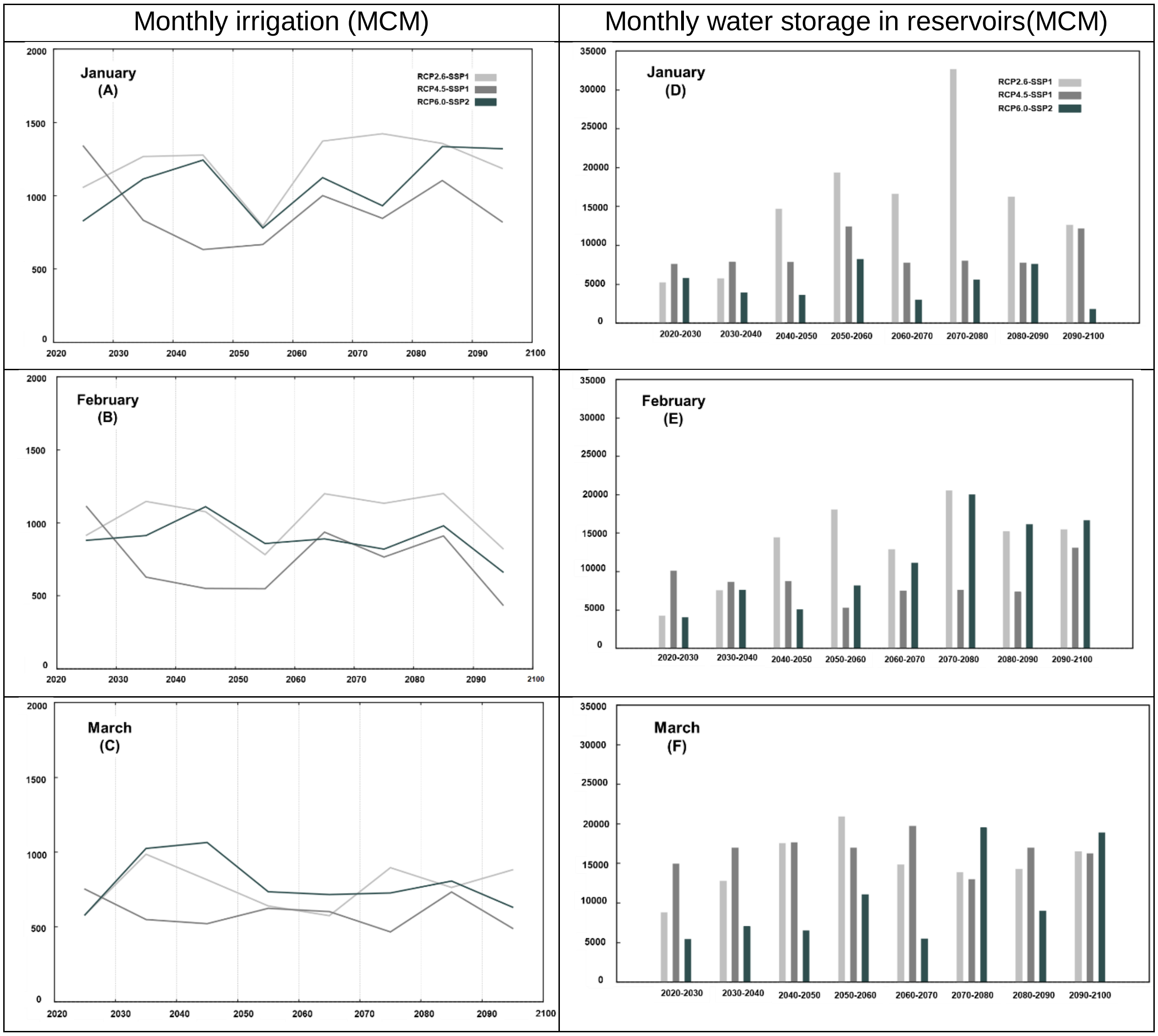


Fig. 3-8a, 3-8b and 3-8c. Decadal irrigation and Fig. 3-8d, 3-8e, and 3-8f decadal reservoir storage for January, February, and March in the entire Magdalena river basin. The simulations combine three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios.

Third, I compare decadal variations of reservoir volume storage for January, February, and March, each year's dry periods. Fig 3-8d, 3-8e and 3-8f display minimum water impoundment for the RCP6.0 scenario for January, February, and March during 80-years, with some exceptions.

In January, reservoir volume-storages are smaller for the RCP6.0 climate scenario than the others for almost all decades (see Fig. 3-8d). The exception is the decade 2020-2030 when RCP6.0 dam storages are higher than RCP2.6. In January, reservoir impoundments are also minor under the RCP 6.0 than RCP4.5 climate scenario.

In February (see Fig. 3-8e), reservoir impoundments are smaller for the RCP4.5 scenario, with some decades exceptions: 2020-2050. The reservoir storage is smaller for the RCP6.0 than the RCP2.6 climate scenario during this month, except 2080-2100.

In March (see Fig. 3-8f), dam storages are also minor in the RCP6.0 scenario, with two exceptions: 2070-2080 and 2090-2100 decades. Impoundment values experience random variations for RCP2.6 and RCP4.5 climate scenarios.

During the first three months of the year, minor reservoir impoundments mainly appear between 2030 and 2050 for the RCP6.0 water availability scenario. For this climate scenario, January displays the lowest storage in the mentioned period (see Fig. 3-8d). When I analyze the three climate scenarios together (RCP2.6, RCP4.5, and RCP6.0), the minimum impoundments concentrate in three decades, 2020-2050, and two months: January and February.

Besides, the monthly volume storage of reservoirs has a clear connection with climate scenarios during the first quarter of a year. January, February, and March storages of reservoirs display lower values under minor water availability (RCP6.0).

Finally, I find that water shortages may appear in the Magdalena region during 2030-2040 (especially in January) when the largest irrigation values and the lowest volume-storage of reservoirs would be present under the scenarios with minor water availability (RCP2.6-SSP1, RCP6.0-SSP2). In this period, it will be water competition between agricultural and hydropower sectors.

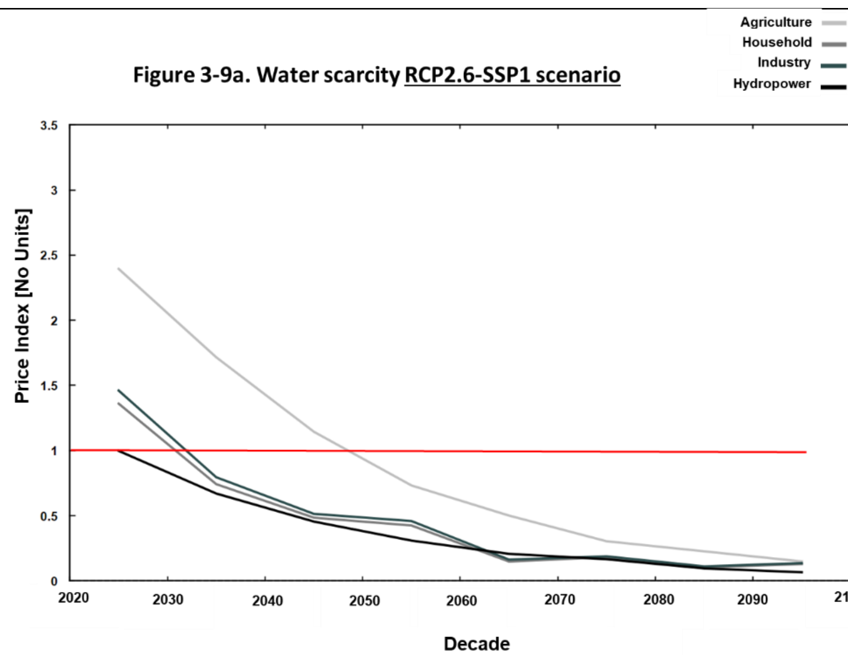
3.1.5 Economic scarcity of water

Fig. 3-9 illustrates the economic scarcity of water through the shadow prices plotting of specific constraints from the CAMARI optimization model, using a price Index. As I mentioned in chapter 2, the CAMARI model is programming in the General Algebraic Modeling System (GAMS). In this modeling language, shadow prices are called marginal values of equations. In an optimization model, shadow prices or Lagrange multipliers provide the change in the objective function optimal values due to a marginal unit change in a constraint (Pulido-Velazquez et al., 2008). The objective function represents the welfare of water consumption in the Magdalena river region derived from water management in the system. In that case, the shadow prices of the regional demand constraints provide the net benefit derived from a unit of increase of water on a specific location. Simultaneously, the shadow price quantifies water resources' real values, also reflecting its scarcity (Liu et al., 2009). Economic scarcity of water means that the water supply price will increase when this resource becomes more scarce. Fig. 3-9a, 3-9b, and 3-9c show the economic scarcity of water demand per sector (agriculture, household, industry, and hydropower) and scenario combinations, with an index computation (model scenario/base scenario). The base scenario is an average of sectorial shadow prices over all scenarios, regions, months, and decades.

For all water availability scenarios, agricultural and hydropower indexes follow a decreasing tendency (see Fig. 3-9a, 3-9b, and 3-9c). For the agricultural sector, the shadow price indexes decline from 2.4 until 0.2 during the research time. In the case of the hydropower sector, the shadow-price indexes slightly decrease between 1.0 and 0.1. Household and industrial shadow prices follow a different pattern per scenario combination. Their indexes decline between 1.5 and 0.2 for the RCP2.6 and among 2.4 and 0.1 for the RCP4.5 climate scenario. For the RCP6.0 scenario, household and industrial shadow prices decline abruptly from 2.7 to 0.25 (2020 – 2050) and after fluctuates between 0.5 and 0.1 (2060-2100).

Economic scarcity of water would emerge when the shadow price indexes are above one. That is the case of the agricultural, household, and industrial sectors, whose shadow prices are above one (1) between 2020 and 2040, for the selected climate scenarios. The agricultural sector will also experience a larger economic scarcity of water than household and industrial sectors under low water availability scenarios (RCP2.6 and RCP6.0). The price for an extra unit of water to supply the mentioned sectors would be higher during the first two modeled decades for the studied climate scenarios (RCP2.6, RCP4.5, and RCP6.0) in the Magdalena basin. Although there is enough water available in the Magdalena basin, the agricultural, household, and industrial sectors will experience economic water scarcity without the optimal infrastructure investment, especially in the period 2020-2040.

Figure 3-9a. Water scarcity RCP2.6-SSP1 scenario



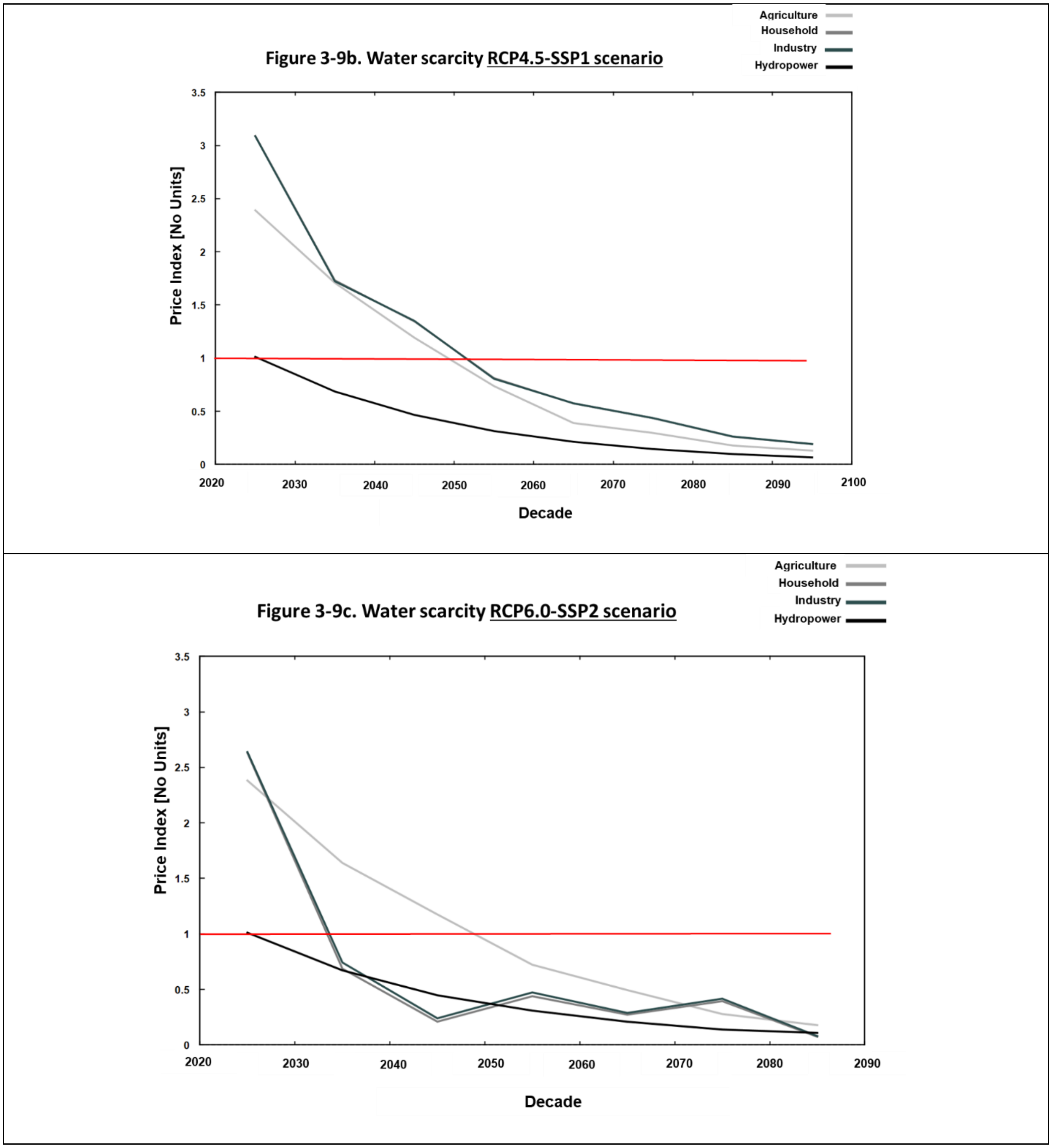


Fig. 3-9. Decadal variation of water economic scarcity per sector in the Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. Price Index (shadow price - model scenario-/shadow price - baseline scenario-) as an indicator of the economic scarcity of water. The shadow prices are the regional and monthly average per decade.

3.1.6 Welfare modeling

The model CAMARI simulates the total welfare of water consumption for hydropower, agricultural, household, and industrial sectors in the Magdalena basin under the selected scenarios. Fig. 3-10 displays decadal net benefits for different climate/development scenarios over 80 years planning horizon (2020-2100). Fig. 3-10 illustrates that the highest value of welfare occurs for RCP4.5, followed by RCP2.6 and RCP6.0 climate scenarios, except the 2020-2050 period. For the RCP4.5 climate scenario, decadal welfare varies between 30 and 34 billion USD for the next eight decades. In the case of RCP2.6, decadal net benefits fluctuate between 15 and 25 billion USD. For the RCP6.0, decadal welfare change among 15 and 22 billion USD per decade (see Fig. 3-10).

To understand the welfare pattern, I display the objective function components (2020-2100) for the studied climate/development scenarios (see Fig. 3-11).

First, total welfare is the result of aggregating total profits and subtracting total costs. Fig. 3-11 distinguishes the benefits as positive values and costs as negative values in the welfare maximization process (see section 2.3.2.1). Second, total benefits are the addition of the endogenous price of agricultural goods, the constant price of agricultural commodities, and the water value of non-agricultural sectors. Third, total costs include endogenous, constant, and calibrated water supply costs, crop production costs, operation and investment costs of water infrastructures, and water costs for power generation.

The endogenous prices for agricultural goods and dam investment are the most relevant components of total welfare (see Fig. 3-11). The endogenous price of agricultural goods is the highest benefit component, and dam investment the highest cost. On the one hand, agricultural goods benefits have similar values for all climate scenarios, circa 400 million USD (See Fig. 3-11). On the other hand, total investment in dams is circa 100 million for the RCP4.5 and 200 billion USD for the RCP2.6 and RCP6.0 climate scenarios (See Fig. 3-11). For the optimal solution, the CAMARI model chooses to build fewer dams for RCP4.5 than the RCP2.6 or RCP6.0 climate scenario (see Fig. 3-5). Interesting to observe is that climate-scenario welfare dynamics seems to be opposite to dams investment behavior but coherent with total surface runoff in the basin. One logical explanation is that welfare for water consumption is influenced directly by hydropower generation and the amount of water available in the Magdalena region. If more water resources are accessible, infrastructure investment declines, but the water uses welfare rises (RCP4.5 climate scenario). In other words, the main driver of general welfare is climate change in CAMARI simulations. When more water is available in the Magdalena river basin, the welfare of water consumption increases.

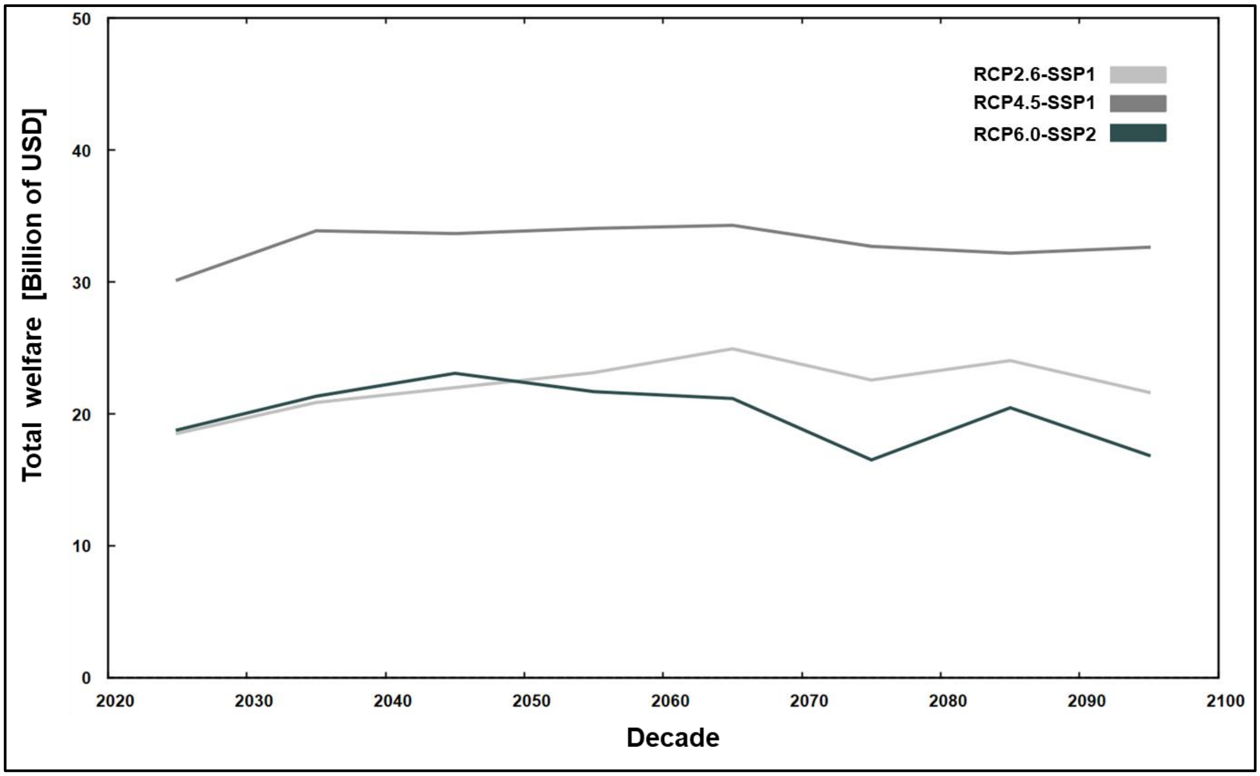


Fig. 3-10. Decadal welfare in the Magdalena basin for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. Decadal welfare is the result of adding monthly welfare values in each decade.

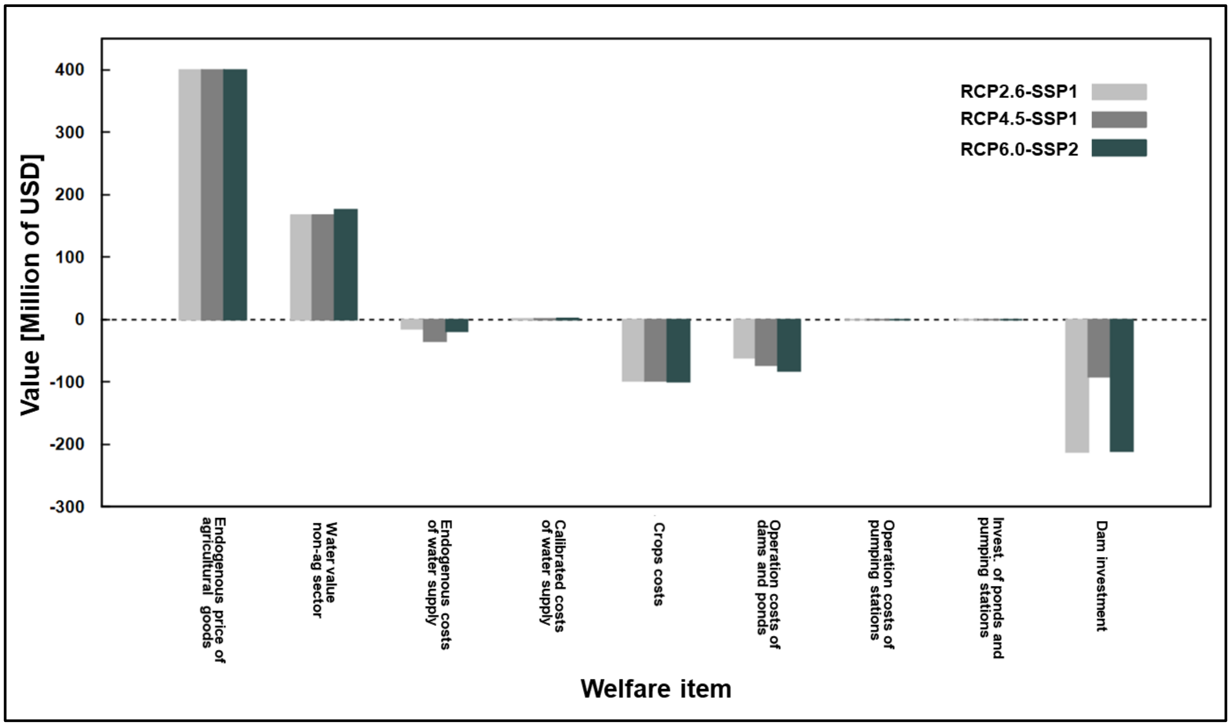


Fig. 3-11. Total welfare components for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios. The total welfare component adds total benefits or costs calculations over eight decades (2020-2100) and 140 regions.

3.2. Spatial scale effects on modeling water management in the Magdalena river basin

In this section, I answer the second research question: How much is the influence of spatial scale variations on water management investments and the welfare for water uses in the Magdalena basin?

Scale assessment on environmental studies has been increasing during the 90´s decade (Wilbanks, 2002), but investigation on the impact of scale variations on water resources is still deficient (Perveen and James, 2010). When the analysis results depend on selecting one spatial scale, several uncertainties will arise at other scales (Goodchild, 1998). Besides, as the resolution becomes coarse, spatial heterogeneity usually declines due to averaging processes (Goodchild, 1998).

Equally important is the increasing requirement of spatially resolved models, including spatial disaggregation of economic data to effectively represent water use dynamics (Bekchanov et al., 2012). However, temporal and spatial connections between water systems and political frontiers are still a challenge to building water-economy models (Bekchanov et al., 2017).

CAMARI model is an example of water-economy modeling to aggregate spatial and temporal data to approach water management alternatives for several climate-development scenarios. Furthermore, the CAMARI model effectively integrates administrative data to various spatial-temporal scales. I develop a simulation with the CAMARI model to study the impact of spatial scale variation in water management alternatives in the Magdalena region, Colombia. The results depict a comparison between optimal investment decisions for different spatial resolutions, water availability, and development projections. Moreover, I describe the correlation between physical scale, welfare for water consumption, optimal investment, and water scarcity in a river basin study. The simulation scenarios contain four spatial resolutions (140, 34, 13, and 5 regions), three water availability projections (RCP2.6, R.C.P4.5, and RCP 6.0), and two shared socio-economic pathways (SSP1 and SSP2) (see table 2-6, chapter 2).
The spatial-time resolution modeling that analysis real-water problems are highly heterogeneous because of the dynamic methods to link the interaction between hydrological, geographical, and economic data. Multiple spatial (1-region or multiregional) and time resolutions(monthly, annual or decadal) may probably affect computational outputs (Bekchanov et al., 2017).

3.2.1 Welfare analysis

The current study explores total and decadal net benefits of water withdrawals from various sectors until the end of the century in the Magdalena river basin. Hence, I identify and analyze the relevant welfare components and their fluctuations for the selected spatial scales, water availability, and development scenario combinations.
First, I analyze the impact of the selected scale, climate, and socio-economic scenarios on 80 years of total welfare of water use in the Magdalena region. In Fig. 3-12, an interesting dynamic can be observed: with the spatial scale reduction from 140-R to 13-R, 80-year total benefits rise circa 5% (~10 billion USD) for the studied climate-development scenarios. Besides, total net benefits decline circa 2% (~4 billion USD) from 13-R to 5-R resolution for all scenario combinations. 80-year welfare shows the highest value for the 13-R resolution analysis under the modeled scenarios. This pattern is due to the welfare's main items: total revenues and total costs (Fig. 3-13). On the one hand, total revenues depict an increasing tendency, from 140-R to 5-R resolution.
On the other hand, total costs are lower for the 34-R and 13-R spatial scales (see Fig. 3-13). As a result, the 13-R total welfare displays the largest values (see Fig. 3-12). As I mentioned in section 3.1.6, the CAMARI model maximizes water consumption's net benefits in the Magdalena region by adding total benefits and subtracting total costs. Total benefits are the addition of the endogenous price of agricultural goods, the constant price of agricultural commodities, and the water value of non-agricultural sectors. Total expenses include endogenous, constant, and calibrated water supply costs, crop

production fees, operation and investment costs of water infrastructures, and hydropower generation charges. Benefits are portrayed as positive and costs as negative values.
Fig. 3-12 also depicts a minimum impact of climate/development scenario variations on 80-years welfare for water use.

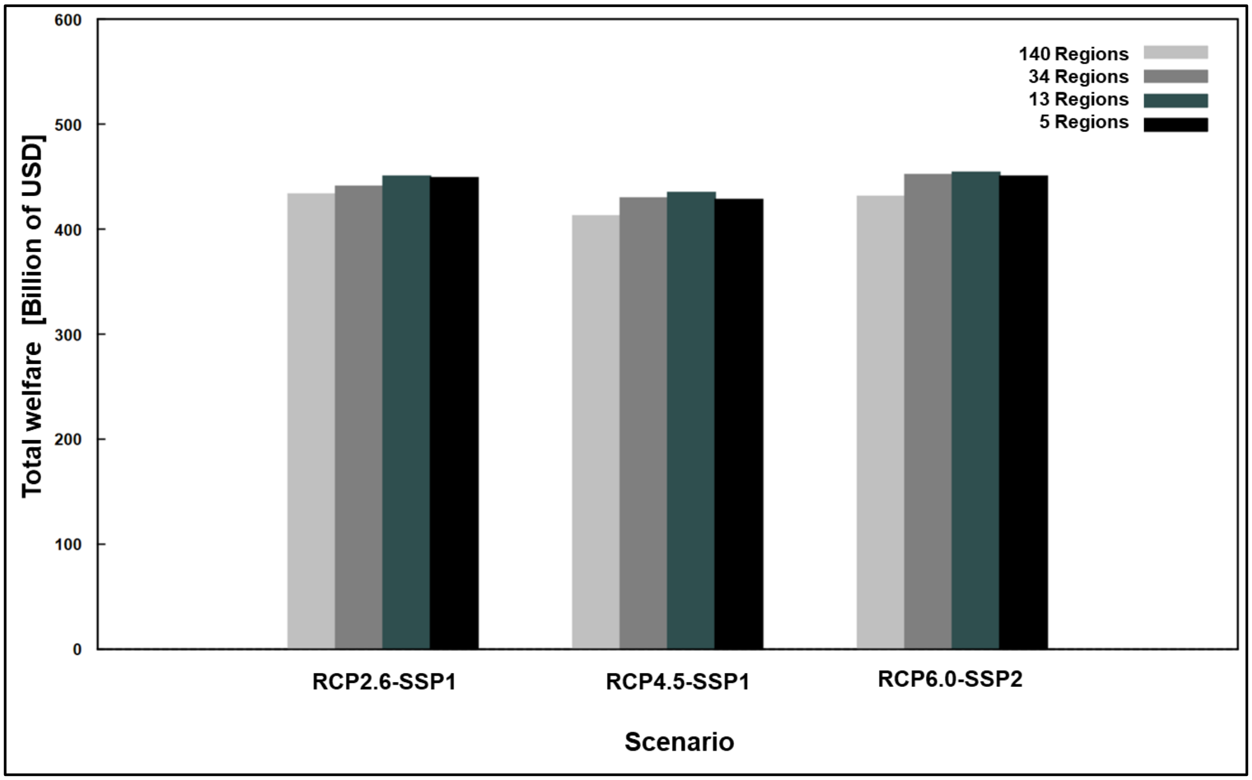


Fig. 3-12. Total welfare for water consumption in the entire Magdalena basin for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2) scenarios. Total welfare adds total benefits over eight decades (2020-2100) and all regions (spatial scale).

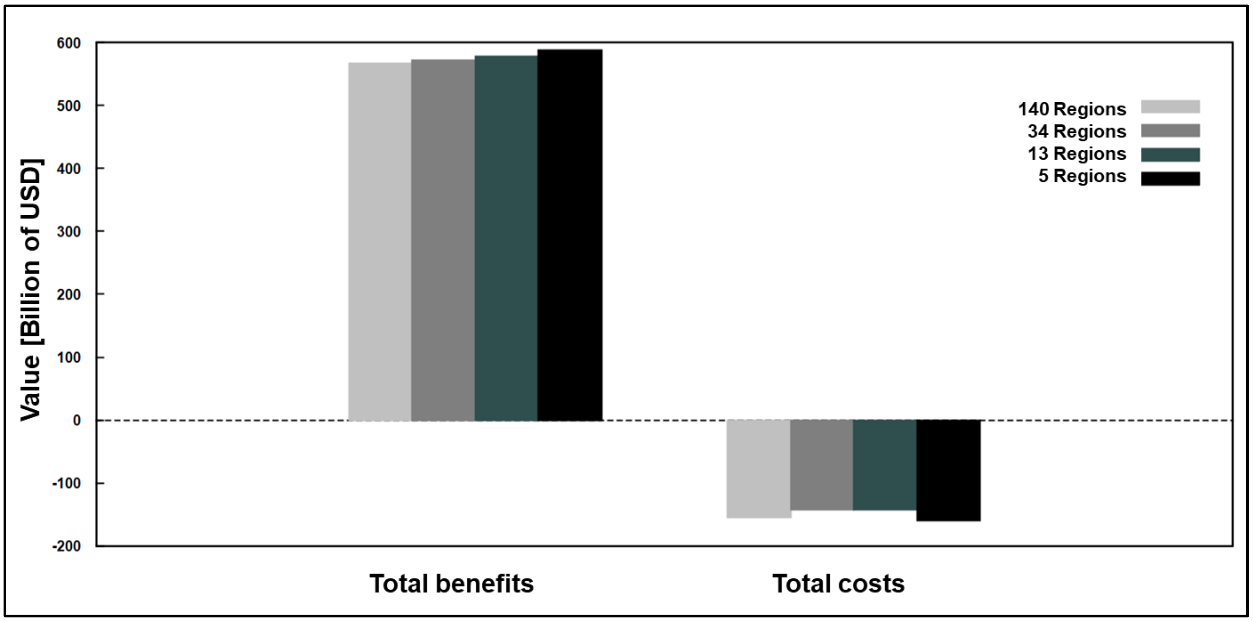


Fig. 3-13. Total welfare for water consumption in the entire Magdalena basin for the RCP2.6 – SSP1 scenario and for four physical scales (5, 13, 34, and 140 regions). Total benefits add agricultural and non-agricultural sector revenues over eight decades (2020-2100) and all regions (spatial scale). Total costs add various expenditures over over eight decades (2020-2100) and all regions (spatial scale).

Second, I display welfare components for one climate scenario - RCP2.6 - to understand the total welfare pattern (Fig. 3-14). I select just one scenario considering the minor influence of climate development on total welfare projections (see Fig. 3-12). Benefits are portrayed as positive and costs as negative values.

Fig 3-14 depicts the most important welfare items: the endogenous price of agricultural commodities, the water values of the non-agricultural sectors, and crop production costs. On the one hand, the agricultural sector's benefits are the highest revenue item, followed by non-agricultural sector benefits. The agricultural commodities prices represent circa 90% of the total welfare (see Fig. 3-14). The endogenous prices for agricultural commodities decline circa 4% from 140-R to 5-R scale simulations. Conversely, the non-agricultural water values increase by 13% between 140-R and 5-R spatial analysis.

On the other hand, the crop production costs' magnitude is circa 25% of total welfare (see Fig. 3-14). 80-years of crop costs decrease 15% from 5-R to 140-R of spatial analysis. To explore the pattern of agricultural costs, I explore decadal projections of crop production. In section 3.2.2, the dynamic features of the agricultural sector will be described.

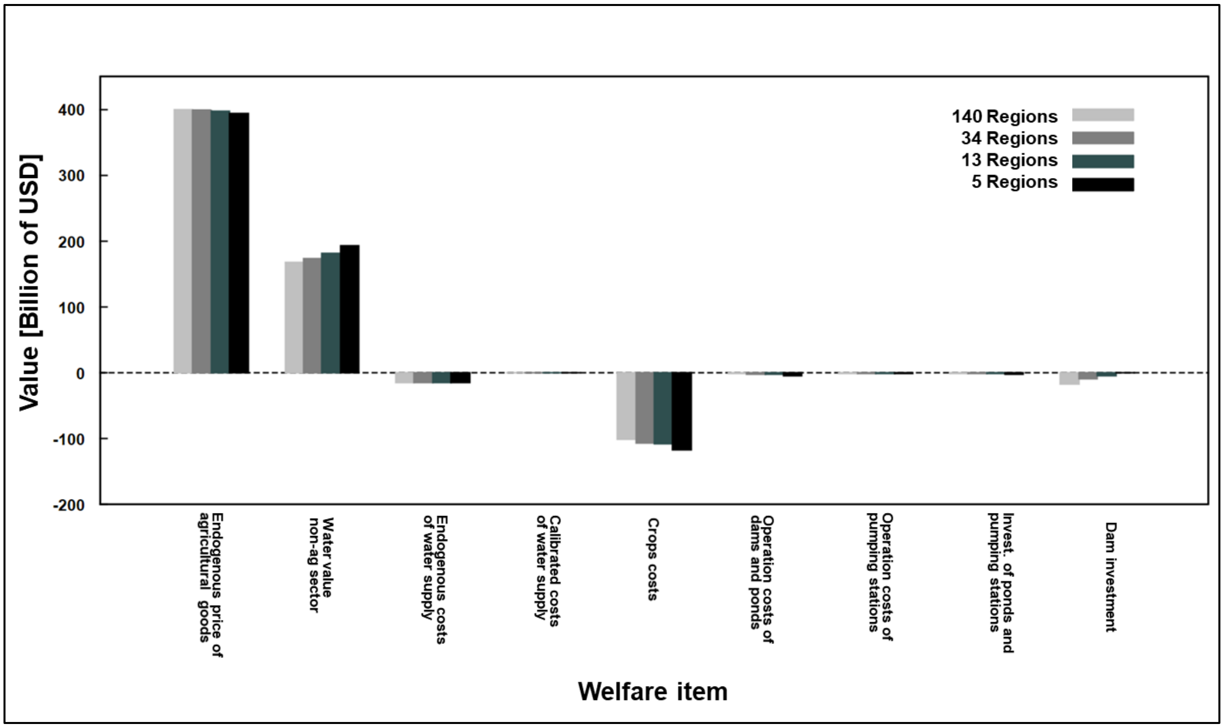


Fig. 3-14 Welfare components values for water consumption in the entire Magdalena basin for the RCP2.6-SSP1 scenario for four physical scales (5, 13, 34, and 140 regions). Welfare component calculation is the result of adding benefits or costs over eight decades (2020-2100) and all regions (spatial scale).

Third, I research the impact of physical scale fluctuations on decadal net benefits patterns. Fig. 3-15 plots decadal welfare for the studied resolutions under the RCP2.6 climate scenario. Decadal revenue shows variations from 44 to 60 billion USD for the studied physical scales. Interestingly, decadal welfare shows values around 60 billion USD between 2060 and 2090 for all spatial resolutions. For the 5-R and 13-R spatial scales, decadal net benefits increase about 20% from 2020 until 2060, stay constant until 2080 and decline 3% until 2100 (see Fig. 3-15). For the 34-R resolution, decadal welfare decreases by 2% between 2030 and 2050, increases by 20% between 2050 and 2090, and declines 8% until 2100. In the 140-R simulation, decadal welfare displays the highest fluctuations, circa 25%, during the research horizon.

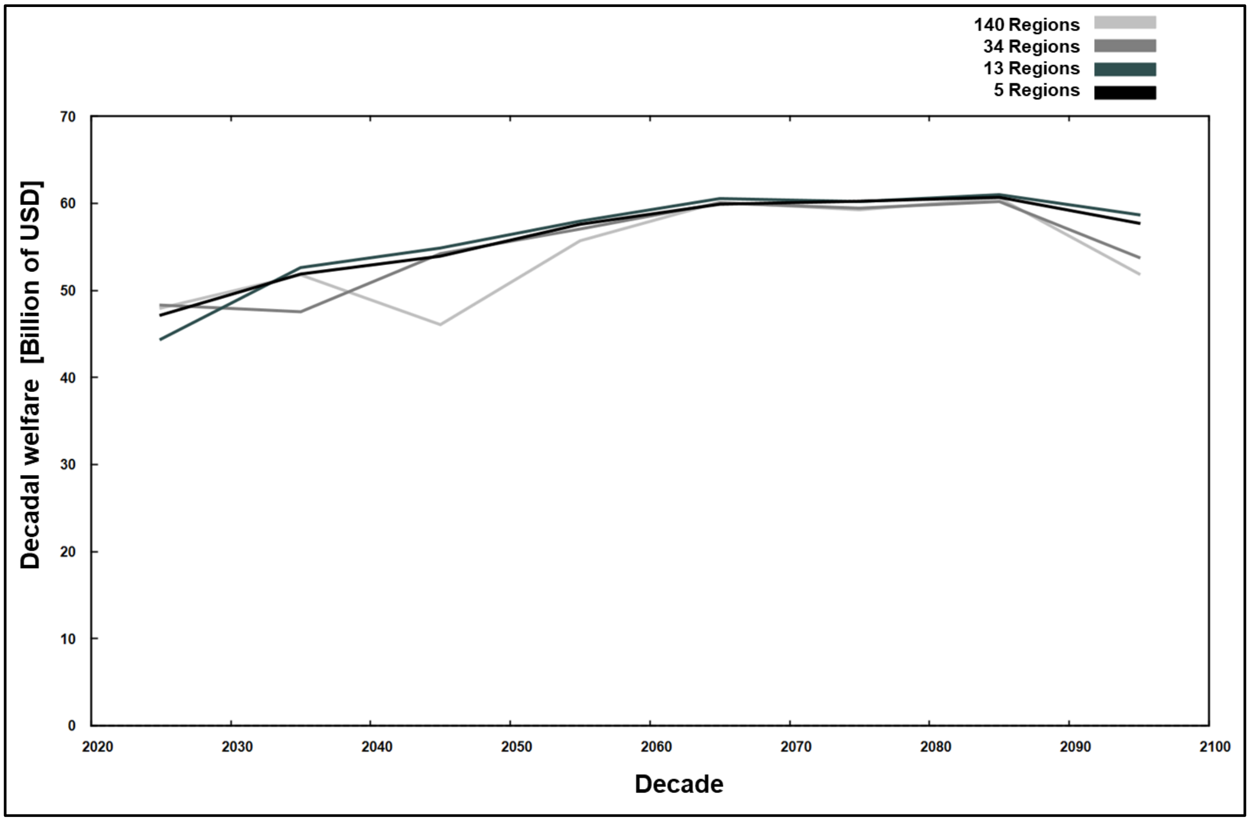


Fig. 3-15. Spatial scale variation of decadal welfare for the RCP2.6 climate scenario and SSP1 development scenario in the Magdalena river basin, billion USD.

3.2.2 Agricultural water use revenues and crop costs analysis

The analysis of welfare behavior for water uses has shown that agricultural goods' endogenous prices are the most relevant revenue item (see fig. 3-14). It helps explore the dynamic of agricultural water use to understand the impact of the spatial scale on the agricultural sector benefits. Fig 3-16 displays the decadal values of agricultural water use in the Magdalena basin for four resolutions, three climates, and two development scenarios. Agricultural water use is the result of the crop areas multiplied by irrigation. First, decadal water withdrawals of the agricultural sector do not follow a declining nor increasing trend. This non-pattern is associated with the crop area variability for different resolutions (fig.3-17). Second, 5-R agricultural water use is more than 300% larger than other spatial scales for all studied climate-development scenarios (see Fig. 3-16). One possible explanation is that the largest agricultural demand (5-R) is correlated with the irrigation spatial pattern for 5 regions. Although the 5-R crop areas are circa 20% higher than other resolutions (see fig.3-17), the model detects more necessity of irrigation for five regions scale. For the 5-R scale, agricultural water withdrawals show significant variations between 13 and 25 billion cubic meters. Third, as opposite as the 5-R scale, fig. 3-16 highlights short decadal fluctuations of agricultural water use for the 140, 34, and

13 region simulations. For these spatial scales, decadal water uses fluctuate between 2 and 8 billion cubic meters. One interesting pattern is observed: between 2030 and 2070, agricultural water demand is higher for the 13-R, following by 34-R and 140-R, for all water availability scenarios. Finally, fig. 3-16 indicates that climate and socio-economic scenarios do not enforce a tendency on the decadal agricultural water withdrawals.

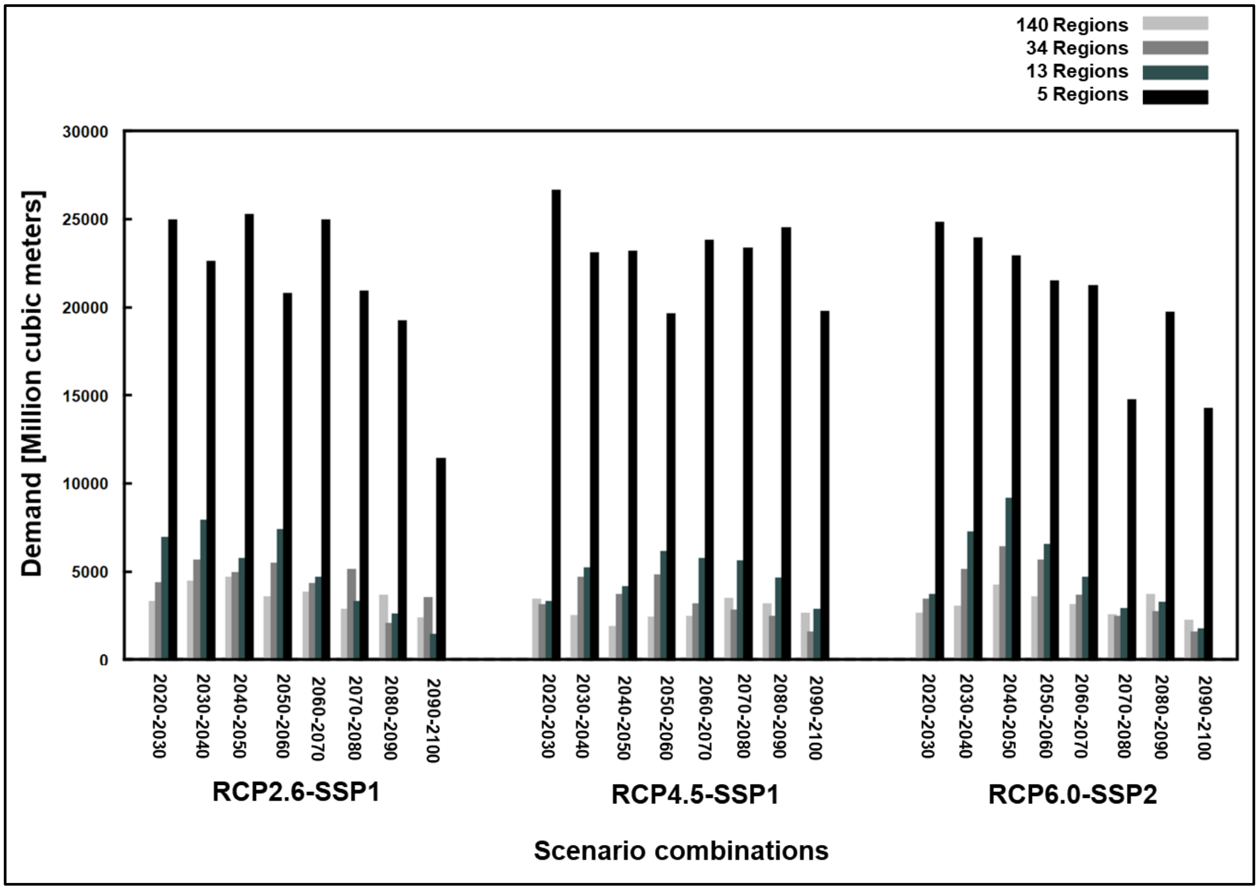


Fig 3-16. Decadal agricultural water withdrawals in the entire Magdalena river basin for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2) scenarios. Decadal water withdrawals of the agricultural sector result from adding agricultural water use over all regions (spatial scale) in each decade.

Another relevant item of 80-year welfare for water consumption is the crop production charges (see fig. 3-17). The crop production costs are the highest expense component of the total welfare for water withdrawals in the Magdalena river basin. Crop production costs are calculated as the product of the yield area by crop price. Fig 3-17 highlights decadal features of crop area in the Magdalena river basin for the selected scenarios. First, the largest agricultural area occurs for the 5-R scale under the selected water/socio-economic scenarios. Second, decadal crop area rises up to 25% from 140-R to 34-R analysis for all decades and climate-development scenario combinations. Third, decadal crop extents fluctuate from 4.9 to 6.8 million Ha (up to 30%), between 140-R and 5-R spatial analysis. Finally, it is not straightforward the impact of climate-development scenarios on crop areas.

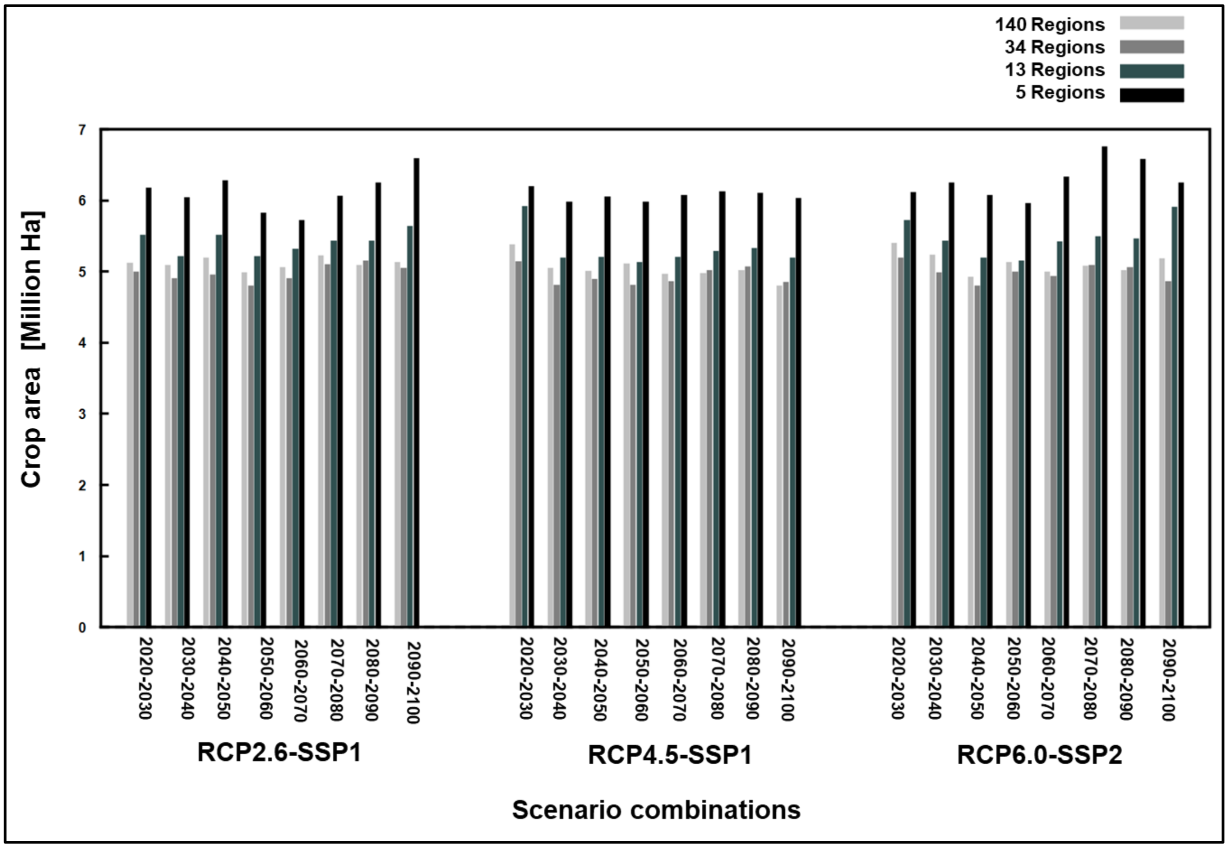


Fig 3-17. Decadal crop area in the entire Magdalena river basin for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2) scenarios. Decadal crop area results from adding crop extents over all regions (spatial scale) in each decade.

3.3.3 Investment analysis and water scarcity

This section compares and analyzes infrastructure capacity projections, investment costs, water management, and water scarcity implications for several spatial scales, climate, and socio-economic scenarios. The modeling includes the geographic location of the constructed dams/reservoirs in the Magdalena river basin. For the CAMARI simulations, it is assumed a 100 life span of the existing dams. Constructed reservoirs have circa 11 billion m3 capacity, which is supposed to decrease 10% per decade (see Fig. 3-18).

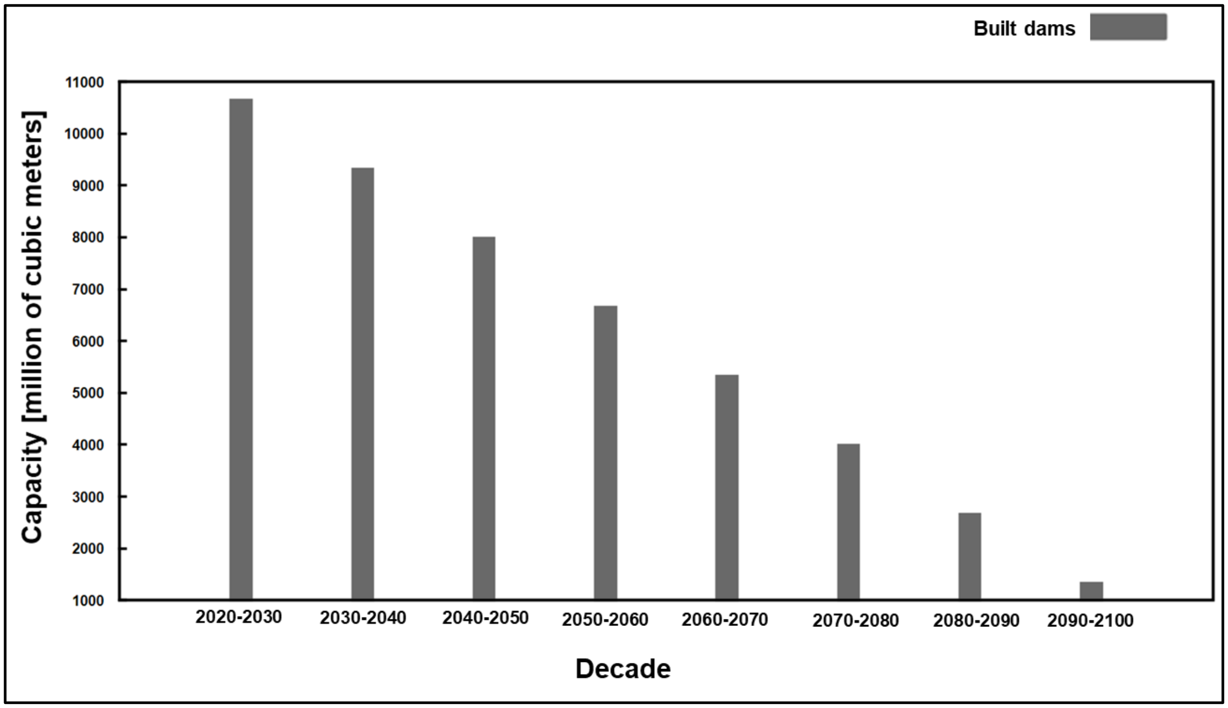


Fig. 3-18. The projected declining capacity of constructed reservoirs in the entire Magdalena river basin during 2020-2100.

One of the most relevant CAMARI model features is the forward-looking behavior with welfare-maximization modeling to select optimal infrastructure investments. The model CAMARI selects to install water infrastructures to supply water to selected economic sectors. The simulations included three water infrastructures: reservoir or dams, pumping stations, and agricultural ponds. In the model, agricultural ponds deliver water to agricultural users, and reservoirs and pumping station to all end users -agricultural, household, industrial, and hydropower sectors-.

One of the main findings of this section is that the capacity projection of optimal infrastructures is higher for the largest spatial scale -140 regions-, in the Magdalena river basin for all climate/development scenarios. Fig. 3-19 and 3-20 highlight total and optimal decadal infrastructure projections for four spatial scales (140, 34, 13, and 5 regions) for the selected scenarios and research time.

First, I explore optimal projections of water infrastructure for the entire modeling horizon. During 80 years of simulation and all studied scenarios, the model CAMARI builds about 35% more infrastructure capacity for the 140-R than 5-R spatial analysis (see Fig. 3-19). A tendency can be observed: 80-years of optimal infrastructure projections will be more than 85% smaller for the RCP4.5 than other climate scenarios for the studied physical scales. For the scenario of higher water availability -RCP4.5-, 80-years projected infrastructure capacity declines 80% between 140-R and 34-R resolution. Conversely, total infrastructure projections increase 5% from 34-R to 13-R and 70% from 13-R to 5-R. Optimal capacity projections change among 4 and 21 billion m3 under the RCP4.5 water availability scenario (see Fig. 3-19).

For the RCP2.6 scenario, total capacity projections decline 2% from 140-R to 34-R, 61% from 34-R to 13-R but increase 40% between 13-R and 5-R spatial scales. Optimal infrastructure projections vary between 12,5 and 32,5 billion m3 capacity under the RCP4.5 climate scenario (see Fig. 3-19).

In the RCP6.0 scenario, optimal capacity projections decrease 85% from 140-R to 34-R, increase 60% from 34-R to 13-R, and 65% from 13-R to 5-R resolutions. The projected capacity of water infrastructures fluctuates between 4,8 and 34,5 billion m3 (see Fig. 3-19).

The erratic pattern of the 80-year capacity is due to the type of optimal infrastructure projected in the Magdalena river basin (see Table 3-2). This table highlights that CAMARI simulations select mainly dams/reservoirs, large capacity infrastructures, for the 140-R scale. In the 34-R scale, the total projected capacity declines, particularly for the RCP4.5 and RCP6.0 climate scenarios. For 13-R, the projected capacity is similar for the RCP2.6 and RCP6.0 and smaller for the RCP4.5 scenario. In the case of five regions resolutions, the model installs a larger total capacity for the RCP2.6 and RCP6.0 than RCP4.5 climate scenarios. For the coarser scale, the model simulations built mainly pumping stations (small water infrastructures).

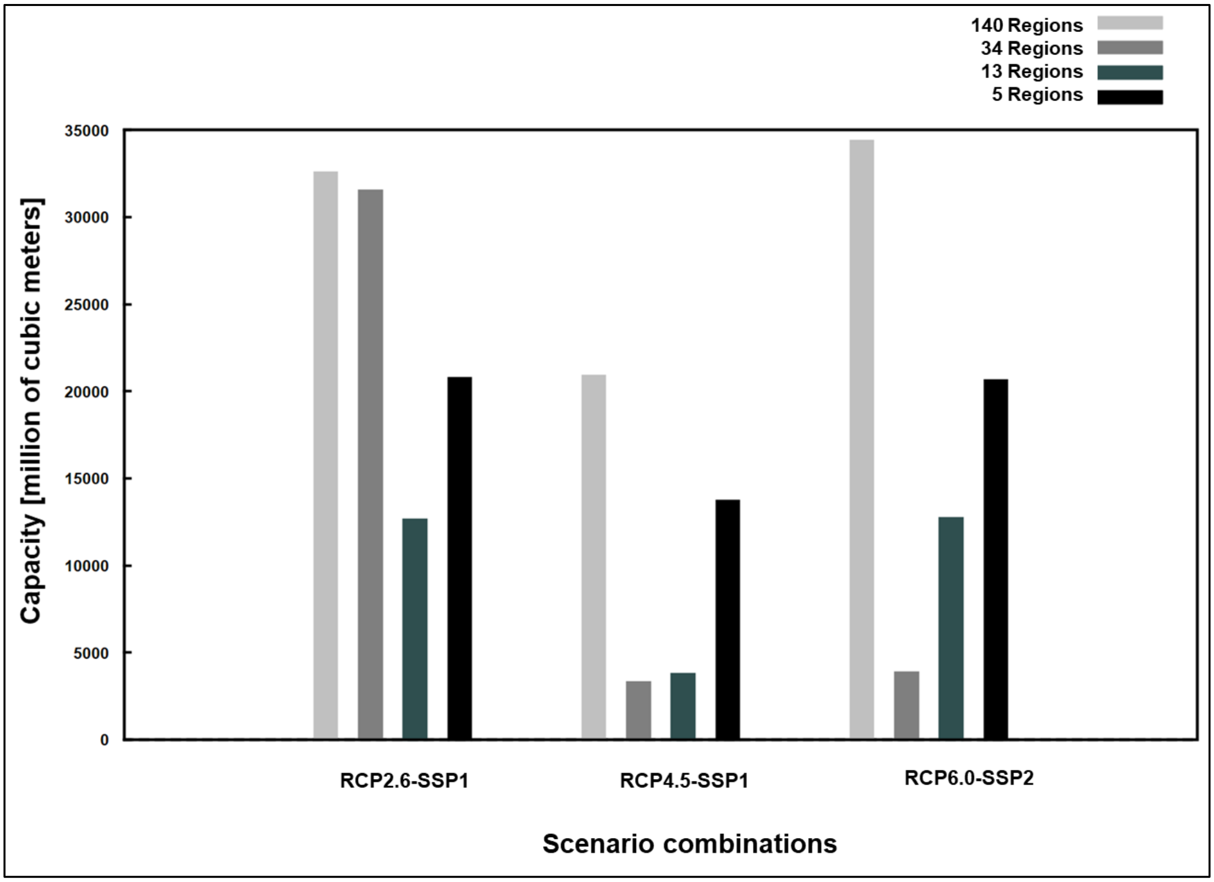


Fig. 3-19. Total optimal capacity in water management infrastructures in the entire Magdalena river basin for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2) scenarios. Total optimal capacity in new infrastructures, adding values for eight decades (2020-2100) and all regions (spatial scale).

	RCP2.6-SSP1 (MCM)			RCP4.5-SSP1 (MCM)			RCP6.0-SSP2 (MCM)		
Resolution (regions)	***Irrig. ponds**	***Pump. stations**	**Dams**	***Irrig. ponds**	***Pump. stations**	**Dams**	***Irrig. ponds**	***Pump. stations**	**Dams**
140	657.2	3911.7	27938.8	127.3	4010.5	16741.9	426.3	3796.0	30106.4
share	2%	12%	86%	1%	19%	80%	1%	11%	88%
34	238.3	3256.3	28002.0	107.5	3193.5		4.7	3192.5	628.0
share	1%	10%	89%	3%	97%	%	0%	83%	16%
13	-	3255.7	9403.0	-	3727.0	-	-	3050.6	9628.8
share		26%	74%	-	100%	-	-	24%	76%
5	0.6	12500.8	8212.8	-	13543.3		0.5	12357.8	8212.8
share		60%	40%	-	100%	%	-	60%	40%

Table.3-2. The total capacity of projected infrastructures in the entire Magdalena region over the 80-years research period (2020–2100) for three climate change (RCP2.6, RCP4.5, and RCP6.0) and two shared socioeconomic pathways (SSP1 and SSP2) scenarios.

Second, I research optimal decadal investment in water infrastructures for several spatial scale simulations in the Magdalena region (Fig. 3-20). The optimal decadal capacity displays extreme variations, from 0.2 million to 6.6 billion m3. A relevant finding is that decadal infrastructure projections are lower under minor water availability -RCP4.5- and lower resolutions (34,13 and 5 regions). Fig. 3-20 highlights that optimal decadal investment is higher (up to 6.6 billion m3 per decade) for the 140-region scale during the last four decades of the century, under all climate/development scenarios. This Figure also displays that the lowest capacity projections (circa 0.2 billion m3) appear for the 34-R resolution, under the RCP4.5 and RCP6.0 climate scenarios (see Fig. 3-20).

The forward-looking behavior of the CAMARI model proposes to install optimal decadal capacity following different patterns for each climate-development scenario.

For the RCP2.6 scenario, decadal projections are larger for the 140-R, followed by 34-R, 5-R, and 13-R, except for 2020-2040. Decadal infrastructures projections fluctuate up to 60% for the 140-R, 30% for the 34-R, 27% for the 5-R, and 25% for the 13-R spatial scale (Fig. 3-20).

In the RCP4.5 climate scenario, optimal decadal investment is smaller than other climate scenarios, particularly for the 5-R, 13-R, and 34-R spatial scales. Decadal projected capacity, between 2020 and 2100, increases 500% for the 140-R and rises 40% for the

5-R resolution. The 34-R and 13-R spatial scales display the smallest decadal capacity variations (circa 3%) and values (300 million m3) (see Fig. 3-20).

Under the RCP6.0 scenario, the decadal projected capacity is higher for the 140-R, following by 5-R, 13-R, and 34-R, between 2030 and 2090. During 2020 and 2100, decadal capacity increase by 80% for 140-R, decrease by 20% for 5-R and varies 50% for the 13-R simulations. In this climate scenario, the decadal capacity projections are also the smallest for 34-R resolution, with projections of about 400 million m3 (Fig. 3-20).

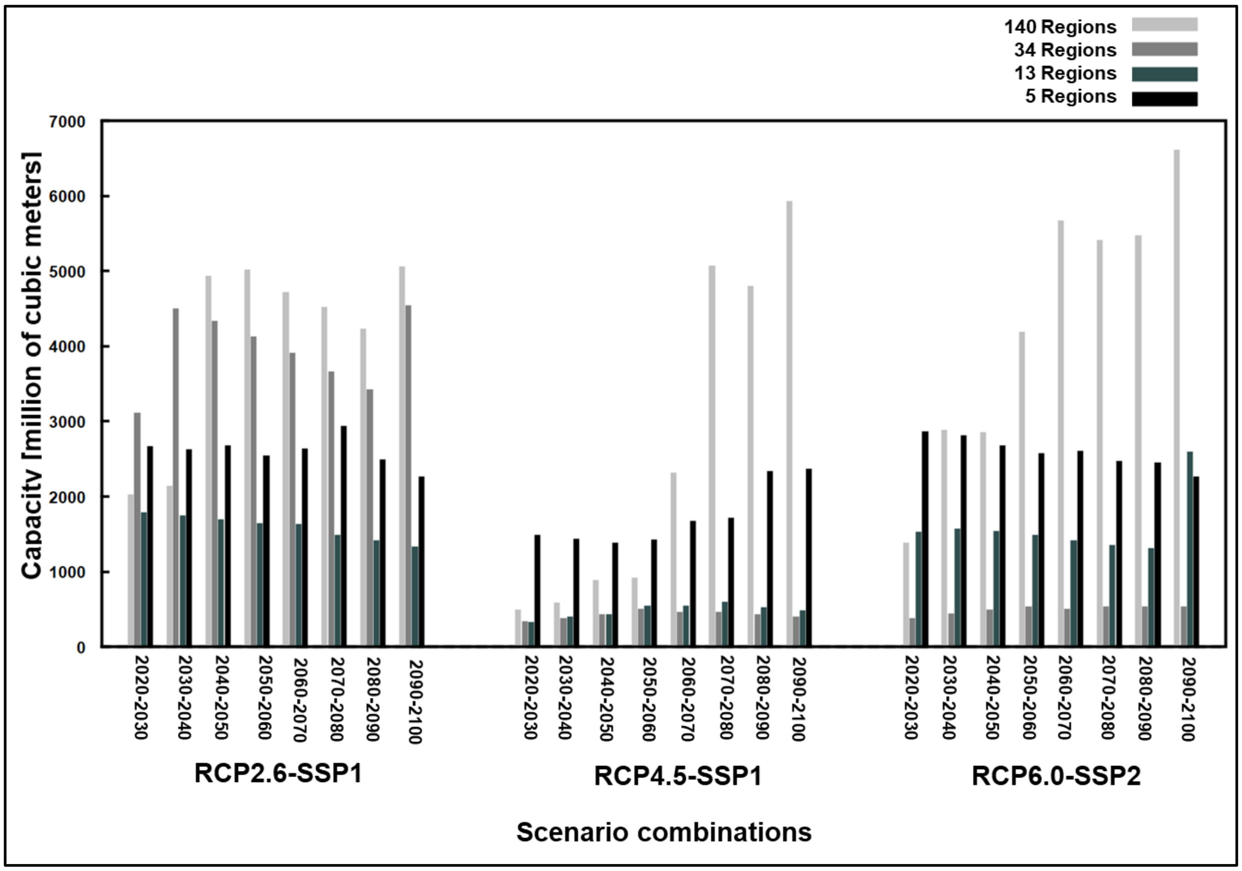


Fig. 3-20. Decadal optimal capacity in water management infrastructures in the entire Magdalena basin for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2). Decadal projected capacity adds values over all regions (spatial scale) in each decade.

Finally, I explore optimal investment costs in water infrastructure for the whole time research. During 80 years of simulations, the model CAMARI builds more infrastructures for the 140-R than 5-R resolution (see Fig. 3-21). Climate-development scenarios do not have an evident impact on 80-year investment, but a spatial scale selection varies considerably projected costs.

For the RCP2.6 climate scenario, 80-year infrastructure investment decreases 50% from 140-R to 34-R, 70% until 13-R, and 85% until 5-R spatial analysis (see Fig. 3-21). Under the RCP4.5 climate scenario, 140-R optimal investment declines 95% to 34 regions, 94% to 13-R, and 80% to 5-R resolution. For the RCP6.0 scenario, 80-year optimal investment decrease 94% among 140-R and 34-R, 80% to 13-R, and 90% to 5-R resolution.
The analysis shows more than 80% optimal investment reduction (~20 billion USD) from 140-R to 5-R resolutions for all scenarios and the studied eight decades. One logical explanation of the optimal investment dynamic is that the model simplified water scarcity for coarser scales modeling, water availability is homogeneously distributed, and fewer infrastructures are required to supply water users. For example, for 5-region resolution, spatial water availability is enough to cover the average water demand, and there are a few signs of water scarcity in the entire Magdalena basin. However, for 140-region resolution, the model CAMARI detects regions where available water would not be enough to supply the demand, and new water infrastructures would be built in the studied region.

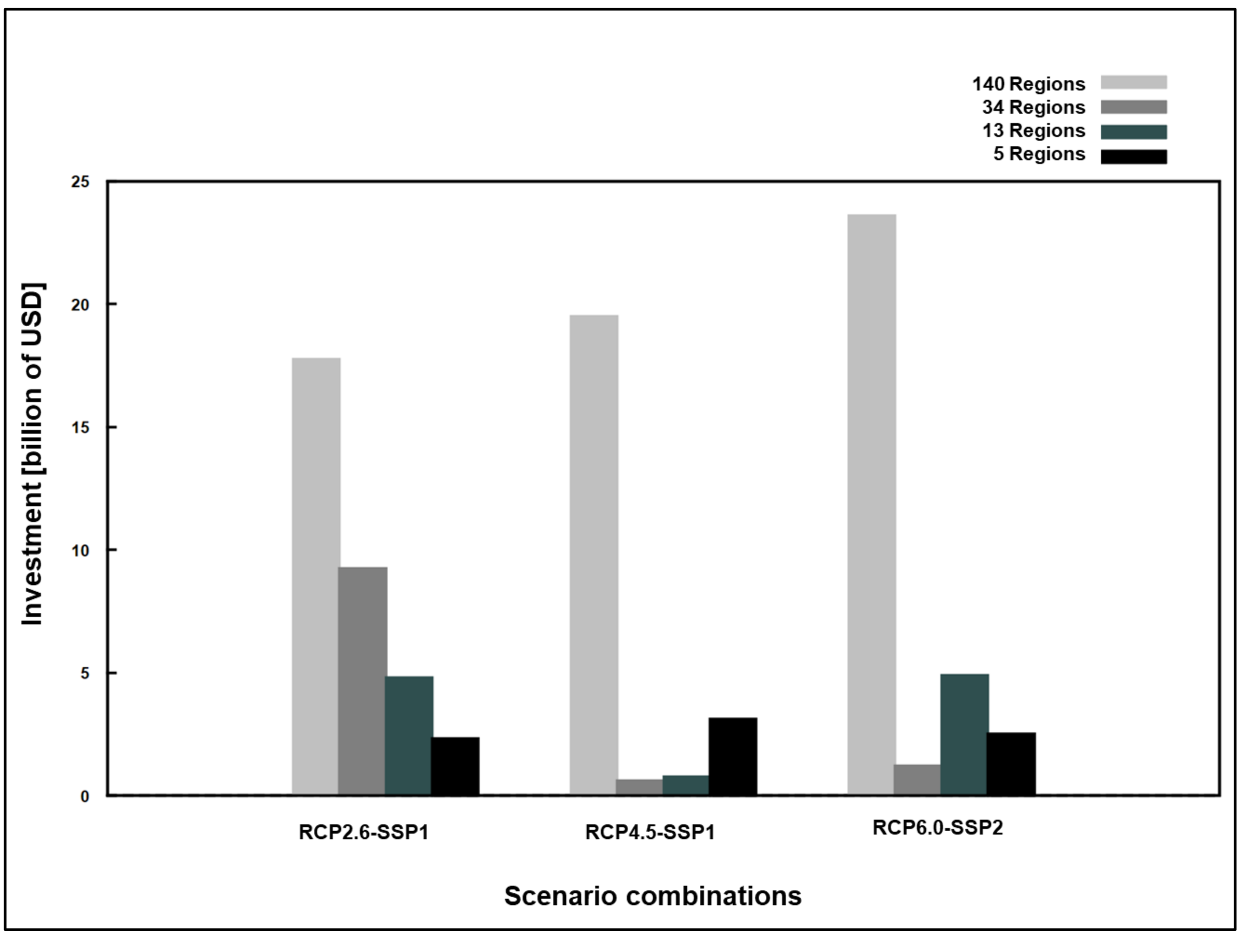


Fig. 3-21. Total optimal investment in water management infrastructures for four physical scales (5, 13, 34, and 140 regions), three climate change (RCP2.6, RCP4.5, and

RCP6.0), and two shared socio-economic pathways (SSP1 and SSP2). Total investment in new infrastructures, adding values for eight decades (2020-2100) and all regions (spatial scale).

4. DISCUSSION

The Magdalena region, South America’s fifth-largest basin, is the most economically and environmentally vulnerable area in Colombia. In this watershed, 95% of Colombia’s thermoelectric and 70% of its hydroelectric power supply are generated. Even though the water availability is circa 300.000 Million m3/ year in the Magdalena basin, water resources are under stress (CORMAGDALENA, 2013, IDEAM, 2018). First, water availability is not uniformly distributed in the area. Second, this region supplies just 10% of Colombia's water demand, although it is home to 70% of the population (~32.5 million inhabitants). Third, the agricultural sector consumes intensively and inefficiently large amounts of water. Finally, large Colombian cities’ location generates high pressure on water resources due to their complex infrastructures for water supply, which implies large pipelines and several reservoirs to connect water sources inside the Magdalena region (CORMAGDALENA, 2013). In addition to the increasing pressure on water resources in this region, it would probably emerge possible water competition between different sectors in the near future. Therefore, modeling water management in the Magdalena watershed will provide scientific tools to explore and compare river management strategies for future scenarios.

This research has mainly two objectives. The first one is to detect future periods of water shortages between hydroelectricity generation and irrigation. The second one explores the impact of spatial scale variation on optimal management solutions in the Magdalena watershed, Colombia.

4.1 Analysis of future water shortages between hydroelectricity generation and irrigation. Optimal investment projections in the Magdalena river basin.

Future water conflicts between hydroelectricity and agricultural sectors can be better understood by analyzing projected climate and socioeconomic scenarios. By CAMARI model simulations, I research possible periods when water competition will emerge between hydroelectricity generation and irrigated food production in the Magdalena river basin. As I mentioned before, in several regions worldwide, existing hydroelectricity generation competes with irrigation water (Zeng et al., 2017). My modeling assessment detects future water conflicts between two main economic sectors in the Magdalena river basin in Colombia.

Although hydropower generation is a low water consumptive sector, water competition relationships will arise in the next decade. After comparing monthly/decadal projections of reservoir storage levels, water availability, and irrigation demand, the CAMARI model simulations detect water-supply timing conflicts. Monthly simulations depict high irrigation uses but low water availability during the first quarter of a year in the Magdalena region.

Monthly time steps can display water management alternatives for water supply problems inside irrigation seasons (Cutlac et al., 2006). The results indicate that water conflicts will arise in the Magdalena region during 2030-2040 (especially in January), when the largest irrigation values and the lowest storage levels of reservoirs would be present under minor water availability scenarios (RCP2.6-SSP1, RCP6.0-SSP2). Between 2030 and 2040, it may occur water competition between irrigation and hydroelectricity generation. Water released for irrigation purposes may reduce reservoir storages, thereby reducing hydroelectricity generation, especially during dry periods, when demand for irrigation and energy may be largest (Tilmant et al., 2009).

This main result of the hydroelectricity analysis follows the recommendations of the research conducted by Zeng et al. (2017). They explored hydropower-irrigation relationships at the global level with support vector machines inside FPU (food production units). The mentioned authors suggested that future climate/development scenarios have to be included to research hydroelectricity-irrigation relationships. Zeng et al. (2017) also detected that the storage of existing reservoirs for hydropower production enhances water supply for irrigation along the Andes, where the Magdalena river basin is located. While this previous research does not detect a current regional competition between irrigation and hydroelectricity, this study demonstrates future water conflicts due to global changes. Developing countries, such as Colombia, have not exploited the whole hydropower potential (Berga, 2016). Climate and socio-economic modeling of hydroelectricity generation is a scientific tool to support this sector growth. Though hydropower generation requires a significant initial investment, this renewable energy source has low operation and maintenance costs (Berga, 2016). Moreover, it is a trend of an increasing expansion of hydroelectricity worldwide. With a total investment of around 2 trillion USD, three thousand seven hundred major hydro projects will be located in 102 developing countries in South America, Asia, and Africa (Zarfl et al., 2015).

In this context, CAMARI simulations also project 99% of dam-reservoir capacity as optimal infrastructures until 2100, under RCP2.6-SSP1, RCP4.5-SSP1 and RCP6.0-SSP2 scenarios to fulfill future water demand of the agricultural, household, industrial, and hydropower sectors. For the next eight decades, CAMARI simulations project to install an increasing dam-reservoir capacity between 15 and 35 billion cubic meters for the RCP2.6 scenario, among 10 and 17 billion cubic meters for the RCP4.5, and between 27 and 36 billion cubic meters for the RCP6.0 (see Fig. 3-5). The increasing number of projected reservoirs responds to the hydroelectricity demand and future water availability in the Magdalena basin. Thus, optimal infrastructure’s projected capacity is higher for climate scenarios of reducing water availability (RCP2.6 and RCP6.0). In multi-use dam projections, hydroelectricity storage is a kind of climate change adaptation (Berga, 2016) that prevents water shortages and supplies water to household, industrial and agricultural sectors.

Another primary outcome of the hydropower analysis depicts that the agricultural, household and industrial sectors will experience economic scarcity of water between 2020 and 2040 for the selected scenario combinations. The price for an extra unit of water to supply the mentioned sectors will be large for the first two modeled decades under the studied climate-development scenarios (RCP2.6-SSP1, RCP 4.5-SSP1, and RCP6.0-SSP2) in the Magdalena basin. While Tarjuelo et al. (2010) associated the economic water scarcity with a lack of investment in water infrastructures in a region, Draper et al. (2003) proposed the shadow prices as an indicator of water scarcity across spatial and time scale. Even though there is enough water available in the Magdalena basin, the agricultural, household, and industrial sectors will experience economic water scarcity without the optimal infrastructure investment, especially in 2020-2040.

Previous studies applied dynamic modeling to explore the benefits associated with hydropower and irrigation in river basins. 35-years of watershed modeling results showed that an expansion of irrigated areas (for various climate scenarios) would decrease hydroelectricity generation but probably raise the region's economic benefit (Hassanzadeh et al., 2014). In the Euphrates River, annual benefits would be 6% higher with a dynamic allocation of water for up/downstream farmers and hydropower generation (Tilmant et al., 2009).

Simulation analysis of the Magdalena region's benefits compares 80-years (2020-2100) of water consumption welfare for future scenarios. First, decadal welfare (see fig. 3-10) displays the highest value for RCP4.5-SSP1 (circa 32 billion USD), followed by RCP2.6-SSP1 and RCP6.0-SSP2 scenarios, with some decade exceptions. Second, the most significant benefit component is the endogenous price of agricultural goods, which 80-years values are circa 400 million USD for all projected scenarios (See Fig.3-11). Third, the analysis confirms the relevance of dam-reservoirs investment (the highest costs) on the welfare dynamic. 80-year investment in dams is circa 100 billion for the RCP4.5-SSP1 and 200 billion USD for the RCP2.6-SSP1 and RCP6.0-SSP2 climate scenarios (See Fig. 3-11). Finally, the results suggest that more abundant water resources (RCP4.5 climate scenario) imply a decreasing infrastructure investment but an increase in total benefits.

Whereas hydroelectricity simulations deliver valuable outcomes into the hydropower-irrigation relationships, this modeling analysis has its shortcomings. First, the study does not include water losses for potential evapotranspiration and located seepages in the reservoirs. Second, hydropower simulation excludes historical information about downstream flows and storage levels of reservoirs. Finally, the simulation results are constrained by the unavailability of municipal historical electricity information.

Recent studies remark the hydropower contribution to climate change mitigation and its important role as an adaption strategy. However, more research has to be done to find solutions to reduce hydroelectricity environmental and social costs (Berga, 2016).

4.2 Impact of the spatial scale variation on modeling water management in the Magdalena river basin

Researchers worldwide have been increasingly applied computational models for integrated river management (Cutlac et al., 2006). Water-economy models, which couple hydrological and economic processes, produce alternative management solutions at various spatial and temporal scales (Bekchanov et al., 2017). These models, which run at several physical-time resolutions, need a suitable level of aggregation to efficiently portray regional land features and water use dynamics (Bekchanov et al., 2012).

CAMARI model is an example of water-economy modeling to aggregate economic, geospatial, agricultural, and climate input data at various spatial-temporal resolutions. With the forward-looking and welfare-maximization feature of the modeling process, it is possible to compare optimal water management outcomes at four resolutions (140, 34, 13, and 5 water regions) in the Magdalena region.

One of the main results of the spatial simulations is that 80-year benefits increase circa 5% (~10 billion USD) with the scale reduction from 140 regions (140-R) to 13 areas (13-R) for the RCP2.6-SSP1, RCP4.5-SSP1, and RCP6.0-SSP2 scenarios (see fig. 3-12). First, total net benefits decline circa 2% (~4 billion USD) between 13 regions and five regions (5-R) scales. Second, the 13-R resolution depicts the highest total welfare under the modeled scenarios. As I explained in section 3.2.1, the welfare behavior follows the selected scenarios' benefits and costs tendencies. Finally, the scale analysis depicts a minimum impact of climate/development scenario variations on 80-years welfare for water consumption.

The spatial simulation results also display that 80-years welfare (under the RCP2.6-SSP1 scenario) contains two relevant components: the endogenous price of agricultural commodities and crop production costs. The agricultural sector benefits are the highest revenue item, which declines circa 4% from 140-R (~400 million USD) to 5-R (~384 million USD) resolution. The crop production costs, the most significant expenditure, increase 15% from 140-R (~110 million USD) to 5-R (~126 million USD) spatial scales (see fig. 3-14).

This last finding is comparable with the estimation of agricultural benefits at two resolutions in the Rio Grande-Rio Bravo Basins in North Mexico (Medellín-Azuara et al., 2008), considering yield projections until 2100. For the mentioned area, climate change varies agricultural benefits from -22,6% to 7.6% (farm-level), and from -10% to 10% (irrigation district scale). Other research extrapolated the economic impacts of climate change from several river basins to the national level, in the USA. Hurd et al. (2004) research displayed that agricultural-sector welfare gains of 65 million USD (1994 USD) with the increase of 1.5°C and 15% precipitation during 39-years modeling periods.

In the Magdalena region, agricultural demand simulations at several resolutions show a variable decadal pattern (see fig. 3-16). In the case of five region simulations, agricultural water use varies between 13 and 25 billion cubic meters per decade. For 13-R, 34-R, and 140-R, decadal water consumption fluctuates between 2 and 8 billion cubic meters. The comparison between spatial simulation highlight that 5-R agricultural water use is more than 300% larger than other spatial scales for all studied climate-development scenarios. Even though the 5-R crop areas are circa 20% higher than different resolutions (see fig.3-17), the model detects more necessity of irrigation for five regions scale (the coarsest scale). One possible explanation of the five regions' agricultural-demand high values is described in the multiscale GIS and statistical analysis outcomes in three river basins (North America, South Asia, and Europe) (Perveen and James, 2010). The authors found that the underlying pattern processes increase the variability of water uses at coarser spatial scales.

Regional water resources should be explored at several physical resolutions. One of water management research's main goals is to understand processes at different scales and find linking patterns across scales (Perveen and James, 2010). In this context, 80-years of spatial simulations build 35% more infrastructure capacity for the 140 regions than five regions in the Magdalena basin. When more water is available (RCP4.5), optimal projections of infrastructures decrease around 85% compare to other climate scenarios (RCP2.6 and RCP6.0) for all the studied spatial scales (see Fig. 3-19). Interesting to observe is that the optimal water infrastructures for larger resolutions (140 regions) are reservoirs but for coarser scales (5 regions) are pumping stations (table 3-2). Another relevant finding is that decadal infrastructure projections are lower for coarser spatial scales (34, 13, and 5 regions) and minor water availability -RCP4.5-. Spatial-time analysis in the Magdalena river basin applies the recommendations from Cutlac et al. (2006). The authors recommended studying the impact of climate change on water storage investment with models that consider long-run decadal steps as the time scale.

Finally, the spatial scales analysis shows more than 80% optimal investment reduction (~20 billion USD) from 140-R to 5-R resolutions, between 2020 and 2100, for the studied scenarios in the Magdalena watershed. One possible explanation of the optimal investment dynamic is that the model simplified water scarcity for coarser scales, water availability is homogeneously distributed, and fewer infrastructures are required to supply water to the end-users. Spatial modeling findings are consistent with those reported by Perveen and James (2010). They concluded that the spatial variability of the water stress/scarcity index declines for coarser scales due to possible intra-cell averaging processes.

Last, increasing water resource pressures in the Magdalena region had motivated my research in water management at various physical resolutions. Even though the scale simulations approach properly data input aggregation between different resolutions, the spatial scale algorithm must be improved to detect physical water scarcity signs and compare the weighted-quantitative future welfare effectively.

In the end, water-economy models (WEMs) are helpful to integrate hydrologic and economic systems, looking for water management strategies at different spatial and temporal resolutions (Bekchanov et al., 2017). An extensive literature review has detected just a few WEMs in South America (Bekchanov et al., 2017). Applications of this modeling in the Magdalena river basin, located in a lower-income country, produce novelty insights.

5. Benefits of forward-looking water management – A case study of the Cauca-Magdalena river basin

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5.1 Introduction

Freshwater is an essential resource for human life. Climate and human activity have influenced water supply in the past and are likely to increase this influence in the future(UNESCO, 2012). Decision-makers and managers in vulnerable regions can benefit from early planning and the forward-looking implementation of adaptation strategies to supply enough affordable freshwater for the people and reduce the water scarcity related impacts on malnutrition, disease, energy shortages, and poverty (UNESCO, 2012). Previous studies on water management adaptation to climate change include factors such as water demand, water supply, water prices, water policies, water trading, investments and operating costs of water infrastructures, and transboundary water allocation. Adaptation through investments in water infrastructures and changes in infrastructure operations plays an important role because a higher storage capacity of infrastructures ensures a safer water supply and serves as a prevention against floods (Olmstead, 2014). The cost of adapting existing infrastructures to climate change is estimated at 2% of total baseline infrastructure provision for OECD countries (Hughes et al., 2010). Globally, Ward et al. (2010) estimated that in order to adapt to climate change, global reservoir storage capacity should be increased to ca. 2090 cubic kilometers until the year 2050, with a yearly average net cost of 12 billion US dollars. These two studies show the magnitude of investments needed to ensure future freshwater supply and highlight the need for efficient planning, as many vulnerable regions are located in low-income countries where funds are limited (UNFCCC, 2007). However, this poses a problem as the rules and processes investment decisions follow are unclear and hard to reconstruct (Olmstead, 2014) and often follow irrational economic behavior and regional particularities and politics more than any optimized procedure.

In this study, we examine how a sophisticated planning algorithm for water infrastructure investments affects welfare compared to simple business as usual decision-making. As water resource planning is increasingly done at the watershed scale (Loucks et al., 2005), we focus in our study on the economically significant Magdalena river basin in Colombia. While Colombia is generally classified as a water-rich country, water shortages are projected in the future without adequate water management infrastructure investments (Domínguez et al., 2008). Currently, all required instruments for an effective integrated water resource management, such as legislation and economic and administrative components for water allocation, pollution control, water demand for various sectors, and ecosystem/watershed management, are present in Colombia. Nevertheless, the instruments are not correctly coupled and applied (Blanco, 2008). To assess the potential benefits of an optimized integrated water management, we use the constrained optimization model "CAMARI". We simulate different scenarios of water infrastructure investment decisions, with i) two myopic business-as-usual decision scenarios, and ii) a forward-looking, dynamically optimized decision scenario. We compare the welfare effects of both scenarios and estimate the benefits of employing sophisticated methods in planning.

5.2 Data and Methods

5.2.1 Study area

The Magdalena River originates at 3685 m.a.s.l. in the Colombian Andes, runs for about 1540 km from South to North through the Western half of the country, and terminates in the Caribbean Sea. The Magdalena catchment encompasses 151 sub-watersheds, based on tributaries classification, whose 109 lower-order subbasins feed 42 tributaries that drain directly into the Magdalena main river. The watershed and the main tributaries cover 257 438 km2, which corresponds to 24% of Colombia's total surface (Alfonso et al., 2013). Due to the complex topography of the Magdalena region, it is challenging to generalize rainfall patterns. In both major valleys – the Magdalena and the Cauca – the highest rainfall (around 3000 mm/yr) is received at intermediate elevations of approximately 1500m. Regions above 3000m height typically receive far less (~1000 mm/yr) and the Magdalena valley bottom slightly less (1700 mm/yr) precipitation (Lopez and Howell, 1967, Restrepo et al., 2006). Mean precipitation for the whole drainage basin is 2050 mm/yr, and average runoff amounts to 953 mm/yr (Kettner et al., 2010). The Magdalena River shows the highest discharge and highest water withdrawals of all rivers in Colombia. More than 70% of the Colombian population lives in its basin, which is therefore of very high socio-economic importance for the country (IDEAM, 2001).

5.2.2 Description of the CAMARI Model

To study investment decisions for various water management infrastructures, we developed a constrained welfare maximization model called CAMARI for the CAuca and MAgdalena RIvers. The model determines the optimal times and locations for the construction of water management infrastructures. At maximum resolution, the model depicts 333 stream-linked subbasins. Time is resolved in two ways. Ten decadal time steps are used to portray changes in water supply and water demand until 2100. These changes are driven by climate change, population growth, and income development. We use a monthly resolution to portray the intra-annual variability of water supply and demand within each decade. We do not represent individual years in order to keep the computational requirements at manageable scales.

We distinguish water demand from households, industry, and the agricultural sector. Water management infrastructures include reservoirs, wet ponds, and pumping stations (intakes). Wet ponds are small reservoirs with a permanent pool of water throughout the year and can be used for high flow mitigation and the supply of irrigation water (Blick et al., 2009). On the other hand, reservoirs are larger structures for water storage and gradual release. Pumping stations extract water from the river and deliver it immediately to the users. In the model, wet ponds supply water only to agricultural users, reservoirs to households and industry users, and pumping stations to all user groups. Construction and operation prices for reservoirs, wet ponds, and intakes were taken from the literature (CASQA, 2003, INEA, 1997).

In the following, the mathematical structure of the model is described. For an overview, all variables and indices are listed in Table 5-1.

The objective function of CAMARI (Eq. 5-1) maximizes the net benefits *W* of water consumption in the Magdalena river region by aggregating total benefits B_{total} and subtracting total costs C_{total} over decades *d* in consideration of a discount factor *f*:

Maximize $W = \sum_{d} \left(f_d \left(B_d^{total} - C_d^{total} \right) \right)$ (5-1)

Total benefits are the sum of agricultural and household/industry sector benefits (Eq. 5-2). Agricultural sector benefits $B_{agriculture}$ are estimated by integrating the area underneath the agricultural water demand function curve; initial household/industry benefits $B_{household,Industry}$ by calculating the product of water price *p* and demand *V*. Both benefits are summed over all subbasins/subregions *r*, decades *d*, months *t*, and, in case of the non-agricultural water demand, $B_{household,Industry}$ over sectors *s* and segments *g*.

$$
\begin{aligned}
&B_{total} = B_{agriculture} + B_{Household,Industry} \\
&B_{agriculture} = \sum_{d,t} \left(\int \rho_{d,t,\text{"agriculture"}} \left(\sum_{r} V_{r,d,t,\text{"agriculture"}} \right) d \left(\sum_{r} V_{r,d,t,\text{"agriculture"}} \right) \right) \\
&B_{Household,Industry} = \sum_{r,d,t,s,g} p_{r,d,t,s,g} \cdot V_{r,d,t,s,g}
\end{aligned}
\qquad (5\text{-}2)
$$

Total costs are calculated as the sum of the costs of water supply, water management operations, and water management installations (Eq. 5-3). Water supply costs are calculated as the sums of endogenous and constant per unit-costs, where endogenous costs of water supply are described as the area underneath an upward sloped marginal cost the inverse supply function, and constant per unit- costs as the product of water supply cost *sc* and the amount of water supply *S*. Water management operation costs are calculated as the product of the cost of water management operation *o* per structure and the amount of water operated *O*. Finally, the costs of water management installations are calculated as the product of infrastructure costs *m*, the number of infrastructures installed *M* and the maximum capacity of the infrastructures *k*. The sub-index *m* represents the storage (m_1), inflow (m_2) and outflow (m_3) of water from a specific infrastructure.

$$
\begin{aligned}
C_{total} = & \sum_{d,t}\left(\int \rho_{d,t,\text{"agriculture"}}\left(\sum_{r} S_{r,d,t,\text{"agriculture"}}\right) d\left(\sum_{r} S_{r,d,t,\text{"agriculture"}}\right)\right) \\
& + \sum_{r,d,t,s}\left(sc_{r,d,t,s}\cdot S_{r,d,t,s}\right) + \sum_{r,d,t,i}\left(o_{r,d,t,i}\cdot(O_{r,d,t,i,m_2}+O_{r,d,t,i,m_3})\right) + \sum_{r,d,t}\left(o_{r,t,intake}\cdot O_{r,d,t,intake,m_1}\right) \\
& + \sum_{r,d,i}\left(m_{r,d,i}\cdot k_{r,i}\cdot M_{r,d,i}\right)
\end{aligned}
\qquad (5\text{-}3)
$$

The objective function is constrained by several physical restrictions. Non-agricultural water demand has to meet exogenously prescribed minimum values:

$$V_{r,d,\mathrm{t},s,g} \geq q_{r,d,t,\mathrm{s},g} \qquad \text{for all } r,d,t,s\neq\text{"agriculture"},g \qquad (5\text{-}4)$$

The amount of water managed through specific infrastructures cannot exceed the established infrastructure maximum capacity from current and previous installations:

$$O_{r,d,t,i,m_1} + O_{r,d,t,i,m_2} \leq \sum_{d,a}\left(c_{r,i,a}\cdot P_{r,d,i,a}\right) + e_{r,d,i} \qquad \text{for all } r,d,t,I \qquad (5\text{-}5)$$

The amount of water contained in a water storage structure equals the water volume from the previous period plus additions minus releases during the current period:

$$O_{r,d,t,i,m_1} + O_{r,d,t,i,m_3} = \sum_{t-1,t} O_{r,d,t-1,i,m_1} + O_{r,d,t,i,m_2} \qquad \text{for all } r,d,t,i \qquad (5\text{-}6)$$

For each decade, we depict the equilibrium situation, i.e. each month is linked to the previous month, and January is linked to December.

The total supply of water has to be less than or equal to the amount of water managed by the infrastructures:

$$\sum_s S_{r,d,t,s} \le \sum_i O_{r,d,t,i,m_3} + O_{r,d,t,intake,m_1} \qquad \text{for all } r,d,t \qquad (5\text{-}7)$$

The water balance between inflow, outflow, environmental flow, and water operated out of the system has to be less than water supply from runoff plus return flow:

$$\sum_i O_{r,d,t,i,m_2} + O_{r,d,t,intake,m_1} + OF_{r,d,t} - IF_{r,d,t} + ef_{r,d,t} - z \cdot \sum_{s,g} V_{r,d,t,s,g} \le s_{r,d,t} \qquad \text{for all } r,d,t \qquad (5\text{-}8)$$

Inflow has to be equal to the outflow between regions:

$$IF_{\mathrm{r},d,\mathrm{t}} = \sum_{\tilde{r},\Delta t} \left(tv_{\tilde{r},r,\Delta t} \cdot OF_{\tilde{r},d,t} \right) \qquad \text{for all } r,d,t \qquad (5\text{-}9)$$

Regional demand has to be less than or equal to water supply:

$$\sum_g V_{r,d,\mathrm{t},\mathrm{s},\mathrm{g}} \le \quad S_{r,d,t,\mathrm{s}} \qquad \text{for all } r,d,t,s \qquad (5\text{-}10)$$

The model represents the age of the installed infrastructures over time. Transition equations for all periods ensure that the number of maintained infrastructures for all advanced age cohorts (index *a>1*) does not exceed the number of the corresponding (*a-1*) active infrastructures installed in the period before (*d-1*):

$$P_{r,d,i,a} \le M_{r,d,i}\Big|_{a=0} \quad + \sum_{(d\text{-}1),(a-1)} P_{r,d-1,i,a-1} \qquad \text{for all } r,d,i,\ a>1 \qquad (5\text{-}11)$$

The total amount of water managed by the infrastructures (storage, inflow, outflow) has to be greater or equal to inflow water managed by the infrastructures:

$$T_{r,d,i} \ge O_{r,d,t,i,m_2} \qquad \text{for all } r,d,t,i \qquad (5\text{-}12)$$

Finally, the declining infrastructure capacity has to be greater than or equal to the total amount of water managed by the infrastructures:

$$\sum_{p,a} c_{r,i,a} \cdot P_{r,p,i,a} \ge \sum_p T_{r,p,i} \qquad \text{for all } r,i \qquad (5\text{-}13)$$

We programmed and solved the above equations in GAMS (General Algebraic Modeling System)(GAMS, 2013b).

5.2.3 Input data

We employed data on both water supply and water demand from sources such as geospatial databases, national statistics, and model outputs (see Table 5-2 for an overview).

Surface runoff data for the years 2006-2099 were provided by the terrestrial hydrology group of the Max Planck Institute for Meteorology in Germany, using the global hydrological model MPI-HM (Stacke and Hagemann, 2012) with climate input data from the gfdl-esm2m global model run under the RCP4.5 scenario (Thomson et al., 2011) in the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013) with a resolution of 0.5°x0.5°.

Based on a literature review, we chose reservoirs, wet ponds, and intake infrastructures as possible infrastructure alternatives (Tarjuelo et al., 2010, Brikke and Bredero, 2003, Blick et al., 2009, Santos Pereira et al., 2009). We define reservoirs as water management structures for water storage and gradual release, wet ponds as constructed small river reservoirs that have a permanent pool of water throughout the year and can be used for high flow mitigation and the supply of irrigation water (Blick et al., 2009), and intakes as infrastructures that extract water directly from the source and send it to the users. In the model, reservoirs supply water to household and industry users, wet ponds to agricultural users, and intakes to all user groups. Construction and operation prices for reservoirs, wet ponds, and intakes were taken from the literature (CASQA, 2003, INEA, 1997).

Historical monthly water prices and water quantities for the Magdalena river basin were taken from the Public Information Service in Colombia (Sistema Único de Información de Servicios Publicos). The database comprises records for states, counties, water supply enterprises, sectors (household, commercial, official or industrial), and regional water tariffs for urban and rural sites covering the period 2004-2012. Current and projected agricultural water consumption was simulated with the generalized crop model EPIC (Williams and Singh, 1995). EPIC was run for the Magdalena watershed with the same climate input data as the hydrological model for the years 1990-2099. It provided monthly estimates of irrigation water use and evaporation for 17 major crops grown in Colombia.

Finally, county-level demographic data for the year 2005 and historical values of the gross domestic product were taken from the National Administrative Department of Statistics (Departamento Administrativo Nacional de Estadísticas de Colombia). The GDP data are classified at the state level and were recorded between the years 2000 and 2011. Water incomes and water price elasticities per sector were taken from the literature (Rosegrant et al., 2002a, Dalhuisen et al., 2003, Krause, 2007).

We aggregated the 333 original subbasins of the Magdalena River Basin into ten aggregated subregions for the simulations. All national, state and county-level data were disaggregated into these regional units. The disaggregation procedure and all parameter sets describing each subregion are described in detail in the supplementary material.

5.2.4 Scenarios

To analyze the effects of different investment decision rules on infrastructure installations and capacity and investment costs, we simulate three scenarios: one fully dynamic optimization scenario and two myopic optimization scenarios. The fully dynamic optimization scenario mimics a far-sighted decision-maker that will invest in water management in the most profitable way possible, with full consideration of projected supply and demand changes over the entire time horizon (2000-2100). The first myopic scenario mimics a short-sighted decision-maker who decides investments assuming that current levels of water supply and demand will persist into the future. The second myopic scenario mimics a decision-maker who assumes that supply will stay constant but that demand will keep changing at the same rate as in the current decade.

For water supply, we simulate three variations, ranging from minimum values, average values to maximum values, all based on the simulation results for surface runoff of the MPI-HM Global Hydrological Model under the RCP4.5 scenario (details see Table 5-3).

Several scenarios of population and income growth rates based on different SSP (Shared Socioeconomic Pathways) storylines were available for Colombia (Fig. 5-1 and 5-2). One set of projections was provided by the OECD modeling framework, in which it is assumed that income levels of different countries will converge to most developed economies (Barro and Xala-i-Martin, 2004). The second set of projections was provided by the IIASA GDP model and is based on the population's per capita income and educational characteristics (Crespo, 2012).

We also vary the discount rate from 1% to 5%, as this parameter can strongly modify the maximization of welfare in the objective equation.

The baseline scenario assumes a fully dynamic optimization, 2010 water supply, and income and population growth rate, and two discount rates. Overall, we simulate 27 scenario combinations.

5.3 Results

The results show that using a fully dynamic optimization procedure generally increases welfare in comparison to the myopic scenarios over the whole time period (Fig. 5-3). The differences increase over time. The only situation where a fully dynamic optimization decreases welfare compared to myopic behavior is the decade 2000-2010. Hereunder a fully dynamic optimization, initial strategic investments are made to optimize welfare over the whole century.

Fig. 5-4 shows that total costs (investments plus operation costs) are always lowest in the fully dynamic scenario, even though differences are minor during the first decades until

2040-2050. In the later decades, differences increase as costs under the two myopic scenarios continues to increase, whereas costs in the fully dynamic scenario even start to decrease until they reach a plateau. The reason for this can be seen in Fig. 5-5, where the water capacity of installed infrastructures is plotted. In the fully dynamic scenario, water supply and demand are accurately predicted for the whole time horizon and integrated into the infrastructure planning so that capacities are adapted to the actual need. In the myopic scenario with increasing demand rates, on the other hand, the need for capacities is overestimated, and thus costs are high. This is also illustrated in Fig. 5-6, where the costs of management of one cubic meter in the Magdalena river basin are shown. Costs are highest under the Myopic Supply and Demand Growth scenario, as installation, operation, and maintenance costs increase the costs of every unit managed. The figure also shows that costs are only rising until the decade 2060_2070, after which they decline in all scenarios. In general, total costs for installing and managing water infrastructures are smaller when full dynamic optimization rules are considered.

Besides different modes of decision making different scenarios of water supply and GDP/population growth rate also influence results (Fig. 5-7). Under average water supply, welfare gains under the fully dynamic decision mode are lower than under more extreme scenarios of water supply. This shows that short-sighted decision-making is not as problematic as long as conditions remain relatively unchanged. However, if the water supply is lower or higher than anticipated, a more far-sighted planning increases welfare markedly. The fully dynamic scenario also increases welfare in comparison to myopic behavior if GDP/population growth is high (AV_OECD3_OECD6), showing that an optimized planning is necessary as demand increases.

Finally, to show that water demand and simulated installed capacity are geographically consistent in CAMARI, Fig. 5-8 depicts water demand and capacity in the ten simulated subregions of the Magdalena river basin. Subregion 1 represents the area which the highest water demand and highest installed water infrastructure capacity newly.

5.4 Discussion and Conclusions

Optimization methods are planning tools to identify the best strategies for capacity and management measures (Loucks et al., 2005). Mass et al. (1962) and Loucks et al. (1981) developed the first studies of water resources that involve economic objectives and constraints. Later studies included optimization approaches for cost-benefit analysis of water resource operation strategies (Belaineh et al., 1999, Labadie, 1997, Labadie, 2004, Lund and Guzman, 1999, Mayer et al., 2002, McPhee and Yeh, 2004, Rao et al., 2004, Watkins and Moser, 2006). Although these existing studies have advanced the integration of economic and physical processes, their modeling scope was limited (Mayer and Muñoz-Hernandez, 2009).

One of the main objectives of integrated water resources assessments is to maximize economic benefits concerning water allocation (Mayer and Muñoz-Hernandez, 2009). Some integrated water studies consider optimization of infrastructure investment by improving water use efficiency (Cai et al., 2002, Cai et al., 2003a, Cai et al., 2003b, Cai and Rosegrant, 2004, Ringler and Cai, 2006), other studies minimize the risk of water shortage (Draper et al., 2003, Jenkins et al., 2004, Pulido-Velázquez et al., 2006), and other studies analyze water markets (Cai et al., 2003a, Cai et al., 2003b, Jenkins et al., 2004, Pulido-Velázquez et al., 2006, Ringler et al., 2006a, Rosegrant et al., 2000, Ward et al., 2006).

Many developing countries face a comparatively high pressure to adapt to climate change. In the introduction, we described the necessity of investments in existing/new water management infrastructures (Ward et al., 2010, Hughes et al., 2010), but also that financial resources in developing countries are limited (UNFCCC, 2007), and that investment decisions are often not economically efficient (Olmstead, 2014). To demonstrate the benefits of using state-of-the-art optimization tools for water management in river basins, we simulated several scenarios of decision-making, water availability, and development rates. For this, we used the newly developed model CAMARI.

The results show that using a tool for optimizing investment decisions increases welfare by 120.000 million USD over the next century in the Magdalena river basin. It also decreases investment costs: At the end of the century and under extreme development scenarios, forward-looking decision-making may save up to 50.000 million USD in investments and operating costs compared to short-sighted decisions. Even though Colombia is classified as a water-rich country (Domínguez et al., 2008), its resources are limited and not equipped to regulate this water supply optimally. New methodologies have to be implemented to plan water resources in an optimal direction with low investment costs.

However, it should be kept in mind that we only used one RCP scenario (RCP4.5), and only a few scenario combinations of water availability and GDP/population growth. Further studies are needed to evaluate the influence of differences RCPs and additional scenario combinations on water management in the Magdalena river basin.

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Supplementary material

Figures

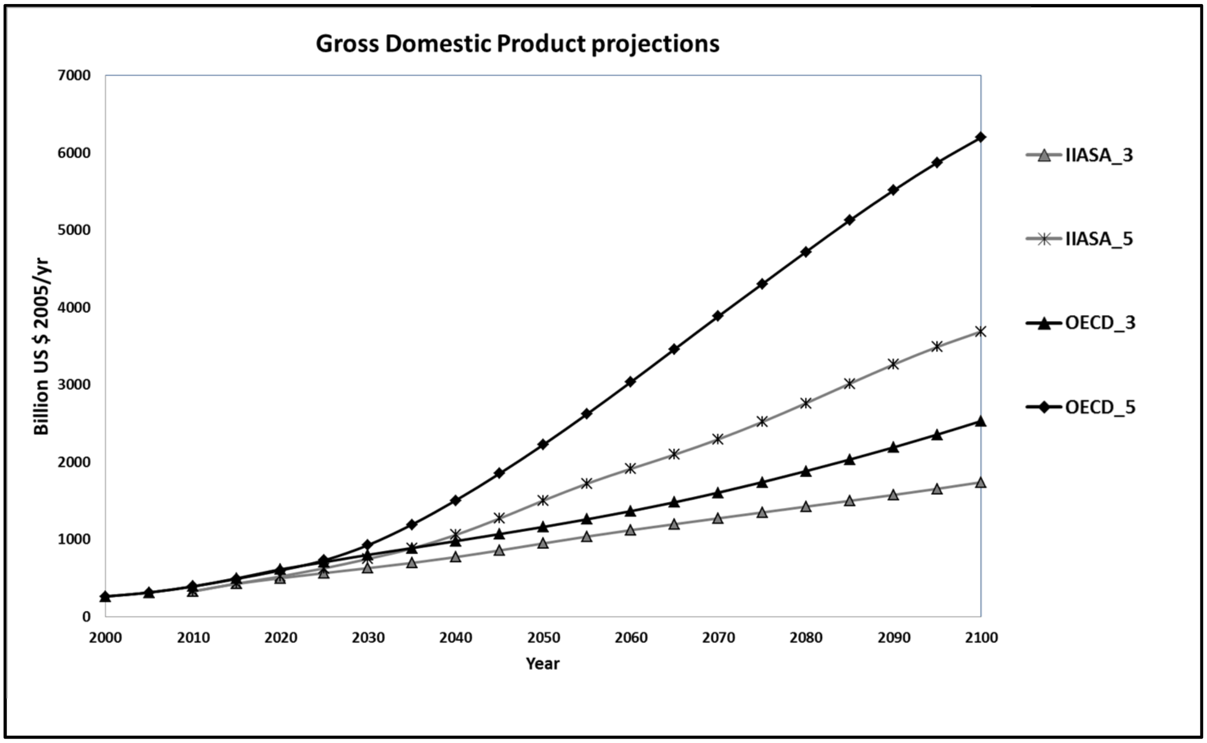

Fig. 5-1. Gross domestic product projections for Colombia. Source: SSP Database (Version 0.93) Link: Link: https://secure.iiasa.ac.at/web-apps/ene/SspDb.

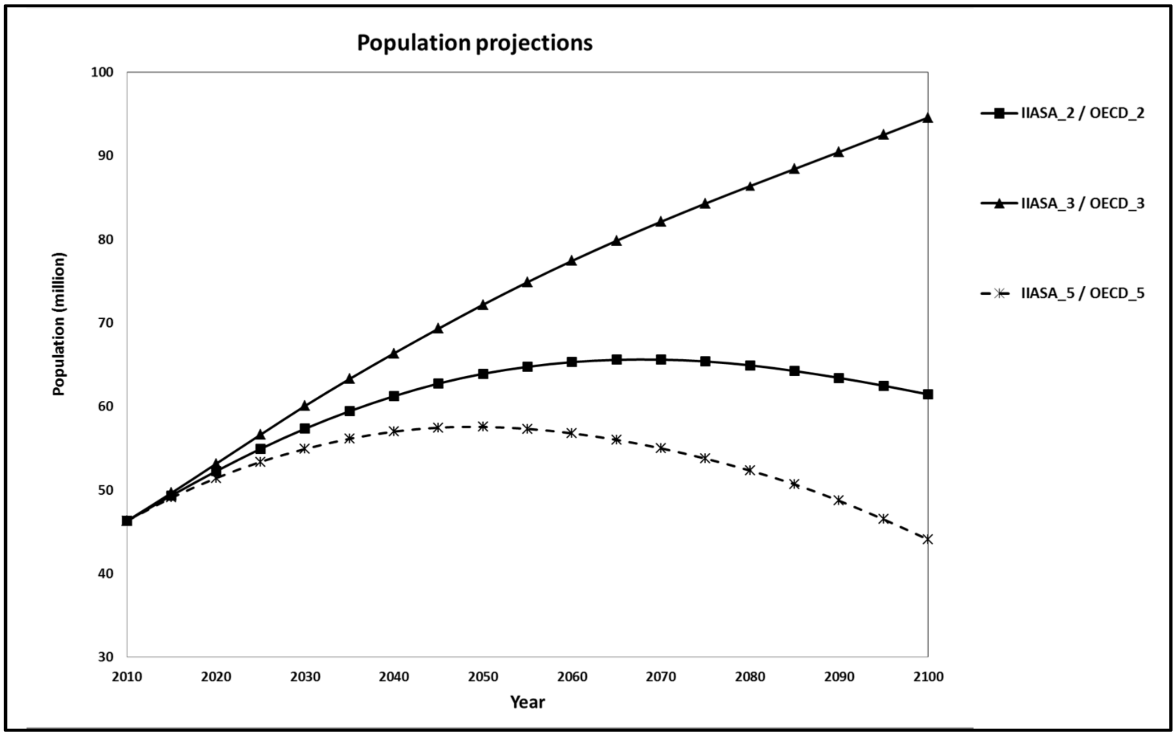

Fig 5-2. Population projections for Colombia. Source: SSP Database (Version 0.93) Link: https://secure.iiasa.ac.at/web-apps/ene/SspDb.

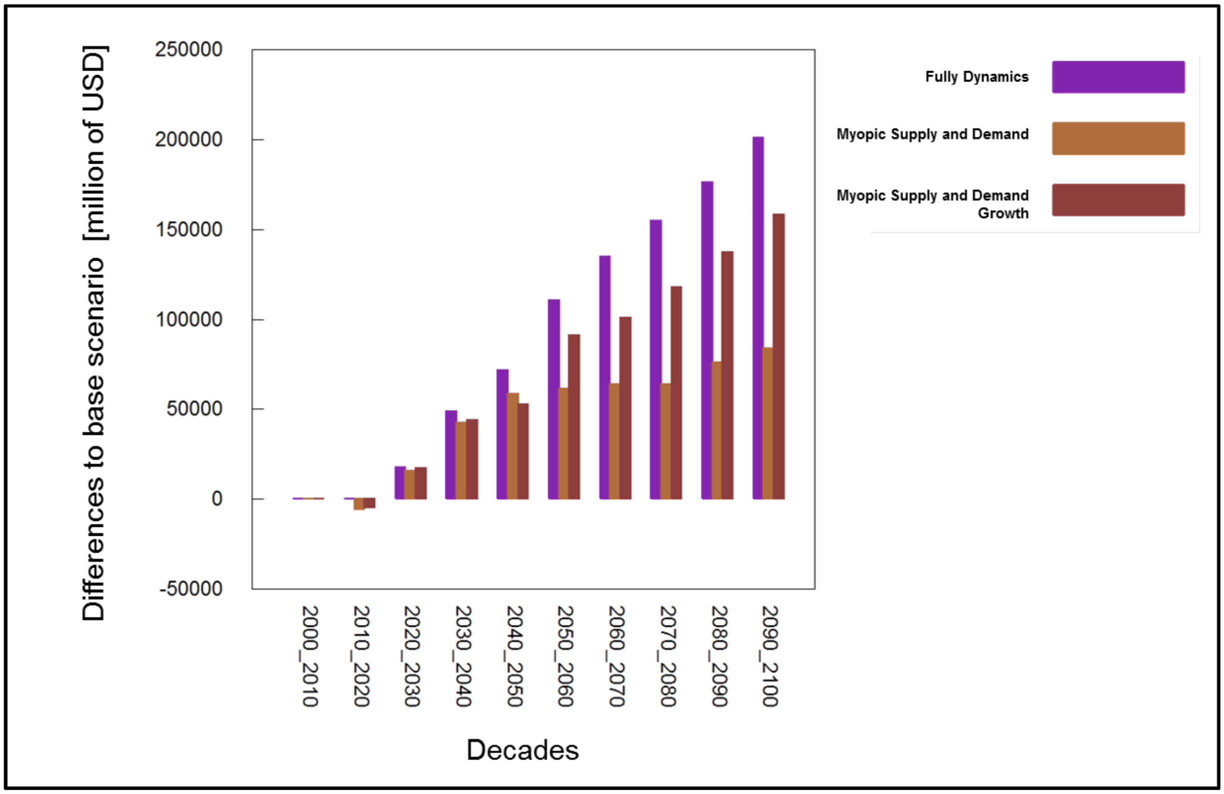

Fig. 5-3. Welfare differences between full dynamic, myopic scenarios, and baseline scenario for the AV DR1 OECD3 OEDC5 scenario.

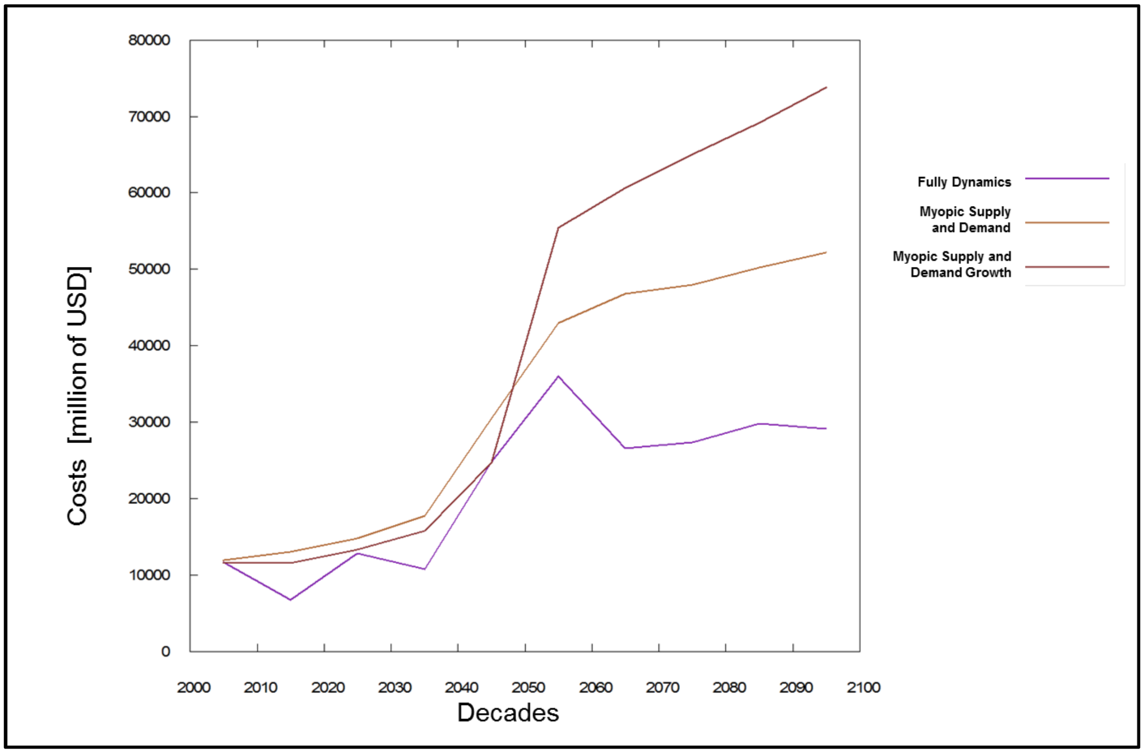

Fig. 5-4. Operation and investment decadal costs for the AV DR1 OECD3 OEDC5 scenario.

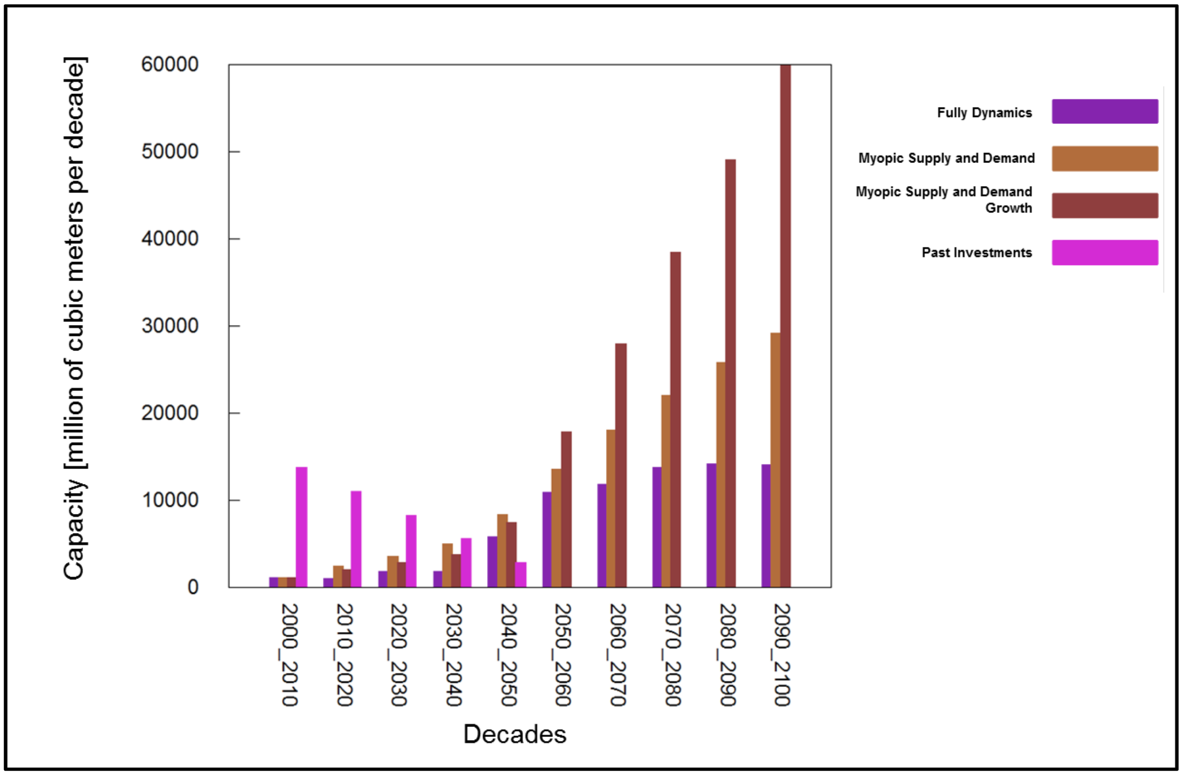

Fig. 5-5. Existing vs. new water infrastructure capacity in the Magdalena river basin under AV DR1 OECD3 OECD5 scenario.

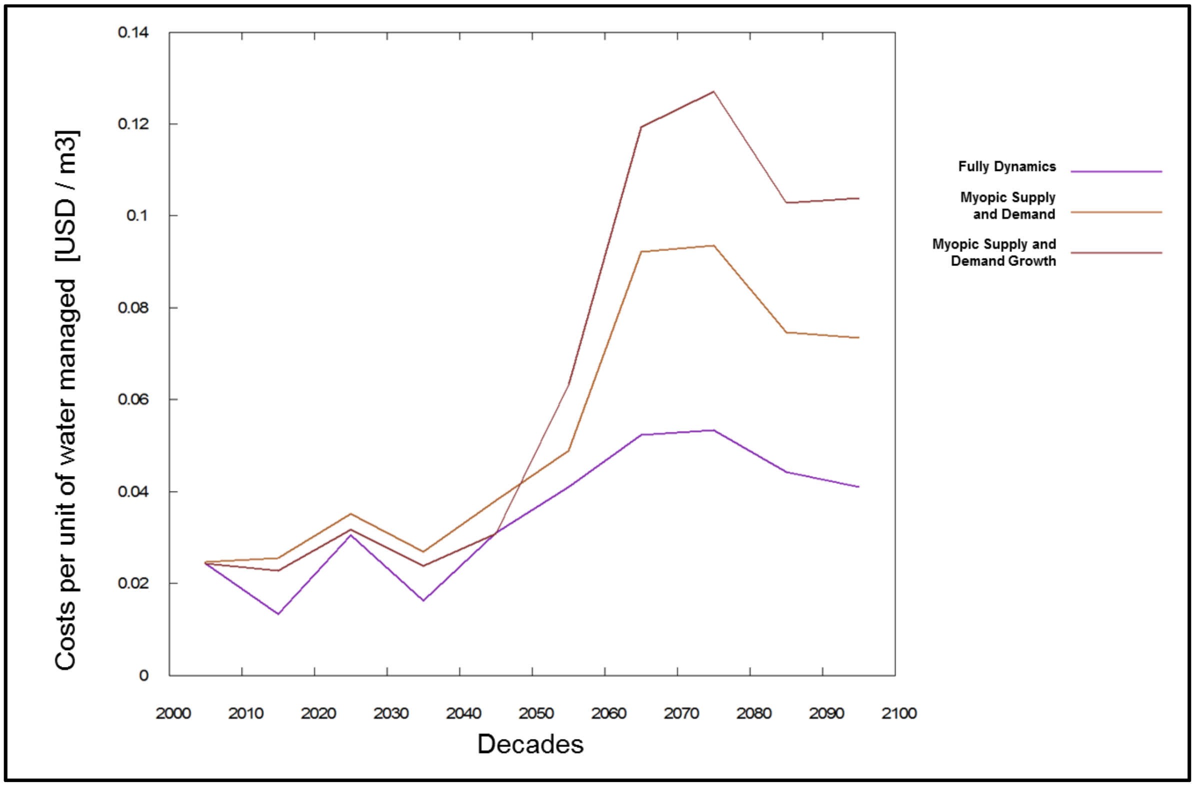

Fig. 5-6. Costs of water managed in the Magdalena river basin under AV DR1 OECD3 OEDC5 scenario.

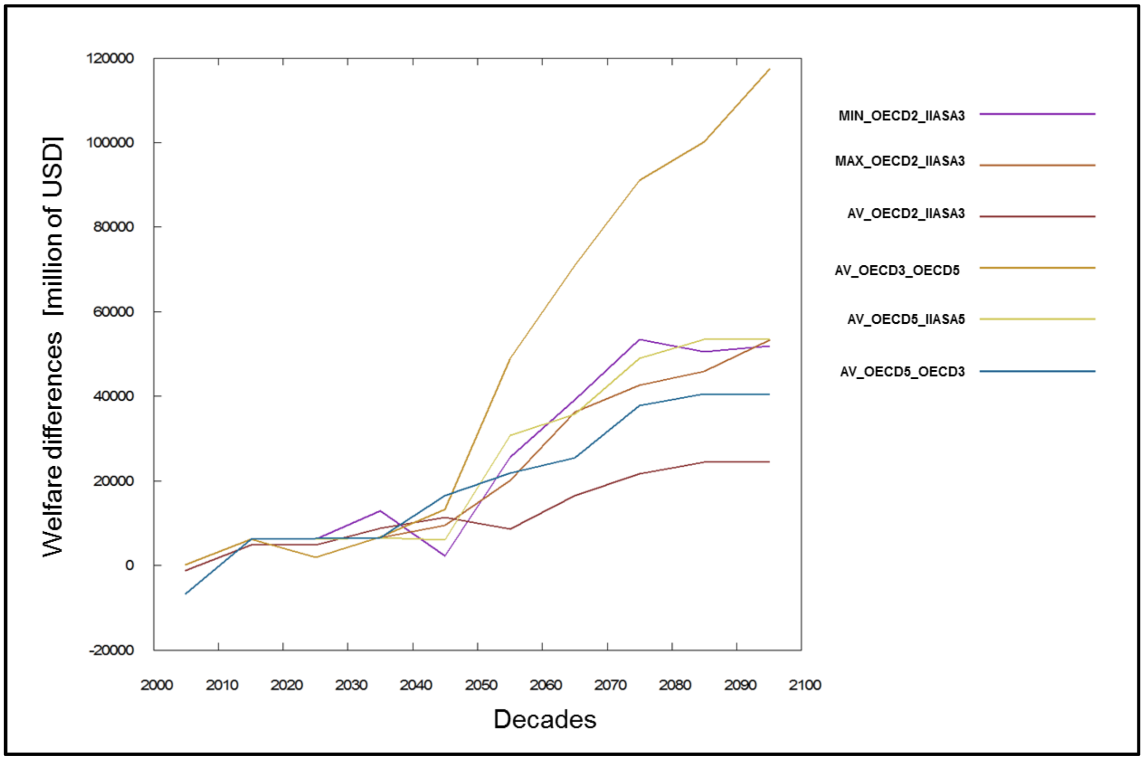

Fig. 5-7. Welfare differences between the fully dynamic and the myopic scenario dependent on different water availability and GDP/population growth rate scenarios.

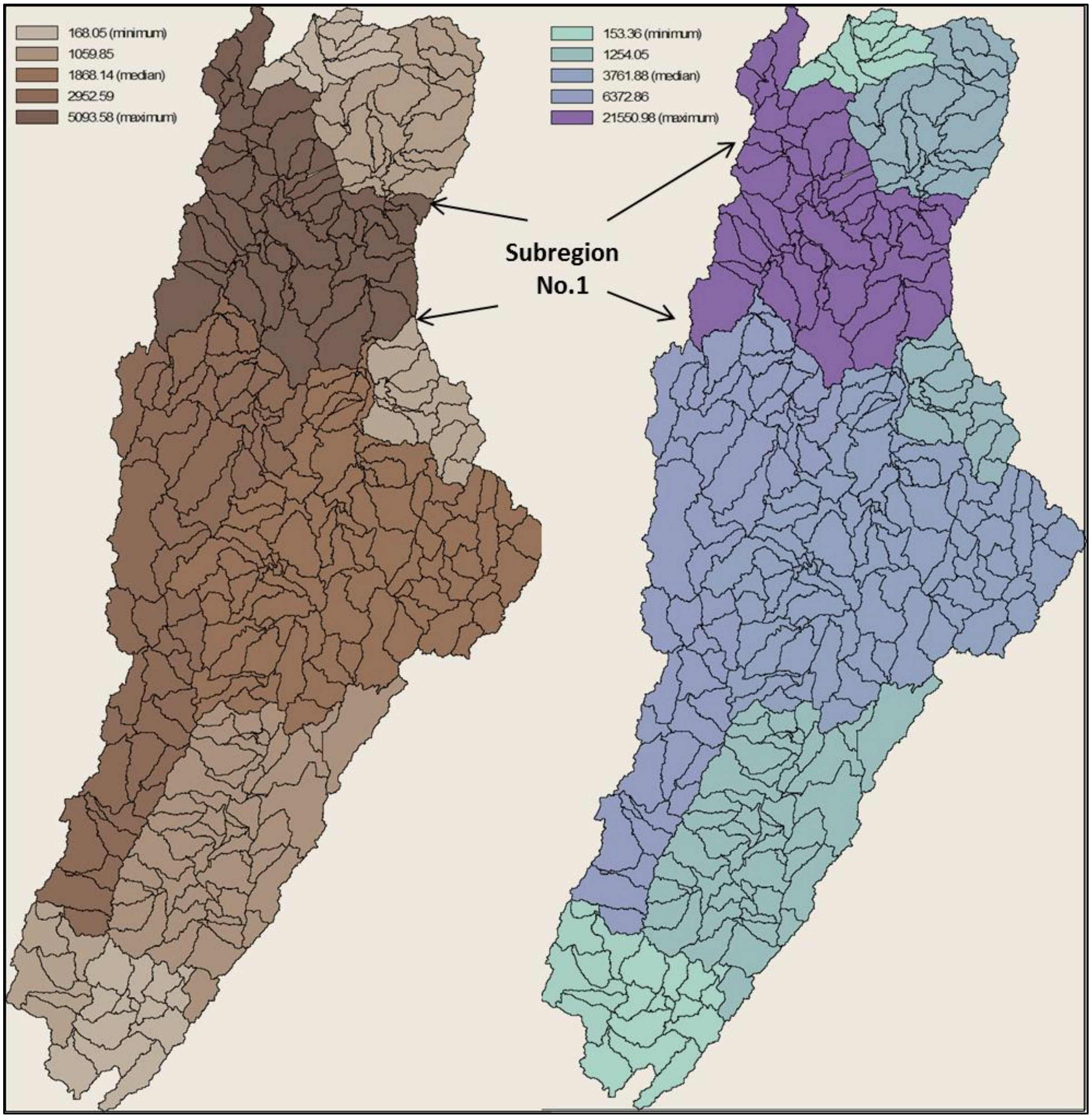

Fig. 5-8. New water infrastructure capacity vs. Water demand in the Magdalena river basin under AV DR1 OECD3 OECD5 scenario for the decade 2070-2080 (Millions of cubic meters per month).

Tables

Table 5-1. Variables and indices used in the CAMARI model.

Variables		**Unit**
B	benefits	million USD
C	costs	million USD
IF	inflow	MCM/month
M	investments in infrastructure	-
O	regional management operations	MCM
OF	Outflow	MCM/month
P	active infrastructures over time	-
S	regional water supply	MCM/month
T	inflow water management operation	MCM/month
V	regional demand	MCM/month
W	Welfare	million USD
Parameters		
c	capacity degradation rate	MCM/unit
f	discount factor	-
e	capacity	MCM
ef	minimum environmental flow	MCM/month
k	maximum capacity	MCM
m	cost of infrastructure installation	million USD/unit
o	cost of operation	million USD/m3
q	water quantity	MCM/month
q; ¯	minimum water consumption	MCM/month
s	subregional water supply	MCM/month
sc	cost of water supply	USD/ m3
tv	travel time	month
ε	elasticity	-
z	return flow coefficient	-
Indices		
a	infrastructure age	decade
d	decade	decade
p	last decade considered	decade
g	sub-classifications of different household and industry demand segments	-
i	infrastructure type (reservoir, wet pond, intake)	-
m	reservoir flows, 1: storage, 2: inflow, 3: outflow	MCM/month
r	subbasin/subregion	km^2
r;~ , r	two connected regions	-
s	sector (agriculture, household, industry)	-
t	month	month

Table 5-2. Input data

Description	Source	Resolution
Topography	NASA Shuttle Radar Topographic Mission	90m*16m
States and counties	GADM database of Global Administrative Areas	-
Land use	United States Geological Survey (2000)	1 km
Water systems	Shuttle Radar Topographic Mission Water Body Data	20m*16m
Climate projections	Intersectoral Impact Model Intercomparison Project (ISI-MIP), sector water. MPI-HM global hydrological model.	0.5°*0.5°
Water management structures	Dams database from AQUASTAT-FAO Installation and operation costs proposals.	-
Residential and industrial water demand and water prices (2004-2012)	Sistema Único de Información de Servicios Públicos	
Agricultural water demand	Erosion Productivity Impact Calculator Model (EPIC), Global Biomass Optimization Model (GLOBIOM)	Daily time step
Population (2005 census), economic indicators	Departamento Administrativo Nacional de Estadísticas	State level
Water income and water price elasticity	(Rosegrant and Cai, 2002b, Dalhuisen et al., 2003, Krause, 2007)	

Table 5-3. Definition of scenarios

Parameter	Variations	Abbreviation	Characteristics
Decision algorithms (3)	Full dynamic optimization,	Fully Dynamics	Full forward-looking behavior
	Myopic, current supply and demand conditions	Myopic Supply and Demand	Full myopic behavior: current supply and demand conditions assumed for the future
	Myopic, current demand rate of growth	Myopic Supply and Demand Growth	Myopic supply but forward-looking demand using current rates of growth
Water supply scenarios (4)	Total average per decade, Minimum per decade, Maximum per decade, 2010 water supply data	AV MIN MAX 2010	Monthly data, 2006 -2099 from surface runoff for RCP4.5
Population and income growth rates (6)	IIASA_GDP_SSP3_v9_130219, IIASA_GDP_SSP5_v9_130219, OECD_Env_Growth_SSP2_v9_130325, OECD_Env_Growth_SSP3_v9_130325, OECD_Env_Growth_SSP5_v9_130325, 2010 population and income data	IIASA3 IIASA5 OECD2 OECD3 OECD5 2010	Quinquennial data projection, 2000 - 2100
Discount rates (3)	1%, 5 %	DR1, DR5	

6. Summary, main conclusions, and outlook

One major aim of this thesis was to explore future periods of water shortages between the agricultural and the hydropower sectors and optimal management solutions in the Magdalena watershed, Colombia. The national electricity generation is especially vulnerable to droughts because of its dependence on hydropower and its limited water storage capacity. Besides, the agricultural sector is the primary water consumer in Colombia. The second aim of this dissertation was to study the effect of spatial resolution variability on optimal water infrastructure investments and the welfare for water uses in the mentioned river basin. Given the Magdalena region's economic and demographic importance in Colombia, it plays a relevant role in researching the dynamic of optimal infrastructure investments, water scarcity, and total benefits for selected physical scales. The tool to address the dissertation's objectives was the CAMARI model, a novel constrained welfare maximization model constructed in the General Algebraic Modeling System (GAMS). CAMARI is a water management, capacity expansion, and optimization model, which maximizes welfare from agricultural production given socio-economic and climate projections. The model was run in the Magdalena basin in Colombia for water supply and demand projections. Achievements on water management analysis in the Magdalena region can be best outlined through this dissertation's chapters.

First, the dissertation's methodology chapter describes the input data, the base model features, and the simulation analyses of the CAMARI model applied in the Magdalena region. CAMARI employs input data from geospatial databases, global studies, national statistics, and model outputs. In the basic model, the maximization of net benefits per water consumption is constrained by several equations. These equations are used to depict physical resource limits, production efficiencies, technical capacity limits of investments, financial restrictions, political regulations, intertemporal and interregional relationships. In the base model directory, all input parameters are assigned to regions considering the spatial scale. The basic model is run with all equations and restrictions. This base model is calibrated by forcing equations for crop area, water supply, and agricultural commodities. In the scenarios simulation directory, the model is run for different scenario-combinations (spatial scale, future climate, and population-income projections), the model-scenarios output is saved, and the final results are compiled. One of the most relevant characteristics of the CAMARI model is the simultaneous optimization of infrastructure investment and agricultural land decisions for multiple future scenarios.

In Colombia, crop areas would probably be affected by climate change. Studies revealed that 80% of crops, in more than 60% of their current cultivation areas, would experience severe impacts in Colombia by the year 2050 (Ramirez-Villegas et al., 2012). Besides, agricultural activities represent 14% of the national Gross Domestic Product and employ 21% of the Colombian population. Inside the Magdalena region, the agricultural sector makes intense and inefficient use of the water resources, which corresponds to 60% of national water demand (CORMAGDALENA, 2013). Alternatively, the Colombian electricity system has a high vulnerability related to water availability. Seventy percent of the power supply comes from large hydropower dams, which 6 percent of their reservoir capacities can save water for more than six months (Giraldo and Robinson, 2018). Modeling the water use dynamic of the agricultural and the hydropower sectors in Colombia provides the tools to investigate water competition and optimal water management investments in the Magdalena region. In the results chapter, simulation analyses are included to research possible water shortages in the studied river basin.

Second, the results chapter explains and illustrates the outcomes of three individual studies. The first study introduces a method to analyze possible water use conflicts among different primary water consumers, projection of hydropower generation, optimal investment in water infrastructures, economic scarcity of water, and welfare for water consumption. Hence, I found through 80-year simulations that agricultural and hydropower sectors in the Magdalena region would probably experience water conflicts during the decade 2030-2040, especially in January. The highest irrigation and minimum storage of reservoirs would occur within this period under less water availability scenarios (RCP2.6 and RCP6.0). Besides, electricity shortages might appear in the Magdalena region because of the low reservoir storage between 2030 and 2040. Hydropower simulation results also illustrate that the agricultural, household and industrial sectors would experience economic scarcity of water for the studied climate scenarios (RCP2.6, RCP4.5, and RCP6.0) during the first three modeled decades (2020-2050). A final simulation result detects that projected dams represent more than 99% of optimal infrastructure investment to supply water to all end users and reduce climate change impacts in the Magdalena region during the research horizon.

In the end, my first study finds connections between water availability, water management, and net benefits. Investment and operation costs of dams are the largest charges on the decadal welfare values. When more water resources are accessible, infrastructure investment declines, but the welfare of water consumption rises.

CAMARI simulations illustrate that less infrastructure investment is required for major water resource availability (RCP4.5), and larger welfare for water consumption would appear. In other words, water supply projections are the main driver of welfare for water consumption in the Magdalena region.

The second study proposes an analysis to research the effect of spatial scale variability on investment decisions, water scarcity, and net benefits for future scenarios in the Magdalena watershed. For all the studied climate/development scenarios, total optimal investment declines 80% (~ 20 billion USD) from 140-regions to 5-regions analysis during the research time (2020-2100). Conversely, 80-year total welfare increases circa 5% (~10 billion USD) from 140-regions to 13-regions simulations for the selected scenario combinations. Spatial scale variations also influence the three relevant net benefit components: the endogenous price of agricultural commodities, the non-agricultural sector water values, and crop production costs. The most relevant findings for coarser scales (5-regions resolution) modeling are: water availability is homogeneously distributed, water scarcity is underestimated, and fewer infrastructures would be installed to supply water users.

Water conflicts have increased with Colombian economic expansion, even though the Colombian mean annual runoff is 1840 mm per year. Domínguez et al. (2010) proposed a water-scarce index to detect Colombian local water problems using water withdrawal ratio to water availability. Nevertheless, the water-scarce index had spatial deficiencies to integrate water demand and surface runoff data. This study provides a forward-looking strategy to analyze water management issues at several resolutions. The optimization simulations connect runoff data and water consumption at the subbasin level, find the relation between water scarcity and water availability, propose optimal infrastructure investment, simulate water demand and supply under several spatial scales.

Moreover, spatial scale analysis outcomes should provide modeling tools to national/local authorities to develop the Magdalena region's management plans. The planning instrument for river basins (POMCA) is one of the instruments established for the Colombian government to achieve Integrated Water Resource Management at the watershed level. POMCA has several objectives: identification of areas to construct water management facilities, assignation of budget to build new infrastructures, and definition of institutional responsibilities for water policy implementation (Blanco, 2008). La Corporación Autónoma Regional del Río Grande de la Magdalena (CORMAGDALENA) is the local institution in charge of the integral water management and policy decisions for the Magdalena River. Optimal infrastructure investments, water availability projections, water scarcity distribution and water use welfare should be employed for CORMAGDALENA to design the Magdalena River POMCA, considering projected scales, climate, population, and income scenarios.

In the end, the physical scale analysis reveals that the projected capacity of water infrastructures would increase by 35%, with a 90% reduction in spatial resolution. Considering infrastructure investment as a kind of adaptation to climate change, optimal investment in water infrastructures at different resolutions could give us a relevant inside into the real cost of adaptation in a river basin.

The third study, a submitted paper, explores the potential benefits of water infrastructure investment decisions under projected changes in water availability and water demand during the century. The results show that employing a model for optimizing investment decisions increases welfare by 120 billion USD over the next century in the Magdalena river basin. Besides, forward-looking decision-making may save up to 50 billion USD in investments and operating costs compared to short-sighted decisions, at the end of the century and under high development scenarios.

The overall importance of this thesis is the forward-looking analysis of optimal investment, the dynamic and endogenous representation of agricultural water demand, the outcomes of the economic scarcity of water resources, the spatial scale research of water management investment, and the simulation results of projected welfare for water consumption in the Magdalena river basin. Besides, hydropower generation, spatial scales, and investment decision simulations propose optimal water management alternatives for the next eight decades for selected future climate/development scenarios. The forward-looking modeling process and its analysis are novel scientific decision-making tools to plan future management strategies in the Magdalena river basin.

However, the dissertation gives significant outcomes in modeling water management in the Magdalena region; my research has some shortcomings. First, the hydropower modeling included an exogenous power demand that is a monthly historical and weighted-average of national electricity demand for the Magdalena region. Second, CAMARI simulations did not comprise historical power prices. Third, hydropower dams were selected as a unique power source in the studied region. Finally, inaccessible historical hydrology caused to the modeling process unavoidable uncertainty in the climate projections.

6.1 Outlook

The research presented in this dissertation may be complemented by further studies in the fields of integrated water management and environmental modeling in the Magdalena river basin.

First, potential improvement should be implemented in the CAMARI model. At the municipality scale, model simulations must include historical power prices and electricity data demand. Besides, alternatives power sources (wind, solar, and thermal generation) should be included as energy suppliers.

Second, because of the high dependence of the Colombian electricity system on hydropower, it is necessary to explore alternatives clean sources of energy instead of building large reservoirs. These large embankments generate a high ecological impact that is often still poorly understood (Buytaert and Breuer, 2013). A suitable alternative to generate electricity should be Small Hydroelectric Plants (S.H.P.) due to their low operation complexity and minor environmental impact compared to other available power sources in Colombia (Duque et al., 2016).

Third, increasing resource pressure has been motivated studies in water availability and water demands at multiple scales. There is no single physical scale appropriate to conduct water management research (Perveen and James, 2010). The ability to aggregate o disaggregate data or output to various scales would help find optimal solutions to future water problems inside the Magdalena region. Consequently, the spatial scale algorithm has to be improved to compare weighted-quantitative welfare outcomes.

Fourth, the CAMARI model should comprise environmental simulations. Recent research in Latin-American dam planning proposes to merge cost-benefit economic analysis, ecological impact on a river basin, and social scientific perspectives (Schulz and Adams, 2021).

Finally, studying future impacts of global change on water management in less developed countries is a high challenge. Two main difficulties are lacking access to local historical data and scientific decision-making tools. Modeling is an option to explore management alternatives and preserve water resources for future generations in Colombia. This thesis is one further contribution.

7. References

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ADDIN

Appendix 1. Supplementary material

Table A1. The final parameter of input data. Last version of the CAMARI model

Parameter	Set	Description
SubbasinArea_data	CM_Subbasin	The area in km^2 per subbasin. There are in total 333 sub-basins.
Landuse_data	CM_Subbasin, SIMUID, AllState, AllLandclasscat, Dataitem	Features: land use, simulation unit delineation, land categories; per subbasin in Km^2.
Rural_data	AllYear, AllPeriod, AllState, AllCounty, AllCompanyID, DataItem	Rural water consumption (2004-2012) in Colombia (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, and total.
Urban_data	AllYear,AllPeriod,AllState, AllCounty,AllCompanyID,DataItem	Urban water consumption (2004-2012) in Colombia (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, total.
Total_data	AllYear,AllPeriod,AllState, AllCounty,AllCompanyID, DataItem	Rural + urban water consumption (2004-2012), in Colombia (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, and total.
Price_data	AllYear,Allperiod,AllCompanyID,AllState, AllCounty,AllLocation,DataItem, AllPriceitem, AllPriceunit	Water prices for water consumption (2004-2012), in Colombia (Colombian pesos). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, provisory, special, nonresidential, and total. Price item includes a constant fee, basic fee, complementary fee, luxury fee, environmental fee, nonresidential price.
Population_Data	AllState,AllCounty,dataitem	The number of inhabitants per state and per county in Colombia. Census 2005.
Countysubbasin_data	AllState,AllCounty,CM_Subbasin,dataitem	County area per subbasin in km^2.
Streamlink_data	CM_Subbasin_up, CM_Subbasin_down,dataitem	Stream connections between subbasins according to the Strahler system.
County_area	AllState,AllCounty,Dataitem	Area of all counties in Colombia per state, in km2.

States_GDP_C	AllState, AllYear	Gross domestic product per state, in thousands of millions of Colombian Pesos, C: current prices in 2011.
States_GDP_K	AllState, AllYear	Gross domestic product per state, in thousands of millions of Colombian Pesos, K: constant prices in 2011.
Reservoir_NewData	Name_Reservoir, Name_River, CM_Subbasin_up,CM_Subbasin_down, ReservoirData	Reservoirs with subbasin connections/location in the Magdalena basin. Reservoirs data includes capacity and geographic location (longitude, latitude).
Rural_data_subbasin	CM_Subbasin,Decade,AllYear,Month, DataItem	Rural water consumption (2004-2012) in the Magdalena watershed (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, total.
Urban_data_subbasin	CM_Subbasin,Decade,AllYear,Month, DataItem	Urban water consumption (2004-2012) in the Magdalena watershed (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, total.
Total_data_subbasin	CM_Subbasin,Decade,AllYear,Month, DataItem	Rural + urban water consumption (2004-2012) in the Magdalena watershed (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, total.
Price_data_subbasin	CM_Subbasin,AllLocation,Decade,AllYear, AllPeriod,DataItem,AllPriceitem, AllPriceunit	Water prices for water consumption (2004-2012) in The Magdalena region (Colombian pesos). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, provisory, special, nonresidential, and total. Price item includes a constant fee, basic fee, complementary fee, luxury fee, environmental fee, and nonresidential price.
Watersupply_cost	CM_Subbasin, Decade, Month, sector	Water supply prices for the agricultural, industrial, and household sectors
Waterpriceelasticities	Country, Sector	Elasticities of water prices for the agricultural, industrial, and household sectors
Waterincomeelasticities	Country, Sector	Income elasticities of water prices for the agricultural, industrial, and household sectors
Runoff_Data	CM_Subbasin,ActiveDecade,AllYear,	

	Month	Water availability projections in millions of cubic meters per month (2006-2099) in the Magdalena watershed.
Population_subbasin	CM_Subbasin,DataItem	The number of inhabitants per subbasin in the Magdalena watershed. Census 2005, Colombia.
Subbasin_GDP_C	CM_Subbasin, AllYear	Gross domestic product per subbasin, in thousands of millions of Colombian Pesos, C: current prices in 2011.
Subbasin_GDP_K	CM_Subbasin, AllYear	Gross domestic product per subbasin, in thousands of millions of Colombian Pesos, K: constant prices in 2011.
Data_crop_Subbasin	CM_Subbasin,CROP,CROPTECH,Dataitem	Crop data from GLOBIOM model, yield (t/ha), area (1000 ha). Different kinds of crops and cropping technologies. Data item includes yield and area.
Total_data_subbasin_company	CM_Subbasin,Decade,AllYear,Month, AllCompanyID,DataItem	Rural + Urban water consumption (2004-2012) in the Magdalena watershed (millions of cubic meters per month). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, total. Includes water company ID (identification number).
Price_data_subbasin_Company	CM_Subbasin,AllCompanyID,AllLocation, Decade,AllYear,AllPeriod,DataItem, AllPriceitem, AllPriceunit	Water prices for water consumption (2004-2012) in the Magdalena basin (Colombian pesos). Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, provisory, special, nonresidential, and total. Price item includes a constant fee, basic fee, complementary fee, luxury fee, environmental fee, nonresidential price. Includes water company ID (identification number).
Rural_User	AllPeriod,AllPeriod,AllState,AllCounty, AllCompanyID,DATAITEM	Rural water users (2004- 2012), in the Magdalena basin. Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, and total users.
Urban_User	AllPeriod,AllPeriod,AllState,AllCounty, AllCompanyID,DATAITEM	Urban water users (2004- 2012), in the Magdalena basin. Data item includes water consumption classification: category 1 to category 6, residential, industrial, commercial, governmental, others, nonresidential, and total users.
Total_User	AllPeriod,AllPeriod,AllState,AllCounty, AllCompanyID,DATAITEM	Rural + Urban water users (2004- 2012), in the Magdalena basin. Data item includes water consumption classification: category 1 to category 6, residential, industrial,

		commercial, governmental, others, nonresidential, and total users.
Price_data_ ConstantFee	AllYear,Allperiod,AllCompanyID,AllState, AllCounty,AllLocation,DataItem,AllPriceitem , AllPriceunit	Water constant fee in Colombian pesos per cubic meter.
Price_data_ ConstantFee_subbasin	CM_Subbasin,AllLocation,Decade,AllYear, MONTH,DataItem,AllPriceitem,AllPriceunit	Water constant fee in Colombian pesos per cubic meter.
Price_data_ ConstantFee_subbasin_ company	CM_Subbasin,AllCompanyID,AllLocation, Decade,AllYear,AllPeriod,DataItem, AllPriceitem, AllPriceunit	Water constant fee in Colombian pesos per cubic meter. Includes water company ID.
Development_data	ALLDevelopScen, AllYear, Decade, Dev_growth	Gross domestic product and Colombian population projections. Gross domestic product in billions of US dollars in 2005 and population in millions of inhabitants. The projections are extracted from SSP Database from IIASA, 2012 (O'Neill et al., 2012).
EPIC_EP_decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average plant evaporation in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities. EPIC model output.
EPIC_ET_decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average evapotranspiration in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities. EPIC model output.
EPIC_IRGA_ decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average irrigation volume applied in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities.
EPIC_PRCP_ decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average precipitation in mm, per subbasin. The parameter includes different crops, crop technologies, and fertilizer intensities. EPIC model output.
EPIC_PRK_ decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average percolation in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities. EPIC model output.
EPIC_Q_ decade	CM_Subbasin,EpicRegion,Tech,ALLCROP, decade,Month,EPICOutput	Decadal monthly average runoff in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities. EPIC model output.
EPIC_SSF_ decade	CM_Subbasin,EPICTech,EPICIntensity,EPI CCROP,quinq,EPICMonth,EPICOutput	Decadal monthly average subsurface runoff in mm, per subbasin. The parameter includes different crops, cropping technologies, and fertilizer intensities. EPIC model output.
Crop_data	CM_Subbasin,EPICRegion,decade,	

	ALLMONTH,TECH,Crop,AllTechItem	Decadal monthly crop data. The parameter includes different crops, cropping technologies, and fertilizer intensities after merging EPIC model output.
traveldelay_data	CM_Subbasin_up,CM_Subbasin_down, timedelay	Water travel calculation among subbasins, in months.
traveldelay_alldata	AggrLevel, AggrSubbasin_up, AggrSubbasin_down, time-delay	Water travel calculation among subregions, in months.

Table A2. Description of sets and elements. Last version of the CAMARI model

Set	Elements	Description
Allregion	Colombia,CM_Subbasin_1, CM_Subbasin_2,…..,CM_Subbasin_333, ACM1_R333*ACM333_R333 ACM1_R140*ACM140_R140 ACM1_R34*ACM34_R34 ACM1_R13*ACM13_R13 ACM1_R5*ACM5_R5 R333,R140,R34,R13,R5	Region classification
AllDataitems	Length_m,area_Km2,area__km2,area6_km2, level1, level2, level3, level4, level5, level6, residential, industrial, commercial, governmental, others, nonresidential, special, provisory, total, temporal, number_of_inhabitans, share_subbasin, share_county, shape_leng, shape_area, stream_order, population, income, level, percentage, all, return_flow	Items
Infrastr	reservoir, wet_pond, pumping station	Infrastructures
Allsector	agriculture, household, industry, hydropower	Water users
Item	inflow, outflow, storage	Water operations
MarketItem	Price, quantity, truncation, elasticity, incomeelasticity, quantity_rural_urban, quantity_rural, quantity_urban, quantity_agriculture, price_constantfee, price_basicfee, price_complementaryfee, price_luxuryFee, price_envcost, price_noresidential, price_actualIndex, price_agriculture, Minimum, share_subbasin_c, share_company, waterconsumption,user_total,constant, minimum, share_subbasin_c, share_company, waterconsumption,user_total,p_elasticity	Price calculation elements
AllPriceitem	actualpriceindex, constant fee, basic fee, complementaryfee, luxury fee, environment cost, consumerprice_no_residential	Price calculation characteristics
AllPriceunit	COP/COP, COP/Customer/Month, COP/CBM	COP: Colombian pesos, CBM: cubic meters
AllLocation	urban, rural	Water consumption location for household and industries

AllPeriod	January, February, March, April, May, June, July, August, September, October, November , December, monthmax , semester1, semester2, annual, y2000, y2001,…,y2050, 1990,1991,….,2099, Quinq1990_1995, Quinq1996_2000,… ,Quinq2095_2100, Dec1990_2000, Dec2000_2010,…..,Dec2090_2100, Decade1, Decade2….,Decade10, Annual, AllDecades	Time characteristics Quinq means quinquennial Dec means decade Y means year
Allage	Age0,age1,….,age10	Infrastructure age per decade.
AllLandclasscat	agriculture, forest, wetland, water_bodies, flooded_forest, dryland, urban, unknown, grass_and_shrub_lands, anylandclass	Classification of land cover
ALLDevelopScen	IIASA_GDP_SSP1_v9_130219 IIASA_GDP_SSP2_v9_130219 IIASA_GDP_SSP3_v9_130219 IIASA_GDP_SSP4_v9_130219 IIASA_GDP_SSP5_v9_130219 OECD_Env_Growth_SSP1_v9_130325 OECD_Env_Growth_SSP2_v9_130325 OECD_Env_Growth_SSP3_v9_130325 OECD_Env_Growth_SSP4_v9_130325 OECD_Env_Growth_SSP5_v9_130325	Development scenario classifications (O'Neill et al., 2012).
Dev_growth	GDP_PPP_billion_US_2005_yr, population_million	Development classification items
EPICCrop	COTP, BARL, COFF, GRSG, WWHT, POTA, OILP, PNUT, SUGC, SOYB, LIMA, LENT, CORN, RICE, CASS, PLAN, YAMS	Abbreviation for the type of crops
CROPTECH	HI,LO,SS,IR_basin,IR_furrow,IR_drip,IR_sprink	Types of crop technologies
EPICTech	0, 1	0: non-irrigated, 1: irrigated
EPICIntensity	HI, LO	Level of fertilizer application
EPICYear	1990,1991,….,2100	Year of EPIC model simulations
EPICMonth	1,2,….,12	Months
EPICOutput	PRCP,PET,ET,EP,Q,SSF,PRK,QDRN,IRGA,QIN,TSOK, SNOA, RZSW	Parameter output from EPIC model

EPICCrop, CROPTECH, EPICTech, and EPICIntensity are a group of subsets for EPIC model simulation. Inside EPICCrop set, COTP means cotton, BAR barley, COFF coffee, GRSG Sorghum, WWHT winter wheat, POTA potatoes, OILP oil palm, PNUT peanuts, SUGC sugar cane, SOYB soybeans, LIMA beans, LENT lentils, CORN corn, RICE rice, CASS cassava, PLAN plantain, and YAMS yams. In CROPTECH subsets: HI means high fertilizer application, LO low fertilizer application, SS no fertilizer application, and IR irrigation. For the EPICTech subsets, 0 means non-irrigated and 1 irrigated. For the EPICOutput subsets: PRCP means precipitation, PET potential evapotranspiration, ET evapotranspiration, EP plant evaporation, Q runoff, SSF subsurface flow, PRK percolation, QDRN soluble Nitrogen from drainage system, IRGA irrigation volume applied, QIN inflow from the water table, and RZSW root zone soil water.

Table A3. Equations and variables structure in the model CAMARI

Variables / Equations	Dam Construction	WM Construction	WM Operation	WM Capacity	Differential Agr. demand variation	Demand non-agricultural sectors	Supply	Input flow into subbasins	Output flow out of subbasins	Differential supply variation	Runoff	Inflow operation variable	Crop	Crop Mix	Demand agricultural sector	Water for power generation	Artificial variable Market subsector	Artificial variable WM Construction	Artificial variable water availability	Artificial variable hydropower	Welfare maximization	Welfare variable	
Objective Function																	+	+	+	+	+	-	=0
Benefit and cost accounting *(d)*	+	+	+		-	-				+					-	+						+	=0
Construction and operation of water infrastructures *(r,d,t,i)*			+	-																			≤+
Water availability and consumption *(r,d,t,s)*						+	-								-								≤0
Water balance between subbasins *(r,d,t)*			+			-		-	+		-												≤0
Amount of water release per sector *(r,d,t,s)*			-				+																≤0
Amount of total water release *(r,d,t)*			-				+																≤0
Amount of water release for the household and industrial sectors *(r,d,t)*			-				+																≤0
The relation between present and past operations *(r,d,t, m≠m3)*			m																				=0
Water management and infrastructure age *(r,d,I,a)*		-		m																			≤0
Limitation on infrastructure construction *(r,d,i)*		+																					≤+
Agricultural demand identity restrictions *(d,y)*					-									+									≤0
Agricultural demand convexity restrictions *(d,y)*														+									≤+
Water movement between subbasins *(r,d,t)*								+	-														=0
Supply convexity constrains *(r,d,t,s)*										+													≤+
Supply identity constraints *(r,d,t,s)*							+			-													≤0
Demand variability for non-agr. sectors *(r,d,t,s)*						+																	=0
Runoff restriction *(r,d,t)*												+											=0
Maximum number of infrastructures *(d,i)*		+																					≤+
Dam construction *(r,d,i)*	-	+																+					=0
Water released from reservoirs *(r,d,t)*			+													-							≥0
Cropland equation *(r,d)*													+										≤+
Crop mix equation *(r,d,c)*													+	-									=0

Variables / Equations	Dam Construction	WM Construction	WM Operation	WM Capacity	Differential Agr. demand variation	Demand non-agricultural sectors	Supply	Input flow into subbasins	Output flow out of subbasins	Differential supply variation	Runoff	Inflow operation variable	Crop	Crop Mix	Demand agricultural sector	Water for power generation	Artificial variable Market subsector	Artificial variable WM Construction	Artificial variable water availability	Artificial variable hydropower	Welfare maximization	Welfare variable	
Product equation (*d,y*)														-	+								≤0
Hydropower and minimum water use (*d,t*)																+							≤+
Hydropower and investment (*r,d*)				-												+							≤+
Hydropower and water release (*r,d,t*)																+							≤+
Variable Type	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	u	u	

m (mixture of signs (-) and (+))
Variable type:
0,1 binary variable
≥0 positive variable
U free variable

Table A4. Data contribution from other researchers to this dissertation

Data	Researcher
Current and projected agricultural data from EPIC simulations	Dr. Livia Rasche
Crop areas and technologies (irrigated/rainfed) from GLOBIOM model	Prof. Dr. Uwe Schneider
ArcGIS data: subbasins delineation, land use, administrative division.	Ruth SOS del Diego
Water availability projections	Dr. Tobias Stacke

Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation mit dem Titel: Water management analysis in the magdalena basin in Colombia, selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel – insbesondere keine im Quellenverzeichnis nicht benannten Internet-Quellen – benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Veröffentlichungen entnommen wurden, sind als solche kenntlich gemacht. Ich versichere weiterhin, dass ich die Dissertation oder Teile davon vorher weder im In- noch im Ausland in einem anderen Prüfungsverfahren eingereicht habe und die eingereichte schriftliche Fassung der auf dem elektronischen Speichermedium entspricht.

Hamburg, den 14.04.2021 Unterschrift

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