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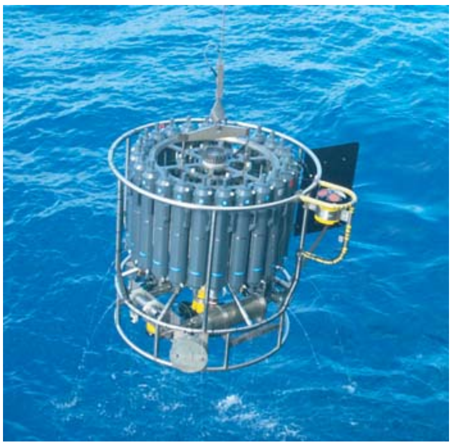
Designing a dynamically integrated water management scheme as an adaptation strategy for global change induced water stress

W.M.T. Harshi Weerasinghe



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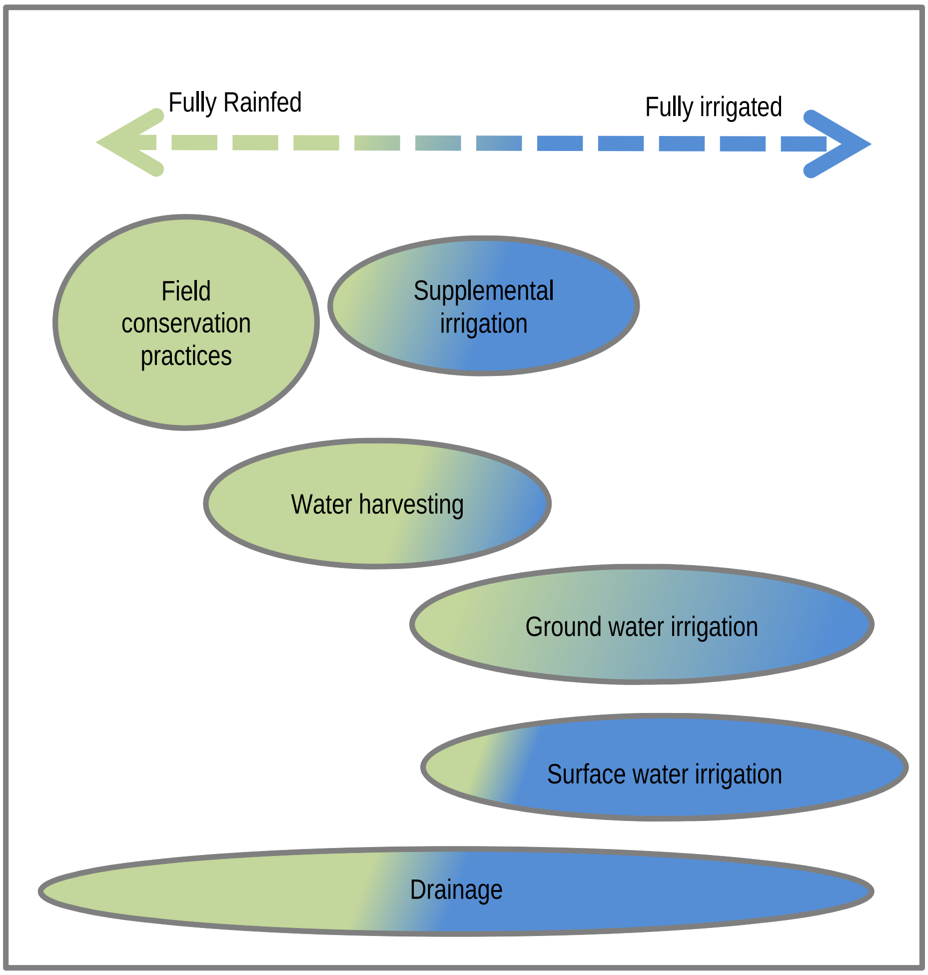

W. M. Thushantha Harshi Weerasinghe

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Cover Picture: The spectrum from rainfed to irrigated - Diverse options for agricultural water management along the spectrum adapted from Molden (2007)

Managing water for agriculture includes a spectrum of options—from producing under fully irrigated to entirely rainfed conditions, to supporting livestock, forestry, and fisheries, and to interacting with important ecosystems. The continuum of water management practices starts with fields or grazing land entirely dependent on rainwater. On-farm conservation practices focus on storing water in the soil. Moving along the continuum, more surface water or groundwater is added to enhance crop production. This additional freshwater provides opportunities for multiple uses, including aquaculture and livestock within the production system.

ABSTRACT

At the first sight, water management might appear to be focused on local matters only. In fact, water management also needs to consider many regional, international, or global factors. Catchments often deal with competitive water use, which means that the consumptive demand for water is higher than the sustainable production. Water resources, management and systematic approach have a direct relationship, because all of these are essential components in an integrated water management plan. Many of the existing irrigation systems are not capable of handling the agricultural water demand in the future. In addition, the cost for rearranging the water management systems would require large investments. Together with the technological improvements assumed in the future, crop yield would increase per additional unit of water, in both irrigated and rainfed systems. In contrast, the arable land per capita is decreasing apart from the soil degradation problem. Probable rainfall pattern changes and occurrence of intense droughts are included in predicted climate change scenarios and these deviations demand for new approaches of water resource planning.

I have developed the 'GWAMP' and 'ADAPT' models to study opportunities for adaptation of water management for agricultural production and impacts of large scale water infrastructure developments on land and water resources and regional welfare. A secure supply of water and food, maintaining the sufficiency of water for food production, relies on the geographical and the climatic conditions as well as economic activities in a region. Water management is often too slow to adapt to the required changes. The first step in managing water is to estimate the physically available amount of water to manage and variations across spatial and temporal scales. Here, the available water quantity is based on the climate change SRES A2 scenario of the IPCC. The concept I present here is to use the adaptation measures to manage blue water, so that optimal production targets can be achieved. The EPIC model provides the blue water requirement/irrigation water requirements that are demanded by the growing crops. There, I try to evaluate the agricultural water requirements and use the adaptation techniques to optimize the scale of irrigation.

The first part of this study describes a suitability assessment for water management structures within a river basin. I developed a model named Geographic Water Management Potential (GWAMP) that uses spatial data analysis techniques to assess suitability. GWAMP is applicable for varying climatic, geographic and socio-economic conditions. Input data are extracted from global data repositories and rescaled to a 30 arc-second spatial resolution. These data include precipitation, evaporation, land cover, soil properties, elevation, slope, population, road density and drainage network. An analytic hierarchical process (AHP) is used to combine suitability for individual factors in to an overall suitability index. The model identifies water harvesting and storage suitability for on-farm water storage, regional dams, check dams, contour bunts, stone terraces, roaded catchments, and percolation pits. The application of the model in six diverse water basins (Ganges, Nile, Sao Francisco, Tocantins, Turkana, Xun Jiang) indicates plausible results in varying climatic, geographic and socioeconomic conditions, even in ungauged basins. The exclusive use of available global data sets permits this method to be used at global level with minor modifications. The identification of potential water management adaptation locations could substantially improve integrated assessment models. The GWAMP model is developed in a GIS environment and estimates suitability level information to implement adaptation technologies based on the decision rules provided. The rain water harvesting technologies considered here include moisture conservation techniques such as check dams, percolation pits and stone terraces on agricultural farms or nearby. Water storage technologies include regional reservoirs and smaller-scale farm tanks in agricultural areas. The significant feature of this decision support system is that decisions can be made based on expert opinion and available guidelines in different domains using a rule-based decision tree.

Furthermore, I have developed the ‘ADAPT’ model to study in combination with the ‘GWAMP’ model the impact of water management adaptation on the land and water resources and regional agricultural welfare. In an integrated systematic approach, the planning of water storage structures needs to be well connected to the water supplies and demand sectors. The systematic approach is important to identify the correct components for an integrated system to analyse and improve the system. Each of the components requires as input resource endowments and produces outputs at optimal level to satisfy the demand attaining a certain level of welfare. The systematic approach for integrated water management, I have proposed here, starts from the runoff generation and extends until the demands for the agricultural production within a watershed are satisfied. The crop production relies on two main types of water reserves. The soil moisture reserves from the runoff (green water) and irrigation water (blue water) to compensate for the depleted soil moisture reserve. A secure supply of water and food, maintaining the sufficiency of water for food production, relies on the geographical and the climatic conditions as well as economic activities in a region. Water resources, management, and systematic approach have a direct relationship, because all of these are essential components in an integrated water management plan. The ADAPT model is designed to represent the dynamics of the water flow within a watershed and elaborately represent the water management activities. These include the dimensional measures of the water harvest and storage structures, material, installation and maintenance of large scale and small scale water infrastructure. The ADAPT model is a mathematical optimization model that jointly represents water management options used as adaptation strategies, land use decisions and crop production. I designed the water management within the model based on one of the fundamental laws of physics that states; ‘mass can neither be produced or destroyed’. Optimal management of water resources is a function of the growth and development of every aspect in a watershed. Traditionally, storage has been achieved with dams and surface reservoirs.

To sum up the insights gained from the studies in this thesis, I can recommend six key elements to adapt water management to ensure sound supply of irrigational water.

- The application of GWAMP in the six case studies demonstrates its suitability to identify potential sites for rain water harvesting and storage. The results confirm that GWAMP is applicable in varying climatic, geographic, and socioeconomic conditions, even in ungauged basins. Furthermore, GWAMP can easily update suitability levels and weighted scores of decision factors on which the potential sites for rain water harvesting and storage are based.
- The analysis of the effect of precipitation on the average suitability score confirms that reduced intensity of precipitation on assuming no change in spatial pattern cannot have a major effect on the average suitability for either water harvest or storage structures. The analysis of the effect of land use change in spatial on average suitability confirms that land use change can have a major effect on the average suitability of land parcels for water harvest and storage.
- The cost incurred with the water management infrastructures is an important fact that needs to be considered in water resource planning. Extensively considering the cost, I developed the ADAPT model, which is coupled with the extensive bio-physical model like EPIC, GLOBIOM and geographical analysis models like HEC-RAS and GWAMP.
- The scenario analysis shows that the water management can have a substantial impact on the extended resource as well as the development of welfare levels in the region. Water management together with foreign commodity demand and biofuel demand can have a combined effect compared to individual influence on the resource use and regional agricultural welfare.
- The water management is moderately sensitive to the biofuel production. The cost of crop production is also increasing due to the initial establishment of water management structures. The water management is not only sensitive to the change in the share of biofuel demand but also sensitive to the overall crop production.
- The simulation results show that the crop production is rather sensitive to the water availability, thus on the level of precipitation. The area of land, which is considered to be one of the resources, used for the crop production is also dependent on the level of precipitation. Specially, the cost incurred with water management is sensitive to the water availability and increases significantly at the reduced water availability. In addition, the marginal cost of water is more sensitive to the change in precipitation, rather than the change in crop production.

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CHAPTER I

General Introduction

In 2007 a comprehensive assessment of water management in agriculture was published, which critically evaluated the benefits, costs and impacts of the past 50 years of water management (Molden, 2007). In this assessment, the following question was raised: Are there enough land, water, and human capacity to produce food for a growing population over the next 50 years—or will I "run out" of water?

The study's answer can be summarized as follows:

"It is possible to produce the food—but it is probable that today's food production and environmental trends, if continued, will lead to crises in many parts of the world. Only if I act to improve water use in agriculture will we meet the acute freshwater challenges facing humankind over the coming 50 years."

How can we achieve this?

1 Agricultural water demand – current and future demand

Humanity faces the unprecedented challenges of a rapidly growing food demand and a shrinking sustainable per capita availability of land and water resources. To make the situation more serious, water shortages in many parts of the world will grow worse due to anthropogenic global environmental change (Grafton and Hussey, 2011). In order to satisfy the needs of a growing population, the farmers have to meet the food demand with diminishing land and water resources. Water management thus may play a crucial role in the attempt to optimize the use of land and water available for agriculture.

After understanding the importance of water management, it is necessary to assess the magnitude of the risk of unavailability of water to decide at which spatial resolution and complex level I should attempt to alleviate adverse effects. Many studies have already tried to estimate the current and future water demands for crop production. According to the Comprehensive Assessment of Water Management in Agriculture, the water demand is expected to increase from currently 7000 km^3yr^{-1} to 9000-11000 km^3yr^{-1} by 2050 (Molden, 2007). Rockström et al. (2009b) estimate that along with the increased water productivity, the water demand for food will increase up to 9000-10000 km^3yr^{-1} by 2050. Today, 3800 km^3 of fresh water is withdrawn per year, of which 70% (2700 km^3yr^{-1}) is used for irrigation. Uncontrolled extraction of water from rivers and unsustainable exploitation of ground water aquifers result in the degradation of water quality of many major rivers and their running dry before reaching the ocean (Molden, 2007). In addition, a competition arises for water resources from non-food crop production like bio energy crops.

Conway (1997) in the double green revolution suggests that over the next few decades, if mankind is to produce enough food for everyone, we shall have to increase food production at a greater rate than in the past 10 years, do so in a sustainable manner, without severely damaging the environment, and ensuring that the food is accessible to all. This entails an efficient management of not only green, but also blue water. Green water is the that infiltrate and remain in the soil and Blue water is the irrigation water. Existing irrigation systems may not be capable of handling the amount of water demanded in the future, yet the cost for rearranging the water management systems would require large investments. If these investments would be made and together with the technological improvements assumed in the future, crop yields could potentially increase per additional unit of water, in both irrigated and rainfed systems (Bouman and Tuong, 2001; Lobell et al., 2009). Furthermore, there is climate change: several projections show changes in rainfall patterns and higher occurrences of intense droughts (Sheffield and Wood, 2008), which make new approaches to water resource planning desirable. Declining runoff rates are recorded in Sub-Saharan Africa, Southern Europe, and parts of Southern Asia and Eastern Australia (Milly et al., 2005). Even though this could not conclusively be tied to anthropogenic climate change, the latest estimations on the radiative forcing, amounting to ~3 Wm^{-2}, correspond to a warming exceeding 2^oC (Ramanathan and Feng, 2008). Hence, there is likely a severe local and global impact on water resource distribution and utilization. In drier climates, relatively small changes in the amount of precipitation or land use may potentially cause relatively large changes in the natural recharge rate of ground water (Eckhardt and Ulbrich, 2003; Scanlon et al., 2005). In order to protect future water supply against these changes, more storage of water is needed including long-term storage to build water reserves in times of water surplus for use in times of shortage. It is therefore crucially important to identify strategies to manage water in such a way that it reaches the agricultural fields in demanded quantities and in the time of need.

2 Established models and their major findings on water management issues

The Food and Agriculture Organization (FAO) has used an integrated hydrologic and economic model designed to understand the key linkages among water, food security, and environment to find remedial strategies for water shortages. The model consists of two integrated modules: the 'food demand and supply' module, which was adapted from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), (Rosegrant et al., 2008), and the 'water supply and demand' module, which uses a water balance model based on the Water Accounting framework underlying the Policy Dialogue Model (PODIUM) (Giraldo et al., 2008), combined with elements from the IMPACT-WATER model (IWMI, 2007). The model estimates food demand as a function of population, income and food prices. Crop production depends on economic variables such as crop prices, inputs and subsidies on one hand and climate, crop technology, production mode (rainfed versus irrigated) and water availability on the other. Irrigation water demand is a function of the food production requirement and management practices, but constrained by the amount of available water. At the global level, food demand and supply are levelled out by international trade and changes in commodity stocks. The model iterates between basin, region and globe until the conditions of economic equilibrium and hydrologic water balance are met. The study concludes that there is a greater scope for increasing food production by improving output per unit of water in existing irrigated areas than by expanding irrigated area.

In an optimistic yield growth scenario (Harris, 1996) show that more than half of the additional food demand can be met by improving the output per unit of water on existing irrigated lands. In South Asia, for example, more than 50% of the cropped area is irrigated, yet productivity is low. If the gap between actual and obtainable irrigated yield could be bridged, the additional food demand by 2050 could be met without expanding the area under production.

According to the FAO's estimations, irrigation can fulfil 75% of the food demand created due to the population increase projected for 2050. In order to achieve this target, the irrigated area needs to be expanded by 55% from the current level. These estimations imply that the investment on improving the efficiency and the productivity of water management structures is more profitable. Income per unit of water used in crop production is higher if the water use is diversified.

In another attempt, the Water Balance Model (WBM) by Vörösmarty et al. (1998) was used. WBM and its descendants predict spatially and temporally varying components of the hydrological cycle and multi-constituent water quality variables (Vörösmarty et al., 1998). The model can be used to estimate the river discharge and impacts of irrigation. The model is a process model which implements the physical processes explicitly.

The applications of the WBM model include quantitative assessments of local watersheds and river systems (Wollheim et al. 2008b, Stewart 2009), impacts of irrigation on climate (Douglas et al., 2006), distribution of land use and hydrologic vulnerability (Douglas et al., 2007), impacts on the water cycle (Wisser et al. 2010, Fekete et al., 2010), and rainwater harvesting and storage for irrigation (Wisser et al. 2009). The study by Wisser et al.(2008) concluded that between 1963 and 2002, global irrigation water used ranged from 2200 to 3800 $km^3\ a^{-1}$, depending on the irrigation and weather data used. Weather driven variability in global irrigation was generally less than ±300 $km^3\ a^{-1}$ globally (<∼10%), but could be as large as ±70% at the national scale (Wisser et al. 2008).

The Water - a Global Assessment and Prognosis, (WaterGAP Model) (Alcamo et al., 2003) considers the whole land area of the world and computes both the terrestrial components of water flow and storage, as well as water use (Gerten et al., 2004). The WaterGAP model has been used in impact assessments to study mainly the water scarcity issues on fresh water resources

Another approach used is the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (LPJml mode) (Bondeau et al., 2007) to assess the green water productivity (Hoff, 2007).

3 Techniques for water management

The global water sector has problems, because the technical, economic and political developments in water management are often too slow to adapt to the required changes (Alcamo et al., 2007). At first sight, water management might appear to be focused on local matters only, such as managing a certain stretch of river. However, water management needs to consider many international or global factors: Catchments often deal with competitive water use, which means that the consumptive use of water is higher than its sustainable production. To properly respond to the complex system of water resources and different types of water users, it is important to verify the valuation methods and the parameters used, which makes the participation of all affected parties very important. The concept of Integrated Water Resources Management (IWRM) can be defined as the procedure that collectively integrates management activities on water resources as a systematic process for the sustainable development, allocation and monitoring of water resources (Biswas, 2004; Jønch-Clausen, 2004; Jønch-Clausen and Fugl, 2001). This promotes more coordinated management of land and water supplies and demands within the river basin.

Water resources, management, and a systematic approach are all essential components in an integrated water management plan. During the recent decades, the interest in integrating water-harvesting techniques in water management plans has increased. Many countries have shown the successful implementation of water harvesting techniques to increase the water availability, either by directly improving soil moisture content or storing water to use it during future stress periods (Ali and Talukder, 2008; DeBano, 2000; Deng et al., 2006; Fox and Rockström, 2000; Kronen, 1994; Li et al., 2000; Li and Gong, 2002; Li et al., 2001; Mupangwa et al., 2006; Oweis and Hachum, 2006; Rockström and Falkenmark, 2000; Unger et al., 1991).

There are many possible integrated water management practices proposed in many studies, often tailored to specific interests, perceptions, investments, priorities and locations of the communities involved. These techniques include applications of both traditional and modern methods. Traditionally, storage has been achieved with dams and surface reservoirs. However, appropriate dam sites with long-term usages are becoming scarce. In addition, dams have a number of disadvantages including the interference with stream ecology, adverse environmental effects, displacement of people for new dam reserves, loss of scenic aspects and recreational uses of the river, high investment costs and potential risk of failure and limited lifespans due to sediment deposition.

4 Shortcomings of existing approaches

The above mentioned approaches consider the available water using a water balance approach, in which the water harvesting and storage capacity are not estimated comprehensively. These incomprehensively analysed factors include the different types of structures built with different materials, selection of appropriate geographic location and appropriate climatic condition. In addition, geographical conditions and agricultural and forestry management practices are not taken into consideration when estimating the cropping area expansion. Cost of installation and maintenance of water harvest and storage structures are not fully considered, which could have a profound impact on the final income. Two main drivers of the availability of irrigation water, i.e. bioenergy demand and precipitation patterns are not treated explicitly in the analysis, even though their impact on land and water resource availability and regional welfare is substantial.

5 Contributions from this approach

In this dissertation, I have developed the ‘Geographic Water Management Potential Model (GWAMP model) and Adapting the Irrigational Water Management Model (ADAPT model).to address some of the above mentioned shortcomings of the analysis in a regional context and to better understand the impact on the land and water resources and regional welfare. While the specific analysis is mostly limited to the Sao Francisco watershed in Brazil, the developed tools are suitable for application in other watersheds as well.

Crop production relies on two main types of water reserves: The soil moisture (green water) and irrigation water (blue water) to compensate for the depleted soil moisture reserve. A sufficient and secure supply of water and food is dependent on the geographical and the climatic conditions as well as the economic activities in a region. The first step in managing water is therefore to estimate the physically available water to manage, as well as the distribution of water stress in time and space. In this approach, the available water quantity is based on the climate change SRES A2 scenario projections of the IPCC (Vera et al., 2006). Precipitation and runoff data are calculated for different land use classes, i.e. crop land, pasture lands, urban lands, forest and wetlands, with the EPIC model (Environmental Policy Integrated Climate, Sharpley and Williams (1990a)) and are used for the estimation of the green water amount. My aim is to manage green water in such a way that the resulting blue water can be used in the most productive and beneficial way. The runoff is calculated in different land parcels as defined in the EPIC model (i.e. crop land, pasture lands, urban lands, forest and wetlands). The concept I present here is to use adaptation measures to manage blue water, so that optimal production targets can be achieved. The EPIC model provides the blue water requirement (irrigation water) of the growing crops. Here, I try to use adaptation techniques to minimize the gap between the supply and the demand for irrigation water by different crops.

In an integrated systematic approach, the planning and management of water storage structures need to be linked to the water supply and demand. The basic principle of a system's approach is connectivity. A system is a set of elements with connections between each other. Any system is composed of subsystems, each being autonomous and open, directly interrelated and integrated with its environment. The systematic approach is important to identify the correct components for an integrated system, to analyse and improve the system. Each of the components requires as input resource endowments and produces outputs to satisfy the demand to attain a certain level of welfare. The systematic approach for integrated water management that I propose here starts from the runoff generation and extends until the demands for crop production within a watershed is satisfied.

With this approach I try to improve on the above mentioned shortcomings of the previous analyses and understand the impact of water management on land and water resources and regional welfare.

6 Outline of the studies and chapters of this thesis

Issues associated with water stress are rising in numbers and call for effective and efficient means for safeguarding the water for agricultural activities. The core to ensure an adequate supply of water for agricultural activities is to adapt water management activities. The efficiency and the effectiveness of water management activities may have a large impact on the land resource utilization and regional welfare. This thesis thus aims at facilitating and strengthening the application of adaptation measures for water management through a quantitative analysis.

The methodological basis for the thesis is the development of the geographic information systems based model GWAMP (Geographic Water Management Potential) and the mathematical programming model ADAPT (Adapting the Irrigational Water Management Model). The GWAMP model is used to assess the land suitability for water management and the ADAPT model is used to assess the resource use, crop demand and the level of welfare attained within a watershed. Figure 1 and Figure 2 present the schematic outlines of the GWAMP and ADAPT models. Setups and model procedures are described in detail in chapter II and chapter III, respectively.

The spatial scope considered in the thesis for the GWAMP model comprises six watersheds with different geographical, climatic, and economic situations, namely the Sao Francisco, Turkana, Nile, Tocantins, Ganges-Brahmaputra and Xingjian basins. The Sao Francisco watershed is categorized as a region having little or no physical and economic water scarcity under the FAO's water stress index (Molden, 2007). I thus use the spatial scope of the Sao Francisco as the reference watershed in the ADAPT model.

The thesis chapters are based on four research papers:

I Weerasinghe H., U. A. Schneider, and A. Loew: Water harvest- and storage- location assessment model using GIS and remote sensing. Hydrol. Earth Syst. Sci. Discuss., 8, 3353–3381, 2011. www.hydrol-earth-syst-sci-discuss.net/8/3353/2011/doi:10.5194/hessd-8-3353-2011 Received: 15 March 2011 – Accepted: 18 March 2011 – Published: 4 April 2011

This paper was presented at the BALWOIS in Ohrid, Macedonia (May 2010), and at the annual retreat of the International Max Plank Research School on Earth System Modelling (October 2010). A different version of the paper was published in the Hydrology and Earth System Sciences and Conference proceedings of the BALWOIS (2010):

Weerasinghe, H., U. Schneider, A. Löw, (2010). "Water Harvest-and Storage-Location Optimization Using GIS and Remote Sensing" BALWOIS 2010. Ohrid, Macedonia. balwois.com/balwois/administration/full_paper/ffp-1653.pdf

In this study, I investigated the suitability of installing water management structures within a river basin. I developed a model named Geographic Water Management Potential (GWAMP) that uses spatial data analysis techniques to assess suitability. GWAMP is applicable for varying climatic, geographic and socio-economic conditions.

II Weerasinghe, Harshi; Schneider, Uwe A, Schmid, E., (2011) Adapting water management to meet agricultural water demand

This paper was presented at the EGU General Assembly 2010 in Vienna, Austria (May 2010) and at the annual retreat of the International Max Plank Research School on Earth System Modelling (October 2011). A different version of the paper was published in European Geosciences Union General Assembly Proceedings (2010):

Weerasinghe, Harshi; Schneider, Uwe A, Assessment of economically optimal water management and geospatial potential for large-scale water storage. EGU General Assembly 2010, held 2-7 May, 2010 in Vienna, Austria, p.6696

This study demonstrates a method to integrate biophysical, trade, and irrigational water feedbacks and geographical suitability assessment in water management planning tools. To illustrate the effect of adapting water management, the land use, level of welfare, water and land prices, and the establishment of water management structures were compared.

III Adapting water management to meet changing different bioenergy demand targets (Manuscript currently in progress)

In this study, I investigated the effect of adapting water management to handle an increasing water demand of biofuel crops. The impact of adapting water management is assessed by comparing the land use, the level of welfare, water and land prices, and the establishment of water management structures.

IV Agricultural water management under changing precipitation (Manuscript currently in progress)

In this study, I investigated the impact of adapting water management under changing precipitation scenarios by analysing the quantity of changed runoff due to climate change. The impact of adapting water management is illustrated by comparing land use, the level of welfare, water and land prices, and the establishment of water management structures.

Figure 1: GWAMP model schematic outline

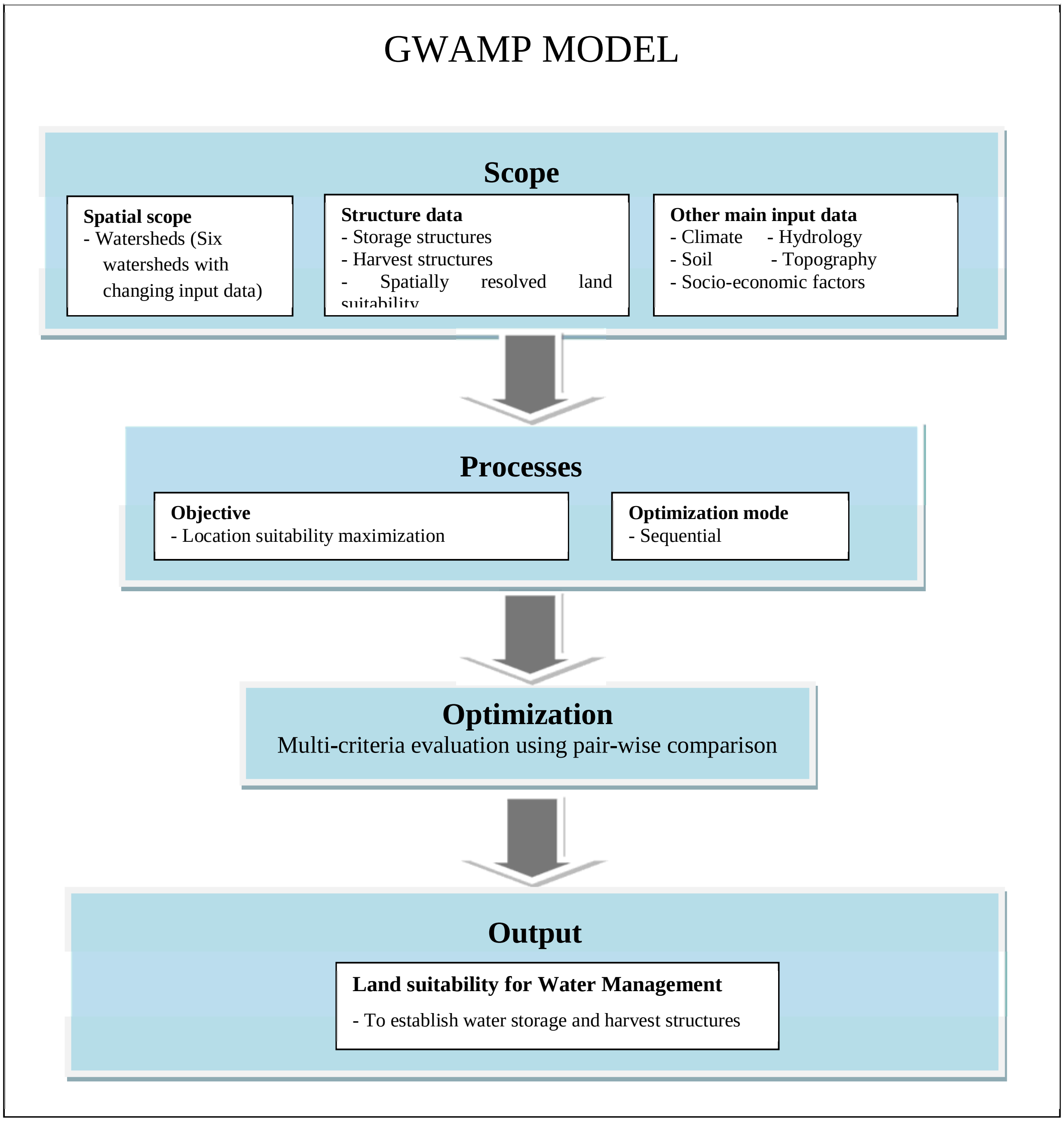
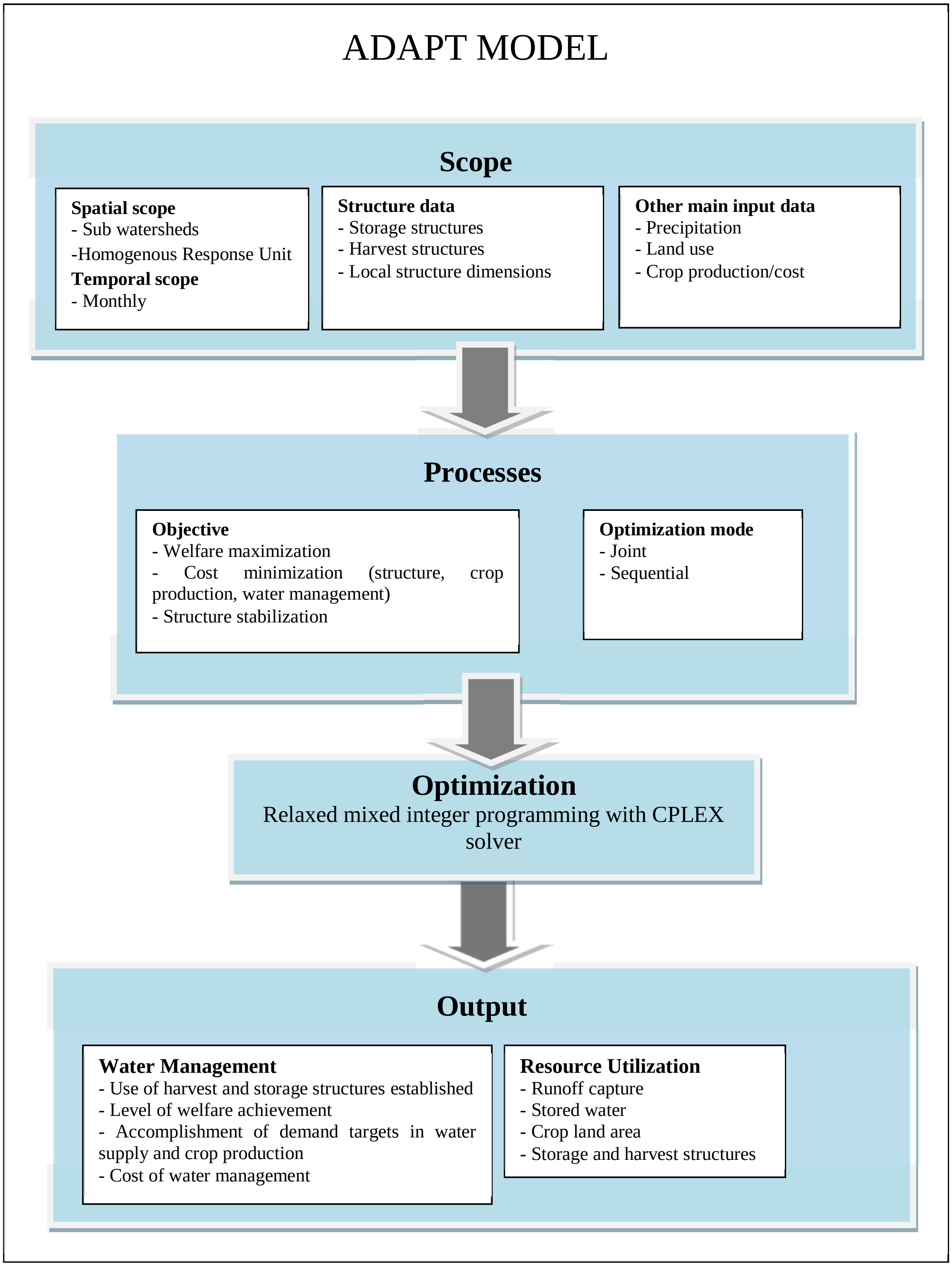


Figure 2: ADAPT model schematic outline



CHAPTER II

Multi-criteria evaluation to identify suitable locations for water

This study describes a suitability assessment of water management structures within a river basin. I developed a model named Geographic Water Management Potential (GWAMP) that uses spatial data analysis techniques to assess suitability. GWAMP is applicable for varying climatic, geographic and socio-economic conditions. Input data are extracted from global data repositories and rescaled to a 30 arc-second spatial resolution. These data include precipitation, evaporation, land cover, soil properties, elevation, slope, population, road density and drainage network. An analytic hierarchical process (AHP) is used to combine suitability for individual factors into an overall suitability index. The model identifies water harvesting and storage suitability for on-farm water storage, regional dams, check dams, contour bunts, stone terraces, roaded catchments, and percolation pits. The application of the model in six diverse water basins (Ganges, Nile, Sao Francisco, Tocantins, Turkana, Xun Jiang) indicates plausible results in varying climatic, geographic and socioeconomic conditions, even in ungauged basins. The exclusive use of available global data sets permits this method to be used at global level with minor modifications. The identification of potential water management adaptation locations could substantially improve integrated assessment models

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), recent improved understanding of global precipitation patterns points to an increase in globally averaged annual precipitation during the 21st century due to global mean warming leading to changes in atmospheric circulation and increases in evaporation and water vapour. However, changes in precipitation will vary from region to region. These changes include an increase in the intensity of precipitation events, particularly in tropical and high-latitude regions, and reduced rainfall over continental interiors during summer due to an increased evaporation. Therefore, many regions are expected to suffer from increased water stress to the point where they have insufficient water to meet basic needs, especially during low-rainfall periods.

The world is facing critical challenges to sustain water resources for the future, and issues are aggravated by the impacts of global change and the necessity for efficient and effective adaptation measures. The term adaptation is widely used to denote measures to control substantial alterations to natural systems or society in the face of adverse impacts brought about by global change. Fresh water resources are often not efficiently used and regulated (Ambast et al., 2002; Seckler et al., 1999). Given the considerable uncertainties around projections of climate impacts on water resources at local and regional scales, adaptation to changing conditions in water availability and demand has always been at the core of water management (Kundzewicz, 2007; Richardson et al., 2009). Adaptation research in the water management sector has been developed over decades in different directions. The effectiveness of adaptation measures in dealing with global change varies widely. Döll et al. (2003) have tried to simulate global renewable water resources and identify the reduction of river discharge by human water consumption at a coarse resolution of 0.5^0. Integrated water management within a watershed is identified as one of the most effective autonomous adaptation strategies. The effectiveness of such adaptation measures and their changing suitability with global change is a field, which demands systematic study. Most of the existing approaches to delineate rain water harvesting potential consider input parameters that are not easily accessible at global or regional scales (Gupta et al., 1997). Therefore it is difficult to incorporate these methodologies into integrated land-use assessment models. Geographic Information System (GIS) techniques are increasingly used for planning, development, and management of natural resources at regional, national, and international level. These applications also include several water-related environmental challenges such as soil erosion, degradation of land by water logging, ground and surface water contamination, and ecosystem changes (Jasrotia et al., 2002). Sharada et al. (1993) studied the application of GIS in entire catchments for site prioritization with respect to soil conservation. The Soil Conservation Service Curve Number (SCS-CN) method (Mockus, 1972) is also used widely in GIS to determine the rainfall-runoff (Hariprasad, 1997; Jain et al., 1996; Srinivas, 1996). Sharada et al. (1993) argue that composite map generation and calculating area statistics with geo-databases is much faster and more accurate. Ross (1993) integrated GIS into hydrologic modelling and found that it reduced the modeller's subjectivity in parameter selection. Many of these existing approaches to identify water harvesting and storage potential use locally available datasets. Therefore, they are not easily applicable in different regions because the data used are not available at a global scale. Potential site selection is often based on assessment of the natural environment. Rather a limited consideration has so far been given to a holistic approach to identify optimal locations for water management measures considering geographic, technical, economic, and social aspects. As mentioned earlier, Global Climate Model (GCM) projections have already provided explicit explanations for potential change in precipitation and land use. However, so far, there has been no comprehensive analysis of the potential for managing a watershed as one unit, combining different adaptation strategies.

The research question I try to address here is how to identify sites for water management in a holistic scenario using high-resolution global datasets. A holistic scenario is defined as containing climate, land cover, topographic, drainage, and socio-economic factors. Yet the key point is to identify a computationally feasible method, while maintaining the accuracy of the results. In this study, I identify potential locations for adaptation measures to harvest and store water. This is done using climate, land cover, topographic, drainage, and socio-economic data for six watersheds. I combine the study with a sensitivity analysis in order to understand changes in potential location identification according to changing precipitation and land use. To represent climate change, I use precipitation variability projected in different IPCC emission scenarios. (Ramankutty et al., 2006) have identified forest, agricultural lands, grazing lands, dry lands, and urban areas as the major drivers of land-use change. To represent land-use change, I use urban, agricultural, and forest land-use scenarios.

The remaining sections of the paper are arranged as follows: Section 2 provides details of the GWAMP model structure. Section 3 contains an explanation of relevant model theories. Section 4 summarizes the adaptation techniques used in the model. Section 5 provides details of the model setup. Section 6 provides a summary of the results and section 7 a comparison of results with existing locations. Section 8 concludes the main findings of the study.

2 Geographic Water Management Potential (GWAMP)

2.1 Model concepts

GWAMP is a spatially resolved model that results in suitability maps for harvesting and storage of rain water. The aim of the model is to identify potential adaptation techniques within a watershed that are applicable in different climatic and geographical conditions.

In contrast to existing approaches, GWAMP is designed to be used in different climatic and geographical conditions, eventually covering the entire land mass. In order to obtain an acceptable level of accuracy and maximize the model's applicability, I have to compromise on scope. I use global datasets to avoid inconsistencies due to different definitions and qualities of local or regional data. Spatial and temporal resolution of the model is a compromise between local characteristics, data availability, and applicability of the model to other regions. Water management adaptation is an important aspect to consider in evaluating the impacts of global change on food production; however, so far, integrated studies have not considered water storage options (Schneider et al., 2011). Therefore, the applicability of GWAMP in changing climate and geographical locations is especially useful as a first step to improve integrated land-use studies. I have selected 1 km x 1 km resolution, with the intention of applying the method globally.

Our approach calculates runoff at 1 km x 1 km resolution and estimates gross runoff potentials. GWAMP can be coupled offline to a GCM. This compatibility is an important feature for assessing adaptation strategies under changing climate. In addition, our approach offers a relatively fast preliminary site selection for water infrastructure development that avoids a time-consuming manual location search. In GWAMP, I consider an entire catchment as the appropriate spatial scale for water resource planning, development, and management. By applying an Analytic Hierarchical Process (AHP) on spatial data, I obtain a suitability score that enables me to determine an overall suitability score for both water harvesting and storage.

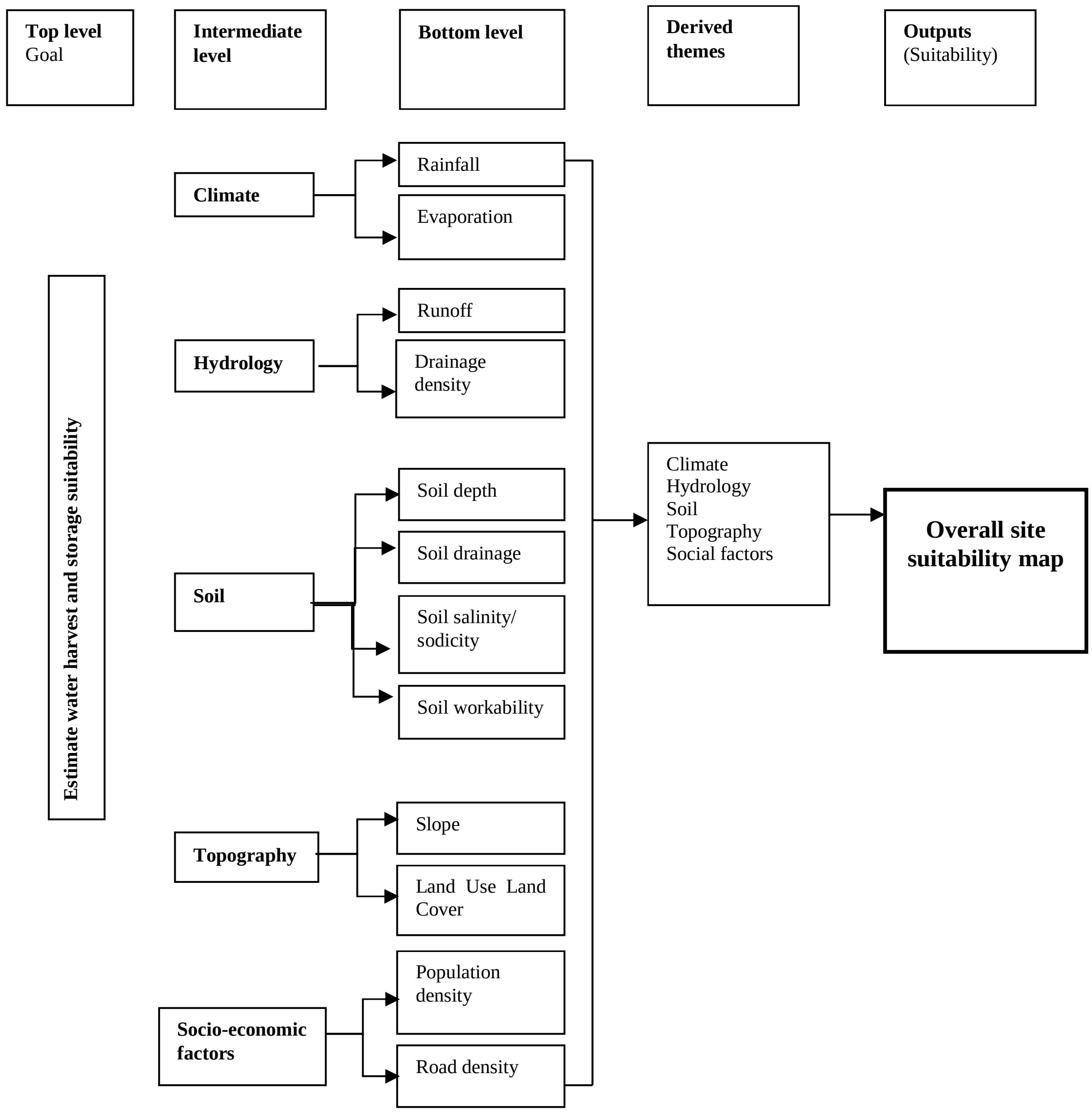
I use the SCS-CN method (Mockus, 1972) to approximate the gross runoff potential. Since our land-use and soil data are resolved at 1 km x 1 km, I believe that the accuracy is adequate for the intended purpose of our estimates. Our specific objective is to estimate the possible gross runoff volume generation, which adaptation techniques have to manage at a maximum occurrence. With the current database, the model can only approximate runoff on land parcels where the soil is not permanently frozen. Land parcels with long-term frost are not considered in the analysis. If more accurate runoff data were available from other sources, the model could be applied to land parcels with permanent frost cover as well. As noted above, the water harvest and storage suitability maps are designed to improve global integrated land-use models, for which land use and land management intensity are endogenous. Evaporation depends on land use and land management intensity (i.e. higher biomass yields usually imply more evaporation). Global integrated land-use models (Adams et al., 1994) are often linked to biophysical models, which compute specific evapotranspiration rates for each land use and land management intensity. Thus, the water harvesting and storage suitability estimate should reflect only the gross runoff potential, i.e. the volume of rainfall that can potentially generate runoff. The actual runoff can be calculated by the integrated land-use optimization model taking decisions to change land use into account. The model already has a developed database at 30 arc-second (~1 km), but it can be easily adjusted to finer or coarser resolutions.

2.2 Model Structure

The GWAMP model is developed in a GIS environment and estimates suitability level information to implement adaptation technologies based on the decision rules provided. The rain water harvesting technologies considered here include moisture conservation techniques such as check dams, percolation pits, and stone terraces on agricultural farms or nearby. Water storage technologies include regional reservoirs and smaller-scale farm tanks in agricultural areas. The significant feature of this decision support system is that decisions can be made based on expert opinion and available guidelines in different domains using a rule-based decision tree. Figure 3 presents the hierarchical structure of the GWAMP model.

From left to right, at the top level I define the main goal, which is to estimate the potential suitability for harvesting and storing water. At the intermediate level, I select, in broad categories, the factors that could affect the decision. At the bottom level, I define the input data. The next step is to combine the input data and develop thematic maps for the broad categories. Finally, combining the thematic maps, I derive suitability maps that present estimated suitability scores. To combine the input data and the thematic data, I use rules defined in the literature, which will be discussed later in this section.

Figure 3: Schematic diagram of the GWAMP model framework



2.3 Input data parameters and data base generation

The required input data for the GWAMP model fall into five main categories, which are explained in the subsections below. I retrieve these data from global data repositories and rescale them to a 1 km spatial resolution to obtain a set of manageable input data at a global scale. The database is in 30 arc-second spatial resolution (~1 km) and projected to the geographic coordinate system World Geodetic Survey 1984 and to the world cylindrical equal-area projected coordinate system. All the downloaded data are resampled and reprojected to match the database configurations.

2.3.1 Climate data

Climate data are represented by precipitation and evapo-transpiration. Present-day precipitation data are downloaded from the WorldClim global climate database (Hijmans et al., 2005) using observations from 1950–2000. Future precipitation data are based on simulations of the Hadley Centre Coupled Model version 3 (HadCM3), considering the A1B, A2a, and B2a scenarios in 2020, 2050, and 2080 (Hijmans et al., 2005). Potential evapo-transpiration (PET) data are downloaded from the CGIAR-CSI data repository (Zomer et al., 2007) at 30 arc-second resolution. Monthly averaged PET (mm/month) data are estimated using the Penman-Monteith equation. I combine these monthly data layers to estimate yearly average PET and this is used as a decision-making criterion in the model. Intensity and spatial distribution of rainfall in a given area are the basis for the design and implementation of a water harvesting or storage system.

2.3.2 Hydrology data

Hydrology data are represented by runoff volume and drainage network distribution. I use the equations from the SCS-CN method (Eq. 1 and Eq. 2) to estimate the runoff.

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10 \right)$$ Eq.1

$$Q = \frac{\left(P - I_a\right)^2}{P - I_a + S}$$ Eq. 2

where

S = Maximum recharge capacity of watershed after 5 days rainfall, mm/month

Q = Monthly runoff depth, mm

P = Monthly rainfall, mm

Ia = Initial abstraction of rainfall by soil and vegetation, mm

CN = Curve Number (unit less), table by Mockus (1972)

Ia contains all precipitation losses before runoff. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Ia is highly variable but is generally correlated with soil and cover parameters. A regression analysis performed by the Soil Conservation Service (USDA, 1972) using recorded rainfall and runoff data from small drainage basins resulted in an average relationship of Ia = 0.2S. This is used to eliminate Ia in Eq. 2.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$ Eq. 3

CN, a dimensionless scalar between 0 and 100, reflects the overall runoff response related to land use, land treatment, hydrological condition, hydrological soil group, and antecedent soil moisture condition (AMC) in a drainage basin. The AMC refers to the soil condition before runoff occurs and is generally assigned to three classes. Here, I consider only AMC II, which is the average condition. The information from the soil map is reclassified into four hydrological soil type groups—A, B, C, and D—based on the infiltration and runoff generating potentials (Niehoff et al., 2002). According to the National Engineering Handbook (Boorman et al., 1995; Mockus, 1972), the characteristics of the hydrological soil groups can be summarized as shown in **Table** 1. The runoff values represent the cumulative annual runoff amount (mm) for each grid cell, estimated yearly cumulative runoff is used as a decision-making criterion in the GWAMP model.

Table 1: Main characteristics of hydrological soil groups

Hydrological soil group	Main characteristics
A	Sand, loamy sand, or sandy loam soils with low runoff potential and high infiltration rates
B	Silt loam or loam soils with moderate to high infiltration rates
C	Sandy clay loam soils with low infiltration rates
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay soils with very high runoff potential and low infiltration rates

The drainage network data are classified into stream orders using Strahler's method (Strahler 1957). In this method, all stream links without any tributaries are assigned an order of 1 and are referred to as first order. Therefore, the intersection of two first-order links will create a second-order link, the intersection of two second-order links will create a third-order link, and so on. The intersection of two links of different orders, however, will not result in an increase in order. Subsequently, I calculate the drainage line density, which identifies how well an area is drained. The drainage line density is used as a criterion for decision making in the GWAMP model.

2.3.3 Soil data

Soil data include information on soil texture, soil drainage, presence of problematic soils, soil workability, and effective soil depth. All of these data are extracted from the Harmonized World Soil Database v 1.1 (HWSD), downloaded from the International Institute for Applied Systems Analysis

(IIASA) data repository (Fischer et al., 2008). The soil workability reflects interrelated soil characteristics such as texture, structure, organic matter content, soil consistency/bulk density, the occurrence of gravel or stones in the profile or at the soil surface, and the presence of continuous hard rock at shallow depth as well as rock outcrops. The soil drainage class is defined based on the possibility of evacuating excess moisture from a soil based on the soil unit's classification name, the soil phase(s) indicated for the dominant unit, and the slope class. Soil drainage is mapped into seven classes ranging from very excessive to very poor. From different types of problematic soil conditions, I extracted only saline/sodic limitations, i.e. high salt content or exchangeable sodium saturation within 100 cm of the surface. The structure of the top soil influences the runoff and the infiltration and percolation rates. The soil depth, along with soil texture, determines the quantity of water, which can be stored in the soil. Data layers of soil texture, soil drainage, availability of problematic soils, soil workability, and effective soil depth are used as criteria for decision making in the GWAMP model, In addition, soil texture information is used to derive the soil hydrologic group to estimate runoff.

2.3.4 Topography data

Topographical data comprise slope and land-cover data. The slope is an important property to assess the suitability of an area for macro-catchment water harvesting. For a given inclination, the runoff volume increases with the length of the slope. The slope length determines the suitability for macro, micro, or mixed water harvesting systems (Prinz and Singh, 1999). Slope data are obtained from the IIASA data repository (Fischer et al., 2008). The slope map contains the average slope (ranging from 0 to 90%) in each grid cell. The slope data are classified into seven categories according to the Food and Agriculture Organization (FAO) guidelines (Fischer et al., 2008). The objective of water harvesting structures on steep slopes is to slow down erosive fast flows, increase shallow ground aquifer recharge, and direct water to surface water storages. Slope class/range is used as a criterion in the GWAMP model.

Vegetation is another important factor that determines surface runoff generation. Studies in West Africa (Tauer and Humborg, 1992) and Syria (Prinz and Wolfer, 1999) have shown that an increase in the vegetation density increases interception losses, retention, and infiltration rates, which consequently decrease the volume of runoff. Land cover describes the physical material on the earth’s surface. The dataset used here was developed within the Global Land Cover 2000 Project and uses the FAO Land Cover Classification System (Fritz and Directorate-General, 2003). Land cover data are used as a criterion in the GWAMP model to estimate runoff.

2.3.5 Socio-economic data

Socio-economic data are represented by population and road density data. The socio-economic conditions of a region are important for planning, design, and implementation of any water-harvesting scheme. The farming systems of the community, the financial capabilities of the average farmer, the cultural behaviour and religious beliefs of the people, as well as public participation are important in implementing activities. I use gridded world population density data (GPWv3, 2005) from the Center for International Earth Science Information Network (CIESIN) data repository. The population density data layer is used as a criterion for decision making in the GWAMP model. Regions with high population density are not favourable for building water management structures. The world network of major roads was downloaded from the FAO spatial data repository (FAO/GIS, 1997). Road line density is determined based on the number of road lines present in a grid cell. Population density data and road density data are used in the GWAMP model.

2.3.6 Elevation data

I use digital elevation data indirectly to develop input parameters for the GWAMP model. I use NASA Shuttle Radar Topographic Mission-Digital Elevation Model (SRTM-DEM) data according to the method described by Reuter et al. (2007). I apply the Fill-Sink operation in ARC-GIS to the dataset to rectify the unusual appearance of sinks and peaks in data during data transfer and image mosaic operation. Seamless data of 3 arc-second resolution are downloaded from the CGIAR server (Jarvis A. et al., 2008). I use the processed DEM to develop the water flow path on the terrain surface and watershed boundaries. A rough boundary for each watershed is downloaded from the World Resource Institute website. Using the boundary data, DEM data are extracted for each watershed along with a 1 km boundary. I process the filled DEM to extract an accurate watershed boundary and flow network using flow direction and flow accumulation raster data. Using the rectified DEM, I create contour data at 50 m height intervals. Contour density, i.e. the number of contour lines per grid cell, is derived from contour data. This data layer is then used to identify valley locations for regional reservoirs. A 50 m contour interval is used in the analysis due to computational feasibility and to assess the variation of undulating topography within a 1 km grid box.

2.4 Multi-criteria Evaluation (MCE)

Suitability assessment tasks involve many decision-making aspects, diverse alternatives in possible outcomes and sometimes qualitative factors by which to assess the outcomes. The purpose of MCE is to investigate alternative choices under multiple, often conflicting, objectives (Voogd, 1983) and to generate overall rankings of these choices (Janssen and Rietveld, 1990). Here, I use MCE to identify the suitability of each grid cell to implement adaptation strategies and represent the result of the process using a ranking score. Following sub sections explain the estimation procedures.

First, a suitability level index (SLI) is used to depict the suitability level of individual factors. The SLI is generated using actual data values and this helps to convert all qualitative and quantitative input data parameters into one common scale. The relative importance weight index (RIWI) is a weight score that represents the relative importance of each factor compared to other factors. The composite suitability index (CSI) is the product of SLI and RIWI.

2.5 Suitability Level Index (SLI)

To represent the suitability level I use a common numerical scale of 1–9 (Table 2). Suitability to implement an adaptation technique on grid cells is evaluated using literature. These rules are explained in sections 3.1 and 3.2. Using the numerical scale, the suitability of the actual parameter value to implement a structure is converted to a suitability ranking score. The chosen ranking system has been used in several previous studies (Diamond and Parteno, 2004; Gosschalk, 2002).

Table 2: Numerical mapping of suitability levels

Suitability level	*Numerical expression*
Optimal	9
Highly suitable	7–8
Moderately suitable	6–5
Marginally suitable	4–3
Not suitable	2–1
Restricted	0

2.6 Relative Importance Weighted Index (RIWI)

The RIWI is calculated based on a method developed by Saaty (Saaty, 1980), where the overall ranking results from a hierarchy of components known as an Analytic Hierarchy Process (AHP). An explanation to AHP is given in the APPENDIX – A. This method considers the relative importance of a diverse set of factors and identifies the most suitable among alternative outcomes. This method largely stems from the theories of human behaviour, including thinking processes, logic, intuition, experiences, and learning theories (Saaty, 1987).

The hierarchical process includes a top level, which comprises the overall objective of the ranking process, intermediate levels, which comprise the factor and sub-factors, and the lowest level, with the possible outcomes of alternative choices. I design the model based on the above hierarchical structure.

The AHP is constructed using a series of pair-wise comparison matrices, which relate each factor to every other factor. This comparison matrix estimates a weight for each factor that describes the importance of each input data parameter contributing to the overall objective. The main factors are then broken down to sub-factors, and pair-wise comparisons are repeated for each sub level of the hierarchy.

2.7 Composite Suitability Index (CSI)

Finally, combining RIWI and SLI I calculate the CSI. Following is the mathematical representation of the score calculations.

Suitability level score at bottom level: S_{itj} $\forall i, t, j = \text{bottom level}$

RIWI: W_{jt} $\forall i, t$

Composite Suitability Index: $C_{it} = \sum_j S_{ijt} \bullet W_{jt}$ $\forall i, t$

$i = 1 ... I$ (Grid cell)
$j = 1 ... J$ (Operation level)
$t = 1 ... T$ (Water management technique)

The higher the index value, (C_{it}), the more suitable the grid cell is for the water harvest or storage technology.

3 Adaptation Techniques

I need to manage excess or depleted amount of water on time and space, which is needed for agricultural water use. In order to manage this water I implement adaptation techniques on the available water. Here, I consider two aspects in selecting and combining adaptation techniques for water management within the watershed, i.e. water harvesting and storage. Water harvesting in its broad scope can be defined as the collection of rainwater and runoff for productive use. Water storage is the collection of water for use when there is a lack of supply. Our objective in using a water harvest structure is to reduce the runoff flow velocity from upstream to downstream and provide an opportunity for further recharge of groundwater aquifers. Here I consider only macro-catchment and floodwater harvesting techniques because our spatial resolution is 1 km^2.

Suitability levels for small-scale farm tanks are determined based on the criteria defined by Lewis (2002). Additionally, the suitability for check dams, percolation ponds, stone terraces, and roaded catchments are determined based on recommendations by Mbilinyi et al. (2005) and Prinz (1996a).

3.1 Water harvesting techniques

3.1.1 Check dams

A check dam is a small barrier of rocks, gravel bags, sand bags, or reusable products, placed across a channel. Check dams reduce the effective slope of the channel, thereby reducing the velocity of flowing water. Usually, check dams are constructed at lower-order streams (up to 3^{rd} order), when the terrain slopes are small to gentle. The water flow can thereby be retarded, and water can be retained temporarily at a lower-level wall. Also, in locations where water table fluctuations are high, check dams are preferable. Soils with low to medium permeability are preferred to allow some recharge downstream of the check dam if necessary. Check dams are mostly located close to agricultural areas and settlements.

3.1.2 Contour bunts

Contour bunts, sometimes also called contour ridges or contour furrows, are small earthen banks with a furrow on the higher side, which collects runoff from an uncultivated strip between the ridges. This technique helps to increase soil moisture under the ridge and the furrow and yield runoff from a short catchment length. Labour requirements are relatively low and contour ridges are easy to make using hand tools. Construction can be mechanized and the technique is therefore suitable for implementation on a larger scale as well as on both cultivated and uncultivated lands. Moderate slopes (0.5–5%) with light or medium soil texture and areas receiving less than 700 mm of rain per year are suitable for the construction of contour bunts.

3.1.3 Percolation ponds

There can still be runoff left in the field, even after the soil pores and farm ponds are filled. This rainwater excess can be collected by constructing percolation ponds in appropriate places. Usually percolation ponds are structures that increase water percolation and soil moisture and retain the silt flow, which would otherwise reach multipurpose reservoirs and reduce their functional lifetime. Flat terrains receiving less than 600 mm of annual rainfall on average and with slopes less than 2%, close to streams and agricultural lands, are preferable for percolation ponds (NRSA, 1995). Soils with adequate permeability are also important to facilitate additional recharge of shallow water aquifers.

3.1.4 Stone terraces

Stone terraces are normally constructed across hill slopes, thereby intercepting the surface runoff. They are normally built on land that receives 300–600 mm average annual rainfall and has a slope up to 25% inclination (Critchley and Siegert, 1991), and they are advantageous in retarding soil loss and conserving soil moisture. Spacing of stone terraces can range from 10 m to 30 m and can be adapted depending on the slope. Soil excavated for the foundation of terraces is used to form a small bund on the upstream side of the terrace. A stone terrace is stabilized by planting suitable vegetation on the land. Construction is labour intensive.

3.1.5 Roaded catchments

A roaded catchment is a water harvesting structure designed to increase runoff inception from the catchment above a dam or a farm tank. The 'roads' of a roaded catchment are parallel ridges of earth with side slopes that cause runoff to be directed into troughs or channels. The surface is lined with clay and compacted to make it smooth and impervious to reduce infiltration and increase runoff. Capture of runoff is increased by increasing the slope of the surface, decreasing surface detention and reducing the permeability of the sloping surface. Medium-terrain slopes (5–16%) are usually used to construct roaded catchments.

3.2 Water storage techniques

3.2.1 Farm tanks

Farm tanks are usually constructed on flat terrain with low soil permeability on, or close to, agricultural land. They are made either by constructing an embankment across a watercourse or by excavating a pit, or a combination of both. The main objectives of constructing farm tanks are to provide drinking water for livestock, to serve as water storage for irrigation of a limited number of fruit plants, and to moderate the hydrology of small watersheds.

3.2.2 Dams

Regional dams are usually created in low-level terrain with low-permeability soil, located closer to valley locations and main water courses. Major decision criteria considered here are geomorphological characteristics, storage capacity, runoff, and river reach. The width and slope of the valley at the dam location are important parameters, which determine the cost of the planned building. The slopes must be stable and resistant to deformation under all operating conditions, including rapid reservoir drawdown, and the overall intensity of the rainfall needs to be rather high. Here I consider medium size dams less than 15 m high, mainly for agricultural purposes.

4 The Model Setup

To test and validate GWAMP, I apply the model in six catchments with diverse geographic and climatic conditions (Table 3).. Here I considered the watershed for the Ganges and Brahmaputra as one unit, since the outlet of the two rives cannot be distinctively demarcated. Last parts of both rivers intersect and merge in the lowlands where the two rivers outflow to the Indian Ocean

Table 3 summarizes the characteristics of all considered watersheds. I analyse the model in three setups: current situation, effect of rainfall pattern, and land-use change.

Current situation

To investigate the potential of water harvesting and storage, I run the model for current land use and recent precipitation data.

Effect of rainfall pattern

To investigate the effect of precipitation changes I use values for current climate and IPCC A1B, A2a, and B2a scenarios for the years 2020, 2050, and 2080.

Effect of land-use change

Numerous studies in the last two decades have estimated the rates of tropical deforestation and other kinds of land cover change around the world (Ramankutty et al., 2006). To understand the effects of these land-use changes I use four defined land-use scenarios, i.e. base, agriculture, forest and urban land-use scenarios. These scenarios are defined by allocating all possible land parcels having a possibility to be converted into the considered land-use class.

Base scenario: Current land use

Agriculture scenario: Allocating all possible land cover classes to agriculture to represent an extreme agricultural situation

Forest scenario: Allocating all possible land cover classes to forest to represent an extreme forested situation

Urban scenario: Allocating all possible land cover classes to urban lands to represent an extreme urbanization situation

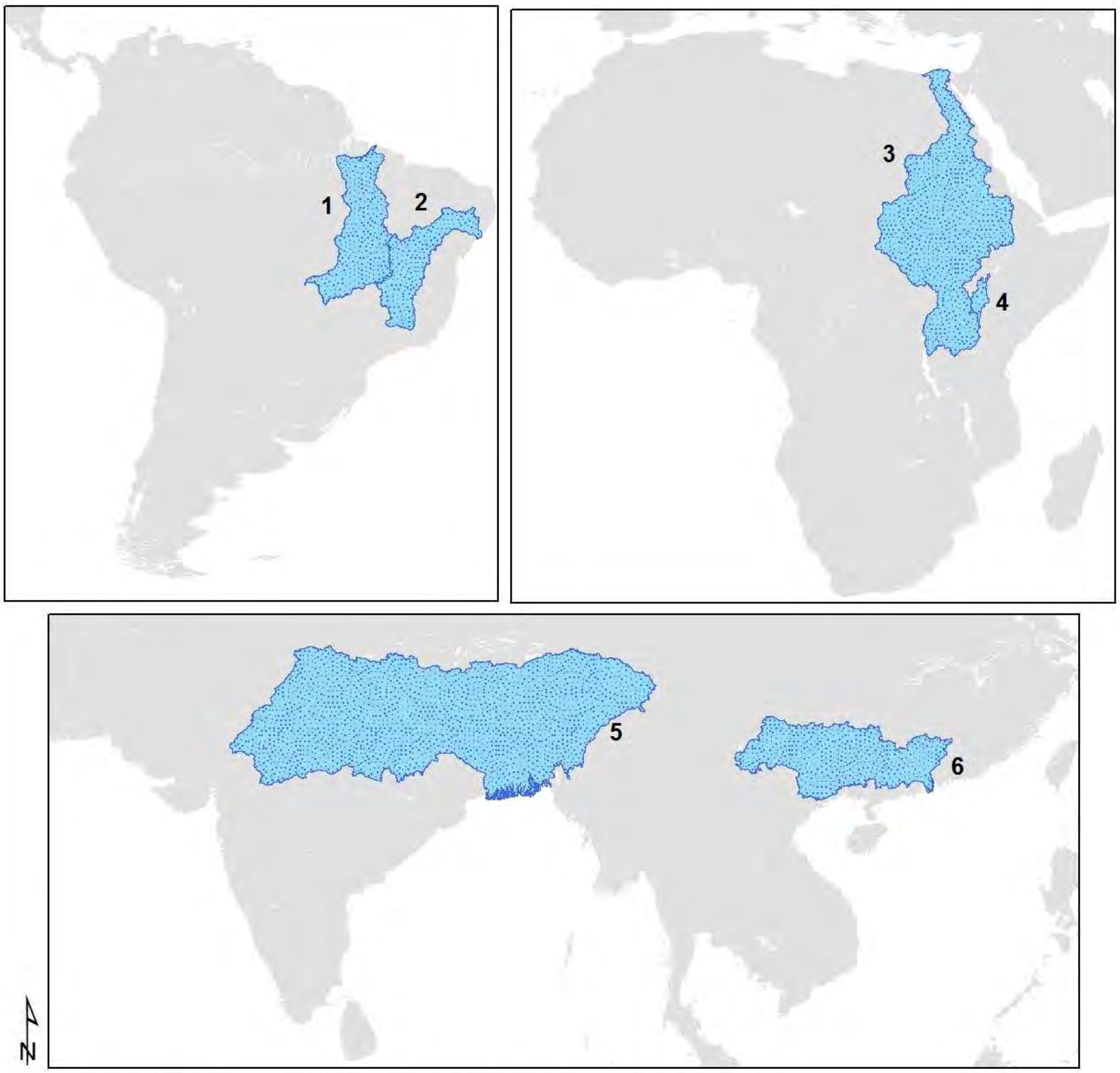
Runoff is calculated for each of the different land cover scenarios by replacing the existing land cover with the corresponding land cover. Subsequently, existing evaporation data are also replaced with the mean evaporation value for changed land cover classes in each month in the basin.

In hypothesis I assume, Urban scenario will give most minimal runoff conditions while Forest scenario will give highest runoff conditions, compared to base scenario.

Table 3: Watershed characteristics

	Land use / land cover variables (%)		Basin area (km2)	Average population density (per km2)	Number of large cities	Number of dams (15–150 m)
Ganges	Forest	4.2	1,016,124	401	11	5
	Agriculture	72.4				
	Urban	6.3				
Nile	Forest	2.0	3,254,853	46	25	19
	Agriculture	10.7				
	Urban	1.0				
Sao Francisco	Forest	3.1	617,814	18	1	47
	Agriculture	60.2				
	Urban	2.8				
Tocantins	Forest	9.9	764,213	5	0	9
	Agriculture	61.5				
	Urban	1.3				
Turkana	Forest	11.9	209,096	61	0	1
	Agriculture	20.8				
	Urban	0.1				
Xun Jiang	Forest	9.6	409,480	194	4	47
	Agriculture	66.5				
	Urban	5.3				

Figure 4: Watersheds considered in the study



1-Tocantins, 2-Sao Francisco, 3-Nile, 4-Turkana, 5-Ganges-Brahmaputhra, 6-Xun Jiang.

5 Results and Discussion

5.1 Current situation analysis

Potential sites for rain water harvesting and storage technologies in the Ganges, Nile, Sao-Francisco, Turkana, Tocantins, and Xun Jiang basins as estimated by the GWAMP model are shown in Figure 5 to Figure 10, respectively. Colour bands represent the suitability for each technique. These maps only show the suitability analysis for current climatic, geographical, and socio-economic conditions. I categorize the techniques into regional water storage, local water storage, and water harvesting. Sao

Francisco and Ganges-Brahmaputhra region shows overall high suitability for most of the structures due to favourable precipitation, terrain and land use characteristics. In the Nile region water suitable areas for water management is concentrated in the mountain regions while desert regions become not suitable to build structures. Regional water storage represents regional dams, local water storage represents farm tanks, and water harvesting represents all water-harvesting techniques. GWAMP allocates potential sites for regional dams close to valleys in the centre of the catchment. Potential water-harvesting sites occur predominantly in the mountainous regions of the catchment, whereas the farm tank locations are distributed throughout the catchment. This is due to the spatial variability in topographical features. For example, towards the catchment boundary, the topography is largely hilly and with less continuous drainage networking compared to central valley regions of the catchment. Suitable sites for stone terraces, however, appear only on a small fraction of land in all catchments.

The most suitable sites for regional dams are located close to the main river and have moderately undulating slopes (0–16%). The evidence of locations where reservoirs already exist agrees with our model results. The results also agree with findings by Mbilinyi et al. (2005), who argue that water reserves are constructed close to streams with slopes where water can easily enter and exit by gravity. Within agricultural areas, suitable sites for farm tanks are located in places with moderately undulating to steep slopes (16–30%) and with loamy sand or loamy clay soils. Suitable locations for percolation pits are found in areas, which combine moderately undulating slopes (5–10%) with clay, silty clay, or sandy clay soils. These characteristics agree with findings obtained by Prinz (1996a). Relatively fine grain soils such as clay and silt have a high water storage capacity and thus are not suitable for percolation pits. According to Hudson (1987) and Jasrotia et al. (2002), stone terraces and check dams are usually built on slopes with unstable soils of coarse texture, low organic matter content, or steep slopes. This characteristic is depicted by GWAMP, which places stone terraces and check dams on steep slopes. Soils with high shares of small clay and silt particles have a larger effective surface area than soils with larger particles, and therefore detain more water (Ball, 2001). This agrees with the model results on locating roaded catchments and farm tanks, which are mainly found on gently undulating slopes (2–5%) with clay, silty clay, and sandy clay soils. Our results are also in agreement with findings by Stanton (2005) that areas with low to medium slopes together with high water holding capacity soils such as clay, silty clay, and sandy clay, are suitable for on-farm tanks with roaded catchments. The relatively low cost of constructing roaded catchments on gently undulating slopes compared to higher costs on steep slopes is a contributing factor.

Figure 5: Estimated water harvest and storage suitability in the Ganges-Brhmaputra Basin

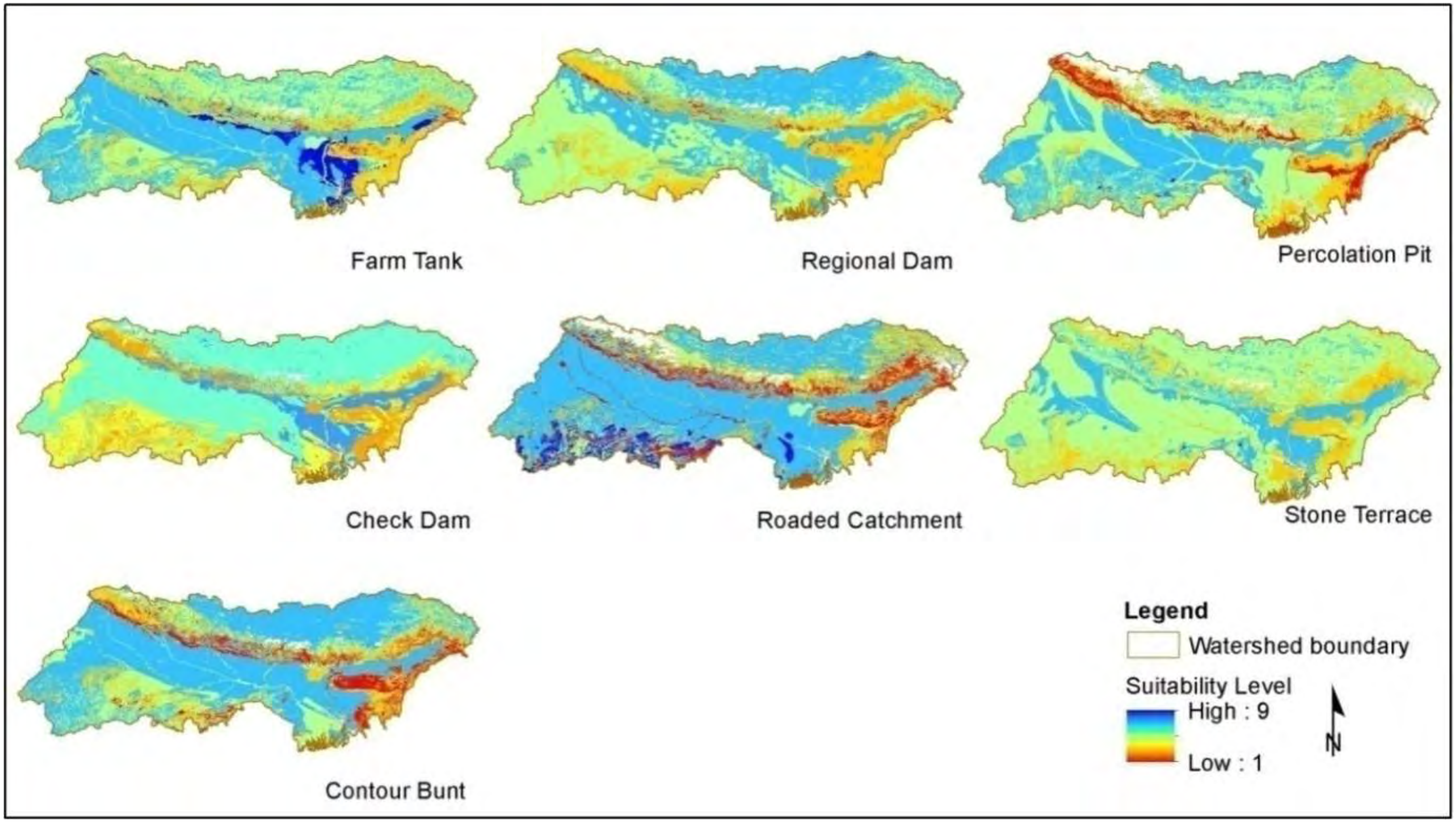


Figure 6: Estimated water harvest and storage suitability in the Nile Basin

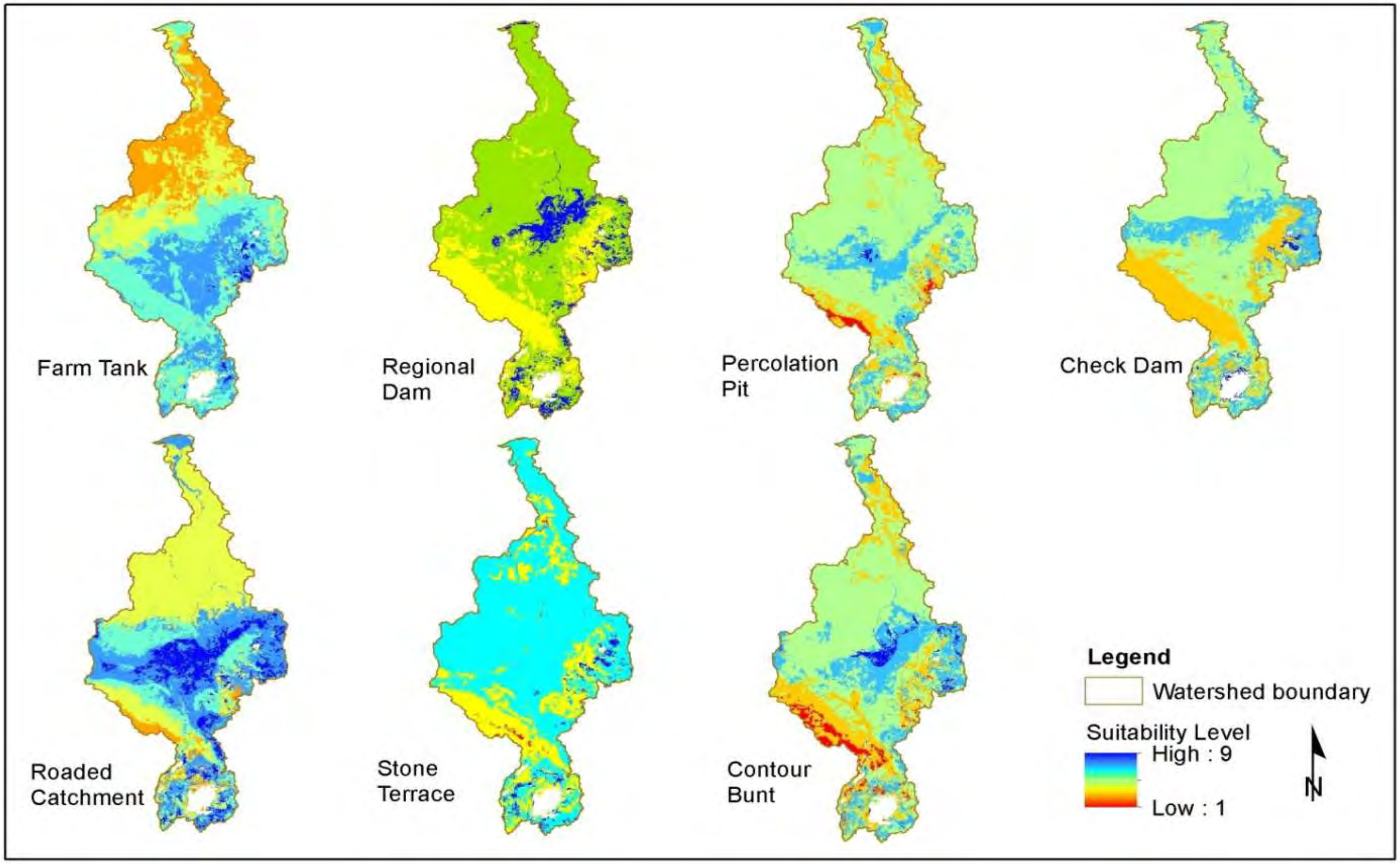


Figure 7: Estimated water harvest and storage suitability in the Sao Francisco Basin

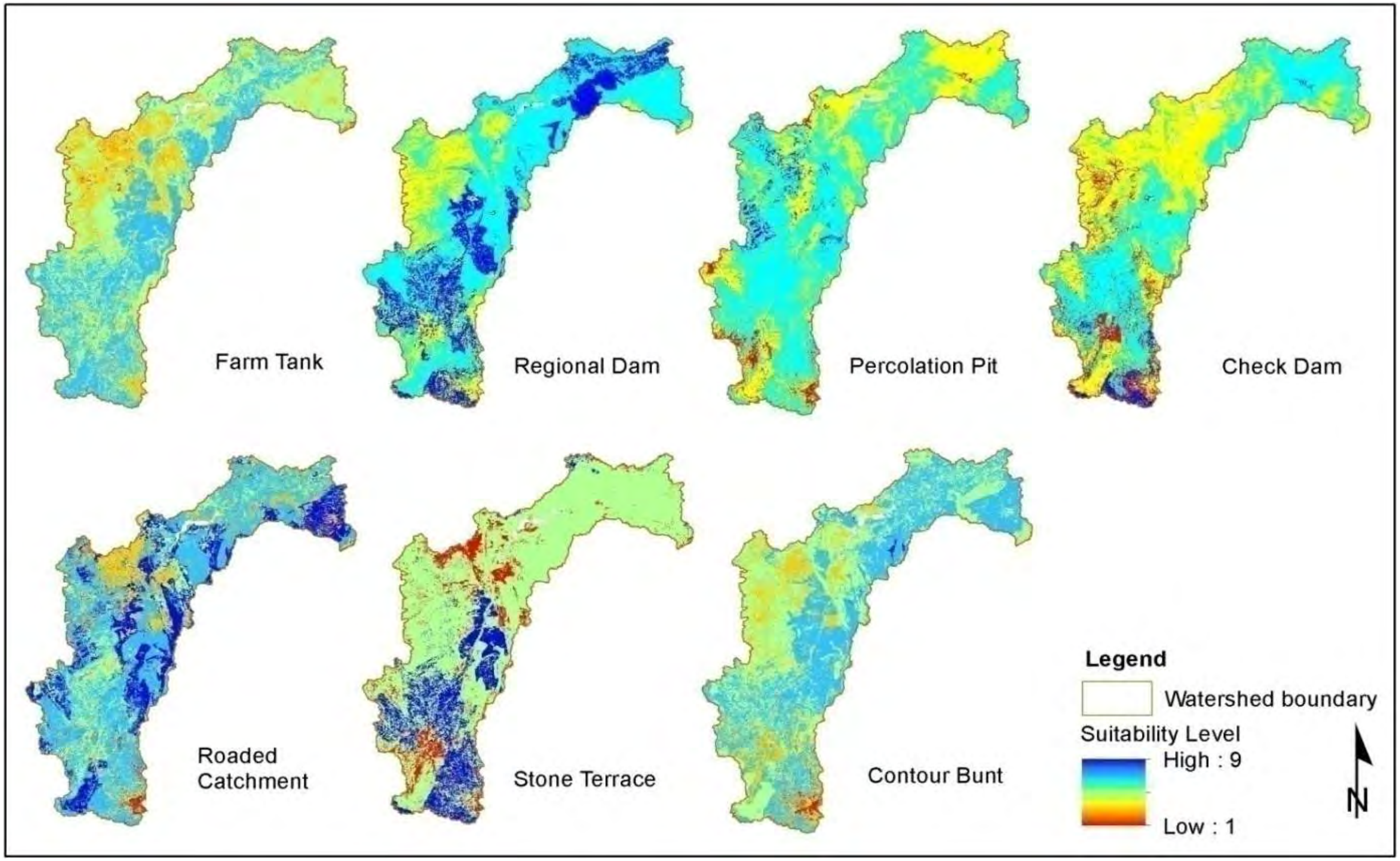


Figure 8: Estimated water harvest and storage suitability in the Tocantins Basin

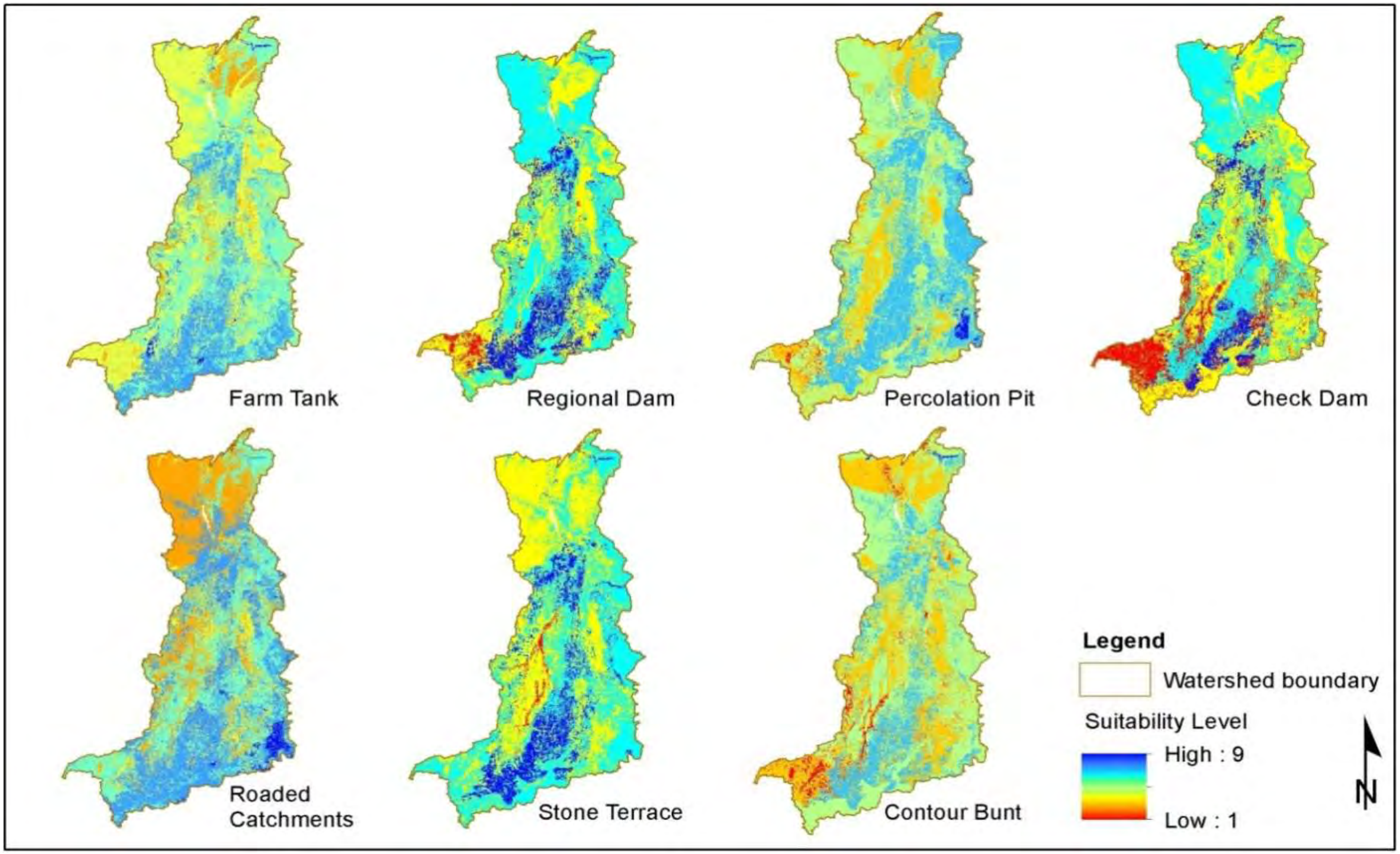


Figure 9: Estimated water harvest and storage suitability in the Turkana Basin

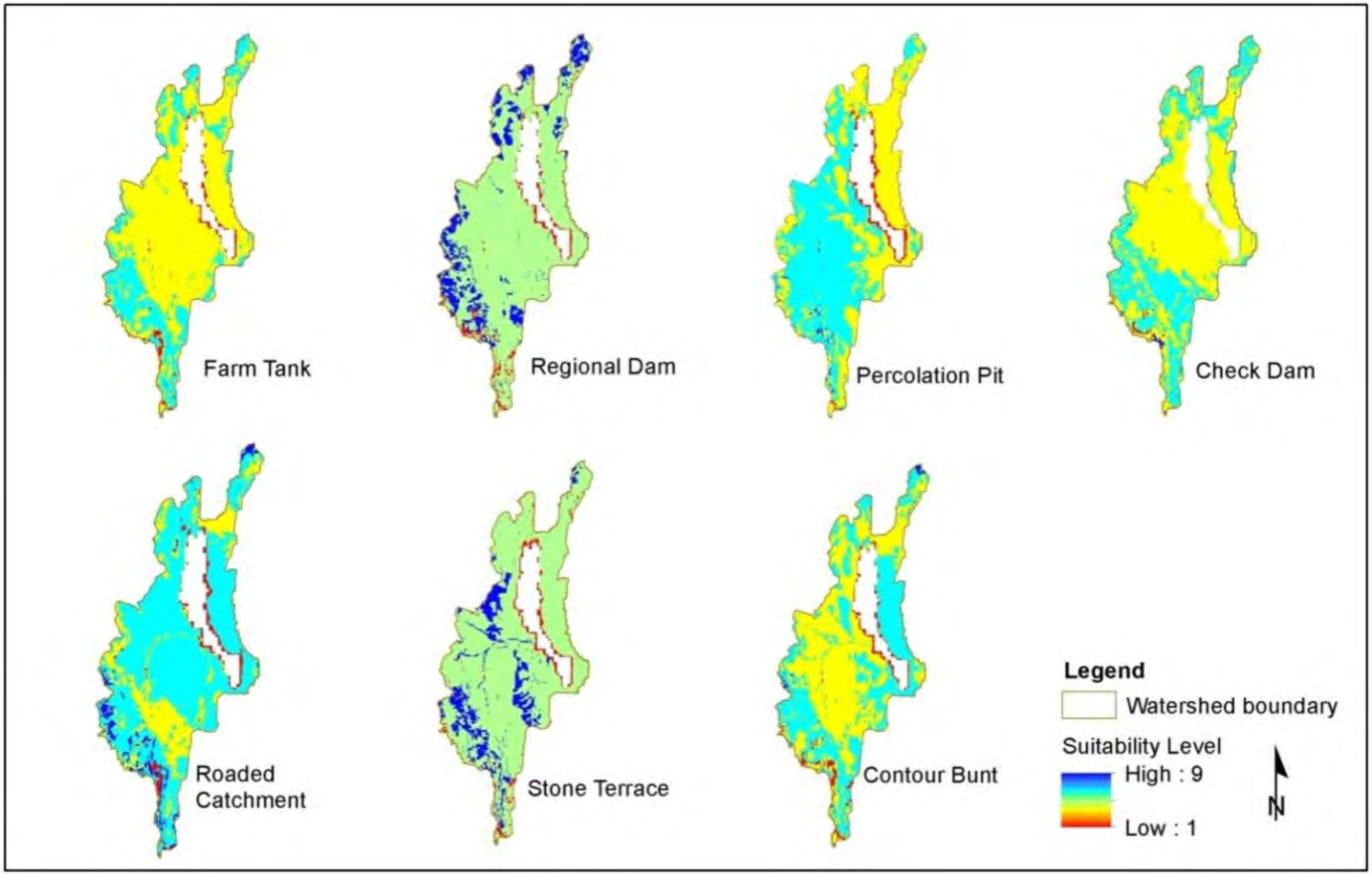
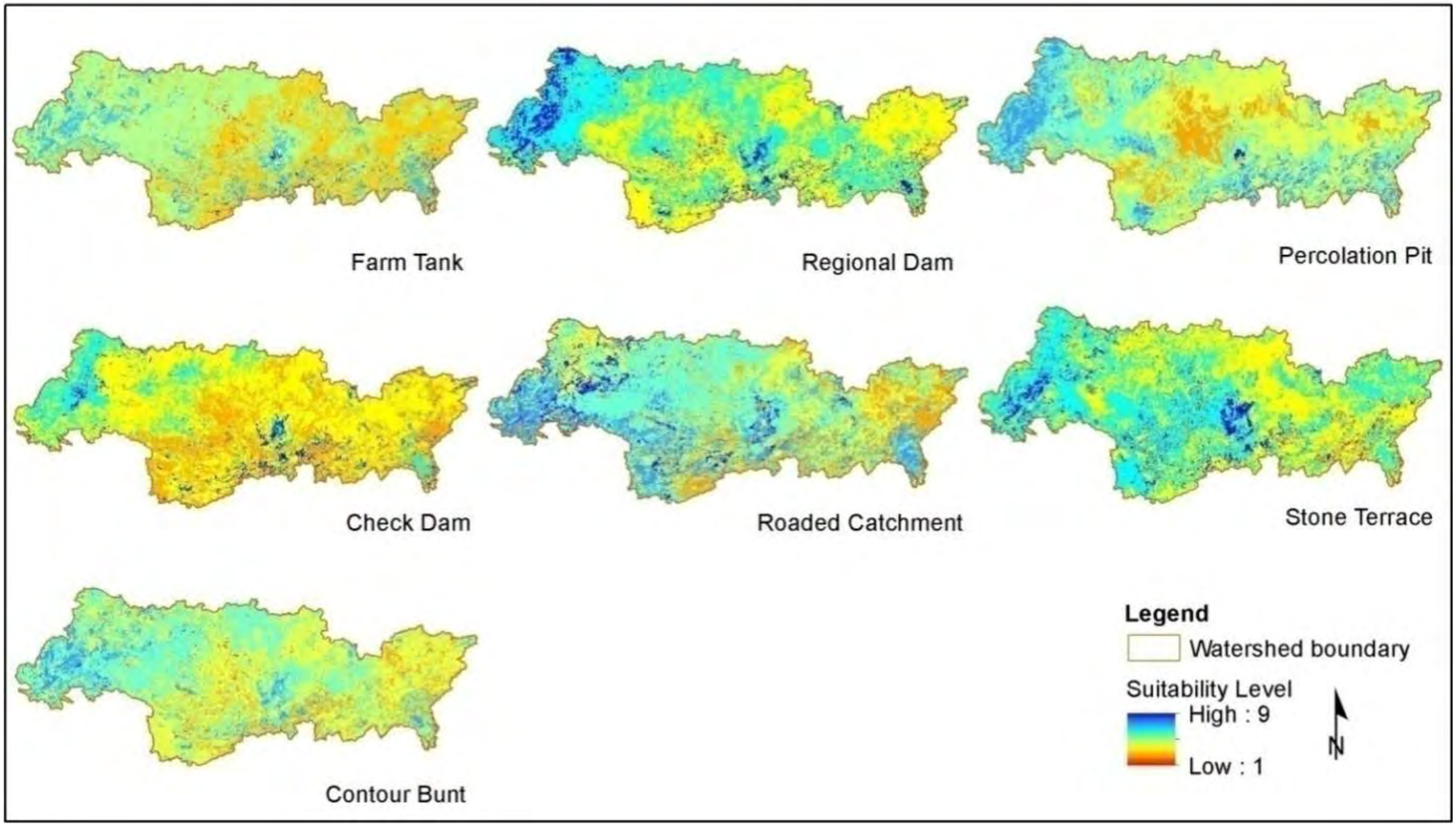


Figure 10: Estimated water harvest and storage suitability in the Xun Jiang Basin



Effect of changed rainfall pattern

Histograms in Figure 11 and Figure 12 present the average suitability score for water storage and water-harvesting structures, respectively. The rainfall patterns vary significantly in different regions where the watersheds are located, as mentioned before. However, no significant difference is observed in the average suitability among different precipitation scenarios over time for either water harvest or storage techniques. Rather, all watersheds show a similar trend. The average suitability score stays around 6 for water storage techniques and around 5 for water harvest techniques, which represent moderate suitability. Also no significant difference can be identified relative to the base scenario for either harvest or storage techniques.

6 Model Evaluation

I use the existing water management structures information obtained from Sao-Francisco and Nile basins to evaluate the performance of GWAMP. I used the ground truth data from the project " Integrated management of land based activites in the Sao Francisco basin" (ANA/GEF/UNEP/OAS: http://www.ana.gov.br/gefsf/defaultXP_en.asp). For the Nile basin I used the data obtained by contacting the Ministry of water resources and energy – Ethiopia, Ministry of water and environment – Uganda and Awulachew et al. (2007). I test the parameterization used to develop the system on suitability levels and relative importance weights. If people behave rationally, the existing water harvest and storage locations should be located where the highest investment returns are achieved, i.e. where the highest economic suitability is. However, the objective of our model is to estimate the suitability of locations for water harvesting and storage based on natural conditions. I believe that economic suitability can only be adequately assessed by an integrated method which links geographic and economic analysis. Thus, I cannot really validate our model results. Nevertheless, it is sensible to assume that there is a substantial correlation between natural and economic suitability. For this reason, I compare our computed natural suitability estimate for harvesting and storage structures with existing locations for these structures. Here I calculate the percentage of overlap between suitable areas from the model results for the base scenario and the areas where the structures exist. The results are shown in **Table 4**. Most existing rain water storage technologies are found in areas classified by GWAMP as having very high or high suitability. The fact that most of the predicted rain water storage technologies are found within the very high to moderately suitable classes and areas producing high runoff indicates that the model can be used to predict potential sites for rain water harvesting and storage technologies.

Table 4: Suitability of locations obtained using the GWAMP compared to the existing structures

Area belonging to each category as a % of the total area covered by the existing structures	Sao Francisco basin			Nile basin		
	Very High	High	Medium	Very High	High	Medium
Regional dams	31.64	18.80	17.08	41.05	34.28	14.67
Stone terraces	8.21	9.02	9.09	10.24	11.97	12.28
Roaded catchments	22.39	28.20	29.48	10.39	10.70	1.15
Percolation pits	11.11	13.61	14.22	6.69	14.65	21.78
Farm tanks	14.93	17.67	19.28	11.12	18.20	21.84
Contour bunts	32.84	25.56	23.69	36.03	31.66	29.17

Figure 11: Average suitability level of land parcels change with precipitation change -water storage

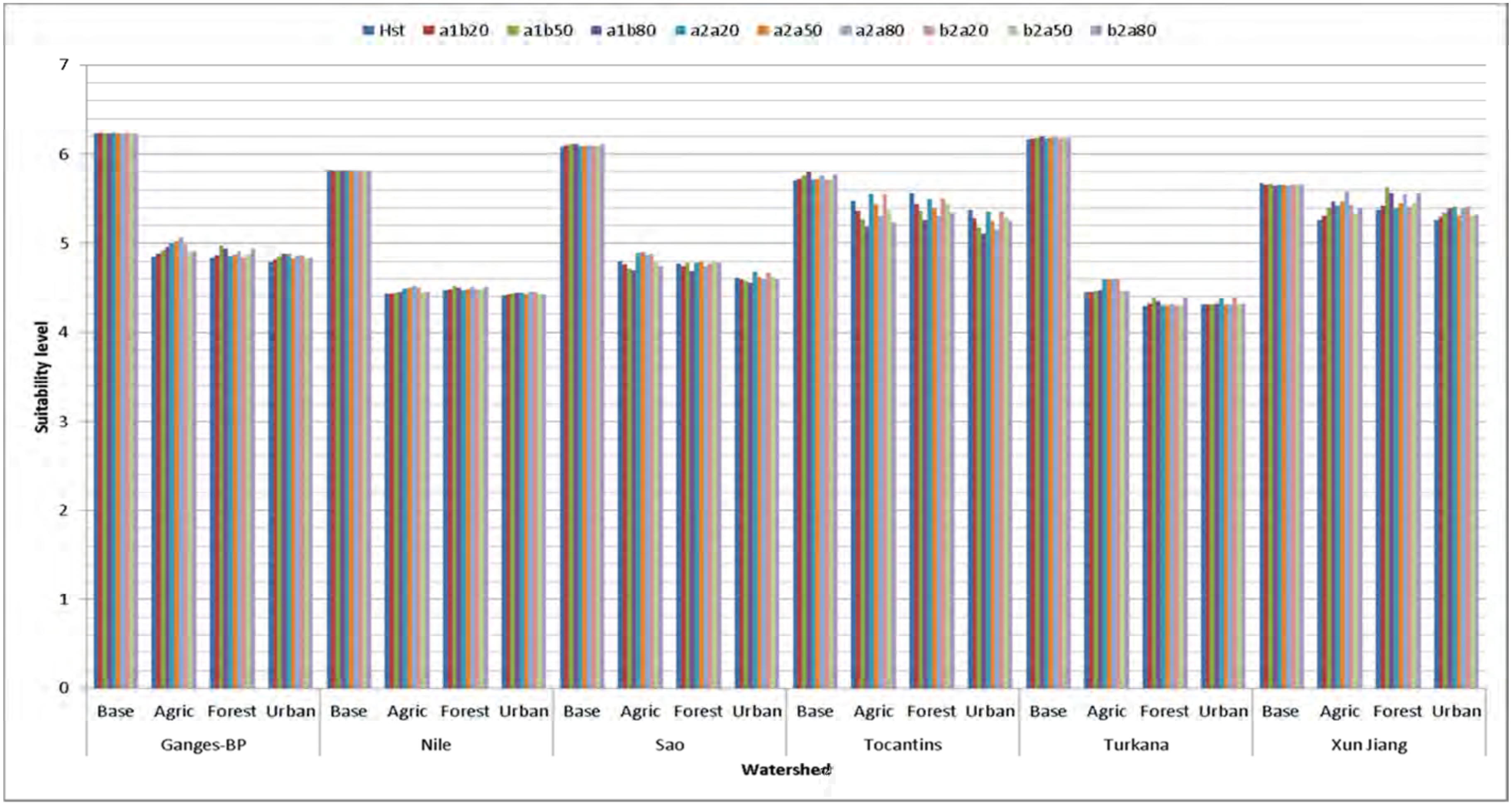


Figure 12: Average suitability level of land parcels change with precipitation change – water harvest

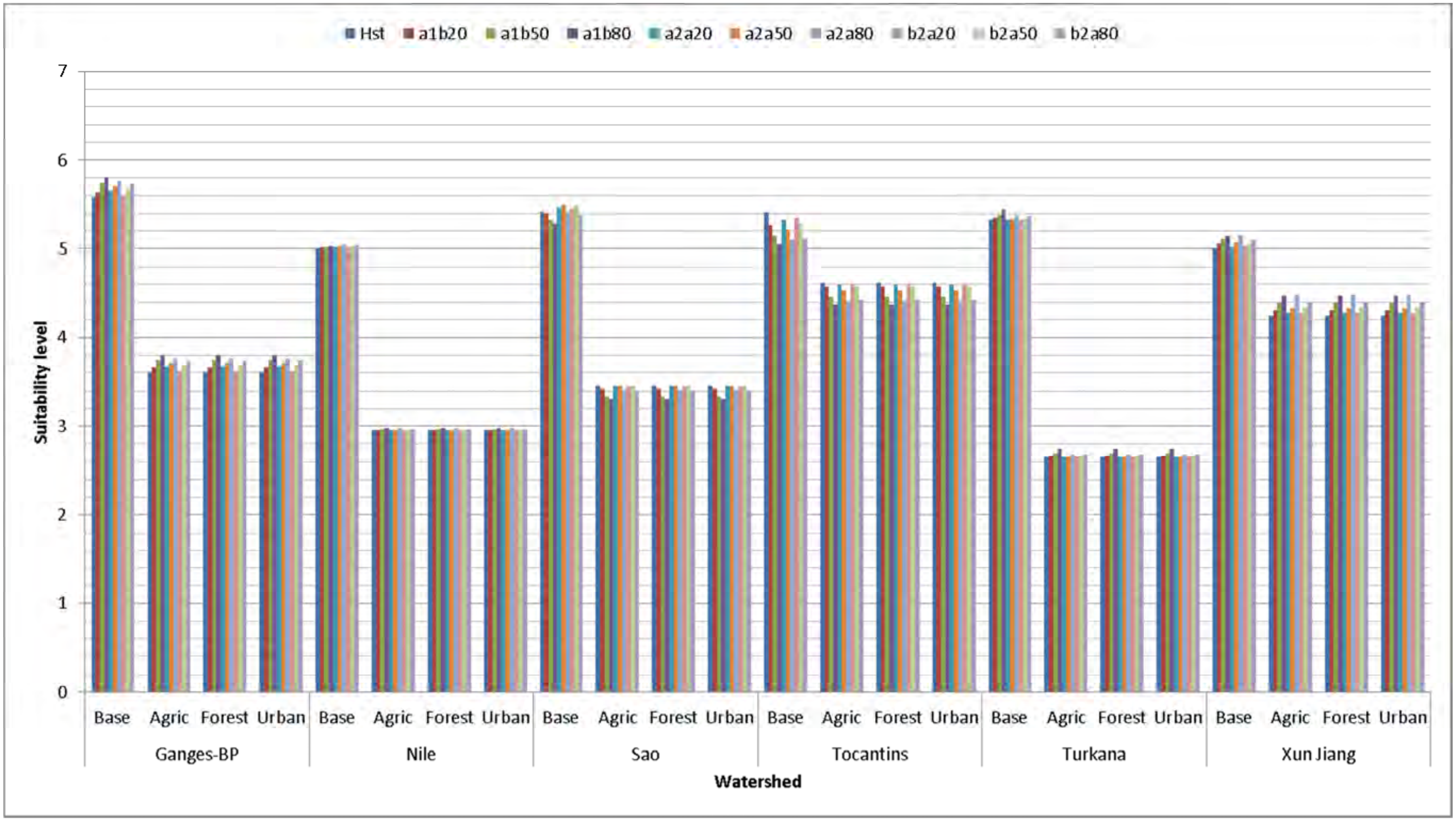
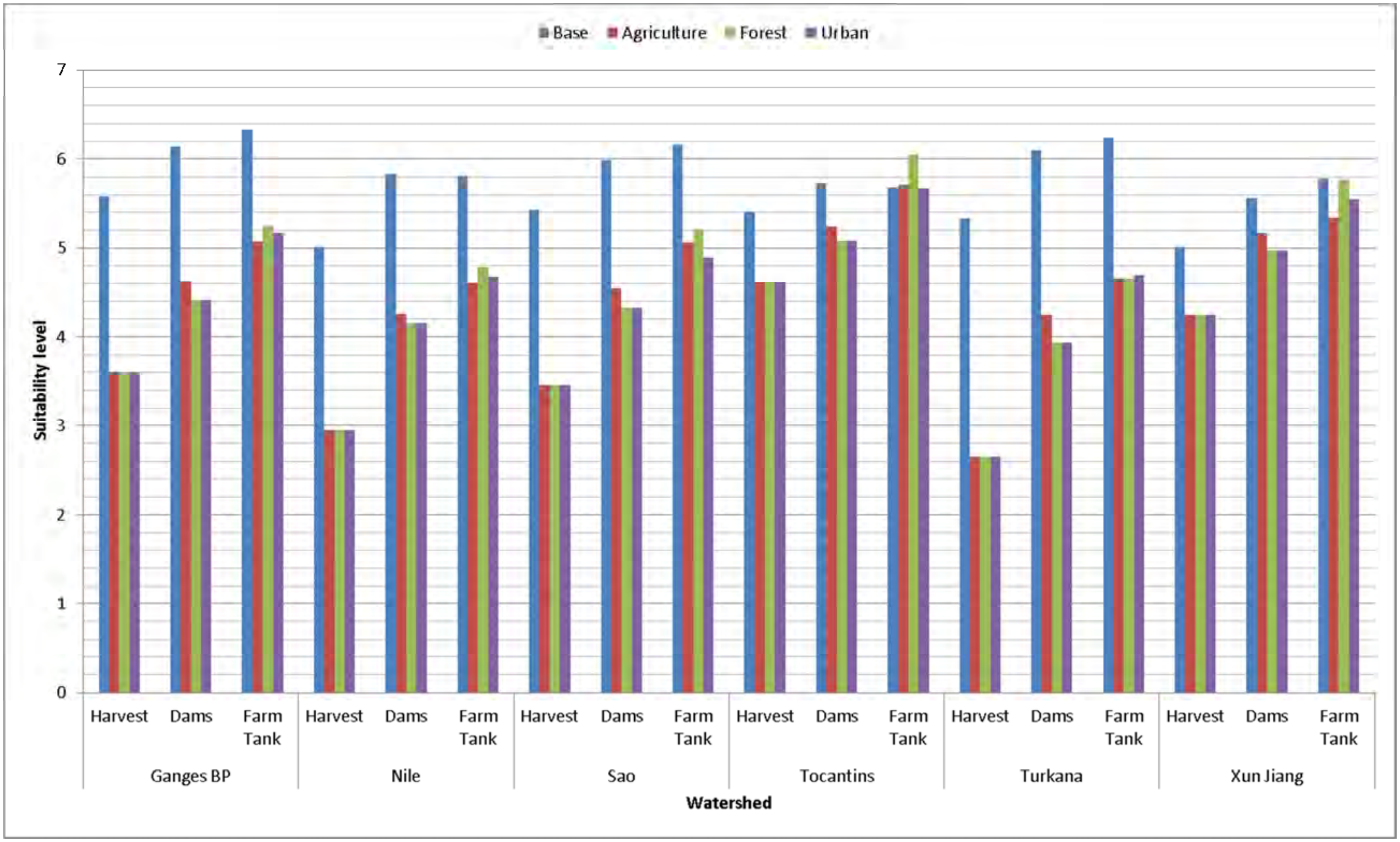


Figure 13: Aggregated average suitability level of land parcels change with land use change



7 Conclusions

Information on identifying potential sites for rain water harvesting and storage has been used for the development and operation of water management programs. This study demonstrates the capabilities of using global data sets and GIS in spatial analysis models. The application of GWAMP in the six case studies demonstrates its suitability to identify potential sites for rain water harvesting and storage. The results confirm that GWAMP is applicable in varying climatic, geographic, and socioeconomic conditions, even in ungauged basins. Furthermore, GWAMP can easily update suitability levels and weighted scores of decision factors on which the potential sites for rain water harvesting and storage are based. The analysis of the effect of precipitation on the average suitability score confirms that rainfall pattern change cannot have a major effect on the average suitability for either water harvest or storage structures. The analysis of the effect of land use change on average suitability confirms that land use change can have a major effect on the average suitability of land parcels for water harvest and storage. GWAMP is designed to be used on a global scale without additional data needs. In particular, it is designed to improve potential water management adaptations in global integrated assessment models and large-scale integrated land-use models.

Acknowledgement

I thank Prof. Hartmut Grassl for his comments and suggestions and the International Max Plank Research School on Earth System Modelling for providing the necessary funding and facilities for conducting the study. I have received financial and data support from the European Community's Seventh Framework Programme under grant agreement No.212535, Climate Change –Terrestrial Adaptation and Mitigation in Europe (CC-TAME), www.cctame.eu; No.226487, European approach to GEOSS (EUROGEOSS), (www.eurogeoss.eu)

8 APPENDIX – A

Constructing the pair-wise comparison matrix

A pairwise comparison matrix for F number of factors (X_1, ..., X_F), reflects the dominance of the factor in the left-hand-side column with respect to each factor in the top row.

$$X = \begin{array}{c|ccc} & X_1 & \cdots & X_F \\ \hline X_1 & w_1/w_1 & \cdots & w_1/w_F \\ \vdots & \vdots & \ddots & \vdots \\ X_F & w_J/w_1 & \cdots & w_F/w_F \end{array}$$

Each matrix entry reflects a ratio scale of the underlying priority weights assigned to each factor, i.e. $X_{FF'} = W_F/W_{F'}$. The weights (W_F) have to be derived from cell entries $W_{FF'}$. Saaty has developed a nine point scale to define the intensity of importance. This scale fulfils two requirements.

Distinct shades of difference in people's feelings when they make comparisons are represented as much as possible.

If scale values are denoted by X_1, X_2, ... , X_p, then let

$X_{i+1} – X_i = 1$, $i = 1, ..., p -1$

The scale is based on psychological experiments and is designed to best reflect priorities in comparisons between two items.

In X, each cell entry is positive and the diagonal elements ($x_{FF'}$) always receive a value of 1. If it is assumed that transitivity of preferences exist (i.e. that if X_1 is preferred by a scale of 7 to X_2, then X_2 is preferred by a scale of 1/7 to X_1) then the reciprocal property $x_{FF'} = 1/ x_{FF'}$ is satisfied and estimates are needed only for those cells which lie above the diagonal. Saaty proved that, if X displays 'cardinal' consistency, in that $x_{FF'}\, x_{F'F''} = x_{FF''}$, then by normalizing the positive reciprocal matrix X so that the columns sum to unity, a solution to w, the vector of overall priority weights, can be obtained by reading any column of the matrix, as each column in this normalized matrix will be identical (Saaty and Vargas, 1984). If I are to impose cardinal consistency on the matrix, then only one row of the matrix needs to be entered and all other values can be derived. If I do not impose cardinal consistency on the matrix, then each column vector may be different and it is necessary to average across the rows to determine the overall priority weights. Here, I can check whether the measures fall within acceptable bounds using Saaty's approach. In order to estimate how each solution option performs with respect to each factor, a series of pairwise comparisons is carried out. For f =1…. F factors and i = 1… S different solution options, the pairwise comparison matrix comparing all plans under the criteria X_F would be

$$A_f = \begin{array}{c|ccc} & A_1 & \cdots & A_S \\ \hline A_1 & a_{f1}/a_{f1} & \cdots & a_{f1}/a_{fS} \\ \vdots & \vdots & \ddots & \vdots \\ A_S & a_{fS}/a_{f1} & \cdots & a_{fI}/a_{fS} \end{array}$$

The nine point scale provides the estimates for ratio weights, the a_{fi}, and the assumed reciprocal properties. The overall priority (OP_i) of each solution option with respect to all factors can be estimated as follows.

$OP_1 = a_{11} (w_1) + a_{21} (w_2) +\ldots+ a_{F1} (w_F)$

$OP_2 = a_{12} (w_1) + a_{22} (w_2) +\ldots+ a_{F2} (w_F)$

$OP_I = a_{1I} (w_1) + a_{2I} (w_2) +\ldots+ a_{FI}(w_F)$

The comparative importance of input data parameters (referred to as factors) is calculated with the CWI. Input data include raster maps, where each layer is a factor in the decision making (constrain layers). For each grid cell, all input thematic layer values are weighted based on the comparative importance of each factor.

In order to obtain the weights from the calculated eigenvector, the values are normalized using the following equation. $w_F = \dfrac{\tilde{w}_F}{\sum_{i=1}^{n} \tilde{w}_i}$

The consistency index is calculated using the following equation.

$$CI = \frac{\lambda \max - n}{n-1}$$

Then the consistency ratio is calculated as the ratio of the consistency index and the random consistency index (RI). RI represents the consistency of a randomly generated pairwise comparison matrix. It is derived as the average random consistency index (Table 5). If CR(a) ≤ 0.1, the pairwise comparison matrix is considered to be consistent enough. The value of CR(a) depends on the number of criteria being compared.

Table 5: The fundamental scale of absolute numbers

Intensity of importance	*Definition*	
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment strongly favour one activity over another
4	Moderate importance	
5	Strong importance	Experience and judgment strongly favour one activity over another
6	Strong importance	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above nonzero	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Source: (Saaty, 2008)

Table 6: Random consistency indices for different numbers of criteria

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Source: Saaty (1982)

$$CR(a) = \frac{CI(a)}{RI(n)}$$

CHAPTER III

Adapting water management to meet agricultural water demand

1 Introduction

Decisions on water resource systems design and management are usually based on qualitative and quantitative information as well as decision makers’ perceptions, which are often based on the interested groups’ priorities. In most of the instances, the decisions are in favour of a certain aspect depriving other aspects in the watershed. For the decisions on water resources systems design and management, it is important to consider the watershed as a whole and the management system as an integrative unit. Therefore, decisions based on an analysis that considers the watershed and management actions as an integrative system, is an important factor for the sustainability of the watershed.

Management of watersheds encounters various activities from identification of the watershed boundary (watershed delineation) to monitoring different physical processes. Identification of suitable land areas for investment and development of water management infrastructure should not only be based on physical parameters (terrain, soils, slope, etc.), but also on social and economic aspects that concern the demand for water. Therefore, integrated analysis is a crucially important factor in watershed planning and management as well as in maintaining the sustainability of associated environmental eco-systems.

The concept of Integrated Water Resource Management has been developed during the last decades, in response to growing water demand and increasing water scarcity. The main objective is to find and implement suitable approaches to mitigate declining fresh water resources to eliminate the water scarcity. In the recent past, many countries have faced challenges of rapidly growing water demands driven by increased population, a higher per-capita water consumption rates, rapidly expanding economic activities, urbanization, industrialization and mechanization (King, 2004).

In satisfying the dietary requirements of an increasing population, the pressure on finite water resources and available arable lands is persistently increasing and will no longer be expandable at some point. Therefore, improving the joint productivity of land and water becomes more important. In some parts of the world, water scarcity issues are aggravated by climate change.

According to the FAO, the global water demand for food production is expected to increase between 70% and 90% by 2050 from the current demand of 7130km^3 (Molden et al.). Another study estimates that global water demand for food production will increase up to 9000-1000 km^{3}yr^{-1}(Rockström et al., 2009a) by 2050. In general, rainfed agriculture is characterized with lower yields and lower water use efficiencies. With the implementation of water management schemes, crop yield can be increased to some extent, in both irrigated and rainfed systems. In addition, a new competition for water resources arises from increased non-food agriculture including bioenergy production.

Projected climate developments with changes in rainfall patterns and corresponding impacts on drought frequencies and intensities demand sophisticated approaches for water planning. Recent assessments indicate a higher frequency of extreme precipitation events, anomalies in rainfall totals over space and time (Bates et al., 2008). Though the specific cause is not clear, runoff in specific regions (Sub-Saharan Africa, southern Europe, parts of southern Asia and eastern Australia) is declining (Milly et al., 2005). The latest estimations on the climate forcing, amounting to ~3wm^{-2}, corresponding to a warming exceeding 2^{o}C (Ramanathan and Feng, 2008), indicate that there is a severe impact by human factor on water resource distribution and utilization, disregarding any complex multiple drivers that could potentially contribute to it.

Sometimes slight changes could also affect the existing water resources to a considerable extent, which is commonly known as tipping points. For example, in a drier climate, little change in precipitation could cause significant change in the natural recharge of ground water. To protect water supplies against these extreme changes, more storage capacity of water is needed, including long-term storage to build up water reserves during times of water surplus for use in times of shortage. To make optimal decisions on water infrastructure development and investment, it is necessary to evaluate the cost and benefits of alternative scenarios for planning water management schemes and decision making. The feasibility of the Integrated Water Resource Management (IWRM) concept in solving the issues related to water availability in these alternative scenarios is not comprehensively understood so far.

This chapter discusses our approach to study whether water scarcity can be eliminated by water management in the Sao Francisco region and develops alternative management scenarios as a solution. I develop the 'ADAPT model' - Adapting the Irrigational Water Management, for the above mentioned two purposes. The following sections explain the ADAPT model and its application in different management scenarios to derive water management solutions.

2 Water available to manage – water shortages

Maintaining the sufficiency of water for food production depends on the geographical and the climatic conditions of a region. Therefore, the water availability to manage for crop production refers to not only the quantitative scarcity but spatial scarcity as well. In this study, I only consider the water available to manage by means of water quantity and geographical location. Crop production basically uses two main types of water reserves. These include the soil moisture reserve (green water) and irrigation (blue water) to compensate the depleted soil moisture reserve.

The first step in planning water management is to understand the amount and distribution of available water resources. For this study, the available water quantity is estimated based on the climate change SRES A2 scenario of the IPCC. Precipitation and runoff data are taken from corresponding EPIC (Erosion Productivity Impact Calculator) model simulations (Schmid et al., 2007) and are used as estimate for the green water amount. The runoff values differ across land use categories employed in the EPIC model (i.e. crop land, pasture lands, urban lands, forest and wetlands). The concept I present here is, using the adaptation measures to manage green water so that optimal production targets can be achieved. The EPIC model simulations also provide the blue water requirements for irrigated crop systems. There, I try to evaluate the water requirement of the crop and use the adaptation techniques to minimize the gap between the demand and the supply of irrigation water.

The global water sector has problems, because the technical and political developments in water management are too slow to adapt to the required changes. At first sight, water management might appear to be focused on local matters only. Such a perception is caused by tasks such as managing a certain stretch of river. Indeed, water management needs to consider many global factors. Catchments often deal with competitive water use, which means that the demand for water is higher than the sustainable yield. To correspond with the complex system of water resources and different types of water users, it is important to verify the valuation methods and the parameters used, which makes the participation of all affected parties very important. The concept of IWRM integrates water resources as a systematic process for the sustainable development, allocation and monitoring of water resources. This promotes more coordinated management of land and water, the river basin and upstream and downstream interests.

During recent decades, the interest in integrating water harvesting techniques in water management plans has increased. Many countries have successfully implemented water harvesting techniques to increase the water availability, either by directly improving soil moisture content or by increasing water storage for use in water-limited periods in the future. These techniques include both applications of traditional and novel methods.

Traditionally, water storage has been achieved with dams and surface reservoirs. However, suitable dam sites with long term usages are becoming scarce (Hossain et al., 2009) and dams have a number of disadvantages including adverse impacts on i) stream ecology , ii) settlements which may need to be displaced, iii) landscape scenery, and iv) recreational uses of rivers. Furthermore, dams incur substantial investment and maintenance costs. In an integrated systematic approach, water storage structures are not managed alone. Storage structures need to be well connected to the water supplies and demand sectors as well. The basic principle of the systematic approach is the connectivity. A system is a set of elements with connections between each other. Any system is composed of subsystems, each being autonomous and open, directly interrelated and integrated with its environment.

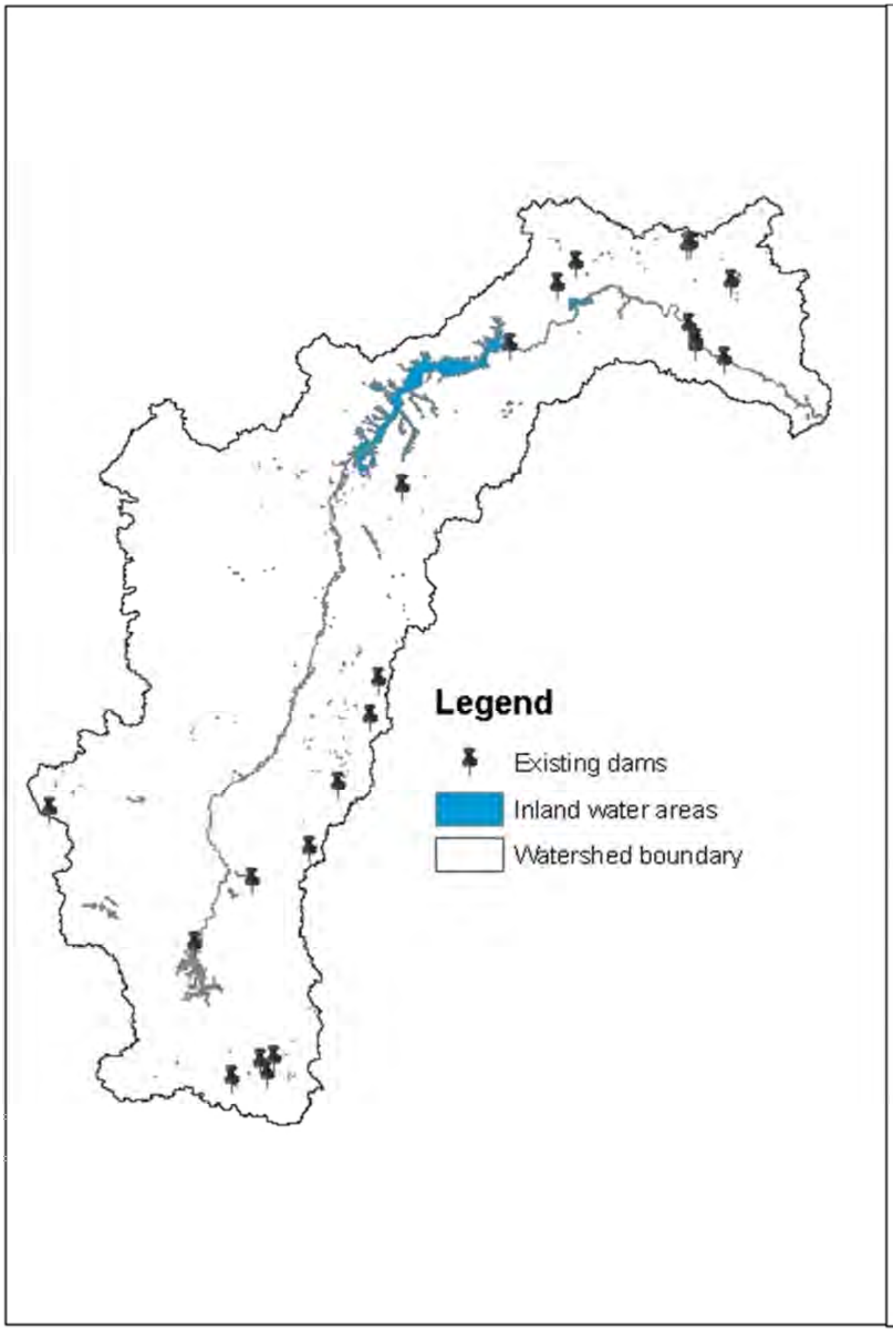
The systematic approach is important to identify a correct bundle of components for an integrated system, to analyse and improve the system. Each of the components requires inputs (resource endowments) and produces outputs at optimal level to satisfy the demand. The systematic approach for integrated water management that I propose here starts from the climate specific runoff generation and continues until the demands within a watershed is satisfied.

3 Water resources and irrigation water use in the Sao Francisco watershed

The Sao Francisco watershed has an area of about 629,885 km2, which is drained by the Sao Francisco river and its connected tributaries (Figure 14). Currently, there are about 20 major dams established mainly for irrigation and hydropower generation and several natural and artificial wetlands in the watershed. The 'Sobradinho' reservoir has the largest surface area in Brazil, having 4225 km2 and a capacity of 34,100 Million m^3. The rainfall ranges from a wetter south, with an average annual rainfall of about 1400 mm, to a drier north with annual average rainfall of only 600 mm. The rain comes in a distinct wet season, which has a peak in December- January each year. This distinctive wet season causes a pronounced seasonal variation in the flow for the Sao Francisco River and its tributaries.

Many discussions about global change stay on the global level. However, a more relevant question is how people can or could react to global change on a local or regional scale. How will agricultural systems perform as a result of environmental change? Within agricultural management, irrigation systems, in particular, have developed a reputation of having low resilience, and are thus vulnerable to change. It is difficult to get exact figures on the total area, currently under various water harvesting and storage structures that contribute to food production water demands. The data on semi-arid and arid regions are more common (Boers et al., 1986; Li et al., 2000; Li et al., 2001; Oweis et al., 2001) . Field studies suggest that yields could be increased by several times by coupling water harvesting with proper agronomic practices (Boers et al., 1986; Critchley et al., 1992; Lal, 2004; Rost et al., 2009). However, the cost of an improved water management scheme can be a major constraint for their widespread adoption. Therefore, it is important to identify the optimal size of the structures, which is economically feasible.

Figure 14: Surface water areas and water reservoirs currently existing in Sao Francisco watershed



4 'Adapting Water Management' Model

I name the model 'Adapting Water Management' (ADAPT). ADAPT is a mathematical optimization model that jointly represents the investment and use of water management options, land use and land management decisions, food demands, and demands for non-agricultural water. I design the water management within the model based on one of the fundamental laws of physics that states; 'mass can neither be produced or destroyed', i.e. mass is conserved and although the energy can be changed, its form cannot be destroyed. Therefore, the two main concepts that connect the system components are mass balance and energy balance (Equation 1).

$$\begin{pmatrix} mass\ at \\ time\ t + \vartriangle t \end{pmatrix} = \begin{pmatrix} mass\ at \\ time\ t \end{pmatrix} + \begin{pmatrix} mass\ enterd \\ during \vartriangle t \end{pmatrix} - \begin{pmatrix} mass\ exited \\ during \vartriangle t \end{pmatrix} + \begin{pmatrix} mass\ used\ for \\ production\ during\ \vartriangle t \end{pmatrix} + losses$$

$$\begin{pmatrix} energy\ at \\ time\ t + \vartriangle t \end{pmatrix} = \begin{pmatrix} energy\ at \\ time\ t \end{pmatrix} + \begin{pmatrix} energy\ produced \\ during \vartriangle t \end{pmatrix} - \begin{pmatrix} energy\ used \\ during \vartriangle t \end{pmatrix} + losses$$

Equation 1: Mass and energy balance

4.1 Model resolution

I use different resolutions: a) raw input data, b) supply components of model, c) demand components of model. Each is described separately in the input data section. I define the basic spatial unit for model simulations, adopting the concept of Homogenous Response Units (HRU) in the GEO-BENE database (Skalský et al., 2008). Unique spatial unit used here is the land unit delineated by the intersection of Sub-watershed and HRU. HRU is unique spatial delineation having the same altitude, slope and soil texture (HRU class definition is given in the Table 7). These characteristics are represented at 5' spatial resolution grid. The HRUs found in the Sao-Francisco watershed is presented in Table 7.

Figure 15 : Water Management Model Flow diagram

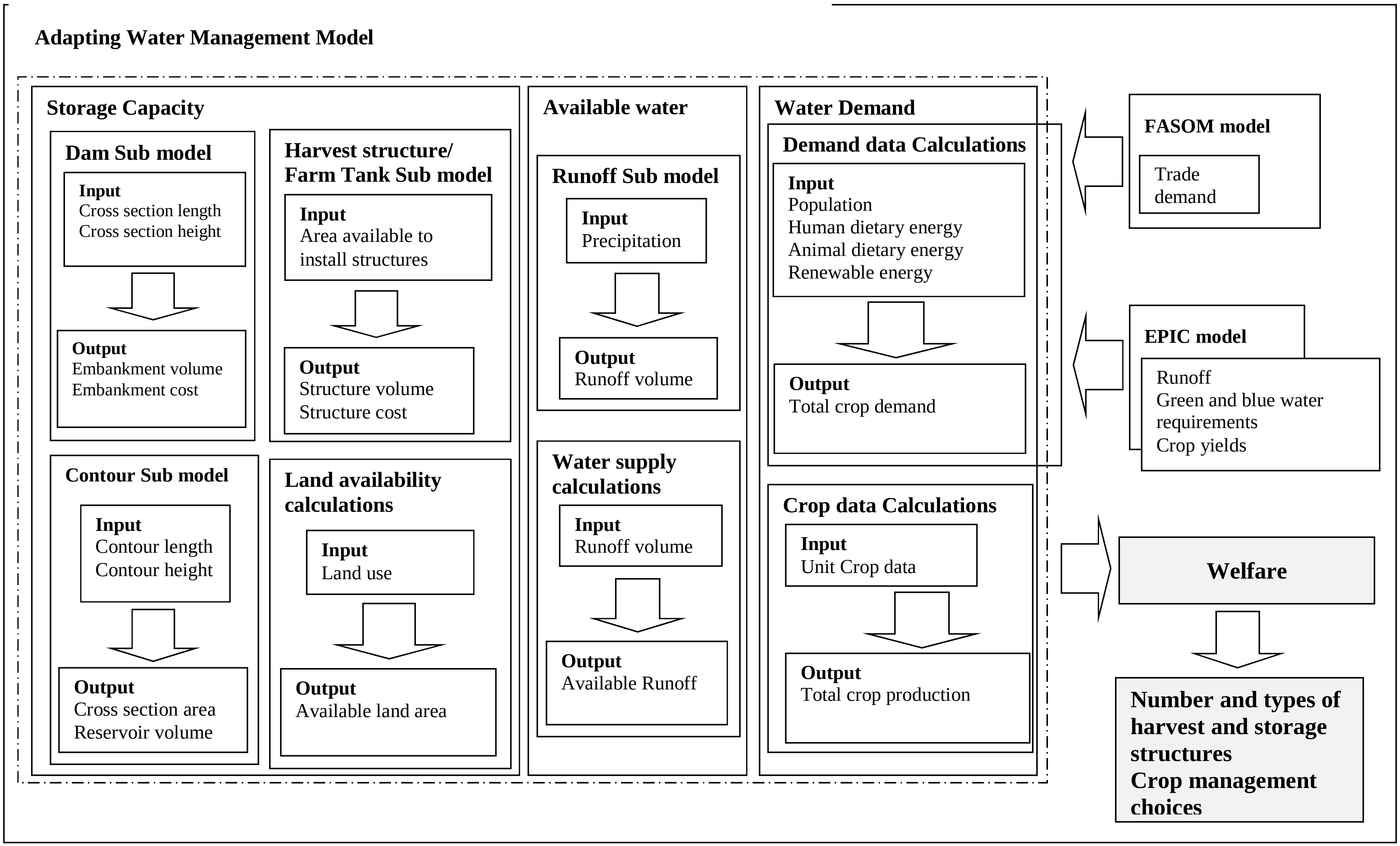


Table 7: Topographic character specifications to delineate HRUs

Topographic character	Unit	Classes
Altitude	Meters	1(0-300), 2(300-600), 3(600-1100), 4(1100-2500), 5(>2500)
Slope	%	1(0-3), 2(3-6), 3(6-10), 4(10-15), 5(15-30) , 6(30-50) , 7(>50)
Soil Type	Texture	1(sandy), 2(loamy), 3(clay), 4(stony), 5(peat) , 88(no-soil)

Source:(Skalský et al., 2008)

Sub watershed is another spatial area demarcation used in defining the spatial unit for simulations. Here, I develop a river network up to 5th river order and derived sub watersheds based on this river network. Derived river network and sub watershed are presented in the Figure 17

I develop the tributary network using the 3-arc second resolution digital elevation data downloaded from the CGIAR server (**Jarvis et al., 2008**). I use the processed digital elevation data to develop the water flow path on the terrain surface and watershed boundaries. The drainage network data are classified into stream orders using Strahler's (**Strahler 1957**) method. In order to obtain a manageable set of data, I divide the Sao-Francisco watershed into 33 sub watersheds (Figure 18) and the Sao-Francisco river into 5 river orders (Figure 17). I use 10-year mean precipitation values for the simulations extending from 1991 to 2100. Names used for different decades are shown in Table 8.

Table 8: Temporal resolution

Decade	Corresponding years
Decade_00	1991 – 2000
Decade_10	2001 – 2010
amesDecade_20	2011 – 2020
Decade_30	2021 – 2030
Decade_40	2031 – 2040
Decade_50	2041 – 2050

Figure 16: HRU distribution in Sao-Francisco watershed

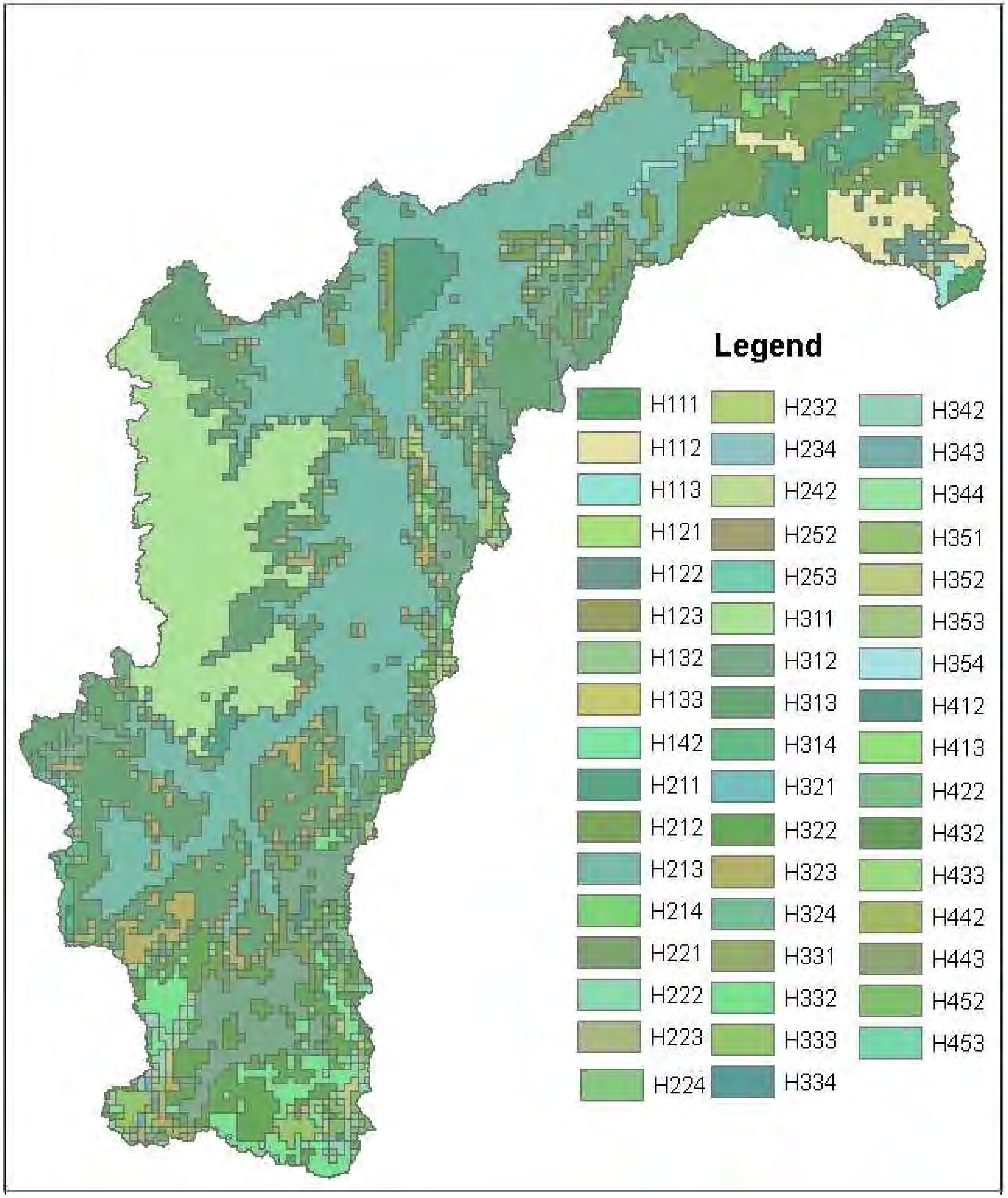


Figure 17: River network distribution in the Sao Francisco watershed

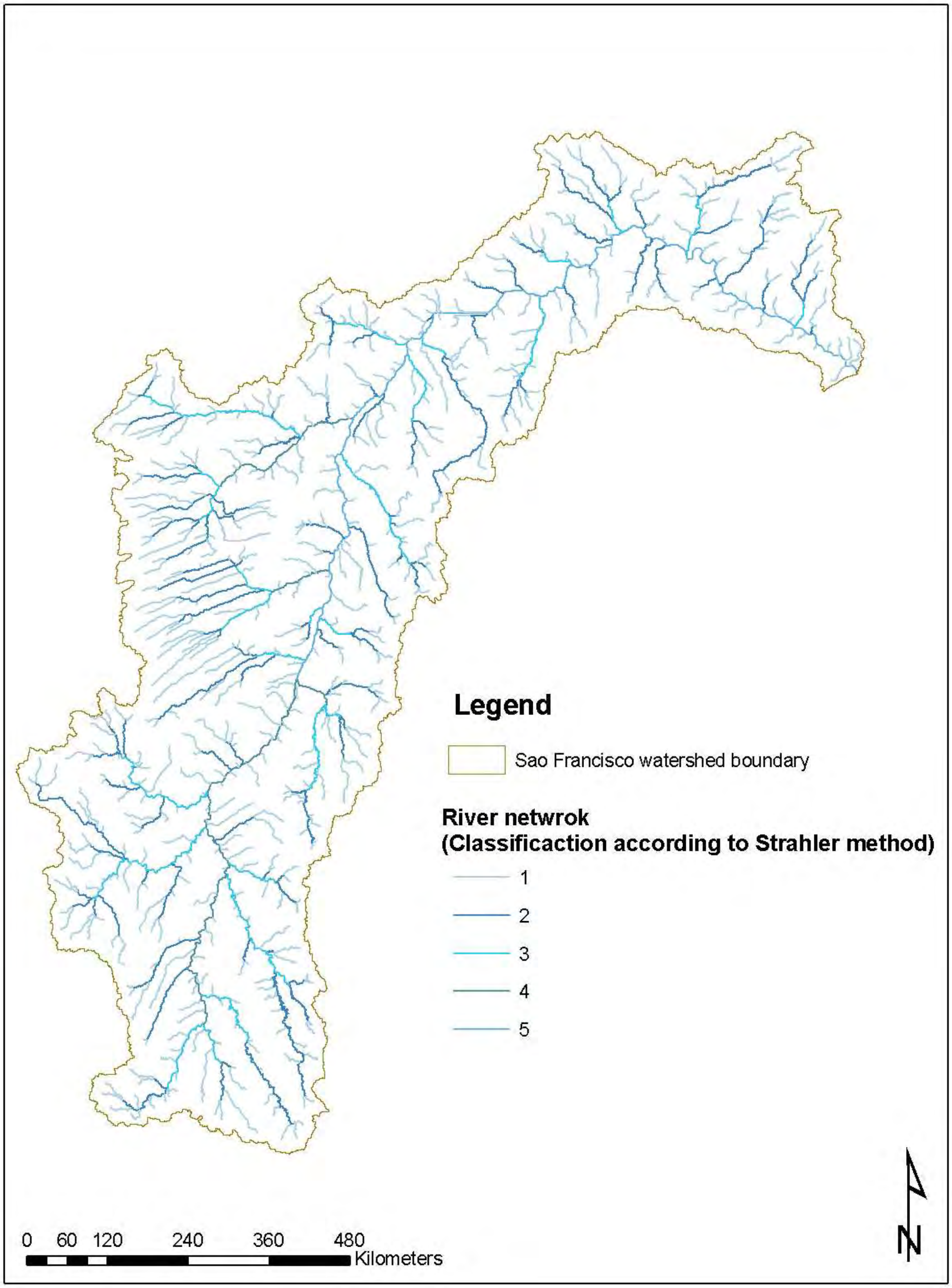
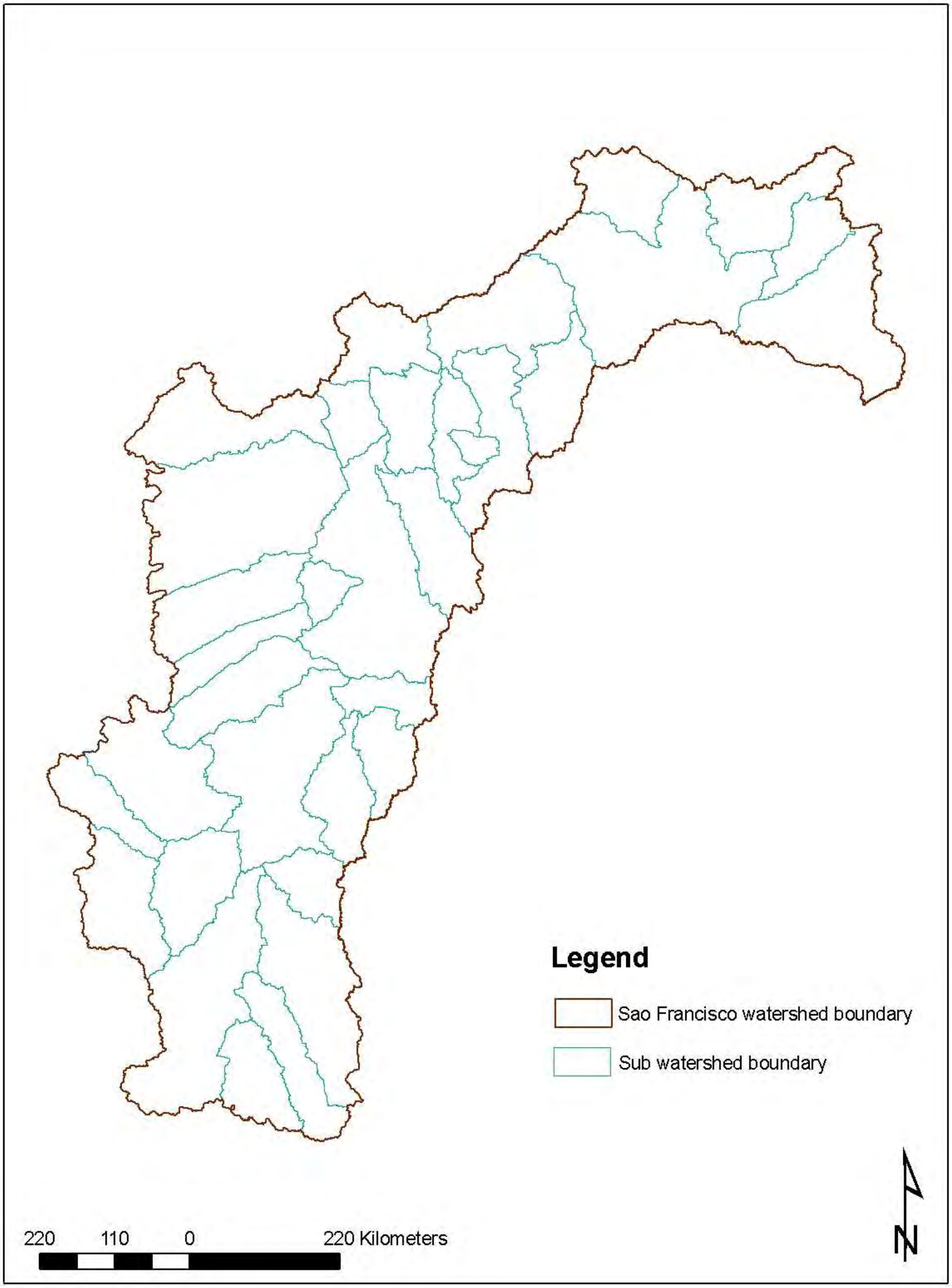


Figure 18: Sub watershed distribution in the Sao Francisco watershed



4.1.1 Demand data calculations

I distinguish the demand for food crops from the local population of the Sao Francisco watershed and from the entire global population outside the watershed. The metabolic energy contained in the food crops is used to determine the minimum food demand from the local population. The computation of human dietary energy demands includes direct processing of crops for food as well as the indirect use of crops as livestock feed. Furthermore, I consider the use of crops for bioenergy production.

The energy requirement of a healthy and well-nourished adult with average physical activity level is 10.29 MJ/day (University, 2004). I used this value as an average and multiplied by the population in the Sao Francisco basin to get the human dietary energy demand estimations. For the bio fuel energy demands, I used the estimations in the GGI A2r baseline scenario (Riahi et al., 2006). In this analysis, I consider an extreme case scenario to experiment with the model behaviour.

The Sao Francisco watershed's internal energy demand is calculated with the following assumptions: The metabolic energy requirements by humans are fulfilled by carbohydrates and proteins from plant and animal sources. The metabolic energy requirements of animals are fulfilled by carbohydrates and proteins from crops. I explicitly represent 5 crops in the model, i.e.: rice, maize, soybean, sugarcane and wheat. Other crops are implicitly represented through a crop multiplier. Crop biomass and animal proteins need to satisfy 75% of the total human dietary energy intake; crop biomass is used to satisfy 60% of the total human energy requirement. The energy production is mainly constrained by the population and land limitations. I consider the population share (in the GGI A2r scenario) with respect to the land share belonging to the watershed [number of persons yr^{-1}]. The external crop demand (Trade demand) is derived from a global forest and agricultural sector optimization model (Gusti et al., 2008; Sauer et al., 2010) and downscaled to the watershed. Downscaling is done by multiplying the total demand with area based weight coefficient. The weight coefficient is the ration between the area of the considered sub-watershed and the total land area of the watershed.

4.1.2 Crop data calculations

The food crop demand consists of two types. In the local context, food crop demand represents the food crop requirement to satisfy the needs within the watershed. The metabolic energy requirement by humans is fulfilled by plant and animal carbohydrates and proteins. The plant energy supply is represented with 5 crop types in the model. i.e.: rice, corn/maize, soya bean, sugarcane and wheat. In addition, this includes the demand of crops for bio fuel production, in order to satisfy the renewable energy demand. In the non-local food crop demand, trade demand is represented. Therefore, the bio fuel energy demand by bio-diesel and bio-ethanol is considered. The food crop demand is estimated with the EPIC model (Sharpley and Williams, 1990b). Depending on the existing soil and land management possibilities, the EPIC model suggests crops possible to plant and their productivity for each HRU

4.1.3 Available water for storage and water supply calculations

Basic water supply data are taken from EPIC simulations. In these simulations, weather data on historical time series of global weather for the period from 1901 – 2000 and 16 climate change scenarios (further referred to as Tyndall, http://www.cru. uea.ac.uk /~timm/grid/TYN_SC_2_0.html) (Mitchell et al., 2004) were obtained from The Tyndall Centre for Climate Change Research of University of East Anglia, Norwich, UK (Skalský et al., 2008). SCS-CN method is then used to estimate the runoff for the entire watershed. This runoff generated in each sub-watershed is then diverted to streams of 5th order corresponding to each sub-watershed.

Using the water flow network, the average travel distance between sub-watersheds and the slope of each stream segment, I calculate the maximum amount of water that is available in each sub-watershed in each month. Using the travel distance of water and slope of each stream section, water availability is estimated at each section for the corresponding month. Adaptation options are applied on this runoff water to optimize its usage for agricultural needs.

4.1.4 Land use calculations

I use the land cover statistics from the FP6 GEO-BENE project's data repository. This gridded data are developed using GLC2000 (Bartholomé and Belward, 2005) and GLU-IFPRI datasets (Skalský et al., 2008). The 23 land cover classes presented in the GLC2000 and GLU datasets are aggregated into 6 major classes for the optimization modelling, in the GEO-BENE dataset (Table 9). The area available for producing selected crops is a fraction of the total area available for cropping. Land cost is accounted for, using the current agricultural area and additional area from other land cover classes

Table 9: Land-cover categorization

Land Cover Class	Original GLC2000 classes
Total Agricultural land	16,17,18
Grassland	13

Forest	1,2,3,4,5,6,9,10
Wetlands	7,8,15
Other Natural vegetation	11,12,14
Land cover classes not relevant	19,20,21,22

According to the FAO statistics, the five crops considered occupied 25% of the total harvested area in Brazil at an estimated 0.01 average rate of change, during the period from 1991 to 2010 per year.

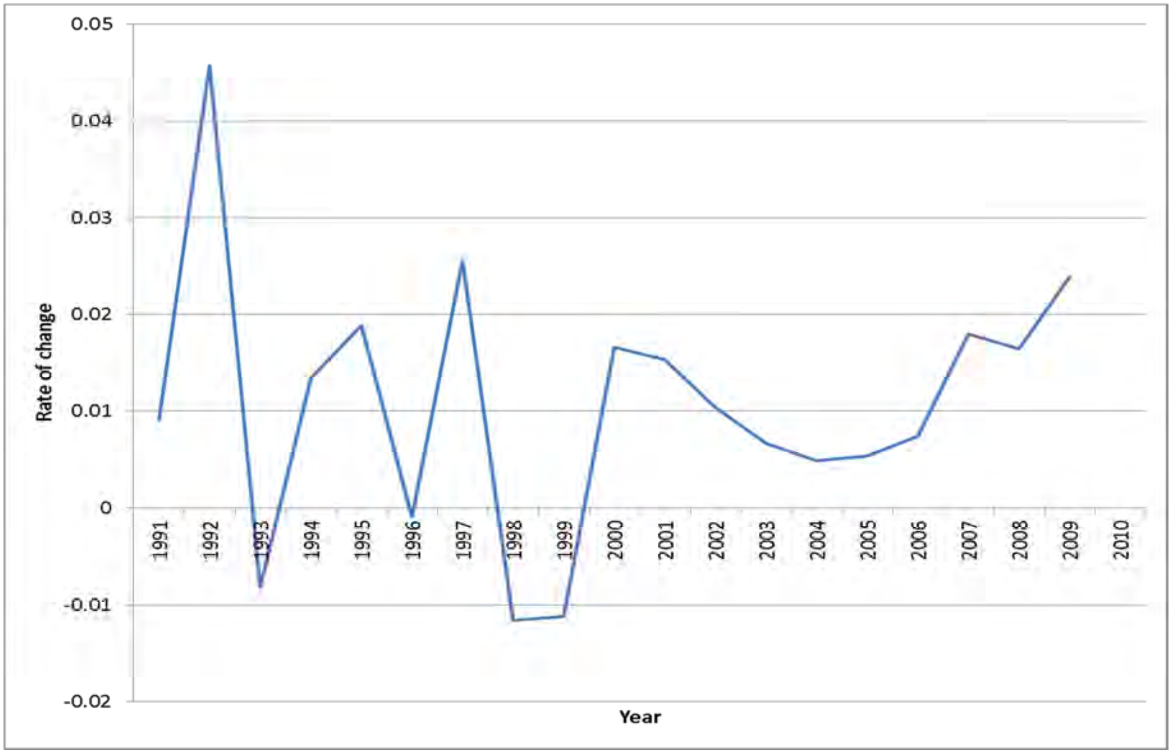
4.1.5 Contour sub Model

I use pre-selected defined cross sections along the river to identify appropriate locations to establish dams and reservoirs. This sub-model generates a database of cross sections, which has a potential to establish embankments. First, I use the HEC_RAS (Ackerman et al., 2000) for defining the cross sections along the river and get the coordinates of the cross section line. Then these data are used to produce the graphs in Contour sub model. The contour sub model is used to estimate the embankment dimensions. This model estimates the maximum width and height possible to build an embankment for each proposed cross section by optimizing the maximum height that can be closed/linked in a cross section. In addition, based on the contour data at a defined altitude, the reservoir volume is also estimated at each cross section.

4.2 Model components

The main equations of the model are explained here. The explanation of the variables and parameters are given in Appendix 1.

Figure 19: Land area occupied by the considered crops in the Sao Francisco watershed: Rate of change of the occupied area by the considered crops :(FAOSTAT, 2009)



4.2.1 Objective function

The water management optimization model's objective is to maximize the total benefits (Equation 2) from food production in the Sao Francisco watershed over the entire time horizon considering the cost of water harvest and storage construction and maintenance, the cost of crop production and marginally increasing cost of water supply. Cost benefit items in future periods are discounted by factor τ.

$$
Max\,Z = \sum_{y} \tau_{(y)} \cdot \begin{bmatrix} \sum_{c} \int \left(\psi_{(y,c)} \left(F_{(y,c)} \right) \right) \\ -(1+\lambda) \cdot \sum_{s,r,\gamma} \left(h_{(s,r,\gamma,y,\alpha=\text{"Cost"})} \cdot H_{(s,r,\gamma,y)} \right) \\ -(1+\lambda) \cdot \sum_{s,r,\rho} \left(t_{(s,r,\rho,y,\alpha=\text{"Cost"})} \cdot T_{(s,r,\rho,y)} \right) \\ -(1+\lambda) \cdot \sum_{s,\upsilon,\delta} \left(d_{(s,\upsilon,\delta,y,\alpha=\text{"Cost"})} \cdot D_{(s,\upsilon,\delta,y)} \right) \\ -\sum_{m} \int \xi_{y} \left(K_{(y,m)} \right) \\ -\sum_{s,r,c,b} \left(n_{(s,r,c,b,y,\alpha=\text{"cost"})} \cdot C_{(s,r,c,b,y)} \right) \end{bmatrix}
$$

Equation 2 Objective equation (1000 USD per year)

4.2.2 Water Harvest calculations

The amount of water harvested by all considered harvesting structures in each sub-watershed and in each month cannot exceed the available runoff after excluding a river base flow requirement from the total runoff (Equation 3).

Water harvested in a HRU within a sub-watershed cannot exceed the maximum capacity over all structures installed within a certain time horizon (Equation 4). All active harvesting structures in a given decade, HRU, and sub-watershed cannot exceed the maximum number of harvesting structures (Equation 5). The total area allocated to water harvest structures cannot exceed the suitable land area for water harvesting (Equation 6).

$$W_{(s,\gamma=rivhvst,y,m,\eta=\text{supply})} \leq \sum_{\gamma} W_{(s,\gamma=damhvststr,y,m,\eta=hvst)}$$

Equation 3 Runoff and harvested water balance ∀s,y,γ,m [MCM]

$$\sum_{m} W_{(s,\gamma,y,m,\eta=hvst)} / e_{(\gamma)} \leq \sum_{\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} \left(h_{(s,r,\gamma,\tilde{y},\alpha=\text{"}volume\text{"})} \cdot H_{(s,r,\gamma,\tilde{y})} \right)$$

Equation 4 Potential water harvesting capacity ∀s,r,γ,y [MCM]

$$\sum_{\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} H_{(s,r,\gamma,\tilde{y})} \leq h_{(\gamma,\alpha=\text{"}Bunits\text{"})} \cdot a_{(s,r,\gamma,\varphi=\text{"}harvest\text{"})}$$

Equation 5 Maximum individual water harvest structure installation restriction ∀s,r,γ,y [units]

$$\sum_{\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} \left(H_{(s,r,\gamma,\tilde{y})} / h_{(\gamma,\alpha=\text{"}Bunits\text{"})} \right) \leq a_{(s,r,\varphi=\text{"}harvest\text{"})}$$

Equation 6 Total area restriction for water harvest structure installation ∀s,r [1000 ha]

4.2.3 Water tank calculations

Water tank storage in a sub-watershed and month is limited by the storage level from the previous months minus the water released for irrigation plus the inflow of water by harvesting in this month (Equation 7). For any tank, the water release in a particular month cannot exceed the water storage capacity in each month (Equation 10). Water stored in tanks in each HRU in a sub-watershed is less than the maximum capacity of total tanks installed in a certain decade (Equation 8). Water tanks installed in each HRU and sub-watershed cannot exceed the total number of tanks allowed (Equation 9).

$$W_{(s,\rho,y,m,\eta=\text{"store"})} \leq W_{(s,\rho,y,m-1,\eta=\text{"store"})} + W_{(s,\gamma=\text{"}road\text{"},y,m,\eta=\text{"}hvst\text{"})} - W_{(s,\rho,y,m,\eta=\text{"}rlse\text{"})}$$

Equation 7 Water supply demand balance equations for water tanks ∀s,ρ,y,m [MCM]

$$W_{(s,\rho,y,m,\eta=\text{"}store\text{"})} \leq t_{(\rho,\alpha=\text{"}volume\text{"})} \cdot \sum_{r,\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} T_{(s,r,\rho,\tilde{y})}$$

Equation 8 Water tank storage capacity restrictions ∀s,ρ,y,m [MCM]

$$\sum_{\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} T_{(s,r,\rho,\tilde{y})} \leq t_{(\rho,\alpha=\text{"}volume\text{"})} \cdot a_{(s,r,y,\varphi=\text{"crop use"})}$$

Equation 9 Maximum tank installation restrictions ∀s,r,ρ,y [number of units]

$$W_{(s,\rho,y,m,\eta=\text{"}rlse\text{"})} \leq W_{(s,\rho,y,m-1,\eta=\text{"store"})}$$

Equation 10 Water release restriction for irrigation ∀s,ρ,y,m [MCM]

4.2.4 Dam calculations

Water stored in each dam location in each month is determined by the remaining storage from the previous months minus the water released to satisfy the river base flow plus the inflow of water from harvesting in this month minus water released for consumption in this month (Equation 11). For any dam, the water release in a particular month cannot exceed the initial water storage in each month (Equation 12). Furthermore, the water stored in each dam cannot exceed the available storage capacity of the respective dam (Equation 13). The total number of dams built over a limited time horizon cannot exceed the maximum number of potential dams (Equation 14).

$$W_{(s,\delta,y,m,\eta=\text{"}store\text{"})} \leq W_{(s,\delta,y,m-1,\eta=\text{"}store\text{"})} + W_{(s,\gamma=rivbse,y,m,\eta=\text{"supply"})} + W_{(s,\gamma=\text{"}rivhvt\text{"},y,m,\eta=\text{"supply"})} - W_{(s,\delta,y,m,\eta=\text{"}rlse\text{"})}$$

Equation 11 Water supply demand balance for dams ∀s,δ,y,m [MCM]

$$W_{(s,\delta,y,m,\eta=\text{"}rlse\text{"})} \leq W_{(s,\delta,y,m-1,\eta=\text{"store"})}$$

Equation 12 Water release restriction for irrigation ∀ s,δ,y,m [MCM]

$$W_{(s,\delta,y,m,\eta=\text{"store"})} \leq \sum_{\upsilon,\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} \left(d_{(s,\upsilon,\delta,\alpha=\text{"}volume\text{"})} \cdot D_{(s,\upsilon,\delta,\tilde{y})} \right)$$

Equation 13 Maximum dam storage restrictions ∀ s,δ,y,m [number of units]

$$\sum_{\upsilon,\delta,\tilde{y}|\tilde{y}\leq y \wedge y-\tilde{y}\leq l|} D_{(s,\upsilon,\delta,\tilde{y})} \leq d_{(s,\alpha=\text{"}count\text{"})}$$

Equation 14 Maximum number of dams restrictions ∀s,y [number of units per year]

4.2.5 Crop production calculations

Area allocated to particular crops cannot exceed the pre-determined maximum share for each crop (Equation 15). Land area (1000 ha) allocated for all crops using all input systems in each sub watershed and HRU in each year for cropping cannot exceed the total available land area for agriculture in a given sub-watershed and HRU (Equation 16).

$$\sum_{b} C_{(s,r,c,b,y)} \leq n_{(c,\alpha=\text{"crop share"})} \cdot \sum_{c,b} C_{(s,r,c,b,y)}$$

Equation 15 Maximum crop share restriction ∀s,r,c,y [tons per year]

$$\sum_{c,b} C_{(s,r,c,b,y)} \leq a_{(s,r,y,\varphi=\text{"crop use"})}$$

Equation 16 Land area restriction for crop production ∀s,r,y [ha per year]

4.2.6 Energy calculations

The total dietary energy $E_{(y)}$ (Pcal) supplied in each year by all crops should fulfil the dietary energy requirements (Pcal/year) and trade crop energy (Pcal/year) requirements (Equation 17). Total dietary energy (Pcal) is a product of cultivated crop area times crop yield times a crop specific energy supply coefficient (Equation 18).

$$E_{(y)} \geq g_{(\pi=\text{"domestic food"},y)} + g_{(\pi=\text{"food trade"},y)}$$

Equation 17 Total energy demand restriction ∀y [Pcal per year]

$$E_{(y)} \leq \sum_{s,r,c,b} \left(n_{(c,\alpha=\text{"energy supply"})} \cdot n_{(s,r,c,b,y,\alpha=\text{"}yield\text{"})} \cdot C_{(s,r,c,b,y)} \right)$$

Equation 18 Total annual energy supply restriction ∀y [Pcal]

4.2.7 Water balance calculations

A fraction of runoff (MCM) should reach the river to sustain the base flow in each month and in each sub-watershed (Equation 19). The total runoff in each sub-watershed in each month is a product of water harvested in the same sub-watershed (MCM), inflow of runoff to maintain the river base flow (MCM), and water harvested in upstream sub-watersheds (MCM) (Equation 20).

$$W_{(s,\gamma=\text{"}rivbse\text{"},y,m,\eta=\text{"supply"})} \geq j_{(s,\eta=\text{"rivmin"})} \cdot j_{(s,y,m,\omega=\text{"actual runoff"})}$$

Equation 19 Minimum runoff allocation for river base flow ∀s,y,m [MCM]

$$\left[\begin{array}{l}\sum_{\gamma} W_{(s,\gamma,y,m,\eta="hvst")} / e_{(\gamma)} \\ +\sum_{s}\left(1-j_{(s,\eta="loss")}\right) \cdot W_{(s,\gamma="rivbse",y,m,\eta="\text{supply}")} \\ +\sum_{\tilde{s},\tilde{m}} h_{(s,\tilde{s},m,\tilde{m},\omega="\text{probability}")} \cdot W_{(\tilde{s},a,y,\tilde{m},\eta="hvst")} / e_{(\gamma)}\end{array}\right] \leq \mathrm{j}_{(s,y,m,\omega="\text{actual runoff}")}$$

Equation 20 Runoff water balance ∀s,y,m [MCM]

4.2.8 Irrigation calculations

The amount of irrigation water in each sub watershed and month cannot exceed the amount of water released from dams and tanks in the respective month and sub watershed (Equation 21).

$$\sum_{r,c}\left(i_{(s,r,c,b="artirr",y,m)} \cdot C_{(s,r,c,b="artirr",y)}\right) \leq \sum_{\rho} W_{(s,\rho,y,m,\eta="rlse")} + \sum_{\delta} W_{(s,\delta,y,m,\eta="rlse")}$$

Equation 21 Irrigation water supply and demand balance ∀s,y,m [MCM per year]

4.2.9 Calibration

The model calibration uses a linear shadow price based cost adjustment which ensures the zero marginal profit condition of observed activities at the observed level to reveal the necessary shadow prices. Here, I first force the model to replicate existing water tanks and dams. From the forced model, the shadow prices of the calibration equations are used to adjust the objective function coefficients of water infrastructure variables (Schneider, 2012).

5 Implementing adaptation options

5.1 Regional dams/Reservoirs

In order to restrict reservoir volume, I use two basic exogenous parameters, applied to gravity dams. I define maximum dam height and embankment lengths from the contour sub model. The maximum dam heights are the most stable dam heights identified by the World Commission on Dams (Dams, 2000) for irrigation dams. I use a force balance (MANUAL, 1995) system approach to estimate the embankment volume. In order to assess the cost with different material combinations, three materials for the core are used. These include asphalt based cores, rock filled cores, and earthen cores.

Figure 20: Cross section view of the gravity

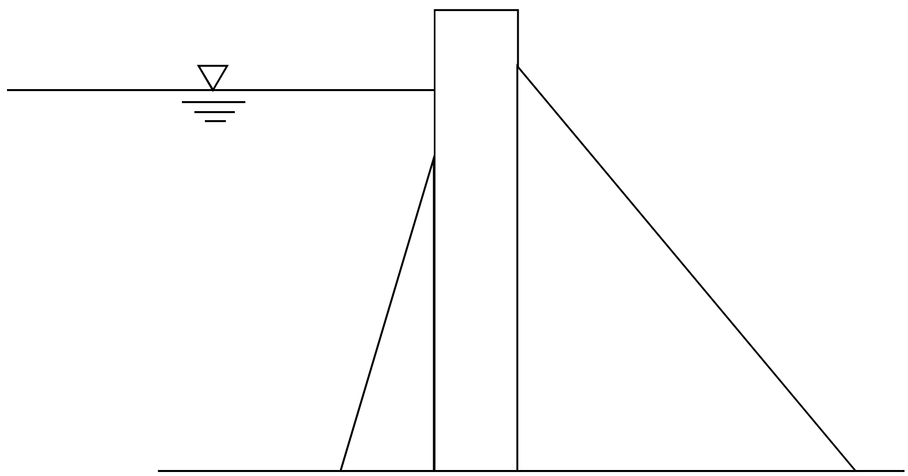
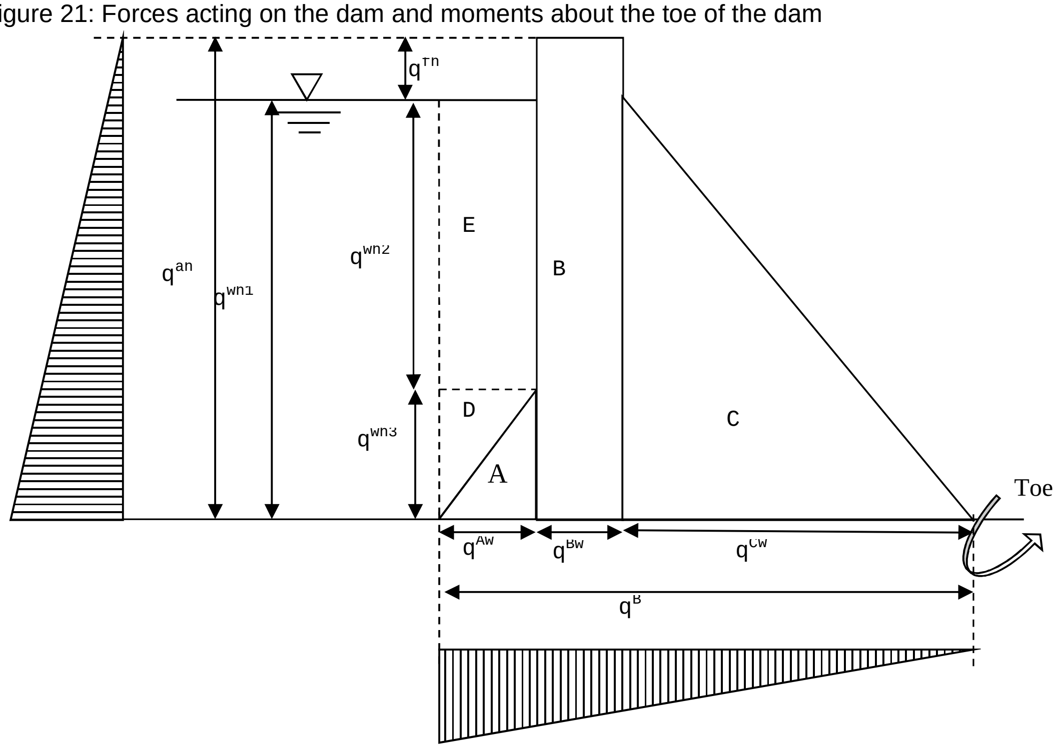


Figure 21: Forces acting on the dam and moments about the toe of the dam



The dimensions of dams are designed based on stability of the dam against overturning (Table 10). Weight of the dam forces into the ground helps it to remain stable. According to the shape of the upstream face of the dam, the vertical component of the water forces on the heel. Horizontal component of the water acts on the dam wall, which is resisted by the dam fill material. Uplift pressure is the upward pressure exerted by water as it seeps through the body of the dam or its foundation.

The factor of safety against sliding is defined as the ratio between resisting forces to driving forces, which expresses the dam's stability on the horizontal plain against the forces acting on the dam. The factor of safety against overturning is defined as the ratio between resisting and overturning moments, which expresses the dam's stability against the moments acting on the toe.

Table 10: Forces acting on the dam and moments about the Toe of the dam

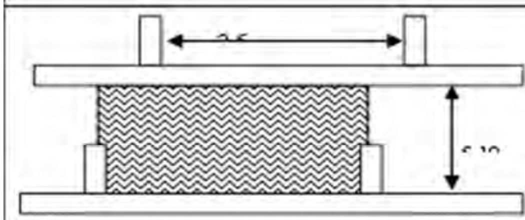
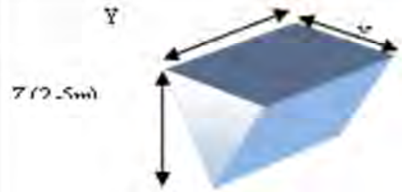
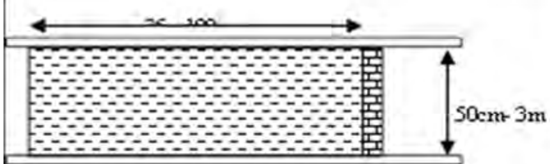
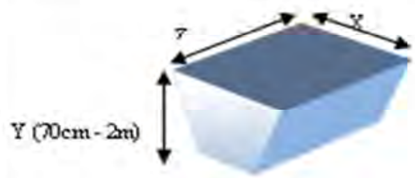
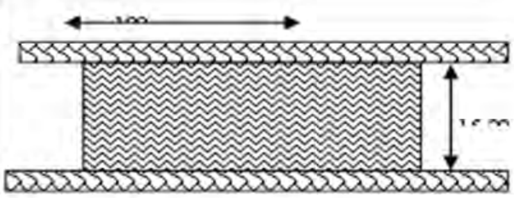
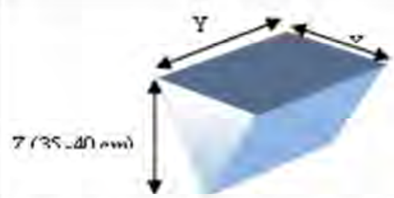
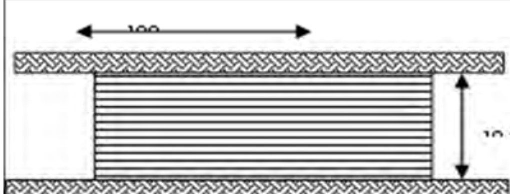
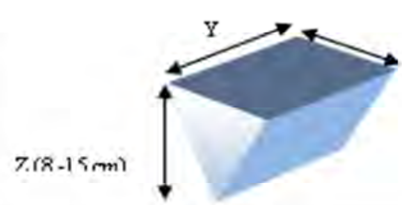
Force / direction		Formula	Length of action
Dam weight ↓			
	Section - A	0.5(qAw.qwh3.Le.Dm.g)	qB-(2/3).qAw
	Section - B	(qBw.qah.Le.Dm.g)	qCw+(0.5qCw)
	Section - C	0.5(qcw.qwh1.Le.Dm.g)	(2/3) qCw
Water weight ↓			
	Section - D	0.5(qAw.qwh3.Le.Dw.g)	(QBw+qCw)+ (0.5qAw)
	Section - E	(qAw.qwh2.Le.Dw.g)	(QBw+qCw)+ ((2/3)qAw)
Horizontal water pressure/ Hydrostatic pressure →		0.5((qwh1)2.Le.Dw.g)	qwh1/3
Uplift pressure ↑		0.5(qwh1.qB.Le.Dw.g)	(2/3).qB

Dm- Density of dam-fill material, Dw- Density of Water, Le-Length of the dam

5.2 Harvest structures

Harvest structures are used in the system to alter the flow rate and direction of the overland water flow. This strategy is mainly used to allocate water to the storage structures so that over land flow can be utilized maximally to satisfy the needs. The standard dimensions for harvest structures are shown in Table 11.

Figure 22: Harvest structures

a)Planer view,	b) Water volume captured by contour bunt
Contour Bunts	
 Volume of material: V_{mat}	 Volume harvested: 0.5(x.y.z.η)
check dams	
 Volume of material: V_{mat}	 Volume of water harvested: (0.5(x+y))z.η :
Stone terraces	
 Volume of material: V_{mat}	 Volume harvested: 0.5(x.y.z.η)
Roaded catchments	
	

5.3 Experimental setup

The main research question of the simulation exercise is to investigate what agricultural benefits can be achieved through various water management investments. This question is important to consider because increasing water scarcity due to climate and socio economic changes may lead to high welfare losses if water management remains at the status quo. As mentioned earlier, I implement the cost of water management explicitly, considering both the installation and maintenance of water harvest and storage structures.

Many studies mentioned in the introduction have tried to explain approaches to manage available water.

In contrast, the approach in this study tries to manage the water from the point of generating runoff and alter the flow properties in space and time. Hence, the harvesting flow rate of the runoff is modified and the paths to travel until the storage points are altered with minimal loss and maximum possible efficiency. In the storages (local and regional), the water is stored and released at times, when the water is required.

In order to obtain a quantitative solution to the availability of water, I use several alternative scenario settings.

I. Water management scenario

In this setup, I quantify the change on the resource use and the impact on the welfare indices at the presence of water management, considering the irrigation water demand for food crop production. Water management is obtained through implementing water harvesting and storage strategies. Scenario levels: No water management, Water management

II. Bioenergy scenario

In this setup, I distinguish different bioenergy targets.

III. Trade scenario

In this setup, I try to quantify the change on the resource use and the impact on the welfare indices at the presence of water management, considering the additional water required for crop production if I introduce trade in to the total crop production. Scenario levels: Doubling and halving of trade requirement

IV. Combined scenario

In this setup, I try to quantify the change on the resource use and the impact on the welfare indices at the presence of water management, considering the additional water required for crop production, if I introduce both bioenergy and trade in to the total crop production. Scenario levels: Doubling and halving of trade requirement

In order to distinguish the impact of water management on the above mentioned climate and energy drivers, I simulate each factor individually and jointly. The simulation events are presented in the Table 11.

NWMGT denotes that no irrigation water is provided for crop production. For WMGT irrigation water is provided for crop production. T denotes the trade activities. Here, I consider 3 levels of trade activities that alter the demand function. No change in the current trade level for crops as 1T and increment of 50% from the current as (1/2) IT and reduction of 50% from the current trade as (1/2) RT. Furthermore, I consider two levels of bio fuel demand that alter the demand function. One event does not consider change in the bio fuel demand (0BF) and other is (3BF), three times increment compared to the current level. In order to understand the impacts water management on the above mentioned drivers in the basic scenario definition, I compare the results of the combined simulation results.

Table 11: Simulation events

	Scenario event
Water management scenario	NWMGT+0T+0BF WMGT+0T+0BF
Bio-fuel scenario	WMGT+0T+0BF NWMGT+0T+0BF
Trade scenario	WMG+50IT+0BF WMGT+50RT+0BF NWMGT+50IT+0BF NWMGT+50RT+0BF
Combine Scenario	WMG+ 50IT+3BF WMGT+50RT+3BF NWMGT+50IT+3BF NWMGT+50RT+0BF NWMGT+100RT+0BF

5.4 Input data for the base scenario

The following figures illustrate the distributions and variations of input data for the 'base scenario'. The 'base scenario' is constructed using the estimated data for the IPCC SRES A2r scenario data and existing condition for the Sao Francisco basin.

The runoff is obtained from the EPIC model simulations for the A2r scenario precipitation projections for the Sao Francisco region. A small fraction from the total runoff is allowed for ecosystem services and recharges the River base flow. Here, I assumed that 2% of the total runoff is allowed for this fraction, which is not harvested or stored for utilization. Figure 23, and Figure 24 present total runoff, total allowance for river runoff and the usable run off, respectively.

Figure 23: Total runoff for the Sao Francisco Basin

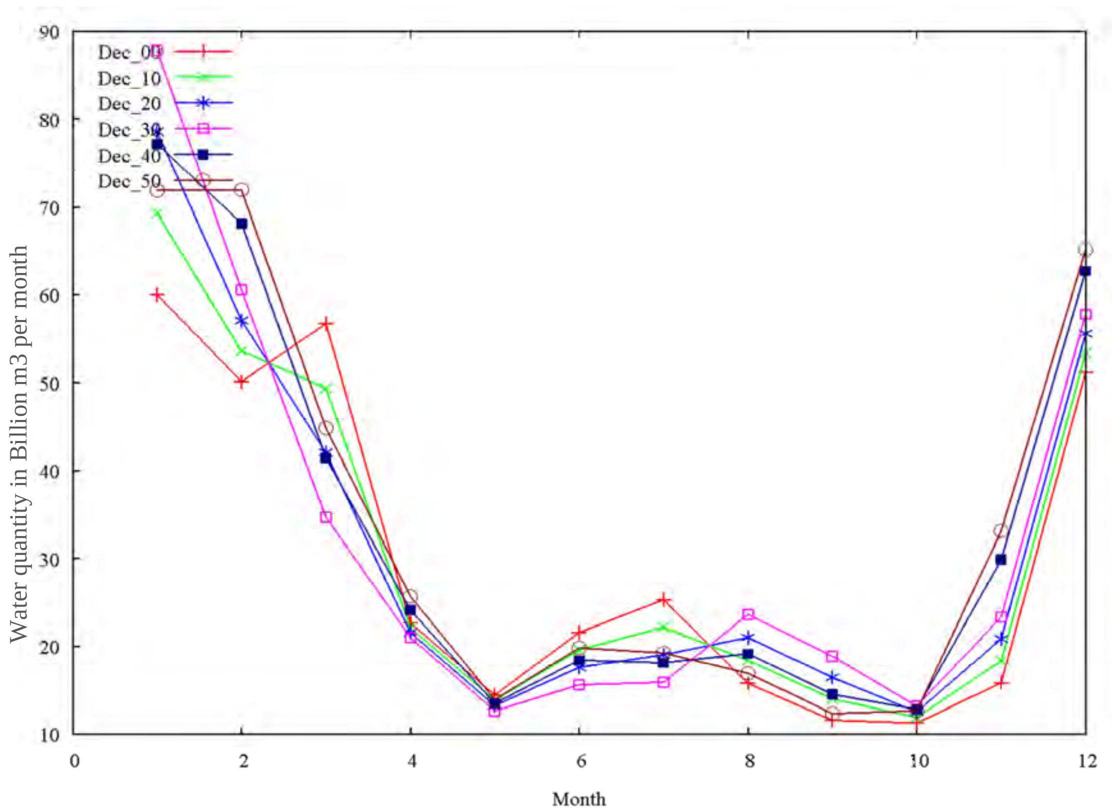


Figure 24 presents the maximum monthly irrigation requirement for the considered crops, in the IPCC SRESS A2r projection. Figure 25 presents the step function to allocate land for land pricing and the Figure 26 presents the water resource allocation for pricing. The step function for land does not change over the decades whereas the step function for the water resource allocation changes over time.

Figure 24: Maximum monthly irrigation for the Sao Francisco basin

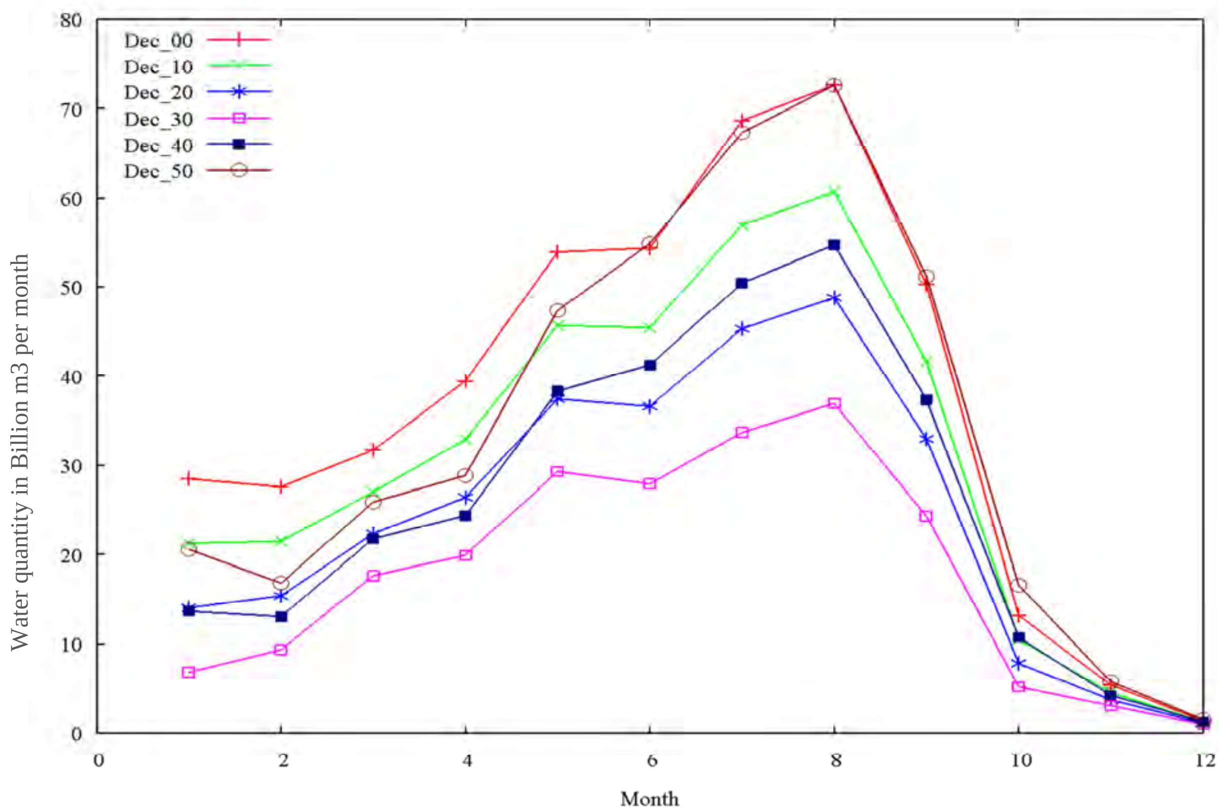


Figure 25: Land resource allocation for pricing for Sao Francisco

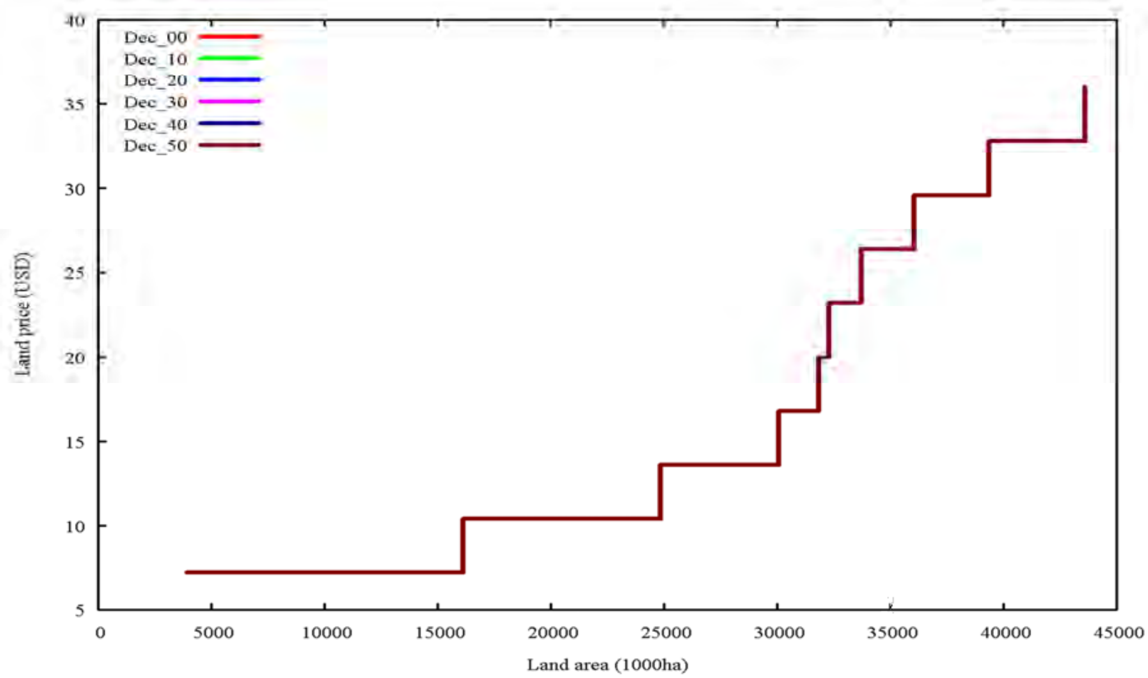


Figure 26: Water resource allocation for water pricing for Sao Francisco basin

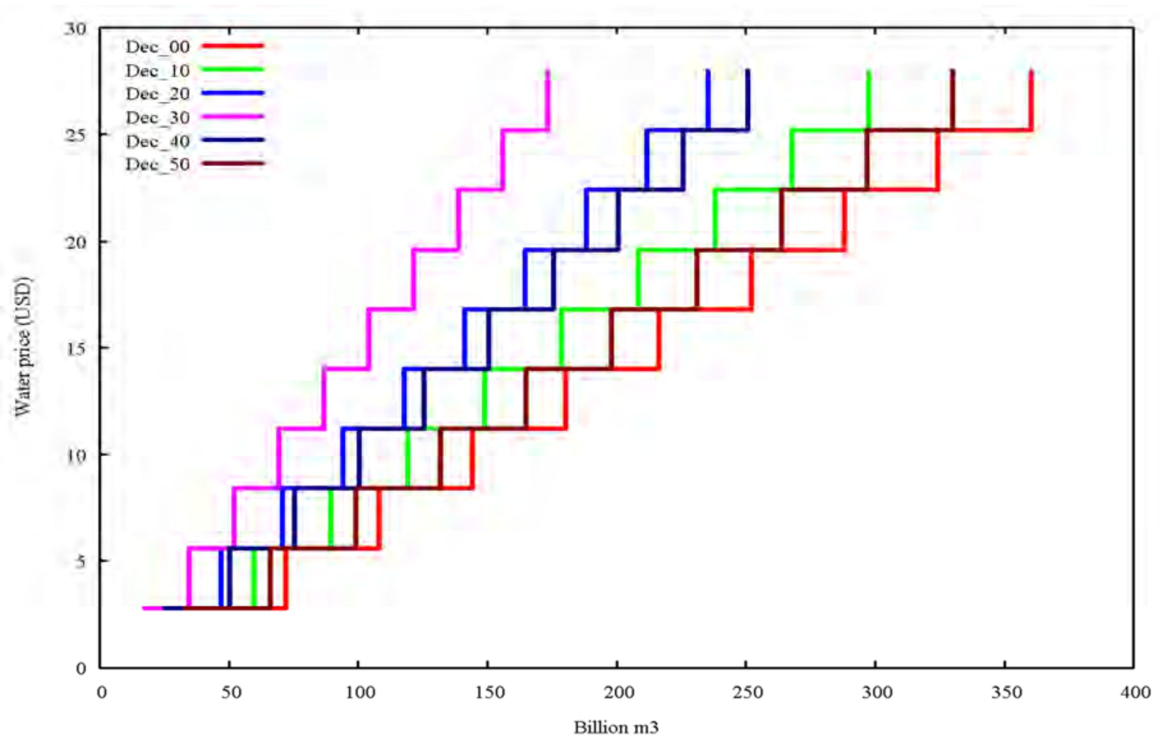


Figure 27 presents the crop yield for different irrigation systems used in the Sao Francisco basin. 'ai' denotes automatic irrigation, 'an' denotes automatic fertilization and ss denotes subsistence agriculture. Automatic irrigation yields the most while subsistence agriculture yields the least. Figure 28 illustrates the irrigation requirement for different crop type. Sugarcane and wheat require most water per hectare. However, in all crops the irrigation requirement reduces over time possibly due to technological advancement. Figure 29 presents the cost of crop production for different crops and Figure 30 shows the crop yield for different crop types. Figure 31 presents the energy demand over time in the basin and Figure 32 presents the crop production over time to satisfy the demand.

Figure 27: Crop yield data (On crop Input system): ai-automatic irrigation, an-denotes automatic fertilization, ss-subsistence agriculture

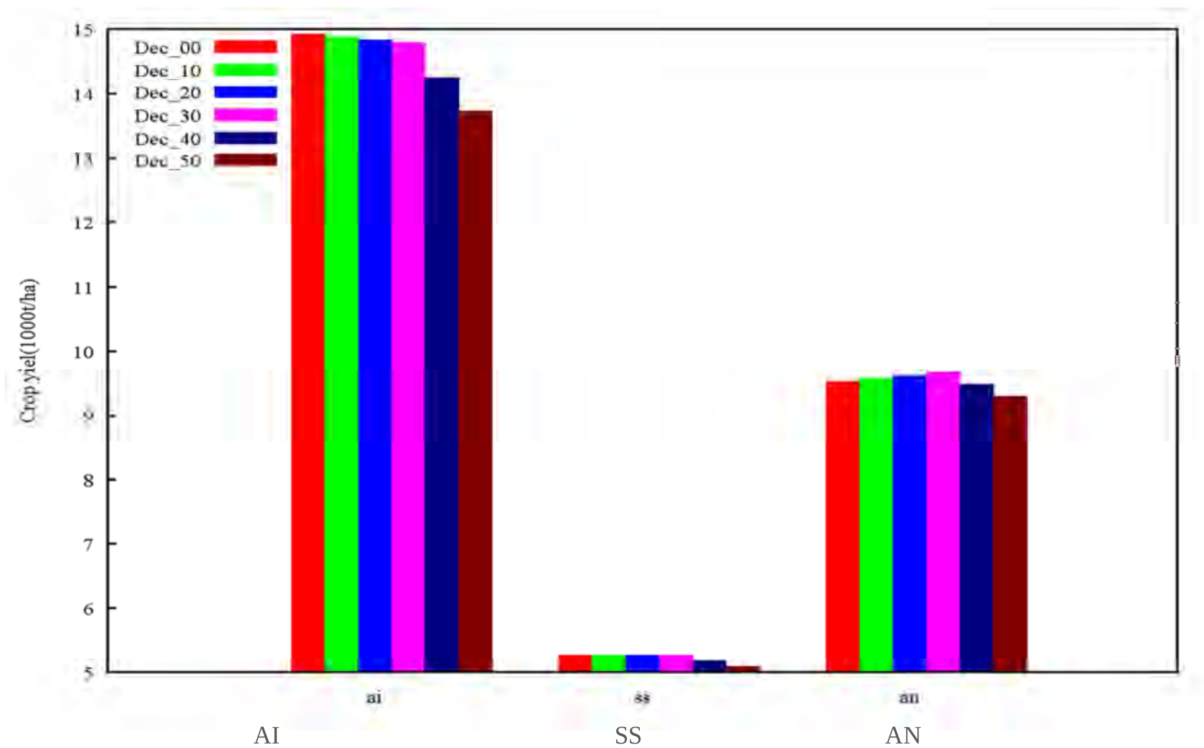


Figure 28: Total Irrigation requirement for different crops: Soya-Soy bean, SugC-Sugar cane, Whea-Wheat

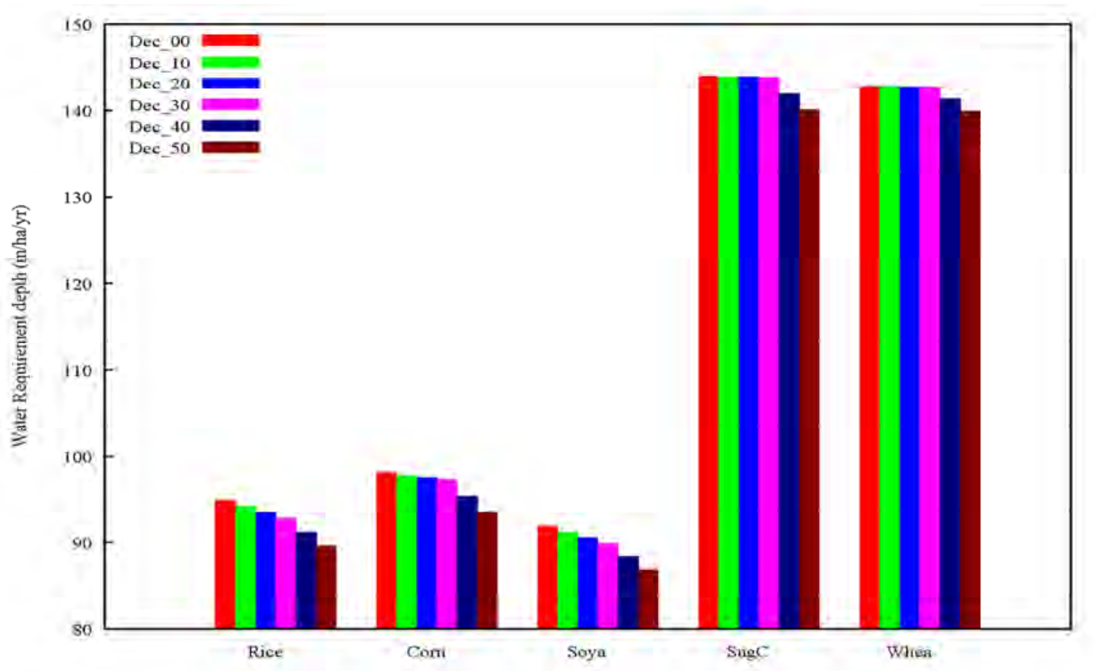


Figure 29: Crop cost data: Soya-Soy bean, SugC-Sugar cane, Whea-Wheat

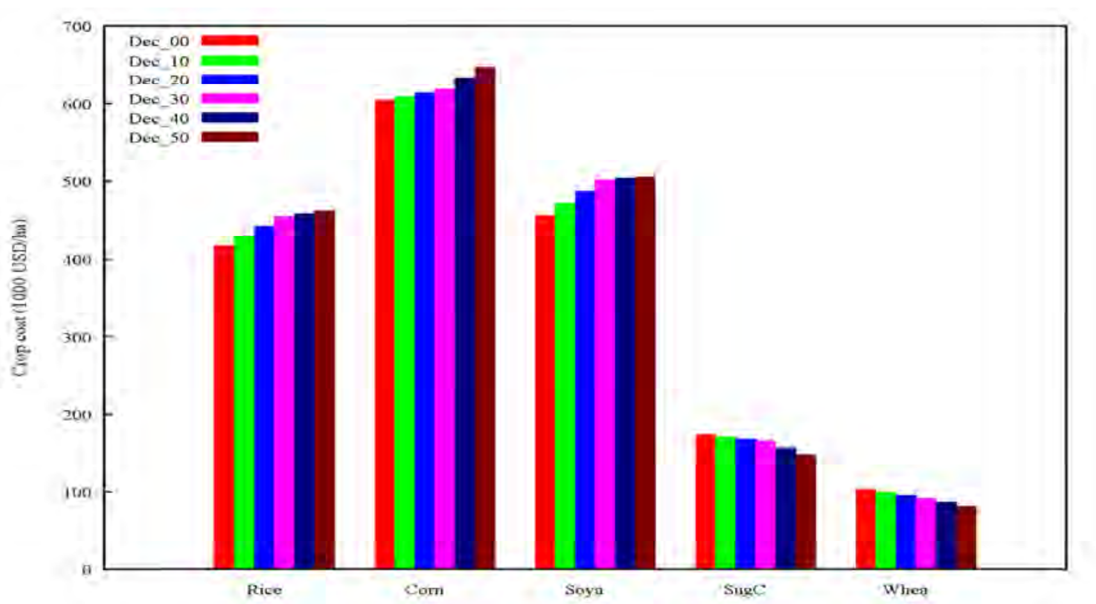


Figure 30: Crop yield data (On crop Type)

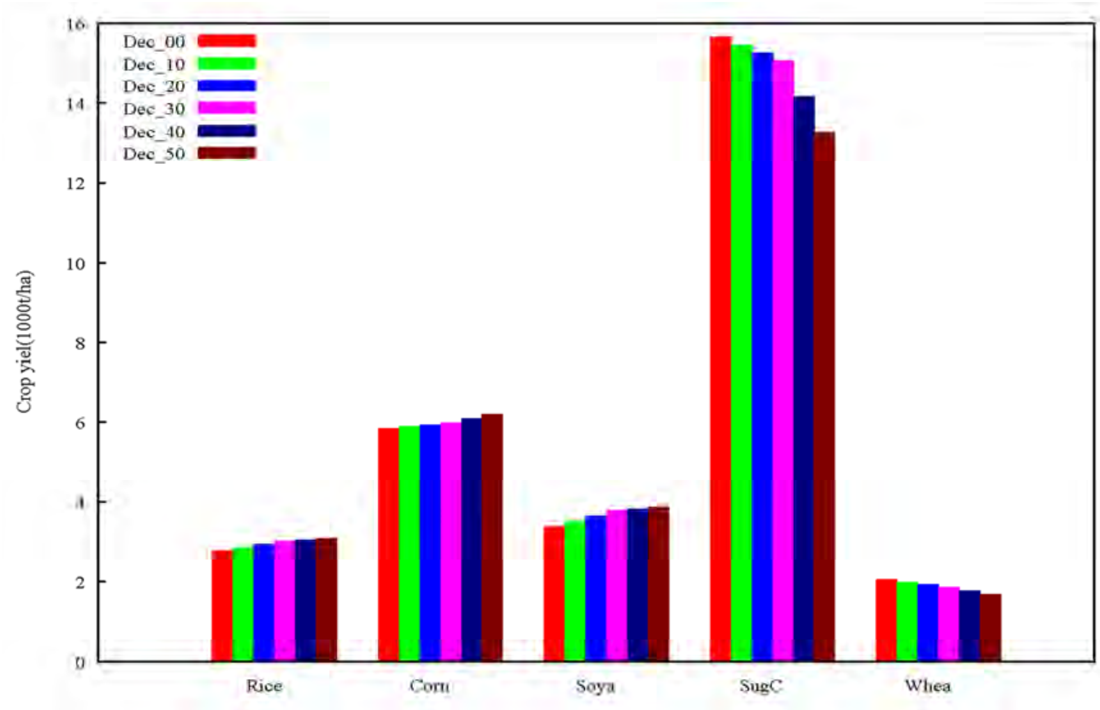


Figure 31: Energy demand data

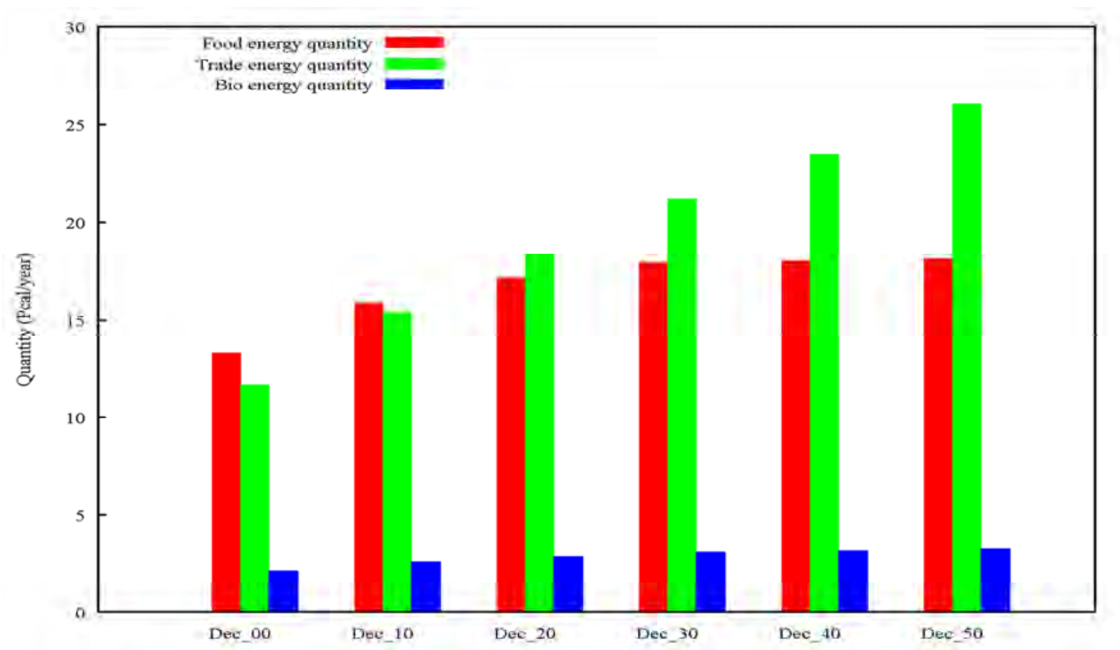
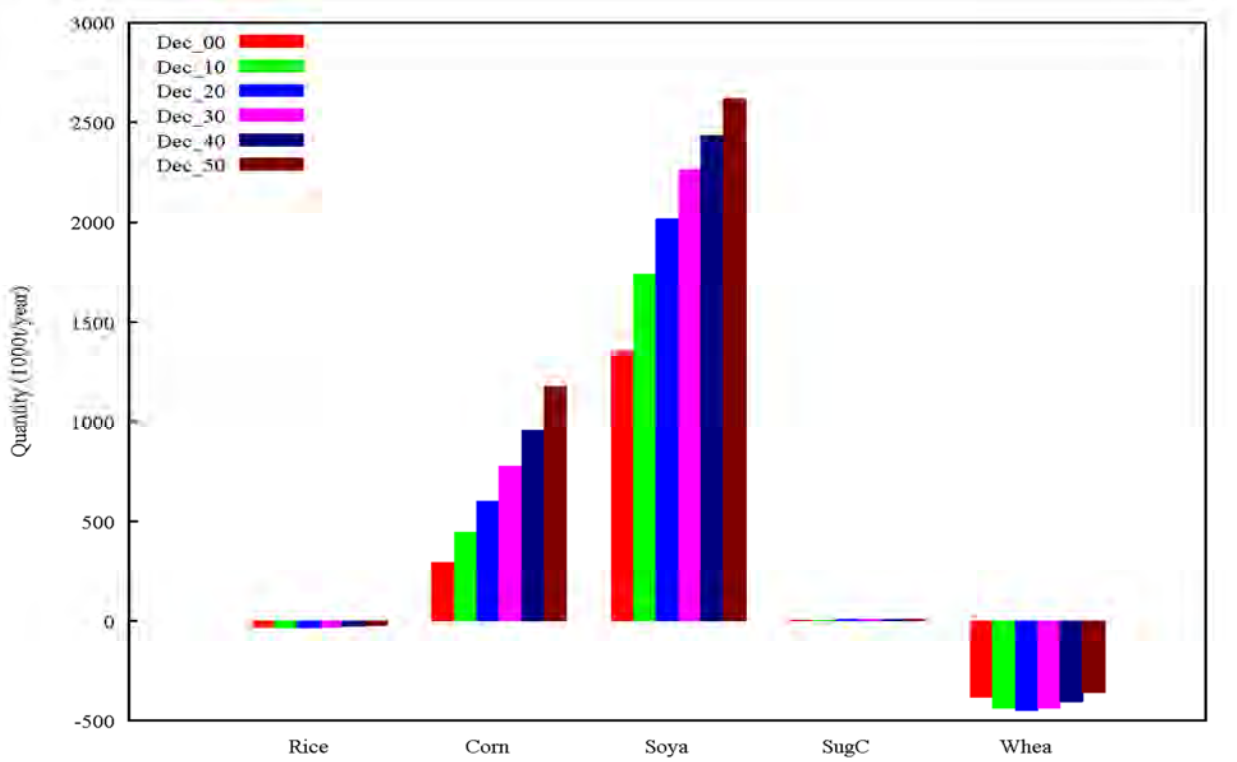


Figure 32: Crop Production for different decades



6 Simulation Results and discussion

This section summarizes the results of the simulations explained in section 3. Here, the impact of water management is evaluated by taking a quantitative measurement on the change of resource use, product supply and demand, welfare indices and the water management infrastructure. The scenario results are rather extent since I use several scenario combinations over five decades and three main driving factors. To provide an abstract idea about the impacts of water management on different driving factors, I aggregate results over the input parameter level and over time. For clarity and ease to understand, I categorize the results under resource use, demand and welfare indices.

In this study, the precipitation is held constant, i.e. precipitation intensity and its distribution remain at present levels. The water management scenario is to identify the impact of water management keeping all the other climate, trade and energy variables constant at the current level. Then, I can explain the impact of introducing the water management activities to the current system when the food demand only comprises the demand for crops to satisfy the food requirements.

The bio fuel scenario identifies the impact of water management keeping all the other climate and trade variables constant at the current level. There, I can explain the impact of introducing the water management activities into the current system if the demand function is altered with the demand for bio fuel as well. In this study, I only consider the bio-ethanol requirements with sugarcane as the preferred crop.

The trade scenario is to identify the impact of water management keeping all the other climate and energy variables constant at the current level. There, I can explain the impact of introducing the water management activities into the current system if the demand function is altered only by the demand for crops to satisfy the trade requirements. I consider only the crop demand for the net trade of corn.

Resource use

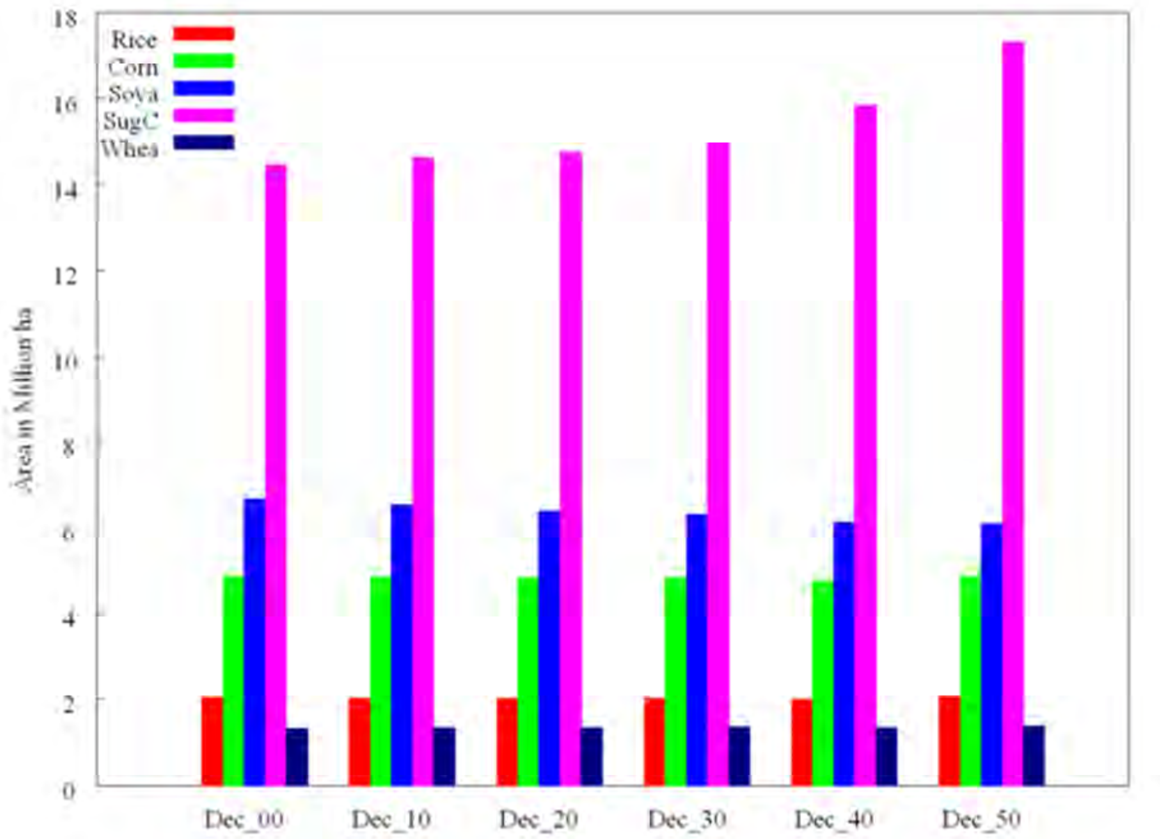
Here, I mainly consider the use of land and water resources. One index to compare the land resource utilization is the land area used for crop cultivation under the different scenarios considered. Table 12 summarizes the land area used in water management scenario and for crop cultivation. In the simulations, with altered water management, I can observe a lower land area usage for the crop cultivation. Comparatively water use in the biofuel scenario is slightly higher than for the water management scenario; however, the pattern of the water use is more or less the same. The energy demand for the bio fuel scenario in the Sao Francisco catchment is comparatively low compared to the other demands for the considered crops.

No matter whether there is a bio fuel demand or not, sugarcane is the main crop while wheat and the rice occupy the smallest fractions land (Table 12, Figure 33). Trade demand also has a considerable impact. Then a considerable extension of land use can be seen. Soya and corn are produced on a considerable fraction of the crop land also at changed water management and extensive trade demand.

Table 12: Land area used for crop production (1000 ha)

	Dec_00	Dec_10	Dec_20	Dec_30	Dec_40	Dec_50
Water management scenario						
NWMGT+0T+0BF	3306.616	3711.229	2784.124	2411.19	1999.477	1979.264
WMGT+0T+0BF	2036.555	2935.506	2142.834	1166.533	1721.527	1224.967
Bio-fuel scenario						
WMGT+0T+300BF	2710.27	2714.584	2313.83	1530.891	1698.55	1479.618
NWMGT+0T+300BF	4657.136	3834.108	3329.842	2282.118	2316.512	2199.61
Trade scenario						
WMG+50IT+0BF	2128.942	2742.602	2425.1	1169.71	1736.687	1180.14
WMGT+50RT+0BF	2021.426	2944.305	1928.979	1684.664	1405.111	1394.469
NWMGT+50IT+0BF	3739.41	3320.777	2686.342	2477.473	1954.38	2041.384
NWMGT+50RT+0BF	2875.407	3888.347	2803.931	2211.347	1946.527	2163.353
Combine Scenario						
WMG+50IT+300BF	2931.574	2620.36	2024.523	1832.661	1762.957	1374.451
WMGT+50RT+300BF	2319.793	2839.734	2543.63	1434.109	1797.48	1575.32
NWMGT+50IT+300BF	3203.945	4492.46	2933.565	2114.141	2640.226	2052.761
NWMGT+50RT+0BF	3727.138	4288.821	3181.958	2107.484	2514.222	2109.853

Figure 33: Land area occupied by different crops (WMGT+ 50IT+0BF)



The aspects of water resource use can be derived from the marginal cost of water management. This gives the price that a customer has to pay if he takes an additional unit of water.

Table 13: Marginal Cost of Irrigation water demand (USD)

	0BF	300BF
Dec_00	2.8	3.5
Dec_10	1.892	2.364
Dec_20	1.278	1.597
Dec_30	0.863	1.079
Dec_40	0.583	0.729
Dec_50	0.394	0.492

Table 13 presents the marginal cost of irrigation water supply per year for different bio fuel scenarios. Compared to the 0BF scenario, the marginal cost of irrigation water demand is 1.25 times higher in 300BF scenario. The cost of water management is less compared to 300BF scenario where the bio fuel production is much higher. I could reason this to be that the Sugarcane requires less water for irrigation compared to other crops but the revenue gain is higher per unit area. In both scenarios, marginal cost decreases over time. All scenarios show that the shadow price is considerably low when the water management is done. In addition, the shadow price decreases over time in both scenarios. At the beginning the shadow price is higher since it includes the cost for installation. Over time with the depreciation of the structures and with the increased profits the marginal value decreases. Increased biofuel demands more water from dams (Figure 34, Figure 35) when the water management is done (Figure 35).

Figure 34: Water harvested for dams and tanks (WMGT+ 50iT+0BF).

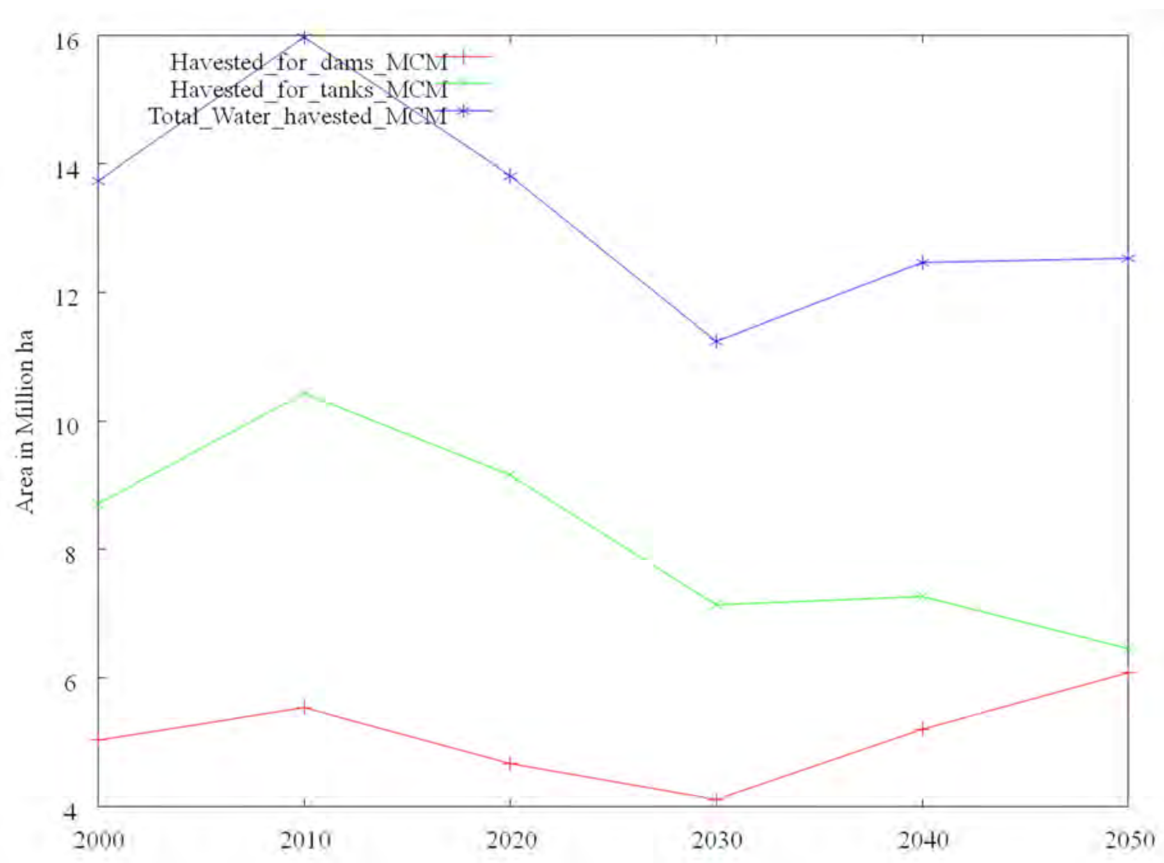
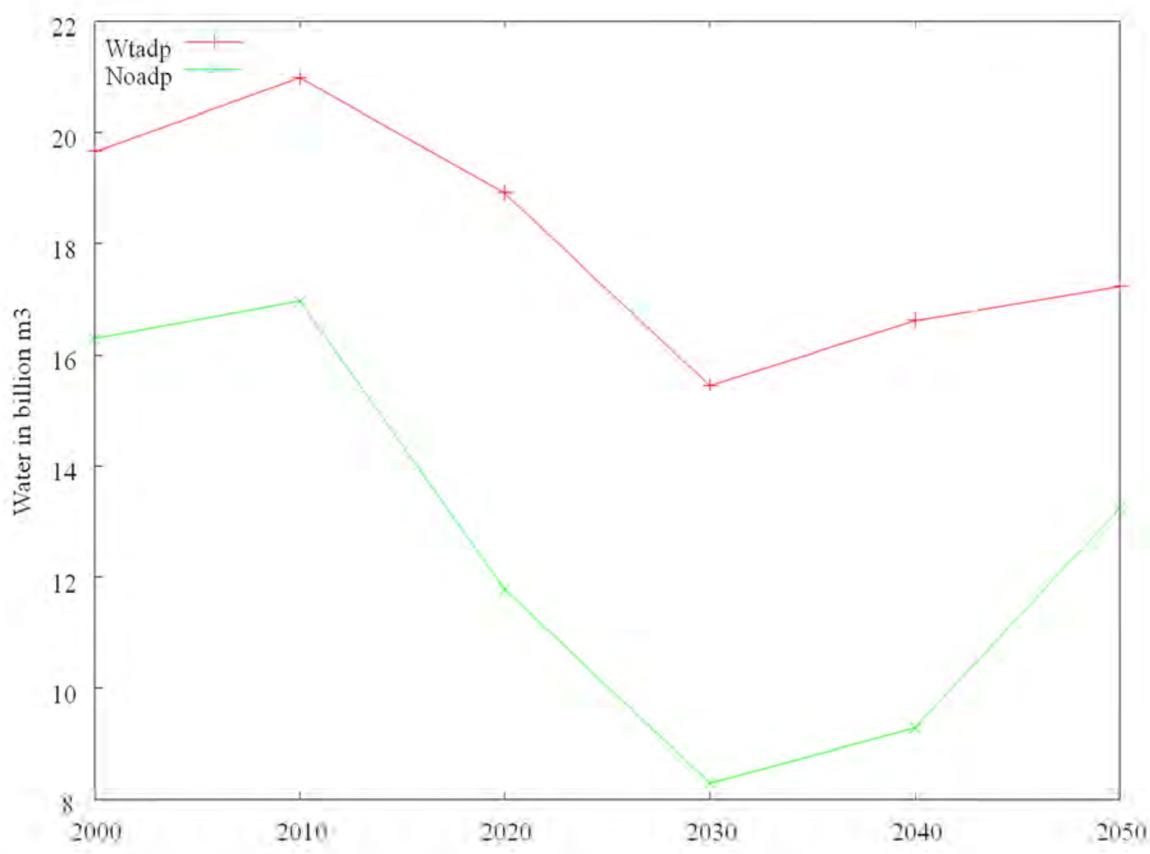


Figure 35: Total Irrigation requirement (300BF + 50idT)

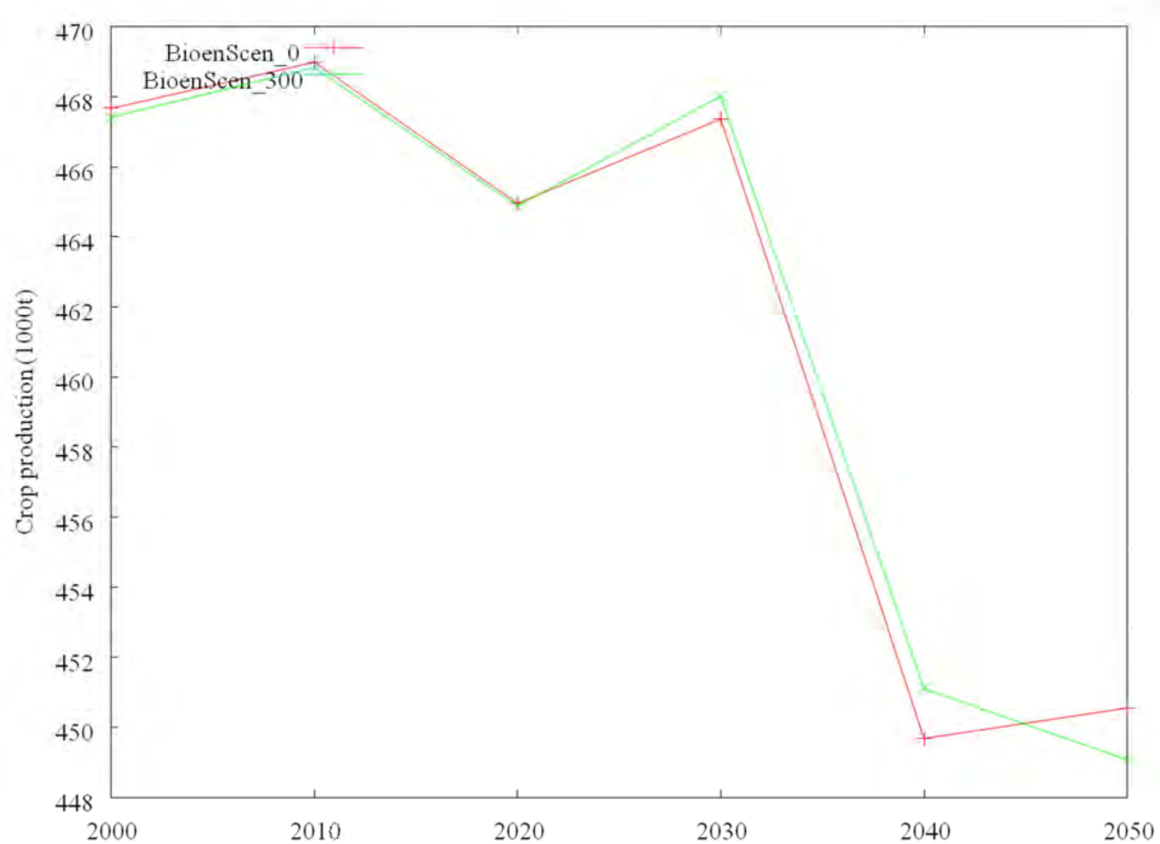


Product supply and demand

Here, I consider the contribution of crop production from the irrigated agriculture and rainfed agriculture. However, the increment or the reduction of trade demand does not show a significant impact on the relative share of the crop production. With extensive water management, the crop production shows a higher yield level.

Figure 36 shows the crop production with and without bio fuel production. With changed water management, the crop production is much compared to the scenarios without water management. The crop production is slightly higher when the bio fuel demand is three times higher. The difference between 0BF and the 300BF scenarios are not significant when the trade is not changed. One interesting feature is that crop production decreases over time. The reason could be the improvement in technology. Along with the increased efficiency, the output per unit of product increases, therefore the crop demand decreases over time.

Figure 36: Crop production at changing bio energy targets (WMGT+50iT)



Water Infrastructure

Figure 37 and Figure 38 present the water infrastructure development and the investments for the water management infrastructures. The required number of structures is significantly higher for the 300BF scenario compared to 0BF. The interesting feature is that when the bioenergy target is increased, more dams are needed compared to the tanks. The number of tanks is two times smaller in the 300BF scenario while the number of dams is 1.5 times higher compared to the 0BF scenario.

Figure 37: Number of water management structures (WMGT+300BF+ 0T)

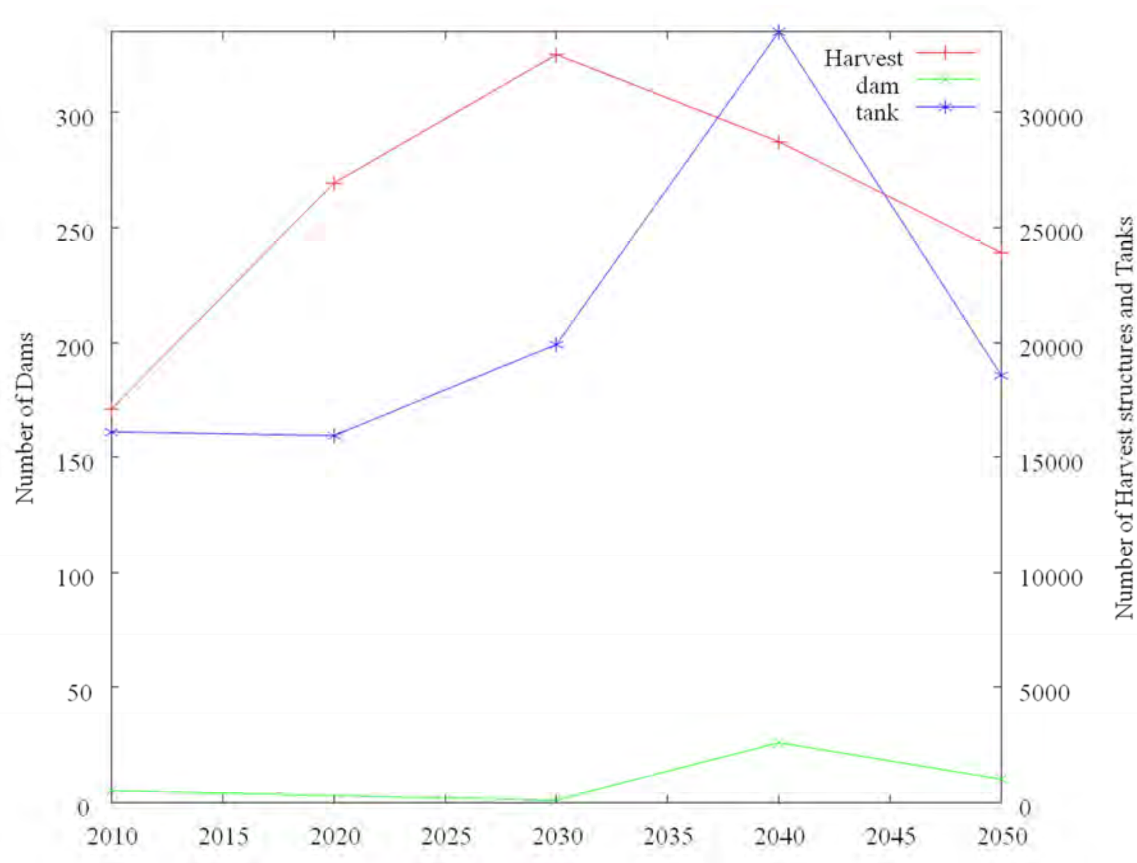
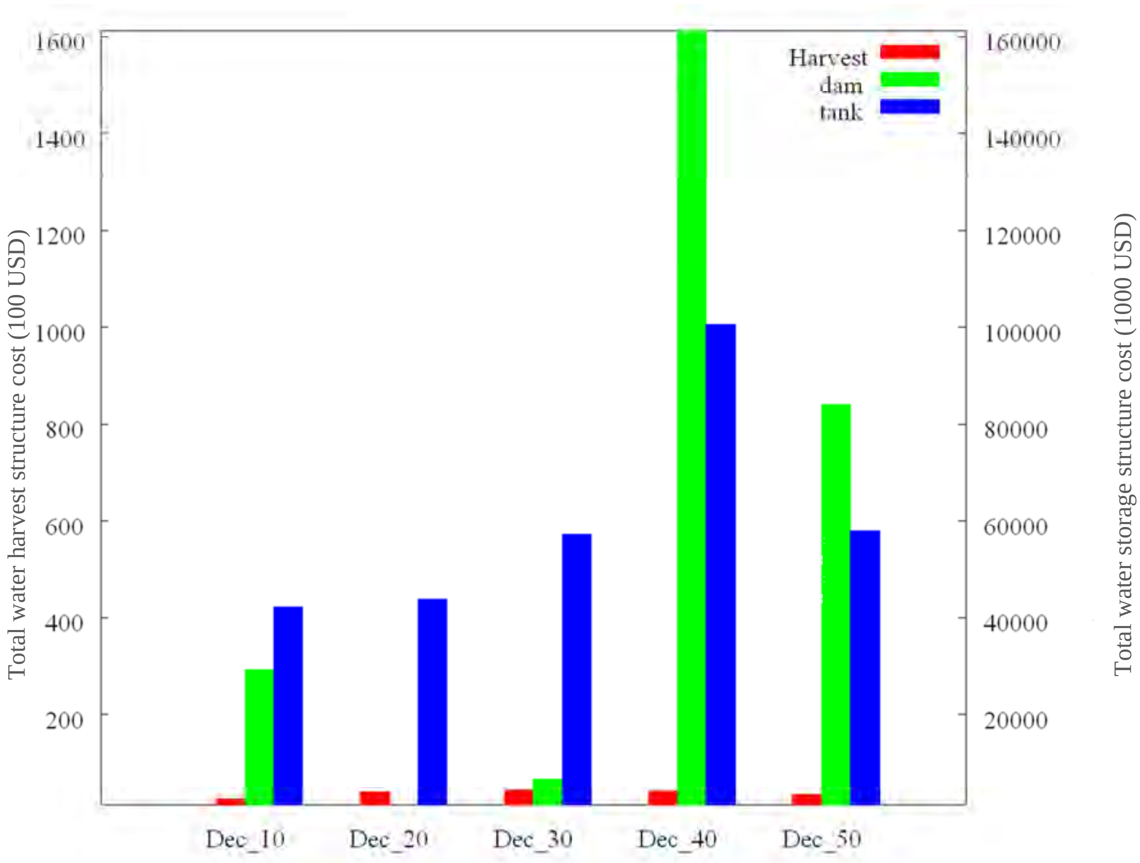


Figure 38: Installation and maintenance cost of water management infrastructures (WMGT+300BF+0T)



<u>Welfare</u>

The level of welfare that can be attained under chainged water management and the combined impact of bio fuel crop production and trade demand on the resource use can be studied through several indices.

One of the indices is the crop production cost with respect to crop type and the input system.

First, the contribution of crop production from the irrigated agriculture and rainfed agriculture is considered. ‘ai’ denotes automatic irrigation and ‘an’ denotes the automatic fertilization. The irrigated agriculture always has a higher crop production compared to the rainfed agriculture due to the high inputs usage. However, the increase or the reduction of trade demand does not show a significant impact on the relative share of the crop production. With extensive water management, the crop production increases.

Figure 39 presents the cost of crop production. The automatic fertilization cost is about four times higher than the automatic irrigation, which is about four times. Increase in trade does not influence to differentiate the cost. Figure 40 illustrates the crop production cost based on different crop types. Comparatively all crops cost is more when the water management is done.

When considering corn, there is a large cost difference when it is produced at larger quantities for multipurpose use and when it is grown for a single purpose. Soya also shows a significant cost increment when the trade is increased. Rice sugarcane and wheat do not show extremely significant difference in the crop production cost. The irrigated agriculture shows a significantly high cost compared to rainfed agriculture.

Figure 39: Cost of Crop production for two t irrigation systems (NWMGT+0T+0BF)

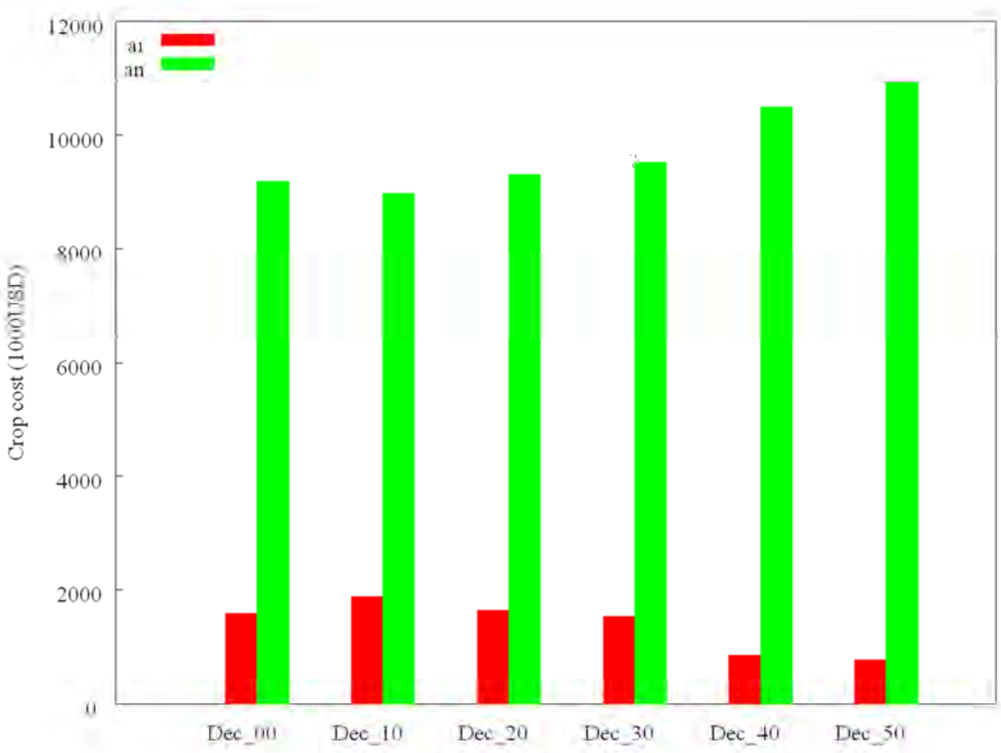


Figure 40: Cost of crop production for different crops and scenarios WMGT+ 50RT+ 300BF

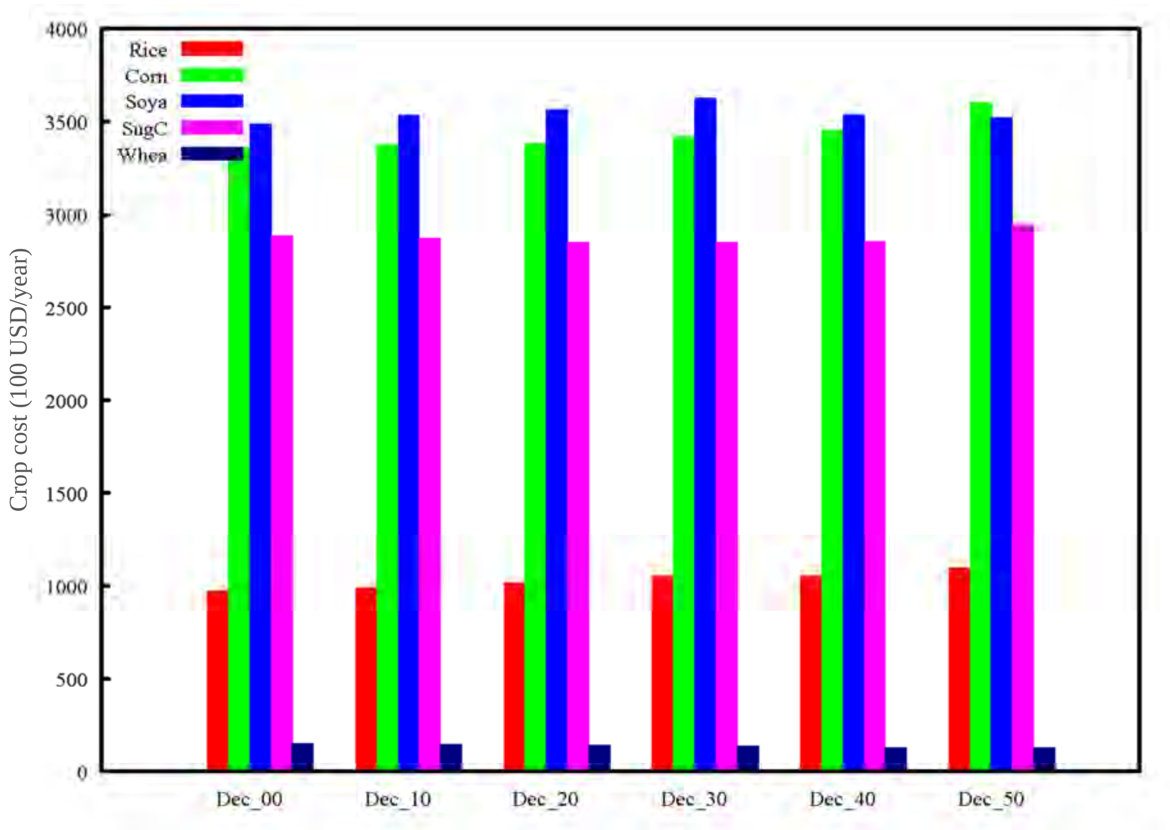


Figure 41 and Figure 42 present the total cost and benefit of crop production over time, and for different biofuel target scenarios. The cost of production is much lesser in rainfed system compared to irrigated agriculture. In both rainfed and irrigated agricultural system, total cost as well as the benefit increase over time.

The increment and the reduction of trade have a significant effect on both total cost and the benefit. If the water management is applied, the total cost gradually increases when the demand increases. The current crop production is incurred less cost than when the bio fuel production target is increased three times. When the water management is not present, the cost of production is not significantly different for current bio fuel target and when the bio fuel target is made three times higher.

Figure 41: Change in the total benefit relative to the base scenario for scenario WMGT + 50iT

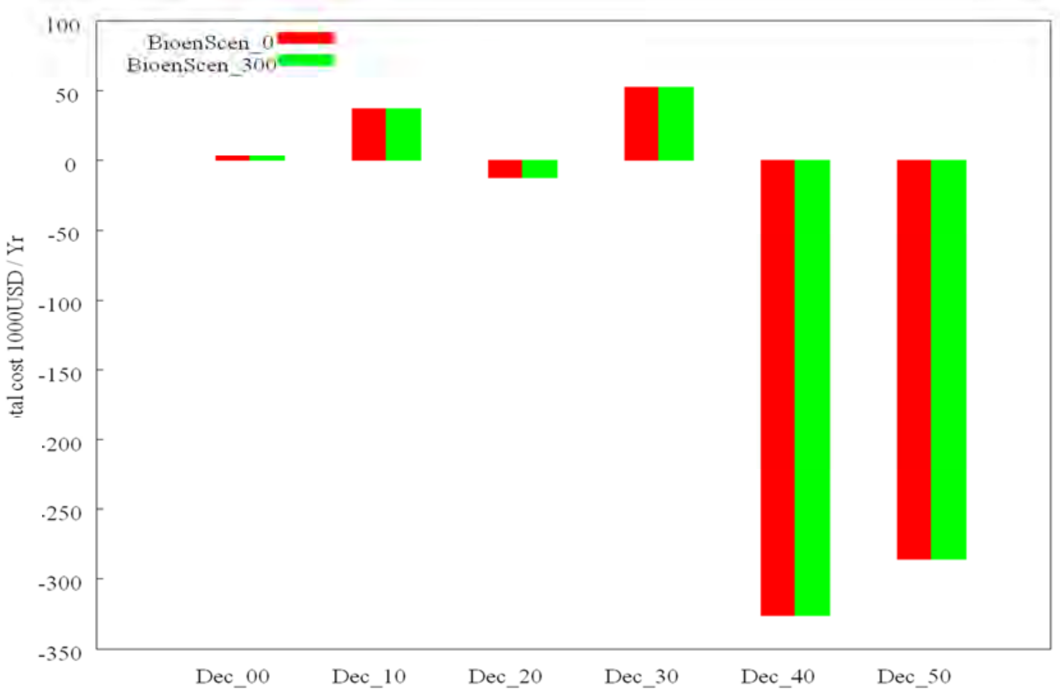
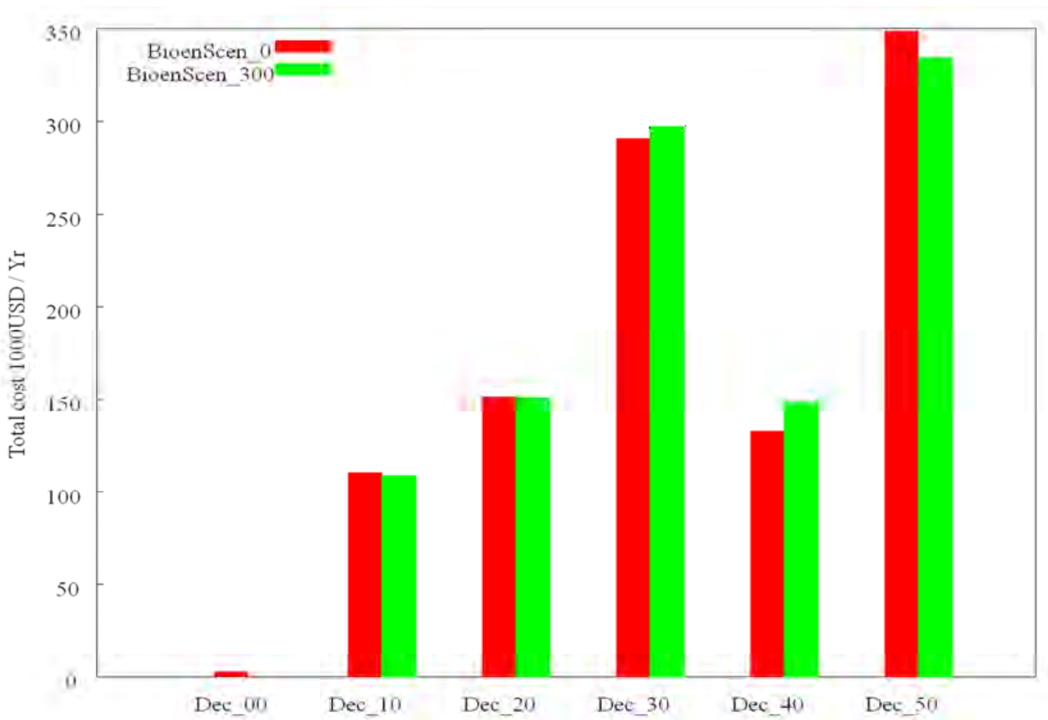


Figure 42: Change in the total cost relative to the base scenario for scenarios WMGT + 50iT



The Figure 42 presents the change in total benefit of crop production with and without water management. When the water management is present the total benefits are doubled than when the water management is not present. The total benefits does not show a significant difference when the water management is not present.

7 Limitations of the model

The total crop demand is determined by the bio fuel demand, foreign commodity demand and human domestic food demand. Irrigation water is supplied through only surface water storages. Groundwater aquifers are not considered for irrigation and water balance. Water harvesting is represented by selected structures for water harvesting and storage. The maximum shares of the area for the selected crops were decided by the historical data. But I cannot prove that it would remain the same for the total time considered in simulations. The costs for structure installation are represented using only the cost for material, labour and maintenance. Depreciation for the use of structures is not considered. This section has only summarized the results of all simulation results. The impact of water management is evaluated for resource use, product supply and demand, welfare indices and the water management infrastructure into account. The scenario results are rather voluminous since I use several scenario combinations over five decades and the three main driving factors. To provide an abstract idea about the impacts of water management on different driving factors, I aggregate results over the input parameter level and time. For clarity and ease to understand, I categorized the results under resource use, supply and demand indices and welfare indices.

8 Conclusions

Following conclusions can be drawn from this study.

The cost incurred with the water management infrastructures is an important fact that needs to be considered in water resource planning. Extensively considering the cost, I developed the ADAPT model, which can be coupled with the extensive bio physical model like EPIC, GLOBIOM and geographical analysis models like HEC-RAA and GWAMP.

Here, I have evaluated the impact of water management on the resource use, product supply and demand, welfare indices and the water management infrastructure. One of the main assumptions is that the precipitation does not change and prevails at the current precipitation level.

When the foreign commodity demand is increased, a considerable extension of land use is needed. Compared to the 0BF scenario, the marginal cost of irrigation water demand is 1.25 times higher in 300BF scenario. The cost of water management is less compared to 3BF scenario where the bio fuel production is much higher. The difference between 0BF and the 3BF scenarios is not significant when the trade is not changed compared to the base scenario. The required number of structures is significantly higher in 300BF scenario compared to the 0BF scenario. The interesting feature is that when the bioenergy target is increased, the model tries to install more dams compared to the tanks. The number of tanks is two times lower in the 300BF scenario while the number of dams is 1.5 times higher compared to the 0BF scenario. Without water management a change, the cost of production is not significantly different for current bio fuel target when the bio fuel target is three times higher.

The scenario analysis shows that the water management can have a substantial impact on resource use as well as the development of welfare levels in the region. Water management together with foreign commodity demand and bio fuel crop demand can have a combined effect compared to individual influence on the resource use and regional welfare.

9 Appendix 1

Indices

α : unit calculations[volume(mcm/unit) , cost(USD/unit),

Bunits(units/ha), count(Number of units), production(tons/ha)]

η : water use (supply, hvst, rlse, store, rivmin, loss)

δ : dam types

ρ : tank types

γ : harvest types (road, rivhvst, damhvststr, rivbse)

υ : station

s : sub watersheds (s' : from sub watershed)

r : HRU

c : crop (supply, price, demand, type, energy supply (Pcal/Yr), mean yield (tons), crop share)

b : input system(artirr, ss)

y : decadal years

m : months (m' : previous month)

x : step (count, length, price)

φ : area (harvest,crop use)[ha]

ω : runoff (coeff, actual runoff [mcm/yr], probability)

π : energy demand(human food, trade, bio-energy)[Pcal/yr]

PARAMETERS

e : efficiency

h : harvest data

t : tank data

d : dam data

a : area

i : Irrigation [mm]

j : runoff

g : energy

n : crop

Variables

W : water

H : harvest

K : water step

Z : objective / cost

T : tank

D : dam

C : crop

E : energy

I : irrigation

Table 14 : Major assumptions made

Parameter	Assumption	Reference
Climate scenario	Since I are defining adaptations for water management, extreme climate situation is used to understand the model behaviour and possibility of integrating adaptation strategies	-
Population	Population density share with respect to the land share [number of persons yr-1]	FAOSTAT
Harvest structure dimensions	Number of units per ha, capacity [mcm], Efficiency, from field experiments as recommendations by FAO	(Sivanappan, 1998) (Oweis et al., 2001; Prinz, 1996a; Prinz, 1996b).
Tank structure dimensions	Number of units per ha, capacity [mcm], Efficiency, from field experiments as recommendations by FAO	FAO
Dam dimensions	Gravity dam structure calculations according to the recommendations by US Army Corps of Engineers	U.S. Army Corps of Engineers publications : EM 1110-2-2200
Storage and harvest structure	5% of the initial investment cost.	

maintenance cost		
Cropping area	Share from the total land area [ha]	EPIC model
	Maximum crop share for individual crops [ha]	FAO-STAT
Current per capita energy requirement	Per capita daily energy requirement is 2790 Kcal yr-1 [Kcal yr-1] Protein and carbohydrate energy demand covers 75% of the total energy demand. This calorie need is only supplied through the representative crops selected in the model.	FAO
Crop energy values	Energy supply from individual crops [Kcal 100g -1yr-1]	GLOBIOM
Water balance	Water inflow from runoff will end-up in river, harvest structures or tank structures	
Irrigation requirement	Crop water requirement by irrigation under different crop management practices [MCM]	EPIC
Trade data	Import and export quantities [tons] Crop price [USD]	GLOBIOM
Crop demand	Crop demand is determined by foreign commodity demand and domestic human food energy Demand [tons]	GLOBIOM
Water availability/ Travel time	Availability of water for harvest and storeage since the runoff is generated	Probability of water as a function of travel distance and time
Benefit from selling crops	Endogenous price calculations using price elasticities	FAO base data

CHAPTER IV

Adapting water management to meet changing bioenergy targets

1 Introduction

High dependence on fossil fuels is recognized as a major factor for global warming (Cerqueira Leite et al., 2009). Therefore, a responsive action is needed to reduce dependence and emissions derived from fossil fuel combustion. Some of the remedial reactions currently in practise are replacing the use of fossil fuels by renewable energy sources and bio-fuels. These interests are mainly motivated by 1) the rising oil prices and recognizing that the global oil reserves are exhausting fast, 2) concern about fuel emissions, 3) the requirements of the Kyoto Protocol and the Bali Action Plan on carbon emissions, and 4) the provision of alternative outlets for agricultural producers (Mussatto et al., 2010). In an attempt to reduce oil dependency, increase the share of renewable energies and contribute to a reduction in declining farm income governments across the world have approved legislative instruments that foster the bio-fuel industry (Sorda et al., 2010). Ethanol is considered as a good alternative to replace oil (Bai et al., 2008).

However, all countries do not have the capacity and resources to produce bio-fuels to fulfil the demand. Some of the resources important in bio fuel crop production are land, water, society and economy. Past studies have addressed some of the governing factors. Cerqueira Leite et al. (2009) have studied the potential impact of land and infrastructure for substituting ethanol for 5% (102 billion liters) of the world demand of gasoline by sugarcane ethanol in the year 2025.

The international market in bio-fuel is still in its primary stage and its full development will require the diversification of production in terms of both feedstock and number of producing countries. This is evident when I consider the share fulfilled by bio-fuels from the total energy consumption and production. One important factor considering the bio-fuel feedstock is maintaining the sustainability of the production. Yet this should be defined to assure sustainability in a broad sense, so that it does not impose additional barriers to trade; policies should be defined to induce market competitiveness and sustainable development (Rosillo-Calle and Walter, 2006). There are several considerations how to integrate bio-fuel into the international energy market. Main feedstock that is used in bio fuel production includes some main food crops. For example sugarcane, sugar beet, sorghum, maize, wheat, cassava.. Therefore, bio-fuels have been at least partially held responsible for the increment in food prices between 2003 and 2008 (Mercer-Blackman et al.; Mitchell, 2008; Schmidhuber, 2007). In addition, some of the bio-fuel processing techniques have resulted in a net negative contribution to reduce GHG emissions for specific types of feedstock crops (Crutzen et al., 2007; Macedo et al., 2004; Pimentel and Patzek, 2005).

Other major impact areas of bio-fuel production are land use and water. Concerning the impact on the land, bio-fuel plantations compete with conventional agriculture, marginal lands and ecological wetlands. Although it is uncertain and difficult to assess, bio-fuels are also debated with respect to wider ecological and socio economic issues (Upham et al., 2009). Bio-fuel assessments need a relatively - high spatial and technical disaggregation to adequately account for heterogeneous land qualities, technological differences and possible adaptations (Havlík et al., 2011). Several studies have been conducted so far to understand the technical, geographical and socio economic potentials. Smeets et al. (2007) have studied the technical potential based on natural science, engineering and geographical factors. Schneider and McCarl (2003) have studied the economic potential based on farm level to global general equilibrium assessments. Bennett and Anex (2008) have studied this aspect using farm level models where the spatial extent is limited to specific regions and resource rents and commodity prices are constant. Yang et al. (2008) has studied the land use impacts and associated externalities using, global general equilibrium models and a top-down approach.

In order to get an explicit idea about the impacts of bio fuels on the diminishing land and water resources as well as social welfare, thorough integrated global assessments are required, which link engineering, geographic and economic tools and address different land qualities, management adaptations and global market feedbacks (Havlík et al., 2011). In the same study, they have used GLOBIOM, the complex biophysical process model to simulate impacts on yields, GHG emissions and water requirements under different land qualities. The irrigation water use has been used as an indicator of intensification and production system change in agriculture and thus is strongly related to mitigating the indirect land use change effects of bio fuel policies. The limitation in the study with respect to water resource is that irrigation water management is studied using irrigation techniques such as 'no irrigation, automatic irrigation'. The irrigation water supply and management are not considered explicitly. The runoff is directly considered as the available water to manage. Here, I try to address this factor concerning the water management and distribution. Using the ADAPT model together with GLOBIOM, I try to extend the study to following facets. From the location where the runoff is generated, I try to change the flow direction and flow rate so that the water coming to storage locations in a considered time period is altered. This altered flow is then diverted to storage locations so that it becomes available in non-rainy seasons and in added quantities. The water management is done using engineering structures and as an adaptation strategy to changing rainfall patterns.

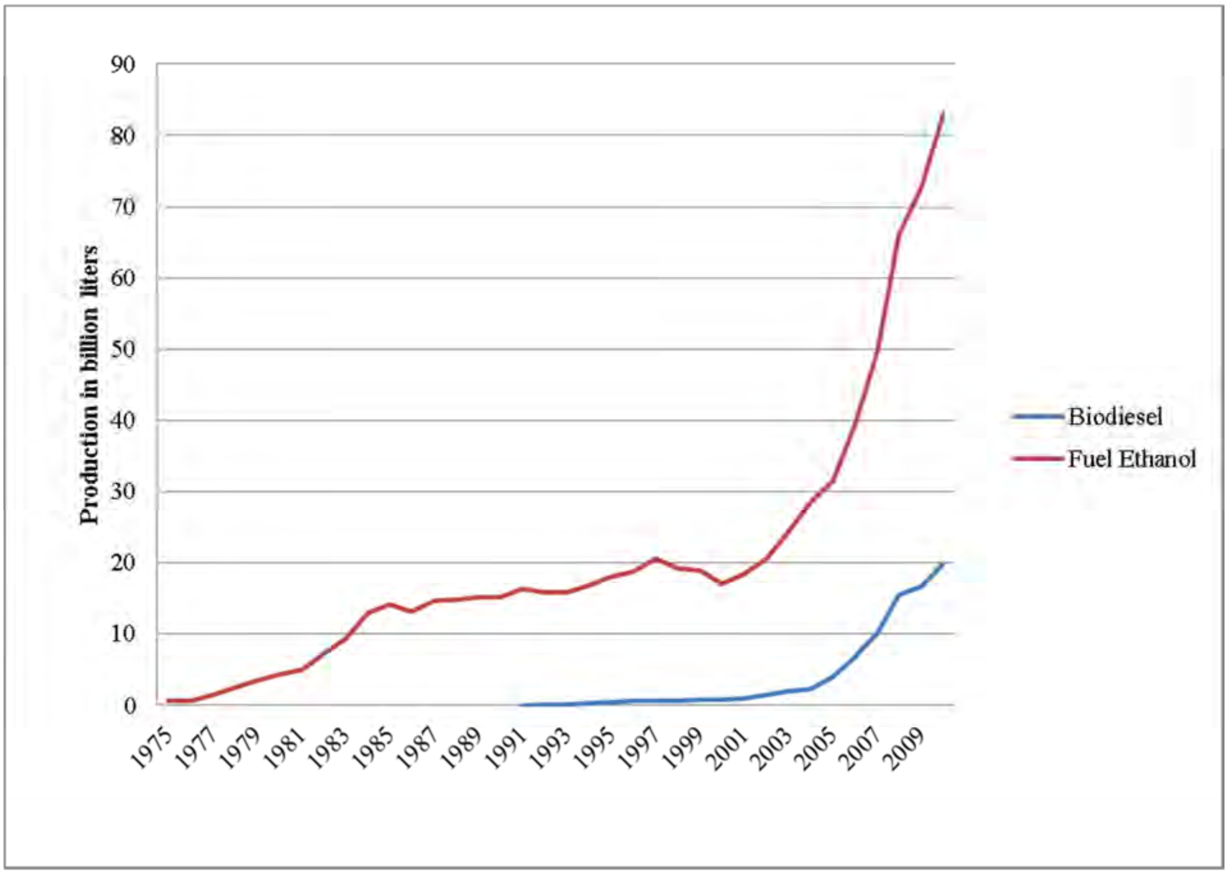
The following chapters are structured as follows. Section 2 provides a detailed description of the experimental setup and the methodology applied experimental setup and results presented in the section 3. Section 4 concludes the chapter.

2 Experimental Setup

Over the last three decades, bio-fuels production has increased dramatically for both first and second generation bio fuels, though it is still not at a considerable fraction from world's total energy production (Brown, 2011). During the period 1975-2010, bio ethanol production increased from 0.5 to 83.0 billion-litres while biodiesel production increased from 0.1 to 19.7 billion-litres (

Figure 43).

Figure 43: International Energy Statistics Note: Original data in US gallons.

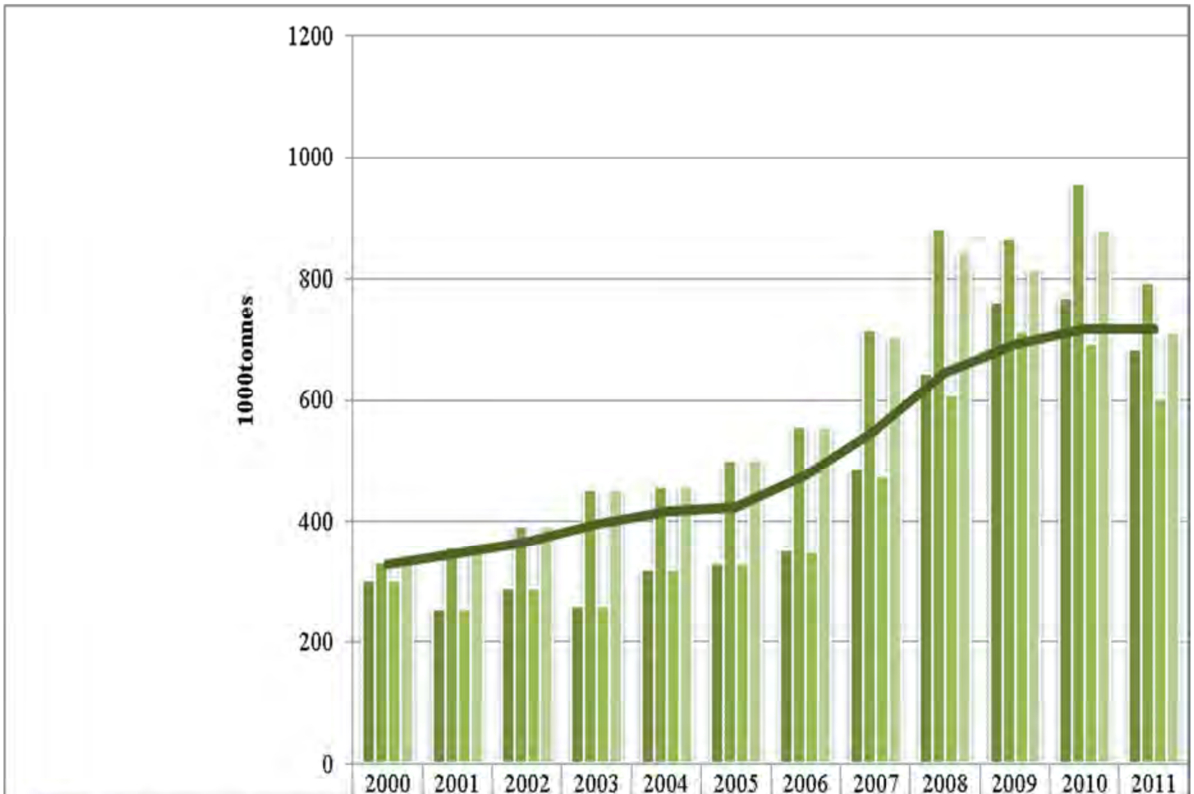


Source: http://www.earth-policy.org/books/wote/wote data (Brown, 2011)

The most common types of bio fuels, bio ethanol and biodiesel,l are mainly produced in USA and Brazil. Currently Brazil is responsible for about 25% while USA is responsible for about 65% of the world ethanol production. When considering the period from year 2000 to 2011, the total bio-fuel production and consumption show an increasing trend in Brazil (Figure 44).

Figure 45 shows the land suitability for sugarcane production in Brazil. The Sao Francisco basin comprises a large land area, which is naturally suitable for sugarcane cultivation. Being an intensively cultivated area, there is still a possibility of expanding commercial sugarcane cultivation. Therefore, I selected the Sao Francisco watershed from Brazil and sugarcane crop to investigate the possible expansion of the bio fuel crop production. This selection is done considering the importance of bio fuel production in Brazil. The fuel ethanol production and consumption also show a gradual increase in average. Bio-ethanol production is mainly obtained from sugarcane in Brazil. The sugarcane production also shows a similar growth in average. Brazil has the most developed and integrated bio-fuels program in the world and Brazil's ethanol is recognized as the most price-competitive bio-fuel in the world. Moreover, Brazil is now also investing in bio-diesel (Sorda et al., 2010). The National Program on Biodiesel Production and Usage (PNPB), initially required 2% of petrol based diesel to be replaced by biodiesel from 2008 to 2012 and an increase to 5% from 2013 onwards (Colares, 2008).

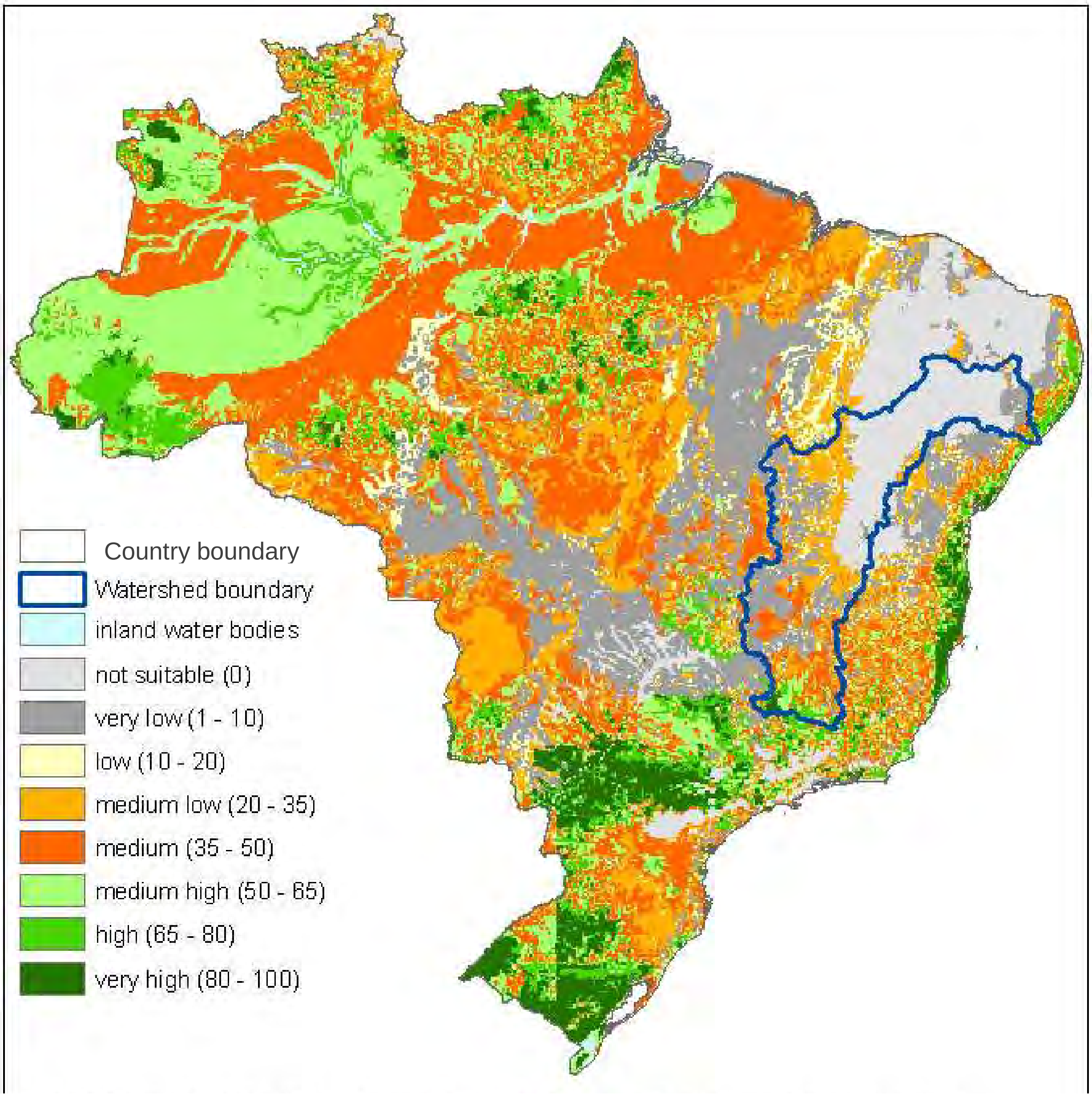
Figure 44 : Yearly bio fuel production and consumption in Brazil since 2000 (International Energy statistics)



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Total Energy Consumption	302.6	256.4	290.5	261.2	321.2	330.0	354.1	486.9	645.1	762.2	769.6	684.5
Total Energy production	333.5	358.4	393.5	452.3	456.5	501.3	557.4	717.6	882.1	866.1	956.1	794.5
Fuel Ethanol Consumption	302.6	256.4	290.5	261.2	321.2	329.9	352.1	475.4	610.4	713.3	692.7	602.9
Fuel Ethanol production	333.5	358.4	393.5	452.3	456.5	501.3	555.2	705.0	845.7	815.8	881.5	711.0
Sugar cane production	327.7	345.9	364.4	396.0	415.2	423.0	477.4	549.7	645.3	691.6	717.5	717.5

3 Experimental Set up

Figure 45: Suitability of land area in Brazil for sugarcane production under rainfed agriculture. Source: World Food and Agricultural Organization



The main research question of the model experiment is what share of total energy supply can be achieved through adapting water management. In order to distinguish the impact of water management on the bio fuel crop production, I simulate the influence of each factor individually and jointly. The simulations are presented in the Table 15.

Table 15: Simulation events

Scenario	**Scenario conditions**	**Description**
Water management	BF levels : 0BF T levels : 0T	
Trade scenario	BF levels : 0BF T levels : 50iT, 100iT, 200iT, 50rT	Only foreign commodity demand changes
Bio fuel scenario_100	BF levels : 0BF, 10BF, 25BF, 50BF, 75BF, 125BF T levels : 0T, 100iT	Doubling of the current bio fuel demand together with foreign commodity demand
Bio fuel scenario_300	BF levels : 10BF, 25BF, 50BF, 75BF, 125BF 150BF, 175BF, 200BF, 300BF T levels : 50iT, 100iT, 200iT, 50rT	Three fold increase of the current bio-fuel demand together with foreign commodity demand

Here, only scenarios with changed water management are considered, since in chapter 3 it was already concluded that changed water management is more beneficial compared to a situation where the water management is not changed. In addition, I try to understand the capacity for an increase in bio-fuel demand. Precipitation is not changed since the objective is to understand the capacity to expand the bio-fuel crop production under current climatic conditions. The irrigation water is provided for crop production, industrial demands and domestic water needs.

T denotes the trade activities. Four levels of trade activities that alter the demand are considered. No change in the current trade level for crops is indicated by 0T and increases in the foreign commodity demand are denoted by 50%, 100%, 200% as 50iT, 100iT, 200iT respectively. Reduced trade activities (50%) are expressed as 50rT. Furthermore, I consider several levels of bio-fuel demand that alter the demand function. No bio-fuel demand is described as 0BF. 10BF, 25BF, 50BF, 75BF, 125BF 150BF, 175BF, 200BF, 300BF consider the increases of bio fuel demand by 10%, 25%, 50%, 75%, 125%, 150%, 175%, 200%, and 300%, respectively, compared to the current level. In order to understand the impacts of water management on the above-mentioned drivers in the basic scenario definition, I compare the results of the combined simulation results.

The water management scenario is to identify the impact of water management keeping all the other climate, trade and energy variables, at the current level. This is the base scenario for comparisons.

The bio-fuel scenario is to identify the impact of water management keeping all the other climate, trade variables constant, at the current level. Only the bio-ethanol production from sugarcane is considered. The ‘Bio fuel scenario_100’ refers to a bio fuel demand increase by 100% and ‘Bio fuel scenario_300’ refers to increasing bio fuel demand up to 300% , with respect to current demand levels.

The trade scenario identifies the impact of altered trade, keeping all the other climate variables, at the current level.

4 Simulation Results and discussion

This section summarizes the results of the above mentioned simulations. Here, the impact of water management is evaluated by taking into account the change of resource use, product supply and demand, welfare indices and the water management infrastructure. The scenario results are rather extent since I use several scenario combinations over five decades and three main driving factors. To provide an abstracted idea about the impacts of water management on different driving factors, I aggregate results for clarity and ease to understand, I discuss the results for changes in resource use, crop production, water management and welfare.

Resource use

I discuss the resources use with land and water resources use in different biofuel demand target scenarios. In the figures, ‘ai’ denotes automatic irrigation and ‘an’ automatic fertilization. ‘AI’ and ‘An’ is the use of sophisticated irrigation systems to distribute water in the irrigation fields. In this setup, the effect of changing bio-fuel demand on the resource use can be isolated. When I consider the different bio fuel crop demand scenarios, the area allocated for crop production under automatic irrigation is always higher compared to the area under rainfed agriculture. Automatic irrigation occupies about one fifth of the land area occupied by the artificial fertilization. When I compare the model results, the land area occupied by the automatic irrigation reduces over time and the area under automatic fertilization increases. The increase of area with automatic fertilization is about 4 million hectare compared to the base scenario (Figure 46). The reduction of area under automatic irrigation is about 2 million hectare compared to the base scenario. However, this is not is a large change in the expansion of the land area but a drastic change in the land area for different cropping systems. This result shows decreasing land fertility with time. However, overall land area expansion until 2050 is about 4% (Figure 47). Hence there is only a slight increase in the land area. One can reason that this is due to higher efficiency per unit land area, and the increase of bioenergy use up to three times does not have much effect. In addition, the human dietary energy demand is much higher compared to the bio-fuel demand (Figure 52). The results also show that the cost of crop production is about 4.5 times higher for the scenario under automatic fertilization compared to under automatic irrigation (Figure 48).

The other parameter to understand the resource use is water use. Water consumption slightly increases when the bioenergy target is 175% of the base scenario. However it increases significantly for the 300% of the bio-fuel crop demand (Figure 46). The total irrigation water requirement scenario changes slightly only for different bio-fuel demands (Figure 49). Water demand is not uniform over the year in every month (Figure 51), with highest demands for, June, to September period. Comparing different bio-fuel demands, the irrigated area has increases to satisfy the excess demand, while the rainfed fraction remains the same. Irrigation water demand by different crops (Figure 50) changes strongest for Sugar cane, due to the use of sugarcane as main crop for bio-fuel. Even increased foreign commodity does not show a significant signal in the change of land and water resources.

Figure 46: Land use change compared to the year 2000 for scenario: Trebling the bio-fuel use but no change in foreign commodity demand

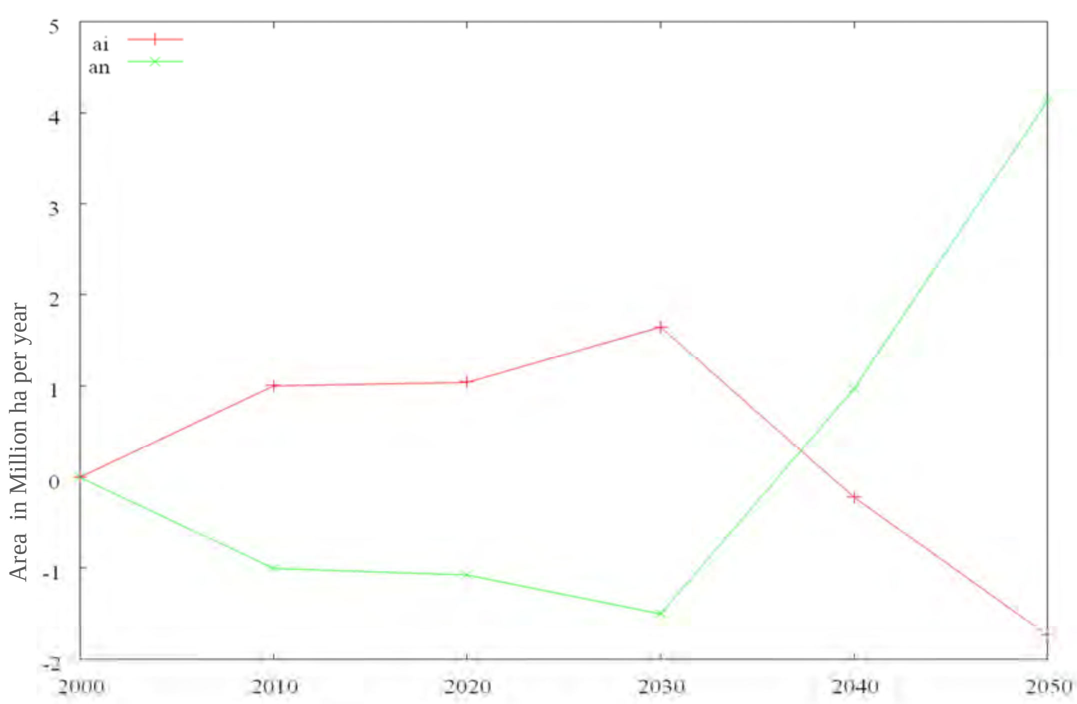


Figure 47: Total land area for crop production for scenario including a doubling of trade and trebling of bio-fuel demand

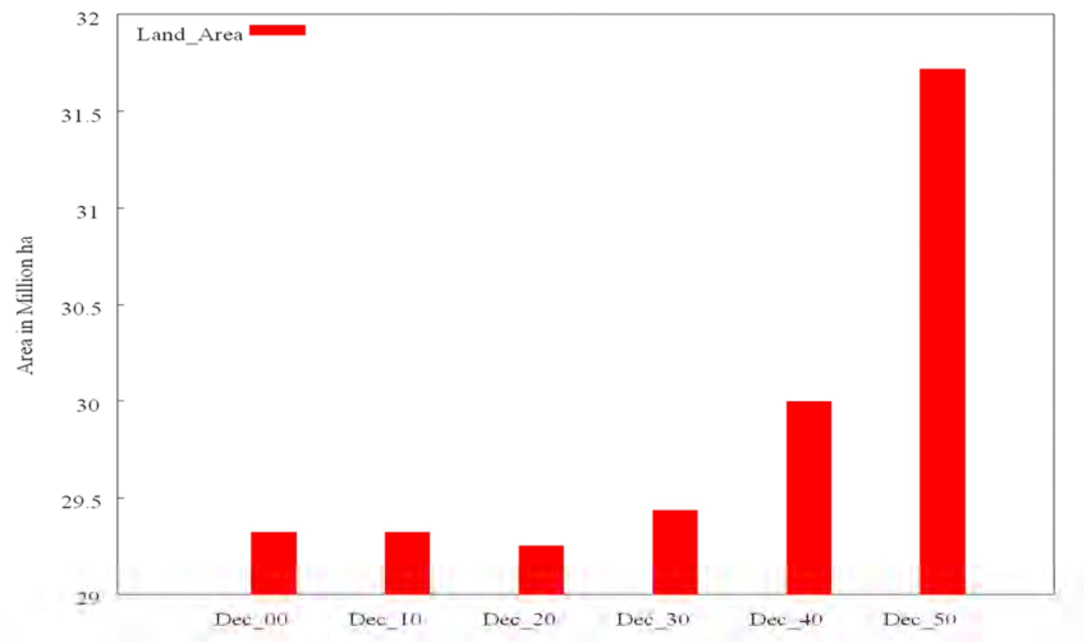


Figure 48: Cost of crop production depending on irrigation type for scenario: Trebling the bio-fuel demand and reducing the foreign commodity demand to half

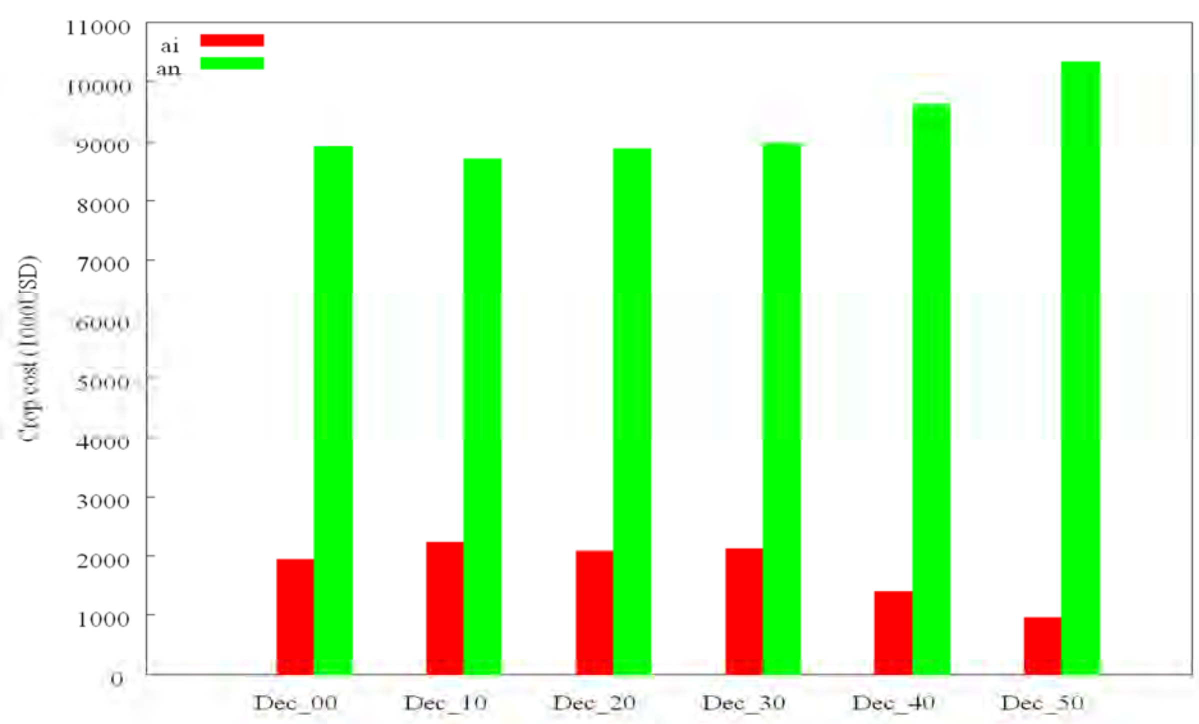


Figure 49: Change Irrigation water for the scenario without trade but all bio-fuel scenarios

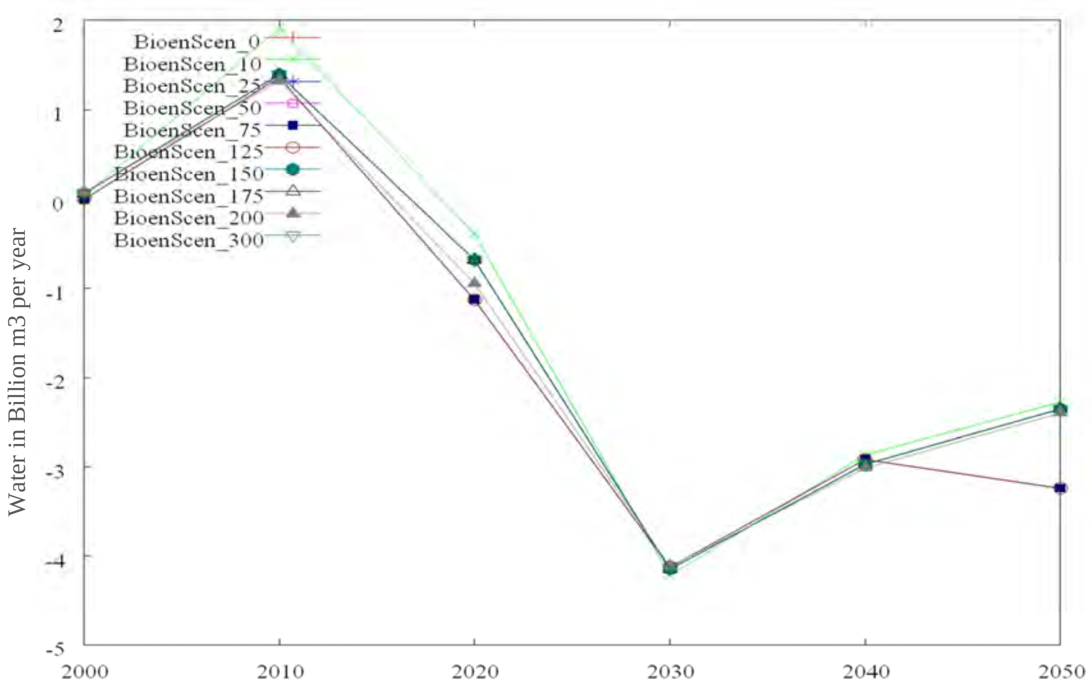


Figure 50: Change in Irrigation water demand for different crops for scenario 200BF+50iT

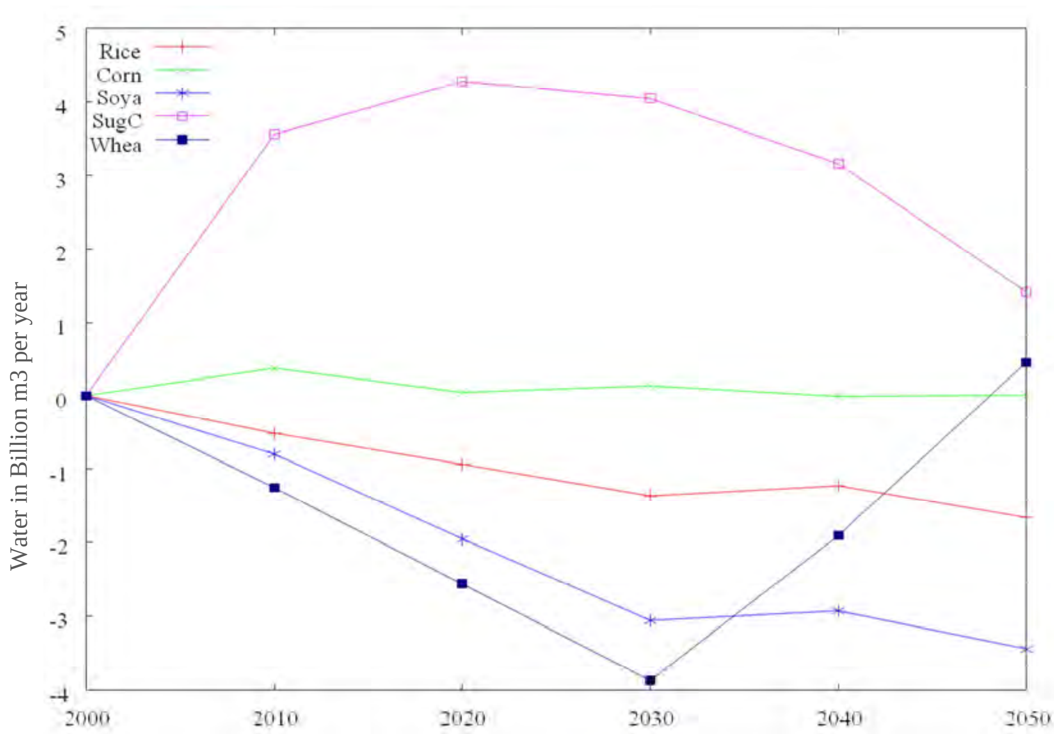
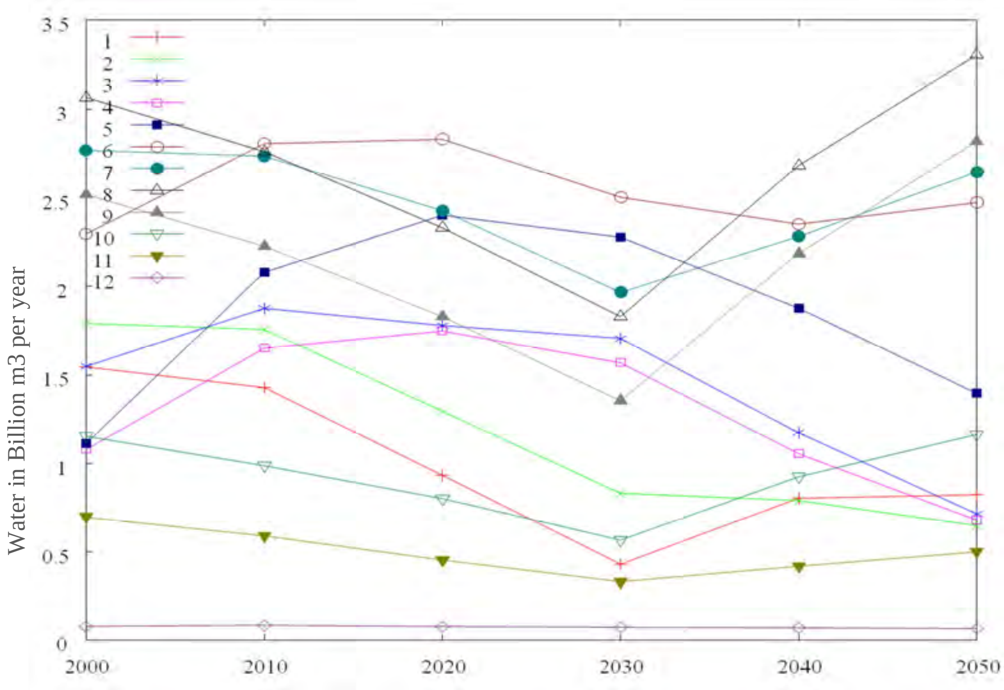


Figure 51: Irrigation water demand in different months (300BF+ 50iT)



<u>Crop production</u>

With the crop production in different bio fuel scenarios, I can compare the level of demand satisfaction. According to our model results, with the increment of bioenergy target the crop production increases less than 10% from the total crop production (Figure 52). The reason I don't observe a significant different in the crop production is that the majority of the crop production goes for human needs. Even I change trade and biofuel demand that does not make a considerable difference in the total demand. When I compare the model results of the crop production against the bio fuel energy demand target (Figure 53) the production is achieved until the 300%. This shows that there is still a large capacity available to increase bio fuel crop production in the Sao Francisco basin. So far only about 5% of the total energy demand is fulfilled by bio fuels. With the results I can argue that, if I ignore the technological development for bio fuel crop production, there is about a chance to increase the share from the bio fuel crop production up to 15% under current conditions.

Figure 52: Crop production (100rT + 300BF)

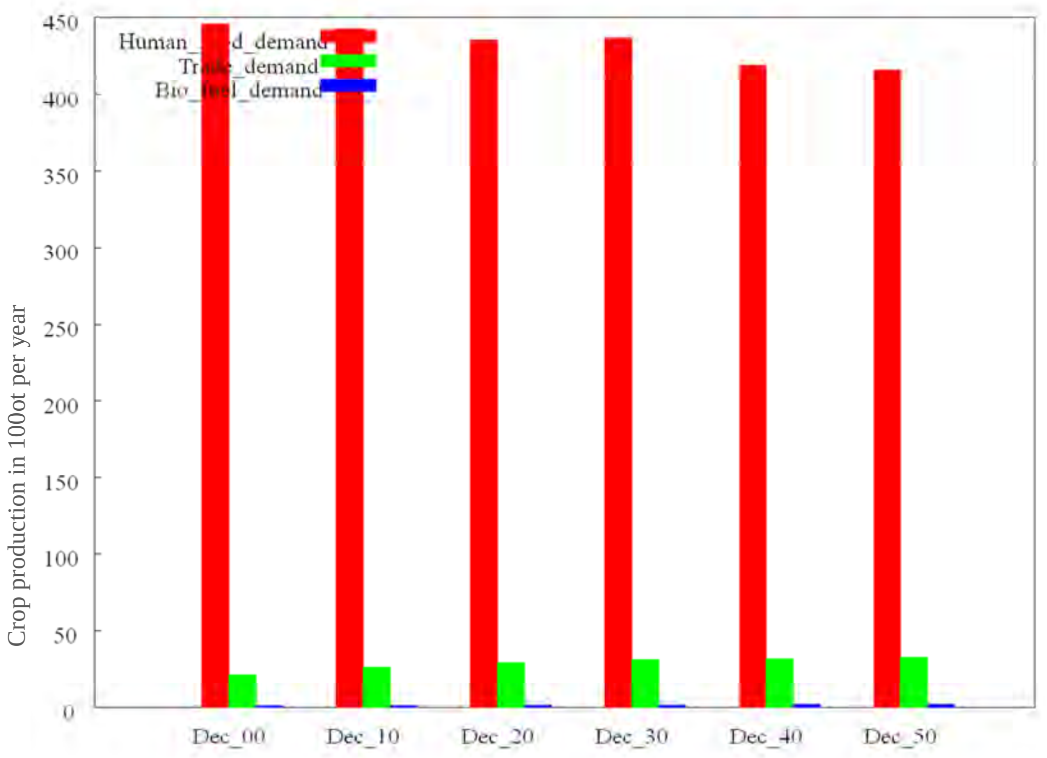
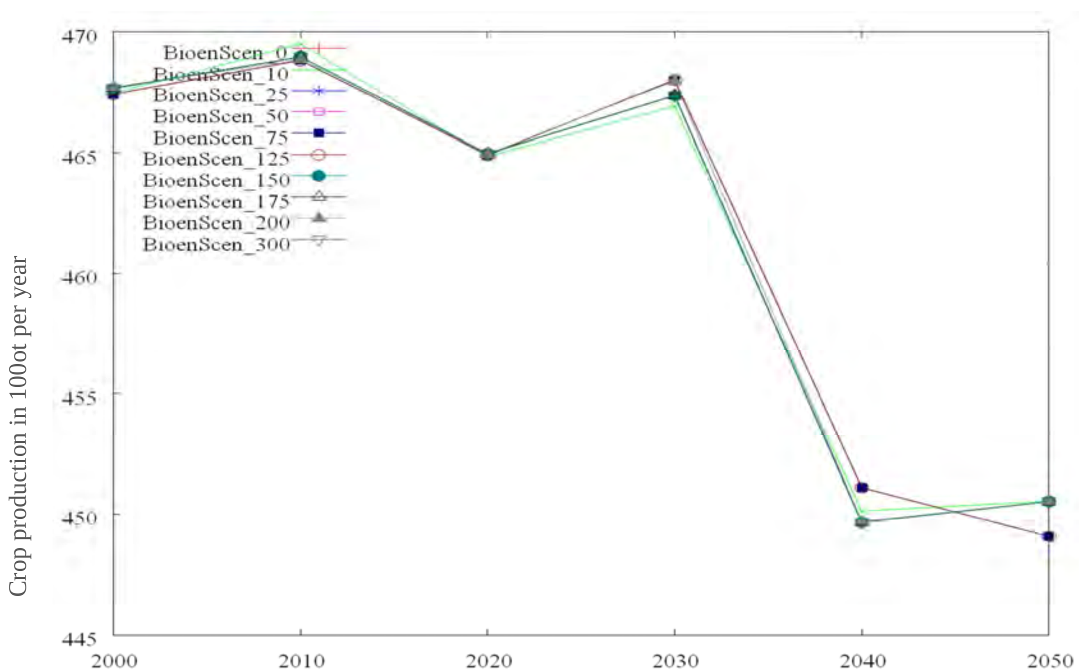


Figure 53: Crop production under changing bioenergy targets (100iT)



Water management

Figure 54 illustrates the number of water harvest and storage structures built when both bio fuel crop demand and foreign commodity demand are present. The number and the capacity of dams built under high bio fuel crop demand are higher since the water required for irrigation is higher. Comparatively, in low water demand scenario, the capacity and the number of structures are low since the demand is low. When considering the water release, the model results show that always a higher amount of water is demanded from the dams compared to the tanks. This gives an indication that when the bio fuel demand is increased the mass water storages are always preferred for crop production than scattered tanks throughout the watershed.

The quantity of demanded irrigation water slightly changes over time according to the demand. However, the demanded water quantity is moderately sensitive to the crop demand if it is used together with the water management, like the case I consider in this study. However, it is not sensitive to the increment of the bio fuel crop water demands only. Since a larger fraction of irrigation water requirement is always demanded by the bio fuel crop production.

Figure 54: Cumulative number of water management structure (10BF + 100iT)

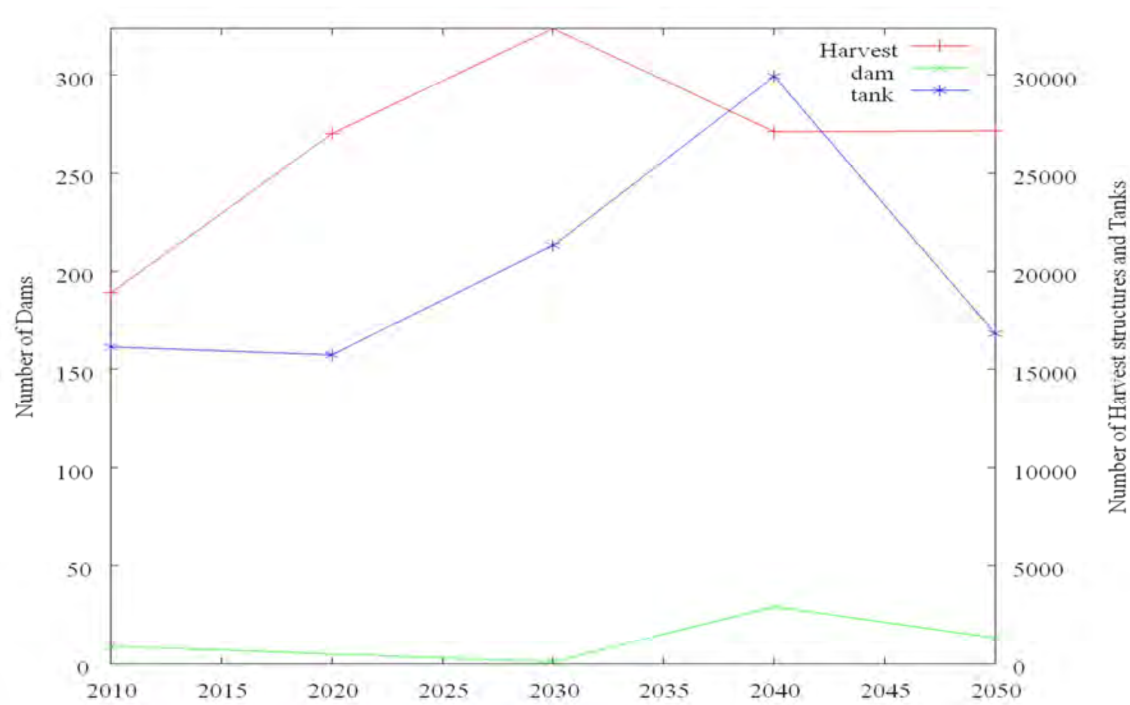
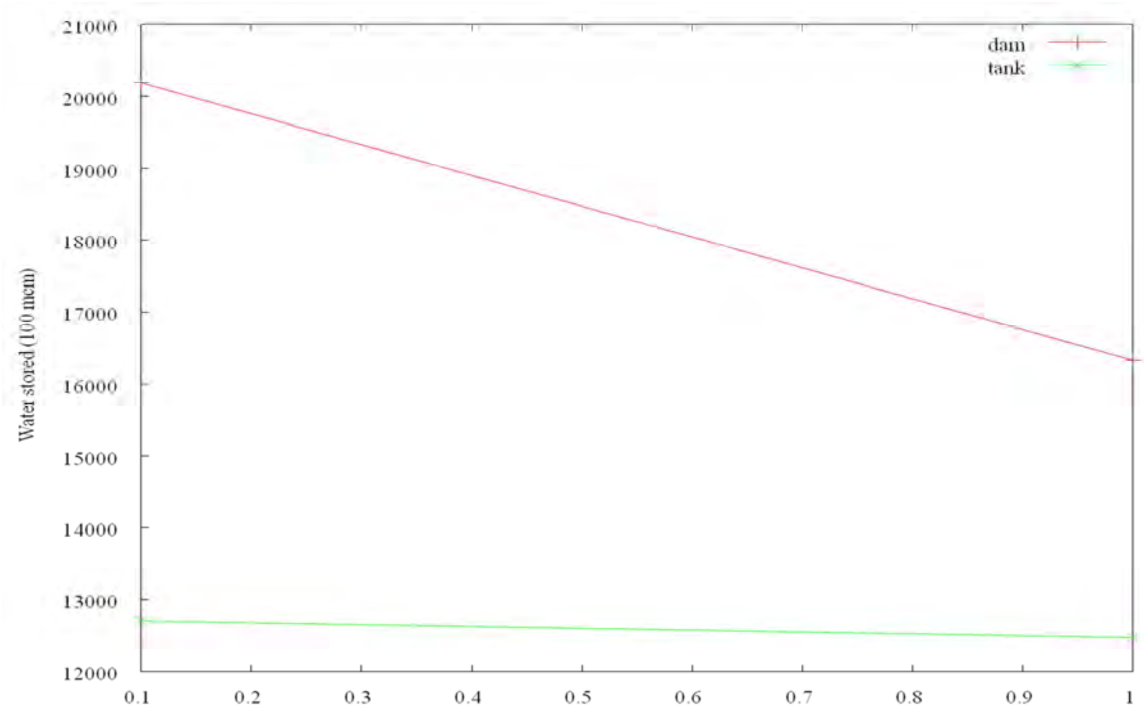


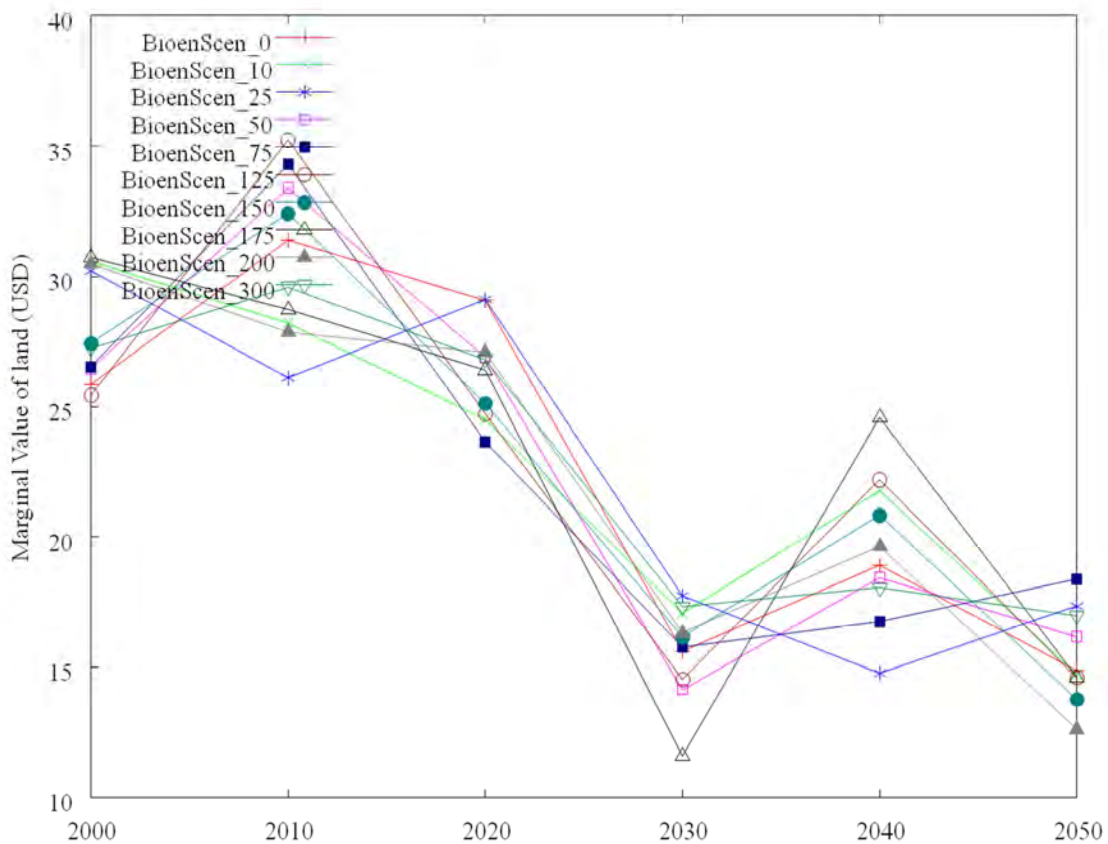
Figure 55: Water stored in water management structures (Decade 2020 + 100iT)



<u>Welfare change</u>

In the Sao Francisco region, the marginal value of land ranges between 25-30 USD when I increase the bio fuel energy demand target from the current level up until 300% (Figure 56). The marginal value of the land is associated with the water management. When the water management is always present, the marginal cost of land is lower when the irrigation water is easily available. In addition, the marginal value of the land decreases over time if it is used in crop production. Other interesting feature is that the marginal value of land is lower when the bioenergy target is increased. This is probably due to the fact that when the water management is installed; the crop production can be implemented without much of additional cost for crop production.

Figure 56: Marginal value of land (100idT)



According to my model results, the Figure 57 and Figure 58 show the change in cost and benefit of crop production respectively including the change in foreign commodity demand . The cost of crop production drastically increases after 30 years and the benefit is also decreased after 30 years. Among the installation cost for water management and water harvesting, dam installation cost is the highest cost per million cubic meter, which is around 250 USD. According to the assumption made in the base model, the reduction of live capacity is done mostly over 30 years. Therefore, after 30 years most of the damns become non-functional. Thus, a huge cost is incurred for water management structure installation. During the initial decade, the cost of crop production is higher compared to the other decades and the benefits comparatively decrease. This is also an indication of additional cost spending for water management structure installation.

Figure 57: The change in the total cost (100iT) compared to the cost in 0BF+0T scenario for year 2000

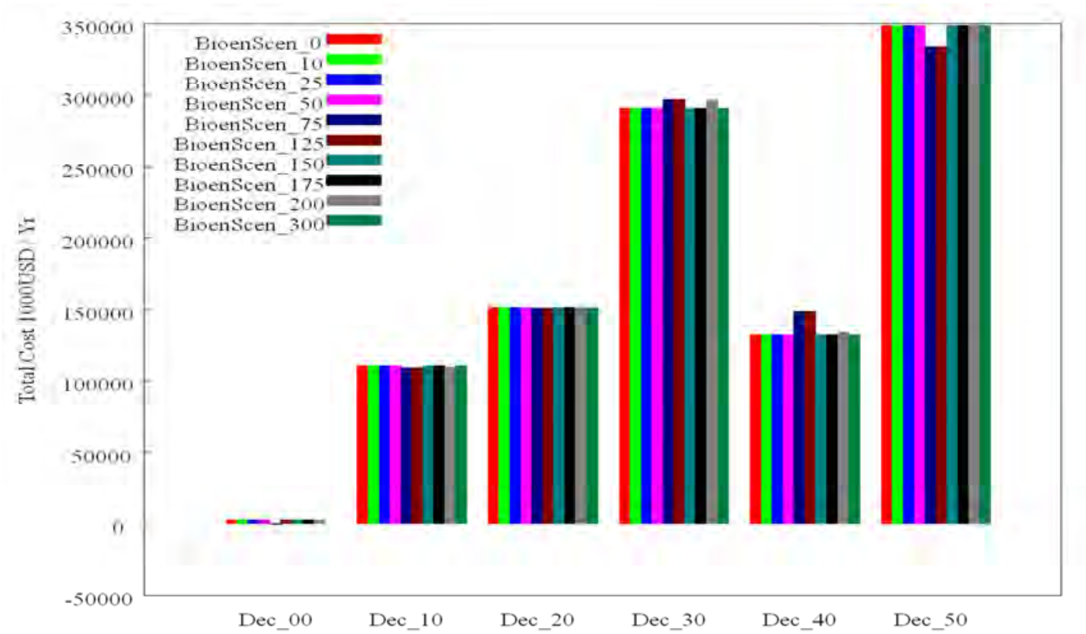
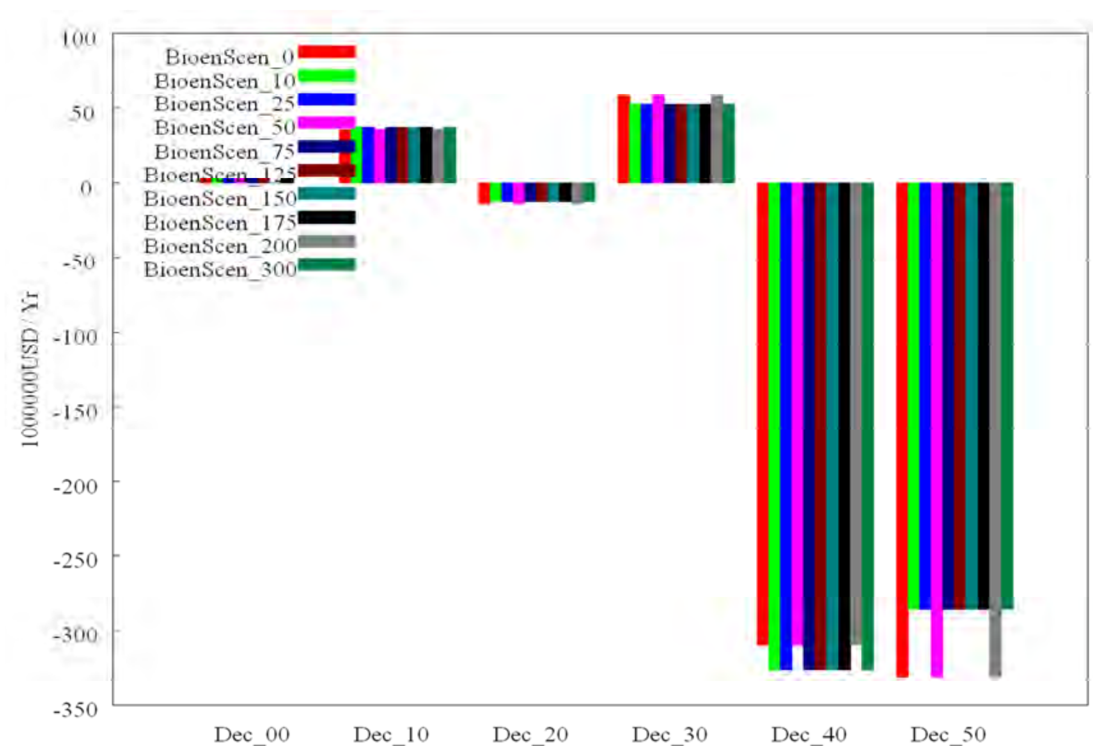


Figure 58: The change in the total benefit for 100iT scenario, compared to the cost in 0BF+0T scenario for year 2000



5 Conclusion

The results show that the land area occupied for cultivating considered crops is mainly under automatic irrigation and artificial fertilization. The increment of land area under irrigation is about 4% on average when I increase the biofuel energy up until 300% from the existing level. Due to the high turnout factor in bio fuel crops and the total demand quantity compared to human dietary energy demand, the impact on the total procedure by increasing biofuel crop demand up until 300% does not make a significant change for resource use. Increment in the biofuel demand encourages development of bulk water storages like dams over small scattered water storages like tanks in the Sao Francisco basin. There is still a large capacity available to increase bio fuel crop production in the Sao Francisco basin. So far only about 5% of the total energy demand is fulfilled by bio fuels.

In the Sao Francisco basin, the marginal value of land used for crop production ranges between 25-30 USD when I increase the bio fuel energy demand target from the current level up until 300%. The marginal value of land is lower when the bioenergy target is increased since the more the water management structure areas are installed; the crop production can be implemented without much of additional cost for crop production.

The cost of crop production drastically increases after 30 years and the benefit is also decreased after 30 years due to new constructions of dams and the increment of the share of high cost irrigation system installed cultivation lands.

With the results I can argue that if I ignore the technological development for bio fuel crop production, there is about a chance to increase the share from the bio fuel crop production up to 15% under current conditions. This proves the policy outlook for Brazil to increase the bio fuel energy demand until 25% by 2020 (Ramos and Wilhelm, 2005) can make it a reality in Sao Francisco region.

CHAPTER V

Agricultural water management under changing precipitation

1 Introduction

Throughout the history, the main sources of energy was fossil fuels (Azar et al., 2003; Demirbas, 2008). The current energy concept of our society is based on extensive use of fossil fuels, limited oil reserves, increase of oil prices and political instability creating in addition related problems climate change and environmental degradation (Baruch, 2008; Koh and Ghazoul, 2008; Stern, 2007). There are two renewable liquid transportation fuels that might replace gasoline and diesel fuel: ethanol and biodiesel. Ethanol is produced from sugar or starch crops, while biodiesel is produced from vegetable oils or animal fats (Demirbas, 2008). Many studies have been conducted to understand and project the consumption of bio fuels (for example: (Havlík et al., 2011; Schneider and McCarl, 2003). However, there are also pressing concerns, whether the production of bio-fuels can meet the projected consumption. The cultivation and production of energy feed stocks require substantial water input. Competing water uses at declining water resources raise the spectre of resource depletion and environmental degradation. Therefore, water management has become a key feature of existing projects and a potential issue in new ones.

This is especially evident when projected climate changes are taken into consideration. The assessment report 4 of the IPCC (Intergovernmental Panel on Climate Change) has reported on projections that the average global air temperature may increase until 2100 by 1.1 to 6.4 °C, relative to the baseline average for the period 1980-1999; precipitation may increase by 20% in some areas, but will decrease up to 20% in others (IPCC, 2007). According to the recently observed trends, it is expected that above average temperature rise will occur over land, causing systematic changes in rainfall patterns. The peak of the air temperature rise will occur in the area of high northern latitudes. The minor air temperature rise is expected to be in the area of Southern Ocean and northern North Atlantic. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (IPCC, 2007). It is argued that the main reach for the concurrent increase in surface temperature carbon dioxide and other greenhouse gas is the concentration increase during the past century. The climate change has multiple effects on the precipitation patterns, droughts and floods. In general, the larger and faster the changes in climate are, the more difficult it will be for human and natural systems to adapt (Stern, 2007). As the crop production is highly sensitive to the climate conditions, the societal sector that would be mostly affected by climate change will be agriculture.

By using a statistical approach, (Fink and Medved, 2011; Motha and Baier, 2005; Salinger, 2005) had concluded that precipitation changes are not significant for bio fuel crop production. Seasonal temperature is an important climatic factor that can have profound effects on the yield of crops and the changes in seasonal temperature affect grain yields, mainly through phenological development processes (Kalra et al., 2008). Land and water resources are critical resources and precipitation is the climatic parameter associated with bio-fuel production. In the future climate scenarios, precipitation varies in wide range. In order to meet the water demand, water flow can be manipulated using adaptation strategies, so that the water becomes available when it is needed. Given that many countries and regions in the world already experience pressure by changing rainfall patterns and land is needed for other socio-economic activities, converting existing cropland to or developing new land for bio-fuel production leads to many critical debates. Factors in this debate include the challenges to subsistence farmers, possible increases of carbon emissions and threat to ecosystem services.

Moreover, the above mentioned factors directly or indirectly are linked with land use and water use changes. Thus, bio-fuel production may aggravate water stress, which is already a growing worldwide issue. A fundamental uncertainty underlying the current understanding of these potential impacts is the water use change that will occur when bio-fuel production increases. Today's question is no longer whether renewable bio fuels will play a significant role in providing energy for transportation, but rather what are the implications of their use and how will it be reflected in the economy, environment, global security and health (Bernard and Prieur, 2007). Historically, bio fuels have been produced from grain-based crops with water supplied solely by rainfall or together with irrigation. Today, forest wood residues, agricultural residues, dedicated energy crops and other herbaceous biomass are being considered as feedstock for ethanol. Although forest wood generally does not require irrigation, the impact of large-scale production of energy crops (especially dedicated energy crops) on water resource availability has not been fully examined yet. However, the amount of water applied per acre has decreased from 25 inches in the 1970s to 20 inches today (Gollehon and Breneman, 2007). This decline in water use is credited to biotechnology, increased use of water-conserving irrigation practices, improved technical efficiency and high-energy costs.

The pressing question in this debate is whether or not the world has sufficient water to allocate it in bio fuel crop cultivation or could there be a potential to manage water as an adaptation strategy to changing climatic conditions that could be utilized without compromising the concerns described above. More specifically, what types of water resources can be used for sustainable bio fuel production, in which quantities the water is available, what are the origins of water resources to manage, destinations of water resources to manage and how to change the current utilization. Answers to above mentioned questions provide the basis for justifying the potential of bio fuel and evaluating the associated environmental and socio-economic impacts. The aim of this study is to use a numerical model based on data that can predict how the changing precipitation will affect yield of feedstock for bio fuel production and examine the use of adaptation measures for the growing issue of water use in energy production by characterizing current consumptive water use.

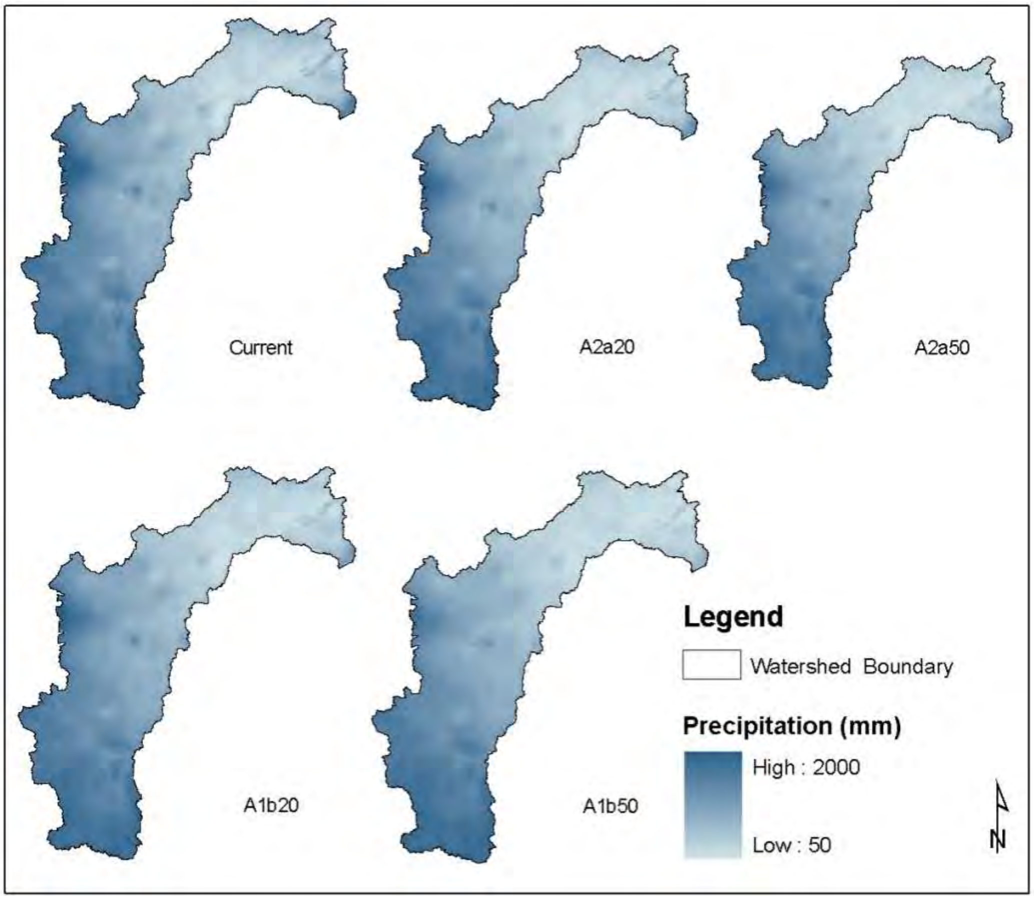
Fresh water is withdrawn from surface water to support agricultural operations or industrial processes or to be used as input to municipal water supplies. Factors like climate, population and the concentration and water intensity of the local economy affect the amount and sustainability of water withdrawals for a given locality and region. Here, only the water use by the agricultural sector is considered. Almost 60% of the world's fresh water withdrawals are used for irrigation.

The following sections are structured as follows. Section 2 provides a detailed description of the experimental setup and the methodology applied. The results obtained are presented in the section 3. Section 4 concludes the chapter

2 Current and Future precipitation scenarios on Sao Francisco

Precipitation in the Northeast of Brazil is influenced by several large-scale precipitation mechanisms: inter-tropical convergence zone, upper air cyclonic vortex and cold fronts (Roucou et al., 1996). The region is characterized by medium rainfall levels but high evaporation rates. From south to north, the precipitation is decreases and low rainfall is registered in the north-eastern region of the Sao Francisco watershed. In the semi-arid zones towards north, the rainfall is highly variable in space and time. Although it rains as much as in many other areas of the world, this semi-arid region is periodically affected by drought with partial or total loss in agriculture, which also affects water supply to the population. The high evaporative demand of this region produces evaporation rates that can surpass 10 mm day-1. The mean deviation of the rainfall from the climatological normal is higher than 30%. The climate on the coast of the region is hot and humid while in the semi-arid is hot and dry. The wet-season of the region is generally between January and June and the dry-season is generally between July and December. The rainy season is centred upon March, April and May. Statistically downscaled current climate data for the region shows the normal annual rainfall ranges from 1800 mm on the coast to less than 250 mm. When considering statistically downscaled data for the IPCC SRESS scenarios (IPCC, 2007), the precipitation pattern changes in magnitude, though there is no considerable change spatially. In the a1b scenario, the magnitude range changes from 200-1820 mm in 2020 to 70-1860 mm by 2050. In the a2a scenario, the magnitude range changes from 300-1900 mm in 2020 to 250-1950 mm by 2050. Thus, the average annual precipitation change in the climate projections varies between 5-16% compared to the current precipitation.

Figure 59: Average annual precipitation in the Sao Francisco basin in different SRESS scenarios



3 Virtual water (VW) and water footprint (WF)

In order to determine the impact of bio fuel production on water resources, I use two physical indicators: virtual water (VW) and water foot print (WF). With both indices, water content in a product or service can be estimated, but there are some important differences between them. A description on how I define and use these indicators is presented below, including their differences. The virtual water content of a product is defined as the volume of water used for its production (Allan, 1997). (Hoekstra, 2003; Hoekstra and Hung, 2003) developed the most common methodology used nowadays to evaluate this index. Virtual water is the water 'embodied' in a product, not in real sense, but in virtual sense. It refers to the water needed for the production of the product (Hoekstra, 2003). The concept of virtual water gains relevance when applied to trade between countries or regions, because imports and exports involve ''virtual water transfers''(Velázquez, 2007). As the endowment of water and the amount of water used vary according to the place of production, virtual water trade between countries can be a way to save water on a global scale (Chapagain and Hoekstra, 2003; Du Fraiture et al., 2004; Oki and Kanae, 2004), as well as a way to enhance the use of global water resources. A country with low water resources could preserve its domestic water resources by importing water-intensive products instead of producing them itself (Velazquez, 2006). (Chapagain and Hoekstra, 2008) investigated that water savings are produced from the physical point of view even though virtual water is not included as a criterion in import and export planning. A country's water endowment does not define its comparative advantage, because it does not represent all of the opportunity costs of production (Wichelns, 2004).

Here, I use the concept of virtual water content as defined by Hoekstra (2003) with a slight modification. According to Hoekstra (2003), the real water content of a product is the volume of water used to produce it at the place of production.

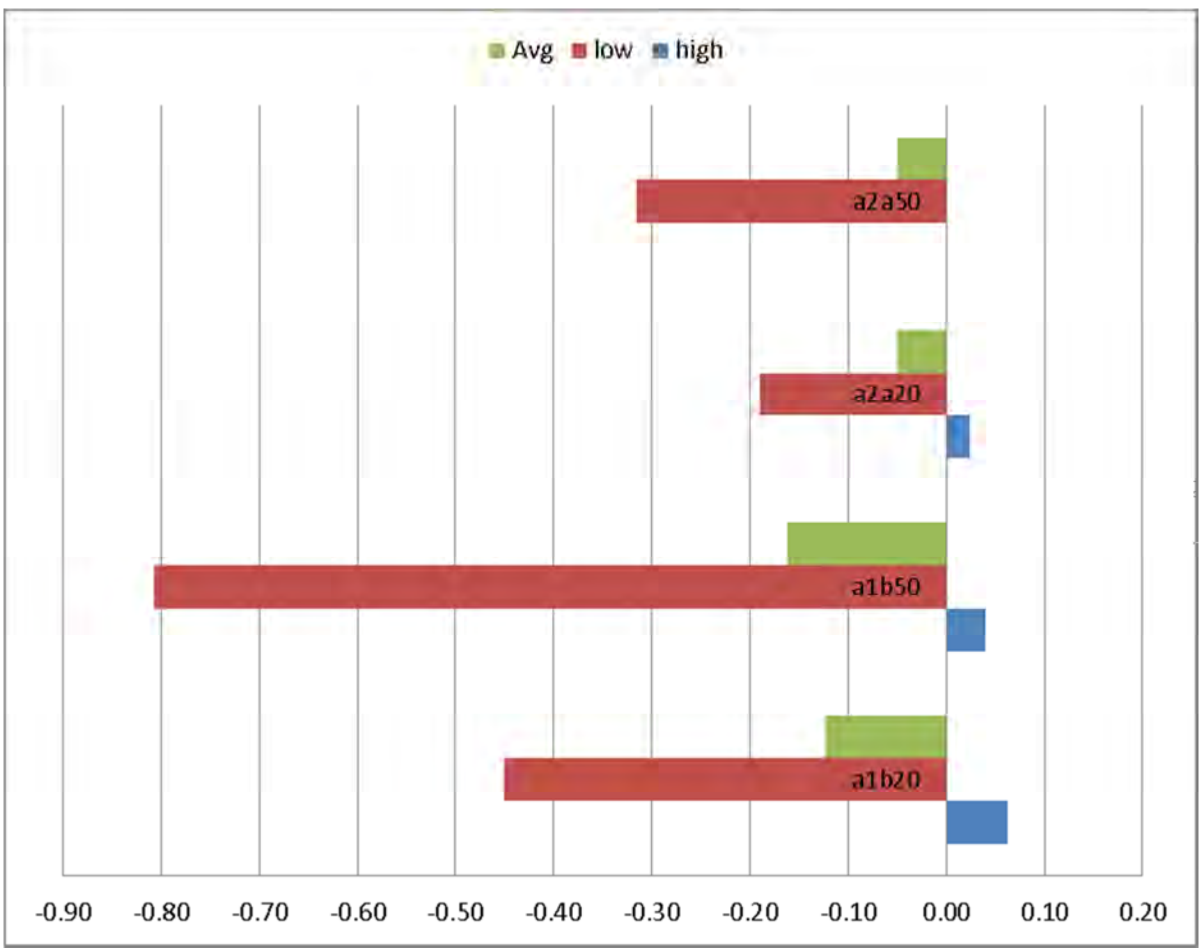
In my study, I use the "Real Virtual Water" concept as the amount of water that a region will have to use in irrigation, instead of importing it. Hoekstra and Hung (2003) used a procedure that takes into account the process of cultivating raw materials and the various industrial stages until the final product is obtained. However, I only consider the water used to obtain raw materials (i.e. agricultural products), excluding the study of the rest of the industrial and commercial steps. The virtual water content of an agricultural product (MCM/t) is estimated from the volume of water used during the crop's growth period (MTM/ha), called the crop water requirement (CWR) (Hoekstra and Chapagain, 2007). The CWR is satisfied by both blue and green water received by plants. It is important to differentiate between them because the use of green water in agriculture is related to more sustainable practices than the use of blue water (Aldaya et al., 2010). In order to understand the irrigation water availability and the change in the water use for crop production, I compare the 'Virtual Green Water content' (VGW).

4 Experimental Setup

The main research idea of the experiment is what amount of water can be made available by adapting water management for irrigation under changing precipitation. In order to study the idea, I decide to compare different precipitation scenarios. Figure 60shows the percentage change in different SRESS scenarios compared to the current precipitation. ‘High’ and ‘Low’ refer to the highest and lowest precipitation levels and ‘Avg’ refers to the average precipitation over the region and time for a specific scenario. The abbreviation indicated the following definitions.

A1b20: A1b scenario in 2020; A1b50: A1b scenario in 2050; A2a20: A2a scenario in 2020; A2b50: A2a scenario in 2050;

Figure 60: Percentage change of Average, Highest and lowest precipitation in different SRESS scenarios compared to the Current precipitation



Although there are drastic differences in precipitation for climate projection scenarios, the average value is always lower compared to the current and ranges between 10-15 %. In order to study the effect of reduced precipitation, I use 5%, 10%, and 15% reduced precipitation scenarios, compared to the current. Here, I use several simulation scenarios to quantify 1) the availability of water for irrigation, 2) resource use and 3) change on welfare measures. In the scenarios, I try to portray individual and combine effects that could cause by bio fuel crop production, the foreign commodity demand and changed precipitation. The simulation events are presented in the Table 15.

Following are the scenario abbreviations: T denotes the trade activities. Here, I consider four levels of trade activities that alter the demand function. No change in the current trade level for crops as 0T and increment of 50%, 100%, 200% from the current as 50iT, 100iT, 200iT, and reduction of 50% from the current trade as 50rT. Furthermore, I consider two levels of bio fuel demand that alter the demand function. One event does not consider the bio fuel demand (0BF) and the other is 100 (100BF), 300 (300BF) increment compared to the current level.

Table 16: Simulation events

Scenario	Scenario conditions	Description
Trade change	P levels : 0P ,10P, 15P BF levels : 0BF T levels : 50iT, 100iT, 200iT, 50rT	Only foreign commodity demand change together with precipitation
Bio-Fuel change	P levels : 0P, 10P, 15P BF levels : 0BF, 50BF, 150BF, 200BF T levels : 0T	Only bio fuel demand change together with precipitation
Combination	P levels : 10P, 15P BF levels : 50BF, 150BF, 200BF T levels : : 50iT, 100iT, 200iT, 50rT	Bio fuel and foreign commodity demand change with precipitation

5 Simulation Results and discussion

The main idea of the study is to investigate the effect of precipitation change on water availability for agriculture, industry and domestic purposes. Therefore, I have selected three extreme precipitation levels and four extreme biofuel production levels and defined scenarios for the experimental setup. The 15P, 10P scenario shows the reduced precipitation by 15%, 10% respectively compared to the current precipitation for the crop cultivation under no change in precipitation. Here, I consider that water management is implemented in all, since I conclude that the water management is more productive compared to a situation where water management is not implemented.

Crop production

The change in precipitation makes rather a significant impact on the irrigation water usage for crop production. Here, I compare the crop production when bio energy demand and foreign commodity demand are not changed, only foreign commodity demand is changed, and only the bio energy demand is changed. When there is no change in precipitation, the crop production slightly increased according to increased demand, which is 5% less than that of the total crop production. This can be reason out as; the major fraction of crop demand is occupied by the human food energy demand.

The crop production under changing precipitation and foreign commodity demand shows significant change in the crop production (Figure 61and Figure 62). A reduced precipitation of 15% can achieve increased bio fuel demand until 200BF. Reducing 15% of precipitation and increasing 200% of bio fuel crop demand reduce the crop production of about 2%. Therefore, if the precipitation is not changed, there is a large capacity to expand the trade and bio energy demand (Figure 62).

Resource use

I explain the resource use with the land use and water resource use. The results show that as the bio-fuel crop production increases the water demand for irrigation also drastically increases. In addition, the decreased precipitation level aggravates the demand for the quantity of total irrigation water. Increased trade also contributes to elevate the total water demand significantly (Figure 61)

Figure 61: Water stored under reduced precipitation (15rdpt +200rT+200BF)

Figure 62: Crop production under changing bio fuel scenarios (15rdpt + 2000T)

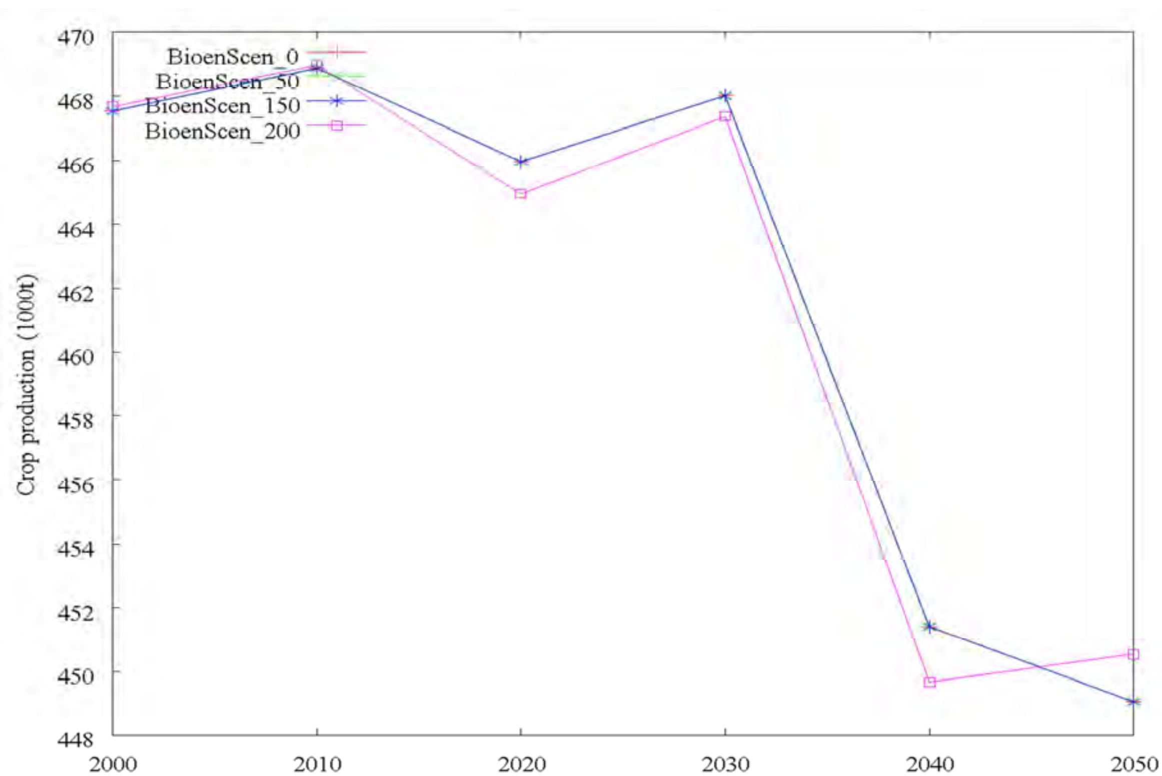


Figure 63: Change in cropping area in different irrigation systems under reduced precipitation (15rdpt +200rT+200BF)

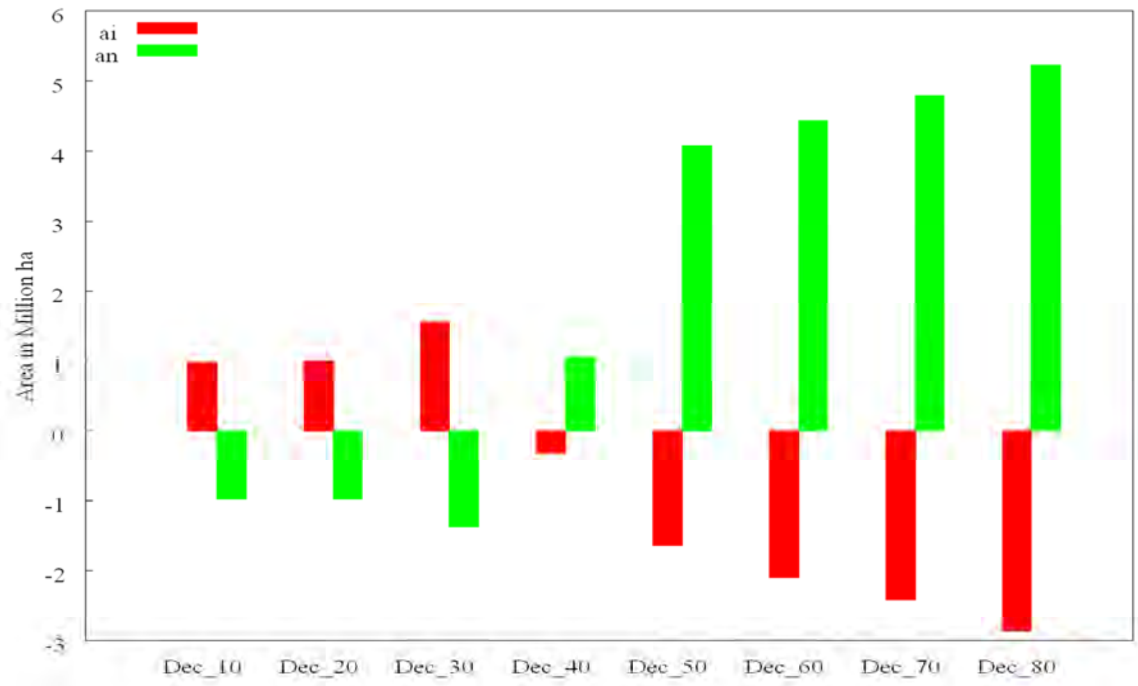
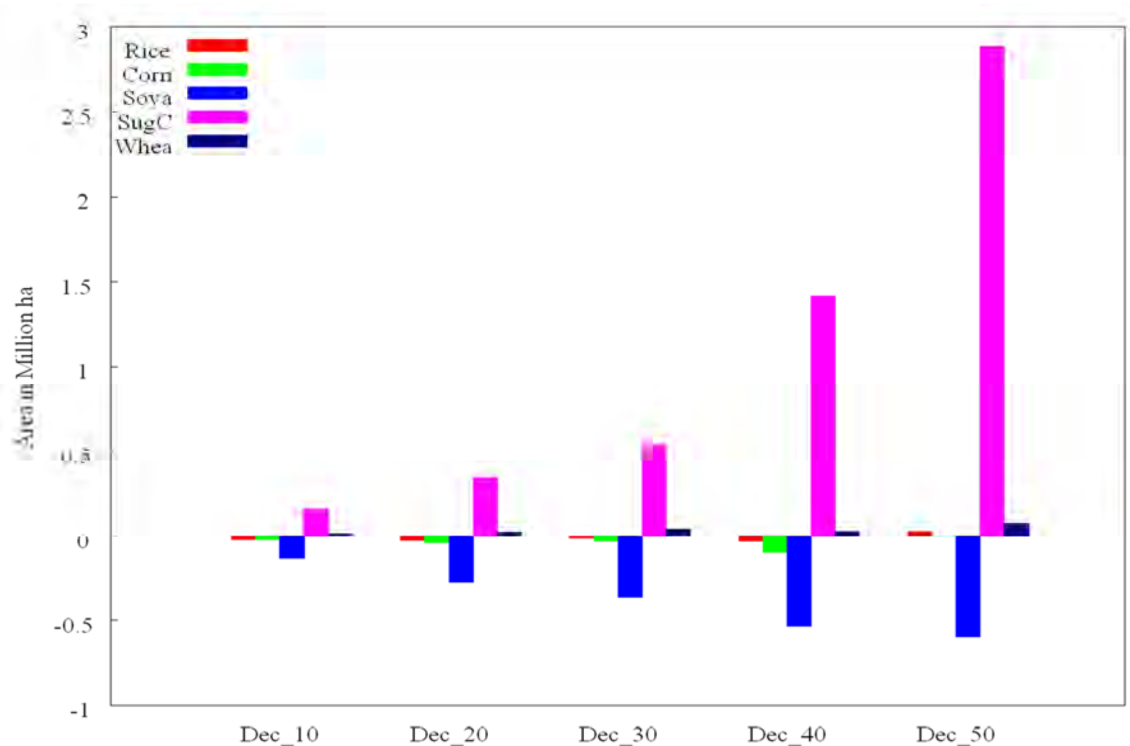


Figure 64: Change in cropping area in for crops under reduced precipitation (15rdpt +0T+200BF)



In addition, the water supply is mainly obtained from tanks than dams. There, I can notice that the majority of irrigation water is obtained from tanks when the precipitation is decreased. The quantity of water used over time against the bio fuel crop share to be fulfilled, slightly changes over time according to the demand. Here, I try to portray the demanded water quantity's sensitive to the bio fuel crop water demand. A larger fraction of irrigation water requirement is always demanded by the bio fuel crop production compared to other crops.

Figure 63 and Figure 64 compare the area under crop cultivation based on water management system and crop type. Accordingly, the automatic irrigation occupies about one fifths of less area compared to the artificial fertilization. Here also I can observe that there is no significant change in the area under cultivation.

Welfare

The comparison of marginal land price under changing bio fuel energy demand and foreign commodity demand levels, fluctuate between 28 USD – 30 USD per ha (

Figure 65). My model results show that when the precipitation is reduced, the marginal land price becomes lower on average compared to current precipitation levels. However, over the time, marginal price of land is decreased. When the demand for bio energy crop production is zero at the presence of reduced precipitation, the marginal cost of land is lower compared to the scenario with rather higher bio fuel demand under reduced rainfall.

The comparison of marginal land price under changing bio fuel energy demand and foreign commodity demand levels reduces over time. Comparatively the marginal cost of water is about 250 USD for dams while it is less than 50 USD for dam water (Figure 66.)

When the water management is done, the benefit gradually increases and the cost gradually decreases for next 30 years. From the cost of installing water management structures, the dam cost is the most prominent expenditure and many dams in the model actively utilized for 30 years. When the water management is needed to be replaced after 30 years, the benefits decrease and the cost increases dramatically. However, the benefits are comparatively low under reduced precipitation. However, under between 10-15 % reduction of precipitation enforces a dramatic reduction of welfare after about 30 years.

Figure 65: Marginal land price for reducing precipitation levels (50BF+50IT)

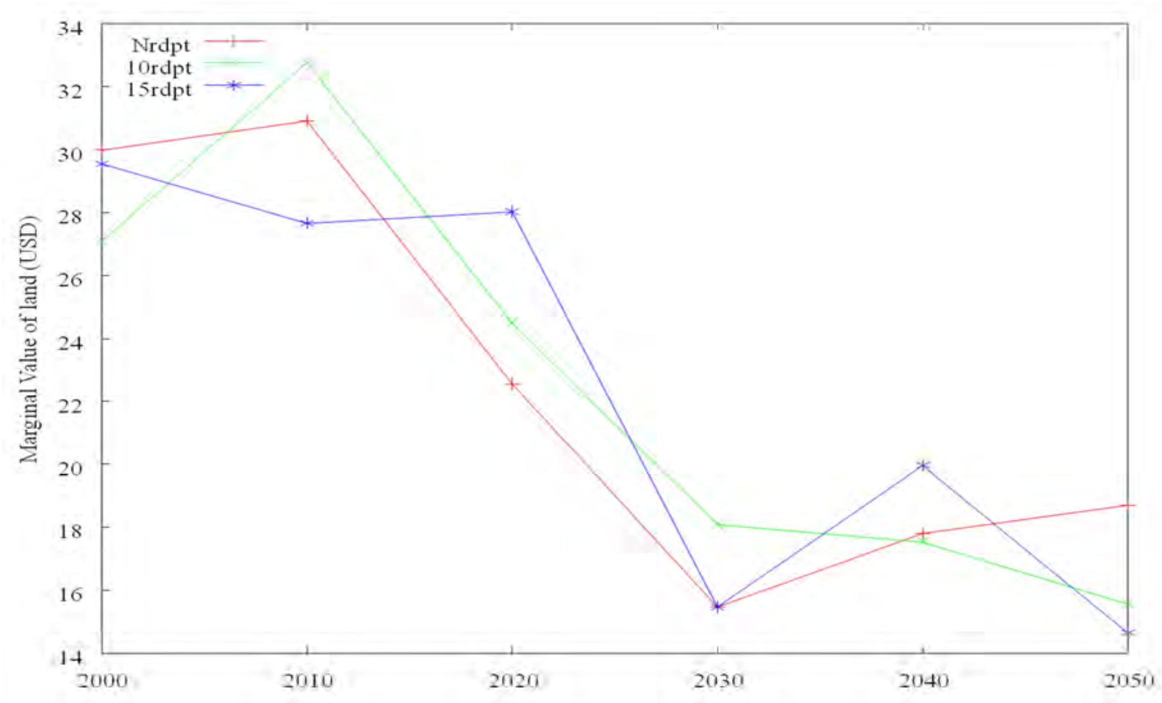


Figure 66: Marginal water price 3 (200BF+50IT+15P)

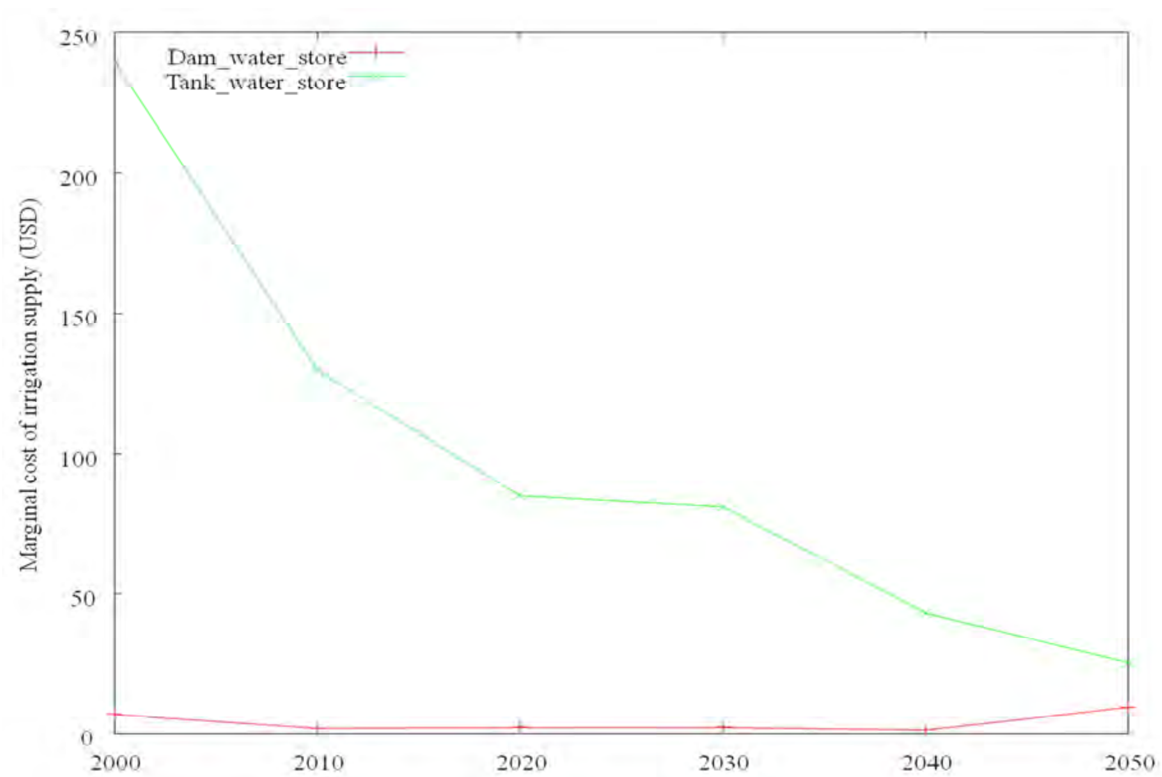


Figure 67: Benefit of crop production (200BF+100rT)

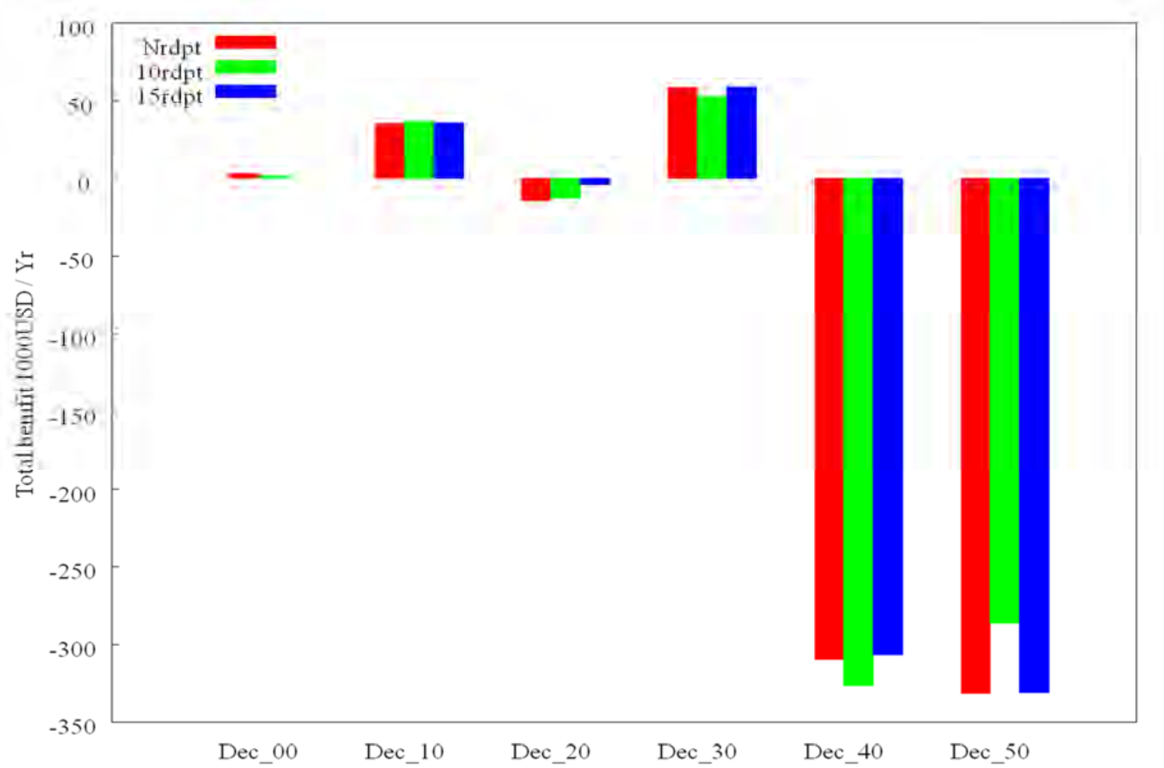
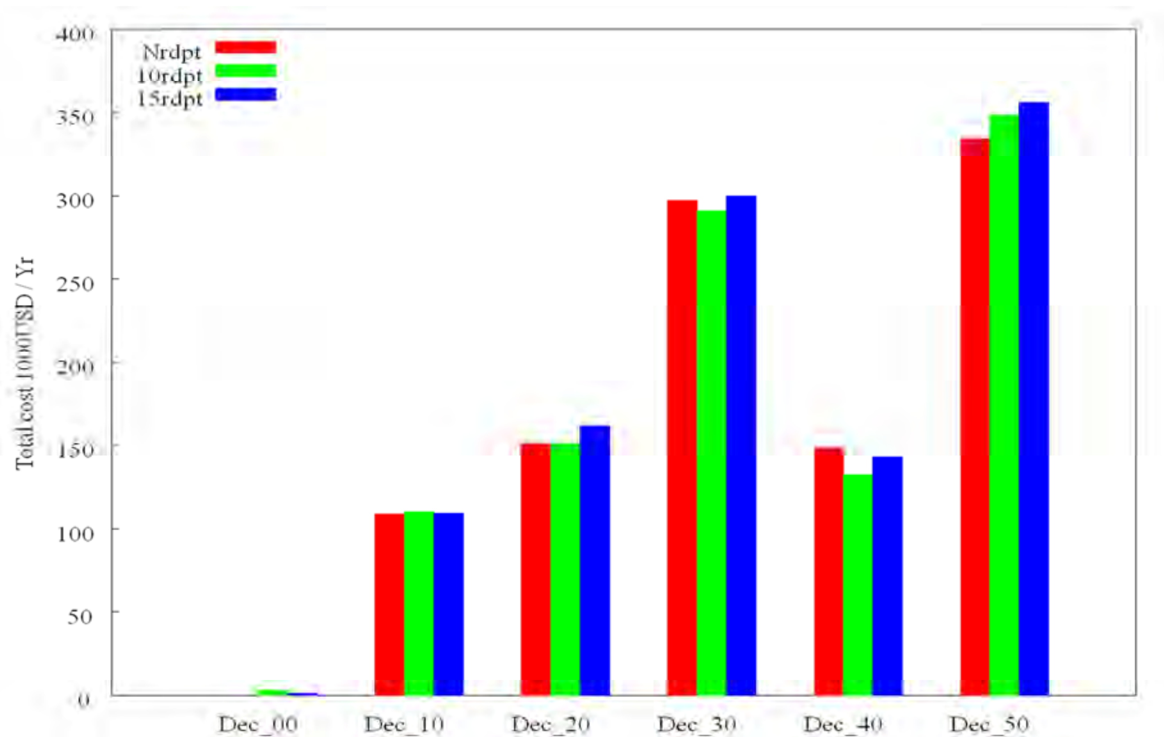


Figure 68: Welfare cost BioenScen_150 200idt



Water management infrastructure

My model results show that when the bio fuel demand and foreign commodity demand are increased, more construction of water management of structures is demanded (Figure 69). The results show that the number of dams is increased compared to the construction of tanks. One of the major causes for this is the cost of installation per unit of water is high in tanks compared to dams. Maximum of 20 dams have become operative at reduced precipitation of 15 %. The investment cost is comparatively low for water harvest structures, which is as low as 50-75 USD pre year, while for dams and tanks, it is high as 1million USD per year and for tanks 160000 USD.

Figure 69: Cumulative number of water management structures (15P + 150BF + 50rT)

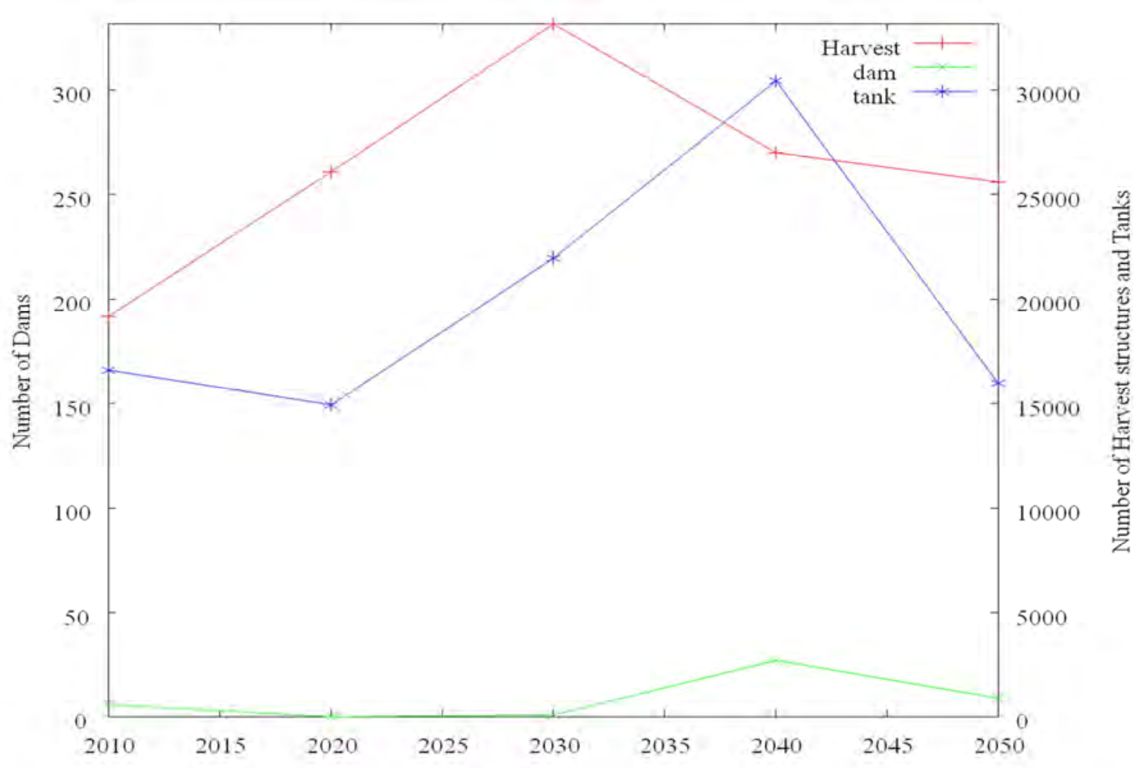
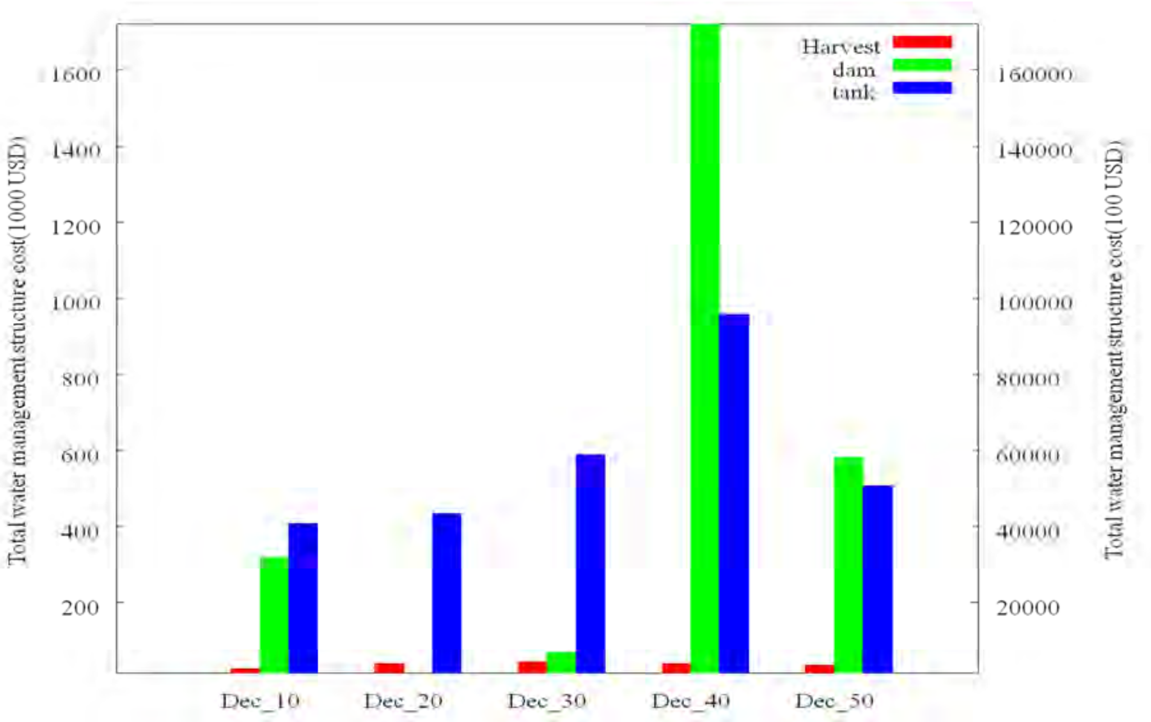


Figure 70: Installation and maintenance cost (15P+150BF+200iT), (Y axis on the left is for dams and right is for harvest structures)



6 Virtual green water content

In my model, I use 'Virtual Green Water content' (VGW) to represent the irrigation water availability and the change in the water use for crop production. This gives an idea of the use and the availability of VGW for crop production, industry and domestic water uses. I can summarize the results as follows.

Table 17: Virtual green water content availability

	0P	10P	15P	0BF	100BF	200BF
0T						
50iT	+	-	-	+	+	-
100iT	+	-	-	+		-
200iT	+	-	-	+	-	-
50rT				+	+	
	0BF	100BF	200BF			

7 Conclusions

My model simulation results show that the crop production is rather sensitive to the water availability, thus on the level of precipitation. The area of land, which is considered to be one of the resources used for the crop production is also dependent on the level of precipitation. Specially, the cost incurred for water management is sensitive to the water availability and increases significantly at the reduced water availability. In addition, the marginal cost of water is more sensitive to the change in precipitation, rather than the change in crop demand by bio fuel production and foreign commodity demand

CHAPTER VI

Summary Conclusions

The overall aim of this thesis was to investigate ways to facilitate and strengthen the application of an integrated water management concept within a watershed in the most beneficial way. The main factors considered throughout to maintain the sustainability of the water resource and manage the adverse effect due to global change.

In most cases, the water management is demanded in a watershed to deal with competitive water use, which means that the consumptive demand for water is higher than the sustainable recharge. On the other hand, water management is needed to adapt the excess quantity of precipitation that falls in a higher rate than it drains off from the river network.

With global change both of these adverse conditions are and will become more acute and widely speeded over many regions and are becoming a global issue in the future. The issue has come to a situation that it is becoming a major threat to the livelihood of people as well, sustainability of natural resources and sound maintenance of ecosystems.

Probable rainfall pattern changes and occurrence of intense droughts are included in predicted climate change scenarios and these deviations demand for new approaches of water resource planning. Existing irrigation systems are not capable of handling the water demand in the future. In addition, the cost for rearranging the water management systems would incur large investments. Together with the technological improvements assumed in the future, crop yields would increase per additional unit of water in both irrigated and rainfed systems. In contrast, the arable land per capita is decreasing apart from the soil degradation problem.

Crop production relies on two main types of water reserves. A secure supply of water and food, maintaining the sufficiency of water for food production, relies on the geographical and the climatic conditions as well as economic activities in a region. Traditional water management is often too slow to adapt to the required changes.

Water resources, management and systematic approach have a direct relationship, because all of these are essential components in an integrated water management plan. During the recent decades, the interest of integrating water-harvesting techniques in water management plans has increased. Many countries have shown the successful implementation of water harvesting techniques to increase the water availability either by directly improving soil moisture content or storing water to use during future stress periods.

These techniques include application of the traditional methods itself as well as enhancement by modern techniques. There are many possible integrated water management practices proposed in many studies. However, there are diverse approaches available according to interests, perceptions, investments, priorities and locations of the communities involved. Management of water resources in the optimal level is a function of the growth and development of every aspect in a watershed. Traditionally, storage has been achieved with dams and surface reservoirs. However, appropriate dam sites with long term usages are getting scarce and dams have a number of disadvantages like interfering with stream ecology, adverse environmental effects, displacement of people for new dam reserves, loss of scenic aspects and recreational uses of the river, high costs and potential for structural failure and reduced sustainability due to sediment deposition.

In integrated systematic approach, storage structure is not managed alone. Storage structures need to be well connected to the water supplies and demand sectors as well. The basic principle of a system's approach is connectivity. A system is a set of elements with connections between each other. Any system is composed of subsystems, each being autonomous and open, directly interrelated and integrated with its environment. The systematic approach is important to identify the correct components for an integrated system, to analyse and improve the system. Each of the components requires as input resource endowments and produces outputs at optimal level to satisfy the demand attaining a certain level of welfare.

Here, I proposed a systematic approach for integrated water management which starts from the runoff generation and extend until the demands for the crop production within a watershed are satisfied.

I developed the 'GWAMP' and 'ADAPT' models to address the above mentioned shortcomings of the analysis and study the impact on the land and water resources and regional agricultural welfare.

To sum up the insights gained from the studies in this thesis, I can recommend five main key elements to adapt water management to ensure sound supply of irrigational water.

- The application of GWAMP in the six case studies demonstrates its suitability to identify potential sites for rain water harvesting and storage. The results confirm that GWAMP is applicable in varying climatic, geographic, and socioeconomic conditions, even in ungauged basins. Furthermore, GWAMP can easily update suitability levels and weighted scores of decision factors on which the potential sites for rain water harvesting and storage are based.

- The analysis of the effect of precipitation on the average suitability score confirms that rainfall pattern change cannot have a major effect on the average suitability for either water harvest or storage structures. The analysis of the effect of land use change on average suitability confirms that land use change can have a major effect on the average suitability of land parcels for water harvest and storage.

- The application of the ADAPT model on the scenario analysis shows that the water management can have a substantial impact on the extended resource as well as the development of welfare levels in the region. Water management together with foreign commodity demand and bio fuel crop demand can have a combined effect compared to individual influence on the resource use and regional welfare.

- The water management is moderately sensitive to the bio fuel crop production. The cost of crop production is also increasing due to the initial establishment of water management structures. The water management is not only sensitive to the change in the share of bio fuel crop demand but also sensitive to the overall crop production.
- The simulation results show that the crop production is rather sensitive to the water availability, thus on the level of precipitation. The area of land, which is considered to be one of main the resources used for the crop production, is also dependent on the level of precipitation. Specially, the cost incurred with water management is sensitive to the water availability and increases significantly at the reduced water availability. In addition, the marginal cost of water is more sensitive to the change in precipitation rather than the change in crop production.

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