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Private exploitation of the North-Western Sahara Aquifer System ⋆

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Abstract

We formulate a hydro-economic model of the North-Western Sahara Aquifer System (NWSAS) to assess the effects of intensive pumping on the groundwater stock and examine the subsequent consequences of aquifer depletion. This large system comprises multi-layer reservoirs with vertical exchanges, all exploited under open access properties. We first develop a theoretical model to account for relevant features of the NWSAS by introducing, in the standard Gisser-Sanchez model, a non-stationary demand and quadratic stock-dependent cost functions. In the second step, we calibrate parameters values using data from the NWSAS over 1955-2000. We finally simulate the time evolution of the aquifer system with exploitation under an open-access regime. We specifically examine time trajectories of the piezometric levels in the two reservoirs, the natural outlets, and the modification of water balances. We find that natural outlets of the two reservoirs might be totally dried before 2050.

Keywords: Hydro-economic model, private pumping, multi aquifer system, groundwater-dependant ecosystems, semi-arid region, simulation.

JEL classification: C61, C62, Q15, Q25

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1. Introduction

Groundwater use has increased significantly worldwide, especially in many arid and semi-arid areas where surface water is scarce. Intensive exploitation, combined with poor management, has caused a substantial drop in groundwater levels, water quality degradation, and significant environmental impacts. Water scarcity affects local activities that depend on water extraction and users located within natural discharge areas. Increasing groundwater extraction can thus threaten water flow and dry up natural springs on which people and ecosystems are dependent. This study investigates the hydrological impacts of unregulated groundwater extraction in an aquifer system. We mainly concentrate on the case of the North-Western Sahara Aquifer System (NWSAS).

Groundwater exploitation has been extensively analyzed in resource economics. Since the seminal work of Gisser and Sánchez [21], many studies have, however, adopted a more interdisciplinary approach to account for hydrological characteristics of the aquifer, and interactions within the hydrological system, as well as feedbacks between the hydrological system and the economic activity (Bekchanov et al. [5], Brouwer [10], Harou et al. [26]). Hydro-economic models (HEMs) have been used to assess and implement water policies at different scales.[1] These models allow to characterize specific features of different water systems - river basins (Cai et al. [12], Pulido-Velasquez et al. [43], or Torres et al. [54]), groundwater aquifers (Medellín-Azuara et al. [34]) or surface-groundwater interactions (Kahil et al. [28], Stahn and Tomini [50] [51]) - and to investigate explicit issues, including droughts and water scarcity (Maneta et al. [32]), water allocation policies (Booker and Young [7], Chatterjee et al. [13], Esteve et al. [18]), nitrate pollution (Graveline and Rinaudo [24], or Peña-Haro et al. [38]), or recently climate change (Connor et al. [14], Esteve et al. [18]). Among all these models, the Gisser-Sánchez's HEM continues to be widely used to analyze potential benefits from optimal management.

Indeed, a large strand of the literature addresses the Gisser-Sánchez effect, stating that policy regulation entails limited benefits. This is evident in a number of studies that has reproduced the Gisser-Sánchez HEM (e.g., Allen and Gisser [2], Brill and Burness [8], Feinermann and Knapp [19], Koundouri [30], Negri [35], Nieswiadomy [36], Provencher and Burt [44], Rubio and Casino [48], Tomini [53]). Such optimization-based HEM has been then used to tackle other issues as uncertainty (Knapp and Olson [29], Gemma and Tsur [20], Tsur and Graham-Tomasi [56]), quality (Roseta-Palma [45], Hellegers et al. [27]), multiple water sources (Burt [11], Provencher [42], Tsur [55], Stahn and Tomini [50]-[52], and Roumasset and Wada [46]). A separate strand of the literature deals with water flows and emphasizes the importance of groundwater flows (e.g., Brozovic et al. [9], Pfeiffer and Lin [41], Esteban and Albiac [17], Guilfoos et al. [25], Perreau et al. [39] or Reinelt [49]). Guilfoos et al. [25] explicitly analyze the role of public policy of a multi-cell aquifer and outline the

[1] Globally speaking, optimization-based models and simulation-based models are often used to analyze water issues at a regional or hydrological basin scale, whereas economy-wide models are used to examine the impacts of water use on a larger scope of the economy (Berrittella et al. [6], Dinar [15], or Duarte and Cholitz [16], or Llop [31]).

spatial effects on welfare gains with an application to Kern County (California). Esteban and Albiac [17] assume that welfare is adversely impacted by environmental damages resulting from groundwater depletion, and they empirically show there are non-negligible welfare gains from the management of two large aquifers in Southern Spain. Perreau et al. [39] also apply their HEM on the Western La Mancha aquifer in Spain, but they go a step further considering aquifer drainage, which contributes to environmental ecosystems. Damages thus result from a reduction in drainage and a piezometric level decline. Although those works are of high interest, they still contrast optimal management to other management regimes. We rather specifically investigate hydrological issues that arise when farmers exploit a multilayer aquifers system without considering future consequences (i.e., myopic behavior). This assumption, especially if we consider the issue of drying up natural springs, is more adapted to our empirical application to the NWSAS.

The NWSAS extends to a large desert and arid area, where surface water is nonexistent. Consequently, the population is highly dependent on this huge reserve of groundwater such that the use of this aquifer system has intensively increased over the last 40 years, mainly for irrigation purposes. Moreover, this water system is shared between Algeria, Libya, and Tunisia. Even if there is a mechanism for the joint management of the NWSAS, the three countries still withdraw water at rates that are beyond renewal rates. The intensive exploitation of this poorly managed resource leads to a series of issues, including declines in groundwater reserves, outlet depletion, and salt intrusion. Furthermore, there is no consideration for water flow toward outlets in the Algerian and Tunisian Chotts or that of usually feeding foggaras in the oases. The risk of drying up such natural springs specifically threatens population and groundwater-dependent ecosystems.[2] Therefore, it is a challenging research to examine possible trends of abstraction in the NWSAS.

The objective of this study is two-folded. First, we extend the settings of Gisser and Sanchez [21] to account for the hydrological and economic features of the NWSAS. To the best of our knowledge, there is no academic application to the NWSAS.[3] More precisely, we develop a stylized HEM with two interdependent superposed reservoirs and natural drainage. Therefore, we account for vertical flows between the two aquifers and horizontal flows, both depending on water stock. Water exchanges between aquifers specifically depend on the relative difference in piezometric levels, while drainage is defined as a linear function of the piezometric level by Pereau et al. [39]. As such, water extraction from one reservoir will impact leakage toward the other reservoir and drainage. Few studies investigate the exploitation of multiple aquifers: Zeitouni and Dinar [57] consider water flows between reservoirs but rather concentrate on contamination of all other connected aquifers; Roumasset and

[2] There are several different groundwater-dependent ecosystems such as oases, *sabkhas* or *Chotts.* We also find *Ramsar* sites in the NWSAS.

[3] Several studies applied to the NWSAS are developed by the Sahara and Sahal Observatory in the context of two international projects: the SASS project (2010-2015) (see http://www.oss-online.org/en/north-western-sahara-aquifer-system-sass) and the NEXUS projet 2016-2019 (see http://www.oss-online.org/en/acting-cooperation-water-sector-mediterranean-nexus).

Wada [47] show in a numerical simulation on the Oahu aquifer system that all resources are simultaneously used in the long run, but the "leakier" aquifer should be used first. These studies essentially concentrate on the optimal use of multiple aquifers. Contrastingly, we consider other economic hypotheses that fit with the NWSAS: both reservoirs are exploited by myopic users with a quadratic stock-dependent cost function, and the water demand is non-stationary. Farmers consequently ignore their impact on the system as a whole.

In a second step, we calibrate parameter values using data from the NWSAS over 1955-2000. We essentially proceed in two steps. We first use the available hydrologic data to calibrate the physical parameters of our dynamic model. We then estimate the economical parameters of the instantaneous water extraction functions by using extraction and piezometric data over 1955-2000. We thus end up with a calibrated dynamic system of the evolution of the piezometric levels of the two main aquifers of the NWSAS that can be used to assess the impact of an open-access regime on the evolution of the state of the NWSAS and environmental flows. We specifically investigate time trajectories of the evolution of the amount of outflows from the system, that of piezometric levels in the two different reservoirs, and the extinction of leakages. We find that the aquifer system is exploited beyond twice the total recharge in the long run. We further find that the natural outlets of the two reservoirs might be dried before 2050. We also ask the question of the sustainability of this exploitation regime by looking at the evolution of the different water withdrawals compared to the recharge.

The paper is organized as follows. In the following section, we provide a description of the NWSAS. Section 3 describes the methodology concerning the aquifer dynamics and the water extraction decisions. Data and calibration are presented in Section 4. In Section 5 we present and discuss the simulation results. Finally,Section 6 concludes the study.

2. Study area

The NWSAS is a large transboundary aquifer system shared by Algeria, Tunisia, and Libya. This geological basin corresponds to a multi-layer aquifer system with depths of 3000m. The aquifer formations have been grouped into two connected homogeneous and superposed reservoirs: the mostly unconfined "Complexe Terminal"(the CT), which constitutes the upper aquifer, and the confined "Continental Intercalaire" (the CI), which is the deepest and the most extended formation of the system. The CT and the CI aquifers are separated by a semi-permeable formation with low permeability, an aquitard. Fig.1 represents the vertical structure of the NWSAS.

Recharge occurs at the outcrops of these regional-scale aquifers representing 20% of the total surface area of the CI and most of the surface area of the CT. The Atlas Mountains and the Central Sahara outcrops represent the main recharge areas for the CI and the CT, respectively. The main discharge areas of this system are represented in Fig.2: The Algerian and Tunisian Chotts, Foggaras (traditional hydraulic systems to capture water from aquifer) mostly in Algeria, and the outlets into the Mediterranean Sea, that is, the Gulf of Gabes and the Sirte Bay. These outflows are of high importance for downstream ecosystems.

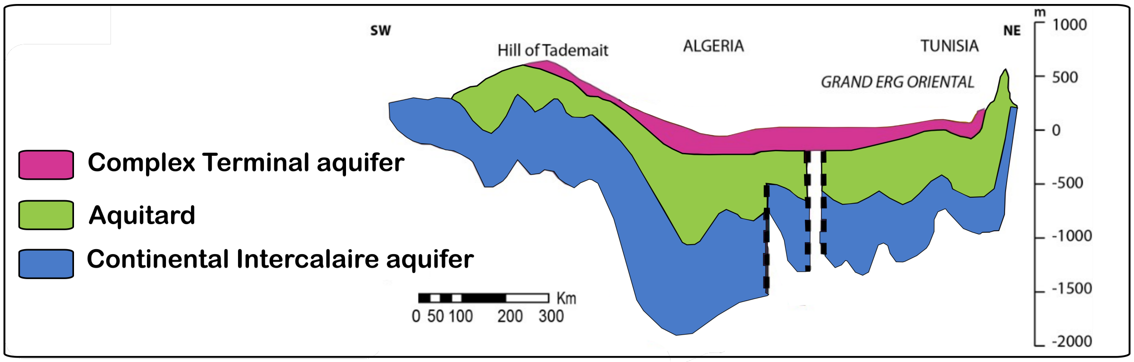

Figure 1: Schematic cross-section of the NWSAS

Indeed, several sites in the NWSAS are recognized as Wetlands of International Importance (Ramsar Sites), for example, the Chott areas in the northern Sahara, some oases, or the Sirte Bay in Libya. More precisely, Chott El Jerid in Tunisia or Chott Merrouane in Algeria is characteristic wetlands of the northern Sahara, where surrounded oases water needs are supplied by the outflows from the CT. In Algeria, the oasis Ouled Saïd in the southern Sahara (Foggaras area, Fig.2) is one oasis still using Foggeras to extract water from the CT, and it represents an important habitat for migratory waterbirds.

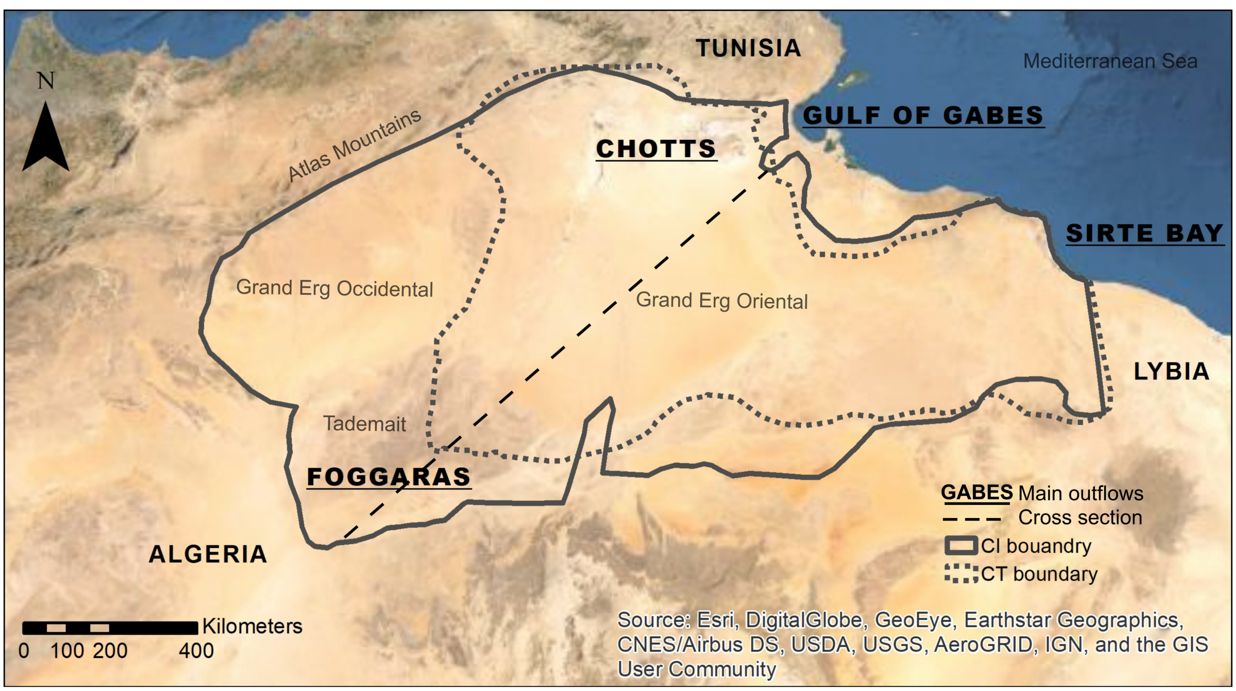

Figure 2: Extension of the CT and CI aquifers with major outflow areas

While water abstraction was quite small and mostly from the CT until the early 80's, the intensive use from both reservoirs in latter years has resulted in declines in piezometric levels.[4] Extraction rates reach nearly three times the recharge rate (AbuZeid and Elrawady [1]). The total number of withdrawal points has increased from 8,800 in 2000 to 18,160 in 2008.[5] A major part of the total withdrawals is extracted for agriculture (approximately 80%).

An important socio-economic survey launched by the Sahara and Sahel Observatory (the OSS report [33]) reveals that the NWSAS is still inefficiently exploited by farmers using private boreholes and having free access to the water network. Moreover, property rights failures are an important issue for the NWSAS exploitation. For instance, it was observed that only 80 out of 5,600 wells in Tunisia are authorized with permits.

Intensive pumping implies several consequences. The first evidence is a depletion of the groundwater reservoirs, which in turn affects pumping costs. Higher costs represent an important issue since pumping now arises in the deeper aquifer, and we observe the end of artesianism in confined sections. Declining groundwater reservoirs storage and piezometric levels also cause discharge decrease (e.g., Gonçalves et al.[23]) affecting downstream users or ecosystems, [6] but also affects the vertical flows between reservoirs. As aquifer exchanges depend on the piezometric levels difference, water moves from the aquifer with the highest piezometric level to the aquifer with the lowest level. In other words, intensive use of an aquifer may drive declines in the storage of the second reservoir, which then may affect pumping decisions.

Despite the international coordination to manage the NWSAS, the growing population in such an arid area would further pressure an already stressed system. Therefore, it is of high importance to understand how short-term private decisions will affect the whole system and the potential feedback on the use of NWSAS.

3. Methodology

This section introduces the HEM of private groundwater extraction for the NWSAS. We first present a stylized hydrological model that summarizes the main physical features of the NWSAS. Second, we suggest an economic model underlying extraction behaviors, given the piezometric levels of both reservoirs. We finally introduce equilibrium conditions to obtain observable extraction functions that can be estimated and integrated in our HEM.

3.1. The hydrological system

Let us consider two superposed reservoirs of different extend and depths. The first layer represents the CI, which is a confined aquifer covering the largest area denoted by A_I. The second layer is an unconfined reservoir of an area of A_T and relatively shallow depth. This corresponds to CT. For the sake of simplicity, we normalize the bottom of the deepest

[4] Total extractions increased from about 1 km3 in 1980 to 2.5 km3 in 2000 (Baba Sy [4], OSS [37])

[5] We exactly know that the repartition was in 2000 as follows: 3,500 points in the CI, and 5,300 in the CT.

[6] Many outflows are under stress, including foggaras in Algeria, the outlet discharges in the Gulf of Gabes in Tunisia, or the Chotts in Algeria and Tunisia.

reservoir to 0, and that of the upper reservoir to $\underline{h}$. Furthermore, the top of the unconfined layer is denoted by $\bar{h}$, which is also the land surface elevation. We denote by $h_i(t)$, $i \in \{I, T\}$, the piezometric level of the CI and the CT measured in meter (m) at time t. It should be noted that a piezometric level is the elevation of the free surface of the water in a well. As the CI is a confined aquifer, it is possible that $h_I(t) > h_T(t)$.[7] Each reservoir is refilled by an exogenous recharge, respectively denoted by $R_T > 0$ and $R_I > 0$. A proportion, $\beta_i > 0$ with $i \in \{I, T\}$, of water, naturally flows out of these two reservoirs when piezometric levels are higher than a fixed leakage threshold, respectively $\tilde{h}_I$ and $\tilde{h}_I$ for the CI and the CT. Following Darcy's Law, the leakage is proportional to the relative difference in piezometric levels and the leakage threshold if positive or zero else. The leakage at time t therefore writes:

$$\ell_i\left(h_i(t)\right) = \beta_i \max\left\{h_i(t) - \tilde{h}_i, 0\right\} \text{ with } i \in \{I, T\} \tag{1}$$

Vertical exchanges between the CI and the CT also exist. The direction of groundwater movements across the semi-permeable layer depends on the difference in the piezometric levels: water flows from the aquifer with the highest piezometric level to the lowest one. Using Darcy's law again, we even know that the amount of water moving from one aquifer to the other is a proportion, $\alpha > 0$, of the difference between both piezometric levels. We can furthermore notice that this amount of water will positively affect changes in the water balance of the aquifer with the lowest piezometric level while it will adversely impact the other aquifer. Vertical flows at time t from the CT to the CI are thus given by:

$$e\left(h_I(t), h_T(t)\right) = \alpha\left(h_T(t) - h_I(t)\right) \tag{2}$$

Of course, the exchange from the CI to the CT is the negative of $e\left(h_I(t), h_T(t)\right)$.

So, if there is no pumping, a standard water balance provides the following dynamics of the two piezometric levels, $h_T(t)$ and $h_I(t)$:

$$\begin{cases} s_I A_I \dot{h}_I(t) = R_I + e\left(h_I(t), h_T(t)\right) - \ell_I\left(h_I(t)\right) & \equiv N_I\left(h_I(t), h_T(t)\right) \\ s_T A_T \dot{h}_T(t) = R_T - e\left(h_I(t), h_T(t)\right) - \ell_T\left(h_T(t)\right) & \equiv N_T\left(h_I(t), h_T(t)\right) \end{cases} \tag{3}$$

Hydrological parameters are summarized in Table 1.

3.2. Pumping behaviors and water demand

Following Gisser and Sanchez [21], we assume a perfectly competitive water market where a representative *water supplier* sells water to any *water users* at $p(t)$ the current water price. Water users do not care about the reservoir this water is extracted. Being mainly farmers, they demand a quantity of water that equates the on-farm marginal return of water to $p(t)$.[8]

[7]This corresponds exactly to the situation observed in the NWSAS. It is even possible that $h_I(t)$ is higher than the ground level (i.e., an artesian behavior), but this last case never occurs under our calibration using bassin-scale average piezometric levels and homogeneous reservoir description.

[8]The reader may wonder whether the existence of a water market is relevant to our case study in which farmers often own their wells. However, as long as this market is competitive, myopic water allocation strategies can be separated from myopic water extraction decisions. This observation keeps our model close to the one of Gisser and Sanchez [21] and allows comparisons.

Symb.	Interpretation	Units	Symb.	Interpretation	Units
A_I	Area of the CI	m^2	A_T	Area of the CT	m^2
R_I	Recharge of the CI	$\mathrm{m}^3\,\mathrm{s}^{-1}$	R_T	Recharge of the CT	$\mathrm{m}^3\,\mathrm{s}^{-1}$
s_I	Storativity coef. of the CI	–	s_T	Storativity coef. of the CT	–
$\tilde{h}_I$	Leakage level of the CI	m	$\tilde{h}_T$	Leakage level of the CT	m
β_I	Leakage coef. of the CI	$\mathrm{m}^2\,\mathrm{s}^{-1}$	β_T	Leakage coef. of the CT	$\mathrm{m}^2\,\mathrm{s}^{-1}$
α	Leakance coef.	$\mathrm{m}^2\,\mathrm{s}^{-1}$	$\bar{h}$	Ground level	m
			$\underline{h}$	Elevation of the CT	m

Table 1: Hydrological Parameters

We even assume, like Gisser and Sanchez [21], that this instantaneous water demand is linear in price, but we introduce a time non-autonomous constant. This term captures the increase of the water demand across time that takes place in the NWSAS area during the last fifty years (see section 4). More specifically, our water demand is given by:

$$w^D\left(p(t),t\right) = \max\left\{a(t) - bp(t), 0\right\} \tag{4}$$

where w^D is the global water consumption in m^3/s at time t, with $a(t)$ the maximal water demand at time t and b the sensitivity of the water demand to a instantaneous price change $p(t)$. We finally assume that after using a part $\gamma \in (0,1)$ of the total amount of water consumption flows back to the upper layer of the NWSAS, that is, to the CT.

The *water supplier* sells the total amount of water on a single market, but she nevertheless arbitrates between extractions from the CI and the CT resp. denoted by w_I and w_T measured in $m^3 s^{-1}$. The optimal extraction strategy follows from instantaneous profit maximization integrating cost functions specific to each aquifer. This is consistent with the study of Gisser and Sanchez [21] as pumping cost depends on the depth from which groundwater is extracted, and both aquifers do not share the same piezometric level. We even extend these standard pumping cost functions to consider all the other costs to supply water (e.g., conveyance costs, maintenance...). More precisely, we consider (i) pumping costs given by the energy to lift one cubic meter of water over one meter, $c\left(\bar{h} - h_i\right) w_i$ with $i \in \{I, T\}$, and c the energy cost, (ii) and a quadratic exploitation cost, $\frac{k_i}{2} w_i^2$. Total water production cost is therefore summarized by:

$$C_i(h_i, w_i) = c\left(\bar{h} - h_i\right) w_i + \tfrac{k_i}{2}\left(w_i\right)^2 \ \text{with} i \in \{I, T\} \tag{5}$$

As the water market is perfectly competitive, the representative water supplier is assumed to be a price-taker and chooses the amount of water pumped in the two respective reservoirs based on the following instantaneous profit maximization:

$$\max_{(w_I, w_T) \geq 0} p \times \left(\textstyle\sum_{i\in\{I,T\}} w_i\right) - \textstyle\sum_{i\in\{I,T\}} C_i(h_i, w_i) \tag{6}$$

The computation of the first order conditions immediately show that extraction in each reservoir requires that the water price is equal to the marginal production cost.

$$p \leq c\left(\bar{h} - h_i(t)\right) + k_i w_i \quad \forall i \in \{I, T\} \quad (= 0 \quad \text{when } w_i > 0) \tag{7}$$

We get the following levels of extraction in the two respective reservoirs at time t:

$$w_i\left(p, h_i\right) = \frac{1}{k_i} \max\left\{p - c\left(\bar{h} - h_i\right), 0\right\} \text{ with } i \in \{I, T\}, \tag{8}$$

and the total water supply:

$$w^S(p, h_I, h_T) = \sum_{i \in \{I,T\}} \frac{1}{k_i} \max\left\{p - c\left(\bar{h} - h_i\right), 0\right\} \tag{9}$$

Table 2 summarizes all economic variables and parameters.

Economic Variables			Economic Parameters		
Symb.	Interpretation	Units	Symb.	Interpretation	Units
$w(t)$	Water consumption	$\mathrm{m}^3\,\mathrm{s}^{-1}$	$a(t)$	Maximal demand at t	$\mathrm{m}^3\,\mathrm{s}^{-1}$
$w_I(t)$	Extraction from the CI	$\mathrm{m}^3\,\mathrm{s}^{-1}$	b	Slope of the demand	$(\mathrm{m}^3)^2$ €$^{-1}\,\mathrm{s}^{-1}$
$w_T(t)$	Extraction from the CT	$\mathrm{m}^3\,\mathrm{s}^{-1}$	c	Coef. of the lift cost	€$(\mathrm{m}\,\mathrm{m}^3)^{-1}$
$p(t)$	Water price at time t	€$(\mathrm{m}^3)^{-1}$	k_I	Coef. of the quad. cost (CI)	€$(\mathrm{m}^3)^{-2}$
			k_T	Coef. of the quad. cost (CT)	€$(\mathrm{m}^3)^{-2}$
			γ	Rate of return flow	–

Table 2: The economic variables and parameters

So far, we just have characterized water demand, the respective amount of water extracted in the two reservoirs, and the total quantity of water production. All that variables will be introduced in the hydrological model.

3.3. Hydro-economic model of private groundwater extraction

We now integrate the hydrological model and the economic model by introducing the economic equilibrium water quantities into the water dynamics (3). This equilibrium results from an instantaneous water price adjustment, which ensures a perfect match between the demand(4) and the supply (9):

$$w^D\left(p(t), t\right) = w^S\left(p(t), h_I, h_T\right) \tag{10}$$

From this market clearing condition, we can derive the equilibrium price $p^*(t, h_I, h_T)$ and obtain the amount of water effectively extracted in both reservoirs at time t, $w_i^*\left(h_I, h_T, t\right)$ with $i \in \{I, T\}$ by using Eq.(8). However, Eq.(9) delineates several cases depending on the two piezometric levels (h_I, h_T) and the time period t at which the market equilibrium is considered. The interior solution where pumping in both reservoirs jointly occurs is specifically characterized as follows.[9] From Eq.(8), we know that extraction in reservoir $i \in \{I, T\}$ only

[9]Other cases may exist where pumping occurs in a single reservoir. However, the joint use of both reservoirs fit with our application to the NWSAS. Moreover, the condition (13) is satisfied for all t in the simulation. We therefore choose to omit these additional cases from our study.

occurs if the equilibrium price is larger than a lower bound $p_i^{\min}(h_i) = c\left(\bar{h} - h_i\right)$. Hence, joint extraction requires that the equilibrium price is larger than the maximum of the two respective lower bounds,

$$p^{\min}(h_I, h_T) = \max_{i=I,T}\left\{p_i^{\min}(h_i)\right\} \tag{11}$$

As water demand is decreasing in price, this situation requires that the demand at that minimal price is larger than the total supply, that is, $D\left(p^{\min}, t\right) > S(p^{\min}, h_I, h_T) > 0$. In this case, the market equilibrium price is, by computation, given by:

$$p^*(t, h_I, h_T) = \tfrac{k_I k_T}{b k_I k_T + k_I + k_T}\left(a(t) + \tfrac{c\left(\bar{h} - h_I\right)}{k_I} + \tfrac{c\left(\bar{h} - h_T\right)}{k_T}\right) \tag{12}$$

if and only if

$$p^{\min}(h_I, h_T) < p^*(t, h_I, h_T) \tag{13}$$

Water extraction in reservoir $i \in \{I, T\}$ at the equilibrium now becomes as follows:

$$w_i\left(h_I, h_T, t\right) = \frac{1}{k_i}\left(p^*(t, h_I, h_T) - c\left(\bar{h} - h_i\right)\right) \quad \text{with } i \in \{I, T\} \tag{14}$$

and water consumption as the sum of the equilibrium water extraction:

$$w\left(h_I, h_T, t\right) = w_I\left(h_I, h_T, t\right) + w_T\left(h_I, h_T, t\right) \tag{15}$$

Finally, we insert water extraction equilibria into water dynamics (see Eq.(3)), accounting for return flows to characterize our HEM for the NWSAS fully. As we have assumed that a proportion $\gamma \in (0, 1)$ of total consumption w flows back to the upper aquifer (the CT), the dynamics of piezometric levels of our HEM are given by:

$$\begin{cases} s_I A_I \dot{h}_I(t) = N_I\left(h_I(t), h_T(t)\right) - w_I(h_I(t), h_T(t), t) \\ s_T A_T \dot{h}_T(t) = N_T\left(h_I(t), h_T(t)\right) - (1-\gamma)\, w_T(h_I(t), h_T(t), t) + \gamma w_I\left(h_I(t), h_T(t), t\right) \end{cases} \tag{16}$$

4. Calibration & parameters estimation

This section calibrates the different parameters to apply the theoretical HEM to the NWSAS. We mainly use two data sources: the work of Baba Sy [4] on the NWSAS and the internal report of the *Observatoire du Sahara et du Sahel* (OSS [37]). We first evaluate the hydrological parameters (Table 1) and estimate economic parameters (Table 2) using observations on pumping rates over 1955-2000.

4.1. The hydrological parameters

NWSAS is one of the largest aquifer systems with a relatively small natural recharge. The CI extends over a greater area with $A_I = 1$ million Km^2 (OSS [37]), whereas the CT covers an area of $A_T = 650,000\ Km^2$ (Gonçalves et al.[22]). The analysis of the groundwater budget of Baba Sy ([4]) even provides some information on the recharge.[10] We deduce a constant recharge rate of $11.4m^3s^{-1}$ for the CI and of $18.2m^3s^{-1}$ for the CT.

As our model is a schematic representation of the entire domain of the NWSAS, most spatial data are averaged over the entire domain. As such, we derive an average elevation of the NWSAS, $\bar{h} = 992m$, using the topographic maps. Maps from Baba Sy [4] are scanned using ArcGIS software to compute a mean value of the bottom of both reservoirs and the average thickness of the aquitard in between.[11] For clarity, we choose to normalize the bottom level of the deeper aquifer (the CI) to zero, $\underline{h}_I = 0$. We then get a value of $\underline{h}_T = 555m$ for the CT and the average thickness of the aquitard, $e = 220m$. This last observation leads to a calibration of the coefficient of vertical exchanges, α, using Eq.(2) between the two reservoirs. Using Darcy's Law, $\alpha = \frac{KA_T}{e} \simeq 0.03m^2s^{-1}$ where the permeability coefficient $K = 10^{-11}ms^{-1}$ and $A_T = 6.5 \times 10^{11}m^2$.[12]. We apply the same methodology to deduce the piezometric levels in 1950 and 2000.[13]. Accounting for our normalization: these piezometric levels are given by:

$$h_I(1950) = 952.4,\ h_T(1950) = 841.9,\ h_I(2000) = 921.4, \text{ and}, h_T(2000) = 821.9 \tag{17}$$

The set of piezometric levels of 1950, which is often identified to the steady-state without pumping, are used as an initial condition for our piezometric dynamics (16), whereas the observed piezometric levels of 2000 are used as control points.

The leakage coefficients, β_i, and the thresholds, $\tilde{h}_i$, present in the leakage equations (1) also are calibrated by using this reference piezometric levels of 1950 and 2000 associated to the estimates of the leakages at the same years provided by Baba Sy's water balances [4] of 1950 and 2000.[14] They are given by: $\ell_I(1950) = 8m^3s^{-1}$, $\ell_T(1950) = 13.7m^3s^{-1}$ and $\ell_I(2000) = 5.4m^3s^{-1}$, $\ell_T(2000) = 4.5m^3s^{-1}$. By linear interpolation, we get $\left(\tilde{h}_I, \tilde{h}_T\right) \simeq (857.02m, 812.12m)$ and $(\beta_I, \beta_T) \simeq (0.084m^2s^{-1}, 0.46m^2s^{-1})$.

Finally, we estimate the two storativity coefficients, s_I and s_T, using the above estimated parameters on leakage, leakance coefficient, data on the piezometric maps for 1950 and 2000, and on water pumping available in the internal report of the OSS ([37])[15] and reproduced in Table 3. These data make it possible to reconstitute the temporal evolution of the piezometry between 1950 and 2000 by using successive water balances and adjusting the storativity coefficients by minimizing the square of the difference, in 2000, between observed and simu-

[10]For details, see Table 10-5 p.157 in Baba Sy [4].

[11]More precisely, we use the maps of top of the CI and the CT (resp. Fig.5-21 p.77 and Fig.5-24 p.78) and maps of the thickness of the CI and the CT (resp. Fig.3-7 p.49 and Fig.3-9 p.51) of Baba Sy [4].

[12]Baba-Sy [4] assesses that the permeability coefficient varies between 10^{-9} to 10^{-12} ms^{-1}, we arbitrarily choose an intermediate value.

[13]We specifically use maps from Baba Sy (Maps 8-1 p.118 and 8-2 p.119) to compute the piezometric levels in 1950 and maps 12-13 p.117-118 in OSS for 2000 ([37]).

[14]For details see Table 10-5 p.157 in Baba Sy [4].

[15]Tables 10-12 (p.103-104) and Tables 16-18 (p.106-108), respectively, provide information on extraction rates in the CT and the CI at country levels. We thus aggregate data to get total pumping rates over the period 1955-2000.

lated piezometric levels. Using Excel's solver, we get $s_I = 0.00051$ and $s_T = 0.00073$ as well as the time series of the piezometric levels given in Table 3.

Years	w_I in $m^3\,s^{-1}$	w_T in $m^3\,s^{-1}$	w in $m^2\,s^{-1}$	h_I in m	h_I in m
1955	0.995	8.832	9.827	952.11	842.34
1960	1.484	9.421	10.905	951.68	842.46
1965	2.561	9.763	12.324	951.04	842.46
1970	3.775	11.878	15.653	950.08	842.22
1975	5.075	13.952	19.027	948.77	841.50
1980	7.056	19.728	26.784	947.00	840.00
1985	17.125	26.948	44.073	943.68	837.26
1990	26.603	37.465	64.068	937.42	833.08
1995	27.992	42.949	70.941	929.43	827.26
2000	28.121	43.011	71.132	921.40	821.90

Table 3: Pumping rates, water consumption and piezometric levels over 1955-2000

Table 4 summarizes all the parameter values.

Symb.	Description	Values for the CI	Values for the CT
A_i	Area	$10^{12}\,m^2$	$6.5 \times 10^{11}\,m^2$
$\bar{h}$	Surface elevation	992 m	992 m
$\underline{h}$	Bottom of the reservoir	0 m	555 m
s_i	Storativity	0.00051	0.00073
R_i	Recharge	$11.4\,m^3\,s^{-1}$	$18.2\,m^3\,s^{-1}$
$\tilde{h}_i$	Leakage threshold	857.02 m	812.12 m
β_i	Leakage coef.	$0.084\,m^2\,s^{-1}$	$0.46\,m^2\,s^{-1}$
α	Leakance coef.	$0.033\,m^2\,s^{-1}$	

Table 4: Hydrological parameter values

4.2. The economic parameters

We now turn to the calibration of the parameters of water demand (4) and exploitation costs (5). First, following Gonçalves et al. [22], we assume that 15% of the pumping returns to the aquifer system, that is, $\gamma = 0.15$, and we make the assumption that almost all return flow reaches the CT. We secondly compute the cost of pumping water, c, using the formula to assess the energy in Joule (J) requirement to lift one cubic meter of water over one meter: $\frac{\rho g}{e}$, with $\rho = 10^3 kgm^{-3}$ the volumetric mass of one m^3 of water, $g \simeq 9.81 ms^{-2}$ the gravity acceleration and e the pump average efficiency fixed at 75%. If we now consider that a liter of diesel oil represents an energy value equal to $\frac{1}{3.787.10^7} J$ and that the average price of diesel oil is $p \simeq 0.23$€ per liter,[16] We can easily assess the pumping cost $c \simeq 7.944.10^{-5}$

[16] This diesel oil price corresponds to an average price in Algeria, Tunisia, and Libyan over 1991-2016, according to the world bank data. This choice seems rather arbitrary, but the pumping cost coef. is so small that changes in the diesel oil price do not change the results.

€$(\mathrm{m\,m^3})^{-1}$. It also remains to specify the non-stationary part of the water demand, $a(t)$. This allows capturing the increase of the water demand observed in the NWSAS area during 1950-2000. The total groundwater consumption over this period (see column 3 in Table 3 or Fig.3) largely suggests the use of a logistic function given by $a(t) = a_0 + \frac{a_1}{1+a_2 e^{-rt}}$.

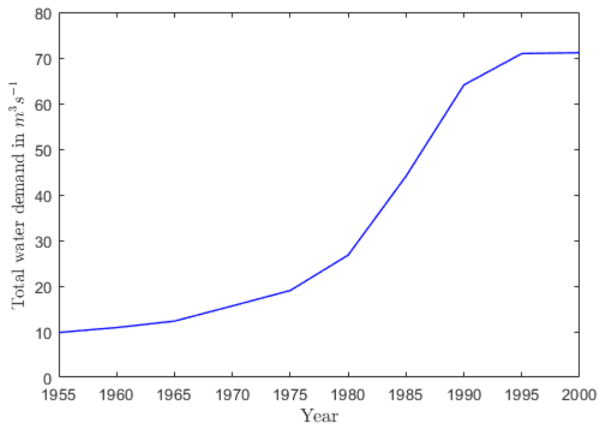

Figure 3: Total Groundwater consumption over 1950-2000

Consequently, four new parameters (a_0, a_1, a_2, r) need to be estimated in addition to the other parameters (b, k_I, k_T). All these parameters are needed to characterize the pumping levels, $w_i\,(h_I, h_T, t)\; i \in \{I, T)$ (see Eq.(14)), which also depend on the piezometric levels of the CI and the CT reservoirs. We will use the set of data in Table 3 to estimate these parameters by solving a nonlinear multi-curve fitting problem based on least-square minimization. As we only have a few data and we know that this estimation method is sensitive to initial conditions, we run a set of 500 estimates using Matlab with randomly chosen initial conditions, and we select the set of parameter values that provides the best curve fit outlined in Fig.4:

Table 5 summaries the estimation of the different economic parameters.

Symb.	Values	Symb.	Description	Values
Drift of the demand		b	Slope of the demand	$51.721(\mathrm{m^3})^2$ €$^{-1}\,\mathrm{s^{-1}}$
a_0	$116.445\,\mathrm{m^3\,s^{-1}}$	c	Coef. of the lift cost	$7.944.10^{-5}$ €$\mathrm{m^{-1}\,m^{-3}}$
a_1	$557.19\,\mathrm{m^3\,s^{-1}}$	k_I	Coef. of the quad. cost (CI)	0.4108 €$(\mathrm{m^3})^{-2}$
a_2	1176.8	k_T	Coef. of the quad. cost (CT)	0.2546 €$(\mathrm{m^3})^{-2}$
r	$0.241\,\mathrm{t^{-1}}$	γ	Rate of return flow	0.15

Table 5: Estimates of Economic parameters

5. Results

The calibration of the parameters is now used to simulate the evolution of the NWSAS after the period 1950-2000. We proceed in two steps. We first discuss changes in the

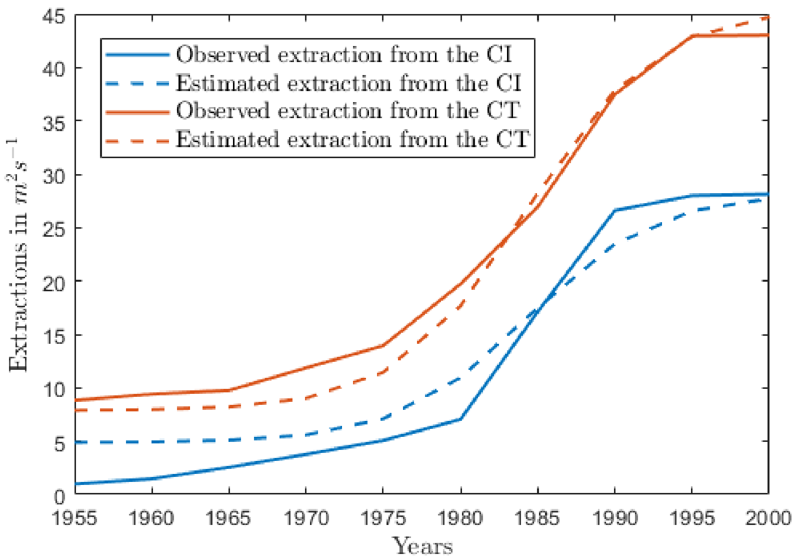

Figure 4: Observed and estimated water extraction paths

piezometric levels of the CI and the CT with the subsequent effects on the natural discharge of both aquifers and vertical fluxes. We then address the question of the sustainable exploitation of this aquifer system.

5.1. On the evolution of the hydrological system

We first characterize the time trajectories of the piezometric levels of both reservoirs, the CI and the CT. Plugging parameter values of Tables 4-5 in the dynamic system (16), we get the following differential system:

$$10^8 \begin{bmatrix} 5.063 & 0 \\ 0 & 4.721 \end{bmatrix} \begin{bmatrix} \dot{h}_I(t) \\ \dot{h}_T(t) \end{bmatrix} = \begin{bmatrix} 79.181 \\ 386.29 \end{bmatrix} + 10^{-2} \begin{bmatrix} -3.3185 & 3.3013 \\ 3.3039 & -3.3249 \end{bmatrix} \begin{bmatrix} h_I(t) \\ h_T(t) \end{bmatrix}$$
$$- \frac{1}{1 + 1176.8 e^{-0.241t}} \begin{bmatrix} 23.351 \\ 28.522 \end{bmatrix} - \begin{bmatrix} 0.084 & 0 \\ 0 & 0.46 \end{bmatrix} \begin{bmatrix} \max\{h_I(t), 857.02\} \\ \max\{h_T(t), 812.12\} \end{bmatrix} \quad (18)$$

The first linear part of this equation mainly reflects the effect of the recharge, the leakance, and the pumping activity (net of the return flow) on the piezometric levels. The non-autonomous term captures the exogenous evolution of the water demand during the period, while the last non-linear term reflects the potential regime shifts induced by the interruption of the two aquifers' natural leakage. By setting the initial conditions to the almost natural piezometric levels observed in 1950 (see conditions (17)), we find a numerical solution to this system using Matlab, which are depicted in Fig.5. We easily observe a significant decline in the two piezometric levels after the mid-1970s. This is consistent with the intensive use of the NWSAS, which started in the same period (see Fig. 4). Such an increase in the exploitation of the system has caused a significant drop in the piezometric levels over the observation period (1950-2000: The CI lost approximately 30 meters and the CT 20 meters.

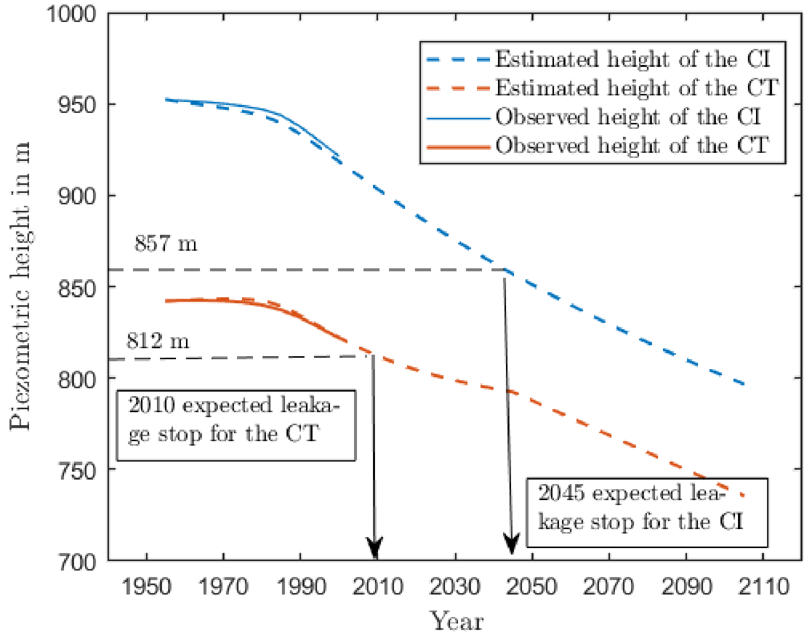

Figure 5: Evolution of the piezometric levels in the NWSAS

If extraction behavior follows the trend observed over 1950-2000, we may expect a further decline. Under the logistic assumption, we can characterize the time trajectories of pumping as follows:

$$\begin{bmatrix} w_I(t) \\ w_T(t) \end{bmatrix} = \begin{bmatrix} 4.2092 \\ 7.2030 \end{bmatrix} + \frac{1}{1+1176.8e^{-0.241t}} \begin{bmatrix} 23.3510 \\ 37.6765 \end{bmatrix} + 10^{-4} \begin{bmatrix} 1.8526 & -0.13075 \\ -0.13075 & 2.9090 \end{bmatrix} \begin{bmatrix} h_I(t) \\ h_T(t) \end{bmatrix} \quad (19)$$

Such exploitation will lead to a drawdown of approximately 150 meters and 100 meters of the piezometric levels of resp., the CI, and the CT, over 1950-2100. Moreover, no steady state appears to be reachable.

Furthermore, we even observe in Fig. 5 that the piezometric levels fall below the CI and CT leakage thresholds. Our model, based on average piezometric levels, suggests that the natural discharges of the CT will dry up after 2010, a situation we locally observed with depleted wells. The discharge of the CI should also be completely dried up in 2045, as we can notice in Fig.6. As soon as the CT reservoir became intensively used, natural leakage sharply declined after a period of the increase until the mid-1970s. This thus suggests that intensive pumping has caused this issue. This is less obvious for the CI. The leakage has diminished since 1950, while this reservoir has been exploited later than the CT. This primary results from a natural process. Indeed, we easily observe that the piezometric level of the CI is always higher than that of the CT. As the vertical fluxes are driven by the differential in the piezometric levels, the CI always feeds the CT. As such, the piezometric level of the CI

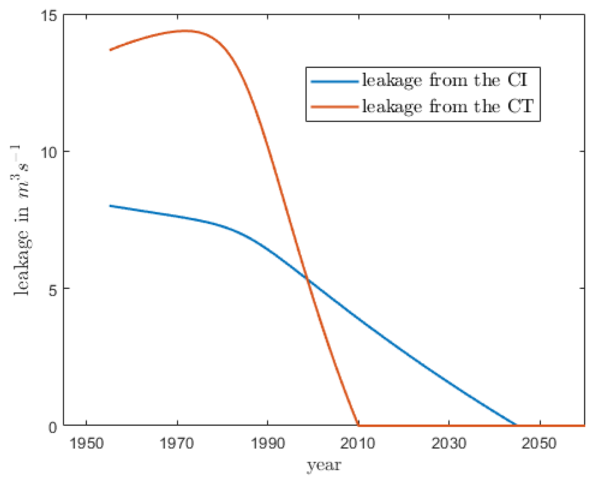

Figure 6: Evolution of the leakages

declines and the natural discharge. As pumping rates have started increasing in the early 1980s, we nevertheless observe a higher decline in the natural drainage of the CI. Even if the decline is slower, natural discharges from the CI should also be dried up. Thus, we can assert that all the remaining natural outlets of the NWSAS are now at risk, with potentially irreversible damage for the downstream users, especially the Saharan ecosystems that benefit from this water.

Declines in piezometric levels finally alter vertical fluxes. Fig. 7 shows that leakance from the CI toward the CT has always decreased. We can distinguish three phases. Over

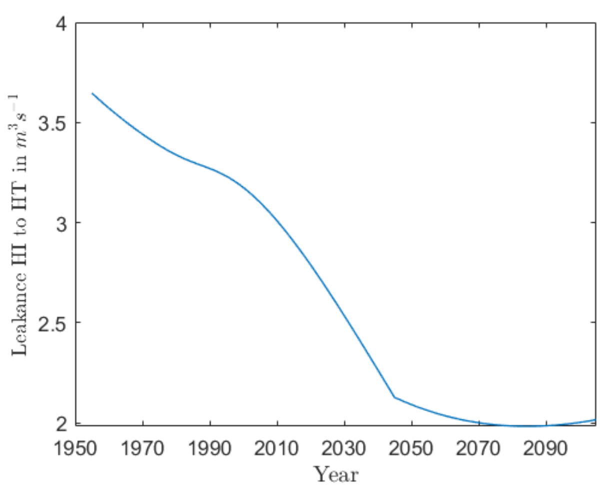

Figure 7: Evolution of the leakance CI->CT

1950-1990, we observe a steady decline since the differential in piezometric levels decrease. This is not so surprising because the piezometric level of the CI declines faster than the level of the CT (3). Indeed, a higher level of water flows out of the reservoir (6). The second phase is characterized by a sharp drop in leakance. This more or less corresponds to the period of the intensive use of the CI and should finish when there is no natural drainage anymore. During this period, the piezometric level of the CI should decline more rapidly than that of the CT, leading to decrease in the differential of both levels, and consequently the level of vertical exchanges of water. The third and last phase is characterized by a stable level of leakance. This thus means that both piezometric levels are decreasing at the same rate.

This last comment calls for greater attention. Indeed, the time evolution of the two piezometric levels results from different levels of inflows and outflows. Typically, the less naturally replenished reservior (the CI) feeds the reservoir that receives the higher level of natural recharge (the CT). Moreover, the CT reservoir receives part of irrigation water, that is, another amount of water extracted from the CI. A perusal analysis of the water balances should thus provide interesting information on the degree of over-exploitation of each reservoir.

5.2. Evolution of the water balances

We now turn to the analysis of the water balance of the NWSAS and that of each reservoir. This allows assessing whether an aquifer is over-exploited by contrasting aquifer inflows with outflows. At the global scale, we will thus compute all water inflows, that is, the sum of pumping net of return flows and natural discharges, to compare with the sum of the two natural recharges. Fig.8 shows that the exploitation of the NWSAS is unsustainable. Total pumping, which was in the mid-1070s far below the total recharge of the NWSAS,

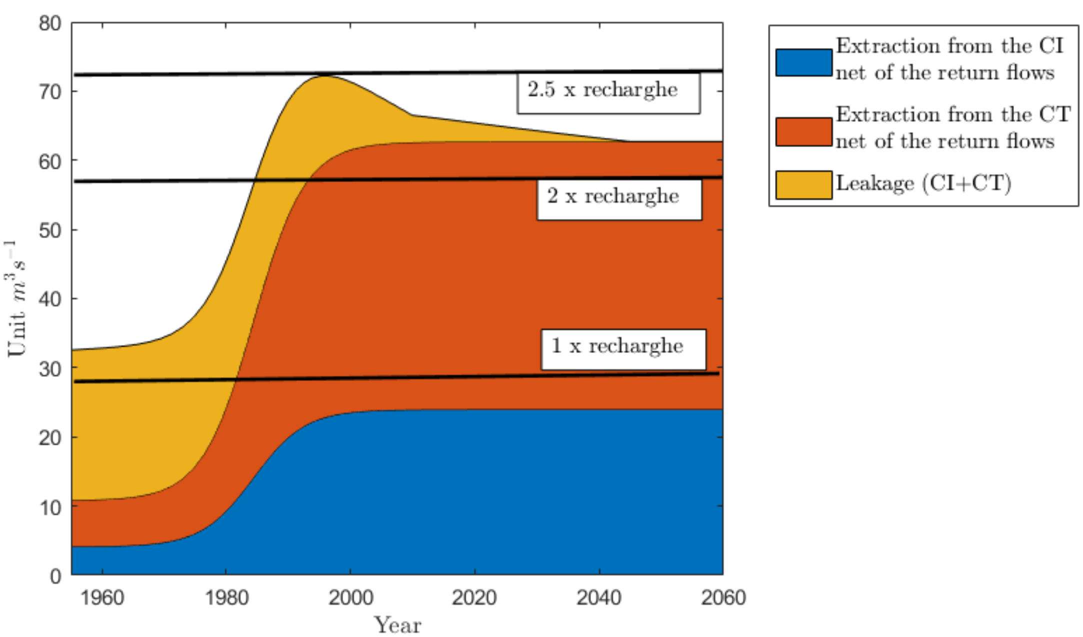

Figure 8: Global water balance of the NWSAS

increased in the late 1990s to twice the recharge so that the total water outflows peak at 2.5 times a recharge. Today, total pumping appears to reach a steady-state at $62m^3s^{-1}$ and total water outflows even decrease due to the gradual disappearance of natural discharges. However, this potential stabilization of water withdrawals is still largely unsustainable as the total recharge is $29.6m^3s^{-1}$.

However, the global analysis hides the heterogeneous situation of both reservoirs. Indeed, water imbalances are larger in the CI than in the CT. This mainly comes from leakance and return flows. Fig.9 shows that an amount equivalent of three times the recharge runs out the reservoir at the end of the nineties. We easily observe that pumping has drastically increased from $5m^3s^{-1}$ in the mid-1970s to an, a priori, stable level at $28m^3s^{-1}$, nowadays. We even know that a minimum amount of $2m^3s^{-1}$ flows to the CT reservoir, and the natural discharge only stops in 2045. Given that the natural recharge is approximately $11.8m^3s^{-1}$, we easily understand that the stock of the CI is tapped. More precisely, the peak water outflows arose approximately 2000 and were well above the triple of the recharge. Even when all springs are dried up by about 2050, the volume of outflows (pumping and leakance) will continue to be more than two and half times the recharge.

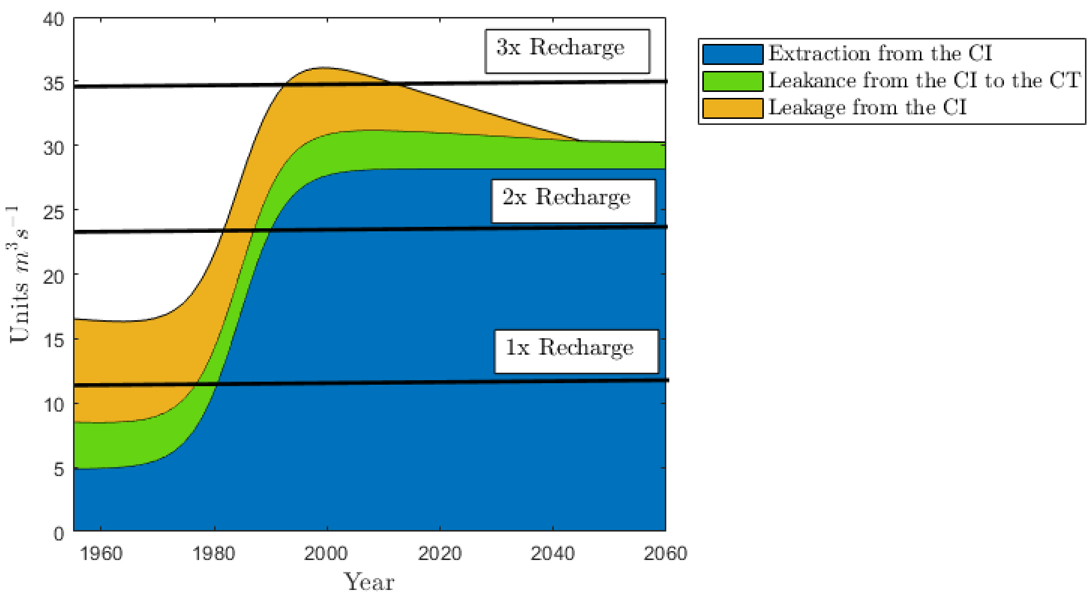

Figure 9: Water balance of the CI

The situation of the CT is less obvious because the reservoir is refilled by return flows and drainage from the CI. Water imbalances are slightly acute. Fig.10 summarizes all the outflows in the positive quadrant and all the inflows in the negative quadrant (except the natural recharge). We can first observe that the pumping level was multiplied by a factor of 4.5 from the mid-1970s to the present. We also know that there is no natural drainage anymore. This improves the balance at, of course, a certain environmental cost. Meanwhile, inflows always come from the CI because of the positive differential in the piezometric levels.

As the CT is the upper reservoir, the majority of return flows reach the reservoir. In addition to the natural recharge of $18.2 m^3 s^{-1}$, the CT will collect in the next 40 years a water inflow, on average, of $13.5 m^3 s^{-1}$. This reduces the pressure on water stock. Nevertheless, total outflows remain larger than twice the recharge.

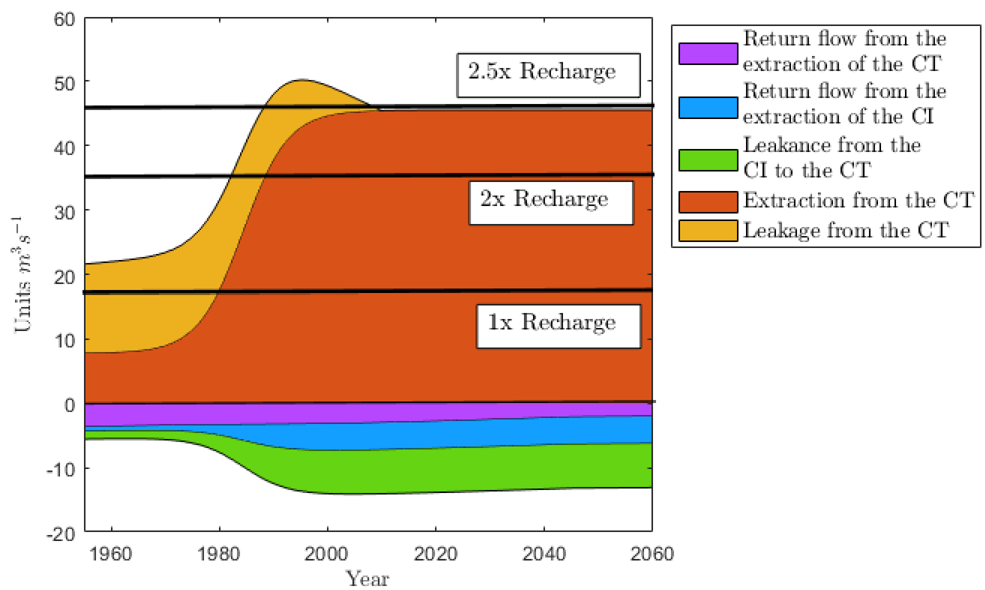

Figure 10: Water balance of the CT

6. Concluding remarks

This study contributes to the literature on applications of HEMs. We studied the state of groundwater resources in the NWSAS, a multilayer aquifer system, which has been intensively exploited for several years. We developed a theoretical model to represent specific features of that groundwater basin and provided a numeric simulation based on a calibration of the different parameters. To construct this model, we borrowed several elements of the hydrologic analysis of the NWSAS (e.g., Baba Sy [3], Gonçalvès et al [22],[23]. Based on these results, we first specified water dynamics for each reservoir, but we accounted for the existence of vertical water flows between layers. In a second step, inspired by the economic literature that tests the robustness of the Gisser-Sanchez effect (e.g., Brill and Burness [8], Tomini [53]), we adopted a growing demand to capture the development of agricultural activity in the region and population growth. Moreover, we introduced a more general cost function to account for pumping costs and other costs associated with water delivery. In a numerical simulation of this integrated model, we highlighted sharp declines in piezometric levels, as well as natural outflows. We especially showed that all outflows will be dried up in a short horizon. We also showed that the actual groundwater exploitation regime is far to be sustainable in the long run.

Even if we do not characterize the optimal use of such a system, we observe that intensive exploitation causes several environmental issues, especially a change in the resource regime since leakages disappear in short term as piezometric levels drop. This thus causes stress on groundwater-dependent ecosystems, local populations, and agriculture. Such observations associated with an unsustainable exploitation regime call for public policies to adequately use water from the ground and protect natural outflows.

Nevertheless, we did characterize the optimal policy to measure benefits from intervention the impacts induced by other property rights regimes. Therefore, it would be interesting to extend this analysis to design socially-optimal exploitation of the NWSAS. This will allow us to examine whether natural outflows will be dried up, especially if the social planner considers damages on ecosystems. As the resource is shared in three countries, it would also be interesting to consider strategic externality and wonder how to design cooperation to help the ongoing cooperative process. Finally, we consider a schematic representation of the entire domain. We could also consider spatial heterogeneity as some areas have only access to one reservoir.

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