# Hydro-economic modelling of an Exhaustible and Transboundary Groundwater: Model Development and Application to North-Western Sahara Aquifer System (NWSAS)

**Bouslama Abdelkader**[1] **Matoussi Mohamed Salah**[2]

**November 2016**

**Abstract** : *The main objective of this research is to develop and implement an integrated hydro economic model that explicitly takes account of the relationships and interactions between all key determinants of groundwater demand. The NWSAS, where the water resources is the limiting factor to any sustainable economic development, is one of the most illustrative examples where the recourse to this vision is more urgent. The relevant result achieved is: When we integrate the degradation cost induced by the groundwater overexploitation in our modelling, the widespread belief among policymakers that it is imperative to mobilize the maximum of water resources to irrigate the maximum widely abundant land and thus improve the poor population welfare, is false. In fact, by increasing the pumped volume, agricultural income grows first rapidly then less strongly before reaching a maximum and then due to the negative impacts of the degradation cost caused by the aquifer overuse, begins to decrease in a sustained and above all irreversible way.*

## I. Introduction

Groundwater plays a key role in promoting irrigation which in turn increases significantly agricultural productivity, especially in arid and semi arid regions. The expected result will be undoubtedly an improvement of food security, farmer's welfare and a reduction of rural poverty. However, these positive effects are unfortunately often obtained at the cost of excessive pressure on the aquifer inducing its overexploitation and even its irreversible degradation.This will undoubtedly deprive future generations of valuable and irreplaceable resources.

The challenge that both decision-makers and researchers in the field have attempted to address for decades is to "find a compromise between water mobilized to substantially improve the user's welfare while achieving resource sustainable management".

[1]**Faculty of Economics and Management of Nabeul**
[2]**University of El Manar, Tunis.**

One solution to tackle this challenge would be to integrate the intrinsic multidisciplinary nature of water resources management in a homogeneous and consistent framework. This interdisciplinary nature requires explicit integration of the economic, technical, environmental, institutional, social and legal aspects in a coherent analytical framework. This integrated management framework in a homogeneous space is even more urgent in arid climate areas where water resources are the most limiting factor to any sustainable economic development. The North Western Sahara Aquifer System (NWSAS), which extends over one million km$^2$ shared by Algeria, Libya and Tunisia, is one of the most illustrative examples of the areas where the use of this vision is more urgent. Indeed, the exponential growth of water demand in this region, which generates substantial income from irrigated production, unfortunately causes a negative impact on the sustainability of the aquifer. To address these challenges, which could be further amplified by the real threat of climate change, the promotion of integrated management of the scarce and valuable resources in an appropriate spatial framework is needed. Hydro economic modeling perfectly meets this requirement.

The main objective of this work is to develop and especially implement an integrated hydro economic model that explicitly takes account of all the relationships and interactions between all variables and key determinants of water demand and its productivity. This paper is organized in five steps:

- The first will be dedicated to a very brief overview of the extensive literature on the hydro economic modeling and especially its applications in contexts similar to that of NWSAS.

- The development of hydro-economic model of the NSAS zone will be the second step. The design of this model will be built on the approach developed by all contributions produced in recent decades.

- The third step presents the data needed for the application of the model to the real context of the NWSAS area. Three categories of data are collected to make this model operational. The first relates to aggregate data to be collected from the different agencies of the countries concerned. The second will focus on microeconomic data collected through socioeconomic surveys in the project we had the chance to drive in the Sahara and Sahel Observatory. In fact, two survey campaigns have collected original information on the behavior of 3,000 irrigators in terms of resource valuation of a highly overexploited groundwater. The last category will cover some results obtained from the quantitative analysis of the water resources demand determinants.

- Thanks to this model, we will proceed to simulate all the feasible scenarios, to present and analyze the obtained results in the fifth section. The most relevant result achieved can be summarized very briefly as follows: The widespread belief, among policymakers that it is imperative to mobilize the maximum of water resources to irrigate the maximum widely abundant land in this vast region and thus improve the welfare of poor population, is unfortunately false. This belief is valid only if the mobilization of this non-renewable resource does not degrade the quality and does not increase the cost of pumping. Knowing that all NWSAS area suffers from continuous degradation and a decline in the water table causing a growth in the cost of extraction, it is imperative to explicitly integrate these two dimensions (degradation and pumping cost) in any appropriate modeling. The model designed demonstrates the existence of an optimal return corresponding to adequate mobilization of scarce and valuable resources. Indeed, by increasing the volume mobilized, we do increase the irrigated areas, and consequently the optimal income for all farmers more and more slowly till it reaches it peak. After that, the optimal income decrease more and more rapidly.

- Finally, we will attempt to translate the obtained principles results in policy implications for a better groundwater management of one of the most fragile region in the world.

## II. Literature review:

The natural and environmental resources Economists, who have been interested in irrigated agriculture, have focused their research on the shortcomings and failures of the market economy, while worrying very little about physical systems (aquifers and river basins). In contrast, hydrologists, who have focused on understanding the physical processes, have addressed the socio-economic component in a rather simplistic way.That is why since the 1970s we have witnessed, the appearance of hydro-economic models to fill this gap by trying to integrate the two components in the same model.

**hydro-economic models of the first generation (1970) :**

Groundwater has always been considered as a common property resource where access is restricted by land ownership. Decentralized management, by the market, of this resource has proven inefficient when the pumping is growing rapidly. In order to meet the concern of policy makers in terms of overexploitation and the risk of rapid exhaustion of the very few renewable resource, many studies on the optimal management of groundwater resources have been developed in recent decades.

Among the major contributions that marked this generation models, we have choose those that seem most representative:

- Cummings & McFarland[3] and Howe and Orr[4] were among the first to develop theoretical decision rules explicitly incorporating the externalities ;

- Scherer[5] and Young & Leathers[6] developed and resolved operational management models that evaluate the relationship between externalities and individual decisions.

- Gisser & Sanchez (GS)[7] have modeled the withdrawals of groundwater in the two most common optical namely "free access" and "centralized management". To compare these two alternatives, GS has developed a model with those main characteristics :

- Water demand is linear;
- The average cost of extraction is independent of the rate of extraction and linearly decreases from the level of the water table;
- As an alternative to decentralized management, farmers are myopic and have chosen their rates of extraction in order to maximize current profits, while in the case of optimal management, the objective function is to maximize the present value of the stream of overall profits.

[3] "Groundwater management and salinity control" (1974)
[4] "Economic incentives for salinity reduction and water conservation in the Colorado River Basin" (1974)
[5] "Water allocation and pricing for control of irrigation related salinity in a river basin" (1977)
[6] "Economic impacts of regional saline irrigation return flow management programs" (1981)
[7] "Competition versus optimal control in groundwater pumping » (1980)

The result of this modeling showed that if the aquifer storage capacity is relatively large, the difference between the two systems is negligible. This result was called by Nieswiadomy[8] the Gisser-Sánchez rule and could be stated thus: "the regulation of the resource is superfluous since the profits it derives negligible".

**Criticism of first generation models:**

Several authors have shown that such models ignore the most basic hydrological rules. Indeed, all these researches are based on the model of the "bathtub", which assumes an instantaneous lateral flow of water. Pumping by a user lowers the groundwater level in the following period by an amount equal to the levy, regardless of its spatial distribution. This hypothesis, which assumes that the spatial distribution of wells is unimportant, that induces the entire aquifer would have a uniform depth. However, the constraints of rock, sand and gravel, which normally affect the table, slow the lateral movement of water and reduce its hydro-conductivity. A hydro-conductivity rate not infinite limits both the spatial extension of the levy of a user on one another and would increase the potential impact of pumping on direct neighbors. This is why it is essential to integrate hydrological rules governing the movement of groundwater in a spatial externalities model. Brozovic& al[9] have shown that when groundwater is explicitly modeled as a spatial resource using realistic hydrologically equations of motion, the effect of an externality could be larger if it is estimated using the model of the bath, especially if we are dealing with unconfined aquifers.

**Hydro-economic models of second generation:**

The models that have emerged from the 1990s explicitly integrated spatial character of the groundwater externality pumping, allowing the explicit integration of the "common property resource" intrinsic nature of these waters.

- Lefkoff and Gorelick[10] were the first to develop an approach that explicitly integrates economic

[8] "The Demand for Irrigation Water in the High Plains of Texas, 1957-80" (1985)
[9] "Optimal Management of Groundwater Over Space and Time" (2002)
[10] "Simulating Physical Processes and Economic Behavior in Saline, Irrigated Agriculture: Model Development" (1990)

modeling in a complex physical system. This approach integrates the economic, hydrological and agricultural components in a unified simulation and optimization model. The final model of hydro-agro-economic simulation developed takes the form of a problem of nonlinear optimization under linear complex constraints.

- Brozovic & al[11] solved the problem of the social planner with users spatially distributed and finite transmissibility. The rates of dynamic optimal pumping were found to be spatially highly variable.

- Saak and Peterson[12] explicitly include the theory of incomplete information and have been able to demonstrate, through their modeling, that better information may:

  - Increase or decrease the equilibrium rate of pumping and,

  - Increase or decrease the equilibrium welfare.

- Maneta & al[13] have developed a three-dimensional hydro-economic model combined with a nonlinear agro-economic model, based on positive mathematical programming, which simulates the behavior of farmers and agricultural production process.

The two contributions of this new generation of models that have focused essentially on empirical aspects of the sustainable management of the very few renewable aquifers are those of Pfeiffer-Lin (2012)[14] and Guilfoos & al (2013)[15].

- The contribution of the research conducted by Pfeiffer and Lin has aimd at empirically estimating the magnitude and extent of the interactions between riparian users of an aquifer. These authors developed a theoretical model capable of generating testable hypotheses. They compared the first order conditions derived from an aquifer management problem conducted by one owner (a social planner) with those obtained from a problem of individuals pumping from an aquifer governed by the rule of "open Access". Although Pfeiffer and Lin know that their suggested solution

[11] "Optimal Management of Groundwater Over Space and Time" (2002)

[12] "Groundwater use under incomplete information" (2007)

[13] "A spatially distributed hydro-economic model to assess the effects of drought on land use, farm profits, and agricultural employment" (2009)

[14] "Groundwater pumping and spatial externalities in agriculture" (2012).

[15] "Groundwater Management : The effect of water flows on welfare gains" (2013).

to the social planner is rather unfeasible in reality, given the complexity of a watershed, they have chosen because they think it could approximate correctly the social planner's solution. In other words they have expected that spatial externalities that arise between the wells are internalized when a single user simultaneously manages all of these wells.

So Pfeiffer- Lin have been the first to empirically measure and quantify the externalities arising from excessive pumping from shared very few renewable aquifers. They have found that the physical movement of water in an aquifer directly addresses both the pumping and other hydrology characteristics affecting the flow in the water table.

The static level of the aquifer would decrease the well level of a user, following a pumping by a neighbor of:

- 10 to 15 cm for a withdrawal of 100 000 m3.

- About 50 cm for a withdrawal of one million $m^3$ in a 3 km radius the following year.

- Guilfoos & al. have tried to bridge the gap between hydrologists, economists and decision makers by developing a detailed multicellular model of an important aquifer characterized by groundwater flow governed by Darcy's law. It is worth mentioning that this law allows the quantification of the gain in welfare of an optimal management explicitly incorporating slow motion runoff.

Guilfoos & al. have shown, based on a spatially detailed description of the withdrawal points and a concentration of water demand, that the gain in welfare of appropriate groundwater management is quite significant, and is approximately 27% in the Kern country in California. They have also shown that heterogeneities in demand are important and highly correlated with gains in wellfare of individual users. Some irrigators in high demand areas could earn up to 39% which is about three times larger than the gain implied by the bathtub models for the same aquifer. Their results also depend on the behavior of farmers. Indeed they have find that if all farmers have a strategic behavior then welfare gain of optimal management will be significantly lower. However, it is in the interest of every farmer to behave in a myopic manner if he believes that others also have a myopic behavior. Policies that lead farmers to adopt strategic behaviors preserving the resource, with appropriate spacing withdrawal points, considerably increase the wellfare. Finally, they show that the explicit integration of correct physical characteristics of the aquifer is very important when assessing the economic policies of aquifer management.

## III. Design of hydro-economic model of the NWSAS area:

Inspired by the approach developed by the contributions produced during the last decades (summarized briefly above), the mathematical model of our hydro-economic system is formulated as a parametric linear programming problem.

The objective function of our model is the sum of the discounted total net revenues of the irrigated agricultural production throughout the NWSAS zone during the time frame set in advance. This horizon is the number of years during which water can be still pumped from the aquifer. This fuction is to maximize under the constraints that describe both the aquifer system and the existing economic, agricultural, social and institutional system.

This objective function can be written as:

$$\max_{\{V_{ij}(t)\}_{i=1}^{I}} \int_0^t e^{-rt} \left(mbha_{ijt} \times X_{ijt}\right) dt$$

with :

- $X_{ijt}$ :irrigated area, in ha, of culture i in area j for year t.
- $mbha_{ijt}$: gross margin per hectare (in US \$), released by the culture i in area j for year t.
- $V_{ij}$ :water volume, in m3, allocated to culture i of zone j.
- $e^{-rt}$ :discount factor.

The Constraints on this objective function explicitly incorporate:

- All hydrological components of sustainable management of the aquifer;
- All agronomic and climatic constraints;
- All institutional and environmental aspects considered important.

These constraints, as we will detail later, will concern aspects that ensure the sustainability of the resource, such as the areas to be irrigated, the amount of resource used, valuing the resource and the preservation of its quality. They will be as follows :

- The first type of constraints (1) represents the ordinary conditions of non-negativity;

$$X_{ij} \geq 0 \;\; \forall ij, \;\; i = crop, \; j = area. \tag{1}$$

- The second type of constraints (2) concerns the total of irrigated area. These areas should not increase, since in a first step at least, we want to produce more with the same amount of water. It will be a constraint for each area.

$$\sum_{i=1}^{nc} X_i \leq S^Z \tag{2}$$

- nc: number of crops;

- $S^Z$: total irrigated area currently in this area.

- The third type of constraints (3) relates to irrigated crops that provide better valuation of m3 of water used. For reasons of economic efficiency, these areas are to maintain if not increase:

$$\sum_{j=1}^{nz} X_{cj} \geq S^c \tag{3}$$

- $X_{cj}$ : irrigated area devoted to culture c in area j;

- $S^c$ : total current area of culture c;

- nz :number of areas.

It will be a constraint of this type for each culture we want to preserve for social or environmental considerations.

- The fourth constraint (4) concerns the total irrigated area of the NWSAS zone. Given the current state of overexploitation of the aquifer, this area must not increase as an increase in irrigated area involves additional water to extract:

$$\sum_{j=1}^{nz} \sum_{i=1}^{nc} X_{ij} \leq S^a \tag{4}$$

$S^a$ : Current total irrigated area.

- The constraints (5) represents the total annual resources allocated to all areas (and cultures) of NWSAS:

$$\sum_{j=1}^{nz}\sum_{i=1}^{nc} V_{ij} \leq R_D^p \tag{5}$$

- $V_{ij}$ :water volume, in $m^3$, allocated to culture i in area j;

- $R_D^p$: annual resources actually allocated to agricultural use:

$$R_D^p = Q + mp \;\; \text{où } p = 1, ..., n \tag{6}$$

- $Q$ : volume of total renewable water corresponding to the natural annual charge.

- $m$ : parameter that represents the volume of water to vary (the "pitch") for determining the optimum amount to be pumped by year (eg, m = 1000 m3, p = 1,2,3, .., Q = 500 m3, so mp = 1000 m3, 2000 m3, 3000 m3 ... and = 1500 m3, 2500 m3, 3500 m3, ...).

- Constraint (7) specifies the cost of degradation of the aquifer resulting from overexploitation caused by overpumping much higher than the natural recharge capacity.

$$f(p) \tag{7}$$

This cost essentially comprises two components:

(1) Increasing pumping costs due to the drawdown;

(2) A cost of degradation of the water quality due to increasing salinization.

The impact of these two costs depends on the resource consumed above the recharge volume. Indeed, as long as this volume does not exceed the groundwater recharge, the quantities pumped are replaced by recharge, so there is no drawdown (no additional cost for pumping) and no degradation quality (no revenu reduction). Gradually, as the water consumption exceeds the recharge volume, water table folds, this will incur an additional pumping to get deeper water. On the other hand, this consumption beyond the amount of charging causes an increase in the salinity of the water, which impacts negatively on the product quality and quantity and, consequently, their gross margin. The margin reduction is proportional to the volume of additional pumped water, so we can introduce this constraint in the objective function:

$$\max_{\{V_{ij}(t)\}_{i=1}^{I}} \int_0^t e^{-rt} \left( (1 - f(p)) \; mbha_{ijt} \; X_{ijt} \right) \; dt$$

## IV. Presentation of data collection and specification of the model:

Before turning to the application of the model itself, we will try to study the various aspects of the problem of NWSAS area, analyze the behavior of the main actor of the system that is the irrigator and the operation of farms in the basin. Let's start by situating our study region:

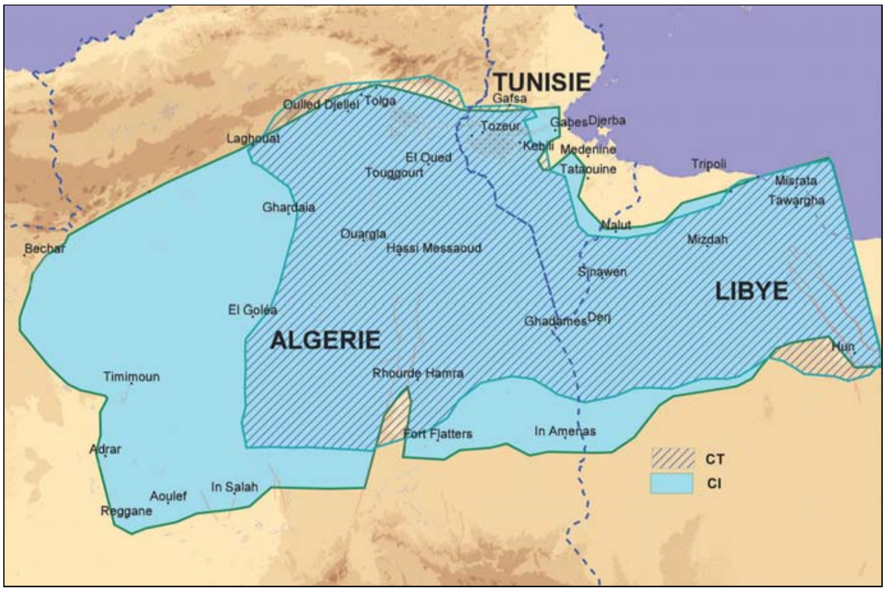


Figure 1: Location of the two aquifers of NWSAS basin. Source: OSS 2014.

The North-Western Sahara Aquifer System (NWSAS) is a deep transboundary aquifer composed of two superposed layers: the Intercalary Continental (CI) with a depth that reaches 3000 m in some areas and the Terminal Complex (TC) with a depth of 300-500 m.

The NWSAS basin covers a total area of one million km$^2$ shared by Algeria (700,000 km$^2$), Libya (250 000 km$^2$) and Tunisia (80,000 km$^2$).

To become operational and be applied to the reality on the ground, the model requires the availability of actual data. Three categories of real data should be collected:

- *Macroeconomic data:* This National and Regional data are collected from statistical offices of ministries and generally available in the regional Headquarters of the three countries. These data concern:

- The currently irrigated areas in each of the selected zones of the NWSAS.

- The distribution by zone of irrigated areas according to production systems.

- *Micro-economic data:* To collect this data category, we have conducted a socio-economic and environmental survey a sample of 3,000 farms, covering the whole of this region, and 2 crop years. The data relate to reap the use of water, soil and different inputs.

For data producing reliable results that can extend to the entire NWSAS region, it is essential to design a sample of farms to investigate that is representative of all the basin irrigators. We wish that our sample is representative at the NWSAS zone as a whole, but also within each country and even each region.

After consultation with the various managers of the resource in the three countries concerned, the areas to be covered by the comprehensive socio-economic and environmental surveys have been selected. It is:

- 5 zones in Algeria (Biskra, El Oued, Ouargla, Ghardaia and Adrar) ;
- 5 zones in Tunisia (Tataouine, Medenine, Gabès, Kébili and Tozeur);
- One zone in Libya (Libyan Jeffara ).

After loading and processing the surveys, we obtained 3,750 valid surveys.

Main results:

Millions of raw data collected during this study allow us to have very relevant calculated data by farm, by region, by country and for the entire NWSAS basin. These data refer to irrigated areas, labor, water, production, livestock, gross margin of the farm (revenues - expenses), water productivity, … Crossing these data has allowed us to draw valuable information on resource consumption by country, by distribution network and by type of crops grown, on cost of water by country and by distribution network and on water productivity, etc.

- *Information derived from the results of the analysis of survey data:* The analysis also has allowed us to draw very important lessons about the behavior of irrigators with the resource and its use. Thus, field observations show that it is better to think in terms of cropping systems rather than crops because farmers often practice several crops on the same parcel (crops in 2 or 3 stages) and irrigate with the same amount of water. It is, therefore, difficult to distribute the water among different crops.

We identified six (6) cropping systems in the region:

- Traditional "oasis denses" system: oasis with crops in three floors: palm trees, fruit trees and vegetable crops;
- "oasis éparses" system: palm trees only;
- The system mainly based on arboriculture;
- The system mainly based on vegetable crops and greenhouse production;
- The open field system (mainly fooder and cereals);
- Livestock dominant system.

Analysis of the data, according to this view, has allowed us to draw useful information for further work. Thus, it can be seen that the cropping systems: mainly based on vegetable crops and greenhouse production, livestock dominant and traditional "oasis denses" much better value the resource than the other three systems. Indeed, the gross margin per hectare and the productivity of water are higher for these 3 systems. We can learn that, for reasons of efficiency in the management of the resource, these three systems must be preserved in order to optimize the allocation of resources.

**Model specification for a given crop year:**

Given the lessons we have drawn from surveys, the model developed in the theoretical part can be presented as follows:

$$\textbf{Objective function:} \text{ Maximize } \sum_{j=1}^{10}\sum_{i=1}^{6} (1-\alpha p)\ mbha_{ij}\ SEI_{ij}$$

- j represent the zone and i the cropping system ;
- $SEI_{ij}$ represent irrigated areas ($X_{ij}$ in previous model) ;
- $f(p) = \alpha p$.

**Constraints :**

1. Non negativity constraint:

$$SEI_{ij} \geq 0 \quad \forall ij \tag{1}$$

2. Constraint total irrigated area by zone:

$$\sum_{i=1}^{6} SEI_i \leq S^z \ , \ for\ every\ zone\ z. \tag{2}$$

3. Constraint "Oasis denses" by zone:

$$\sum_{j=1}^{10} SEI_{4j} \geq S^{OD} \ , \quad for\ j = 1 \ldots 10. \tag{3}$$

4. Constraint livestock farming by zone:

$$\sum_{j=1}^{10} SEI_{6j} \geq S^{El} \ , \quad for\ j = 1 \ldots 10. \tag{4}$$

5. Constraint vegetable crops by zone:

$$\sum_{j=1}^{10} SEI_{5j} \geq S^{CM} \ , \quad for\ j = 1 \ldots 10. \tag{5}$$

6. Constraints resources:

$$\sum_{j=1}^{10}\sum_{i=1}^{6}\delta\ wha_{ij}\ SEI_{ij} \leq R_D^p \tag{6}$$

$$R_D^p = Q + mp, \qquad p = 1...n.$$

The results generated by the parametric linear program depend entirely on three crucial parameters namely:

- $\alpha$ represents the negative impact, which reduced the gross margin per irrigated hectare, following two types of costs arising from the overexploitation of the aquifer. The first being the cost of pumping which increases with the folding table following the excessive pumping and the second is the cost of quality and quantity degradation.

Note: Both of these costs would require an appropriate study to assess properly through a collection of real data from specialized services of the different agencies of the countries concerned. The elements required to calculate these costs, which are not estimated by these organizations will require specific surveys among irrigators themselves.

Since the data on these types of costs are not available now, we will drive our calculations and simulations on fictitious data.

- $\delta$ represents the proportion of the volume of irrigation water really consumed, also called consumptive use. In fact, a part of the water assigned to the irrigated plot, seeps into the table or forms a surface or groundwater table, while the other part is permanently used. According to experts, this coefficient depends on the nature of the soil and infiltration coefficient, but it is equal, on average 70 % of the delivered volume.

- $m$ is the "pitch" of the simulation or the amount of water pumped beyond the volume of renewable water Q.

## V. The model Implementation and main results interpretation:

For the implementation of our model, we chose the LINGO software (for Linear Interactive and Global Optimizer) of LINDO systems. This software is both complete and powerful to build and solve optimization models.

The way it is constructed makes the model complicated to use for the uninitiated, because you have to enter all data in specific locations, otherwise its performance may be compromised. Therefore, in a second step and to facilitate the use of the model, we have created a clear and simple Excel interface, from which any user will be able to introduce its settings and run the model.

Using this interface requires no special knowledge, except the model parameters, as shown in the following figure:

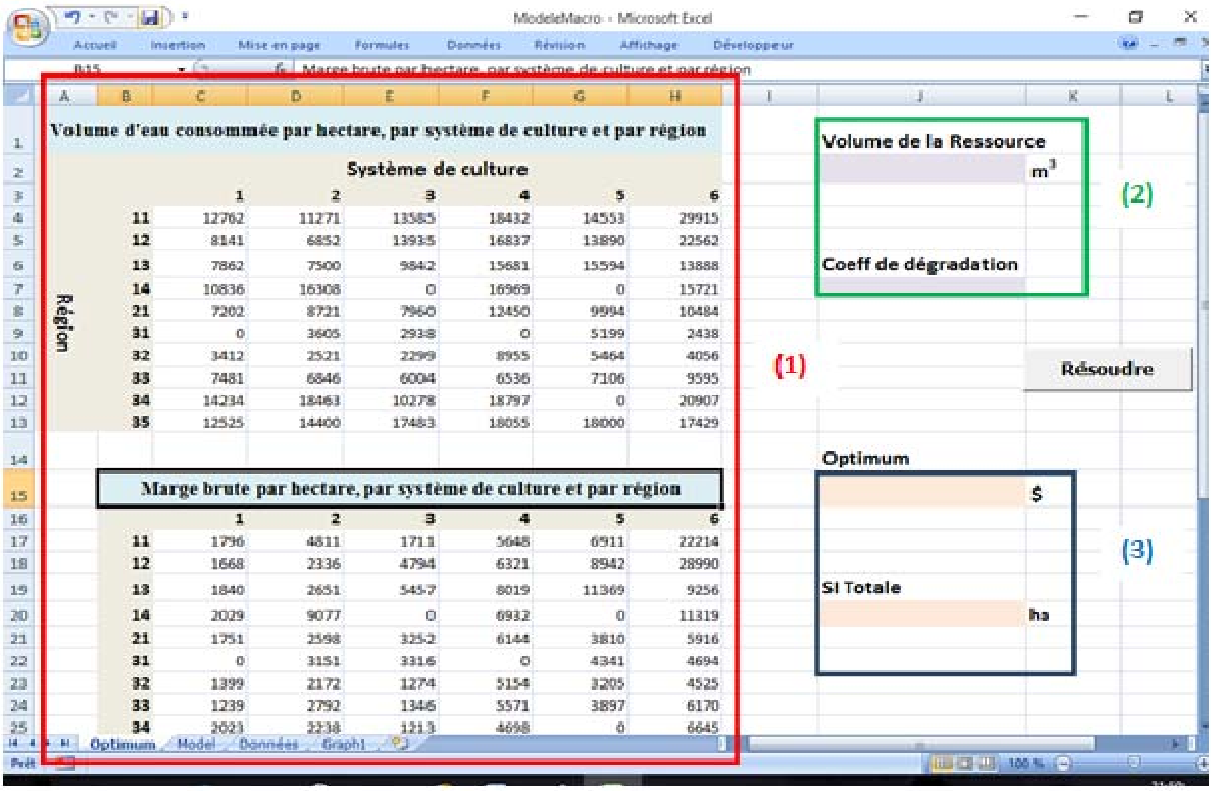


Figure 2: Excel interface to run the model.

The inputs of the model are divided into three groups:

- The base data, fixed, to be used for the internal operation of the model, are introduced once into the file (1). It is:

  - Water volume consumed per hectare for each region and each cropping system;
  - Gross margin per hectare for each region and each cropping system.

- The variable data, introduced by user: amount of available resource (2);

- Calculated data: it is the degradation coefficient, which is calculated based on the amount of resource to be used (2).

We changed our LINGO program, to make the link between the model and the Excel interface. Thus, instead of data entered manually, we tell the program to go look for theminour Excel interface. Similarly, to have results better presented and easily exploitable, we show the model location where it needs to send these results (3).

Thus, once the volume of resource is inserted, the user has only to click on the "Solve" button, then the Excel file call LINGO file that contains the program. LINGO file import the inputs of Excel file, run the model and return the results to Excel file.The outputs of the model will be played on the Excel interface (3). These outputs are the optimal income of all irrigated activity in NWSAS zone and the total irrigated area corresponding to this optimum.

The model provides, also, irrigated areas, by region and cropping system, corresponding to the optimal solution.

**Model simulation and interpretation of results:**

All data presented above correspond to the current status of the areas, water consumption, gross margins, etc. We can call it the present scenario. This scenario is built on the current state of the use of ground water in different regions of the NWSAS zone with the distinctive features of the current management, including:

1. The underground resource is used according to the rule of "open access.". This principle simply means that the resource is used in a free manner without any restrictions. Any user can collect the required amount according to his needs.

2. Energy is heavily subsidized in the three countries.

3. The investment cost of the resource, which includes primarily the cost of deep drilling and construction of collective distribution networks, is fully supported by the local authority for users of the public networkand partially supported for individual users.

4. The state supports, particularly in Algeria, cereal production on vast irrigated areas with

giant pivots.

The simulation, in this scenario, is to vary the amount of resource available and see the results on the irrigated areas by cropping system and the overall income of the entire NWSAS zone.

A first simulation is conducted on the basis of a parametric linear program defined above and values assigned simultaneously to the three parameters we just defined, as follows:

- The "pitch" of increasing the pumped volume is 50 Mm$^3$ ($m$=50) ;
- The proportion of the actual consumptive use of water allocated is 70 % ($\delta$ =0,7) and 30% returns to the aquifer;
- A fictitious value of $\alpha$= 0,01 ;
- A value of the available resource = 2 billion m$^3$.

Once you click on "Solve", the model runs and we get the results shown in the following figure:

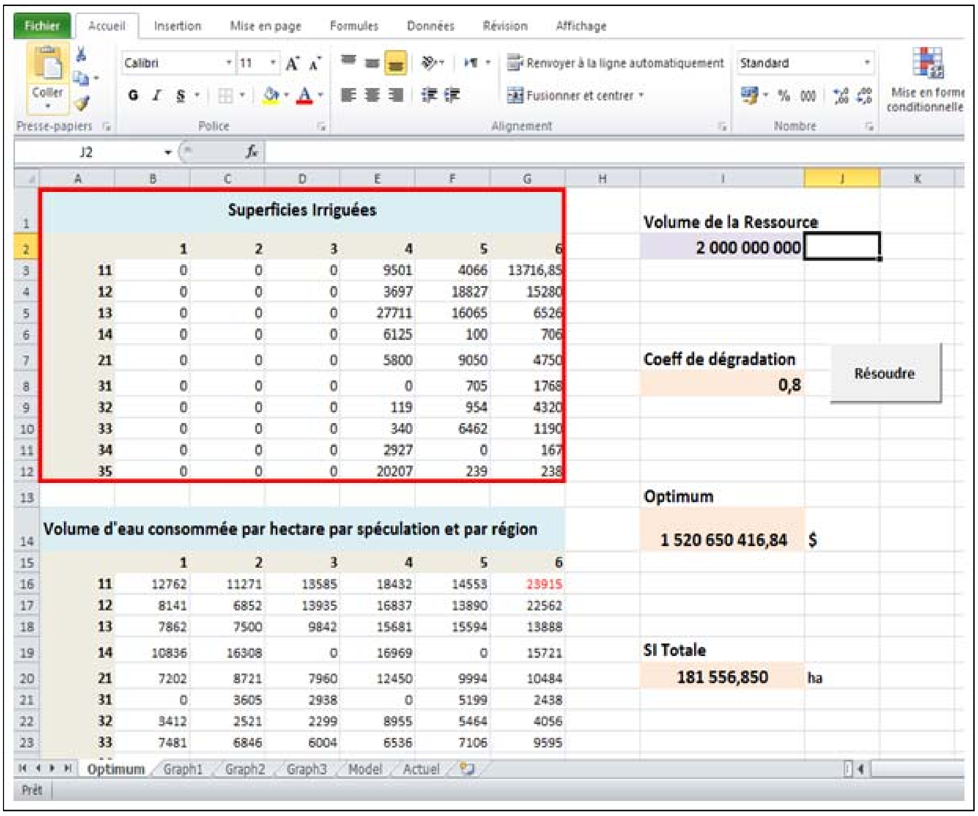


Figure 3: Results of model's run

We obtain the optimal income for all irrigators, the irrigated area by zone and cropping system (red box) and the Total Irrigated area, for a resource available volume of 2 billion m$^3$. We can test the model, as we wish. To do this, simply introduce a value for the resource that is a multiple of 50 million and > 1.55 billion $m^3$.

By testing our model with three successive values for the amount of available resources, which are 1.55 bn $m^3$, 1.6 bn $m^3$ and 1.65 bn $m^3$, we obtain the following results:

| | **1,55 Bn $m^3$** | **1,6 Bn $m^3$** | **1,65 Bn $m^3$** |
|---|---|---|---|
| **Optimal Revenu ($)** | 1 060 711 326 | 1 129 558 604 | 1 196 570 305 |
| **Total irrigated area (ha)** | 150 559,7 | 153 725,6 | 156 891,5 |

Looking at the results more closely, we note that if the amount of water available increases, the optimal income increases and the total irrigated area also increases. This may suggest that to improve the welfare of the population of the NWSAS zone, we need just to increase the volume of resources available to them, which will allow them to expand their irrigated areas, produce more and earn more. Resource managers rely on this reasoning in promoting irrigated agriculture. However we will demonstrate that this approach is illusory when excessive pumping of groundwater provokes overexploitation and even involves the irreversible dégradation.

To check what has been raised, we will simulate the model with values of the amount of available resource from 1 bn $m^3$ (which is roughly the amount of annual recharge) to 3.5 bn $m^3$, with a pitch of 50 $Mm^3$.

**Interpretation of simulation results:**

When running our simulation with the parameters- indicated previously, our model does not find optimal solution for quantities of resource from 1 bn $m^3$ to 1.5 bn $m^3$. This result is explained by the fact that in the current situation of average resource consumption per hectare, by area and cropping system and with lower limits on the areas of cropping systems to preserve we can not respect all the constraints of the model with an amount of resources lower then 1.55 bn $m^3$. From a volume of water equal to 1.55 bn m3 available, the previous simulation gives us the following results:

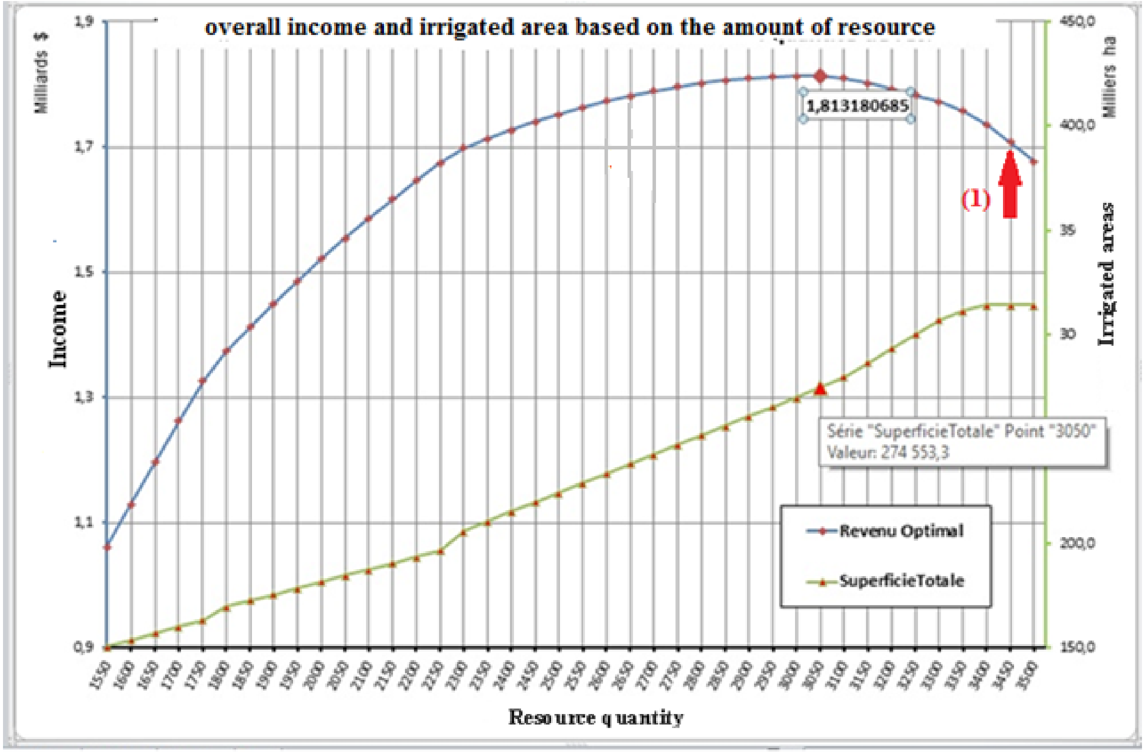


Figure 4: Overall income and irrigated area based on the amount of resource.

This confirms that when the amount of available resource increases, the optimal income begins to grow rapidly, then less quickly, alongside a growth in the total irrigated area, up to a maximum (which corresponds to an amount of resource = 3.05 bn $m^3$ and a total income = $ 1,813,180,685). From this point it begins to decrease slownly, then more rapidly, although the total irrigated area continues to grow.

The only explanation for this result is the introduction of our degradation cost. Indeed, the allocation of an additional quantity of the resource will permit the irrigation of an additional area, thus increasing the quantity produced and, consequently, the income. On the other hand, the consumption of an additional quantity beyond the recharge volume results in degradation of the water quality and higher pumping costs, which affects, negatively, the production and consequentlythe income. In the ascending part of the curve and to the optimal value, the increase in income due to the exploitation of additional acreage balances the environmental costs. However, the influence of these costs graft, increasingly, this increase in income up to cancel. Beyond the optimal solution, the damage caused by overexploitation is more expensive than the additional revenue collected by irrigation of larger areas. Thus, the optimal income begins to decrease, although the irrigated areas continue to grow.

Thus, the optimal solution reveals that with water volume available of 3.05 bn $m^3$, we have:

- A total income for the NWSAS region = $ 1,813,180,685;
- A total irrigated area in the region = 274 553.33 ha;

This solution economically optimal can be politically and socially difficult to implement immediately. Therefore, we believe that this solution should be applied progressively, with accompanying measures to compensate for losses that would affect some farmers and incentives to push them to migrate as quickly as possible to systems that would achieve this optimal solution.

On the other hand, if we compare the optimal solution with the current situation, we obtain:

| | **Irrigated area (ha)** | **Volume Consumed (US$)** | **Global income (US $)** |
|---|---|---|---|
| **Actual** | 314 085,00 | 3 767 603 483,18 | 1 609 305 862,95 |
| **Optimal** | 274 553,33 | 3 050 000 000,00 | 1 813 180 685,48 |

The results, which are very clearly illustrated by this table, confirm our initial assumption that the mobilization of a volume of water far greater than the natural recharge to irrigate more agricultural land in a region where this factor is abundant, would produce an income significantly lower than the optimal solution resulting from our modeling. This negative result is indeed a waste of scarce and precious resources in one of the most fragile region in the world.

This result is confirmed in our figure (4), where we see that the total revenue generated by the mobilization of 3.45 $Mm^3$ is only 1.7 M US $, lower than the Optimal solution which allows to obtain 1.8 MUS $ with only the use of 2.7 $Mm^3$. What invalidates the belief, widespread among decision makers, that the more we mobilize the resource the higher will be the obtained income.

In that context and with current data and settings we explained previously, we can say that a decision maker should not allocate more than 3.05 bn $m^3$ for irrigation in the NWSAS area.

This result depends greatly on the coefficient of degradation incorporated in our model, since the evolution of income depends on the amount of environmental costs to be supported by the irrigator. To see the importance of this factor, we will do the simulation with different coefficients, keeping constant all other parameters. Thus, we will make simulation with $\alpha = 0.01$, $\alpha = 0.015$ and $\alpha = 0.02$.

The results obtained by our model are shown in the following figure:

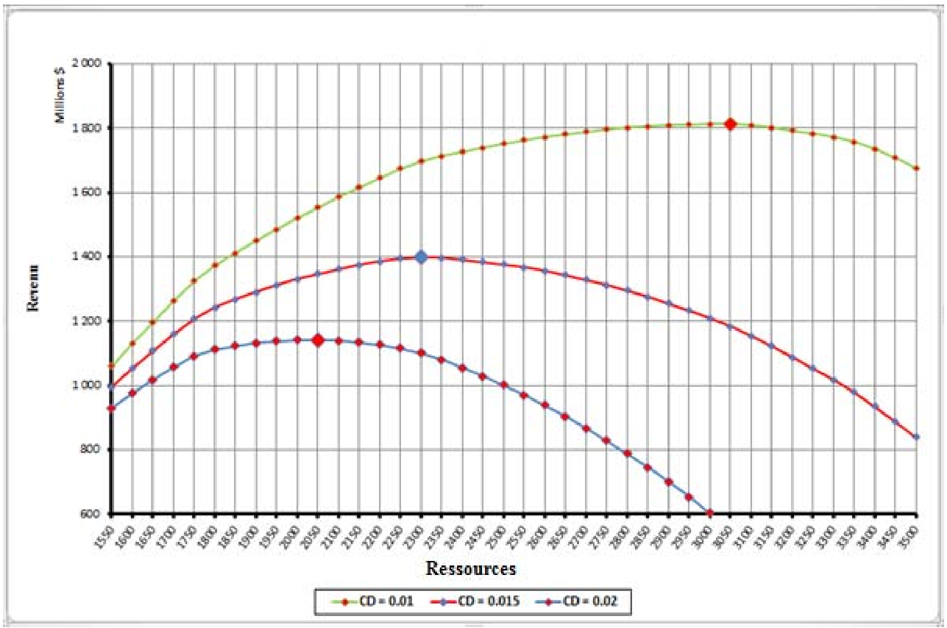


Figure 5: Evolution of resource-based income for different CDs

We note that the smaller the degradation coefficient is, the higher the optimum is and the larger the amount of resources available to the optimum is. This means that the total irrigated area is larger. This result is logical since this degradation coefficient negatively affects the gross margin of farmers. It suggests, too, the urgency of finding solutions to conserve resources and limit adverse environmental effects of over-exploitation to avoid the increase of degradation coefficient, which results in a decrease in revenue for the same amount of used resource.

However, in the three simulations, income starts increasing, when increasing the amount of available resources, reaches a maximum and then decreases more or less rapidly.

The conclusion that can be drawn from this chart is:

*Whatever the degradation coefficient, allocate a volume of water greater than the optimum volume given by our model is a waste of resource.*

This result demonstrates that contrary to what farmers think, who always ask for extension of irrigated areas and contrary to the path followed by some stakeholders and even policy makers in the field of irrigation water which is to create more and more irrigated areas, the expansion of irrigated areas does not always mean an improvement of farmers' income. On the contrary, from a certain point, when the harmful effects of overexploitation are felt acutely, the expansion of irrigated area means lower welfare of farmers.

## VI. Key results and their Policy implications

The most interesting results we have obtained are

- Below a certain amount of mobilized resource, there is no optimal solution, this result makes sense because using current consumption of all farms and taking to keep, as such, existing areas of some profitable cropping systems, if not increase, we arrive at an amount of incompressible resource. Below this amount, we can not achieve these objectives;

- Contrary to the belief of the majority of farmers and decision makers in the field of water allocation, increasing the groundwater mobilization and, consequently, irrigated areas does not systematically lead to an improvement of the overall income of all irrigators. Indeed, if we refer to the evolution of irrigated areas and the amount of resource consumed since the 50s until today and if you look at the projections for 2020 or 2030, we realize this trend has been the expansion of those areas and increasing amounts of water mobilized and this trend is not ready to reverse in the future. This shows that the prevailing idea is that by increasing the irrigated area we systematically improve farmers' incomes. We have just shown that this idea is false because it ignores the negative impact of the resource deterioration due to overexploitation.

Despite the use of a hypothetical degradation coefficient due to lack of data to calculate the real one, testing our model with three different values for this coefficient and get convergent outputs, allowing us to conclude that our results are valid.

Our model tells us that, whatever the degradation coefficient used, increasing the amount of available resources, so the irrigated areas, the optimal income of all NWSAS farmers starts growing then less quickly reaches a maximum and begin a decline phase which is becoming faster.

This result seems fundamental to the management of the resource and should be taken into account by all decision makers in terms of irrigation water and especially by politicians who define country strategies.This is important because continuing in the single sense of irrigation area expansion inevitably leads to the depletion of the resource and jeopardizing all the population of the NWSAS region at more or less long term.

We believe that the model we have developed integrates all aspects of sustainable management of this resource. Indeed, our model takes into account the hydrological aspect, the economic aspect, the environmental aspect by incorporating the concept of resource degradation and its impact on the sustainability of its use as well as the social aspect.

Moreover, this model is very easy to use thanks to the use of Excel interfaces, which are intermediate between the model and the user, making its possible use for people without training in modeling. This result seems interesting, because we believe that our model should be used by people working in the field of irrigation and water management who are not asked to have special skills in modeling or even in computer.

Finally, the model can be operated, with specific data on different scales: regional, national or global.

This modeling to analyze and quantitatively evaluate all relationships and actions of human activity on the aquifer, offers decision makers an appropriate tool to help them design and especially implement coherent and above all feasible economic policies. In addition, this model, which explicitly incorporates economic calculation at the heart of water resources management by evaluating the goods and services generated by the different uses of this resource, gives them the means to discuss on an appropriately quantified base with leaders of other sectors of the economy at national arbitrations.

## References

Brown, G., and R. Deacon. (1972). "Economic optimization of a single-cell aquifer". Water Resources Research 8:556–564.

Brozovic, N. D. L. Sunding and D. Zilberman (2002). “Optimal Management of Groundwater Over Space and Time”. Frontiers in Water Resource Economics 29: 109-135.

Brozovic, N. David L. Sunding and David Zilberman (2010). “On the spatial nature of the groundwater pumping externality” Resource and Energy Economics 32(2):154 – 164.

Burness S., Brill T. (2001). "The role for policy in common pool groundwater use". Resource and energy economics, vol. 23, n° 1, p. 19-40.DOI : 10.1016/S0928-7655(00)00029-4

Cummings, R. G., and J. W. McFarland. (1974). "Groundwater management and salinity control". Water Resources Research 10(5):909–915.

Eckwert B., Zilcha I (2001), "The Value of Information in Production Economies", Journal of Economic Theory, 2001, vol. 100, issue 1, pages 172-186.

Feinerman, E., and K. C. Knapp. (1983). "Benefits from groundwater management: Magnitude, sensitivity and distribution". American Journal of Agricultural Economics 65:703–710.

Gisser, Micha and David A. Sanchez. (1980). “Competition Versus Optimal Control in Groundwater Pumping”. Water Resources Research 16:638–642.

Gisser, Micha. (1983). “Groundwater: Focusing on the Real Issue”. Journal of Political Economy, pp. 1001–1027.

Guilfoos Todd, A. D. Pape, Neha Khanna, Karen Salvage (2013) “Groundwater management: The effect of water flows on welfare gains”. Ecological Economics 95, 31-40.

Hotelling, Harold. 1931. “The Economics of Exhaustible Resources” Journal of Political Economy 39:137–175.

Howe, C. W., and D. V. Orr (1974), "Economic incentives for salinity reduction and water conservation in the Colorado River Basin", edited by D. Yaron, pp. 121-138, M. Dekker, New York, 1974.

Lefkoff, L. J., and S. M. Gorelick. (1990a). "Simulating physical processes and economic behavior in saline, irrigated agriculture: Model development". Water Resources Research 26(7):1359–1369.

Lefkoff, L. J., and S. M. Gorelick. (1990b). "Benefits of an irrigation water rental market in a saline stream-aquifer system". Water Resources Research 26(7):1371–1381.

Maneta,M.P., M. O. Torres, W. W. Wallender, S. Vosti,R. Howitt, L. Rodrigues, L. H. Bassoi, and S. Panday (2009) "A spatially distributed hydro-economic model to assess the effects of drought on land use, farm profits, and agricultural employment", Water Resources Research, Vol. 45, W11412.

McKinney C. D. X. Cai, M. Rosegrant, C. Claudia, C. A. Scott (1999). "Modeling Water Resources Management at the Basin Level: Review and Future Directions", SWIM Paper No. 6, International Water Management Institute, Colombo, Sri Lanka.

Nieswiadomy, Michael. (1985). "The Demand for Irrigation Water in the High Plains of Texas, 1957-80." American Journal of Agricultural Economics 67(3):619–626.

OSS. (2008). "Système aquifère du Sahara Septentrional. Gestion concertée d'un bassin transfrontalier". Collection synthèse n°1.

Pfeifer, L., Lin, C., (2012). "Groundwater pumping and spatial externalities in agriculture". Journal of Environmental Economics and Management 64 (1), 16–30.

Saak, Alexander E. and Jeffrey M. Peterson. (2007). "Groundwater Use Under Incomplete Information". Journal of Environmental Economics and Management 54:214–228.

Scherer, C. R., (1997). "Water allocation and pricing for control of irrigation related salinity in a river basin", Water Resour. Res., 13,225-238.

Young, R. A., and K. L. Leathers (1981), "Economic impacts of regional saline irrigation return flow management programs", in Salinity in Irrigation and Water Resources, edited by D. Yaron, pp. 201-214, M. Dekker, New York, 1981.