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Economic analysis of water use and management in the Middle Drâa valley in Morocco

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Claudia Heidecke

aus Münster

Referent:	Prof. Dr. Thomas Heckelei
Korreferent:	Prof. Dr. Karin Holm-Müller
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Abstract of the Dissertation

Economic analysis of water use and management in the Middle Drâa valley in Morocco

Claudia Heidecke

In arid and semi arid regions of the world irrigation is crucial for agricultural production as it stabilizes the water supply for crops and, hence, prevents extreme fluctuations in production and prices. In the Drâa river basin in southern Morocco agricultural production is highly dependent on irrigation as precipitation rates are not sufficient for crop water requirements. The objective of the thesis is to analyze the economic impact of water use on agriculture for the Middle Drâa river basin. The thesis develops an integrated approach for water management of the six Drâa oases and contributes to the discussion of the impact of climate change and water shortage on the income situation of the farmers in arid regions.

At first an introduction to the economics of water management and a methodological background for this study is given. This is followed in Chapter 2 by an analysis of water resources and water management. Water for irrigation is provided by two sources: surface water from releases of a reservoir and groundwater from shallow aquifers. Ground- and surface water use and their interactions constitute a complex system of conjunctive water use between the six oases.

Chapter 3 analyses agricultural production which is an important activity in the region. Survey data is used to understand farmer’s production structure and strategies under water scarcity which confirmed that water is the major production constraint.

The thesis proceeds along four papers in which a model is developed and applied for policy analysis. The model maximizes farm income over all oases under water resource constraints. In order to realistically represent the situation, the conjunctive use of surface and groundwater and their interactions are endogenously modeled.

In the first paper in Chapter 4 the model is applied in a recursive-dynamic evaluation to assess the impact of groundwater charges on agricultural water use. The paper concludes that groundwater pricing stabilizes water availability and groundwater tables over years.

The second paper in Chapter 5 builds upon Chapter 4 and compares surface and groundwater pricing and a combination of the two options. The relationships between water use and income are analyzed in detail. The chapter concludes that groundwater pricing is a favorable option as the stabilization function of groundwater can thus be internalized. Pricing only surface water would not meet the goal of resource conservation and would impose an extreme financial burden on the farmers.

In the third paper in Chapter 6 the model is further extended to incorporate water quality being an important constraint to crop yield formation. Sensitivity analysis is conducted to distinguish the effects of water deficit and salt rates in irrigation water.

The fourth paper in Chapter 7 addresses the impact of climate change on the income situation considering water quantity and water quality. Water inflow distributions are estimated based on historical data and climate change scenarios and are introduced into the model as a random variable to capture the stochastic nature of surface water availability. Monte Carlo technique is applied to obtain water use and farm income for current and for future climatic conditions. The stabilization value of groundwater is derived for all scenarios. It is found that the stabilization value decreases under increasing water scarcity as the share of groundwater use increases which raises the concentration of salt in irrigation water that reduces the economic value of groundwater.

In the end of the thesis the major findings are summarized and recommendations for future research of water management are given.

Keywords: Conjunctive water management, integrated hydro-economic modeling, Morocco, water economics, water use, water quality

Kurzfassung der Dissertation

Ökonomische Analyse der Wassernutzung und des Wassermanagements im Mittleren Drâa-Tal in Marokko

Claudia Heidecke

In ariden und semi-ariden Gebieten der Erde ist Bewässerung für die landwirtschaftliche Produktion entscheidend, um Wasserverfügbarkeit zu gewährleisten und Preise und Produktion zu stabilisieren. Im Drâa-Einzugsgebiet im südlichen Marokko ist die Landwirtschaft abhängig von der Bewässerung, da der Niederschlag den Bewässerungsbedarf der Pflanzen nicht decken kann. Ziel dieser Arbeit ist die Auswirkungen von Wassernutzung auf das landwirtschaftliche Einkommen im Mittleren Drâa-Tal zu analysieren. Die Dissertation entwickelt einen integrierten Ansatz für das Wassermanagement im Drâa-Tal und trägt zur Diskussion über die Auswirkungen von Klimawandel und Wasserknappheit auf landwirtschaftliche Einkommen in trockenen Regionen bei.

Zu Beginn der Arbeit wird ein Überblick über ökonomische Aspekte von Wassermanagement gegeben sowie die verwendete Methodik eingeordnet. Danach werden in Kapitel 2 Wasserressourcen und Wassermanagement untersucht. Kapitel 3 analysiert die landwirtschaftliche Produktion, die eine wichtige wirtschaftliche Aktivität in der Region darstellt. Die Ergebnisse einer Befragung werden ausgewertet, um das Produktionssystem und die Strategien der Landwirte unter Wasserknappheit zu verstehen.

Anschließend folgen vier Artikel, in denen das Modell entwickelt und zur Analyse von Politikoptionen angewendet wird. Das Modell maximiert landwirtschaftliches Einkommen der Oasen unter knappen Wasserressourcen. Die gemeinsame Nutzung von Oberflächenwasser und Grundwasser und ihren Interaktionen wird endogen abgebildet.

Im ersten Artikel in Kapitel 4 werden rekursiv-dynamische Berechnungen durchgeführt, um die Auswirkungen einer Grundwassersteuer auf die landwirtschaftliche Wassernutzung zu untersuchen. Die wichtigste Schlussfolgerung des Kapitels ist, dass eine Grundwassersteuer die Wasserverfügbarkeit und die Grundwasserstände stabilisiert.

Der Artikel in Kapitel 5 baut auf Kapitel 4 auf und vergleicht eine Grundwassersteuer mit einer Oberflächenwassersteuer und einer Kombination aus beiden. Aus den Ergebnissen wird deutlich, dass eine Grundwassersteuer die bevorzugte Variante für die Ressourcennutzung und das landwirtschaftliche Einkommen darstellt.

Im dritten Artikel in Kapitel 6 wird die gemeinsame Nutzung von Oberflächen- und Grundwasser um den Aspekt der Wasserqualität erweitert.

Sensitivitätsanalysen werden durchgeführt, um den Effekt der Wasserknappheit von dem Effekt der Salzkonzentration im Bewässerungswasser zu unterscheiden.

Im letzten Artikel in Kapitel 7 werden die Auswirkungen des Klimawandels auf das Einkommen der Landwirte unter Berücksichtigung von Wasserqualität und Wasserquantität untersucht. Die Verteilung der Stauseezuflüsse wird basierend auf historischen Daten und Niederschlagsdaten aus den Klimaszenarien geschätzt und anschließend als Zufallsvariable in das Modell integriert. Unter Verwendung von Monte Carlo Simulationen werden Wassernutzung, Einkommenseffekte und Stabilisierungswerte von Grundwasser für derzeitige und zukünftige Situationen diskutiert.

Am Ende werden die wichtigsten Erkenntnisse der Arbeit zusammengefasst und Empfehlungen für weitere Forschungsmöglichkeiten gegeben.

Stichwörter: Wassermanagement, integrierte hydro-ökonomische Modellierung, Marokko, Wasserökonomik, Wassernutzung, Wasserqualität

Résumé de la thèse de doctorat
Analyse économique de l’utilisation et de la gestion de l’eau dans la vallée du Drâa Moyen au Maroc

Claudia Heidecke

Dans les régions arides et semi-arides l’irrigation des cultures est essentielle pour la production agricole, pour stabiliser la disponibilité de l’eau et par conséquence pour stabiliser les prix et la production. Dans le basin versants du Drâa au sud du Maroc la production agricole est dépendante de l’irrigation parce que le taux de précipitations n’est pas suffisant pour les besoins en eau des cultures. Le but de cette étude est d’analyser l’impact économique de la disponibilité de l’eau et des changements climatiques pour la vallée du Drâa Moyen. Au cours de cette étude, un outil d’évaluation intégré pour la gestion de l’eau dans la vallée du Drâa a été développé. Les stratégies analysées dans cette thèse apportent leurs contributions à la discussion sur l’impact des changements climatiques et des pénuries d’eau sur les revenus des agriculteurs dans les régions arides.

En début de thèse, une introduction sur les aspects économiques de la gestion de l’eau est présentée aussi qu’un classement de la méthodique utilisé. Ensuite dans le Chapitre 2 les ressources en eau et la gestion de l’eau sont analysées. L’irrigation est assurée par deux sources principales: l’eau de surface provenant des lâchers de barrage et l’eau souterraine des nappes phréatiques. Ensuite la gestion de l’eau au niveau nationale et locale est comparée.

Le Chapitre 3 étudie la production agricole, une activité importante dans la région. Les données de l’enquête permettent d’analyser les pratiques culturales des agriculteurs et les stratégies utilisées en cas de pénurie d’eau. L’enquête confirme que l’eau est la principale contrainte pour la production agricole dans la région.

Ensuite, quatre articles individuels succèdent dans lesquels le modèle est développé et appliqué pour les analyses politiques. Le modèle maximise les revenus agricoles pour tous les oasis en considérant les contraintes principales : l’eau et la surface agricole. Dans le but de donner une image réaliste de la situation, les interactions entre l’eau de surface et l’eau souterraine sont modélisées endogène.

Dans le premier article (Chapitre 4), les simulations récursive-dynamique sont utilisées pour analyser l’effet d’une charge de l’eau souterraine sur l’utilisation de l’eau d’irrigation. La conclusion le plus importante est que la tarification de l’eau souterraine peut stabiliser la disponibilité de l’eau et le niveau de la nappe phréatique.

L’article dans le Chapitre 5 compare un charge de l’eau souterraine avec un charge de l’eau de surface et une combinaison des deux. Les relations entre la disponibilité de l’eau et les revenus agricoles sont analysées en détail. L’article conclut que la tarification de l’eau souterraine est un meilleur choix par rapport à un système de tarification mutuelle de l’eau de surface et de l’eau souterraine. Non seulement la tarification de l’eau de surface n’atteindrait pas le but de conservation des ressources mais aussi imposerait des charges financières plus lourdes aux agriculteurs.

Dans le troisième article (Chapitre 6), l’approche conjonctive est approfondie pour prendre en compte les aspects liés à la qualité de l’eau comme une contrainte importante sur le rendement des cultures. Les analyses de sensibilité sont appliquées pour distinguer l’effet de la pénurie d’eau avec l’effet de la qualité de l’eau.

Dans le denier article en Chapitre 7, l’impact des changements climatiques sur les revenus a été évalué avec une simulation aléatoire des afflux d’eau. Cela était nécessaire en vue de capturer la nature aléatoire de la disponibilité des eaux de surface. La distribution des afflux d’eau est estimée à la base de donnés historique aussi que pour les donnés des changements climatiques. Avec les simulations Monte Carlo les impacts sur les revenus agricoles ainsi que la disponibilité de l’eau sont analysées pour la présente et le futur. La valeur de stabilisation de l’eau souterraine est dérivée pour chaque scénario.

À la fin de la thèse les premiers éléments sont résumés et des recommandations pour la recherche dans le futur sont données.

Mots clés : Gestion de l’eau conjonctive, model hydro-économique intégré, Maroc, utilisation de l’eau, qualité de l’eau

Abbreviations

cbm	Cubic meter
CIA	Code d’investissement agricole
DH	Moroccan Dirham
DRPE	Direction de la recherche et de la planification de l’eau
GW	Groundwater
GWC	Groundwater charge
ha	Hectare
IMPETUS	Integratives Management Projekt für einen effizienten und tragfähigen Umgang mit Süßwasser in West Afrika
kg	Kilogram
MDH	Million Moroccan Dirham
MIVAD	Modèle intègre de la vallée du Drâa
Mm^3	Million cubic meter
N	Number of observations
ONEP	Office National de l’Eau Potable
ORMVAO	Office Régionale de Mise en Valeur Agricole
PAGER	Programme d’Approvisionnement Groupé en Eau Potable des Populations Rurales
SW	Surface water
SWC	Surface water charge
TWC	Total water charge

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1 General Introduction

1.1 Research objective

Water is one of the most essential resources of the world. Its various uses for food production, domestic water use and the use in industry and services makes water a precious and valuable resource that is a necessity for human beings and crucial for the economic development of a country. However, water availability is facing serious risks and challenges. The growing world population and rising living standards lead to an increasing demand for water in all areas, for food production or for the growing needs of households and industry, while at the same time per capita supply is being reduced (Rosegrant et al. 2002).

During the last century water use increased at a higher rate than population growth. By 2025, it is estimated that 1.8 billion people will be living in areas of absolute water scarcity and another two-thirds of the population might be living under water stress conditions (FAO 2007). Moreover, estimates suggest that "climate change will account for twenty percent of the increase in global water scarcity" (UNESCO 2003: 10).

Agriculture is by far the largest consumer of water with around seventy percent of the total water use in the world. In Northern Africa agriculture is responsible for 86 percent of the total water withdrawals (FAO 2005). Particularly in arid regions irrigation is essential for local food security. It stabilizes the water supply for crops and, hence, prevents extreme fluctuations in production and prices. Water withdrawal for irrigation is expected to grow by about 14 percent in developing countries until 2030. Although some countries use large quantities of water for crop production, irrigation still takes up a relatively small share of the total water resources of the world. Some regions, however, already have to cope with severe water scarcity, in particular the Middle East, North Africa, and large parts of Asia (FAO 2003).

In the arid Drâa basin in southern Morocco irrigation is crucial for agricultural production which is the major economic activity. Farmers may use surface water for irrigation, which is provided in monthly releases from a central reservoir, or they may extract groundwater from shallow aquifers beneath the oases. Since the introduction of motor pumps, groundwater has been increasingly used to stabilize the variable and uncertain surface water supply. As a result, groundwater tables have fallen while salt concentrations of groundwater have increased due to overexploitation. Water pricing as a tool to prevent unsustainable extraction of water has been implemented in other basins in Morocco but has not been practiced in the Drâa valley so far.

The aim of this dissertation is to analyze the interactions of groundwater and surface water use and their impact on agricultural production and income in the Drâa river basin. Furthermore, the impact of climate change on agriculture and water use shall be quantified using numerical modeling approaches. Scenario analysis is conducted to investigate future development and management options for a sustainable water use in the Drâa valley.

1.2 Methodological background

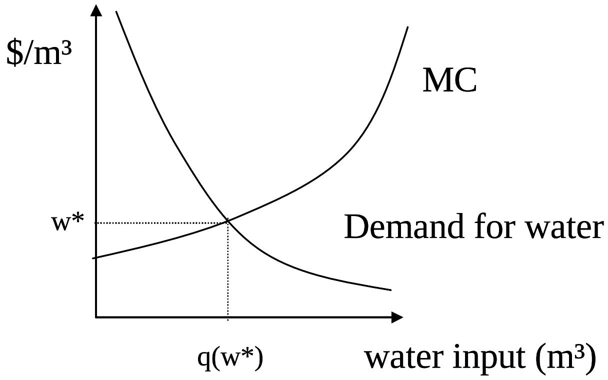
In this thesis a hydro-economic model is developed and applied for the Middle Drâa valley. Hydro-economic modeling approaches have been developed to holistically assess water management on larger scales. The use of such modeling approaches is based on economic theory and economic assumptions of water resource use. The methodological background of this thesis shall thus be approached in this section by first giving a brief overview about the theoretical considerations of water economics. This is followed by a summary of conjunctive water use studies that have increased the focus of the economics of ground- and surface water use since the 1960's. Finally, hydro-economic modeling approaches are described that have been developed in the last decades to address more complex water management questions on the river basin scale.

Economic analysis of water use

For economic analysis the specific characteristics of water provide a methodological challenge. In liquid state, water is a movable resource and tends to flow within the hydrological cycle. This makes it difficult to assign exclusive property rights to specific water resources, leading to substantial externalities of use and common property problems among user groups. Overexploitation and water pollution often cannot be traced back to a specific user which leads to substantial deviations between private and social costs of water use. These externalities have been proven difficult to internalize through management schemes and policies. Moreover, particularly in semi-arid environments, water supply is highly volatile in quantity and quality both within and between years, thus burdening production plans of farmers with high levels of uncertainty. Groundwater resources are even more complex to assess than surface water resources as it is difficult to measure potential groundwater quantities, yields, and the locations and dimensions of aquifers, making the monitoring of the groundwater resources costly (Young 2005). Groundwater resources have a unique value for irrigation because they contribute to a more stable water supply and thus reduce the risk for agricultural production in water scarce areas. It is therefore necessary to account for both, groundwater and surface water, and their specific economic values in an economic assessment of the conjunctive use[1] of water.

Theoretically, if water is traded within a market system, the value of water could be determined along economic principles. The interactions of supply and demand determine water use and water price when the market is in equilibrium. In Figure 1-1, the intersection at q^* and w^* represents water use and price where the water demand curve intersects the marginal cost (MC) curve of water supply. In this point, water use and price is optimal from the perspective of the representative water supplier and consumer, respectively, i.e. there are no excess supplies or demands.

Figure 1-1: Water supply and water demand



Source: Own presentation

In Figure 1-1 water is regarded as one input, and no distinction is made between groundwater and surface water supply. In so-called conjunctive water resource systems farmers may choose between surface and groundwater on the basis of quality and availability considerations. Water sources in such a case might be both more or less perfect substitutes, but may also reveal complementary characteristics, for instance when a water resource delivering water of low quality might be useful for irrigation only if it is mixed with water of higher quality from another source.

As far as the quality of water affects soil quality and crop yields, water from different sources and quality should be considered as different inputs. To give an example, surface water availability can influence the demand function of

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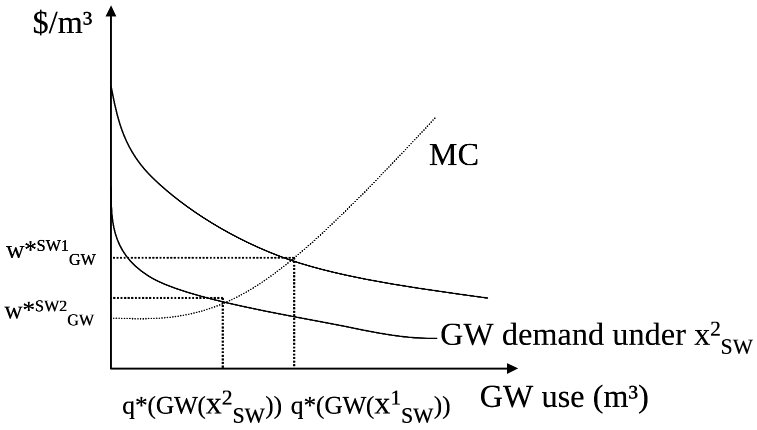
[1] The term 'conjunctive water use' signifies that "groundwater and surface water sources are two components of one system and should be managed as such." Gemma and Tsur (2007: 540)

groundwater. Consider two water resources, groundwater (*GW*) and surface water (*SW*) and let them have different qualities and a maximum annual availability limit of x_h where $h = SW, GW$. If the maximum annual availability level of SW is held constant, denoted by x_{SW}, the derived demand for *GW* can be calculated. The GW demand is thus dependent on the water availability provided by SW. Thus, if SW availability is held constant at two different levels x^1_{SW} and x^2_{SW}, assuming that $x^1_{SW} < x^2_{SW}$, two different demand curves can be derived for *GW* (see Figure 1-2). Under these considerations the w^* depicts the optimal price, dependent on x_h , and q^* the optimal water use, depending on the price w and x_h, assuming that marginal costs *MC* of supplying *GW* do not change. For an analytical derivation of the optimal price and water use, see Tsur et al. (2004).

Figure 1-2: Demand for groundwater under two different surface water availability levels



Source: Own presentation based on Tsur et al. 2004

The considerations in Figure 1-2 change the representation of water as one single input factor for production and highlight the complexity of an economic assessment of water management if conjunctive use of water and water quality aspects are considered. One can imagine also accounting for different water supply costs for different water resources and accounting for the social costs of water use that arouse typically through the overexploitation or the pollution of a resource. These specific considerations have been summarized by Spulber and Sabbaghi (1998) and shall not be further displayed here.

Literature review of conjunctive water use

In the following a selection of research is presented that has investigated the conjunctive use of water from an economic perspective. Particular attention is directed to groundwater management and the conjunctive use of groundwater and surface water. This set of research approaches are more theoretically founded and address simple approaches with single crops or single water withdrawals. In contrast, more complex modeling approaches have been developed during the last decades that apply mathematical programming techniques to investigate hydrological aspects from in economic point of view in entire river basins. An overview about such hydro-economic modeling approaches thus follows.

Burt (1964, 1966, and 1967) was one of the first to investigate groundwater management issues by means of an economic analysis. He addressed the temporal allocation of groundwater resources with the help of sequential decision theory by maximizing discounted net benefits over time to derive the optimal extraction rate for each year. With his work he provides a general framework that was later expanded upon by other authors. One example is the work by Anderson et al. (1983) who use a model for renewable aquifer stocks to discuss the development of groundwater over space and time for a basin in California and to discuss a privatization option for managing groundwater resources in this basin.

Tsur (1990) and Provencher (1995) focus on the specific stock nature of groundwater which is used when surface water is scarce. Tsur (1990) discusses the buffer role of groundwater in a static modeling approach. He distinguishes between two values of groundwater, the first to increase the overall mean of water supply and the second, to mitigate fluctuations in surface water availability. He shows that the value of groundwater increases the more uncertain surface water supply is. Tsur and Graham-Tomasi (1991) apply the approach by Tsur (1990) and conclude that the high value of groundwater is especially due to the buffer characteristics of groundwater in comparison to surface water. The value of groundwater has been calculated by Gemma and Tsur (2007) for a water district in India. Knapp and Olson (1995) discuss artificial recharge of aquifers in a conjunctive use setting and compare optimal and common property withdrawals of water. Provencher and Burt (1994) use a stochastic setting for conjunctive water management in which they integrate a random variable for surface water supply into a model of interrelated aquifers. They compare Monte Carlo simulations and Taylor series for the approximation of optimal groundwater pumping policies and conclude that the results of both methods are quite similar. Smith and Roumasset (2000) develop a model for conjunctive management which is flexible to time and space and hence are able to incorporate multiple demand sites and water transfer between them.

In the above studies of conjunctive water management, groundwater and surface water differ with regard to quantity, time, and certainty of availability, which leads to the buffer or storage function of groundwater. Besides the temporal difference in availability, the two resources are regarded as perfect substitutes. Water quality aspects have rarely been analyzed economically in conjunctive use settings. Roseta-Palma (2006) applies a conjunctive water use model with water quality aspects. She compares two water resources of different quality where the overall water quality used for irrigation is the weighted average of the two resources. She sets up a static approach to extend the work by Tsur (1990) by water quality aspects. The main conclusion is that the buffer value depends on the relationship of quality between the two resources. From her work it can be seen that the consideration of water quality in conjunctive water management leads to a more realistic analysis of the value of water in comparison to approaches where water quality is not considered but where it is a relevant problem in the setting being analyzed.

Hydro-economic models

The holistic analysis of water management strategies on the river basin level needs even more complex approaches than the studies mentioned above because hydrological characteristics need to be considered parallel to water demand of different users. Therefore, more complex programming approaches have emerged during the last two decades. An overview of hydro-economic modeling approaches can be found by McKinney et al. (1999) and Brower and Hofkes (2008). In principle, hydro-economic models can be differentiated into compartment modeling approaches or holistic modeling approaches. The compartment modeling approaches are characterized by exogenous modules where hydrological and economic models are run separately but are connected via data exchange. The holistic modeling approaches, in contrast, incorporate hydrologic and economic modules in one endogenous model where water demand and water supply are solved simultaneously.

The integrated river basin model used in this study to evaluate conjunctive water management is a holistic modeling approach. Examples of integrated holistic hydro-economic river basin models can be found by Cai (1999), by Ringler (2002) or by Rosegrant et al. (2000). Cai (1999) developed a prototype for a holistic hydro-economic river basin model and applied it to a basin in Central Asia. The principle achievement of his work is the incorporation of many agronomic, economic, and hydrologic features and processes into one modeling approach allowing their simultaneous simulation. He proposes also a dynamic version of the model for the optimization over several years to analyze water management options. The model includes water demand and supply, groundwater and surface water resources as well as water quality aspects. It is driven by an economic optimization problem but is constrained by major hydrologic balances.

This prototype model has since served as the basis for other applications such as an integrated hydro-agronomic-economic model for the Mekong basin by Ringler (2002) and for the Maipo basin by Rosegrant et al. (2000) and is used in this thesis to develop an integrated hydro-economic model for the Middle Drâa river basin.

1.3 Structure of the thesis

Against this background an integrated hydro economic river basin model is developed for and applied to the Middle Drâa River basin, and used to integrate and assess the conjunctive nature of water use and problems of salinity in the area, as well as to simulate policy options for a sustainable water use in the future. The thesis includes four papers, which each start with an introduction to the specific research question, proceed with the methodological refinements of the model version used in the paper, a presentation of results and major findings and conclusions at the end of the paper. To give the reader a comprehensive picture of the specific situation in the Drâa valley and to explain the development of the integrated hydro-economic model, the thesis starts with an evaluation of the specific characteristics of the Drâa valley and an assessment of water resources and management and agricultural production.

To be more specific, Chapter 2 analyzes and discusses water resources and water management in the basin. As surface water and groundwater resources differ with respect to their overall quantity, quality and in their availability for the users, they are regarded separately. Subsequently, Section 2.3 discusses water management issues in Morocco on a national level, and outlines the specific features of water management in the Drâa valley. The region is characterized by a centralized water management regime, but traditional water rights and water distribution rules remain which need to be taken into account when discussing a sustainable water management for the region. Against this background Section 2.4 derives consequences for the integration of water resources into a modeling approach and points out possible management options to be analyzed in the scope of this study.

Chapter 3 provides an overview of agricultural activities with a focus on agricultural production in the six Drâa oases. A survey conducted in 2005 allows an analysis of farmers' production structures and strategies to deal with water scarcity. Water extraction costs and agricultural gross margins are analyzed in Section 3.4. The chapter points out the consequences for an assessment of water availability on land use in an integrated modeling approach in Section 3.7.

The basis of all four papers in the subsequent chapters is an optimization model called integrated model of the Drâa valley (MIVAD) that has been developed for the regional agricultural situation. The model maximizes agricultural income under resource constraints for the six oases of the Middle Drâa valley. The major constraints relate to water quantity but also to water quality aspects. The model represents the relationships between groundwater and surface water quantity and quality with the help of hydrological and groundwater balances on the water supply side, and agriculture as the major water user on the water demand side. Each paper develops one specific aspect of the model and evaluates policy options for water management.

The first paper in Chapter 4, which has been published in the Journal of Agricultural and Marine Science together with Arnim Kuhn, incorporates household water use and electricity generation in addition to the revenues from agricultural production in the objective function. In Section 4.3, groundwater pricing is discussed as one policy option on the basis of groundwater costs that have been derived from the agro-economic survey described earlier in Chapter 3. The key message of the paper is that pricing of groundwater can stabilize the marginal value of irrigation water over years and can thus stabilize groundwater tables. Problems of implementing a water pricing schemes are discussed in the conclusions of the paper.

The second paper which is included in Chapter 5 and which has been published in the African Journal of Agricultural and Resource Economics together with Arnim Kuhn and Stephan Klose, builds upon the modeling approach in Chapter 4. It focuses on interactions of surface and groundwater in the Drâa valley and outlines challenges for conjunctive modeling approaches in Section 5.2. The model version of Chapter 4 is improved in this paper by calibrating the model to the local conditions and refining the groundwater dynamics. Water pricing in the Drâa valley is discussed as a policy option distinguishing between surface and groundwater pricing and a total pricing of water. The paper concludes that groundwater pricing is favorable to surface water pricing as the first option internalizes the stabilization value of groundwater. The importance of groundwater recharge from the river into the shallow aquifer is presented in Section 5.5 by means of a sensitivity analysis which is included in the annex of the chapter.

In Chapter 6, which comprises the third paper published in the Water Management proceedings IV together with Arnim Kuhn, water quality is introduced into the model which is a tremendous environmental threat in the region. The increasing salinisation of soils and water for irrigation is affecting crop yields and hence income from agriculture. In this paper crop yields are reduced according to the degree of water deficit and to the degree of salinity concentrations in irrigation water. The latter influence is depending on the specific salt tolerances of plants. By means of a sensitivity analysis in Section 6.3 the influence of quantity and quality is discussed using comparative-static simulation exercises. The paper shows that water quality considerations are essential for a realistic assessment of crop yields and income in the study region.

The fourth paper in Chapter 7 has been written together with Thomas Heckelei and combines the salinisation component with the interaction of surface and groundwater to simulate the influence of stochastic reservoir inflows in the Drâa valley. A random variable for two climate change scenarios is estimated in Section 7.3 and introduced to evaluate future water use and agricultural income. The combination of water quality and water quantity in an integrated river basin model leads to complex results that are analyzed with the help of Monte Carlo simulations in Section 7.4. Model runs with and without salinity effects show that without salinity the net benefit of groundwater is overestimated. The key message of the paper is that climate change will increase the probability of farmers to receive farm incomes below the subsistence level and will increase the use of groundwater for irrigation in the future.

All four papers apply adjusted and modified modeling approaches. The first two papers are based on a deterministic but recursive-dynamic exercise. The third paper which deals with salinity aspects is a deterministic, comparative-static modeling approach. The last paper focuses on stochastic modeling elements simulating one agricultural year in a comparative-static way. In the overall conclusions in Chapter 8 key findings of this thesis are pointed out. The four papers presented in Chapter 4 to 7 are compared and advantages and disadvantages of each are discussed. At the end of this thesis limitations of the developed and applied approaches are discussed and future research directions are identified.

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2 Water resources, use and management

The following chapter describes the available water resources and the current demand in the Middle Drâa valley[2]. The aim herby is to identify requirements and to define assumptions necessary for developing an integrated model approach to assess political and environmental changes with special focus on water use. For the analysis of policy options for water management it is also central to evaluate current water management practices in Morocco and in the Drâa valley. Consequently, water supply and water demand are compared first whereas surface water supply and groundwater supply are discussed followed by an evaluation of water demand for the different existing economic sectors. Domestic water use is analyzed, followed by water use in the service sector, and finally water use in agriculture, as the largest user of water in the region. At the end the three sectors are compared according to their share of total water use. Furthermore, an overview of current water management policies at the national level is given and water management in the Drâa valley is analyzed in detail. At the end of this chapter conclusions are derived for the assessment of water management in an integrated modeling framework.

2.1 Water supply

Being one of the driest river basins of the world (Revenga et al. 1998) water in the Drâa valley is a rare and precious resource. The Middle Drâa valley is located around the 6° meridian/longitude and around the 30° latitude, and is surrounded by the Mountain range Jbel Sagrho to the north, the Jbel Bani to the east, the Sahara Desert to the south and the Anti Atlas Mountains to the west. Administratively, the region belongs to the province of Zagora which again comprises eleven rural communities. The Middle Drâa valley is supplied by the Drâa River which begins at the intersection of the River Dades and the River Ouarzazate and runs along a 200 kilometers belt of six aligned palm tree oases and drains into the salt lake Lak Iriki in the far south (Ouhajou 1996). The oases are named from north to south: Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua and Mhamid.

Water in the Middle Drâa Valley can be obtained using surface water from the river from releases of the reservoir (in so called "*lâchers*") or pumping groundwater from the shallow aquifers. Therefore, it is important to distinguish the two resources.

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[2] The Drâa region can be separated into the Upper Drâa valley and the Middle Drâa valley. The Upper Drâa valley is located south of the High Atlas Mountains and north of the Anti Atlas Mountains including the city of Ouarzazate. The Middle Drâa valley is located south of the Anti Atlas Mountains. In Figure 3-1 in Chapter 3 the location of the Middle Drâa valley and its oases are depicted.

Surface water is the largest resource for water use in the area. Only one tenth of the total exploitable resource is provided by groundwater in normal years. In dry years, when less surface water is available, the share of groundwater used for irrigation increases. Groundwater is extracted by farmers with the help of privately owned motor pumps. Data available on the volume of groundwater used is often old and unreliable. The data in Table 2-1 shows an approximation in order to compare the relations between the different water sources.

Table 2-1: Potential water resources in the Middle Drâa valley

	Average Year		**Dry Year**	
Potential resources	**Mm³**	**%**	**Mm³**	**%**
Surface water resources (Drâa and tributaries) *****	225	85	102	56
Extracted groundwater resources ******	40	15	80	44
Total exploited resources	265	100	230	100

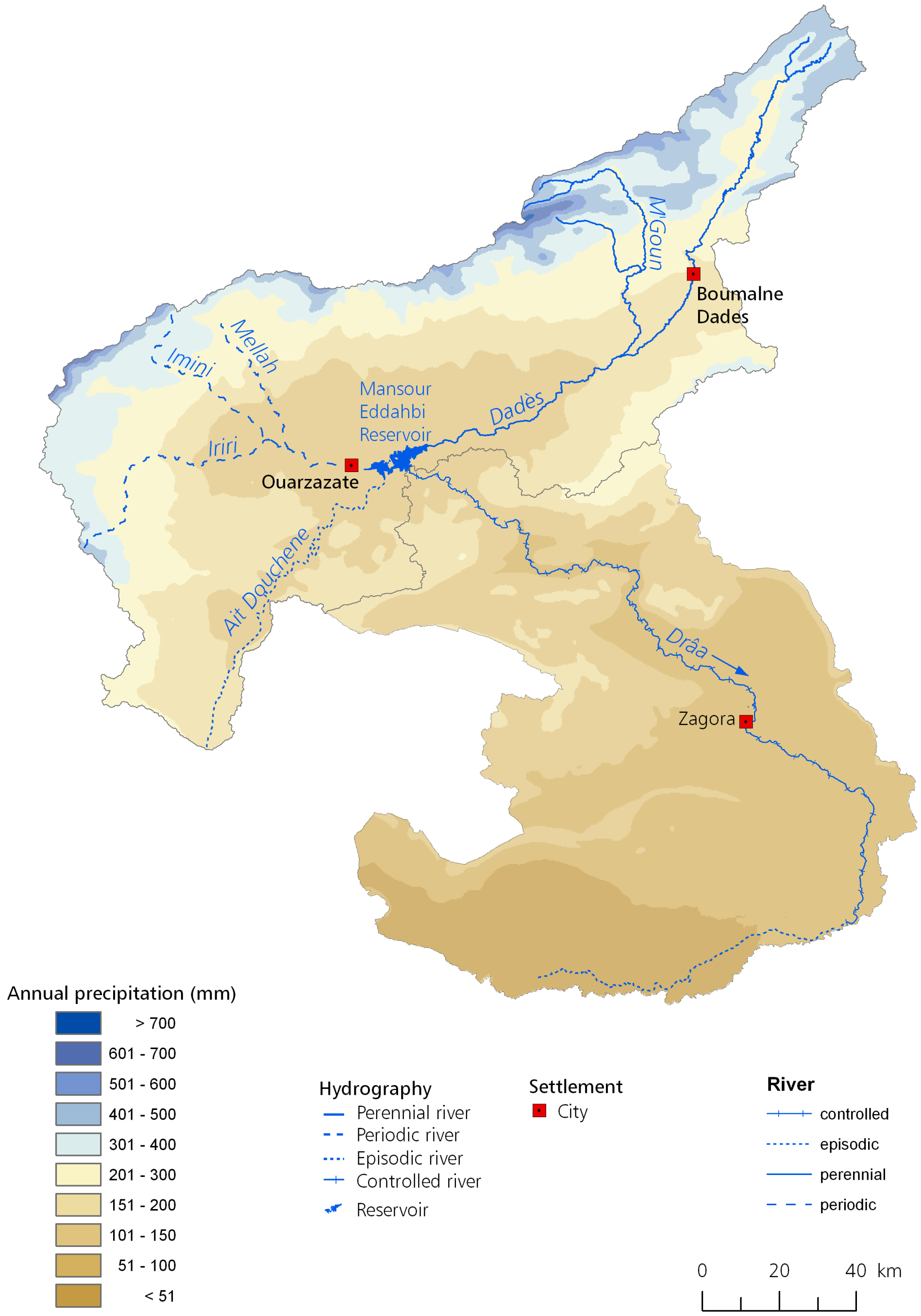
*Source: * own estimations based on average and lower quartile of lâchers between the years 1972 and 2003, DRPE 2004, ** groundwater use data on average and dry years by DRPE 1998*

Surface water

The availability of surface water in the Middle Drâa basin is largely dependent on the amount of precipitation in the Upper Drâa basin. In the basin of Ouarzazate and in the High Atlas Mountains precipitation leads to run-off which is stored in the Mansour Eddahbi reservoir. From there water is released in monthly periods (*lâchers*) to supply the Middle Drâa valley with water for irrigation.

The Drâa river basin is characterized by arid climatic conditions (Hübener et al. 2005). Precipitation decreases generally from North to South as depicted in Figure 2-1. The highest precipitation rates can be found in the High Atlas Mountains where precipitation is partly available in form of snow (Schulz 2006, Cappy 2006). Melted snow makes up a great part of the water available for the Mansour Eddahbi reservoir and also plays an important role with regard to water storage. Schulz (2006) has investigated in detail the importance of snow in the High Atlas Mountains and the role of inflows into the reservoir. Annual precipitation north of the Anti-Atlas Mountains is around 200-300 mm. South of the Anti-Atlas annual precipitation rates decline to 100-200 mm (Schulz 2008) whereas rainfall varies extremely during the year with less rain in the summer months but more rainy days in the winter period.

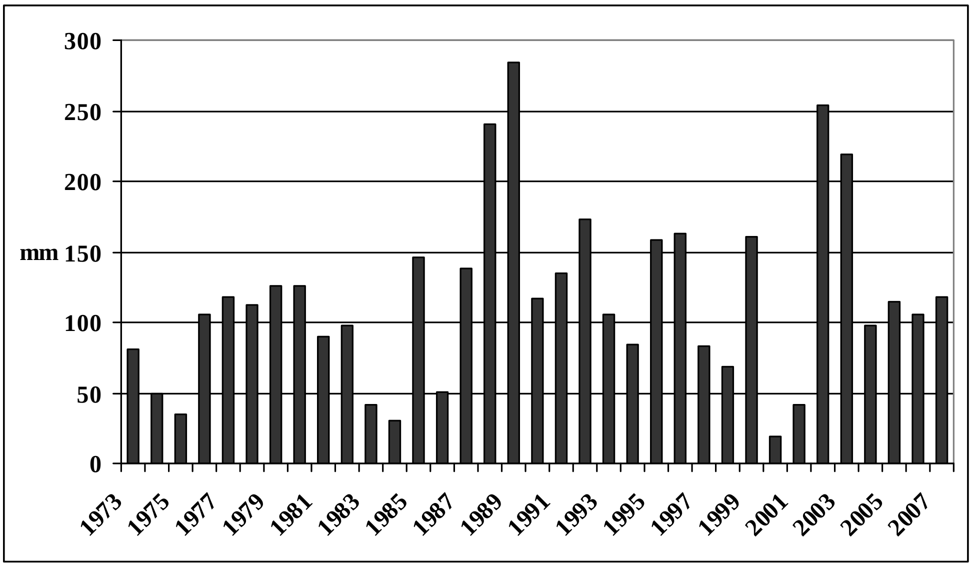
Figure 2-1: Annual precipitation sums in the Upper and Middle Drâa basin



Source: Schulz 2008

The inter-annual precipitation variability becomes obvious from Figure 2-2. Mean annual precipitation in Ouarzazate is around 117 mm but faces a standard deviation of 63 mm. Especially long periods of drought were experienced in the 80's and during the last few years (ORMVAO 2000).

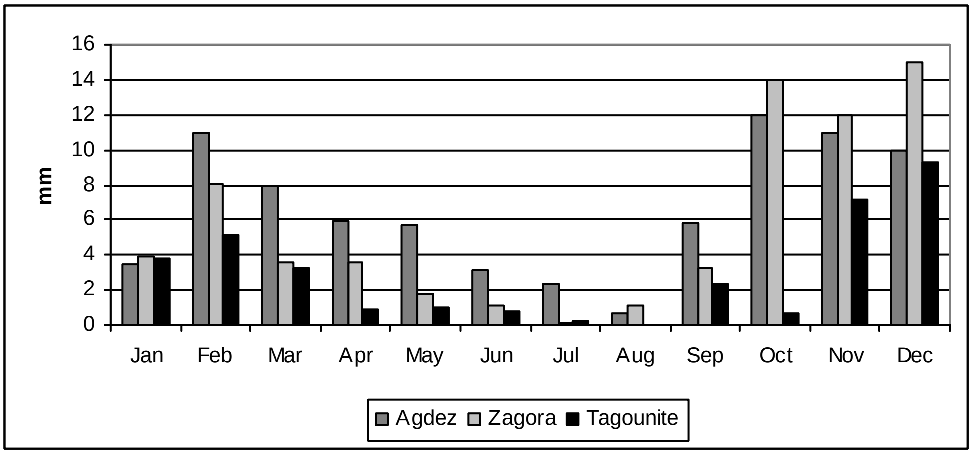
Figure 2-2: Annual precipitation in Ouarzazate from 1973 to 2007



Source: Fink et al. 2008. Note: Monthly data of years 2003 and 2006 were incomplete and completed with average monthly data from 1973 to 2007.

Generally, two precipitation maxima can be distinguished within one year: the first around October to December, and the second around February and March (ORMVAO 2000). Especially the first rainfall peak is important with respect to agricultural sowings. In the Middle Drâa valley precipitation is much lower in general compared to the region upstream of the reservoir. Figure 2-3 shows precipitation rates for three major villages in the Middle Drâa valley. Tagounite which is located the furthest south faces lower precipitation rates than Agdz which is the furthest north of the Drâa oases, but even there monthly precipitation reaches only a maximum of less than 20 mm. Mean annual precipitation in the Middle Drâa valley amounts to 60 mm in Zagora (ORMVAO 2000). Due to the distribution of rainfall and the high precipitation variability in the area, rainfall in the Middle Drâa valley does not allow for rainfed agricultural production. It is nevertheless a contribution to the recharge of groundwater aquifers, as well as for the development of pastures in the surrounding mountains and rangelands (Pletsch 1971). Consequently, the surface water availability in the Middle Drâa valley depends on the releases of the Mansour Eddahbi reservoir or to a limited extent on small tributaries in the Middle Drâa valley.

Figure 2-3: Average monthly precipitation in the Middle Drâa valley in mm (1980-2000)

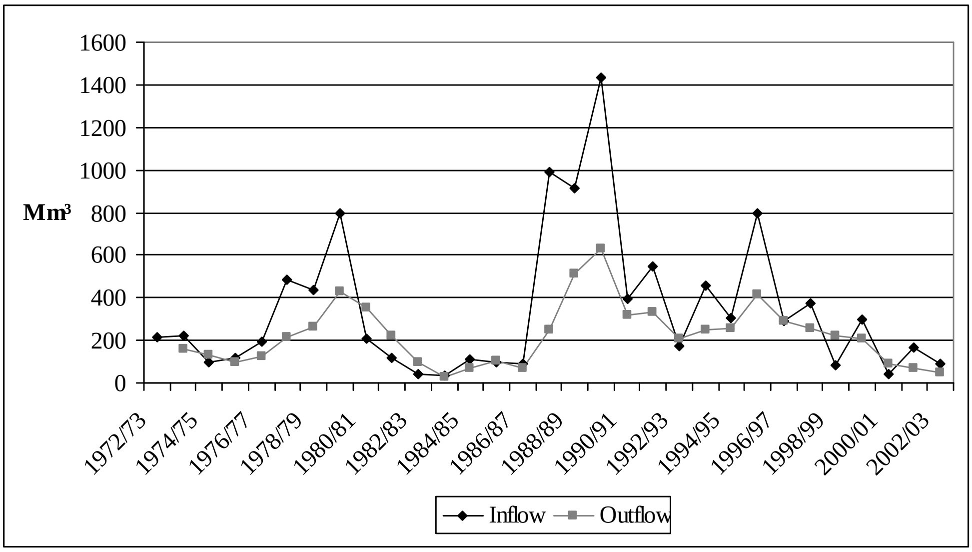


Data source: ORMVAO 2000

The most important tributaries to the barrage Mansour Eddahbi are three rivers: the River Dades, the River M'Goun, and the River Ouarzazate (ORMVAO 1990) with its three main tributaries Mellah, Iriri und Imini. The River Dades, the River M'Goun and the tributaries of the River Ouarzazate all have their origin in the High Atlas Mountains. At the point of their confluence at Zaouit N'Ourbaz, where the River Drâa begins, the reservoir Mansour Eddahbi was constructed in 1972. At this location another river, the Ait Douchene, which originates in the Anti-Atlas Mountains, joins the Drâa River, but has a minor importance for the inflows into the Drâa River. Altogether the River Dades contributes 58% and the River Ouarzazate 40% to the reservoir. The remaining two percent come from the River Ait Douchene (Ouhajou 1996, Chamayou et al. 1977, Schulz et al. 2008).

The inflows and outflows of the Mansour Eddahbi reservoir, important for the surface water availability in the Middle Drâa valley, are depicted in Figure 2-4. On average inflows into the reservoir amount to approximately 340 million cubic meters, whereas average annual releases were 225 million cubic meters. Both have a large variability and the annual trend of inflows and outflows is declining during the last years.

Figure 2-4: Inflows and outflows of the Mansour Eddahbi reservoir from 1972-2003



Source: DRPE 2004 Note: The figure reports inflows and outflows from 1972 onwards as this was the year the reservoir started to operate.

Water availability and storage capacity of the reservoir is additionally affected by high evaporation rates and sedimentation. Evaporation above the surface of the reservoir varies in accordance with its fill level and many climatologic factors such as wind and temperature and amounts to an average of 63 million cubic meters per year (ORMVAO 2002). Sedimentation has become an increasing problem for the reservoir as the total volume declined from 560 million cubic meters in 1972 when its construction was completed, to 460 million cubic meters in 1998 (DRPE 1998). Within thirty years it has lost 20% of its initial storage capacity (Bzioui 2004) leading to less storage capacity of water for irrigation of the downstream oases.

Surface water is hence provided by the Mansour Eddahbi reservoir but is highly variable from year to year. Direct precipitation in the Middle Drâa valley is less important for the water availability, whereas precipitation from the Upper Drâa valley contributes to the inflows into the reservoir.

Groundwater

Groundwater plays an important role for irrigation in addition to surface water and is the main source for the drinking water supply. Its consumption varies depending on the total amount of surface water available. Particularly, its storage value to stabilize the variable surface water availability for agricultural production has to be taken into account for an economic analysis. Data available on the dimensions and volumes of aquifers is comparably old and its reliability is often doubtful. Nonetheless, the available data helps to understand the processes of the groundwater dynamics and the quantity of groundwater available in the region.

Each of the six oases in the Middle Drâa valley is assigned a shallow groundwater aquifer (Klose et al. 2008). Sizes of aquifers and total reserves of groundwater vary between each oasis see Table 2-2. The largest groundwater reserves can be found in Fezouata with 127 million cubic meter of groundwater available. Mezguita and Mhamid have the lowest groundwater reserves with less than thirty million cubic meters.

Table 2-2: Area of aquifers and total natural reserves in the Drâa oases

	Total area of the aquifers (km^2)	**Total natural reserves (Mm^3)**
Mezguita	45	22.5
Tinzouline	69	34.5
Ternata	178	71.3
Fezouata	196	127.1
Ktaoua	160	86.4
Mhamid	70	16.8

Source: Heidecke et al. 2008, on the basis of Ouhajou 1996

The average balance of recharge and discharge of the aquifers is given in Table 2-3. The amount of discharge due to pumping is probably underestimated regarding the current situation of groundwater extraction. Recharge of aquifers depends primarily on the infiltration of irrigation water on the fields as well as the infiltration of water from the river bed. In times of water scarcity aquifer recharge is affected strongly by surface water availability which is visible in downing groundwater tables. Scenarios with the groundwater balance model (BIL) estimate that groundwater tables are likely to decrease by another two meters until the year 2020 under the assumptions of the climate change scenarios by the IMPETUS project (Klose et al. 2008).

Table 2-3: Recharge and discharge of aquifers

Annual natural replenishment of groundwater	**Mm³**	**%**	**Annual groundwater discharge**	**Mm³**	**%**
Infiltration of rainfall	3.9	5.4	Drainage /foums	20	31.1
Lateral afflux	20.4	33.1	Pumping	10	15.9
Infiltration of irrigation water	38.2	60.5	Drainage downstream	4.9	7.7
			Direct evapotranspiration	28.0	44.1

Source: Ouhajou 1996

Since the construction of the Mansour Eddahbi reservoir in 1972, the number of motor pumps has increased constantly. It is estimated that in 1977 the six oases had about 2000 motor pumps; by 1985 this figure had doubled (Faouzi 1986). Nowadays the number of motor pumps has increased to nearly 7000 for the whole Drâa valley as depicted in Table 2-4. However, due to the downing of groundwater tables and the competition of water extraction not all motor pumps extract water 24 hours a day.

Table 2-4: Number of motor pumps in 1977, 1982, 1985 and 2005 in the Drâa oases

	1977	**1982**	**1985**	**2005**
Mezguita	216	260	860	2,600
Tinzouline	499	590	1,200	945
Ternata	785	920	1,500	1,150
Fezouata	383	448	710	850
Ktaoua	108	130	220	1,300
Mhamid	10	15	30	60
Total	2,001	2,363	4,520	6,905

Source: Faouzi 1986, CMV 2005

According to DRPE (1998), annual groundwater extraction amounts to an average of 40 million cubic meters but can vary from 20 million cubic meters in a rather wet period (1992-93) to 82 million cubic meters per year in very dry period (1986-87). Survey results[3] allowed to derive average daily pumping hours of motor

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[3] The agro-economic survey was conducted in 2005 which was a very dry year. The survey is explained in detail in chapter 3.

pumps in the Middle Drâa valley of 4 hours. Even if the 7000 motor pumps work only 200 days a year, this would lead to a volume of 90 million cubic meters of groundwater pumping in a dry year assuming that on average a motor pump delivers 17 cubic meters per hour[4]. For the increase in the number of motor pumps Faouzi (1986) gives two reasons: first, the amount of water released from the reservoir is not sufficient for the irrigation of plants, and second the time between reservoir releases is too long for plants with high water requirements, e.g. vegetables, alfalfa and henna. Groundwater quality is an increasingly important issue in the Drâa valley. Salinity concentrations of groundwater are naturally high due to the geological characteristics of the region (ORMVAO 2000), but salt concentrations are increasing because of high evaporation impact and the increasing use of groundwater for irrigation (Ouhajou 1996). Concentrations are increasing from North to South reaching salt levels that constrain agricultural production especially of salt sensitive plants (Table 2-5).

Table 2-5: Salt concentration of groundwater (grams per liter) and "agricultural areas suffering from soil salinity" (%)

		Min (g/l)	**Max (g/l)**	**Average (g/l)**	**1968 (%)**	**1980/81 (%)**
North	Mezguita	0.3	3.5	1.5	12	24
↓	Tinzouline	0.4	7	2.5	31	32
	Ternata	0.4	8	2.5	35	42
	Fezouata	0.8	15	4	40	66
	Ktaoua	1.5	18	5	68	73
South	Mhamid	1.5	16	5	57	62

Source: Ouhajou 1996, ORMVAO 1996. Note: percentage values are rounded

In comparison, the River Dades has average salt rates of 0.4 to 0.6 grams per liter, the River M'Goun between 0.8 and 0.9 grams per liter and the River Ouarzazate on average 1.5 grams per liter (ORMVAO 2000). As surface water contributes to aquifer recharge in the Drâa valley, dilution of salt concentration is taking place.

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[4] Measurements by Stephan Klose, Steinmann Institute of Geology, University of Bonn

Future predictions of water supply

Climate change studies for southern Morocco indicate that the average temperature might rise significantly between one and two degrees in the future until 2050. This would lead to a decrease of snow in the High Atlas Mountains and also to a loss of water storage for runoff. Precipitation is more difficult to predict for the region. Scenario calculations by the IMPETUS project (Born et al. 2008a) indicate that average precipitation rates might decrease within the next fifty years under assumptions of climate change scenarios A1B and B1 of the IPCC (IPCC 2007)
A1B characterizes a scenario of rapid economic growth and a rapid introduction of efficient technologies. Energy consumption does not depend on one sole energy source. B1 differs from scenario A1B in the assumption that the economy will shift towards a service and information society followed by the introduction of clean and resource-efficient technologies (Born et al. 2008b).

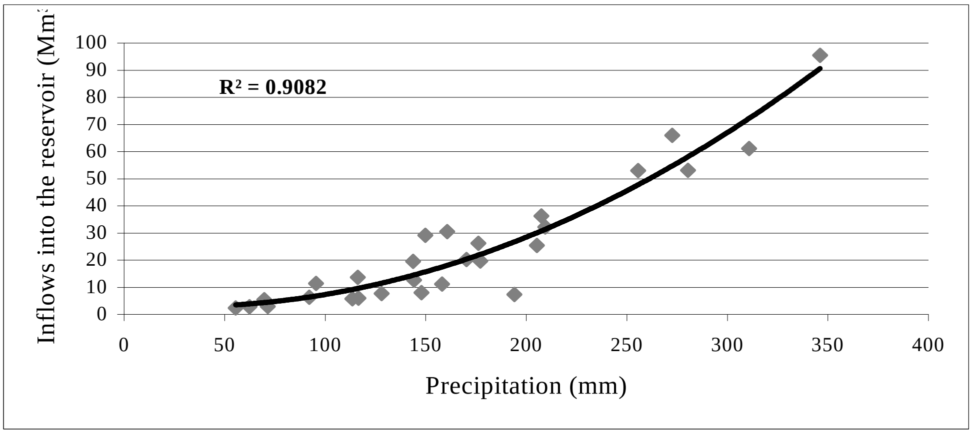
Table 2-6: Annual precipitation (past simulation and climate scenarios A1B and B1)

Years	**1960-2000**			**A1B (2001-2050)**			**B1 (2001-2050)**		
Ensemble runs	**901**	**902**	**903**	**911**	**912**	**913**	**921**	**922**	**923**
Average (mm/year)	155	166	176	136	131	155	147	150	141
Variance	1,859	1,858	2,813	2,554	2,807	3,457	1,720	1,975	1,633
Standard deviation	43	43	53	51	53	59	41	44	40
Variation Coefficient	28	26	30	37	40	38	28	30	29

Source: Data was provided by the IMPETUS project, Speth and Dieckrüger 2006, own presentation of data

Comparing the reference data from 1996 to 2000 with two future climatic scenarios A1B and B1 from 2001 to 2050 in Table 2-6 where each climate scenario is composed out of three ensembles runs calculated by Born et al. (2008a), the average annual precipitation is decreasing from the reference runs to the scenarios. Scenario A1B describes a scenario with even less rainfall and the highest average variation coefficient. Relating precipitation to inflows into the reservoir a high correlation is found (Schulz et al. 2008) as depicted in Figure 2-5. This enables to compute the future availability of surface water for irrigation in the Middle Drâa basin. Future availability of reservoir inflows (an important variable for the modeling approach) can be calculated on the basis of a simple regression depicted in Figure 2-5.

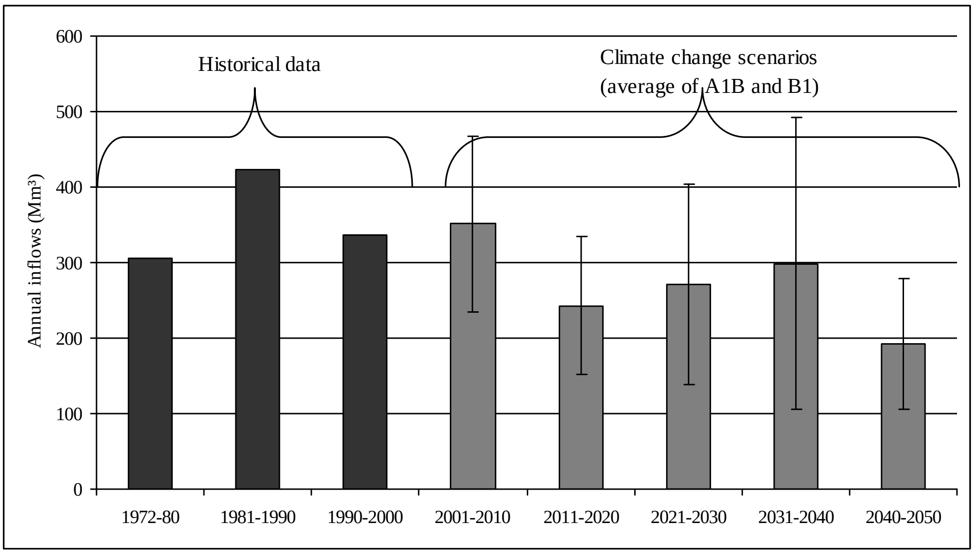
Figure 2-5: Relationship of precipitation and reservoir inflows in the basin of Ouarzazate from 1975 until 2000



Source: Data from DRPE

Figure 2-6 shows the annual inflows into the reservoir for the past and for the climate change scenario calculations.

Figure 2-6: Inflows into the Mansour Eddahbi reservoir- historical data and climate change scenarios until 2050.



Source: Data was provided by the IMPETUS project, Speth and Dieckrüger 2006; Note: Climate change scenarios represent the average of six ensemble runs of scenarios A1B and B1 and the standard deviation.

In short, future surface water availability in the Middle Drâa valley is likely to decrease and will be more variable. This would consequently result in less groundwater as surface water and groundwater resources are directly linked through infiltration and discharge.

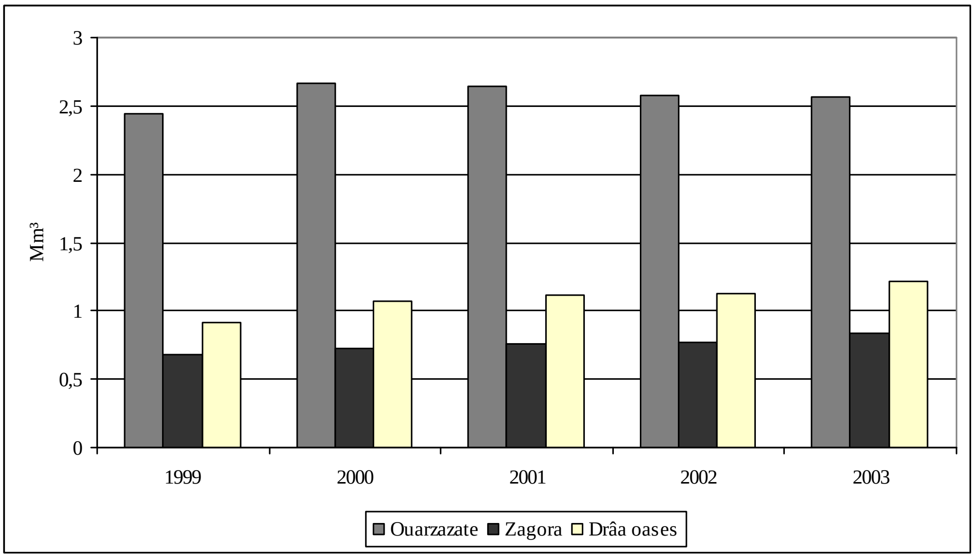
2.2 Water demand

This section distinguishes three main consumers of water, namely villages, tourism and agriculture. The water consumption for villages includes drinking water for households and also smaller industries and services. Water demand for tourism is regarded separately as tourism is one of the relevant economic sectors besides agriculture. Then, agricultural water demand is examined. Water requirements for different crops and oases are pointed out. As agriculture is the major water user, and water is its major production constraint, agriculture is discussed in more depth in Chapter 3.

Drinking water demand

Villages consume around ten percent of the water used in the Drâa valley. The province of Ouarzazate consumes around 2.5 million cubic meters of water per year, as depicted in Figure 2-7.

Figure 2-7: Average water provided to the municipalities Ouarzazate and Zagora



Source: ONEP 2004

The district of Zagora uses much less water between 0.5 to one million cubic meters per year although there was a slight increase between the years 1999 and 2003. Water for the district of Zagora is drawn from the groundwater aquifers and is very important for the water balance in the Middle Drâa valley. Water for the province of Ouarzazate is mainly drawn from the Mansour Eddahbi reservoir.

For the municipalities in the entire Drâa basin, including the municipalities of Zagora, Agdz, Tagounite and Mhamid, drinking water demand was calculated to be 1.2 million cubic meters in 2003. This is expected to rise to 14.8 million cubic meters by 2020 (DRPE 1998). The pricing system for drinking water use from ONEP, the official water authority, is structured as a block tariff rate system (Table 2-7) where the price for water is dependent on the total volume provided.

Table 2-7: Price for domestic water use in Dirham per m³

Block	Price (DH)
1. Block 0-24 m^3	2.54
2. Block 24-36 m^3	7.91
3. Block 36-60 m^3	11.75
4. Block 60-120 m^3	11.8

Source: ONEP 2004

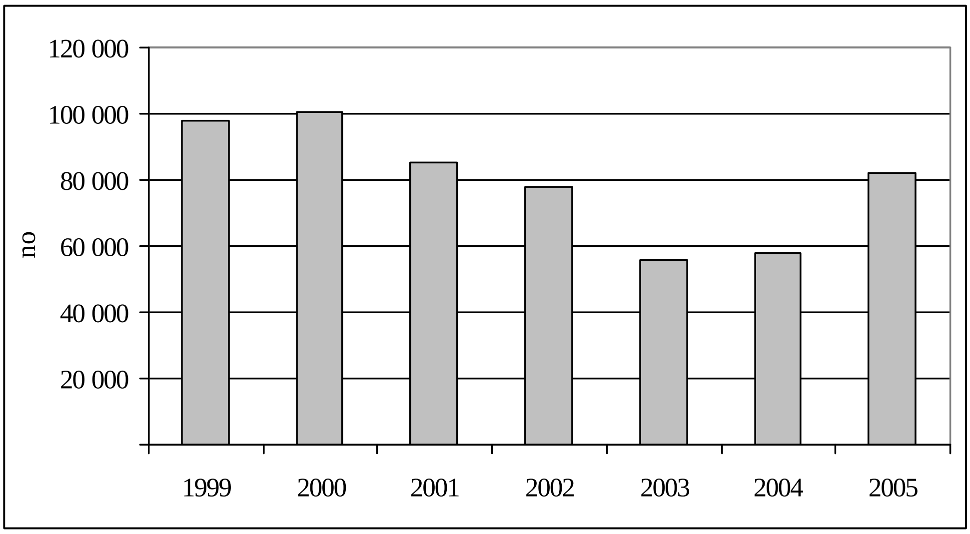
Drinking water demand of the rural population is not included within the data of the official water authority. In 1998, 26% of the population did not have access to potable water supply from the official water authorities (ONEP). However, under the program PAGER an increasing share of the rural population is connected to a municipal pipeline system from 14 % in 1995 to around 70 % in 2002 (DRPE 1998). Rural water consumption has been analyzed in one village of the Middle Drâa valley by Rademacher (2007) who found that approximately 32 liters of water are consumed per person and day in a middle size rural household (in the municipalities this is around 100 liters of per person and day). If this is extrapolated to the population of the Middle Drâa region, a total domestic water use of 3.3 million cubic meters is derived. This shows that half of the water extracted from wells or the river is not accounted for with the official water authorities and has to be kept in mind for a analysis of the water balance.

Water demand by tourism and industry

The major economic activities in the provinces of Ouarzazate and Zagora are agriculture, tourism, some mining industries for copper, small handicrafts and other small industrial activities such as dairy production and the processing of date palms. Pletsch (1971) recorded that 89 percent of the population in 1967 were employed in agriculture constituting 91 percent of income generation. Nowadays this situation changed. Regarding family income, remittances from family members who have migrated into bigger cities or to foreign countries play an increasingly important role (Rademacher 2008), and are estimated to be around 60% of the monetary income (Direction de l'Amenagement du Territoire 2006). This is confirmed by Storm (2009) who noted from a survey that 67 percent of the farmers in the oasis Ternata receive additional income other than from agriculture, of which 50 percent are remittances from migrated sons.

Another important economic sector in the Drâa region is tourism for safaris in the Sahara Desert. Tourism is therefore especially important in a few hot spots, namely the city of Ouarzazate, as well as Zagora and Mhamid which are the starting points of safaris. Altogether, it provides an alternative activity and supplements income for a large part of the local and regional population, although hotels are often owned by foreign investors. The number of tourists in the region of Zagora varies, and declined especially in the aftermaths of events such as the terrorist attacks of the 11th September 2001 and in Casablanca in 2003 (Martin 2006). However, since 2003 the number of tourists visiting the region of Zagora has increased again (Figure 2-8).

Figure 2-8: Number of tourists in the region of Zagora per year from 1999 to 2005



Source: Direction Régionale d'Agadir 2007

Data about the water used for tourist activities is rare. Water is mainly drawn from wells owned by the hotels but a rough approximation of total water use is made in this thesis. Platt (2006) conducted a survey to analyze the number of hotels and their water use in the Middle Drâa valley in the year 2006. The complete inventory count found 45 hotels in the Drâa oases ranging from bigger hotels to smaller hostels. Table 2-8 summarizes the results of the survey. On average a hotel has one well used for additional water needs, around 15% of its total water use. Around 2400 cubic meters of water are consumed per hotel per year, which leads to around 1.2 cubic meters per tourist per night. Even if it is assumed that each tourist consumes about 1.2 cubic meters per day including water that is used by the hotels for pools and gardening, the total amount of water used by tourism hardly exceeds 0.1 million cubic meters per year.

Table 2-8: Hotels and their facilities and water use in the region Middle Drâa valley

	Average	**Maximum**	**Minimum**	**Stand Deviation**
Private Well (No)	0.93	3	0	0.58
Depth (m)	23.6	114	0	26.05
Extraction per day (m³)	1.8	19.2	0	3.96
Nights/year (no)	4726	42000	30	9103
m³/year (tap)	1974	12775	75	3006
m³/year (well)	366	1460	0	365
m³/year (total)	2389	14235	100	3168
Water used (liter/night)	1123	5329.07	68.5	1519

Source: Data was provided by Platt 2006
Note: The survey was conducted by Platt (2006) in the year 2006 in the Middle Drâa valley. The extraction rates of wells are an estimation of the hotel owners therefore data only shows an approximation of the water use of tourists.

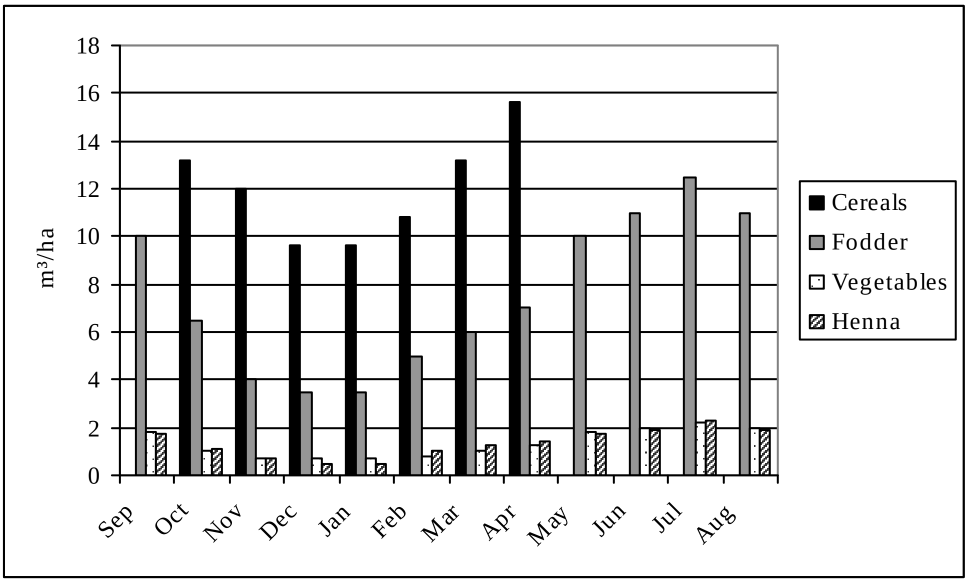
Industry plays only a minor role. It is hardly developed and only found as small factories or family enterprises. The number of factories varies strongly according to sources from five to 44 according to different statistics of Ouarzazate. In the annual statistics of 2006 only one enterprise with eight employers and five million Dirham of turnover is listed for the circle of Zagora (Direction Régionale d’Agadir 2007).

The region of Ouarzazate is also known for its mining industries of silver, manganese, cobalt, chrome and lead (Chambre de Commerce, d’Industrie et de Services de Ouarzazate et Zagora 1998) employing 1.3% of the active population (DRPE 1998). No robust data can be found on the amount of water used by industry but the industry sector can be considered as a minor consumer of water in the region.

Irrigation water demand

Agriculture is by far the largest user of water in the region. Farmers depend on water to irrigate their fields as rainfed agriculture is not possible and hardly practiced. Water use for irrigation is presented in detail in Chapter 3. Here, only the dimension of water requirements and use by agriculture shall be discussed. The water requirements per crop throughout the year are highly variable as crops need different amounts of water in different time periods as presented in Figure 2-9.

Figure 2-9: Total water requirements per months and hectare for different crops.



Source: Outabiht 1985

Table 2-9 summarizes the average amount of water required per crop and per oases for the major crops if the total area is cultivated.

Table 2-9: Water use per oases and crop in Million m³ per year

	Cereals	**Legumes**	**Vegetables**	**Alfalfa**	**Henna**	**Water for Date palms**	**Total demand**
Mezguita	10.49	0.35	1.25	11.99	0.20	1.65	25.94
Tinzouline	22.43	0.55	2.10	12.84	1.01	2.60	41.53
Ternata	28.80	3.49	2.16	15.69	1.89	6.25	58.28
Fezouata	19.74	1.25	1.48	12.15	0.33	5.26	40.21
Ktaoua	26.42	2.84	1.13	6.71	0.11	12.67	49.88
Mhamid	7.88	0.83	0.05	2.43	0.03	4.39	15.61
Total demand	115.77	9.32	8.17	61.80	3.57	32.82	231.46

Source: DRPE 1987

Cereals consume the highest share of water. The water consumed by date palms can only be regarded as an approximation as they are cultivated in between other crops and can therefore make use of infiltrated water from other crops. Ternata, the largest oasis, also consumes the largest amount of water as the calculations are made on a summation of water requirements per hectares.

Summing up it could be shown that agriculture is by far the largest consumer of water with approximately 230 million cubic meters. Household water use amounts to 5.3 million cubic meters of water which is only around 1.5 percent of the total water demand. Even considering the estimation by DRPE 1998, which predicts a water demand of 14 million cubic meters in the year 2020, household water demand would still not exceed 14 percent of total consumption. The water consumption by tourism is, in contrast, very low and not significant for the water balance with 0.1 million cubic meters of withdrawals.

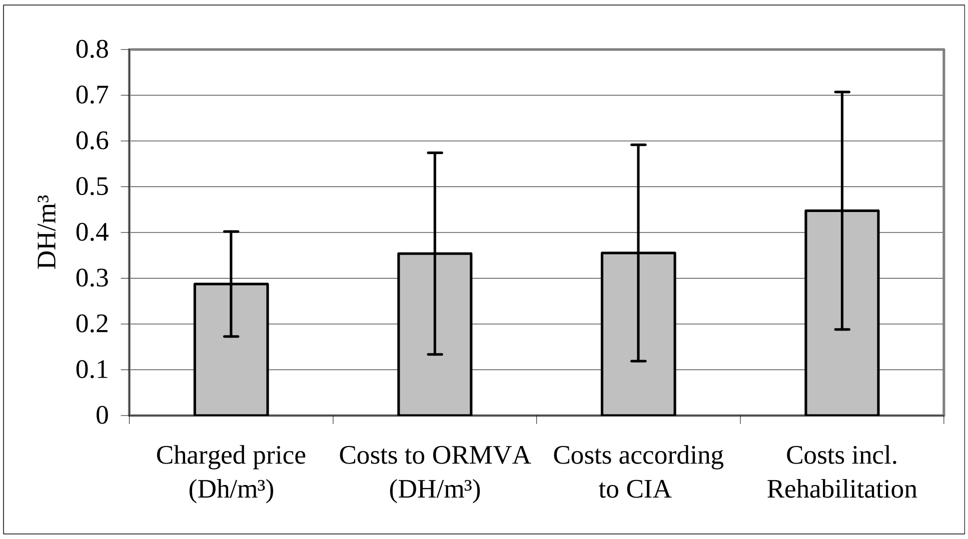
In the following section, national and local level water management for agricultural production will be examined.

2.3 Irrigation water management

National Regulations

Current water management in Morocco on the national level is a heritage from traditional Islamic water rights together with formal legislation that goes back to the beginning of the French protectorate from 1912. With the beginning of the French protectorate, the government classified surface water as public property with the argument that water was traditionally owned by the sultans and therefore belonged to the state, and second that this concept was more in line with the general Islamic perceptions. This was modified and adapted in several steps to include subsurface waters and to clarify the role of irrigation water use. In 1925, a decree was passed to respect existing traditional water rights, but special authorization was needed if water use exceeded 40 m^3 per day. Furthermore, a law was passed to organize water user associations for irrigation water and to assist the development of small networks for irrigation and their infrastructure. Since Morocco's independence in 1956, legislation has been reformed but still contains many parts of former rules and regulations. Ambitious water management plans have been designed to improve irrigation and the management of water resources which have increased state intervention in Morocco's water sector. Dams and irrigation systems were developed at high costs and infrastructure in small and large scale irrigation schemes were developed together with the authorization of water use and the implementation of water charges. The government focused on the development of agriculture and irrigation to promote an agricultural oriented economic growth. An agricultural investment code (CIA) was introduced in 1969 (Ministère de l'agriculture et de la réforme agraire 1969), a legal framework that clarifies irrigation water use and production in agriculture. The CIA regulates farmers' mutual water rights and duties, as well as policies related to land consolidation, change in cropping patterns, technology development and financing. Theoretically, large scale irrigation perimeters shall thus be imposed by a charge that is calculated on the basis of the initial cost recovery, a full costs recovery of operation and maintenance costs through volumetric pricing and a minimum consumption charge to cover operation and maintenance of the irrigation scheme. In addition an energy part shall be added if pumping or lifting activities are involved (Doukkali 2005). However, current charges realized in irrigation perimeters in Morocco vary greatly between the regions and hardly cover the costs by the state. Figure 2-10 summarizes the water charges which are on average 0.30 Dirham per cubic meter. The standard deviation of these costs and charges indicates that a high variation of charges and costs exist between the regions in Morocco (compare Figure 2-10). Water charges have been revised since the 1980s because under-financing of irrigation water led to a deterioration of the irrigation infrastructure. Water charges, however, still do not cover all operation and maintenance costs (Oubalkace 2007) nor the cost of amortization and replacement of irrigation infrastructure.

Figure 2-10: Irrigation water charges and water costs in large irrigation perimeters in Morocco



Source: Doukkali 2005, own presentation of data

Two agricultural offices have been exempted from water charges, the ORMAV of Tafilalet and the ORMVA of Ouarzazate, which is in charge of the Drâa river basin (Doukkali 2005). This can be explained by the poverty situation of the rural population in these regions and the political priorities to maintain stable living conditions of farmers in the area.

In 1995, Morocco initialized new institutional reforms in the water sector passing the water law 10/95 (Ministere de l'industrie, du commerce et des nouvelles technologie 1995). Under this new institutional setting decentralized river basin agencies have been formed to integrate and coordinate water resources at the river basin scale. Formally, the river basin agencies have the right to control water storage and allocation as well as groundwater pumping and pollution and shall work in close cooperation with the agricultural offices ORMVA's which are in charge of irrigation perimeters, the water user associations, the national authority of drinking water supply ONEP and environmental agencies (Doukkali 2005). During the last years the Drâa river basin was under the supervision of the river basin agency of Souss-Massa at the Atlantic coast but managed together with the ORMVAO. Recently, a discussion is going on about the creation of a new river basin agency for the Drâa River Basin (Agence du Bassin du Drâa) that would also be in charge of monitoring and management of water resources in the Middle Drâa valley.

Regional Level

Water management in the Drâa valley changed tremendously with the construction of the Mansour Eddahbi reservoir in 1972: it became much more centralized. On 26 February 1969, the Moroccan minister of public transport and a Soviet organization signed an agreement to construct a reservoir at Zaouit n'Ourbaz, near Ouarzazate. The constructions started the same year and were finished in 1972 (Ouhajou 1996).

Originally, the reservoir had a volume of 560 million cubic meters. The lake of the reservoir covers an area of 5 hectare with a depth that varies from 63 to 70 meters (Abou-Otmane 2002). The three main goals of the reservoir were

(i) to provide irrigation water for the Drâa oases in the Middle Drâa valley of, back then 19,000 ha of agricultural land in total and

(ii) to protect the Middle Drâa valley from floods

(iii) and to produce electricity with the help of two turbines (ORMVAO 1995).

The water from the reservoir is not released continuously but in larger quantities called *lâchers* whereas the period of water release and the quantity released varies (Faouzi 1986). The water releases in larger amounts is necessary in order to deliver water to the southern oases as well.

A technical committee is responsible for the management and the decisions regarding the periods and quantities of lâchers. Members of this committee are the governor of the province of Zagora, the local authorities, representatives of the population and the farmers, and the regional agricultural office ORMVAO. The ORMVAO presents a program of the water distribution of the previous years, with the actual fill rate of the reservoir and the predicted afflux. Generally, the committee meets twice a year, at the beginning of the agricultural calendar and after the first phase of irrigation. In cases of severe droughts, the committee even assembles before the beginning of each lâcher (Faouzi 1986).

The irrigation system of the Middle Drâa valley comprises five local dams that direct the water to the oases for irrigation (Table 2-10) (Ouhajou 1996). The construction of the dams of Agdz and Tansikht ended in 1975 (Faouzi 1985), Ifly in 1973, Azaghar in 1967 and Bounou 1956 (Ouhajou 1996).

Table 2-10: Local dams in the Middle Drâa valley

Local dam	**User (oasis)**	**Capacity in m^3/s**
Agdz	Mezguita	3.14
Tansikht	Tinzouline	6.77
Ifly	Ternata and Fezouata	11
Azaghar	Ktaoua and Mhamid	11 and 3.3
Bounou	Mhamid	4

Source: ORMVAO 1981, Faouzi 1986, Ouhajou 1996

From these five dams water is directed into the major channel system called seguias. In total 89 seguias can be found in the Drâa valley. These seguias provide water to around 80 to 1000 ha each depending on the flow velocity that varies between 50 and 1200 liters per second and have a total length of 200 kilometers (Ouhajou 1996). The seguias provide the connection to the tertiary irrigation system in the Drâa valley (Faouzi 1986). The tertiary system consists of small channels, open channels made of mud, that direct water onto the field. They are the basis of the traditional irrigation system of the Drâa valley and are constructed and maintained by the inhabitants of the village in a collective manner and are the property of the village (Liebelt 2003).

The distribution of the lâchers begins downstream with the last oasis, Mhamid, in contrast to the general rule that water is used upstream first (Faouzi 1986). The amount of water that is diverted to each oasis is discussed in the committee of water distribution but there is no clear rule as to how this water is distributed. As the total volume that is left over after infiltration into the river bed and evaporation losses is difficult to measure, Table 2-11 shows an estimation of available water to each oasis in the water management program of 1992 assuming different infiltration losses. Water which is released from the reservoir takes approximately 22 days until it reaches the southern oases depending on the amount released as this determines the flow velocity (ORMVAO 1995).

Table 2-11: Allocation of surface water between the six Drâa oases and expected infiltration of river water in 1992

	Volume (Mm³)	**%**
Total lâchers	**31.69**	**100**
Infiltration into the river bed	10.80	34.1
Water for Mezguita- Tinzouline	4.39	13.8
Infiltration Mezguita- Tinzouline	1.54	4.9
Water for Ternata- Fezouata	5.81	18.3
Infiltration Ternata- Fezouata	2.32	7.3
Water for Ktaoua-Mhamid	4.7	14.8
Infiltration Ktaoua- Mhamid	2.12	6.7

Source: ORMVAO 1995

The distribution of the water for irrigation among the farmers in each oasis is defined by the users on the basis of traditional property rights. Altogether three different forms of traditional property rights can be distinguished: the system “melk”, “allam” and a mix of these two. The rights may vary from seguia to seguia and there are even different rules within one seguia (Ouhajou 1996).

The system “melk” classifies water as private property: Water is thus independent from the fields of the owner. This water can be sold or bought, or rented to neighbors. The parts of the property rights were originally distributed proportionally according to the investment in the construction of the seguia. The water owners of one seguia distribute the water taking turns. Every circulation of turns is called “nouba”. In 56 of the 89 seguias in the area, water is distributed according to this distribution rule (Ouhajou 1996).

The distribution rule according to the system “allam” classifies water as a collective property of the users. This means that water is dependent on the irrigated area and water can only be sold, rented or bought together with the field. The part of the water directed to one irrigated parcel is equal to the proportion of size of this parcel to the whole area irrigated by this seguia. The order of distribution is determined by the location of the parcel to the seguia, normally to topographic location within the system. Consequently, in the “allam” type seguias water is distributed upstream to downstream. The number of seguias applying this kind of distribution rule is less common and was applied to 27 of the 89 seguias in 1996 (Ouhajou 1996).

The third kind of water distribution rule is a combination of the two others. The allam rule can then be found at the beginning of the seguia, the rule melk at the end or vice versa.

It can be concluded that the distribution of water within one oasis is complex and follows different rules depending on the village of the farmer. Furthermore, rules are adjusted in times of water scarcity to assure that all farmers receive a share of the water available, although this can often not be realized. After the migration of people or the abandonment of fields water rights are often transmitted or sold to neighbors but unfortunately no register of water rights is available.

2.4 Conclusions of the chapter

This chapter showed that water is an important but scarce resource in the Drâa valley. Comparing the different users, agriculture is the largest consumer of water. However, water requirements of crops can often not be fulfilled as water supply is highly variable. Although the reservoir Mansour Eddahbi was constructed to overcome this problem, water demand could not be met in times of drought during the last years. Households, industry and services only use a minor share of water compared to agriculture. Domestic demand is of highest priority for the Moroccan government and is always met first in times of scarcity. Furthermore, the authorities reserve a storage volume in the reservoir to be able to meet the drinking water demand in all times.

In contrast to domestic demand, agricultural water use is directly affected by less water availability in the Mansour Eddahbi reservoir and hence fewer releases from the reservoir for irrigation in the Middle Drâa valley. Farmers in the Drâa oases have reacted to reduced and more unreliable water availability by exploiting their shallow groundwater aquifers with wells and to a large part also with motor pumps. This has led to a downing of groundwater tables and higher salinity rates of irrigation water during the last few years. If climate change occurs in the form of the scenarios presented in this chapter, even less water is expected for irrigation in future years.

Current water management practices in Morocco and in the Drâa valley in particular have been presented in this chapter. It can be concluded that water pricing is commonly practiced in other irrigation perimeters in Morocco whereas in the Drâa valley, pricing elements have not been implemented so far. A stringent monitoring of groundwater and surface water resources is, however, indispensable for a sustainable water use and for the preservation of the resources for future generations. The formation of a new river basin agency for the Drâa River provides an opportunity to revise water management practices in the Drâa valley and to discuss an integrated approach of water management with stakeholders on different levels. The analyses of conjunctive water use and agricultural production in this thesis should support the discussion of sustainable water use and future development of the Middle Drâa basin to better face the challenges of climate change, salinity and water scarcity. For the quantitative assessment of policy options with a model the following requirements and assumptions can be inferred from the hydrological relationships presented in this chapter.

(i) Surface and groundwater need to be analysed conjunctively within an integrated modelling framework. Surface water resources constitute the largest source of water supply, but groundwater resources are increasingly used for irrigation. It could be shown that especially in times of scarcity, farmer's switch to more groundwater use for irrigation to meet necessary crop water requirements.

(ii) The availability of surface water is determined by the Mansour Eddahbi reservoir. As the reservoir is a central management tool for regional water management in the Drâa valley, the inflows into the reservoir and releases from the reservoir should both be incorporated in the assessment tool.

(iii) Aquifers are entities that are located beneath each oasis. These entities are interconnected along a gradient from North to South through lateral flows but also through the discharge into the river bed. The groundwater and river water balances are important as they form a complex system and determine the water available to each oasis. These need to be reflected in a model to allow the determination of the economic value of water at each demand point.

(iv) An analysis of possible management options is a key necessity for a sustainable future water management. The consequences regarding water use and income for the oases need to be analysed for each management alternative to be able to provide a comprehensive picture for water managers in the region. An emphasis on water pricing options for the Drâa valley is recommended as water pricing is already practised in other basins and is currently discussed by decision makers as a possible option for water management in the Drâa valley.

(v) The evaluation of future developments is identified as a significant issue as climate change might reduce water availability and population growth might increase domestic water use in the region. The incorporation and evaluation of climate change scenarios along the IPCC scenarios of the IMPETUS project is hence advisable.

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3 Agricultural production patterns and strategies under water scarcity - empirical results from a farm survey

3.1 Introduction

Characterized by a semi arid to arid climate, subsistence farming and small cultivated parcels, date palm oases provide a living environment for a large part of the rural population in the Drâa valley in the south of Morocco. As discussed in Chapter 2, agriculture is the largest water user in the Drâa region and it depends highly on irrigation. Farmers rely on water for irrigation from the Mansour Eddahbi reservoir and groundwater from shallow aquifers. Located south of the High Atlas Mountains on the edge of the Sahara Desert water scarcity has always been a problem for agricultural production. During the last ten years a drought has aggravated the situation of farmers in the Drâa oases. In 2005 annual reservoir releases were 115 million cubic meters which is only half of the average releases during the years 1972 to 2005 (Direction Générale de l'Hydraulique 2006). This has had large influences on the cultivation patterns and the production behavior of farmers in the Drâa oases.

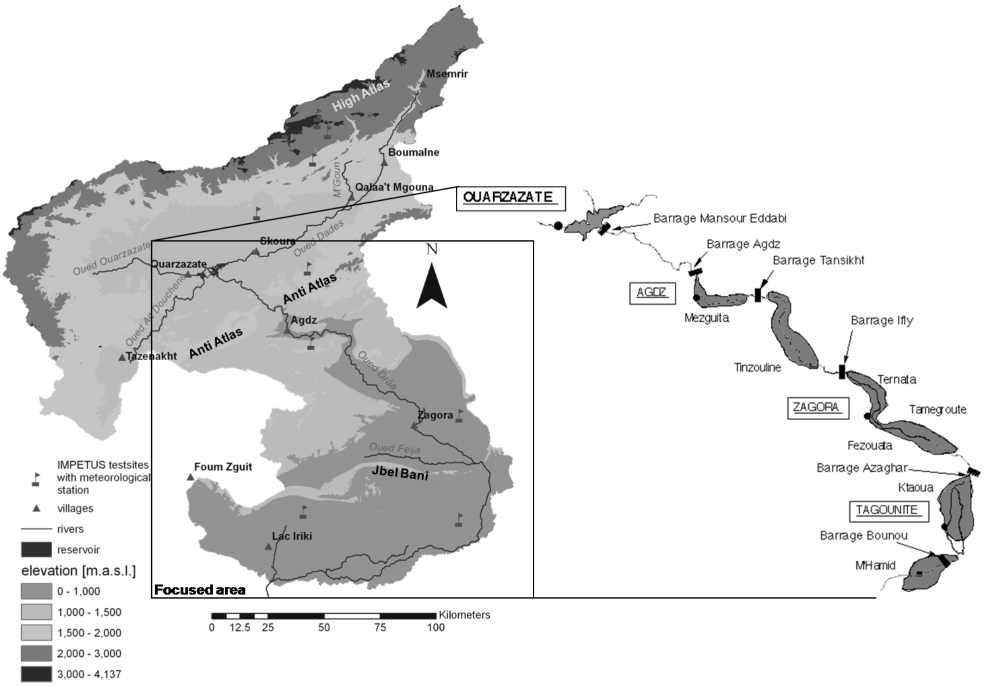
The aim of this chapter is to identify the key features of agricultural production and irrigation that need to be considered for the assessment of water management options and future development possibilities of the Middle Drâa valley. The chapter shall provide a background for the construction of an integrated model for the Drâa valley and its key elements. To be more precise this chapter analyses the specific characteristics of agricultural production, land and irrigation water use in the six Drâa oases. This analysis is based on statistical data from local offices and results of a survey conducted by the author in 2005. During the survey, 115 farmers were asked about their behavior and production structure. This was done in order to develop a model based on current practices and adaptation possibilities. Hereby, the relationship between water availability, cultivated area and crop yield is a key element for the adjustment of agricultural production under water stress. To measure economic performance an assessment of gross margins of the main crops based on empirical data is presented. Further, it is analyzed whether it is possible to estimate water input demand functions based on the empirical data.

The chapter is developed along the following path: First the survey construction and implementation is described. Afterwards the farm structure of the six oases and the sample of the survey are presented. In the next step production for major crops in the Drâa valley namely date palms, cereals, fodder, vegetables and henna are depicted as well as livestock production. Then, production costs and gross margins are calculated and discussed. Based on the survey, an attempt is made to estimate a production function with an Ordinary Least Squares (OLS) regression. Difficulties for using these estimations are addressed. Farmers' strategies to cope with water shortages are presented together with an analysis of secondary data available on the province level. The conclusions at the end of this chapter derive essential requirements for the MIVAD modeling approach that is used in the following chapters.

3.2 *Farm structure*

The farm survey presented in Annex 2 at the end of this thesis was carried out along the Drâa River in all six oases of the Middle Drâa valley: Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua, and Mhamid (from north to south along the River Drâa) as depicted in Figure 3-1.

Figure 3-1: The Drâa catchments and the six Drâa oases



Source: Klose et al. 2008

The interviews took place in October and November 2005 with the help of two translators who translated from Tashlahit, the language of the Berber, or Arabic into French. Altogether, 115 interviews were conducted with approximately 20 farmers per oasis, all from different villages within one oasis. The villages were chosen according to their location to account for differences in soil quality which depends on the distance to the river bed. Additionally, differences in water supply were considered by taking villages upstream and downstream along the River Drâa into the sample. Three to four villages were thus chosen per oasis. The time of the survey was the peak of a drought season of several years where farmers had lost most of their harvests in previous years and were often unmotivated and rather pessimistic about their future. It has to be stated that the sample size of 115 farmers (0.64 percent of the farmers' population) is too small to be representative for the region with approximately 18,000 farms in total. Official data sets for agricultural production that distinguish between the six oases are rare and out of date. The most recent is the agricultural census from 1996. Hence, survey results provide a data update and comparisons and they offer an insight into agricultural production patterns, problems, and future challenges.

The Middle Drâa Valley is characterized by a 200 km belt of six aligned oases with a width that varies from 100 m to 10 km. The total surface of the six Drâa oases is nearly forty thousand hectare of which 26,118 hectare are arable land and irrigated (ORMVAO 1995). The Drâa catchment includes the Upper and the Middle Drâa valley. Only the six oases of the Middle Drâa valley are analyzed which are displayed in Figure 3-1 in the focus area.

The six oases vary in size and the number of farmers (compare Table 3-1). Ktaoua is the largest oasis with over 7000 ha of farmland. Mhamid, in the far south is the smallest oasis.

Table 3-1: Farmland, parcels and number of farmers in the Drâa oases

Oases	**Surface (ha)**	**Farmland (ha)**	**Field parcels (No)**	**Farm (No)**
Mezguita	3596	2419	30963	3225
Tinzouline	5864	4015	39349	3473
Ternata	7831	5858	47785	4244
Fezouata	5581	3825	32857	2857
Ktaoua	11032	7770	56905	3027
Mhamid	3305	2231	16089	1195
Total	37209	26118	223948	18021

Source: ORMVAO 1995, Ouhajou 1996

Most farmers live in the central oasis Ternata which is also close to the biggest city Zagora with 42,000 inhabitants. Agriculture in the Drâa valley is characterized mainly by subsistence farming. This means that farmers cultivate primarily for their own consumption and hence produce a large variety of crops. Different sorts of vegetables are cultivated within one field to assure a diversified diet for the family. Additionally, dates from palm trees are often sold on the local market and are sometimes even exported. In good years, other crops are also sold on the local market. However, market structures and infrastructure are poorly developed. The average farm size differs among the oases. Fields are split up in little parcels separated by date palms and small dams. According to the official data listed in Table 3-1 from 1995, the average farm size in the area is around 1.5 hectares per farmer which can be derived by a division of farmland by farms.

Survey results gave a higher average farm size of about six hectares per farm of which around five hectares were cultivated in 2005 (Table 3-2). This confirms the assumption that the survey is biased towards larger farms and that small farms are less represented in the survey or that farmers who participated in the survey misjudged the size of parcels cultivated on the farm. It might also be possible that farm size increased during the last ten years due to land transfer from farmers who left the area in course of migration but this was not explicitly noted by the farmers during the survey. In the survey the size of area was approached in different ways in order to get a better picture of the farm size and land cultivated in the oases. First, the total area in hectare was recorded if farmers knew their farm size in hectare units. As this was rarely the case, the number of parcels of each farmer and their maximum and minimal size were noted. According to these results an average parcel is half a hectare. Additionally, the parcels under cultivation for each crop were noted in square meters. From this the hectares cultivated in 2005 are derived in Table 3-2.

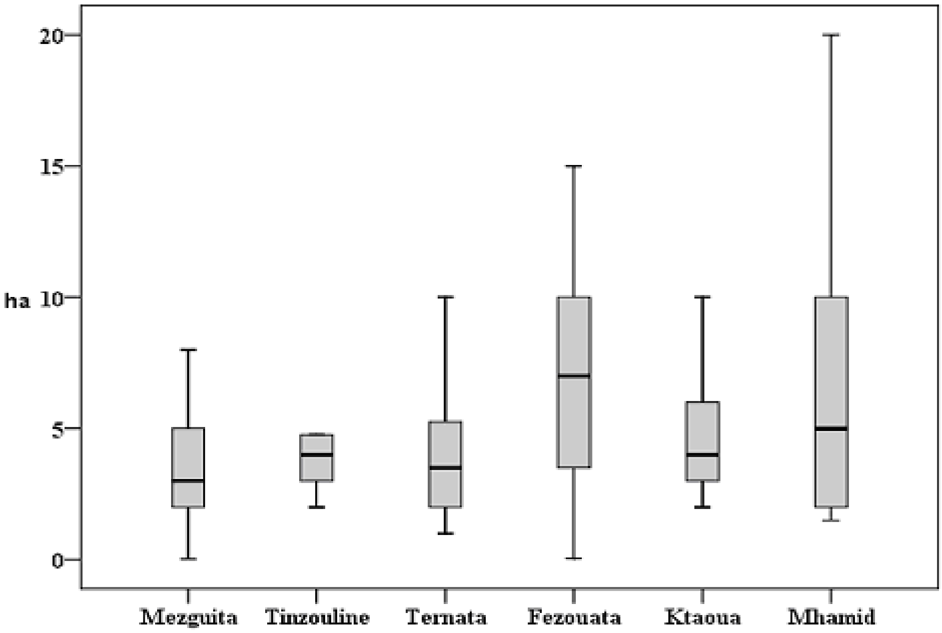
Table 3-2: Average farm sizes and parcels per farmer and oasis according to the survey in 2005

Oases	**Hectares per farm**	**Hectares cultivated in 2005**	**Number of parcels per farm**	**Size of biggest parcel (m^2)**	**Size of smallest parcel (m^2)**
Mezguita	5.2	6.5	11.1	4,217	2,187
Tinzouline	4.7	4.5	9.9	8,945	500
Ternata	6.4	6.2	14.0	5,198	278
Fezouata	9.5	7.2	13.4	14,221	2,101
Ktaoua	7.3	2.7	16.5	4,683	286
Mhamid	5.2	2.0	7.3	22,513	4,110
Average	6.4	4.9	12.3	9,793	1,516

Source: Survey 2005, N= 115

Regarding the box whisker diagram in Figure 3-2 farm sizes also vary greatly within the oases. The black lines in the bar diagram represent the maximum and minimum values that do not fall into the box which represents the upper and lower quartile.

Figure 3-2: Average farm size per oases and variation in hectare



Source: Survey 2005

It can be summarized that the farm structure within the oases is very heterogeneous. Farm sizes range from a few square meters to several hectares. Differences between the oases are also found as arable land and the number of farmers vary. Each oasis provides a living area for at least 1000 farmers at minimum.

3.3 Land use and livestock

In the following, differences of agricultural production between the six oases are pointed out. Furthermore, a quantification of agricultural production is attempted by calculating the average crop yield, average water use per crop and hectare, and average fertilizer and labor input per hectare. The derived production information is necessary for establishing and verifying the assessment model used in the remaining chapters. The cropping mix alters from north to south as depicted in Table 3-3 according to official data from the agricultural office ORMVAO for the agricultural year 1993/94. Whereas in the northern oases maize is still cultivated during the summer months, it is hardly found in the southern oases. Also, lucerne, vegetables and henna which are very water intensive are cultivated less in the southern oases.

Table 3-3: Crops cultivated in 1993/94 in the Drâa oases in hectares

Oases	**Cereals**	**Maize**	**Vegetables**	**Legumes**	**Lucerne**	**Henna**	**Total**	**Number of date palms (in 1000)**
Mezguita	2,600	200	95	75	850	120	3,740	271
Tinzouline	1,900	100	215	40	550	150	2,855	184
Ternata	4,700		692	36	1,190	180	6,798	330
Fezouata	2,200		77	5	510	40	2,832	254
Ktaoua	4,900		225	58	550	60	5,803	245
Mhamid	1,900		35	22	200	0	2,157	131
Total	18,200		1,349	236	3,850	550	24,185	1,417

Source: ORMVAO 1995

The southern oases are primarily characterized by date palm production as well as cereal production in the winter months. Altogether, cereals make up 90 percent of the crops cultivated in total, lucerne five percent, the rest is for a mixture of vegetables and henna, and a minority of some other crops that are not taken into account in this analysis. This cropping mix changes depending on water availability.

In the following, the principal crops and livestock keeping are characterized in more detail using survey results. The quantity harvested and the amount of input factors were recorded and divided by the total hectare per crop and farmer. Then, the average is derived over all oases. Maximum and minimum values are equally presented with the analysis together with the number of observations (N) which vary depending on the input used. The amount of surface water used per crop is only recorded by some farmers as surface water was hardly available in 2005. Surface water use is derived by the number of lâchers the farmers received and used for the irrigation of the specific crop. It is assumed that with one lâcher a farmer receives approximately 1000 cubic meters per hectare which is a rough approximation but is an average estimated for the allocation of one lâcher by Ouhajou (1996). The amount of groundwater used for irrigation of specific crops is easier to investigate as farmers generally know the hours they turn on their motor pumps. The cubic meters of water used is calculated based on the assumption that, on average, a pump delivers 17 cubic meters per hour (Klose 2005).

Date palms

The major characteristic of the Drâa oases is the cultivation of date palms, providing the only cash crop. Palm trees are grown on the field together with crops and sometimes small bush trees such as grenadines or figs which characterizes the cultivation in different layers (Toutain 1977). Palm trees are an important feature for agriculture as they provide micro climatic conditions for other cultivation layers, decrease wind erosion and evaporation through shade. Date palms are an important source for nutrition as they are rich in sugar, vitamin B, C and D and are rich in salt minerals (ORMVAO 2003a). Altogether over 1.4 million date palms can be found in the region as presented in Table 3-4. But from a number of over 15 million palm trees at the beginning of the 20th century, the situation has changed drastically due a specific palm tree illness called Bayoud, water stress and the aggradations of sand from the Sahara Desert (ORMVAO 2003b).

Table 3-4: Date palms in the six Drâa oases

Oases	**Number of date palms (in 1000)**	**Density (trees/ha)**	**Productive trees (%) in 1981**	**Number of trees affected by Bayoud (%) in 1981**
Mezguita	271	112.5	0.64	10.73
Tinzouline	184	47.9	0.66	12.14
Ternata	330	56.3	0.68	5.08
Fezouata	254	68.8	0.64	10.49
Ktaoua	245	31.0	0.61	7.09
Mhamid	131	59.2	0.70	7.29
Total	1,417	54.6	0.65	8.48

Source: ORMVAO 1981, ORMVAO 1995

Sixty percent of the existing palm trees can be classified as productive palm trees in 1981. On average 54 trees per hectare are cultivated. This density decreases from north to south. On average a farm possessed 155 trees in 1981 (ORMVAO 1981). According to the survey in 2005 an average of 293 trees per farm is derived which underlines that the survey is biased towards large farms. Table 3-5 summarizes production characteristics based on survey information. On average a farmer cultivates 68 trees per hectare. Average yield per hectare is around 565 kilograms, but yield per tree provides a more reliable picture. On average palm trees can yield 18 kg per tree in the southern regions of Morocco (ORMVAO 2003b). In 2005, due to water scarcity, the yield decreased to 12 kilogram per tree on average.

Cultivated in between other crops, date palms are mainly irrigated indirectly with other plants in normal years. In times of scarcity farmers tend to irrigate trees only. This has two reasons: First of all, trees are perennial crops so they have a long term value for farmers, and second it is the major income source from agriculture.

Table 3-5: Characteristics of date palm production in the Drâa valley

N = 115	**Average**	**Minimum**	**Maximum**	**N**
Trees per farmer (No)	293	15	2,200	115
Yield per ha (kg/ha)	565	0	9,800	92
Yield per tree (kg/tree)	12	0	107	92
Surface water (m^3/ha)	681	81	1,000	15
Groundwater (m^3/ha)	96	6	255	38
Labor (DH/ha)	464	8	5,357	27

Source: Survey 2005

The water applied in Table 3-5 refers to water use by date palms only when they are irrigated solely without other crops. This leads to comparable small amounts of irrigation water use by trees, but it has to be kept in mind that date palms generally profit from the infiltration of water applied to other crops. Labor costs for date palm production are mainly incurred at the time of the harvest. Special workers climb up the trees and cut fruits with a knife from date palms that can grow up to 30 meters.

Date palms are sold frequently on the local market. In a dry year when yields are poor, most dates are used for own consumption or for fodder for animals. During the last few years the importance of palm trees as a cultural heritage and economic good has been increasingly recognized. Research projects and organizations have invested in the research of the illness Bayoud and palm tree production (ORMVAO 2003b).

Cereals

The major crops cultivated on arable land are cereals. Winter wheat, barley and sometimes maize in the summer months are cultivated whereas winter wheat takes up by far the largest share (compare also Table 3-3). In the survey, average wheat yield is around 0.8 tons per hectare (see Table 3-6) which is very low compared to other years and other Moroccan areas. Bearing in mind that 2005 was a very dry year with enormous water scarcity, yields of cereals are lower than average yields for the region. Generally, yields are lower in the Drâa valley compared to other regions in Morocco and in the world as only small parcels are cultivated sometimes with a mixture of other crops and trees. In comparison, the average Moroccan yield is 1.4 tons per hectare and worldwide average is 2.8 tons per hectare (FAO 2008).

Table 3-6: Characteristics of wheat production in the Drâa Valley

Wheat	**Average**	**Minimum**	**Maximum**	**N**
Area (ha/farmer)	2.59	0.2	15	96
Yield (kg/ha)	868	50	4,000	96
SW (m^3/ha/year)	1,295	167	7,000	19
GW (m^3/ha/year)	2,540	100	14,280	57
Fertilizer (kg/ha)	365	22	7,500	40
Labor (DH/ha)	3,120	63	21,429	58
Barley				
Area (ha/farmer)	0.78	0.13	6	96
Yield (kg/ha)	607	28	3,333	52
SW (m^3/ha/year)	964	166	4,000	16
GW (m^3/ha/year)	1,375	322	16,320	27
Fertilizer (kg/ha)	118	22	341	17
Labor (DH/ha)	2,970	167	12,000	19

Source: Survey 2005

Fertilizer and labor input for wheat production are high compared to other cereals cultivated in the Drâa valley. Wheat and barley profit from much irrigation although they are less water intensive than vegetables or lucerne. Together with date palms wheat is of priority to the farmers as wheat is used for flour and homemade bred, an important part of the Moroccan diet.

Average barley cultivation is approximately 0.78 hectares per farm. Barley is used for consumption and fodder and is cultivated more in the southern than in the northern oases.

Maize is cultivated in the summer months from May until November and is only cultivated in the northern oases in rotation with wheat. Maize is primarily used for fodder. In 2005, maize cultivation was 0.41 hectare per farm.

Lucerne

Lucerne (alfalfa) is the most important crop for fodder production in the Drâa valley. Lucerne is a perennial plant and harvested up to seven times a year. In the Drâa valley, lucerne lives between three to five years. It is harvested in small bundles whereas each bundle weighs approximately 3 to 5 kilos, and is then transported by means of donkeys to the farm or households, respectively. The yield per hectare is difficult to measure as bundles vary between each farmer. Hence

Table 3-7 only provides an approximation as harvested bundles are converted into kilograms per hectare. On average farmers cultivate 0.78 hectare of lucerne. The estimated yield from the survey is around one ton per hectare and year.

Table 3-7: Characteristics of alfalfa production in the Drâa Valley

	Average	**Minimum**	**Maximum**	**N**
Area (ha/farmer)	0.78	0.1	10	96
Yield (kg/ha)	1,144	107	9,000	48
GW (m³/ha/year)	540	27	5,787	42
Labor (DH/ha)	2,720	105	9,000	11
Fertilizer (kg/ha)	292	16	1,500	28

Source: Survey 2005

Vegetable

Vegetables are cultivated primarily for household consumption. Some farmers have sufficient production to sell a part on the local market but in general family members harvest from the field what they need for the day. Different vegetables are cultivated within one parcel mixing carrots, potatoes, pulses, tomatoes, and onions on the same field.

Table 3-8: Characteristics of vegetable production in the Drâa Valley

N=71	**Average**	**Minimum**	**Maximum**	**N**
Area (ha/farmer)	0.46	0.13	3	96
GW (m³/ha/year)	1,076	103	5,312	18
Labor (DH/ha)	2,676	320	8593	10
Fertilizer (kg/ha)	151	13	520	20

Source: Survey 2005

An aggregate of vegetables is presented in Table 3-8. Therefore, yield per hectare cannot be directly observed. Although 2005 was a dry year, all farmers cultivated some vegetables with an average of 0.46 hectare per farm.

Henna

Henna is an ancient plant in the Drâa valley. It used to be exported but the production was reduced as it is not able to compete with production from other parts of Morocco and North African countries. Nevertheless, a small amount is still cultivated for the farmers' own consumption, and is used as color for handicrafts and traditional hand paints. As its cultivation requires a large quantity of water, cultivation of henna is only practiced in the northern oases and has been overall reduced during the last few years. Only ten farmers cultivated henna with an average of 0.65 hectare per farm.

Livestock production

Livestock is of great traditional importance in the Drâa valley. Livestock is not only a source of income, but also plays a role with regard to food supply, hedging and prestige. A high number of cattle, sheep and goats assure the meat consumption of a large part of the local population.

Transhumance is practiced in the total area of the ORMVAO as the High Atlas Mountains and Anti Atlas Mountains provide wide pastures for grazing. In the Drâa oases a smaller number of livestock is kept near the house which profit from fodder cultivated in the oases, namely alfalfa, barley, dates, maize, but also leftovers of food from the house. Based on data from 1981, it is estimated that the fodder is composed by 60 percent of alfalfa, by 30 percent of dates, by 11 percent of straw, and the rest by maize leaves (ORMVAO 1981). Table 3-9 shows the number of cattle, sheep and goats in the Drâa oases that are kept on the farm. This does not include herds for transhumance. Sheep are the most important animals, the number of goats and cattle is significantly smaller.

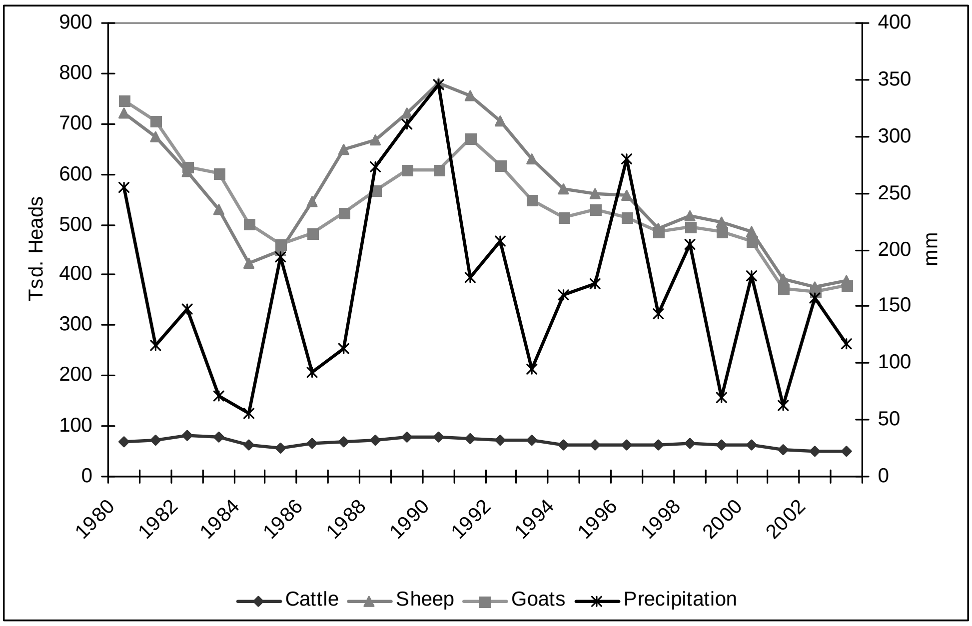
Table 3-9: Livestock in the Drâa oases in heads

Oases	**Cattle**	**Sheep**	**Goats**
Mezguita	3,233	12,832	1,909
Tinzouline	4,291	17,584	2,118
Ternata	4,291	16,326	846
Fezouata	3,382	11,951	410
Ktaoua	1,707	13,544	2,881
Mhamid	420	5,520	1,920
Total	17,224	77,757	10,084

Source: ORMVAO 1981

The number of animals is subject to yearly fluctuations due to varying forage availability as a consequence of precipitation availability. This is mainly due to the latent water stress of plants. Precipitation tends to trigger the development of important herbaceous plants. The correlation of water or precipitation to the number of livestock becomes obvious in Figure 3-3: the total number of livestock for the Upper and Middle Drâa valley including transhumance is related to precipitation.

Figure 3-3: Livestock in the Drâa region and precipitation from 1980 to 2003

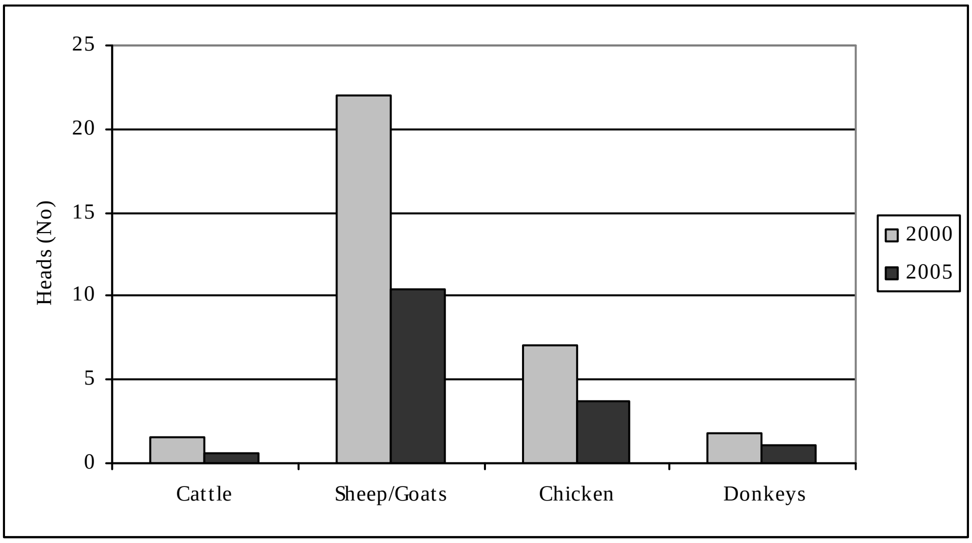


Source: Heidecke and Roth 2008, data from ORMVAO (1980-2003)
Note: Livestock numbers refer to the number of animals in the province of Ouarzazate and Zagora, therefore the number of animals in total is higher than for the Drâa valley only

A high correspondence to water availability is visible. From the mid-1990s the number of goats and sheep decline constantly due to the continuing drought. The number of cattle is also declining. As cattle are not used in transhumance they do not vary to the same extent as sheep or goats (Heidecke and Roth 2008).

In times of water scarcity, animals are sold, or die from illnesses or starvation. Figure 3-4 shows the number of livestock per farmer in 2005. Additionally, the number of livestock in the year 2000 is presented based on information by the farmers. In particular, cattle, sheep and goats were reduced immensely during that time period.

Figure 3-4: Number of livestock per farmer in the Drâa oases in 2000 and 2005



Source: Survey 2005

The relation of livestock to precipitation underlines again the importance of water availability in the Drâa valley and the economic value of water in the region.

3.4 Production cost analysis

Income from agriculture is difficult to obtain or to calculate as farmers do not record their costs and revenues. Many farmers are illiterate and have problems to calculate their income. Furthermore, income is always a difficult topic to ask for in an interview. However, as neither official income data nor revenue estimations exist for the rural population in the region, a calculation approach of gross margins is even more important. Additionally, calculations can be used to validate model results of an optimization model which aims at maximizing agricultural income. This section analyzes variable production costs for the major input factors, water, fertilizer and labor.

As we have seen, agricultural production relies on irrigation water. Farmers have increasingly established wells with motor pumps to stabilize water availability (see also Chapter 2). Motor pumps consume fuel and oil. Additionally, costs for operation and maintenance of pumps are incurred each year. The variable costs for groundwater pumping were analyzed by means of the farm survey. Table 3-10 summarizes the results for the amount of water pumped on average per day and total costs of groundwater pumping (including gas, oil, and operation and maintenance costs) in Dirham (DH) assuming that on average motor pumps delivers 17 cubic meters per hour.

Table 3-10: Costs for groundwater exploitation

Oases	**Cubic meters (m³/day and pump)**	**Total cost (DH/m³)**
Mezguita	127.84	0.63
Tinzouline	88.45	0.63
Ternata	76.50	0.62
Fezouata	127.5	0.49
Ktaoua	34.27	0.46
Mhamid	55.13	0.63
Average	84.95	0.58

Source: Survey 2005, Heidecke 2008

On average this results in pumping costs of 0.58 Moroccan Dirham per cubic meter, which is approximately 2 US cents per cubic meter. For the farmers in the oases this is already a large share of their direct production costs and increases their consciousness for the value of water. This is also reflected in a willingness to pay study conducted in the area (Storm 2009) which showed that in general farmers are aware about their irrigation costs, especially for groundwater, and are even willing to pay more for water in times of water scarcity.

Farmers basically use two types of fertilizer. One is a general nitrate-kali-phosphate compound fertilizer. Additionally, farmers use an ammonium-phosphate fertilizer. Both fertilizers are bought on the local markets in bags of 50 kilograms whereas each bag costs 100 Dirham. The amount of fertilizer applied to each plant has been investigated above.

Seasonal workers are sometimes employed although farms are small and farmers should have enough labor provided by family members. Therefore, labor costs are comparably high for subsistence farming, which seems to be astonishing at first sight. But peak harvest seasons and irrigation schemes require a great deal of labor input. Farmers who receive money from remittances of migrated family members or micro credits use theses funds to finance additional labor, especially during peak seasons of the harvest of cereals and dates.

Machinery used is treated as a variable input factor. Farmers in general do not own machinery to work their fields. A few tractors available in each oasis are rented out to farmers for 100 Dirham per hour. Therefore, variable costs for machinery are easy to calculate and are thus included in the gross margins calculation.

Costs for seeds vary between the crops. They are often provided by the regional agricultural office ORMVAO. Table 3-11 presents a calculation of the gross margin of wheat assuming that the entire harvest is sold on the local market. Although production for own consumption is often practiced, this assumption of prices is necessary to remunerate production for economic analysis.

Table 3-11: Gross margin of wheat per ha in the Drâa valley in 2005

	Unit	**Quantity in survey**	**Price per unit**	**Total costs from survey (DH/ha)**
Tractor	h	10	100	1,000
NPK	kg	365	2	730
Irrigation	m³	2,540	0.58	1,473
Seeds	kg	2	400	800
Labor	DH			3,120
Total costs	DH/ha/year			7,123
Total revenues	DH/ha/year	868	4	3,472
Gross Margin	DH/ha/year			**-3,651**

Source: Survey 2005
It is assumed that the entire harvest is sold on the local market. Results are based on averages over a sample of 115 farmers with high variations (see above). The year of the survey was a very dry year leading to lower yield of wheat than average.

In the gross margin calculations from the survey data, labor is a very costly input factor although farmers earn hardly any money from agricultural production. Negative gross margins are however quite common in times of scarcity as farmers have often already invested in fertilizer and seeds, but because of the water shortage do not receive the expected yield. Another explanation is that farmers are not aware of their losses as they do not keep accounting records. Table 3-12 summarizes gross margins for wheat, date palms, alfalfa and barley that have been calculated from the survey data.

The highest gross margins are obtained by date palm production. This is due to the high market price of date palms which varies according to the quality but has been set at an average price of 10 Dirham per kilogram for this calculation. In addition, production costs are low for date palms as date palm production does not require fertilizer, seeds or machinery input. Hence, the only variable production costs are water and labor for harvest.

Table 3-12: Gross margins for major crops in the Drâa valley in 2005 in DH per Hectare

	Dates	**Wheat**	**Barley**	**Alfalfa**
Costs (DH/ha)	520	7,123	4,003	3,617
Revenues (DH/ha)	5,650	3,472	2,428	2,288
Gross Margin (DH/ha)	5,130	-3,651	-1,575	-1,329
Gross Margins without Labor costs (DH/ha)	5,595	-531	1395	1391

Source: Survey 2005
It is assumed that the entire harvest is sold at 10 DH/kg for dates, 4 DH/kg for cereals and 2 DH/kg for lucerne.

The gross margin calculations reveal that in times of water scarcity farmers might even make losses depending on the crops they cultivate and the quality of the date palm harvest. The cost analysis shows that around twenty percent of the production costs are due to groundwater pumping in the year 2005. However, a harvest of wet years might change the picture completely. To be able to assess the living conditions in the Drâa valley and to be able to draw conclusions from the economic impact of climate change in the region, an economic valuation of the different crops in the area and their input factors under different climatic conditions are important to develop a assessment model which endogenously adjusts the cropping pattern as a reaction to water scarcity and other external factors.

3.5 Production estimation

Regarding yield formation, survey results are evaluated with a focus on input factors and crop yields of wheat. Yield formation of wheat is then estimated using OLS regression with groundwater and fertilizer use as explanatory variables. Table 3-13 summarizes the cross regional correlation according to Pearson for crop yield of wheat and for different input factors of wheat over all oases. Wheat is picked as an example as it is the major crop cultivated in the oases besides date palms and it provided the most reliable survey results. According to the survey wheat yield is highly correlated with groundwater use and fertilizer as presented in Table 3-13. Surface water is also highly correlated with yield but due to lack in observations this correlation has to be treated with caution.

Table 3-13: Pearson correlation between yield and input factors for wheat

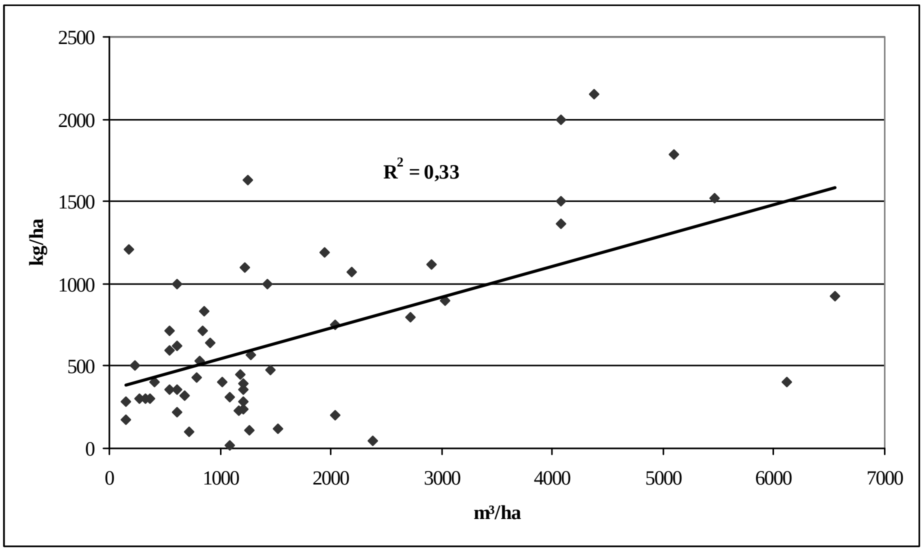
	Yield	GW	SW	Fertilizer	Labor
Yield	1				
Groundwater	.365** (57)	1			
Surface water	.812** (19)b)	a)	1		
Fertilizer	.719**(40)	.451*(30)	.246 (3)	1	
Labor	- .127 (58)	.367*(40)	.742 (7)	.087 (34)	1

Source: Estimated on the basis of survey results, 2005
*Note: ** The correlation is significant on a 0.01 (2-sided) level.*
** The correlation is significant on a 0.05 (2-sided) level.*
a) Could not be calculated as only one matching pair was available
b) Number of observations in brackets; for surface water only 19 observations were available

Labor is not significantly correlated with yield. This is not surprising as labor input is difficult to quantify as specifications between family and employed labor are missing.

Survey data reveals that the relation of wheat yield and groundwater input is highly variable as shown in Figure 3-5. This is also reflected in the very low coefficient of determination for the linear trend line.

Figure 3-5: Relation of groundwater water use and wheat yield (N=57)



Source: Survey 2005, all farmers using no groundwater are excluded.

Some outliers seem to use a large quantity of groundwater but only produce a small crop yield, while others have higher crop yields although they claim to have used little groundwater for irrigation.

Only groundwater is included in the analysis, as surface water is not reliable due to different sizes in channel systems and hence different water flows. This makes it difficult to compare yield formation and water used. The amount of groundwater was calculated by the number of hours a motor pump is working multiplied by the cubic meters an average motor pump delivers measured by Klose (2005).

Estimation results for a simple Ordinary Least Squares (OLS) regression, by including groundwater and fertilizer as explanatory variables, shows that the multiple correlation coefficient is $r = 0.56$. The coefficient of determination which is the proportion of variability in the data set that is accounted for by this regression is $R^2 = 0.33$.

Table 3-14: Factors determining wheat yield - results of ordinary least squares regression (OLS)

Regression-Statistics	
Multiple correlation coefficient (r)	0.57
Coefficient of determination (R^2)	0.32
Standard error	654
Number of observations	67

	Coefficient	**Standard error**	**T-Statistics**	**P-value**
Intersection	663.01	101.92	6,504	1,36E-08
Groundwater per ha	0.07	0,.027	2,425	0,0181
Fertilizer per ha	0.45	0.088	5,099	3,26E-06

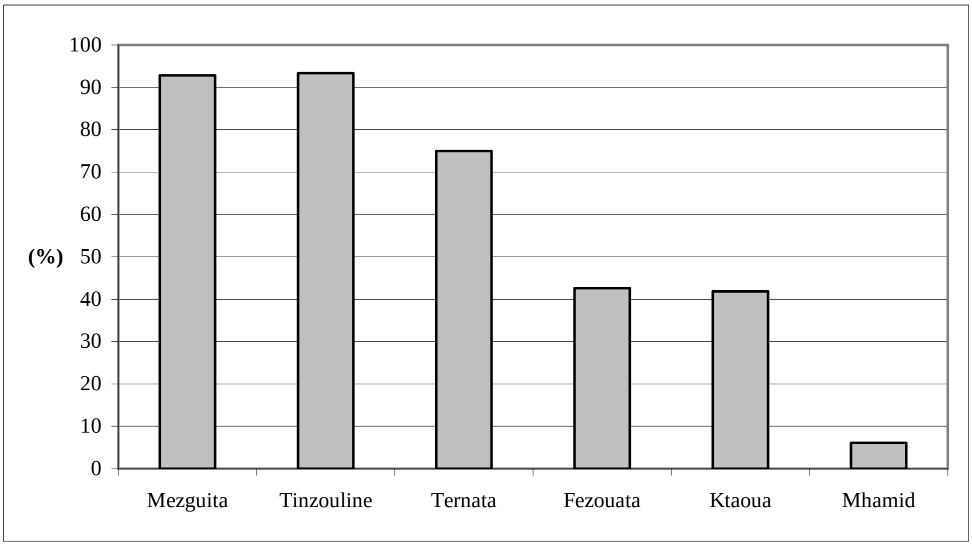
Source: Survey 2005, own estimations, only observations have been considered where at least groundwater or fertilizer were included as input

A sample size of 67 observations is included in the estimation. All input factor have significant coefficients. As only groundwater is included the use of this estimation for a yield production function to be included in a simulation model seems inappropriate, as surface water is also a major input factor in wet years. Furthermore, this function does not include water quality aspects of irrigation water as this is difficult to determine without measuring the electric conductivity for each well. For the construction of a river basin model, yield functions for all crops cultivated would be needed. However, the survey data did not provide reliable results for their estimation. Therefore, a method representing physiological relationships of plants seems to be more appropriate for the modeling approach.

3.6 Farmers' behavior and strategies under water scarcity

In times of water scarcity farmers tend to reduce their cultivated area. In 2005, when the survey was conducted, farmers had faced a period of severe drought for several years. The northern oases Mezguita and Tinzouline still profited from groundwater use for irrigation. The southern oases, Fezouata to Mhamid, had neither surface water nor groundwater of good quality to be able to irrigate their entire fields. Figure 3-6 displays this problem. Fezouata, Ktaoua and Mhamid only cultivated forty percent or less of their total cultivable area in 2005.

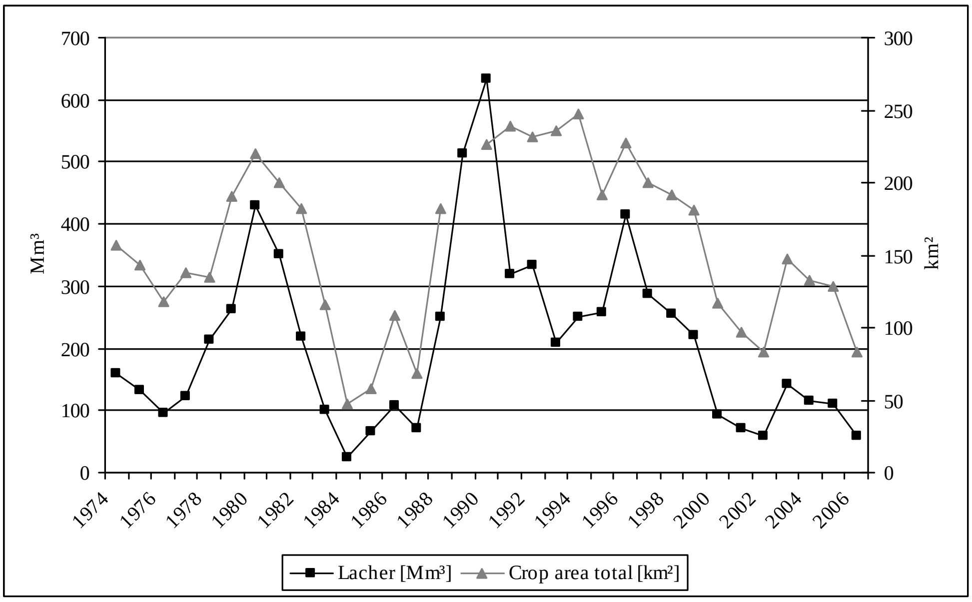
Figure 3-6: Percentage of area cultivated in 2005



Source: Survey 2005

Comparing this with official data available of the last three decades for the Drâa valley in Figure 3-7 a strong relation between the water available in form of lâchers and cultivated land in square kilometers is noticeable.

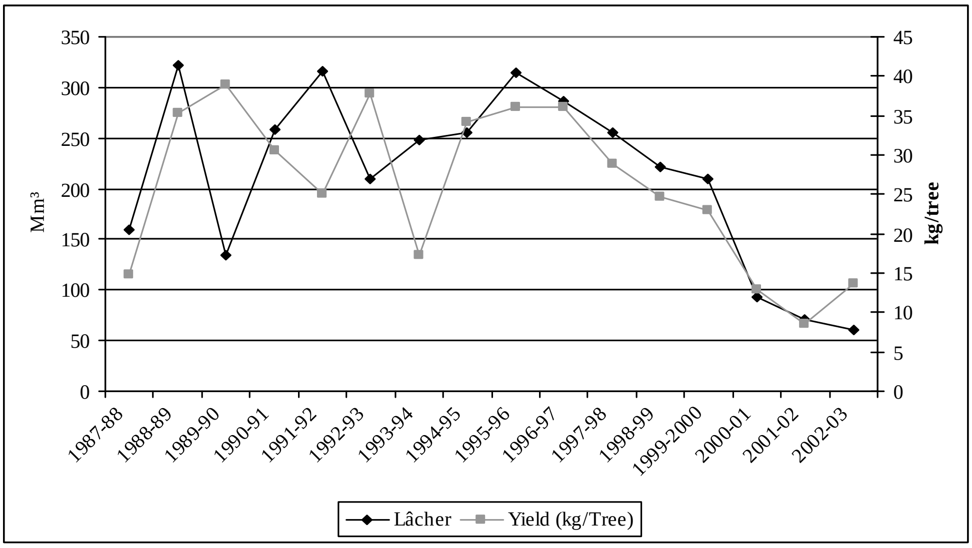
Figure 3-7: Relation of water availability and area cultivated from 1974 to 2006



Source: ORMVAO 2003c

Here, lâchers and agricultural area are highly correlated r = 0.83. In addition precipitation lâchers of the reservoir are plotted against crop yields of date palms during the last decades (Figure 3-8).

Figure 3-8: Relation of surface water availability and yield of dates in deci tons per tree from 1978 to 2003

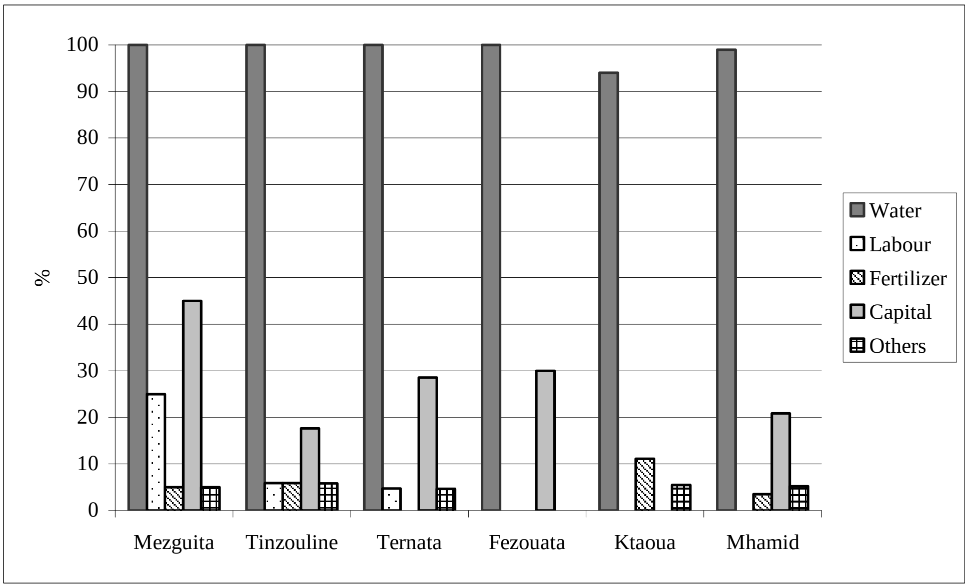


Source: ORMVAO 2003c

Yields of date palms, measured in kilogram per tree, are highly correlated to the amount of available surface water (r= 0.65).

Since water is essential for agricultural production, farmers' behavior and production strategies are strongly related to climatic conditions. Time series underline that there is a high relationship between the available water and agricultural production. Yield and the area cultivated correspond to water availability in the region. Moreover, the survey confirmed that from the farmer's point of view the major production constraint is water as indicated in Figure 3-9. Capital is also observed as a production constraint but is not assigned the same importance as water.

Figure 3-9: The major production constraints in percent %

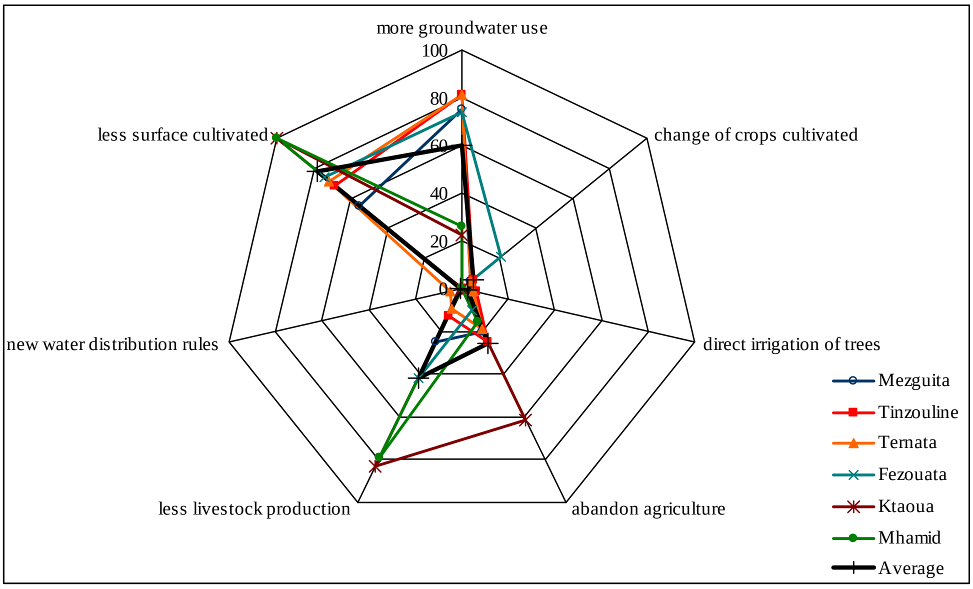


Source: Survey 2005
Note: Multiple answers possible. Percentage indicates the percentage of farmers responding to the option positively.

Insufficient capital and labor are recognized as additional production constraints especially in the oasis Mezguita. As this oasis is one of the richest in surface water availability and good groundwater quality, more capital and labor input might help to develop agricultural production. As the southern oases suffer from the greatest water scarcity, the importance of other production factors and the appraisal of other constraints than water availability are by far lower than in the north.

Under extreme water scarcity, the main reaction of the farmers is to reduce land under cultivation; also important is the reaction to increase the use of groundwater for irrigation as can be seen in Figure 3-10. This is also reflected in the increase of the number of motor pumps and the downing of groundwater tables during the last years of the drought. Furthermore, a reduction in livestock is an option to deal with water scarcity as animals consume a great deal of fodder which is highly water demanding.

Figure 3-10: Farmers reaction under water scarcity



Source: Survey 2005
Note: Multiple answers were possible.

Information on other saving options for farmers is not available for the Drâa valley as farmers hardly practice accounting. However, survey results by Storm (2009) in the oasis Ternata reveals that 67 percent of farmers in the oasis Ternata receive income also from other sources than agriculture. From these 67 percent, the major alternative income sources are remittances from sons (50 percent) and other jobs than agriculture (47%). These alternative income sources are often used to survive periods of drought and to invest in farming although profits are instable. This also explains the possibility of negative gross margins in times of scarcity.

3.7 Conclusions and consequences for modeling

This chapter discussed the survey results and focused on the problems related to agricultural production under water scarcity and farmers' reaction to water shortages. To summarize the strengths and weaknesses of agricultural production in the region it can be stated that the Drâa valley provides food and additional income for a large part of its rural population. The Drâa valleys scenery with date palms and small agricultural farms provide the background for tourism and has hence a specific economic value. Agriculture as practiced nowadays is, however, immensely affected by water availability. In times of water scarcity agricultural production is not lucrative for the farmers especially with water intensive crops. Thus, farmers either reduce the area cultivated or change their cropping patterns. Latter is practiced in the abandonment of the cultivation of summer crops or vegetables throughout the year. During the last few years the number of date palms decreased due water scarcity and resulting tree illnesses. Altogether, yields have risen during the last years due to fertilizer availability, but crop yields remain weak compared to other areas of the world. Agriculture provides a subsistence level and an activity for many people who would otherwise be unemployed. Hence, it is of importance to assess the future development of the region, in particular to analyze climate change effects on land use and on the population and to discuss water management options. On the basis of this chapter the following conclusions can be drawn which have to be considered for the hydro-economic modeling approach in the remainder of the thesis.

(i) It could be shown that the six oases are seperate entities that should be regarded separately within a modeling approach. Chapter two depicted the differences of water resources endowments of the oases, of water quantity as well as water quality. This chapter has identified particularities in agricultural crop production with a gradient from north to south and different cropping patterns for each oases. For example, maize which is still cultivated in the northern oases is not cultivated in the south. Each oases should thus be considered as a single production system.

(ii) Furthermore, the chapter has shown that the major crops cultivated in the Drâa oases are palm trees, wheat, barley, lucerne and a mixture of vegetables. Maize and henna production play only a small role in some oases. A distinction should also be made between lucerne and date palms as perennial crops, in contrast to annual crops which are easier to adjust from one year to the next.

(iii) It could be shown that livestock is kept on the farms. Livestock varies according to fodder availability. Hence, fodder production should be represented within a modeling approach.

(iv) The evaluation of production costs and gross margins showed that a difference exists from an economic point of view between groundwater and surface water resources. Surface water is free of charge whereas costs are incurred for pumping groundwater. Hence, groundwater use is less attractive than surface water use, especially in view of the fact that groundwater quality is often worse due to problems of salinity. Nevertheless, in 2005 groundwater was often used to sublement surface water as surface water was not sufficient to fullfill crop water demand.

(v) Water is an essential input factor for agricultural production and also constitutes the major production constraint. This relationship could, however, not be obtained for all crops in the Drâa valley. The model has to account for the relationship between surface and groundwater regarding quantity and quality aspects; thus, yield formation should be represented by physiological relationship of the plants. Furthermore, water quality plays a great role in yield formation. A farm profit function that adjusts crop yield according to water quantity and quality, and determines crop land at the same time, would result in a more realistic analysis of farm adaptations to water scarcity.

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4 Simulating groundwater charges for the Moroccan Drâa River Basin[5]

Abstract

تقييم ضريبة على المياه الجوفية في منطقة الدرع جنوب المملكة المغربية
كلوديا هايدك وأرمين كهون
الخلاصة: تعتمد الزراعة في الواحات الستة في منطقة الدرع جنوب المملكة المغربية على المياه
الجوفية. تشتكي المنطقة من جفاف
متواصل خلال السنوات الأخيرة. نقص الأمطار مع زيادة نسبة التبخر نتج عنها نقصان في مياه وادي
الدرع. إضافة إلى الظروف
المناخية إزدادت نسب ضخ المياه الجوفية بالإستعمال الغير المراقب لمضخات المياه. تتميز المزارع
بصغر حجمها وهذا يزيد من
ضعف الإنتاجية زيادة على أن المنتجات في معظمها تذهب إلى الإستهلاك العائلي. لذلك فإن المداخيل
التي يتحصل عليها المزارعون
تفي بتغطية مصاريف الأسمدة وتكلفة ضخ مياه الري فحسب. تقدر كلفة ضخ المياه ب 0.58 درهم
للمتر المكعب والتي تقع على
كاهل المزارع. لا يدفع المزارعون أي أداء أخر للدولة مقابل ضخ المياه الجوفية. تظهر نتائج هذه الدراسة
أن أحد الحلول للحد من
إستنزاف المياه الجوفية هو إرساء ضريبة تقدر ب 0.42 درهم/م3. غير أن إرساء مثل هذه الضريبة
سينتج عنه تقليص المساحة
المزروعة بنسبة 50 بالمائة.

Agricultural production in the six oases in the Drâa Region in southern Morocco is highly dependent on irrigation using mainly traditional irrigation channels or motor pumps. The basin has been suffering enormously from a continuing drought during recent years. Declining rainfall and high evapotranspiration rates in the semi-arid region lead to lower flows into the Drâa River. Farmers increasingly pump groundwater with motor pumps, which lead to a rapid drop in the groundwater tables of the aquifer. However, agricultural production is economically inefficient and based on subsistence farming. The income a farmer gets by selling a share of his production on the local markets hardly covers the variable costs for fertilizers

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[5] This paper has been published in the Journal of Agricultural and Marine Science (2006), 11 (1), 47-54, Oman, together with Dr. Arnim Kuhn. It has been presented at the “International conference on economic incentives and water management” in Oman 17-22. March 2006.

and irrigation water. Farmers pay only the pumping cost estimated at 0.58 DH/m³. To prevent a further drop in the groundwater table, and hence to conserve water resources, the introduction of a water charge is evaluated with the MIVAD River Basin Model (RBM). This shows that imposing a water charge of 0.42 DH/m3³ leads to stable groundwater tables, but with a decrease in cropping area by 50%.

4.1 Introduction

Charging farmers for scarce irrigation water use is increasingly regarded as a means of encouraging efficient water allocation (Cornish et al. 2004). In this context, water pricing regimes have been established for most irrigation perimeters in Morocco in order to meet the needs for operation and maintenance of irrigation systems as well as to encourage investments in water-saving irrigation technologies. The Drâa valley is the only river basin where this national strategy has not yet been implemented (Serghini 2002). But as a consequence of the continued drought during the last few years, the supply of centrally distributed river water has become more and more unreliable, pushing farmers to increasingly rely on groundwater. This has inevitably led to declining of groundwater tables and an increase in salinisation. This paper aims at identifying a groundwater charge sufficiently high to substantially curb the downing of groundwater tables. For this purpose, the effects of pumping costs in the current situation as well as additional groundwater water charges on farm income and sustainable water availability in the region are simulated using an integrated River Basin Model (RBM). Empirical information on water costs and cropping profitability are obtained from a farm survey.

The paper is organized as follows. First, a brief overview of water pricing in other watersheds in Morocco is provided. Then, the Drâa River Basin water management is described. After a description of the research methodology the alternative water charges for agriculture in the Drâa valley are compared, followed by a conclusion. The results presented are based on an interdisciplinary research carried out by the IMPETUS project (available at: www.impetus.uni-koeln.de) which aims at an integrated assessment of the water cycle as well as water management alternatives for the region.

4.2 Irrigation and Water Pricing in Morocco

In 1969 the Ministry of Rural Development passed the Agricultural Investment Code (CIA) including a framework for the introduction of water prices for irrigation water in Morocco. Except for the Drâa basin, all other watersheds in Morocco have adopted water pricing schemes in the past years. Investment costs of irrigation water are shared between the general budget (60 percent) and the beneficiaries (40 percent), i.e. the farmers who are organized in newly established water user groups. The CIA determines the water charges in order to recover all costs of operation and maintenance (O&M) as well as depreciation. Table 4-1 shows the level of water charges in the different watersheds in Morocco.

Table 4-1: Irrigation rates and O&M costs for different agricultural regions in Morocco

ORMVA	Current water charges (DH/m³)	O&M Costs (DH/m³)
Moulouya	0.19 - 0.34	0.22 - 0.57
Haouz	0.17	0.14 - 0.22
Loukkos	0.40	0.46 - 0.66
Souss_Massa	0.38 - 0.50	0.25 - 0.89
Tadia	0.17	0.09 - 0.14
Doukkala	0.18 - 0.25	0.12 - 0.23
Doukkala	0.34 - 0.41	0.33 - 0.37
Gharb	0.19 - 0.40	0.24 - 0.44

Source: Tsur et al. 2004 Note: Irrigation costs for Large Scale Irrigation Systems, Rate of exchange to US$: 1Moroccan Dirham ~ 0.12 US$ (April 2006)

In addition to the volumetric water charges, farmers with more than five hectares of land are obliged to pay a fixed charge of 1500 Dirham per hectare and year. However, 80 percent of Moroccan farmers do not fit in this category. Altogether the Moroccan pricing system has contributed to the notorious under-financing of irrigation schemes (Serghini 2003). It can be seen that in most cases actual water prices are lower than needed to recover O&M (Tsur et al. 2004). Moreover, it is an open question as to whether the design and levels of the water charges are suitable to ensure a sustainable use of surface and groundwater resources by farmers.

4.3 Study Area: The Drâa River Basin

The Drâa river basin (see Figure 4-1) is one of Morocco’s smaller river basins located close to the Algerian border in the south-eastern part of the country. Its location between the High Atlas Mountains and the Saharan desert is characterized by low rainfall ranging from about 54 mm to 106 mm per year. During recent years droughts have seriously afflicted the region.

Figure 4-1: The Drâa catchment area

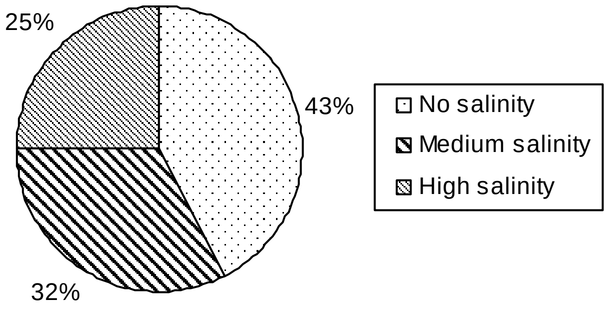
Along the Drâa valley there is a belt of six oases (see Figure 4-2), characterized by the cultivation of palm trees, cereals, different kinds of vegetables, and alfalfa and barley for animal forage. Most farms are of small size and are basically subsistence farms (Ouhajou 1996).

Figure 4-2: Belt of the six oases included in the survey

In 1972 a large water reservoir was built near the provincial capital Ouarzazate, gathering the river inflows from the mountainous areas. Since then, surface water distribution has been managed in a centralized manner where water is released periodically from the reservoir. Beyond its function as a buffer against shorter droughts and the production of hydropower, another purpose of the reservoir was to distribute water more evenly across the oases from north to south, giving the southern oases the chance to use water for irrigation first, while the northern oases had the advantage that their groundwater storage was filled up (Ouhajou 1996). Nevertheless, since 1990 river basins south of the Atlas Mountains have been characterized by negative hydrologic balances and these are likely to worsen further until 2020 (Ait Kadi 2002).

Until the beginning of the drought of the 1990's this centralized water management helped to stabilize irrigation water supply. But due to declining rainfall and high evapotransipration rates, water releases from the reservoir are becoming more and more scant and irregular, and are mainly intended to fill up groundwater levels of the aquifers below the oases. Consequently, mining of groundwater has increased considerably as a result of farmers digging private wells and installing motor pumps. Nowadays an average farmer owns two wells with motor pumps which run almost 12 hours per day during the cropping season, according to survey data. As a result the groundwater table has declined and salinisation has increased during the last few years (see Figure 4-3).

Figure 4-3: Problem of salinisation in the Drâa region as perceived by farmers



Source: Own Farm Survey, 2005; N= 60
Note: Data according to farmers own assumption of salinisation; measurements of electronic conductivity have been conducted in some cases for verification

To evaluate the impact of a water pricing scheme it is necessary to look at farmers' income margins to see whether farmers are able to cope with the increasing costs, in a short as well as in a long-term perspective. Table 4-2 illustrates gross margins for alfalfa and wheat with local prices and total production costs per hectare.

Table 4-2: Gross margins and production costs for wheat and alfalfa in the Drâa Basin

	Wheat	**Alfalfa**
Yields (kg/ha)	1,912	735
Price per kg (DH)	4	2
Total irrigation cost (DH/ha)	762	540
Machinery cost (DH/ha)	878	647
Cost for seeds (DH/ha)	679	581
Fertilizer cost (DH/ha)	1,037	275
Total variable costs (DH/ha)	3,356	2,043
Gross margin per ha	4,292	-573

Source: Farm Survey, 2005 and own calculations; N= 60
Note: Labor costs have not been taken into account. Moreover, it is assumed that irrigation costs are all variable costs (predominantly fuel) as farmers usually do not take the depreciation of motor pumps or other irrigation technologies into account.
Average gross margins are not weighted for individual farm sizes
Rate of exchange to US$: 1 Moroccan Dirham ~ 0.12 US$ (April 2006)

Gross margins for date palms are difficult to determine as variable costs were even more difficult to identify as compared to other crops. Gross profits are assumed to amount to approximately 200 Dirham per tree according to the survey results. Taking into account that farmers cultivate basically for self-consumption, the low level of the gross margins appears to be realistic, resulting in low remuneration for family work, but not leading to ‘visible’ monetary losses. However, with increased water costs, the negative gap widens. Many farmers, particularly those who do not cultivate date palms as cash crops will find it difficult to pay for additional water charges. As farmers will not stop the over-exploitation of groundwater until the aquifers are either depleted or salinized to an extent which makes water use for irrigation impossible, charging prices for groundwater use might be an option to curb the depletion of the common resource. However, as this price would have to be paid for from the already narrow agricultural profits, it is unlikely that water prices would leave the current size structure and performance of farms unchanged.

4.4 Methodology: the MIVAD model

The following section investigates two questions: which price level would preserve groundwater resources and thus enable oasis farming in the longer perspective, and which changes regarding the extent cropping activities would this price level require? Both questions can be answered by simulating alternative water costs with the MIVAD model (Modèle Integrée de la Vallée du Drâa), an integrated hydro-agro-economic river basin model (RBM, see also Rosegrant et al. 2000) for the Drâa Region. MIVAD is an economic optimization model which simultaneously maximizes agricultural and hydropower generation profits as well as consumers' utility from drinking water consumption (see Formula 4-1).

Formula 4-1: Objective function of the MIVAD Model

$$MAX\,(obj) = \left\{ \begin{array}{l} \sum\limits_{oases} Profit(\text{irrigation in agriculture}) \\ \sum\limits_{municip.} Utility(\text{drinking water use}) \\ \sum\limits_{powerst.} Profit(\text{hydropower generation}) \end{array} \right\}$$

The objective function of MIVAD is subject to a variety of constraints, represented by bounds and balance equations related to hydrology (river, groundwater and reservoir balances), agronomy (crop yield response, area and cropping patterns) and general technological aspects (hydropower, pumping by public and private agents) all of which have to be taken into account. Agricultural production is represented as an LP exercise involving six stylised 'oasis farms'. The response of crop yields on water stress is modelled by a modified Penman-Monteith function (Allen et al. 1998). Spatial relationships are represented in a node network representing different in- and outflows, reservoirs and water demand sites. Water distribution is modelled between the nodes. The network of the Drâa river basin actually starts with the inflow node that defines exogenously for each month the reservoir inflow.

The model is run over several years as a recursive-dynamic model, with each year divided into twelve months which are solved simultaneously. MIVAD is written and executed using GAMS (General Algebraic Modelling System). Data used in the model have been mainly obtained from public official data sources and from the IMPETUS database. In addition, data from an agro-economic survey covering 60 farmers with different resource endowments that was conducted in autumn 2005 in the six oases along the Drâa river (see figure 3) are intended to round off the database of the model in the near future. Currently they contribute to the validation of the model results.

4.5 Simulating Alternative Groundwater Charges

Two water cost scenarios are simulated against a common background, a sequence of five years with low precipitation in the High Atlas and thus low water flows into the Mansour Eddahbi reservoir. The magnitude of inflows was chosen as the average of the five driest years during the recent twenty years. It is further assumed that the reservoir is already running at its minimum fill rate of 30 percent.

The next important step is to identify appropriate groundwater pumping costs and additional water charges. Costs for pumping water are fairly high in the Drâa Region compared to the free surface water from the Drâa River. Farmers need up to one and a half liters of diesel fuel per hour, depending on the condition of the motor pump. Furthermore, lubricant oil needs to be changed regularly to ensure the reliability of the pump. Operation and maintenance costs of pumps account for 500 Moroccan Dirham on average per pump and year. On average, farmers in the Drâa Region manage to pump approximately 14 to 22 cubic meter of water per hour depending on the type of the motor pump and the amount of water in the well (Klose and Reichert 2006). This amounts to variable pumping costs of 0.58 Moroccan Dirham per cubic meter of irrigation water, depending on the capacity and efficiency of the motor pump as well as local petrol prices. The fixed costs of groundwater pumping (mainly the maintenance and replacement of pumps) are more difficult to measure. Moreover, it is not certain whether fixed costs are well known to the farmers and influence their decisions regarding groundwater use. The farm survey results indicate that the use of inputs is often not oriented at profitability only, but also at keeping up a certain production level for subsistence. This is possible because the increasing share of remittances in local incomes enables an implicit subsidization of the households' farming activities. In general, remittances are an important contribution to Moroccan household incomes (Sorensen 2004).

It is therefore very likely that farmers rather take variable instead of full pumping costs into account when deciding on groundwater use. Therefore, scenarios for pumping costs of 0.58 Dirham (the variable pumping costs according to the survey data) as well as costs of 1.00 Dirham per cubic meter have been simulated. The idea is to increase the economic scarcity of water so that groundwater use becomes more sustainable within a five-year period of drought.

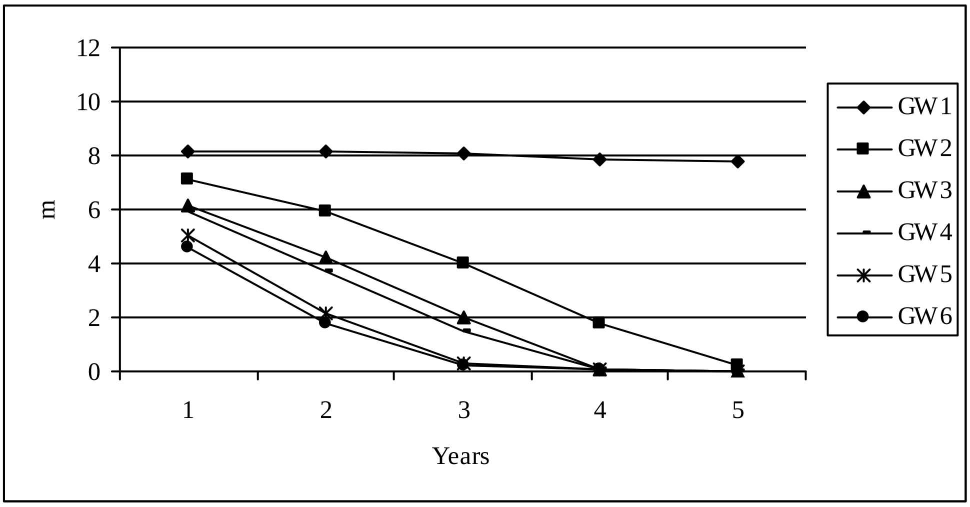
Table 4-3 summarizes the agricultural water use for the different scenarios. Groundwater pumping is significantly lower at total pumping costs of 1.00 Dirham per cubic meter. However, this means that less than half of the available land resources would be cropped, and that agricultural profits would contribute less to household incomes. Water use has become much more efficient, which is reflected in higher average shadow water prices, i.e. the marginal value of water. Moreover, the agricultural profit produced by one cubic meter of irrigation water – the average value of water – increases from 0.36 to 0.50 Dirham.

Table 4-3: MIVAD results for the Drâa valley assuming different pumping costs

Water costs	**0.58 DH/m³**	**1.00 DH/m³**
Agricultural river water use (Mm³)	46.41	46.41
Ag groundwater use (Mm³)	133.18	20.63
Shadow agric. water price (DH/m³)	0.54	0.94
Total agricultural water use (Mm³)	179.59	67.04
Ag profits total (MDH)	64.04	33.76
Use of available crop area (%)	71.24	45.74

The following two figures (Figure 4-4 and 4-5) show the development of the groundwater levels of the different aquifers belonging to the oases.

Figure 4-4: Simulated groundwater tables in meters at water costs of 0.58 Dirham/m^3



With the actual pumping costs of 0.58 DH/m³, a depletion of groundwater resources occurs within five years for all aquifers except one which is big enough to supply enough water for the farmers. By contrast, a water charge of 0.42 DH per m³ leads to stable groundwater levels since in such a case the total cost to the farmer would increase to 1 DH/m³. However, this water charge would require the installation of water meters on each of the wells, and an administrative mechanism to monitor water use and the collection of charges.

Figure 4-5: Simulated groundwater tables in meters at water costs of 1.00 Dirham/m^3

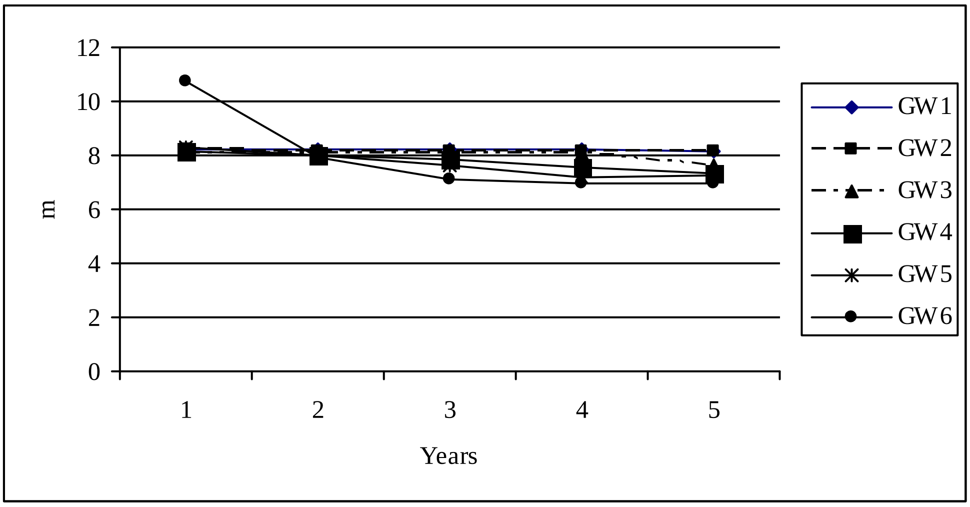
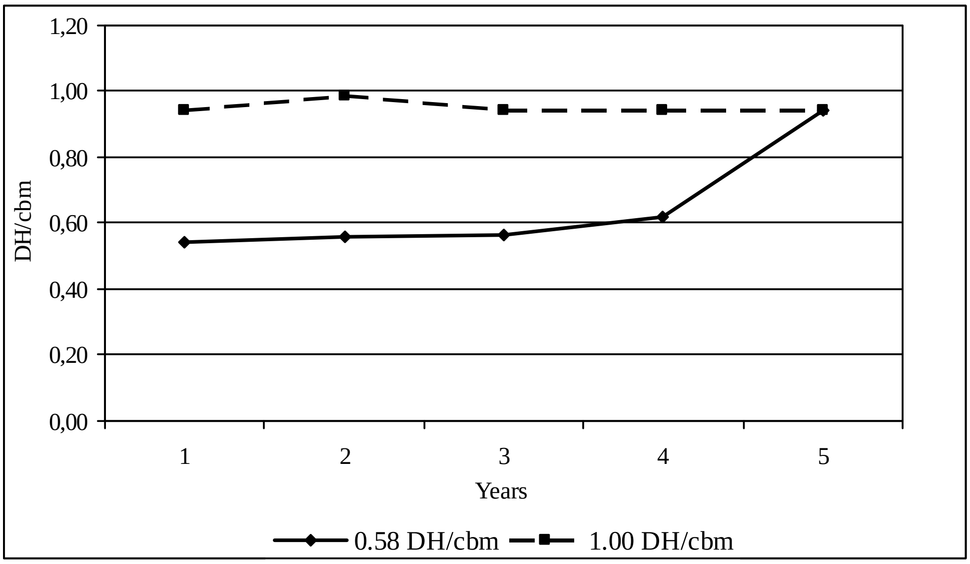


Figure 4-6 depicts the increase of shadow prices over a period of five years depending on costs for irrigation water. Due to the increasing irrigation costs, water resources become scarcer economically. Farmers pump less water due to an increase in costs and change their cropping patterns to achieve greater water efficiency. This process is reflected by an increase of the marginal value of water, the so-called agricultural water shadow price.

Figure 4-6: Development of shadow prices under different water costs over the 5-year simulation period



With pumping costs of one Dirham per cubic meter the agricultural water shadow price remains most stable with values of under one Dirham. For pumping costs of 0.58 Dirham the marginal value of water is nearly as high as the direct pumping costs that farmers are already paying at the moment (see Figure 4-4). Shadow prices increase in the course the simulation period, reflecting the depletion of groundwater resources as shown in Figure 4-4.

4.6 Conclusions

Although the Agricultural Investment Code has not yet been implemented in the Drâa River Basin, this does not mean that the use of irrigation water has been free of costs for the farmers in this region during the last few years. The survey shows that, on the one hand, direct costs for groundwater pumping exist and are even higher than prices farmers are charged for in other basins. On the other hand, if only variable costs at these levels are taken into account in the farmers' decision-making, they are unlikely to work as an effective constraint to excessive groundwater pumping. The simulation results which only take variable costs into account display a quick depletion of groundwater resources, which matches quite closely the development of the recent years in the Drâa valley. This means that, at least from a perspective solely oriented at resource sustainability, it would be justified to complement these costs with a water charge. According to the simulation results, it can be shown that groundwater tables can be stabilized by introducing charges. With an additional charge of 0.42 Dirham, the current (variable) costs of 0.58 Dirham would increase to 1.00 Dirham per cubic meter.

This 'sustainable' water charge, however, would be four to five times higher than the water prices charged in the other irrigation perimeters in Morocco. That indicates that the question of charging for irrigation water needs to be treated with much care as farmers already operate at the subsistence level. In a situation where huge families have to be fed, drought conditions squeeze farm incomes in a way that the emigration of the young men is often the only way to ensure the livelihood of those family members who stay in the Drâa valley. Introducing water charges without considering the depressed economic situation of farms would put an end to most of the small farm entities in the region. Water pricing should therefore not be introduced as an isolated solution, but should rather be embedded in a broader approach towards rural development in the region aiming at both poverty reduction and resource conservation.

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5 Water pricing options for the Middle Drâa River Basin [6]

Abstract

This paper discusses the possible effects of various ways of charging for water in an integrated modeling framework adapted to the Drâa River Basin in southeastern Morocco. Declining surface water availability in the basin has led to an increase in groundwater use for irrigation in recent decades, even though groundwater extraction is more costly than using surface water. The trade-off between the pricing of ground and surface water is discussed based on recursive-dynamic simulations over a ten-year period. The results identify groundwater pricing as an economically and environmentally favorable option, assuming that revenues from water charges are redistributed to farmers.

Keywords: River basin model, water pricing, water management, conjunctive water use, Morocco

Cet article traite de l’impact des stratégies alternatives de la tarification de l’eau dans le cadre d’une modélisation intégrée, adaptée au bassin du Drâa, dans le sud-est du Maroc. Lors des dernières décennies, une baisse du niveau des eaux de surface a entraîné une augmentation de l’utilisation des eaux souterraines destinée à l’irrigation bien que l’extraction de ces eaux soit plus onéreuse que l’utilisation des eaux de surface. On discute le compromis entre la tarification des eaux de surface et celle des eaux souterraines en se basant sur des simulations dynamiques récursives sur une période de dix ans. Les résultats identifient l’option favorable tant au niveau économique qu’environnemental que représente la tarification des eaux souterraines, à condition de redistribuer aux agriculteurs les revenus issus des tarifs de l’eau.

Mots-clés : *Modèle de bassin versant ; Tarification de l’eau ; Gestion des eaux ; Utilisation conjonctive de l’eau ; Maroc*

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[6] This paper has been published in 2008 in the African Journal of Agricultural and Resource Economics, Vol. 2 (2) together with Arnim Kuhn and Stephan Klose

5.1 Introduction

The Middle Drâa Valley in southeast Morocco is a typical example of an arid river basin where surface water and groundwater resources are hydraulically interconnected. The use of both water resource types by farmers for irrigation purposes is known as a ‘conjunctive system’ (Gemma and Tsur 2007: 540), which is typical for river basins in arid regions where groundwater is used as a complementary source during periods when surface water is scarce. The inter-temporal management of conjunctive water resources has been addressed by numerous authors since the 1960s. Buras (1963), Burt (1964) and Bredehoft and Young (1970) were among the first to simulate such systems with dynamic linear programming models that yielded optimal water extraction and allocation plans over multiple locations and periods. The theoretical background of conjunctive water use with a focus on the role of groundwater aquifers as buffers was elaborated by Bear and Levin (1970) and Gisser and Mercado (1973), and later refined by Tsur and Graham-Tomasi (1991) and most recently by Gemma and Tsur (2007). The authors demonstrate the existence of a steady-state in which groundwater recharge and use are in equilibrium under different assumptions, and identify the stock or buffer value of the groundwater source. To arrive at optimal water use plans, quantitative restrictions such as quotas or the taxation of groundwater use are suggested (e.g. Noel et al. 1980) with water pricing often oriented at the shadow values of water use. Applying this principle proves difficult when taking the spatial and temporal peculiarities of hydrological flow processes into account in more detail. Pongkijvorasin and Roumasset (2007) arrive at different prices for farmers according to their location along a river when calculating efficiency prices for ground and surface water based on the distance between the demand sites. It is widely accepted among resource economists that effective pricing of irrigation water supports efficient allocation and conservation of resources (Dinar and Subramanian 1997).

Charging for water is a common practice in most river basins in Morocco, even though price levels are primarily aimed at recovering the costs of water supply, while efficiency or resource preservation considerations are less important (Tsur et al. 2004). In the Drâa Valley, it has so far been possible to avoid charging for either surface or groundwater (Serghini 2002, Doukkali 2005), mostly because the region is one of the poorest and most remote in the country. This paper discusses simplified irrigation water pricing strategies for the Drâa Valley in a recursive-dynamic framework. Two key assumptions are that a) farmers can extract water from different but interconnected sources, namely surface water from the Drâa River and groundwater from local aquifers, and that b) neither farmers nor the water management agency take long-term expectations of future water supply into consideration.

As the Drâa Valley is characterized by highly volatile surface water supply conditions, optimal multi-annual water use plans or water charges are difficult to identify. Moreover, given the frequent droughts in the region, ‘optimal’ use rights or price levels derived from a fully dynamic simulation model would probably seem too restrictive to farming communities to be politically acceptable. Thus, rather than working out an optimal inter annual water management regime, this paper investigates whether simplified water pricing systems might still be better than the current water management system in the study area over a period of ten years. The study in particular focuses on a comparison between surface and groundwater pricing regimes. Cornish et al. (2004) discuss different experiences of surface and groundwater pricing, and point out that increasing charges for surface water only could lead to groundwater being overexploited. This paper thus tries to answer two questions: is there a trade-off between simplified surface versus groundwater pricing schemes, and what role does the conjunctive nature of the water resources play in this context?

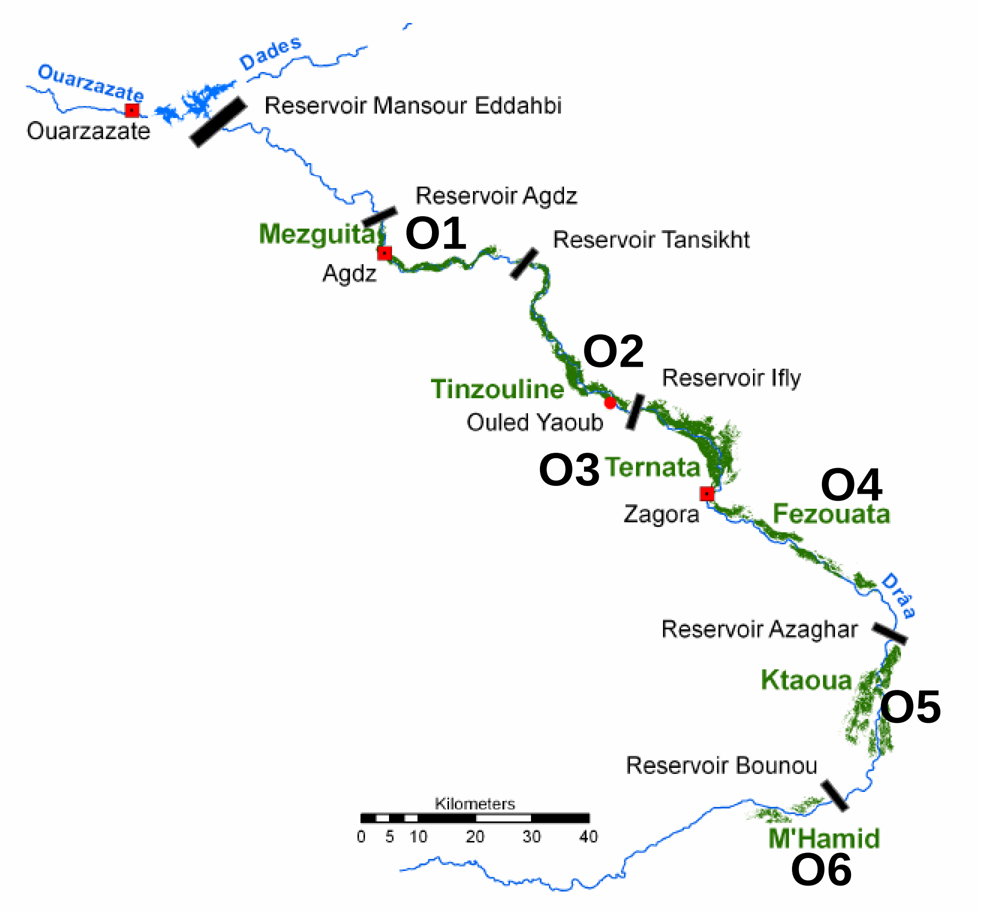
The remainder of the paper is organized as follows: we first describe the study area and its hydrologic and hydro-geologic setting. Then we explain the simulation model used, after which we show the results for different pricing options for the Drâa Valley.

5.2 Water resources

Most farm production in the Middle Drâa Valley (i.e. downstream from the Mansour Eddahbi reservoir) is found in six oases along the course of the Drâa River (Figure 5-1). Because of the arid climatic conditions in the area, irrigation water is the most important production resource for cropping and the most limiting factor in most years.

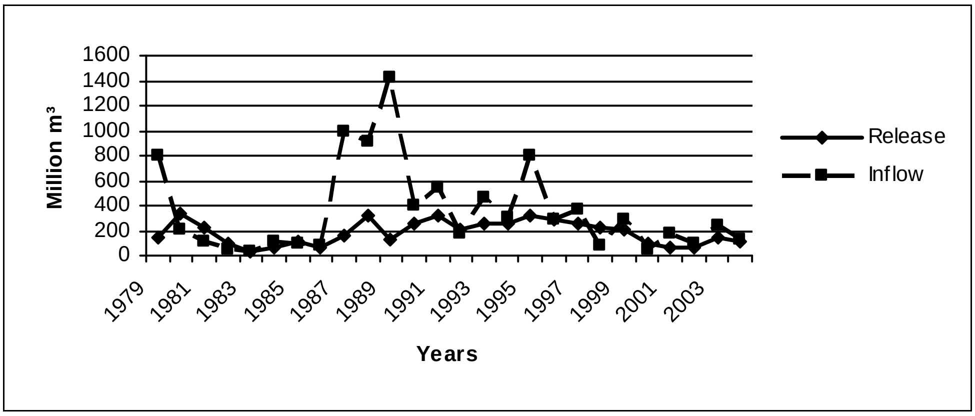
Decisions about the distribution of surface water among the six oases are made ex ante at the basin level by a committee at the beginning of the agricultural year (ORMVAO 1995). Surface water for irrigation is periodically released from the Mansour Eddahbi reservoir to improve the reliability of the water supply. Released water is directed to the southern oases first and then retained in small local reservoirs. From there, water is directed through a traditional channel system onto the fields and distributed according to traditional local water property rights (Ouhajou 1996).

Figure 5-1: The six oases Mezguita (O1), Tinzouline (O2), Ternata (O3), Fezouata (O4), Ktaoua (O5) and Mhamid (O6) along the Drâa River



Because of declining rainfalls in recent years and high evapotranspiration rates, the fill rate of the Mansour Eddahbi reservoir has been decreasing (see Figure 5-2). The reservoir balance has become increasingly negative, which has led to more and more irregular releases during recent years. Nowadays the releases of the reservoir are sometimes used just to fill up the declining groundwater levels, exploiting the fact that water easily infiltrates into the shallow aquifers below the riverbed.

Figure 5-2: Water balance of the Mansour Eddahbi reservoir from 1972/73 until 2002/03.



Source: Data Source : Direction Générale de l'Hydrologie, Rabat 2004

In contrast to decisions about surface water, decisions about groundwater pumping are made by individual farmers who own pumps. It is assumed that each of the six oases has an underlying aquifer with specific hydro-geological characteristics (see Table 5-1).

Table 5-1: Total area and natural reserves of the aquifers of the oases

	Mezguita	**Tinzouline**	**Ternata**	**Fezouata**	**Ktaoua**	**Mhamid**
Total area of the aquifers (km^2)	45	69	178	196	160	70
Total natural reserves (Mio m³)	22.5	34.5	71.3	127.1	86.4	16.8

Source: Oujaou 1996, own calculations

As compared to the total storage volume of the Mansour Eddahbi reservoir (439 million cubic meters in 1998, down from the initial 560 million cubic meters in 1972 due to sedimentation, see Abou-Otmane 2002), the total natural reserves of groundwater are estimated to represent 359 million cubic meters of water storage capacity (Table 5-1), meaning that almost half of the total water storage capacity of the Drâa Valley is contained in groundwater aquifers. However, declining rainfall reduces the pluvial aquifer recharge as well as the lateral groundwater afflux (Aoubouazza and Meknassi 1996; Direction de la Région Hydraulique d'Agadir de Souss-Massa et Drâa 2001). The general hydrographic trend in fact reveals declining average groundwater levels since 1996. At the same time the number of motor pumps has increased remarkably during the last 30 years (see Table 5-2). Figures on the number of motor pumps are only available to 1985, which illustrates the problem that groundwater use is insufficiently monitored. Survey data for 2005 suggest that the number of motor pumps has increased tremendously in the last two decades. Basin-wide water management faces a typical conflict between long-term resource conservation goals for the entire basin and short-term income considerations for individual farmers.

Table 5-2: Development of motor pumps and pumping capacity

	Number of motor pumps			**Water pumped in 1985 (Mio cbm)**	**Pumps per farmer in 1982**	**Pumps per farmer, estimated for 2005**
	1977	**1982**	**1985**			
Mezguita	216	260	860	4.64	0.08	1.85
Tinzouline	499	590	1,200	6.48	0.17	1.76
Ternata	785	920	1,500	8.10	0.22	1.48
Fezouata	383	448	710	3.83	0.16	1.30
Ktaoua0	108	130	220	1.19	0.04	0.35
Mhamid	10	15	30	0.16	0.01	0.53

Source: Faouzi 1986, own estimations from field survey in 2005

5.3 The MIVAD Model

This study uses a numerical simulation model[7] based on positive mathematical programming (PMP, Howitt 1995) to compare alternative water pricing options for the Drâa Basin. There are several reasons for this rather normative approach. Most importantly, basin-wide information on water use at the farm level is scarcely available in the case study region. This applies particularly to the use of groundwater. Moreover, the impact of cost changes on water use patterns cannot be estimated ex post as costs of water use are not documented over the years, and because charging for water has not yet been tried in the case study area. Thus, the pricing experiments presented in this study are in effect ex ante evaluations of programming models to decide which ones are suitable for situations where observed data on important variables are scarce or even absent. Finally, programming models allow the derivation of water shadow prices at different locations and periods, thereby delivering a point of reference for administrative water price levels.

Mathematical programming approaches have been widely applied to water resources issues, especially in those cases where the insufficient availability of data means that econometric estimations are not possible. The simulation model

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[7] A detailed description of the model is available from the authors on request.

MIVAD (Modèle Intégré de la Vallée du Drâa) is designed as a hydrologic-economic optimization model in which spatial relations are represented in a node network representing points of withdrawal along the river, water reservoirs, groundwater bodies and agricultural water demand sites. As such, MIVAD is similar to models that have been recently applied by Cai (1999) to the Syr Darya Basin, by Rosegrant et al. (2000) to the Maipo Basin in Chile, by Ringler (2002) to the Mekong Basin, and by Obeng-Asiedu (2004) to the Volta River Basin. However, these modeling approaches simulate one aquifer per demand site where the aquifers are not interconnected with each other (Cai et al. 2006). In the Drâa Valley the aquifers that are situated below the belt of oases are hydraulically interconnected, which has been taken into account in the present modeling approach.

Basically, MIVAD is a planning model that maximizes the net agricultural revenues of the six farming communities (oases) subject to land and water resource constraints. Agriculture is represented by one aggregate farm per oasis, involving the eight most relevant crops in the area: wheat, barley, alfalfa, corn, date palms, henna, pulses and an aggregate of vegetables. All cropping activities are characterized by specific input needs, yield functions, prices and water requirements. The parameters of the PMP-terms in the objective function are calibrated using a priori supply elasticities (Heckelei and Wolff 2003), which are principally different for annual and perennial crops. Endogenous crop yield functions in the model are designed as non-linear approximations of the ratio between actual and maximum evapotranspiration according to the Modified Penman function (Allen et al. 1998), making crop yields a function of water application per hectare.

Available cropland is specific to the oasis (farm community) level. Water resources available to the oases, by contrast, are represented by a highly complex hydrological system which is assumed to be governed by a centralized water distribution agency. This ‘virtual planner’ distributes irrigation water to the various oases and municipal users in order to maximize the utility from water use for the entire region.

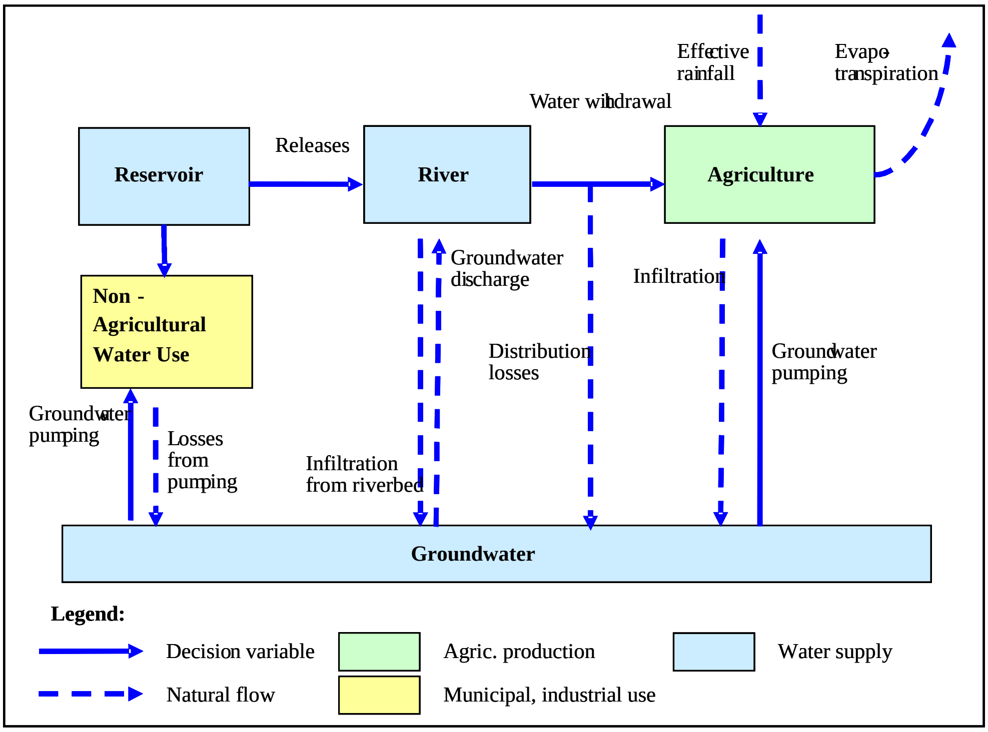
The hydrologic framework in MIVAD

The hydrological modeling network of the Drâa River Basin actually starts with the river node that defines the exogenous monthly inflows into the Mansour Eddahbi reservoir from the High Atlas Mountains. From the reservoir, water is released to the Drâa River and flows downstream, partly infiltrating and percolating to the alluvial aquifers subjacent to each oasis. For each of these aquifers a specifically adjusted groundwater balance is part of the model.

In the Drâa Valley, however, aquifers are not closed entities, but interconnected by discharges in the same direction as the river flow. The relatively small flow sections between the aquifers are limited by non-pervious rock formations at the lower end of each oasis. Groundwater discharge is calculated as 1-D flow by the Darcy equation (Darcy 1856) which depends on the hydraulic conductivity of the alluvial deposits, the flow section and hydraulic gradients between the aquifers. In case of very high groundwater levels, a discharge into the river bed may occur too, but this process is less important under the current dry conditions in the Drâa Valley.

Lateral inflows from rain water infiltrating the catchment area of each aquifer also contribute to groundwater recharge, but have played only a minor role in most years. By contrast, infiltration from the river bed into the aquifers appears to be a decisive factor for the groundwater balance in the case study region. It is also an important element of groundwater management by the authorities, who occasionally use reservoir releases to replenish the groundwater bodies in the river basin. The coefficient for the groundwater recharge by river water infiltration has proved to be a pivotal factor in hydro-geological models (Simmers 1997). First estimations of the recharge coefficient for the Drâa Valley yield values between 10 and 25% of the river water flow. The interactions between ground and surface water resources in the model are illustrated in Figure 5-3. A hydrological balance is formulated for each river node in the model.

Figure 5-3: Hydrologic interactions in MIVAD



5.4 *Determination of decision variables*

There are several levels in MIVAD at which decisions on land and water use are made to arrive at an optimal distributional pattern that maximizes the sum of agricultural gross margins. Decision variables include crop areas in the individual oases (A_i), and various variables related to water use: seasonal water application per crop measured in terms of crop evapotranspiration (ETA_i), water withdrawals by oases from the river (W^S) or the underlying groundwater body (W^G), the fill levels of the groundwater aquifers (R^G), the downstream flows between river nodes (F^S), and fill levels (R^R) and releases (F^R) from the central reservoir. The Kuhn-Tucker conditions for local optima that determine the levels of these decision variables are discussed in the following. Indices denote available cropping activities (i), locations such as river nodes, aquifers and oases (f), and months (t) within a one-year period.

The first-order condition of the objective function with respect to crop area (A_i) is represented by the following non-linear relation between marginal costs (MC_i) and marginal revenues (MR_i) from cropping:

$$MC_i^L\left(\left(\sum_t \lambda_t^A \cdot W_{i,t}^A\right), \lambda^L\right) \geq MR_i^L\left(\overline{P_i} \cdot Y_i, \overline{AC_i}, A_i\right) \qquad \perp \quad A_i \geq 0$$

(W^A = application of irrigation water per hectare; λ^A = shadow price of water for crop irrigation; λ^L = shadow price of cropland; P_i, Y_i, AC_i, = crop prices, yields, and accounting costs, respectively).

The complementarity between the MC-MR-difference and the quantitative decision variable is denoted by the '$\perp$'-sign. Water application per crop (W^A) itself is a function of seasonal evapotranspiration per crop (ETA_i), which ultimately determines crop yields (Y_i), but also of the local irrigation and groundwater shadow prices:

$$MC_i^{irrig}\left(ETA_i^{seas}, \overline{ETM_{i,t}^{stage}}, A_i, \lambda_t^G, \lambda_t^A\right) \geq$$
$$MR_i^{irrig}\left(ETA_i^{seas}, \overline{ETM_{i,t}^{stage}}, \overline{Y_i^{max}}, \overline{ky_i^{seas}}, A_i, \overline{P_i}\right) \quad \perp \quad ETA_i^{seas} \geq 0$$

(ETM_i^{stage} = yield-max. monthly evapotranspiration; λ^G = shadow price groundwater; Y_i^{max} = maximum crop yield; ky_i^{seas} = seasonal crop water deficit coefficient)

Surface water for irrigation depends on releases from the upstream reservoir. The reservoir has a limited storage capacity and, assuming that the periodic inflows of river water into the reservoir are known ex ante within a one-year horizon, the monthly fill levels (R^R) are chosen such that the shadow prices of reservoir water (λ^R) equal over all periods t.

$$\lambda_t^R \geq \lambda_{t+1}^R \quad \perp \quad R_t^R \geq 0$$

Releases from the reservoir (F^R) occur when the shadow price in the reservoir (λ^R) is equal to or lower than the shadow price at the adjacent river node (λ^S):

$$\lambda_t^R \geq \lambda_t^S \quad \perp \quad F_t^R \geq 0$$

Similarly, when the shadow price of water at the river node upstream is equal to the river node downstream, a river flow ($F^S_{f,f+1}$) should occur between these nodes. If, however, there are infiltration losses ($infil^{SG}$) of river water into the local aquifers, the decision rule becomes more complex, involving also the shadow price for groundwater in the aquifer belonging to the downstream rive node (λ^G). Increasing river-aquifer infiltration will, ceteris paribus, decrease the incentive to let water flow downstream, particularly as long as λ^G is low or zero, i.e. as long as the groundwater aquifer will not be exhausted in any month in the one-year period.

$$\lambda^S_{f,t} \ge \overbrace{\lambda^S_{f+1,t}\cdot\left(1-infil^{SG}_{f,f+1}\right)}^{\text{Share of outflows available at next node}} + \lambda^G_{f+1,t}\cdot \overbrace{infil^{SG}_{f,f+1}}^{\text{Share of outfl. infiltr. into downstr. aquifer}}$$

$$\ge \lambda^S_{f+1,t} - \left(\lambda^S_{f+1,t} - \lambda^G_{f+1,t}\right)\cdot infil^{SG}_{f,f+1} \quad \perp \quad F^S_{f,f+1,t} \ge 0$$

As water for irrigation also infiltrates into the local aquifers, the shadow price relation governing withdrawals by oases from river nodes (W^S) are also quite complex, involving the shadow price at the river node (λ^S), and the shadow price of irrigation water in the oasis (λ^A), but also groundwater shadow prices, the shadow price of the surface water distribution rules (λ^{distr}), and financial costs (including charges) of surface water withdrawals (c^S). Thus, losses within the canal system of the oases mean that water becomes more costly for farmers, an effect that will be dampened, however, as soon as groundwater becomes scarce and its shadow price positive.

$$\lambda^S_{f,t} + \overbrace{c^S_f}^{\text{Costs / charges of surface water use}} + \overbrace{\frac{\lambda^{distr}_f}{\sum_t W^S_{f,t}} - \sum_f \left(\frac{\lambda^{distr}_f \cdot \sum_t W^S_{f,t}}{\sum_{f,t} W^S_{f,t}{}^{2}} \right)}^{\text{Opportunity costs of the distribution rules}} \ge \overbrace{\lambda^A_{f,t}\cdot\left(1-loss^{SG}_f\right)}^{\text{Marginal value of irrigation water net of losses}} + \overbrace{\lambda^G_{f,t}\cdot loss^{SG}_f}^{\text{Value of infiltration into the groundwater}}$$

$$\ge \lambda^A_{f,t} - \left(\lambda^A_{f,t} - \lambda^G_{f,t}\right)\cdot loss^{SG}_f$$

$$\perp \quad W^S_{f,t} \ge 0$$

(with lossSG = coefficient determining the infiltration losses occurring at surface water withdrawals by oases).

Groundwater pumping (W^G) is determined in a simpler way, as groundwater use is not subject to distribution rules or infiltration losses. The local irrigation water shadow price has to be equal to the shadow price of the groundwater aquifer plus the costs (including charges) of groundwater extraction (c^G).

$$\lambda^G_{f,t} + \overbrace{c^G_f}^{\text{Costs / charges of groundwater use}} \ge \lambda^A_{f,t} \quad \perp \quad W^G_{f,t} \ge 0$$

Analogous to water in the reservoir, the fill level of the aquifer is determined by the inter-temporal relation between shadow prices of groundwater in the aquifer, but also by the shadow price in the river node (in the case of discharge into the river)[8] and the shadow price in the downstream aquifer (due to inter-aquifer flows as a represented by the Darcy equation, the latter which renders the shadow price relation to be non-linear in R^G)[9]. Increasing inter-aquifer flows would thus decrease the socially optimal aquifer fill levels and reward more local pumping.

$$\overbrace{\lambda^G_{f,t} - \lambda^G_{f,t+1}}^{\text{Intertemporal difference of GW shadow prices in f}} \quad \overbrace{-\lambda^G_{f,t} \cdot darcy\left[R^G_{f,t}, R^G_{f+1,t}\right]}^{\text{Costs of groundwater outflow to the downstream aquifer}} + \overbrace{\lambda^G_{f+1,t} \cdot darcy\left[R^G_{f,t} - R^G_{f+1,t} \uparrow\right]}^{\text{Value of groundwater outflow to the downstream aquifer}} \geq 0$$

$$\leftrightarrow \lambda^G_{f,t} + \left(\lambda^G_{f+1,t} - \lambda^G_{f,t}\right) \cdot darcy \;\geq \lambda^G_{f,t+1} \quad \perp \quad \overbrace{R^G_{f,t}}^{\text{Fill level of aquifer}} \;\geq 0$$

All shadow prices in the model are complementary to the hydrologic balances at certain locations. The entire shadow price system is finally driven by the irrigation water shadow price λ^A, as the use of water for irrigation is the only use component that enters the objective function in the version of MIVAD presented here. λ^A thus represents the opportunity costs of water use for farmers, and is dependent on the marginal value productivity of irrigation water. The opportunity costs of water are also a yardstick for the willingness of farmers to incur costs for obtaining access to irrigation water resources. The complex hydraulic relations between the local water sources, however, can lead to large differences in local irrigation water shadow prices. Water pricing that is oriented at simulated marginal water costs becomes politically delicate under such conditions,[10] particularly when the parameters of hydraulic interactions are uncertain. Moreover, the model assumes that expectations about future water supply – which would be useful for determining optimal inter-annual water price levels – are not taken into account by the water distribution agency. The fact that depleted water buffers in reservoirs and aquifers can actually be found in the case study region after a series of dry years supports this assumption. The simulations carried out for this study test to what extent simplified pricing schemes that do not require a multi-annual perspective will nevertheless lead to better results than no charge at all for water.

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[8] This case is omitted as it only happens when there is abundant water in the aquifer.

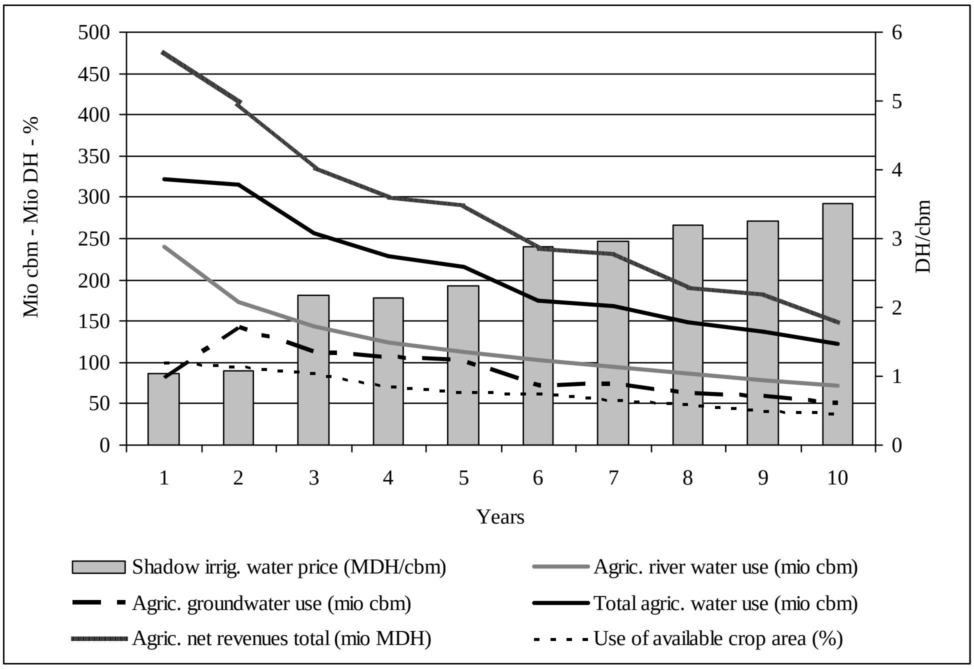
[9] The ‘Darcy factor’ increases with the metric difference between the levels of the neighbouring aquifers.

[10] This conclusion has also been drawn by Pongkijvorasin and Roumasset (2007).

5.5 Simulation results

The following results show scenario calculations for a ten-year period, simulating an increasingly severe drought and farmers' adaptation under different pricing regimes for irrigation water. In the base run (Figure 5-4) we assume the first year to be a 'normal' year with average rainfall. Surface water availability is simulated to become scarcer each year with a decrease of 6.5% annually, arriving at 12% of the surface water initially available at the end of the ten-year period. Fixed non-irrigation water demand is assumed to increase exogenously at 3.1% annually for urban and 0.8% for rural areas due to population growth. We assume a 15% rate of groundwater recharge by river water infiltration of flows at each river node per month.

Figure 5-4: Base run (assuming declining river water availability and variable costs for pumping of 0.58 DH/cbm)



Calculations based on a farm survey estimate variable costs of pumping groundwater for irrigation purposes at 0.58 Moroccan Dirham (DH) per cubic meter (cbm) (approximately 7 US cents/cbm in May 2007, see Heidecke and Kuhn 2006) including fuel as well as operation and maintenance costs. The base run (Figure 5-4) assumes that neither ground nor surface water is charged for. Nevertheless, groundwater use is less attractive because of the extraction costs, while surface water use is free of costs.

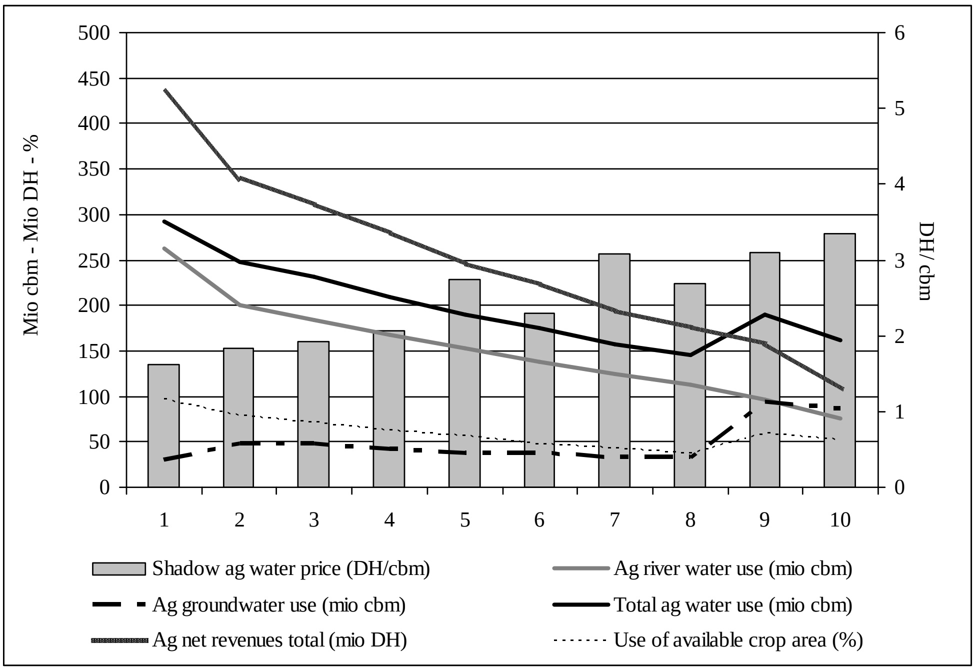
The declining availability of surface water in the base run leads to the use of more groundwater for irrigation. After two years the extraction of groundwater reaches 140 million cubic meters per year and slightly declines afterwards when aquifers are fully exploited and groundwater shadow prices assume non-zero values. The average water shadow price increases with the decreasing availability of surface water from the Drâa River. The fact that these water shadow prices for irrigation by far exceed extraction costs indicates that an effective resource preservation policy would have to consider the pricing of groundwater beyond the extraction costs of 0.58 DH/cbm. Total net revenues from agricultural production decrease constantly from nearly 500 million DH to less than 200 million DH during the ten-year period. Tree counterfactual scenarios are simulated: a charge for surface water only (SWC) of 1.0 DH/cbm, a charge for groundwater only (GWC) of 1.0 (resulting in groundwater costs of 1.58 DH/cbm when also considering the extraction costs of 0.58 DH/cbm), and a 'total water charge' with charges for both water resources (TWC). The TWC scenario simply combines the water charges of the SWC and GWC scenarios, making groundwater still more expensive for farmers than surface water. To evaluate the efficiency of the different pricing regimes, net revenues of agricultural producers are compared to 'total basin revenues'. These 'total basin revenues' contain agricultural revenues plus all revenues from water charges which represent the taxation of farmers, but which are also available for redistribution to the farmers as income transfers. Such transfers are assumed to have no further allocative effects in the model. Total basin revenues are also discounted at 5% and 10% to account for the farmers' preference for short-term incomes (Table 5-3).

Table 5-3: Results for the base run, the SWC, GWC, and TWC scenarios for several indicators as averages over ten years

	Base run	**SWC**	**GWC**	**TWC**
Agric. river water use (Mm³)	123.06	117.07	151.08	137.00
Agric. groundwater use (Mm³)	86.03	92.91	49.36	66.32
Irrigation water shadow price (DH/m³)	2.46	2.46	2.27	2.30
Agric. net revenues total (MDH)	279.92	141.25	245.76	61.84
Sum of water charges (MDH)	0.00	117.07	49.36	203.31
Total basin revenues (MDH)	279.92	258.32	295.12	265.15
Total basin revenues (discounted at 5 %)	238.07	218.85	248.54	224.65
Total basin revenues (discounted at 10 %)	207.31	189.86	214.58	194.92

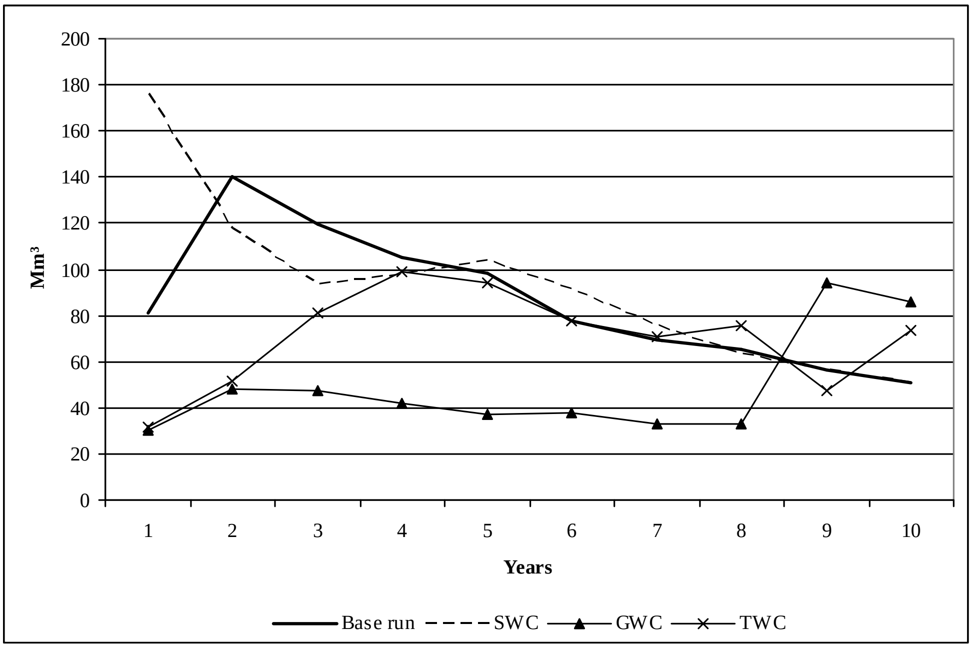
The three pricing scenarios yield markedly different results with respect to revenues and resource use. Under surface water pricing, groundwater use becomes more attractive, which leads to higher groundwater use than in the base run, which is likely to be unsustainable. At the same time the basin wide revenues (including surface water charges) are 8% lower than in the base run. When both water sources are charged for (TWC), groundwater water use decreases, but at the cost of an excessive taxation of farmers. Charging only for groundwater (GWC) yields the most favorable results, both, with respect to resource conservation and in terms of total basin income. This seems counterintuitive at first sight, but when looking at the GWC results in more detail over the entire period (Figure 5-5), the higher income can be explained by the fact that groundwater pricing prevents wasteful groundwater use in the earlier years and thus eases water scarcity in the further course of the scenario. This is also reflected in the fact that average water shadow prices are lowest in the GWC scenario.

Figure 5-5: Scenario calculations of charging only groundwater (GWC)



With a charge for groundwater only, the total agricultural water use is more stable over the entire period than in the base run and in the other scenarios, resulting in a higher stability of farm incomes. When comparing groundwater use over all pricing options (Figure 5-6), groundwater use is lowest in the GWC scenario, and highest in the base run and SWC scenarios in the first years. This changes when aquifers are depleted in the latter scenarios, while groundwater is still available in the later years of the GWC scenario under severe surface water scarcity.

Figure 5-6: Groundwater use of the six oases over a ten year period for the base run and for charges on ground- and surface water



Regarding farmers' net revenues and the basin-wide income for the scenarios (Figure 5-7), the advantage of groundwater availability in future years has direct effects on incomes. Naturally, farmers' net revenues are the highest in the base run where farmers are not charged for water at all; however, the GWC scenario only slightly reduces farmers' net revenues and yields even higher basin-wide revenues, especially in the later years. Discounting the basin-wide revenues, revenues at the end of the simulation period are of lower importance; nevertheless the groundwater charge remains the best option (see Table 5-3).

Figure 5-7: Net revenues and basin wide revenues

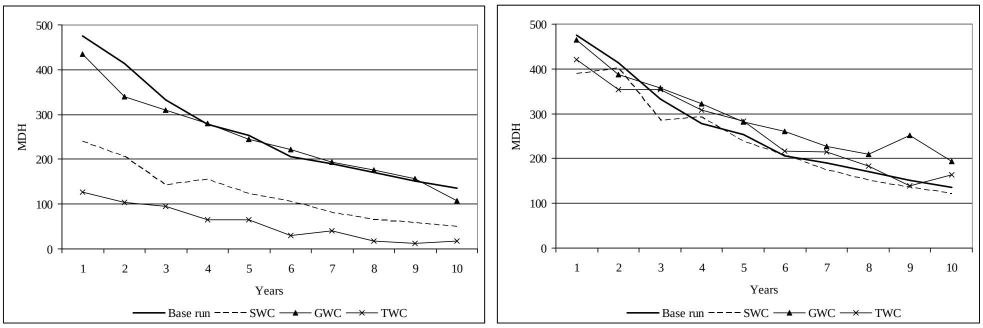
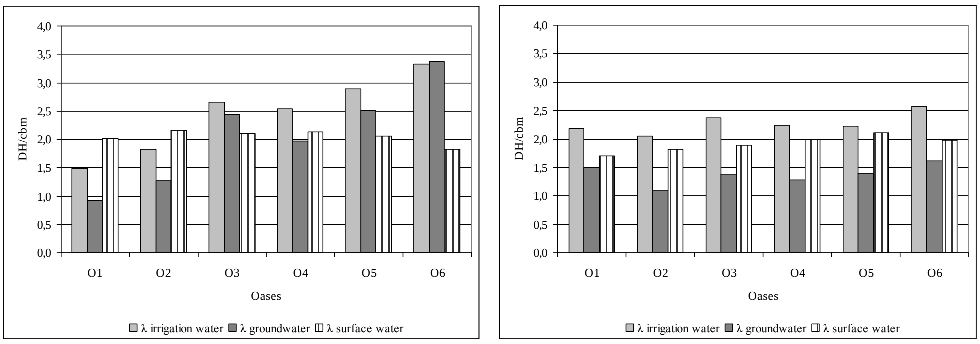


Figure 5-8 shows the average shadow prices in DH/cbm for irrigation water, surface water, and groundwater at the level of individual oases across the entire simulation period. In both scenarios the shadow prices of surface water are more or less equal across the oases due to the nature of surface water as a common pool resource. Small variations between the oases can be explained by differences due to infiltration losses and the effects of distribution rules. In the base run, groundwater shadow prices and hence irrigation water shadow prices increase from the northern oases to the southern oases. Broadly speaking, shadow price differences between aquifers can be greater than those for surface water, since groundwater resources are hydrologically more isolated. While the hydraulic connections between aquifers tend to reduce the differences in water scarcity, the dominant infiltration losses from river flows contribute to increasing the inter-aquifer differences in water shadow prices. The groundwater charge obviously reduces the variation of both groundwater and irrigation water shadow prices across oases. Altogether, surface and groundwater shadow prices are smaller when a water charge is applied, since farmers have to pay more for the same marginal value of water.

Figure 5-8: Shadow prices for the six oases for the base run and for GWC (average over a ten year period)



The scarcity of surface water directly affects the availability of groundwater due to the infiltration into the river bed. To examine the economic effect of this hydrological process more closely, all pricing scenarios are repeated at a groundwater recharge coefficient of 10 and 20%, respectively (Annex 1). Assuming a higher recharge coefficient of 20% instead of 15%, more groundwater is able to infiltrate into the river bed, making surface water even scarcer. The higher the natural infiltration from river to aquifer, the more favorable groundwater pricing appears to be compared with the other options. This also indicates that the suitability of a pricing scheme is sensitive to hydrological parameters and to the availability of ground and surface water.

5.6 Conclusions

Charging for water has so far been avoided in the Drâa Valley as farmers' incomes were deemed too low to pay for additional water charges. However, the obvious overexploitation of groundwater resources in recent years indicates that the current patterns of water use will not be sustainable in the long run, particularly if the average surface water availability is bound to worsen in the course of population growth and climate change. This paper discusses charges for irrigation water as an option for regional river basin water management, focusing on groundwater conservation and income stabilization as primary goals.

The comparison of water pricing regimes for the Drâa Valley in Morocco shows that groundwater charges, in contrast to surface water charges, lead to the highest basin-wide incomes, and are at the same time more effective in terms of groundwater preservation. This is because the buffer function of groundwater resources, i.e. using groundwater stocks to mitigate water scarcity in future years (Tsur and Graham-Tomasi 1991), can be better exploited when groundwater overuse in years with less overall water scarcity is avoided through taxation. Charging for groundwater thus emulates the allocative effect of realistic future expectations of water supply and replaces an explicit accounting for the buffer value of groundwater stocks to some degree.

Even though a considerable amount of surface water can also be stored in the reservoir, which thus also functions as a buffer, charging for surface water leads to an overuse of groundwater when surface water is still sufficiently available. When surface water becomes scarce in the later years, groundwater resources are already exploited under the special water availability scenarios used in this study. It is also likely that the existing distribution rules for surface water restrict efficient allocation by the central planner, which increases the value of the locally and temporally more flexible groundwater resources. Enforcing a tax as a replacement for considering a buffer value is thus much less effective in the case of surface water. A sensitivity analysis of the natural rate of surface water infiltration into groundwater aquifers does not alter these conclusions.

A water pricing system should be designed to induce efficient use of irrigation water, to avoid taxing farmers excessively, to be acceptable to farmers with respect to the levels and interannual stability of water charges, and to contribute to long-term resource conservation goals, particularly with respect to groundwater. The results of the simulations suggest that a groundwater pricing scheme is the alternative that best meets these requirements, except for the issue of administrative costs, which are probably much higher for groundwater than for surface water. However, the estimated benefits of charging for groundwater might outweigh its higher administrative costs, particularly since a charge for groundwater appears to create much less pressure through taxation of resource use, which could increase its acceptance among water users.

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10% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (Mm^3)	139.56	135.22	155.54	153.09
Agric. groundwater use (Mm^3)	66.80	71.01	42.35	46.55
Consumption water use (Mm^3)	5.94	5.94	5.94	5.94
Total agric. water use (Mm^3)	206.36	206.23	197.89	199.64
Reservoir fill rate in %. end	0.31	0.34	0.31	0.31
Agric. net revenues total (MDH)	289.74	127.26	252.52	66.28
Basin revenues total (MDH)	289.74	262.48	294.86	266.30
Use of available crop area (%)	66.50	68.93	58.50	68.41
Shadow irrig. water price (DH/cbm)	2.47	2.46	2.34	2.58
Total basin revenues (discounted at 5%)	246.04	222.59	249.37	225.50
Total basin revenues (discounted at 10%)	213.96	193.21	216.03	195.46
15% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (Mm^3)	123.06	117.07	151.08	137.00
Agric. groundwater use (Mm^3)	86.03	92.91	49.36	66.32
Consumption water use (Mm^3)	5.94	5.94	5.94	5.94
Total agric. water use (Mm^3)	209.09	209.98	200.43	203.31
Reservoir fill rate in %. end	0.31	0.33	0.31	0.31
Agric. net revenues total (MDH)	279.92	141.25	245.76	61.84
Basin revenues total (MDH)	279.92	258.32	295.12	265.15
Use of available crop area (%)	65.94	69.69	58.96	60.60
Shadow irrig. water price (DH/cbm)	2.46	2.46	2.27	2.30
Total basin revenues (discounted at 5%)	238.07	218.85	248.54	224.65
Total basin revenues (discounted at 10%)	207.31	189.86	214.58	194.92
20% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (Mm^3)	111.82	101.60	147.75	132.93
Agric. groundwater use (Mm^3)	99.07	111.06	51.91	69.48
Consumption water use (Mm^3)	5.94	5.94	5.94	5.94
Total agric. water use (Mm^3)	210.89	212.67	199.66	202.41
Reservoir fill rate in %. end	0.31	0.33	0.31	0.31
Agric. net revenues total (MDH)	271.45	149.84	239.85	60.17
Basin revenues total (MDH)	271.45	251.44	291.76	262.58
Use of available crop area (%)	66.62	69.19	57.89	60.39
Shadow irrig. water price (DH/cbm)	2.52	2.48	2.26	2.33
Total basin revenues (discounted at 5%)	231.56	213.23	245.98	222.80
Total basin revenues (discounted at 10%)	202.21	185.16	212.56	193.49

6 Considering salinity effects on crop yields in hydro-economic modelling- the case of a semi arid river basin in Morocco[11]

Abstract

Agricultural production, especially date palm cultivation, is the major food and income source for people in the Drâa basin in Southern Morocco. However, the semi-arid river basin faces very low rainfalls and suffered from a continuing drought over the last years. River water, as the principal source for irrigation, has been increasingly substituted by groundwater mining. This has led to an unsustainable downing of the groundwater table, increased salinisation problems, and has posed further constrains on the agricultural production potential. Without targeted water resources management, water available for irrigation will soon be depleted or too saline to be used for most crops. Consequently, farmers will not be able to maintain their production levels, and subsequently lose an important source of family income. The relationship between water use and agricultural production is represented using an integrated hydro-agro-economic simulation model with a spatial water distribution network of in- and outflows, balances and constraints. The model results are driven by profit-maximizing water use by agricultural producers which are primarily constrained by both water availability and quality. Crop yields are influenced by quantitative irrigation water application deficits and by the salinity of irrigation water. Results show considerable differences depending on whether salinity is incorporated or not. When salinity is considered, yields tend to be much lower despite increased irrigation water needs to enable a reduction of soil salinity through leaching.

Keywords: nonlinear programming, water allocation, water quality, salinity

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[11] This paper has been reviewed and published in: Water Resources Management Proceedings, WIT Press 2007- together with Dr. Arnim Kuhn. It has been presented at the Water Resources Management conference in Kos 17-19 May 2007. Furthermore, it has received a certificate of an outstanding paper contribution at this conference.

6.1 Introduction

The Drâa river basin is located in South-East Morocco at the edge to the Saharan desert. The area faces pre-Saharan climatic conditions with naturally low rainfalls. The precarious water situation has been aggravated by subsequent droughts and by increasing salinity of both ground- and surface water in recent decades. Water salinity adversely affects the yet poor agricultural production potential. During the last years the salt content of irrigation water has further increased (ORMVAO 1996), leading to very low agricultural output levels and the need for the farm households to identify additional sources of income. Hence, a holistic water management should take into consideration the impact of salinity on agricultural yields.

Since 1972 a centrally managed reservoir, the Mansour Eddahbi reservoir, supplies a belt of six oases along the Middle Drâa River basin with irrigation water. Due to increasing surface water scarcity, farmers progressively established wells with motor pumps and are using groundwater instead of river water for irrigation. However, groundwater use has the drawback of very high salt contents especially in the two most southern oases, Ktaoua and Mhamid. The average values for salt content are shown in Table 6-1. It should be noted that groundwater salinity is markedly higher than that of surface water.

Table 6-1: Salt content of ground and surface water in the Drâa basin

Oasis	Groundwater (g/l)	River water (g/l)
Mezguita	1.5	0.64
Tinzouline	2.2	0.79
Ternata	2.5	1.04
Fezouata	4.0	1.04
Ktaoua	5.0	1.32
Mhamid	5.0	1.32

Source: Bouidida, A. 1990, Ministère du Commerce, de l'Industrie, des Mines et de la Marine Marchande, 1977

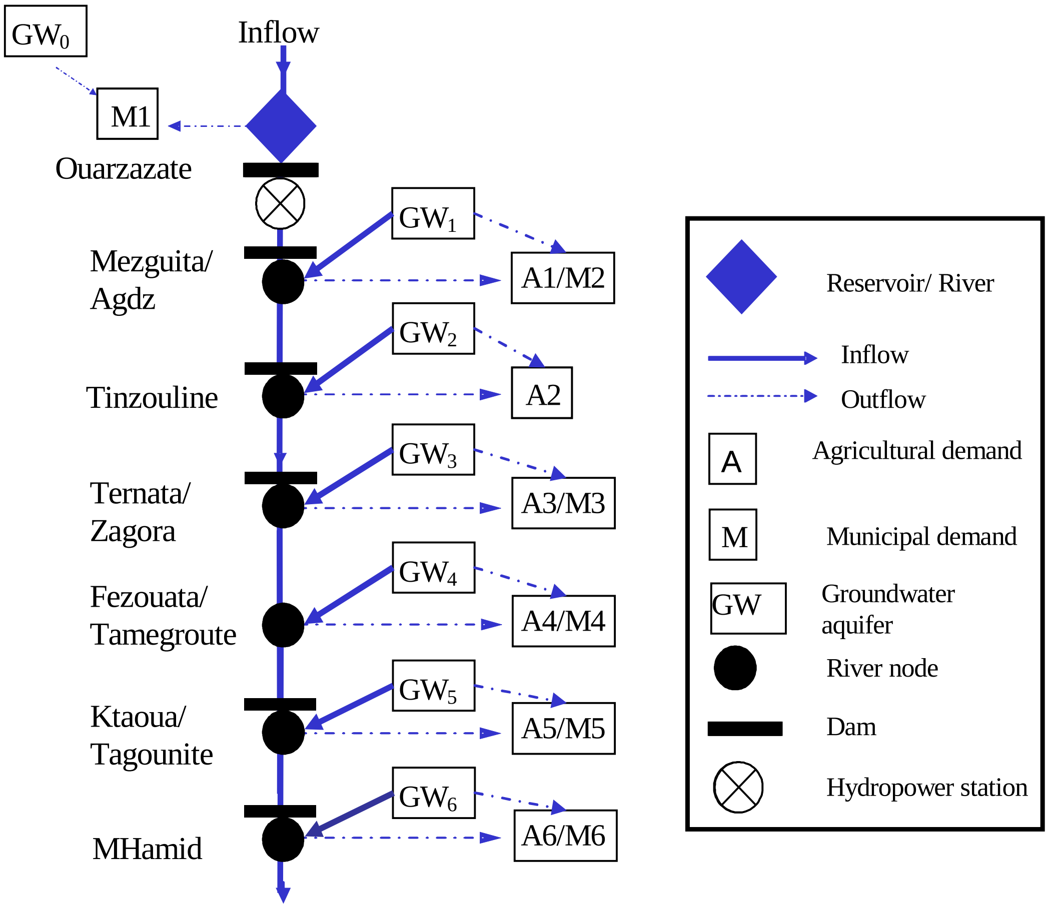
For the Drâa basin irrigation water salinity is tremendously high (locally sometimes up to 10 milliohms/cm in the South), but so far seems not to have been sufficiently considered in water management in the region.

Water quality, especially salinity, has been addressed in various simulation models dealing with irrigated agriculture. Lee and Howitt (1996) use a Coob-Douglas production function according to Dinar and Letey (1996) to account for water salinity in a nonlinear programming model. Also, Cai et al. (2006) use a production function taking the water deficit, salinity rates, and technology levels for yield formation into account. By contrast, the integration of water quality aspects in the hydro-economic model MIVAD (Modèle integrée de la Valée du Drâa) presented in this article is formulated as a yield function containing factors reflecting both seasonal water deficits and salinity levels.

6.2 *The role of salinity in the Drâa basin model*

The hydro-economic river basin model MIVAD is a nonlinear water allocation model that consists of a node-link network representing the six oases along the Drâa River. MIVAD is similar to the class of river basin models as designed by Rosegrant et al. (2000). The spatial structure of the model is presented in Figure 6-1 where the interconnection between supply and demand is represented with arrows.

Figure 6-1: Spatial structure of the MIVAD model



Source: Kuhn et al. 2005

The objective of the model is to maximize agricultural profits taking into account various constraints and balances. In MIVAD, farmers can make choices in cropping on two levels: the absolute area to be cultivated with a certain crop mix that is kept constant, and the yield levels for the different crops which depend on water application of different quantity and quality (i.e. salt content).

More precisely, actual yields are calculated by reducing the maximum yield of a crop by a water deficit factor and a salinity reduction factor. This has been applied by Dinar and Letey (1996) to a seasonal crop water production model. It is assumed that there is a maximum crop yield pmaxyield to be achieved with average technology (seed variety, fertilizer use, chemicals, seedbed preparation etc.). The actual yield in a certain year may be lower than the maximum due to insufficient water supply to the crop and salinity response. The yield function is based on the following relation:

$$vcropyiel_{dma,crop} = pmaxyield_{crop} \cdot vdef\_maxi_{dma,crop} \cdot vyie\_sali_{dma,crop} \tag{1}$$

with *pmaxyield*, maximum yield for the different crops (per ha), *vdef_maxi*, yield reduction factor due to periodically or generally, insufficient water application (crop water deficit), *vyie_sali*, yield reduction factor due to salinity.

In MIVAD it is assumed that water application to crops is a decision that is made by farmers for the entire cropping season based on a-priori information on the amount of irrigation water available. The yield reduction factor due to crop water deficit (*vdef_maxi*) is calculated as a non-smooth approximation of the seasonal water deficit *vdef_seas*.

$$vdef\_maxi_{dma,crop} = \Big(1 + \exp\Big(\alpha \cdot \big(-vdef\_seas_{dma,crop} + \beta\big)\Big)\Big)^{-1} \tag{2}$$

with *vdef_seas* being the seasonal water deficit as calculated by using seasonal ky-values (FAO 1986), α a slope coefficient of the approximation curve, and β a coefficient determining the position of the curve.

Monthly evapotranspiration consists of two components: total irrigation water applied to a crop (*v__w_a_cr*, which the farmer can choose to take from surface or groundwater sources) reduced by a leaching factor (to be explained later on), and the effective rainfall in the area.

$$\begin{aligned} & veta\_stag_{dma,crop,pd} = \\ & v\_\_w\_a\_cr_{dma,crop,pd} \cdot vleachfct_{dma,crop} \\ & \quad + vcroparea_{dma,crop} \cdot peff\_rain_{dma,pd} \end{aligned} \tag{3}$$

with *v__w_a_cr* irrigation water available to a crop both from surface water and groundwater, *vleachfct* leaching factor, *peff_rain* effective rainfall in mm, where the leaching factor (see formula 4) is calculated according to Ayers and Westcot (1985) as:

$$(4) \qquad vleachfct_{dma,crop} = 0.01 \cdot \exp\ (\delta \cdot vet\_ratio_{dma,crop}) + pirr\_effy$$

with *vet_ratio* actual evapotranspiration (ETa) divided by maximum evapotranspiration (ETm), *pirr_effy* irrigation efficiency factor (constant).

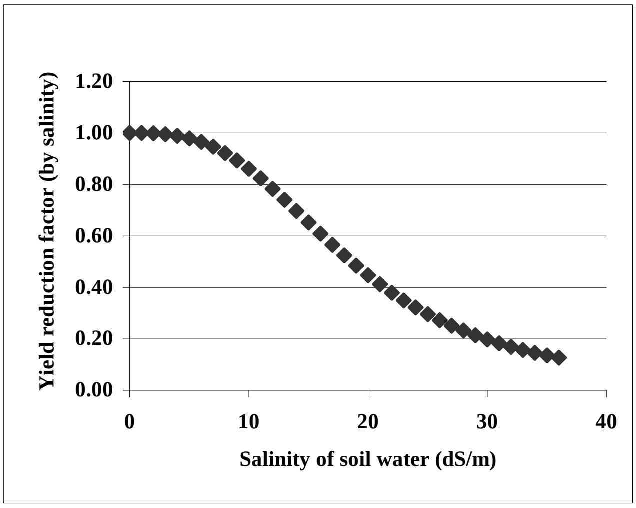
The leaching factor not only determines the amount of irrigation water which percolates into deeper soil layers, but also plays an important role for the level of soil salinity. Salt concentration in the soil is a result of the fact that evaporation of irrigation water leads to an accumulation of salt in the topsoil. This is especially the case in the most southern oases, Ktaoua and Mhamid, as evapotranspiration in the area is high and insufficient leaching leads to an accumulation of salt on the surface. During and after irrigation days, leaching into deeper soil layers might occur and help to keep soil salinity in check, while during the rest of the time plants may still suffer from irrigation water deficit. This is why the leaching factor used in MIVAD contains a constant additive component (pirr_effy) reflecting the leaching losses of furrow irrigation.

The salt content of water consumed by crops (salinity) is another important factor for yield formation. The yield reduction factor due to salinity is calculated on the basis of a modified discount function (Steppuhn et al. 2005). The salinity of soil water (*vyie_sali*) is calculated as:

$$(5) \qquad vyie\_sali_{dma,crop} = \left(1 + \left(vsoilsali_{dma,crop} \big/ psal\_thre_{crop}{}^{psal\_slop_{crop}}\right)\right)^{-1}$$

with *vsoilsali* being the salinity level of the soil water consumed by crops, *psal_thre* the crop-specific salinity level at which the yield is depressed by 50 percent, and *psal_slop* a slope parameter. The effect of the slope parameter is displayed in Figure 6-2.

Figure 6-2: Effect of salt reduction factor on yields



The soil water salinity level can be derived from the salinity level of the irrigation water multiplied by a concentration factor specific for each crop and oasis.

$$vsoilsali_{dma,crop} = vsalinity_{dma} \cdot vcon\_fact_{dma,crop} \tag{6}$$

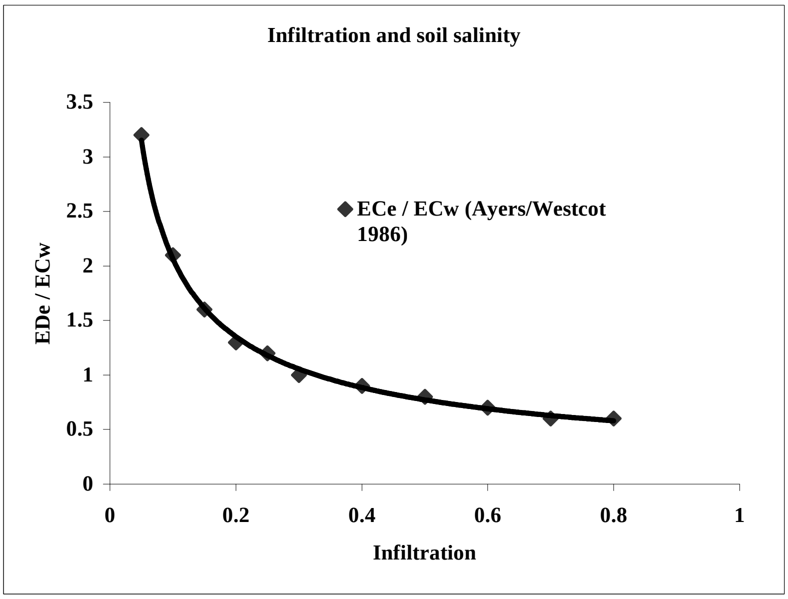
with *vsalinity* being the salinity level of irrigation water and *vcon_fact* the concentration factor. Salinity of irrigation water is the average of the salinity levels of surface (= river) and groundwater used for irrigation, respectively.

The concentration factor describes the ratio of salinity in irrigation water to the salinity of soil water and can be calculated as a function of the variable ‘leaching factor’ (*vleachfct*) that has already been mentioned in equation 5. On the basis of results from Ayers and Westcot (1985), the leaching concentration factor *vcon_fact* is calculated as:

$$vcon\_fact_{dma,crop} = \left(\beta \cdot vleachfct_{dma,crop}\right)^{-\rho} \tag{7}$$

with β a level parameter, and ρ a slope parameter .

Figure 6-3: Soil salinity as a nonlinear function of the leaching factor



6.3 Results of simulations involving salinity

To evaluate the effect of salinity on crop yields and agricultural profits, comparisons with and without a salinity effects on crop yields have been carried out for three different water supply scenarios. Table 6-2 summarises simulation results for different levels of surface water availability for all oases of the Drâa basin: a normal year, a medium and a dry year. The normal year relates to an average of inflows into the surface water network of the basin from 1972 to 2002, the dry year presents the average of the ten driest years over the same period (23 % of the water amount of a normal year), and the intermediate year is an average of the other two (62 %, respectively). If salinity is not considered, surface water for irrigation is more and more substituted by groundwater the more surface water becomes scarce. As total water use is nevertheless decreasing, agricultural profits are decreasing as well, primarily because the total cultivated area is decreasing, but also because yield levels are lowered, as is shown in Table 6-3.

Table 6-2: Basin-wide simulation results for normal, medium and low water availability without and including salinity effects

	Without salinity			**With salinity**		
	Normal	**Medium**	**Low**	**Normal**	**Medium**	**Low**
Ag. river water use (Mm³)	165.3	89.4	16.9	188.8	118.4	17.9
Ag. groundwater use (Mm³)	63.3	92.0	76.7	23.9	14.0	6.5
Total ag. water use (Mm³)	228.6	181.4	93.5	212.7	132.4	24.4
Total water use (Mm³)	233.8	186.6	98.7	218.0	137.6	29.6
Use of available crop area (%)	63.9	50.7	26.0	47.7	32.0	6.1
Agric. profits total (MDH)	260.4	189.6	79.6	171.0	119.4	20.5

Results look completely different when the yield-decreasing effect of salinity is considered. As surface water is free of charge for farmers and less saline than groundwater, surface water is strongly preferred for irrigation of agricultural crops. However, when surface water becomes scarcer, for example in the intermediate and dry water supply scenarios, it would be increasingly substituted by groundwater, even though groundwater pumping is costly for the farmers. This is not the case when salinity is considered: groundwater is by far not used as extensively particularly in the dry year due to the fact that its use would not contribute to keep yields per hectare at profitable levels. This ultimately leads to a far more pronounced decrease in crop areas to only 6% of the maximum area available to farmers.

When water scarcity alone is taken into account, farmers will probably decrease crop areas, but also crop yields to a minor extent to deal with the scarcity situation. But in a situation which combines water scarcity and high salinity of the water available, farmers face a more complicated dilemma, as a reduction of the amount of irrigation water per hectare as in the scenario without salinity would swiftly increase soil salinity and depress yields by far more. The reason is that the leaching effect of irrigation would decrease by more than the pure water reduction, an effect which is explained by the non-linear relation between water application and leaching as shown above.

A closer look at the individual effects of water scarcity and salinity reveals that salinity effects are indeed much higher than the impact of water scarcity (see Tables 6-3 and 6-4). The scarcer the water gets, the more intense are the effects of salinity, as more groundwater is used, and as leaching to keep soil salinity down becomes more expensive. It is no surprise that crops that have both a high drought and salinity tolerance (see Table 6-4, first column) such as wheat, barley or date palms suffer the smallest yield reduction effects as compared to the scenario without salinity (see Table 6-3).

Table 6-3: Yield levels (in % of maximum yield levels) for normal, medium and low water availability

	Without salinity effects			**With salinity effects**		
	Normal	**Medium**	**Low**	**Normal**	**Medium**	**Low**
Wheat	95.9	94.1	92.5	96.2	92.7	91.6
Barley	82.5	68.2	66.3	87.6	74.4	74.9
Pulses	97.9	97.2	95.3	91.0	83.3	75.5
Vegetables	98.5	99.1	99.7	58.8	64.4	69.2
Henna	80.2	85.4	86.1	67.3	72.8	72.3
Date palms	77.5	82.2	83.9	70.5	75.6	77.5
Alfalfa	71.1	77.3	78.9	37.8	39.5	38.7

Table 6-4 decomposes the yield reduction effect under salinity into the water deficit and the salinity effect which together constitute the yield function (see equation 1). Moreover, the sensitivity of the different crops with respect to water deficit and salinity as used in the model are reported in the first column. Water needs of crops (and implicitly the sensitivity to water stress) are expressed as the evapotranspiration at the maximum yield level under local climate conditions in millimeters per annum. The higher the water need of a crop, the higher the crop is assumed to be prone to water stress. The sensitivity regarding salinity is expressed as an index calculated by dividing the level parameter *psal_thre* by the slope parameter *psal_slop* (see equation 5). The lower the index, the more sensitive is the crop to the salt content in the soil water.

Table 6-4: Decomposing the yield reduction under salinity into a water deficit and a salinity effect (figures denote the share of the maximum yield)

	Sensitivity of crops to yield-reducing factors	**Normal**	**Medium**	**Low**
Water deficit effect	*Max. water need*			
Wheat	513	1.00	0.99	0.97
Barley	509	0.96	0.88	0.83
Pulses	431	1.00	1.00	1.00
Vegetables	659	1.00	1.00	1.00
Henna	1848	0.90	0.92	0.93
Date palms	1786	0.83	0.87	0.88
Alfalfa	1848	0.77	0.76	0.76
All crops		0.92	0.92	0.91
Salinity effect	*Salinity tolerance*			
Wheat	6.35	0.96	0.94	0.95
Barley	4.61	0.95	0.93	0.95
Pulses	1.80	0.89	0.82	0.78
Vegetables	2.03	0.57	0.63	0.70
Henna	3.78	0.72	0.79	0.77
Date palms	6.70	0.85	0.87	0.88
Alfalfa	3.30	0.50	0.51	0.51
All crops		0.78	0.78	0.79

Table 6-4 shows that for most crops yield reduction originates from salinity (the reduction factors are much smaller) and not from the ‘pure’ irrigation water deficit. Moreover, it is difficult to predict the yield reduction on the basis of the sensitivity to water stress and salinity alone. The profitability of crops might still justify a high water input level, which is exemplified by vegetables: the overall salt content of irrigation water does hardly allow yield levels above 70 % of the maximum yield. Nevertheless, vegetables are heavily leached in order to allow reasonable yields. Alfalfa yields, by contrast, are allowed to drop, as this crop generates less profit than vegetables.

6.4 Discussion

Accounting for salinity in yield formation and production models has enormous effects on simulation results regarding resource use, which is highly relevant for basin-wide water management decisions. Most importantly, the on-farm effects (water use from different sources, cropping choice, yield levels) become more difficult to predict when salinity comes into play. The decision situation facing the farmers is indeed highly complex, even when simulated in a deterministic setting with perfect foresight as in this article. Moreover, if the salinity of irrigation water were to further increase in the coming years, the trend towards using groundwater for irrigation could perhaps be reversed. This effect could be demonstrated in more detail by employing a salt flow balance, which so far has not been addressed due to a lack of empirical data. As to resource management aspects, both groundwater availability and salinity should be considered when deciding on the optimal allocation and distribution of surface water among the oases, as far as this is in the domain of a central water distribution agency.

Furthermore, the cropping mix cultivated is likely to shift to more salt-resistant crops with increasing salinity. The model version on which the results in this article are based is keeping the crop mix fixed and only adapts total cropping area and crop yields. A suitable calibration method allowing for a more flexible cropping mix needs to be further refined.

6.5 References

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7 Impacts of changing water inflow distributions on irrigation and farm income along the Drâa river in Morocco[12]

Abstract

Irrigation water is essential for agriculture in the arid Drâa River basin in Morocco but climate change leads to increasingly unreliable water supply in the area. This paper analyses impacts of changing water inflow distributions on irrigation and farm income extending a conjunctive river basin model towards a stochastic modeling approach. Regional climate scenarios are used to derive a maximum likelihood density estimate of current and future water supplies. Based on these distributions, Monte Carlo simulations are performed to obtain stochastic model results on surface and groundwater irrigation as well as economic indicators for six oases along the river. The probability of farmers to receive revenues below the subsistence level is around two percent under current conditions, but this is likely to rise to rates of 6 to 15 percent depending on the underlying climate change scenario. The composition of water sources for irrigation will shift to more groundwater use. The river basin model is able to represent complex spatial interactions between oases as well as a partial complementarity between groundwater and surface water irrigation due to salinity management effects. Interestingly, the value of groundwater is not necessarily increasing under future climatic conditions as salinity problems are aggravated with expanded groundwater use.

JEL classification:
C61, Q18, Q25, Q54

Keywords:
Conjunctive water management, stochastic simulation, agricultural income, stabilization value of groundwater, climate change, Morocco

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[12] A modified version of this paper will be published in 2010 in *Agricultural Economics* 41, pp: 135-149 together with Prof. Thomas Heckelei (http://www.wiley.com/bw/journal.asp?ref=0169-5150).

7.1 Introduction

The Drâa valley south of the Anti-Atlas Mountains in southern Morocco is characterized by a belt of six oases with agriculture being the major economic activity for the local population. Although a significant part of household income is provided by remittances from family members that migrated to bigger cities or to Europe, agriculture is the most important source for food and still very relevant for supplementing income. Irrigation is essential in the region with average annual rainfall of less than 100 mm. However, water availability is highly unreliable showing extended drought periods with high temperatures in recent years. Meteorologists predict even higher temperatures as well as increasing volatility and decreasing average amounts of precipitation in coming decades. Hence, it is of significant interest how these climatic changes affect agricultural land use and farmers' income in the future.

Farmers have basically two choices of water for irrigation: surface water from the Mansour Eddahbi reservoir and groundwater from the shallow aquifers that are located under each oasis but are interconnected along a hydraulic gradient from North to South (Klose et al. 2008). Complex economic and hydrologic interactions between water sources and uses differentiated by timing and location lead to the development of the hydro-economic river basin model, MIVAD (Modèle intégré de la vallée du Drâa, Heidecke et al. 2008). This simulation model depicts the economically motivated use of agricultural land and water in the six oases observing hydrologic relationships and allows simulating impacts of water management options on resource use and economic indicators. Water pricing policies (Heidecke et al. 2008) and salinisation effects on yield formation (Heidecke and Kuhn 2007) have received specific attention in previous applications of the model.

The aim of this paper is to analyze the possible effects of climate change on the distribution of farm income and water resource use. The stochastic nature of water availability is considered by available regional projections of precipitation under climate change scenarios A1B and B1 of the Intergovernmental Panel of Climate Change (IPCC 2007) derived within the IMPETUS project[13] (Born et al. 2008, Paeth et al. 2008) for southern Morocco. In order to perform the analysis, MIVAD is extended to include reservoir inflows as a random variable. The distribution of water inflows is estimated using historical data and projections from climate change scenarios. Monte Carlo experiments with the model are then conducted for

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[13] IMPETUS: Integrated management approach to the efficient and sustainable use of water in West Africa (www.impetus.uni-koeln.de)

random draws from the estimated inflow distributions. This allows deriving and assessing probability distributions of farm income and water use patterns under different climatic conditions. It also renders the possibility to evaluate the combined effect of an increasing variability of surface water supply and salinity problems on the value of groundwater not considered in previous work.

In the following chapter previous relevant studies of conjunctive water management and stochastic modeling approaches of water management are discussed. Subsequently, a description of the methodological approach is given. Monte Carlo results for the different scenarios are presented and discussed in section four. The final chapter concludes and discusses limitations of the analysis thereby pointing at relevant directions for future research.

7.2 Background

Water management has gained importance also in the economic literature during the last decades. In many semi-arid regions of the world water becomes scarcer each year due to population growth, economic development and climate change. The value of water increases as quantity constraints tighten for household and industry use, specifically for agricultural production. Early studies focused on either surface or groundwater resources. Economic aspects of groundwater management have been addressed by Burt (1964), Buras (1963), Gisser and Sachez (1980) and Feinerman and Knapp (1983). In most watersheds however, both, ground- and surface water, are used for irrigation. Therefore, increasing attention has been given to the conjunctive management of groundwater and surface water use with the understanding that “ground and surface water sources are two components of one system and should be managed as such” (Gemma and Tsur 2007: 540). In a static conjunctive water use model Tsur (1990) identifies the specific value of groundwater to serve as a buffer against the variability of surface water. This stabilization value SV is defined as the difference in profits under certainty when surface water supply is fixed at its mean to the profits under uncertain conditions when surface water is a random variable (Gemma and Tsur 2007). Tsur and Graham-Tomassi (1991) calculate the value of groundwater in a dynamic context which they then called the buffer value of groundwater. The value of groundwater has been further analyzed by Gemma and Tsur (2007) who assess the value of groundwater for the Coimbatore district in India. Provencher and Burt (1994) use a stochastic setting for conjunctive water management integrating a random variable for surface water supply into a model of interrelated aquifers. Roseta-Palma (2006) was one of the first to address water quality aspects in a conjunctive use model recognizing that poor water quality may negatively affect crop yields and thus also the value of groundwater. The research mentioned above derives the value of water analytically within the context of simple models. Conjunctive water management in reality is however often subject to a variety of cropping pattern, a multitude of spatially differentiated water uses and supplies and more complex relations between crop yield, water quantity and quality.

As a response to this challenge, complex river basin models integrating hydrologic interactions with economic models started to emerge (see, for example Cai 1999, Ringler 2002, and Cai et al. 2006). These models are characterized by a detailed description of water use and water supply formulated within numerical optimization models as the derivation of analytical behavioral function was no longer possible. Heidecke et al. (2008) use the MIVAD river basin model for the Drâa valley in Morocco to evaluate different water pricing policies, but the deterministic modeling version does not allow predicting yearly variations in income or water management indicators under different climatic scenarios. The studies mentioned above evaluate the substitution between ground- and surface water resources and derive corresponding water values as well as optimal management approaches, but they do not take water quality issues into account. For the Drâa basin salinity rates of groundwater are a major constraint of agricultural productivity. However, the scarcity of surface water in times of drought makes groundwater use attractive in addition to surface water use. This paper uses the conjunctive hydro-economic river basin model by Heidecke et al. (2008) and includes quantity and quality aspects of irrigation water building upon the analysis of salinity effects by Heidecke and Kuhn (2007), but amending the modeling approach by incorporating a stochastic water inflow variable. With this extension the probability distribution of future water use and its impact on farm income is evaluated. Relationships between ground- and surface water are analyzed highlighting the effects of salinity impacts and the value of groundwater under changing climatic conditions.

7.3 Modeling Approach and Data

In this section we give an overview on the simulation model focusing on the most relevant aspects for the interpretation of results. A full mathematical representation is given in the appendix.

The model maximizes total agricultural income π for all oases o and for all crops c cultivated which depends primarily on cultivated land X and crop yield Y which again depends on irrigation water quantity w and water quality s applied. The model is given by:

[1]

$$\underset{X,Y,W,S}{MAX}\,\Pi = \sum_{o}\left(\sum_{c}\left(X_{o,c}\cdot\left(P_c\cdot Y(w,s)_{o,c}-\sum_{i}\left(I_{c,i}\cdot IP_i\right)\right)\right)-\sum_{pd}\left(GW(w,s)_{o,pd}\cdot z\right)\right)$$

$$-\sum_{o}\left(Q(\varepsilon_c)X_o+\frac{1}{2}Q(\varepsilon_c)X_o{}^2\right)$$

with *X*, the area cultivated in each oasis *o*, *P*, exogenous product prices for the crops *c* cultivated, and *Y*, the crop yield which is determined by water quality *s* and quantity *w*. Other inputs than water *i* such as fertilizers and labor are crop specific and constant per unit of activity. Thus, *I* represent the required variable inputs *i* for the amount of crops cultivated, *IP* the exogenous input prices for *i*, *GW*, the amount of groundwater used for irrigation, and *z*, the costs per unit of groundwater used. The last term in bracket is the non-linear cost term for calibrating the model and represents the costs for deviation of the observed cropping patterns in the year 2000. The model is calibrated using the positive mathematical programming technique (PMP) (Howitt, 1995), but introducing supply elasticities as prior information in the specification step (Heckelei 2002, Heckelei and Wolff 2003). The elasticities for the perennial crops, date palms and henna, are more inelastic compared to the other crops as farmers give priority to these for financial reasons and try to preserve them in times of water shortage.

Seven major crops *c* are represented in the model, namely wheat, barley, maize, alfalfa, a vegetable aggregate, and henna and date palms as perennial crops. Water requirements per month and salt tolerances are crop specific. Yield is derived from a maximum yield reduced by a factor accounting for water deficit and a factor referring to the salinity tolerance of the crop according to equation 2:

$$Y_{o,c} = Y_{\max_c} \cdot \left(1 + \exp\left(\lambda \cdot \left(-Wdef_{o,c} + \delta\right)\right)\right)^{-1} \cdot \left(1 + \left(r_{o,c} / l_c^{\gamma_{crop}}\right)\right)^{-1} \qquad [2]$$

with *wdef* as the water deficit derived from a ratio of actual to potential evapotranspiration, *r* the salinity of soil water, *l* the crop-specific salinity level at which the yield is depressed by 50 percent, and λ, δ and γ as specific parameters. The salinity of irrigation water in equation 3 is determined by the initial salt content in surface and groundwater and calculated as the average salinity rates of groundwater (GW) and surface water (SW) used for irrigation whereas groundwater quality is more deteriorated due to the geological characteristics in the Drâa valley (Klose et al. 2008).

$$S = \frac{S^{sw} + S^{gw}}{w} \qquad [3]$$

The salinity of soil water *r* is reciprocally determined by the salinity rate of irrigation water and depends on the amount of water leached[14].

The model represents agricultural production of the oases as six aggregate farms and each constituting a separate water demand site for agricultural irrigation. The

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[14] For a more detailed discussion of the model's salinity representation see Heidecke and Kuhn 2007.

municipal water demand for four bigger villages in the area is assumed to be exogenous as municipal water takes up only a small share of total water use and is of highest priority. The demand sites are interlinked by a spatial network of water demand and supply points. The simulations are made in monthly periods solving them for one year simultaneously over all oases.

Water supply is coming from two sources: surface water and groundwater[15]. Surface water is determined by the inflows into the reservoir where it can be stored and released to the oases during the year. At the beginning of the year the reservoir is filled at forty percent of its total capacity. Within the year, releases are possible that exceed this fill rate, however at the end of the year, the reservoir needs to carry 60 million cubic meters of water. This assures that water is left over for future water needs and represents the current management practice in the Drâa valley. Water can be released from the reservoir in monthly periods. From there it is distributed between the oases according to the oases share of crop area planted and their crop water requirements. In contrast, groundwater is locally available from a shallow aquifer located beneath each oasis and is used to complement surface water for irrigation. However, aquifers are connected with each other according to specific flow gradients and are connected with the river as groundwater can discharge into the river depending on the fill level of the aquifer. Thus, groundwater use in an oasis upstream affects groundwater availability in the oases downstream the river. The connection of the different supply and demands sides of water are complex in such that ground- and surface water use in each oasis affect the water supply in the oasis upstream and downstream.

For the scenario calculations in this paper, inflows are introduced as a random variable to simulate stochastic surface water availability. Like many hydrological variables (Fernandez and Salas, 1990, Phien, 1993) this distribution of water inflows is believed to have the form of a gamma distribution:

$$f_x(x;\alpha,\beta)=\left(\frac{1}{\left(\beta^{\alpha}\Gamma(\alpha)\right)}\right)x^{\alpha-1}e^{-x/\beta} \qquad [4]$$

Figure 7-1 shows the inflows into the reservoir from historical data from 1940 to 2006 indicating the significant fluctuations from year to year. The linear trend line points at the decreasing average water availability over time, however, mainly related to the decline since the nineties.

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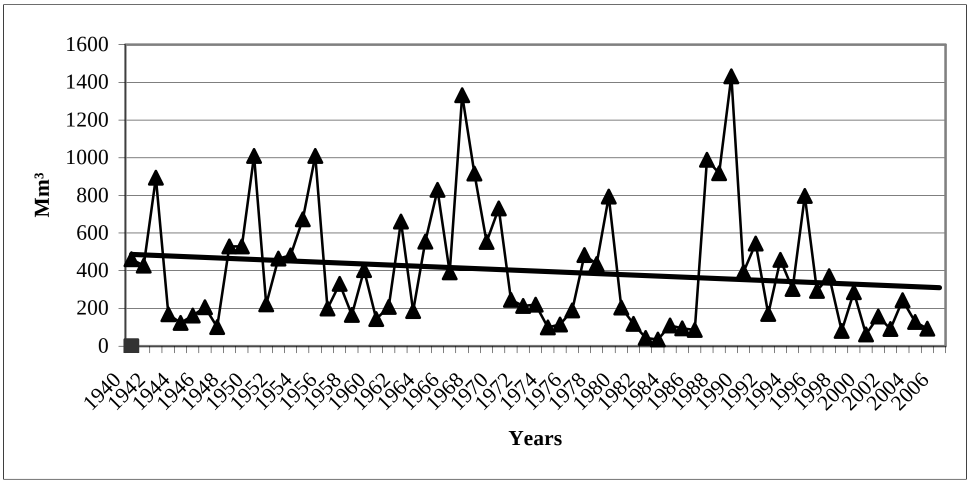
[15] For more details on the hydrologic relationships in the model see Heidecke et al., 2008.

Figure 7-1: Yearly water inflows into the Mansour Eddahbi reservoir from 1940 to 2006 (in Mm³)



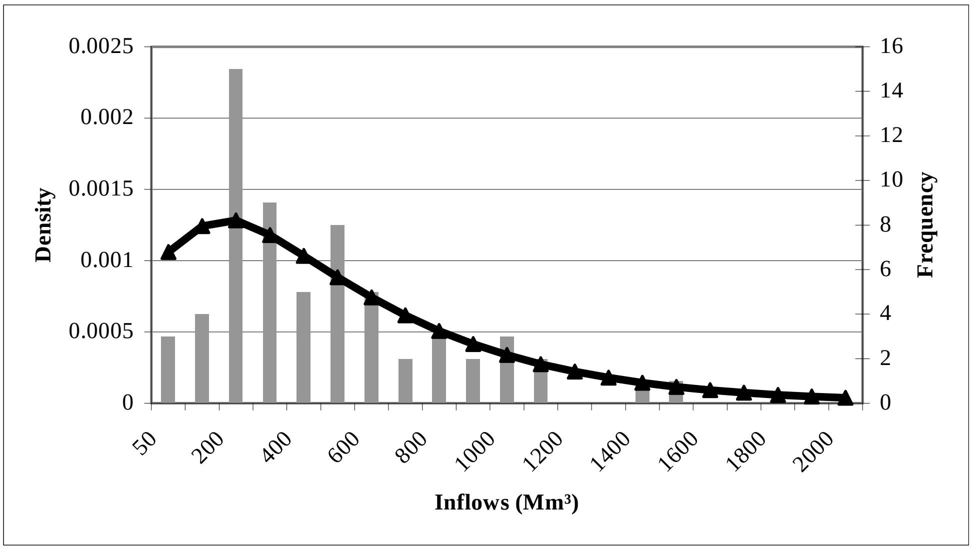
Source: Data from Direction Générale de l'Hydraulique, 2007
Note: The reservoir Mansour Eddahbi was built in 1972; before 1972 inflows directly entered the river Drâa

The parameters alpha and beta of the gamma distribution which are assumed to underlie yearly inflows into the reservoir are estimated using the maximum likelihood technique. A log likelihood function of the gamma distribution (equation 5) is maximized following Kalvelagen (2005):

$$\begin{gathered}\ln\ L(\alpha\,,\beta\,;x) = \\ n \cdot [\ln(\beta) - \ln(\alpha) - \ln\ \Gamma(\beta)] + \ (\beta\ - 1)\cdot \ln(\beta\ \cdot x\ /\ \alpha))\ \ - (\beta\ \cdot x\ /\ \alpha)\end{gathered} \qquad [5]$$

with α > 0, ß > 0 being the shape and scale parameter of the distribution, respectively, and with n number of observations of inflows x. Figure 7-2 shows the estimated probability density function with α = 403 and parameter β = 1.405 (also compare Table 7-1) providing a reasonable fit to the historical yearly inflows as displayed in the histogram. This distribution is used to draw 1000 outcomes of yearly reservoir inflows for each simulation.

Figure 7-2: Frequency of yearly inflows into the Mansour Eddahbi reservoir from 1940 to 2000 and estimated probability density function of inflows for the same period



Source: Historical inflows from the Direction Générale de l'Hydraulique, Morocco, and own estimations

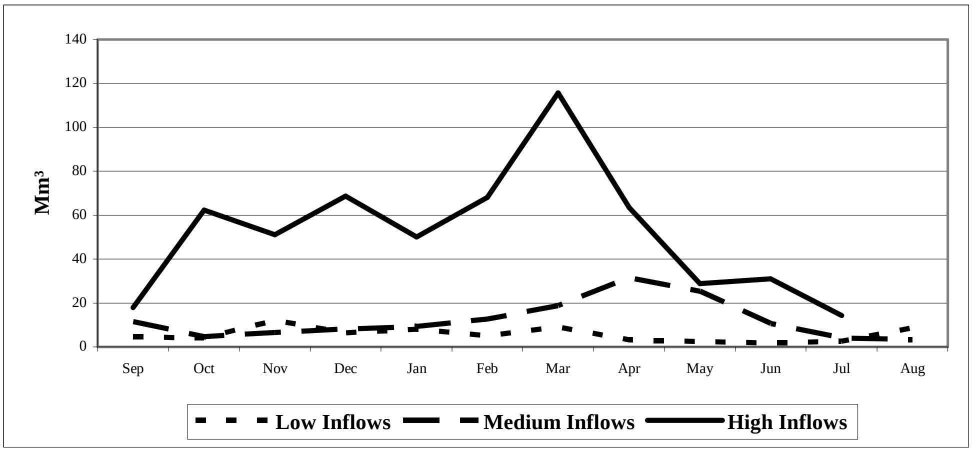
The gamma parameters are not only estimated for historical data, but also for climate change scenarios A1B and B1 of the Intergovernmental Panel on Climate Change (IPCC 2007). Scenario A1B is characterized by higher CO_2 emissions assuming rapid population and economic growth and by the intensive use of fossil and non-fossil energy resources. In contrast, scenario B1 assumes lower CO_2 emissions due to a rapid change of economic structures resulting in a service and information technology society (IPCC 2007). The inflow data of the IPCC Scenarios A1B and B1 originate from REMO model calculations of the IMPETUS project (Born et al. 2008, Paeth et al. 2008) simulating regional precipitation scenarios relevant for the inflows considered here based on different runs of the IPCC scenarios A1B and B1.

As historical precipitation data and reservoir inflow data are correlated (Schulz et al. 2008), inflows are calculated on the basis of the precipitation data from the scenarios. Annual precipitation *(x)* is transferred into reservoir inflows *(y)* with the help of a simple regression function with a coefficient of determination of 0.96:

$$y = 7.6136\text{x} - 899.76 \;\; ; \;\; \text{R}^2 = 0.96 \qquad [6]$$

The resulting annual inflows are distributed among the months depending on the percentage of inflows of the annual cycle. The annual cycle differs according to the total level of annual inflows (Figure 7-3). For example, during a period of drought a minimum of water continues to reach the reservoir of approximately fifty million cubic meters per year (Schulz et al. 2008). Therefore, three different monthly distributions for the annual cycle are distinguished from the historical data from 1940 to 2000.

Figure 7-3: Annual cycle of inflows for three different inflow levels (based on available data from 1940 to 2000)



Source: Direction Générale de l'Hydraulique, Morocco, 2004 and own calculations.

The parameters of the gamma distribution for the climate scenarios are estimated using the computed inflow data from 2000 to 2050. To make the climatic scenarios more distinctive, scenario data of the three ensemble runs for each scenario are summarized to represent one climate scenario. Hence, 150 observations are used to estimate parameters alpha and beta based on the maximum likelihood presented above, resulting in alpha values for A1B and B1 of 0.8 and 1.1 and beta values of 265 and 271, respectively (compare Table 7-1).

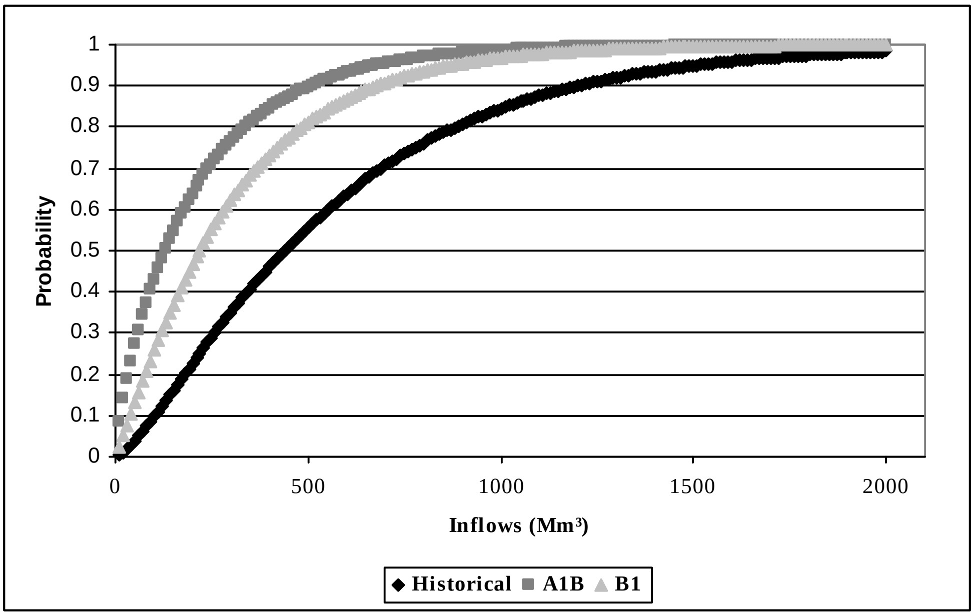
Table 7-1: Distribution parameters for historical inflows and for IPCC scenarios A1B and B1; N = 150.

	1960-2000	**B1(2000-2050)**	**A1B (2000-2050)**
a	1.405	1.117	0.779
b	403.699	270.670	264.934
1. Moment μ = ab	567.238	302.338	206.358
2. Moment $\sigma^2 = ab^2$	228959	81833	70190
Likelihood	-299.646	-989.571	-983.533

Source: Parameters estimated on the basis of data from Born et al. 2008, Paeth et al. 2008

This leaves two possible future distributions of inflows based on scenario calculations from 2000 to 2050. Regarding the cumulative distribution function of inflows for the historical distribution and for scenarios A1B and B1 (Figure 7-4), it is obvious that the probability of getting low inflows is the highest in scenario A1B (compare characteristics of IPCC scenarios above or at IPCC 2007). The second moments of the gamma distributions show that the variation of inflows decreases from the historical inflows to the climatic scenarios.

Figure 7-4: Cumulative distribution of model inflows for historical observations and scenarios A1B and B1



Source: Own estimations

In the following results are presented from three Monte Carlo experiments of 1000 draws per climate scenario with stochastic reservoir inflows for the historical situation and for the two climatic scenarios B1 and A1B evaluating distributions of agricultural income and water resource use. The stabilization value of groundwater is calculated following the concept of Gemma and Tsur (2007) but with the specifications of water quantity and quality considerations in this paper. In equation 7 the stabilization value (SV) is calculated as:

$$SV = \pi(X, Y, S, W_{SW(\mu)}) - E\left\{\pi(X, Y, S, W_{SW(\alpha,\beta)})\right\} \qquad [7]$$

where the profits under consideration of $W_{s(\mu)}$ indicating that the simulations for the stabilization value are made under the assumption that groundwater is not available and presents the value to stabilize surface water availability at its mean μ, are subtracted by the expected profits considering $W_{SW(\alpha,\beta)}$ which is the expected income of the Monte Carlo simulations of the gamma distributed inflow distributions. The value of groundwater of increasing the total mean of water available in the system, the augmentation value (denoted AV), is defined as:

$$AV = \pi(X,Y,S,W_{GW,SW(\mu)}) - \pi(X,Y,S,(W_{SW(\mu)}) \qquad [8]$$

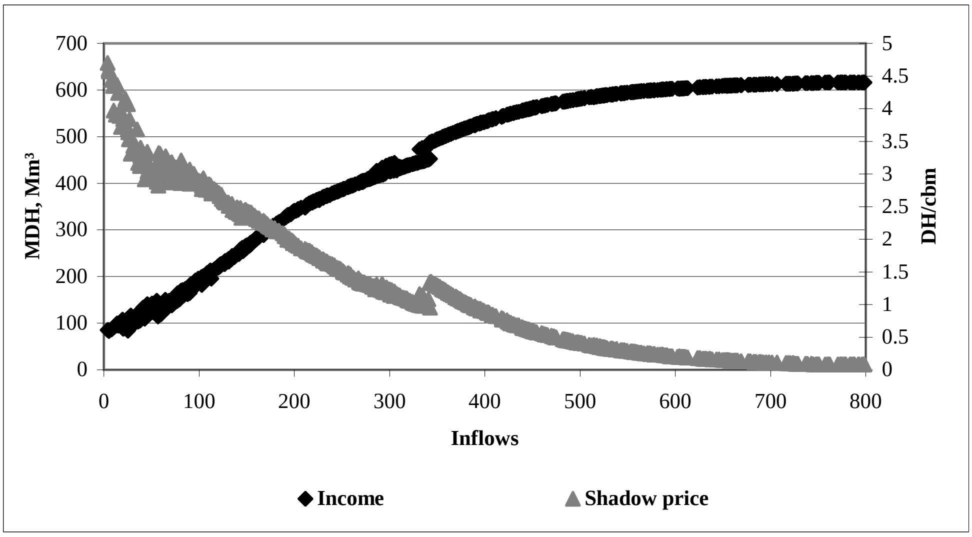
The AV thus defines the difference between the agricultural income with groundwater use and surface water use at the mean $W_{GW,SW(\mu)}$ minus the income without the possibility to use groundwater. The sum of SV and AV represents the net benefit of groundwater and can be summarized in equation 9 as:

$$NB = \pi(X,Y,S,W_{GW,SW(\mu)}) - E\left\{\pi(X,Y,S,W_{SW(\alpha,\beta)})\right\} \qquad [9]$$

7.4 Results

Under the historical climate regime total agricultural income varies from 82 to 617 Million Moroccan Dirham (MDH) in total for the whole region depending on the amount of water available in the system as determined by the inflows into the reservoir (Figure 7-5). Income rises constantly with declining marginal income starting at 82 MDH and stagnating at a level of 617 MDH.

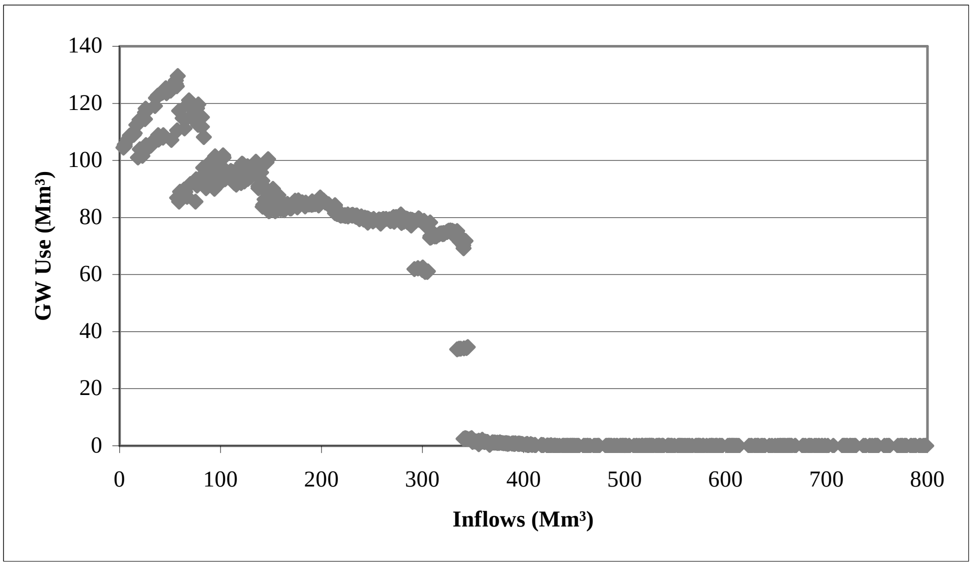
Figure 7-5: Relationship of inflows (Million cubic meters) to total agricultural income (Million Moroccan Dirham (MDH) and water shadow prices (DH/cubic meter)



Source: Own estimations
Note: Only results of inflows fewer than 800 Million cubic meters are presented (78 % of all draws)

Inflows greater than 800 Million cubic meters (Mm³) of surface water do not have any relevant further impact on agricultural income and water shadow prices as it is no longer limiting at this level due to restricted agricultural land resources in the model. The bound on area is realistic for the Drâa valley as the agricultural land is limited by surrounding mountains and the Sahara Desert and cannot be easily extended. The small break in the results in Figure 7-6 at inflows of 320 to 340 million cubic meters is due to computational difficulties. At this level, further lowering of inflows makes groundwater use profitable for the first time in some oases as surface water becomes scarce. The determination of the optimal amount of groundwater to be used takes into account quite complex interrelationships between water sources and demand sites. Groundwater is locally available and its quantity is not introduced as a random variable nor directly changed, nevertheless it is indirectly affected by the amount of inflows due to infiltration into the river bed and from infiltration of irrigation losses in each oasis. If surface water is abundantly available, groundwater use is not lucrative for the farmer since groundwater extraction implies cost for fuel and gas, whereas surface water extraction is free of charge to the farmer (compare Figure 7-6).

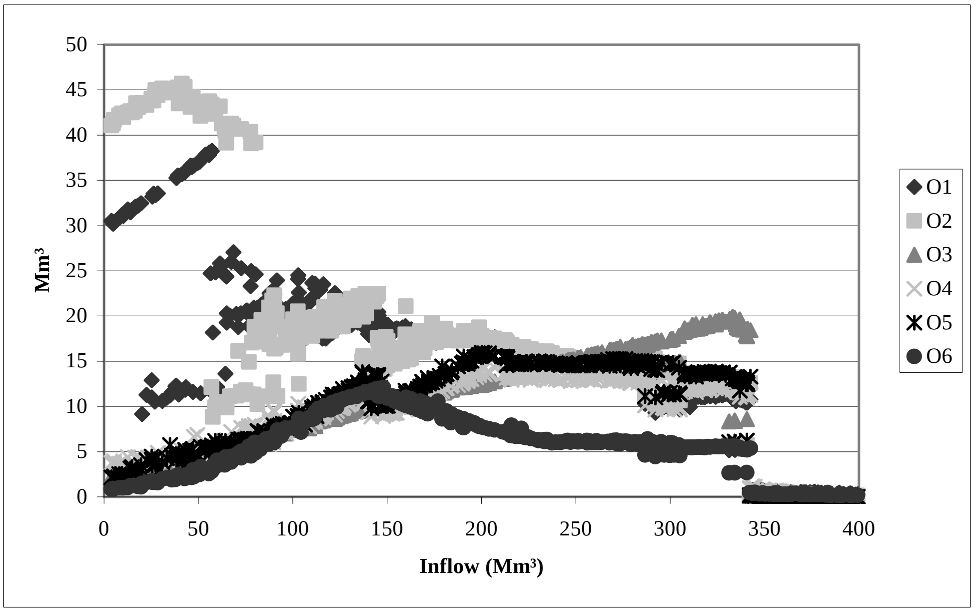
Figure 7-6: Relationship of inflows to groundwater under historical climate conditions



Source: Own estimations
Note: Only results of inflows fewer than 800 Million cubic meters are presented (78 % of all draw).

With reservoir inflows lower than 340 Million cubic meters groundwater is used for irrigation and its use generally rises with further decreasing inflows, as the simultaneously increasing value of water makes it economically more attractive for the farmer to supplement water supply with more costly groundwater. The high variation of groundwater use in Figure 7-6 at reservoir inflows between 0 and 200 Million cubic meters is mainly due to the specific characteristics of the oases and effects of salinity rates. Oases in the Drâa valley have different endowments in groundwater resources as aquifer volumes and gradients vary between the oases. Furthermore, groundwater is more saline compared to surface water and salinity rates are increasing from north to south. This combination makes total groundwater use in times of water scarcity difficult to predict. One the one hand, farmers prefer to use surface water for irrigation as surface water is free of charge and no negative salinity impacts on productivity occur. On the other hand, groundwater is used as a reserve in months of water scarcity to fulfill the annual crop water needs. It has to be noted that surface water use is also complementary to groundwater under certain conditions. The salinity in irrigation water is determined by the average of the salinity rate in surface water and groundwater. Hence, also highly saline groundwater is used for irrigation if supplemented with surface water to reduce the overall salinity rate of irrigation water. This leads to considerable and seemingly erratic changes of total groundwater across the oases (Figure 7-7).

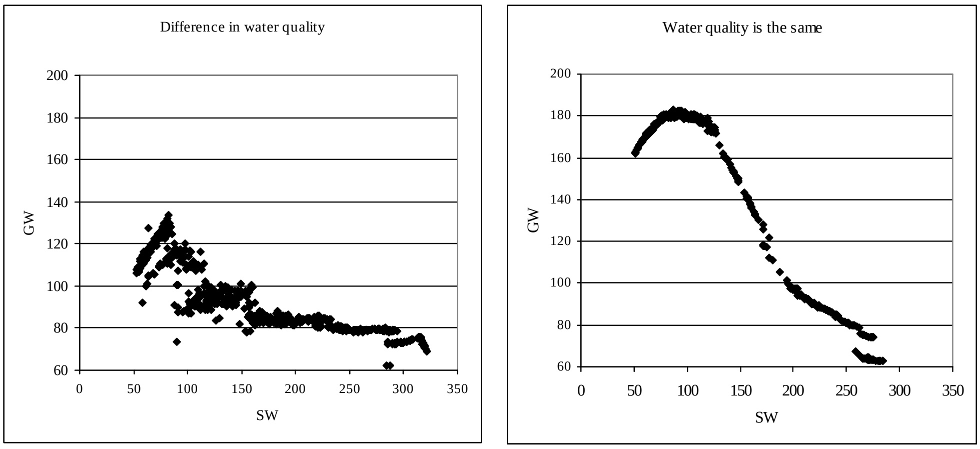
Figure 7-7: Groundwater use for cultivated area in the six oases depending on reservoir inflows under historical climate conditions



Source: Own estimations

Figure 7-7 demonstrates that the southern oases (O4 to O6) use less groundwater as salinity rates are high. When inflows are larger than 150 million cubic meters groundwater is used in conjunction with surface water to extend the cultivated area to its limit. With inflows below this level the full available area cannot be profitably used. Furthermore, the shallow aquifers are connected with each other in such a way that water flows to the next aquifer depending on the fill level. Local groundwater use is therefore determined by the overall regional water scarcity, by its salinity rates, by resource use in other oases, by the crops and area cultivated and by the amount of surface water available for supplementation. If salinity effects are not considered in the model, effects are more distinctive. If the quality of surface and groundwater is assumed to be the same, the resources are nearly perfect substitute goods (Figure 7-8). Considering the differences in quality, the substitution effects are less obvious as surface and groundwater have a substitution as well as a complementary relationship. The different characteristics and functions of groundwater are very important for an integrated water management. Taking water quality into account as has been done in this paper highlights the complexity and the interactions of surface and groundwater usage.

Figure 7-8: Complementary and substitution effect of surface and groundwater use for the historical climate situation with and without salinity effects



Source: Own estimations
Note: Only results of inflows fewer than 350 Million cubic meters are presented as groundwater use goes to zero with larger inflows.

To summarize the relations in the model and the effects of variation of inflows, Table 7-2 presents correlation coefficients between inflows and some output variables of the model for historical climate conditions. Surface water use shows the strongest linear relationship to the amount of reservoir inflows with a correlation coefficient of 0.84.

Table 7-2: Pearson correlations between input and output parameters of under historical climate conditions

	Reservoir inflows	Groundwater use	Surface water use	Shadow price	Income
Reservoir Inflows	1				
Groundwater use	-0.69	1			
Surface water use	0.84	-0.90	1		
Shadow price	-0.74	0.90	-0.94	1	
Income	0.73	-0.94	0.94	-0.99	1

Source: Own estimations

Agricultural income is also positively but less strongly correlated as other factors are influencing the amount of gross margins besides surface water use, for example water quality and yield formation. Shadow prices are negatively correlated as higher inflows lead to decreasing water scarcity. Groundwater use is of course negatively correlated as explained above but an increase in reservoir inflows and surface water use also leads to a replenishment of groundwater tables, therefore the coefficient is smaller with -0.69.

Income from agriculture differs significantly between the oases due to specific endowments in land and water resources, and thus different cropping possibilities and yield formation (Table 7-3). Oases number six i.e. faces the lowest agricultural net revenues as salinity rates are highest. Being the closest to the Sahara Desert, evaporation leads to high salinity rates in soil and water. Also, maize and vegetables are not cultivated in the southern oases due to water shortages. The highest agricultural income is obtained in the third oasis. This is due to the amount of available arable land as well as to the endowment with high quality and quantity of water resources. Dividing the total agricultural income of an oasis by the number of farmers in this oasis and by the days of the year, we get the average income per farmer per day (Table 7-3). Comparing this amount to the minimum standard of living of one Dollar per day per person, this seems to be even lower, as farmers have to feed large families with sometimes up to twenty family members. One should take into account, however, that results only refer to income obtained from agricultural production. Farmers in the Drâa valley also receive a large amount of money from remittances of migrated family members which are estimated to be around 60 percent of the total household income for the southern regions of Morocco (MATEE 2006).

Table 7-3: Agricultural income and resources use for six oases under current climate conditions

	Agricultural income (MDH)	No. of Farmers	DH per farmers	DH per farmer per day
O1	64.61	3225	20034	54
O2	74.22	3473	18603	51
O3	131.55	4244	15223	42
O4	63.76	2857	22614	62
O5	94.42	3027	21344	58
O6	36.12	1195	54066	148
Total	77.45	21024		
Standard Deviation	29.69			

Source: No. of farmers (Ouhajou, 1996), and authors' estimations
Note: 1 US $ = 7.3 Moroccan Dirham; 1 MAD = 0.14 US $; www.oanda.com June 2008

Unfortunately, data on overall income is not available for the region. Thus the calculation of agricultural income provides an approximation of the economic situation. Nevertheless, the results on agricultural income per capita per day give an idea, how vulnerable the population in the Drâa valley is. These already poor farmers will face an even more unreliable water supply in the future. Regarding the results of the climate change scenarios A1B and B1 in Table 7-4, an increase in the vulnerability of farmers is conceivable. In the current situation average income is 465 million Dirham per year with a standard deviation of σ =168. The probability of receiving an income from agriculture under 100 Million Dirham (around 2 dollar per day for each farmer in the region) is around 2%, the probability of having at least 200 Million Dirham for the region is 88%. The upper and lower quartiles underline this picture. The probability is 50 percent to get revenues from agriculture in the range of 352 and 615 Million Dirham.

Table 7-4: Analysis of agricultural net revenues, surface- and groundwater resources

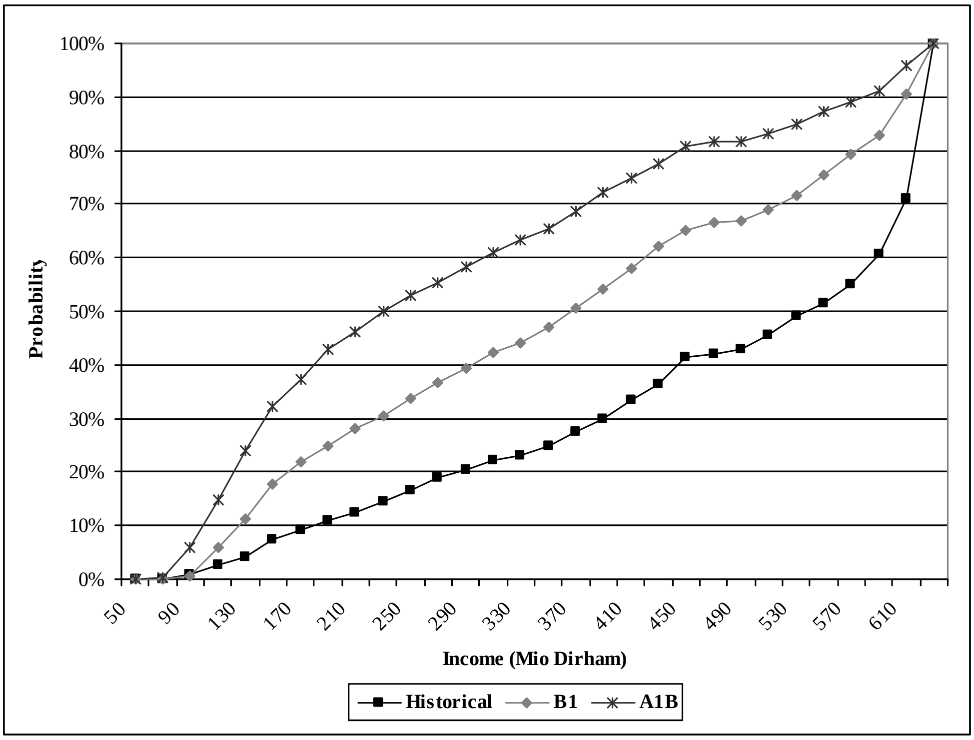
	Agricultural Income			SW Use			GW Use			Shadow price		
	(Million Moroccan Dirham)			(Million cubic meters)			(Million cubic meters)			(Dirham per cbm)		
	Hist.	**B1**	**A1B**	**Hist.**	**B1**	**A1B**	**Hist.**	**B1**	**A1B**	**Hist.**	**B1**	**A1B**
Mean	464.7	353.0	277.0	406.4	272.0	201.7	36.9	55.7	71.7	1.11	1.98	2.58
% Hist.		- 24.0	- 40.4		- 33	- 50		-50	-94		-78	-132
N	993	995	993	993	995	993	993	995	993	993	995	993
Stand. Dev	168.2	179.8	177.1	210.1	190.4	169.7	44.4	48.1	45.1	1.10	1.21	1.30
Var Coeff	0.36	0.51	0.63	0.52	0.70	0.84	1.00	0.86	0.63	0.99	0.61	0.50
Max	616.9	615.9	615.9	664.7	664.6	664.6	128.8	129.8	132.6	1.04	5.18	5.70
Min	82.3	77.2	0.0	51.5	49.4	49.1	0.0	0.0	0.0	0.08	0.08	0.00
Q(.25)	352.7	190.4	76.8	222.9	119.3	72.5	1.0	0.5	5.1	0.08	0.89	1.90
Q(.75)	615.2	532.4	406.0	662.0	384.5	266.3	90.7	97.1	108.3	1.01	2.92	3.50

Source: Own estimations

Under the two climate change scenarios the situation looks worse. In the slightly more positive scenario B1 average agricultural income decreases to 353 Million Dirham with a higher standard deviation compared to the base run. Ground- and surface water use change as water in general becomes scarcer (with water shadow prices around 2 Dirham per cubic meter on average) and farmers have to use more groundwater for irrigation. The 25% quartile shifts from 352 Mio Dirham to 190 Million Dirham; the probability of incomes under 100 Million Dirham is six percent in scenario B1. The average income per farmer per day decreases to 55 Dirham per day which is approximately ten dollars per day per farm.

In the worst case scenario A1B, average agricultural income is down to 277 Million Dirham with an even higher standard deviation. Average income per day per farmer under this scenario decreases to 42 Dirham. As surface water availability decreases, groundwater use for irrigation increases immensely to nearly twice as much as in the base run. Here, also the variation in water use increases. The increasing scarcity of water is reflected in the higher average shadow price which doubles on average for scenario A1B compared to the base run and can reach 5 Dirham per cubic meter in times of severe scarcity. With a fifty percent probability farmers receive incomes between 76 and 406 Million Dirham from agricultural production. The probability of receiving a total income that is lower than 100 million Dirham increases to 15 percent. The cumulative distribution of income (Figure 7-9) underlines this picture. The distribution of incomes shifts to the left from the current situation to scenario B1 and A1B.

Figure 7-9: Cumulative distribution of incomes for current climate conditions and scenarios A1B and B1



Source: Own estimations

The stabilization value (SV) of groundwater calculated according to equation 7 decreases under the changing water inflow distribution in the future (compare Table 7-5). Currently, the stabilization value is 123 Million Dirham. Under assumptions of scenario B1 and A1B the stabilization value decreases to 96 and 53 Million Dirham, respectively, as the variation of inflows decreases according to Table 7-1. The net benefit of groundwater (NB) decreases from 132 to 101 and 59 Million Dirham, respectively. Normally, one would expect that increasing water scarcity would lead to an increase in the NB. However, an increasing share of groundwater use leads to a higher salinity concentration in the irrigation water and thereby to lower crop yields. A modeling exercise without salinity effects for all climate scenarios illustrates this point. Without salinity, the SV and NB in all scenarios is higher than before and in the most extreme scenario A1B, the SV is about twice as large as in the corresponding case with salinity effect, because groundwater reduces variability in irrigation water availability without negatively affecting crop yield. This effect is also visible for the augmentation value (AV) of groundwater defined in equation 8. The AV increases when moving to less favorable climate conditions with and without salinity effects, but the increase is much stronger for the latter case. Overall, the net benefit of groundwater without salinity increases - as theoretically expected - under the future scenarios compared to current conditions, but it decreases with incorporation of the salinity effect. This simulation exercise again shows that it is absolutely necessary to consider water quality for a relevant analysis of conjunctive water use systems.

Table 7-5: Net benefit, augmentation value and stabilization value of groundwater with and without salinity effects in Million Dirham

With salinity impact	**Historical**	**B1**	**AIB**
Net benefit of groundwater (NB)	132	101	59
Augmentation Value (AV)	0	5	6
Stabilization Value (SV)	123	96	53
Without salinity impact	**Historical**	**B1**	**AIB**
Net benefit of groundwater (NB)	137	144	155
Augmentation Value (AV)	9	21	74
Stabilization Value (SV)	128	123	81

Source: own calculations

7.5 Conclusions

This paper provides a model based Monte Carlo simulation analysis to analyze the impacts of stochastic water inflows on water use and agricultural income in the Drâa valley in southern Morocco under current and projected climate conditions. Historical data and regional meteorological modeling results for two IPCC climate scenarios are used to estimate distributions of yearly surface water supplies. Draws from these three distributions are converted to monthly inflows and employed to parameterize surface water availability in a hydro-economic river basin model. The combination of stochastic climate conditions with joint surface and groundwater use including water quality aspect represents a unique contribution to the literature on conjunctive water modeling approaches. It allows depicting the substitutive and complementary relationship between surface and groundwater irrigation under different available water quantities. The complex nature of water management is further illustrated by the incorporation of hydrological dependencies between spatially differentiated water sinks and sources. The analysis enables reservoir managers to better understand current and possible future water use behavior in the different oases of the basin and to derive the value of groundwater as well as to quantify its stabilization value now and in the future.

Results show that the variation of inflows into the reservoir and hence the variation of surface water available for irrigation has a large influence on incomes from agricultural production in the Drâa region. As expected, the amount of groundwater pumped from shallow groundwater aquifers depends negatively on the amount of surface water available. This leads to more groundwater use and decreasing water tables under drought conditions. However, the specific relationship between groundwater and surface water use is rather complex and the modeling results show switches between the complementary and substitutive nature of these two water resources when surface water starts to become scarce. Furthermore, changing irrigation patterns in one oasis impacts upon water supply in another oasis and thereby changes the relative preference of surface and groundwater application which leads to seemingly erratic irrigation behavior in the transition from abundant to scarce water availability.

Farmers are very vulnerable to climate change and water availability and incomes from agricultural production can get very low in times of extreme water scarcity. The simulation of the two climate change scenarios show that reservoir inflows overall decrease, and the probability of very low inflows increases. This will directly affect agricultural incomes and water use in the region. Farmers in the area face low incomes in general. Under climate change average incomes decrease and low income years become more likely as the probability of low inflows into the reservoir increases. As groundwater use will increase as well, problems of declining groundwater tables and higher salinity rates are also more likely. The region needs policy actions to sustain food and income security on the one hand, but resource conservation on the other. Against this background the results demonstrate that a stochastic simulation exercise provides a more comprehensive picture regarding the impact of uncertain resource availability on agriculture and income compared to deterministic applications.

Turning to the limitations of the analysis, we need to follow meteorologist and underline the uncertainty of global and regional climate change predictions. A broad discussion arose during the last years whether it is possible at all to predict climate changes in the near future. Therefore, the estimated distributions of yearly reservoir inflows have to be treated with caution. Nevertheless, the distribution patterns of output variables should already give a good idea on the general impacts of climate change on the distributions of water use variables and income.

An extension of the river basin model to a stochastic dynamic approach would help to evaluate a planning horizon over several years as well as to incorporate risk management instruments and related investment behavior. Also, other than agricultural uses of water might become more relevant in the future. Currently, agriculture is the largest user of water in the region and water supply for irrigation is the most volatile. The municipal or household use is of highest priority from the governmental point of view and is tried to be kept as stable as possible, but does not make up more than five per cent of overall water use. Therefore, the focus of the current model is justified. However, increasing energy prices might ask for a specific consideration on the trade off between electricity generation – today rather seen as a side effect – and agricultural use in the Drâa value in the future.

7.6 References

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8 Conclusions

8.1 Summary of results

This thesis discussed water management policy options and consequences for farmers using a hydro-economic modeling approach called MIVAD (Modèle intégré de la vallée du Drâa) for the Middle Drâa river basin in southern Morocco. Water use and agricultural production were evaluated using farm survey data. Scenario analysis was conducted with the MIVAD model. The most important findings shall be summarized in the following.

First of all, water resources were evaluated by differentiating between groundwater and surface water resources. Water demand sectors have been described and analyzed according to the share of water consumption and their economic importance for the region. It was concluded that water is provided by surface and groundwater, and agriculture is the largest consumer of water. In the future, water supply is likely to be reduced which increases water scarcity in the region and tightens water supply for irrigation.

Chapter 3 analyzed agricultural production using results of an agro-economic survey conducted in 2005 by the author. A focus was on the relationship of water availability and farmers' strategies to cope with periods of drought. From survey results it was shown that farmers do not only adjust the area cultivated, but also change their cropping patterns under water scarcity. Also, crop yields decrease if water requirements are not satisfied. The insights from chapter 2 and 3 give the background for the modeling approach developed in the subsequent chapters.

In Chapter 4 to 7 a modeling approach for conjunctive water management was continuously developed, and discussed along four consecutive papers. The papers refer to single aspects of the model approach, highlight methodological parts or water management options such as water pricing for the Drâa valley. All four papers have as basis the hydro-economic model MIVAD. In the following the major findings of the analysis in each paper will be summarized.

The first paper in Chapter 4 discusses the implementation of a groundwater pricing scheme in the region in contrast to the current situation where water is not priced at all with the help of a five-year recursive-dynamic simulation exercise. Pricing methods in other river basins in Morocco are discussed first. Then, two simulations are compared. The first simulation only considers groundwater pumping costs, which are derived from the survey explained in Chapter 3. The second scenario evaluates an additional groundwater charge of forty-two Moroccan cents leading to irrigation water costs of one Dirham per cubic meter. It was found that a groundwater charge leads to more stable groundwater tables, and a less drastic depletion of the groundwater aquifers. This could be shown by evaluating the filling levels of the aquifers for the six oases and the irrigation water shadow prices as an indicator of the marginal value of water. The pricing option is discussed together with considerations of implementation difficulties such as acceptance of the local population and administrative costs.

In Chapter 5 the model version of Chapter 4 is extended and refined by introducing a calibration approach to the observed cropping pattern by using a calibration technique in tradition of positive mathematical programming (PMP) by Howitt (1995) but introducing supply elasticities as proposed by Heckelei (2002) and Heckelei and Wolff (2003). The paper explains in detail the hydrologic and hydro-geologic characteristics of the region and its transformation into the hydro-economic model MIVAD. The infiltration of water from the river bed into the aquifers is introduced into the model. This was necessary because it turned out that aquifer recharge is a decisive factor to determine the amount of available groundwater and is important to calculate the groundwater balance. However, aquifer recharge from river bed infiltration is a parameter which has not been investigated in the region. The aquifer recharge was introduced into the groundwater balance and was found to be a very sensitive factor for groundwater use and thus influencing the results of the water pricing scenarios. This was evaluated along a sensitivity analysis at the end of the chapter. In this paper modeling simulations over a ten-year period are made with a recursive dynamic modeling version. Policy options of water pricing are discussed by distinguishing between groundwater pricing, surface water pricing and the joint pricing of ground- and surface water. Scenario analyses along a ten year drought are compared with respect to water use and income. Reservoir inflows are reduced continuously which negatively effects agricultural surface water availability and use. Agricultural income is consequently reduced. It is found that the implementation of a groundwater charge leads to conservation of the groundwater resources until surface water is extremely scarce. It is further found that shadow prices for irrigation water are more stable over the years, which demonstrates the stabilizing role of groundwater and the positive effects of a groundwater charge. Further it could be shown, that surface water pricing does not lead to resource conservation because it increases groundwater use for irrigation tremendously. The joint pricing of surface and groundwater poses extremely high charges on farmers. In the end, this paper concludes that groundwater pricing is a favorable option for a more sustainable water management in the region and also supports income security if charges are diverted back to the farmers or invested in better irrigation technologies.

The third paper presented in Chapter 6 extents the MIVAD model by including aspects of salinity. This was judged to be necessary because salinity is a great environmental problem in the region and is negatively affecting crop yields. The model is applied in comparative-static simulations to compare salinity effects on crop yields on an annual basis. Results without irrigation water salinity and with salinity are compared and scenario calculations are made for three different initial situation of water availability: average, low and high water availability. The relationship between crop yields and salinity is modeled in this paper. The eight crops simulated with MIVAD are represented with their different salt tolerances. Therefore, also the yield effects of salinity in irrigation water differ between them. The paper demonstrates that salinity has an enormous impact on crop yields and income. Furthermore, it can be shown that groundwater is used less for irrigation as groundwater is more saline and thus less attractive for irrigation compared to a situation without salinity effects. It can be concluded from the chapter that a simulation of water management policies without explicit consideration of salinity effects may lead to an overestimated farm income. Furthermore, effects of a groundwater charging scheme would probably be less effective as groundwater is used less for irrigation as a result of high salinity levels.

The fourth paper in Chapter 7 uses probability statements instead of point estimated model simulations to be able to draw a more comprehensive picture on model results. For this, the MIVAD model which includes the development of salinity effects from Chapter 6 was extended to include a random variable to simulate the inflows into the reservoir. Reservoir inflow is the major exogenous parameter of the model as it determines the amount of water available for the Middle Drâa valley. By treating inflows into the reservoir as an uncertain outcome the stochastic behavior of surface water availability for the Middle Drâa valley is reflected. The distribution of the inflows is estimated using maximum likelihood techniques and data from reservoir inflows over the last sixty years. Additionally, distributions were estimated for two climate change scenarios (IPCC scenarios A1B and B1). Agricultural income and water use is evaluated for the historical distribution and for the two climate change scenarios with the help of Monte Carlo simulations. The paper concludes that agricultural income is likely to decrease in the future. It could be shown that the probability to receive an average farm income below the subsistence level, which was defined by two dollars per farmer and day, is around two percent under the current inflow distribution, but this is likely to worsen to 6 or even 15 percent under the assumptions of the two climatic scenarios presented in this paper. Groundwater use for irrigation is likely to increase with decreasing surface water availability. Altogether, the stochastic simulations provide a comprehensive picture of the relationships of water availability and agricultural income for the Drâa valley. Furthermore, it is found that the substitutive effects of surface and groundwater are changed when water quantity and water quality aspects of irrigation water are considered. The stabilization value of groundwater as defined by Tsur (1990) is calculated for all scenarios. It is found that the stabilization value is not necessarily increasing under future climatic conditions as salinity problems are aggravated by increased groundwater use counterbalancing the supply stabilization effect. This might lead to an overestimation of the net benefit of groundwater if water quality aspects are not considered.

The MIVAD model was refined for each of the scenario analysis in the four papers by adjusting data, parameters and equations. The methodology was also developed along the needs for each analysis. Thus, modeling results differ between the papers and cannot be directly compared. The first two papers (Chapter 4 and 5) do not consider water quality but focus on the interactions of hydrologic and economic aspects and water pricing as a policy options. By ignoring salinity, scenarios are more distinct and easier to interpret, but neglect the ecological consequences of salinity in irrigation water. Paper three in Chapter 6 discusses salinity effects with comparative-static exercises and points out the enormous influence on crop yields. Chapter four accounts for salinity in irrigation water and discusses its impact on water use. The simulations change between the chapters from comparative-static to recursive-dynamic and later to stochastic modeling exercises. In the deterministic settings in Chapter 4 to 6, average values of inflows have been taken as the basis for the simulation. For the recursive-dynamic exercises inflows are reduced over the years. The stochastic simulations in chapter 7 comprise the entire range of inflows by taking the distribution of inflows over the last 60 years as well as the possible distribution of future inflows into account which has the advantage that model results can be interpreted along statistical evaluations.

Water pricing has been discussed in this thesis as one option for water management in the Drâa valley. Water charges of 0.4 to 1 Dirham per cubic meter have been analyzed. These charges have been chosen because charges in other basins in Morocco lie within the same range and shadow prices have indicated this value of water. A willingness to pay study for the region (Storm 2009) showed that farmers were willing to pay around one Dirham per cubic meter for additional groundwater irrigation and between 2 and 4 Dirham per cubic meter for additional surface water. This indicates that the value of water for the farmer is higher than the current cost of groundwater extraction and higher than surface water which incurs no costs at all. This study thus supports the findings of the scenario analysis with the MIVAD model in chapter 4 and 5 that water pricing might be a feasible option. Groundwater pricing will contribute to a more sustainable groundwater use and can preserve groundwater tables. It could be shown that groundwater pricing can support the preservation of the aquifers as groundwater is preserved until surface water is very scarce. Hence, pricing could avert groundwater overexploitation. If charges would be redirected to the farmers, farmers' could even gain a comparable income, as water is used in a more efficient way, and resources are managed with a long-term profitability. Water pricing in the Drâa valley is currently discussed by the official authorities as one option to manage water more sustainable in the future. The results of this thesis provide a basis for this discussion.

Sustainable water management is a crucial issue in the arid Drâa valley. Under the assumptions of the climate change scenarios in this study, water is likely to become even scarcer in the future and agricultural production will be even more constrained by water availability. The water management authorities need to find a solution for the Drâa region that fulfills two objectives. First, water resource conservation is essential for long term sustainable water use. Second, income security of farmers is a necessary political objective to ensure feasible living conditions for the rural population. It could be shown that these two objectives are not always contradictive. Groundwater pricing, for example, can improve the two objectives if charges are distributed back to the farmers.

For further research the discussion of alternative water management options for sustainable water use but also for a sustainable development of the region is desirable. Different water pricing options have been evaluated which is an ongoing topic in Morocco. Other policy options such as water use restrictions, water trading or water transfers from other basins might be conceivable for the region. A comparison of different scenarios with different modeling concepts could help to provide a comprehensive and more holistic picture of water management possibilities.

River basin management as such has not been analyzed before in this region and is profiting now from a lot of data and knowledge that has been derived during the course of the IMPETUS project. A hydrologic agronomic and economic model like the MIVAD model integrates a large part of this knowledge and provides a more holistic picture for planners and policy makers.

8.2 Limitations and suggestions for future research

This research has provided insights for water managers and policy makers in the Drâa valley. However, the MIVAD model still faces some limitations that shall be pointed out in the following, together with suggestions for future research directions.

(i) The value of drinking water is not included in the objective function of the MIVAD model but is cosidered as a fixed proportion of the water balance. As drinking water consumption makes up only 1.5 percent of the total water use in the Drâa valley, the focus on agricultural water demand seems appropriate. For future research the incorporation of drinking water demand might be useful if domestic water use increases in the future due to population growth, improved living standards and increasing number of tourists.

(ii) This study used a recursive-dynamic modeling version to evaluate the effects of water use over a period of years. For the discussion in this thesis this approach is found to be appropriate as reservoir management in the Drâa basin is subject to a short term planning perspective due to the lack in capacity and monitoring tools. Thus, the annual planning horizon of the MIVAD model reflects the current reservoir management policies and allows a detailed analysis of the hydrological processes and their impact on agriculture and income. For future research a dynamic model with a five to ten year horizon would be interesting to be able to assess reservoir management options with a long term planning horizon.

(iii) The value of water can be obtained from the marginal values (shadow prices) of the water constraints of the MIVAD model. However, the calibration method of positive mathematical programming might have an influence on the marginal values. If model results were to be used as the basis for the implementation of a water pricing scheme by using marginal values as water charges the impacts of the PMP calibration on model results should be further analyzed.

(iv) Another possibility to calibrate the model might be a calibration to observed shadow prices by Storm (2009). However, he only derived shadow prices for the oasis Ternata. Follow-up studies for the entire Drâa valley would increase the reliabiliy of the results as shadow prices differ between the oases because of different resources endowments.

(v) The hydro-geological balance in MIVAD was derived from a geological balance model from the IMPETUS project (Klose et al. 2008). Thus, the paramterization of groundwater dynamics in MIVAD could be implemented in detail and were compared and validated with results from the geological balance model. However, the river flow and infiltration of river water into aquifers are less empirically validated. This has to be left for future research.

(vi) The data basis for the Drâa region was fairly poor, out of date and often inconsistent. During the IMPETUS project a data basis comprising the last years could be established with data of many disciplines. In the future, harmonized data sets and long term data series would improve modeling and might also allow estimations and econometric analysis of the impact of climate change on agriculture and farm income.

8.3 References

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9 Annex

1 Model description of the MIVAD Model (November 2008)

Model indices (sets)

pd	Time index within a simulation year (months)
dma	Oasis (irrigation water demand site)
dmm	Municipal demand site
n	River node where water is withdrawn
n_lo	River node located downstream of the actual node
n_up	River node located upstream of the actual node
gw	Groundwater aquifers belonging to oasis *dma*
res	Reservoir
crop	Crop (wheat, rye, corn, alfalfa, vegetables, beans, henna, date palms)
prof	Production factors (labour, machinery, fertilizer, pesticides)

Model variables

V__W_A_CR	Irrigation water available to a crop both from surface water and groundwater
V_GOALVAR	Objective variable (total water-related benefits in the basin)
V_GW_HEAD	Groundwater table of an aquifer
VAGPROFIT	Gross profit of farmers in oasis *dma*
VCON_FACT	Concentration factor translating irrigation water salinity into soil salinity
VCROPAREA	Crop area for a crop per oasis
VCROPRIC	Selling price of the crop
VCROPYIEL	Crop yield in tons
VDEF_MAXI	Yield reduction factor due to insufficient water application (crop water deficit)
VDEF_SEAS	Seasonal water deficit (linear-limitational version, calculation see below)
VDP_STAGA	Field infiltration of irrigation water per month
VPUMP_DMM	Mobilized groundwater for municipal use
VET_RATIO	Irrigation water application divided by maximum evapotranspiration (*ETm*)
VETA_SEAS	Seasonal (annual) crop evapotranspiration (*ETa*)
VETA_STAG	Stage (monthly) crop evapotranspiration (*ETa*)
VFL_N_DMA	Water withdrawal from the river for an oasis
VFL_N_RES	Flow from a river reach to a reservoir
VFL_RES_N	Flow from a reservoir to the river
VFLRESDMM	Water withdrawal from the reservoir for municipal demand sites
VGW_DIS_G	Groundwater inflows from upstream aquifer, and outflows to downstream aquifer
VGW_DIS_R	Groundwater discharge to the next river node
VGW_PRICA	Costs for pumping groundwater (fixed)
VGW_RECHG	Recharge of a groundwater aquifer
VGWCHANGE	Change in the groundwater table per aquifer and period
VINFLOW_A	Available river water for a demand site *dma*

VINFLOW_M	Water use of households and industry (fixed, shifted between simulation years)
VLEACHFCT	Leaching factor
VPMP_COST	Nonlinear cost term to calibrate the model
VPUMP_DMA	Mobilized groundwater for the irrigation of a crop in oasis *dma* from aquifer *gw*
VRI_DIS_G	Infiltration of river water into groundwater aquifers
VRIVERFLO	water flow from an upstream river node to a downstream river node
VSALINITY	Average salinity level of irrigation water applied from different sources
VSOILSALI	Salinity level of the soil water consumed by crops
VSTOR_RES	Reservoir storage
VYIE_SALI	Yield reduction factor due to salinity
λ	Marginal value of irrigation water for agricultural use

Model coefficients (parameters)

α	Slope coefficient of the approximation curve of the water deficit function
β	Coefficient determining the position of the curve of the water deficit function
δ	Slope of the non-linear leaching function (constant)
PMPA	Constant in PMP cost term
PMPB	Slope parameter in PMP cost term
P_GW_AREA	Surface of the groundwater aquifer
P_GW_DIFF	Altitude differences between adjacent aquifers at maximum fill levels
P_GW_PERM	Kf value in Darcy formula
P_KY	Slope coefficient of the linear seasonal water deficit function
PEFF_RAIN	Effective rainfall in mm
PFACTNEED	Non-water production factor needs (fertiliser, labour etc.)
PFACTPRIC	Production factor prices
PGW_CRSCT	Width of the outflow gap of the aquifer
PGW_SALIN	Salinity of water taken from aquifer *gw* (constant)
PGW_YIELD	Groundwater yield coefficient
PGWHEADMX	Maximum fill level of the aquifer
PGWLENGTH	Distance between the aquifers
PINFILRI	Infiltration coefficient of the river
PINFL_SAL	Salinity of surface (river) water in oasis *dma* (constant)
PIRR_EFFY	Irrigation efficiency factor (constant)
PLOSS_DMA	Distribution loss rate of irrigation water from river to field
PLOSS_DMM	Distribution loss rate in municipal water supply system
PMAXYIELD	Maximum yield for the different crops (per ha)
PPOWEREFF	Power production efficiency
PRES_EVAP	Evaporation losses from the reservoir
PSAL_SLOP	Slope coefficient of the function determining yield reduction by salinity
PSAL_THRE	Crop-specific salinity level at which yield is depressed by 50 percent
PWATREQCR	Water requirements for achieving a maximum crop yield per period
PWATRQFCT	Factor distributing seasonal water requirements to crop stages
V_GRAD_GW	Groundwater gradient
γ	Constant factor in the Darcy formula
κ	Level parameter in the soil salinity concentration function
ρ	Slope parameter in the soil salinity concentration function

Model equations

Objective function
$$\max V\_GOALVAR = \sum_{dma} VAGPROFIT_{dma}$$

Agricultural profits

$$VAGPROFIT_{dma} =$$
$$\sum_{crop}\left(VCROPAREA_{dma,crop} \cdot \begin{pmatrix} VCROPPRIC_{crop} \cdot VCROPYIEL_{dma,crop} \\ -\sum_{prof}\left(PFACTNEED_{crop,prof} \cdot PFACTPRIC_{crop,prof} \right) \end{pmatrix} \right) - VPMP\_COST_{dma}$$
$$-\sum_{gw}\sum_{pd}\left(VPUMP\_DMA_{gw,dma,pd} \cdot VGW\_PRICA_{dma} \right)$$

PMP cost term

$$VPMP\_COST_{dma} = \sum_{crop}^{n} PMPA_{dma,crop} \cdot VCROPAREA_{dma,crop} + PMPB_{dma,crop} \cdot \left(VCROPAREA_{dma,crop} \right)^{2}$$

1. Yield formation as a function of water application and salinity

Yield function
$$VCROPYIEL_{dma,crop} = PMAXYIELD_{crop} \cdot VDEF\_MAXI_{dma,crop} \cdot VYIE\_SALI_{dma,crop}$$

Seasonal water deficit, smoothed
$$VDEF\_MAXI_{dma,crop} = \left(1 + \exp\left(\alpha \cdot \left(-\left(VDEF\_SEAS_{dma,crop} - \beta \right) \right) \right) \right)^{-1}$$

Seasonal water deficit, linear
$$VDEF\_SEAS_{dma,crop} = 1 - P\_KY_{crop} \cdot \left(1 - \left(\frac{VETA\_SEAS_{dma,crop}}{\sum_{pd} PWATREQCR_{crop,pd}} \right) \right)$$

Determination of seasonal ETa
$$VETA\_SEAS_{dma,crop} = VETA\_STAG_{dma,crop,pd} \,/\, PWATRQFCT_{crop,pd}$$

Determine the leaching factor
$$VLEACHFCT_{dma,crop} = 0.01 \cdot \exp\ \left(\delta \cdot VET\_RATIO_{dma,crop} \right) + PIRR\_EFFY$$

Water use to max. requirements
$$VET\_RATIO_{dma,crop} = VWATUSEHA_{dma,crop,pd} \,/\, PWATREQCR_{crop,pd}$$

Salinity yield reduction factor
$$VYIE\_SALI_{dma,crop} = \left(1 + \left(VSOILSALI_{dma,crop} \Big/ PSAL\_THRE_{crop}{}^{PSAL\_SLOP_{crop}} \right) \right)^{-1}$$

Determine soil salinity
$$VSOILSALI_{dma,crop} = VSALINITY_{dma} \cdot VCON\_FACT_{dma,crop}$$

Soil salinity concentration factor
$$VCON\_FACT_{dma,crop} = \left(\kappa \cdot VLEACHFCT_{dma,crop} \right)^{-\rho}$$

Average irrigation water salinity

$$VSALINITY_{dma} = \sum_{pd} \frac{\left(VINFLOW\_A_{dma,pd} \cdot PINFL\_SAL_{n} + \sum_{gw} VPUMP_{gw,dma,pd} \cdot PGW\_SALIN_{gw} \right)}{\sum_{crop} V\_\_W\_A\_CR_{dma,crop,pd}}$$

2. Hydrologic processes which link water sources with irrigation water use

Stage ETa is irrig. water plus rain

$$VETA\_STAG_{dma,crop,pd} = VWATUSEHA_{dma,crop,pd} \cdot VLEACHFCT_{dma,crop} + PEFF\_RAIN_{dma,pd}$$

Water use per hectare and total

$$VWATUSEHA_{dma,crop,pd} = V\_\_W\_CR\_A_{dma,crop,pd} / VCROPAREA_{dma,crop}$$

Sources of total irrig. water use

$$\sum_{crop} V\_\_W\_A\_CR_{dma,crop,pd} = VINFLOW\_A_{dma,pd} + \sum_{GW} VPUMP_{dma} \quad \left[\lambda_{dma,pd}\right]$$

Inflows to oasis in period

$$VINFLOW\_A_{dma,pd} = VFL\_N\_DMA_{n,dma,pd} \cdot \left(1 - PLOSS\_DMA_{dma}\right)$$

3. Hydrologic balance equations for river nodes, groundwater dynamics and reservoir storage

River node balance

$$\begin{aligned}
&VRIVERFLO_{n,n\_lo,pd} + VFL\_N\_RES_{n\_res,pd} + VFL\_N\_DMA_{n\_dma,pd} + VRI\_DIS\_G_{n\_gw,pd} \\
&= \\
&VRIVERFLO_{n\_up,n,pd} + PLATINLFO_{n,pd} + VFL\_RES\_N_{res\_n,pd} + VGW\_DIS\_R_{gw\_n,pd}
\end{aligned}$$

Infiltration river – groundwater

$$VRI\_DIS\_G_{n\_gw,pd} = VRIVERFLO_{n\_up,pd} \cdot PINFILRI$$

Intertemporal groundwater heads

$$V\_GW\_HEAD_{gw,pd} = V\_GW\_HEAD_{gw,pd-1} + VGWCHANGE_{gw,pd}$$

Groundwater change balance

$$\begin{aligned}
&VGWCHANGE_{gw,pd} \cdot PGW\_YIELD_{gw} \cdot P\_GW\_AREA_{gw} \cdot 10 \\
&= \\
&+VGW\_RECHG_{gw,pd} + VGW\_DISG_{gw-1,pd} + VDP\_STAGA_{gw,pd} + VRI\_DIS\_G_{n\_gw,pd} \\
&+VPUMP\_DMM_{dmm,pd} \cdot \left(1 - PLOSS\_DMA_{dmm}\right) + VFL\_N\_DMA_{n,dmm,pd} \cdot PLOSS\_DMA_{dma} \\
&-VPUMP\_DMM_{gw,dmm,pd} - VPUMP\_DMA_{gw,dma,pd} \\
&-VGW\_DIS\_G_{gw,pd} - VGW\_DIS\_R_{gw,n,pd}
\end{aligned}$$

Field infiltration if irrigation water

$$VDP\_STAGA_{dma,pd} = \sum_{crop} V\_\_W\_CR\_A_{dma,crop,pd} \cdot VLEACHFCT_{dma,crop}$$

Groundwater recharge from rain

$$\begin{aligned}
&VGW\_RECHG_{gw,pd} \\
&= \begin{pmatrix} P\_AQ\_AREA_{gw} \\ - \sum\limits_{dma \leftrightarrow gw} VCROPAREA_{dma,crop} \end{pmatrix} \cdot \sum_{dma \leftrightarrow gw,pd} PEFF\_RAIN_{gw} \cdot PINFILTR
\end{aligned}$$

Inter-aquifer flow (darcy formula)

$$\begin{aligned}
&VGW\_DIS\_G_{gw,pd} \\
&= \gamma \cdot \begin{pmatrix} P\_GW\_PERM_{gw} \cdot V\_GRAD\_GW_{gw,pd} \\ \cdot PGW\_CRSCT_{gw} \cdot V\_GW\_HEAD_{gw,pd} \end{pmatrix}
\end{aligned}$$

Groundwater gradient

$$V\_GRAD\_GW_{gw,pd} = \frac{\begin{pmatrix} P\_GW\_DIFF_{gw} - \left(PGWHEADMX_{gw} - V\_GW\_HEAD_{gw,pd}\right) \\ + \left(PGWHEADMX_{gw+1} - V\_GW\_HEAD_{gw+1,pd}\right) \end{pmatrix}}{PGWLENGTH_{gw}}$$

Aquifer discharge at maximum fill level

$$\begin{aligned} & VGW\_DIS\_R_{gw,n,pd} \\ & = PGW\_YIELD_{gw} \cdot VDISHFACT_{gw,pd} \cdot PGWHEADmx_{gw} \cdot P\_GW\_AREA_{gw} \cdot 10 \end{aligned}$$

Discharge factor for aquifer ‘overflow’

$$VDISHFACT_{gw,pd} = 0.5 \cdot \left(1 + \frac{V\_GW\_HEAD_{gw,pd}}{PGWHEADMX_{gw}} + \sqrt{\left(\frac{V\_GW\_HEAD_{gw,pd}}{PGWHEADMX_{gw}} \text{ -1} \right)^2} \right) \text{-1}$$

Reservoir balance

$$\begin{aligned} & VSTOR\_RES_{res,pd} = VSTOR\_RES_{res,pd-1} + VFL\_N\_RES_{n,res,pd} \\ & -VFLRESDMM_{res,dmm,pd} \cdot (1 - PLOSS\_DMM_{dmm}) \\ & -VFL\_RES\_N_{res,n,pd} - PRES\_EVAP_{res,pd} \end{aligned}$$

4. Fixed water demand for non-agricultural water use

Power generation

$$VPOWERGEN_{pwst,pd} = \frac{VFL\_RES\_N_{res,n,pd} \cdot 9.81 \frac{m}{s^2} \cdot 57m \cdot PPOWEREFF_{pwst}}{3600}$$

Withdrawals by municipal demand sites

$$\begin{aligned} & VINFLOW\_M_{dmm,pd} \\ & = VFLRESDMM_{res,dmm,pd} \cdot (1 - PLOSS\_DMM_{dmm}) \\ & + VPUMP\_DMM_{dmm,pd} \cdot (1 - PLOSS\_DMM_{dmm}) \end{aligned}$$

5. Stochastic supply of inflows into the reservoir

Inflows into the reservoir

$$VFL\_N\_RES_{n,res,pd} = Gamma(x; \alpha, \beta)$$

2 Agro economic survey (November 2005)

Questionnaire pour les agriculteurs
Ferme/Nom d'agriculteur : ________________________
Lieu : ________________________
Date : ________________________
Interviewer : ________________________

Questions générales sur le système agricole

1. Quelle est la taille de vos terres agricoles (propriété plus terres louées) ? _______
   Ou : Combien de parcelles avez-vous ? ______
   (Si l'espace total est inconnu, l'enquêteur peut ajouter l'espace des parcelles individuelles dans le tableau)
   Ou : Quelle est la taille de la plus petite et de la plus grande parcelle ? ______ (spécifier l'unité)

2. Est-ce que vous avez affermez de qn une partie de votre terre cultivée ?

   ÿ Oui, environ _____ ha (ou ______ parcelles)
   ÿ Non

3. Est-ce que vous avez louez à qn (ou affermez de qn) une partie de votre propre terre ?

   ÿ Oui, environ _____ ha (ou ______ parcelles)
   ÿ Non

4. Conditions du contrat de terre louée

5. Quelles sont les cultures principales que vous cultivez ? (Cultures annuelles et cultures permanentes) ? Ecrivez tous aussi les différentes légumes !

6. Est-ce que la surface agricole totale que vous cultivez, varie chaque année ?

   ÿ Pas de variations
   ÿ Variation négligeable
   ÿ Variation forte

7. De quels facteurs dépend la décision sur la surface agricole totale que vous cultivez ?

   ÿ Disponibilité en eau
   ÿ Disponibilité de main d'oeuvre
   ÿ Disponibilité d'intrants
   ÿ Le capital
   ÿ Autres facteurs ___________________________________

8. Quelles mesures différentes appliquez-vous pour que le sol ne se dessèche pas ?

ÿ Houer régulièrement après l’application d’eau
ÿ Couvrir / abriter le sol avec des résidus végétaux
ÿ Couvrir / abriter le sol avec du plastique
ÿ Rien
ÿ Autre : ______________________

9. Est-ce que vous avez un problème de salinisation sur votre surface agricole ? (*Expliquez le problème de la salinisation au cas ou le paysan n’a pas compris* …) Spécifier le problème de salinisation !

	Pourcentage (%) de la surface agricole
Pas de problèmes de salinité	____
Quelques problèmes (quelques parcelles)	____
Grands problèmes (toutes les parcelles)	____

10. Quelles mesures est-ce que vous prenez contre la salinisation ?

ÿ Lessivage avant le semis
ÿ Préférer l’utilisation d’eau souterraine
ÿ Préférer l’utilisation d’eau des lâchés
ÿ Retourner, Labourer le sol
ÿ Rien
ÿ Autre : __________________

11. Avez-vous des animaux ? Lesquels ? Combien d’animaux avez-vous, (si vous voulez répondre cette question) ?

Espèce	**Nombre**
Moutons, chèvres	____
Vaches	____
Poules	____
Ânes, mules	____
Dromadaires	____

Maintenant remplir le tableau !

Ressources de production

12. Aimeriez-vous élargir votre surface agricole l'année prochaine?

ÿ Non
ÿ Oui, environ _____ ha (ou ______ parcelles) dont ____ parcelles louer
ÿ Oui, environ _____ ha (ou ______ parcelles) dont ____ sont achter pour ___DRH/ parcelles

13. Quels sont les obstacles principaux pour un élargissement ?

ÿ la surface agricole disponible
ÿ l'eau disponible
ÿ la main d'œuvre disponible
ÿ le capital disponible

14. Est-ce que vous avez accès à un service de conseil agricole (public ou privé)?

ÿ Oui
ÿ Non

Si oui, quand a eu lieu la dernière visite ?___________ Normalement passe _______ fois par années ?
Ecrivez quequ''il font ?

Irrigation

15. Comment irriguez-vous vos champs ? (**robta**, autres canaux, tuyaux, canaux Plastique, goutte à goutte)
Caractérisez le système en choisissant la terminologie convenable

16. D'où est principalement votre eau d'irrigation ?

ÿ de l'oued, si possible ______%
ÿ nappe phréatique (avec une pompe), si possible________%

17. Quel est le système d'irrigation exercé, le *melk* ou l'*allam* ?
(*Expliquez la différence entre les deux systèmes …*)

ÿ melk
ÿ allam

18. Pouvez-vous remplacer une quantité insuffisante d’eau de l’oued par l’eau souterraine que vous pompez?

ÿ Oui, totalement
ÿ Non, seulement environ ______ % de la demande

19. Combien de puits avez-vous ?

Nombre de puits : __________

20. Vous avez des pompes motorisées? Que fabricant /type de pompes avez-vous ? Combien d’heures/ de jours marche la pompe ?

21. Que est le facteur limitant pour pomper d’eau de la nappe ?

ÿ Coût de huile et gasoil
ÿ Coût pour installer un nouveau pompe
ÿ Contrat ou communication avec des voisins, quaid, etc.
ÿ Quantité disponible dans la nappe
ÿ Autre_______________

22. Quels sont vos coûts pour un litre/une heure d’eau qu’on pompe de la nappe ?
(Enquêteur doit aider : gasoil, réparations, dépréciation)
___ *litre huile par heures ; coût d’un litre d’huile*_____

23. Les puits ont-ils de l’eau suffisante toute l’année ? Est-ce qu’il y a des mois de pénurie ?

ÿ Suffisant d’eau toute l’année
ÿ Pas suffisant. Mois de pénurie __________

24. Savez-vous de combien d’eau d’irrigation vous avez besoin ?

ÿ Oui, environ ______ mètres cube en tout par année agricole
ÿ Oui, environ ______ heures de lâcher ? ________ heures de pompage ?
ÿ Non

25. Quels sont les avantages des différentes sources en eau pour l’irrigation des cultures ?

Source	*Dépenses modérées*	*Disponibilité régulière*	*Salinité peu élevée*	*Autres*
Eau de l’oued				

Eau souterraine				
Autre : ________________				

26. De qui est-ce que vous recevez des informations quand il y a un lâcher ?

ÿ Voisins
ÿ Kaids
ÿ Autres personnes : ______

27. Quand est-ce qu'on vous donne des informations sur les lâchers ?

Normalement, ____ jours à l'avance

28. Combien de parcelles est-ce vous pouvez irriguer avec le dernier lâcher ?

______ Parcelles

29. Si on a annoncé un lâcher savez-vous si l'eau suffira pour toute la surface agricole que vous cultivez ?

ÿ Toujours
ÿ Généralement
ÿ Parfois
ÿ Jamais

30. S'il n'y a pas assez d'eau d'un lâcher comment est-ce que vous réagissez ?

ÿ pompage de la nappe phréatique
ÿ changement du plan de culture
ÿ diminution de la surface agricole
ÿ irrigation directe des arbres fruitiers avec un arrosoir
ÿ abandon de parcelles qui sont déjà sous culture
ÿ nouvelle répartition de droits d'eau (échange de droits d'eau, renoncement provisoire de droits d'eau de quelques agriculteurs en faveur d'autres)
ÿ diminution du troupeau d'animaux

31. Si vous avait un rendement de récolte superflue, vous investiriez

ÿ dans un système d'irrigation moderne
ÿ dans de pompes motorise
ÿ dans des intrants agricole
ÿ dans de nouveau terre
ÿ dans autre activité a cote de agriculture par exemple le tourisme

32. En cas de mesure de salinité et des coordonnées :

Coordonnées de GPS : _____ °N _____ °E _____ m

Conductrice : _____ uS/m³

33. Que est le facteur limitant pour pomper d’eau de la nappe ?

ÿ Coût de huile et gasoil
ÿ Coût pour installer un nouveau pompe
ÿ Contrat ou communication avec des voisins, quaid, etc.
ÿ Quantité disponible dans la nappe
ÿ Autre_______________

34. Comment est-ce que la production agricole a changé dans les dernières 5 années ?
ÿ diminution de surface agricole
ÿ plus d’eau de la nappe
ÿ changement des cultures : production moins de ______
plus de ______
ÿ Ecrivez plus ici

35. Dans le prochaine 5 années comment expectez vous votre future ?
ÿ diminution de surface agricole
ÿ bondonner l’agriculture
ÿ plus de coopérations avec des voisins
ÿ plus d’eau de la nappe
ÿ changement des cultures : production moins de ______
plus de ______
ÿ Ecrivez plus ici

36. Si vous avait un rendement de récolte superflue, vous investiriez
ÿ dans un système d’irrigation moderne
ÿ dans de pompes motorise
ÿ creusiez de puits plus profond
ÿ dans des intrants agricole
ÿ dans de nouveau terre
ÿ dans autre activité a cote de agriculture par exemple le tourisme

37. Combien de personnes vous nourrirez avec votre production ?

38. Vous avez accès à d’eau potable de ONEP ?

39. Vous avez accès à des camions d’eau ou des stations d’eau ?

40. Système de rotation
ÿ Rotation spatiale ?

ÿ rotation temporelle ?
ÿ culture mixte par exemple Lucerne avec du blé ?
Spécifié les cultures :

Revenu et utilisation des produits	***Quantité***	***Prix***
Surface cultivée (en ha ou autre mesure, ou % de superficie totale)		XXX
Quantité de produit principale		
Consommation du ménage (en %)		XXX
Fourrage (en %)		XXX
Vente (en %)		XXX
Paiement pour louer la terre (en %)		XXX
Coûts de la production	***Quantité (si connu)***	***Coûts (si connu)***
Semence		
Engrais		
Produits phytosanitaires		
Main d'oeuvre salariée pour:	XXX	XXX
Préparation de sol		
Semis		
Autres …		
Autres …		
Récolte		
Opérations après la récolte		
Coûts 'eau pour la production	***Quantité (si connu)***	***Coûts (si connu)***
Combien d'heure de pompage seulement pour cette culture		
Coûts de transport	***Quantité (si connu)***	***Coûts (si connu)***
Transport d'engrais a la ferme		
Transport au marché		
Coûts pour utilisation des machines	***Quantité (si connu)***	***Coûts (si connu)***
Count pour louez un tracteur		
Cout pour louer un treshing, battre		