A multiobjective discrete stochastic optimization approach to shared aquifer management: Methodology and application

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[1] Negative effects from groundwater mining are observed globally. They threaten future supply locally. Especially in semiarid to arid regions, where aquifers are the sole freshwater resource, this is problematic and can lead to an excessive rise of provision costs. Proper resource management in such environments is crucial. In many instances, however, aquifers are common property resources. In such cases and depending on resource characteristics and the nature of competing uses, their management is inherently multiobjective, and benefits from cooperative management are likely to be substantial. This paper presents a methodology for the determination of optimal, cooperative allocation policies in multiojective aquifer management problems. Our model couples a finite difference aquifer model with an economic model that accounts for water provision costs. Discounted temporal installation and pumping and conveyance costs determine the vector-valued objective function. Each of the objectives characterizes the individual present costs over a given time horizon that the corresponding decision makers wish to minimize. Constraint handling is implemented by the option of moving wells. A multiobjective evolutionary algorithm is coupled to the management model so as to approximate cooperative tradeoff policies on the Pareto surface. These solutions can be ranked against existing, noncooperative status quo strategies. Consequently, the simulation-optimization model is applied to the northwest Sahara aquifer system which is used noncooperatively as a resource by Algeria, Tunisia, and Libya. We find that significant capital gains can be achieved by the establishment of intelligent pump scheduling. Since each country could benefit, a strong incentive toward the implementation of such cooperative strategies exists.


1. Introduction

[2] Globally, consumptive groundwater use totals approximately 750–800 km³/year [Shah et al., 2000]. Driven by increasing food demand, irrigated agriculture accounts for 80 percent or more of total withdrawals. Large-scale groundwater depletion nowadays is visible in major regions of the Middle East, South and Central Asia, North China, North America and Australia [Gleick, 2002]. As a consequence, well yields decrease, pumping costs rise and pumped water quality can deteriorate where pollution sources are present. Additionally, related resources such as aquatic ecosystems and soil fertility may become adversely affected [Konikow and Kendy, 2005].

[3] Similar problems exist in the semiarid to arid zones of northern Africa where fossil groundwater is being mined for the provision of irrigation water. In this region, water for desert irrigation is pumped from two aquifers, the intercalary continental (IC) and the terminal complex (TC), that constitute together one of the largest groundwater systems in the world, the northwest Sahara aquifer system (NWSAS). Algeria, Tunisia and Libya together share this transboundary resource. Figure 1 shows a map outlining the NWSAS system boundaries.

[4] The NWSAS is mined and its stock is being run down. Yet, a simple back of the envelope calculation shows that the NWSAS constitutes a resource for exploitative use for many centuries to come. Under the assumption that 10% of the estimated 10,000 km³ water stored in the NWSAS can be extracted in a technically and economically feasible way, reserves will last for more than half a millennium assuming a constant maximum future demand of 500 m³/s. On quantitative grounds therefore the reliance of irrigated agriculture on NWSAS groundwater is not threatened. The scale of the NWSAS and its properties suggest that undesirable consequences from mining will never adversely affect its entire productive potential.

[5] Pursuing purely exploitative strategies for this reason, however, is a fallacy for at least two reasons. First, the rise of marginal extraction costs above an economic limit will cause economic exhaustion long before physical exhaustion. The decrease of the ratio of resource to capital employed is mainly due a general lowering of piezometric...
heads. An end of artesian conditions over parts of the basin imply that water harvesting for free is getting less and less of an option. Second, and related to destorage, a steady increase of salinity has been observed since the 1970s in highly exploited regions. Where boreholes deliver saline groundwater which is no longer suitable for irrigation purposes, a relocation of the pumping sites has to take place. This too can potentially lead to an excessive development of groundwater prices. Thus there exists a clear incentive for the countries to explore optimal management strategies that prevent undesired resource degradation.

It is for the spatial resource characteristics as well as aspects of distribution and location of economic activity to determine the nature of any optimal allocation pattern. In the case of groundwater, the managers have to choose appropriate pumping locations from where the water can be pumped and consequently conveyed to the final sinks, that is, the demand centers. Success or failure of public or private sector water provision facilities depends crucially on the locations chosen for those facilities.

A finite set of wells, as determined by the planners, can supply demand centers with groundwater. Generally, any set of built wells with sufficient capacity connected through an appropriate conveyance network is suited for such purpose. According to the planners preferences and resource as well as capital constraints, they might opt to concentrate a few boreholes locally. Similarly, environmental and capital constraints allowing, it might be preferable for them to spread the demanded quantity regionally over a large number of boreholes. Thus, given individual preferences, each one of the decision makers faces the following set of questions: (1) How many pumping facilities should be located? (2) Where should such facilities be located? and (3) How should local water pumping be distributed over such facilities in time? so as to minimize the associated costs.

Under the assumption that multiple planners try to develop their resource share so as to maximize individual benefits, their objectives become conflicting. In the highly exploited central region of the basin for example, declining piezometry is a composite effect from local pumping and regional, transboundary abstraction. The search for best allocation policies on the catchment scale therefore becomes a multiobjective optimization problem. Between individually best policies, many tradeoff solutions to the allocation problem exist. In fact, each spatial configuration of resource allocation is a trade-off between the individual objectives of the planners involved. Any strategic agreement on a coordination of allocation and subsequent cooperation depends on whether the outcome of such planning is an improvement over the status quo allocation, that is, the payoff for each one of the planners if such agreement were to fail. For each decision maker, the status quo is simply his security level because he can guarantee at most this much simply by never agreeing to any cooperative strategy at all [Binmore, 1994]. Instead of a single optimal allocation policy, a decision-supporting management tool should therefore identify a set of compromise solutions, for which none of the trade-offs contained can be said to be better than the others in the absence of preference information. We denote such set as set of Pareto-optimal policies. The Pareto surface and its shape in the objective space is determined by this set.

There is an apparent lack of general management tools, that allow consistent analysis of geographically distributed allocation policies within fragmented political economies [Dinar, 2004]. To address this issue, a compre-
hensive approach to multistakeholder decision making with regard to common property groundwater resource allocation is presented in this paper. We propose a formulation based on search before decision making; that is, optimization is performed without any preference information given (see Hwang and Masud [1979] for alternative approaches). The result of the search process is a set of Pareto-optimal candidate solutions from which the final choice of an allocation policy is made by the decision makers involved.

After a review of related work in section 2, the simulation model methodology is presented in section 3. It includes the option of moving wells based on a heuristics that mimics well relocation in response to constraints. Subsequently, the coupling of this model with a multi-objective evolutionary algorithm is described in section 4. We demonstrate the practical applicability of the approach using the NWSAS management problem in section 5. Model results and policy recommendations are finally discussed in section 6.

2. Related Work

The generation of a Pareto-optimal set of policies to a multiobjective optimization problem can be achieved by utilizing classical methods such as the weighting method, the constraint method, goal programming and the minmax approach. Their underlying basic principle is the aggregation of the objectives into a single, parameterized objective function by analogy to decision making before search. However, difficulties may accompany classical optimization strategies. Some techniques, for example, the weighting method where a positively weighted sum of objectives is minimized, may be sensitive to the shape of the Pareto surface. That is to say that they are not able to produce all Pareto-optimal solutions in case of nonconvex trade-off surfaces. Furthermore, problem knowledge may be required which may not be available in the case of large and complex search spaces. Deb [1999] mentions further application areas where their use is restricted. Moreover, classical methods all have in common that they require several optimization runs to obtain an approximation of the Pareto-optimal set. As the runs are performed independently from each other, synergies can usually not be exploited which, in turn, may cause high computation overhead.

Recently, evolutionary algorithms (EA) have become established as an alternative to classical methods through which (1) large and complex search spaces can be handled and (2) multiple alternative trade-offs can be generated in a single optimization run. Furthermore, they can be implemented in a way such that both of the above mentioned difficulties are avoided [Zitzler, 1999].

In the simulation-optimization groundwater literature, there exist several examples of the application of stochastic optimization techniques that are inspired by evolutionary principles to nonlinear, discrete-continuous groundwater management problems [Dougherty and Marryott, 1991; McKinney and Lin, 1994; Rogers and Dowla, 1994; Wang and Ahlfeld, 1994; Wang and Zheng, 1997; Zheng and Bennett, 2002]. None of the above studies, however, uses these recent optimization techniques in a context of multiple, conflicting objectives. The paper by Erickson et al. [2001] where the authors investigate pump-and-treat strategies to remove the most contaminant at the least cost within a small well catchment is a notable exception. In all of the cited studies, the genetic algorithm solution compares favorably with the solution found using the gradient-based methods.

3. Formulation of Management Model

3.1. Simulation-Optimization Model

The simulation-optimization model presented here is multiobjective with a problem-dependent number $m$ of deterministic cost objectives to be minimized. The number of objectives is equal to the number of decision makers involved. Present water provision costs are associated with a resource allocation policy by the coupling of a finite difference groundwater model with an economic valuation approach. Facility and pipeline installation costs as well as pumping and conveying costs are taken into account on the supply side. The model involves both, discrete (i.e., well location and time schedule of pumping) and continuous decision variables (well yields and state variables), subject to conditions which any feasible solution must satisfy.

Water is assumed to be conveyed in directed networks from source locations, that is, the wells, to corresponding sinks, that is, the demand centers. The option of moving wells is implemented in case of constraint violations. Drawdown as well as gradient constraints are respected. Finally, territorial restrictions such as political boundaries within a catchment can be represented according to strategies pursued (e.g., cooperative, noncooperative, etc.).

The optimization goal is to minimize the $(m \times 1)$ vector valued cost function $f(q, h, \cdot)$ whose components are defined by equation (6), subject to

$$h(t) \geq h(lb)$$

$$\nabla h(t) \geq 0$$

$$\sum q_{m}^n(t) = Q_{m}^n(t) \quad \forall \ m, t$$

where $q$ is the $(I \times T)$ decision matrix of pumping with $I = \sum_{m} \sum_{i} I_{m}^{i}$ being the total number of boreholes becoming active from time $t = 0$ to $t = T_{end}$ with $q$, the allocation policies by decision makers are described. $f(q, h, \cdot)$ is the vector of the summed present costs from $t = 0$ to $t = T_{end}$. Equation (1) is head, gradient and pumping constraints and define the set $\Theta$ of feasible decision matrices $q$ and states $h$. More precisely, if $h_{m}^{n}(t)$ is the head at location $x = L_{m}^{n}$ at $t$ as calculated by the solution of equation (3), then $h_{m}^{n}(lb)$ denotes the drawdown constraint at that particular place.

$$\nabla h(t) \geq 0$$

are gradient constraints where applicable. The gradient constraint criteria can be thought of being head constraint criteria in the Moore neighborhood (with range $r = 1$) of potential sources of salination. Finally, $Q_{m}^n(t)$ at time $t$ is the total water quantity demanded by the $n$th decision maker that controls the $n$th demand location $x = D_{m}^{n}$. $\sum q_{m}^n(t)$ indicates that at time $t$, this quantity is supplied by the $i$ boreholes that deliver water to $x = D_{m}^{n}$.

The optimization task is to find a set $\Theta^* \in \Theta$ of Pareto-optimal location allocation policies $q^*$ in the sense that an improvement in one cost component of $f(q^*, h^*, \cdot)$ can be achieved only at the expense of another. Here, we assume that the costs represent a magnitude which the
decision makers, according to their value judgment, wish to minimize. In mathematical terms, we seek to find
\[ \Theta^* := \{ q^* \in \Theta : f(q^*, h, \cdot) < f(q^*, h, \cdot) \} \]  
(2)
with \( \Theta^* \) being the set of tradeoffs on which future discussions on the common utilization of the groundwater resource under consideration can be carried out.

3.2. State Model

[17] The hydraulics of groundwater flow in an aquifer is governed by the following diffusion-type equation
\[ \nabla \cdot (m(x)K \nabla h(x,t)) + q(L,t) = S \frac{\partial h(x,t)}{\partial t} \]  
(3)
where \( K \) is the spatially variable hydraulic conductivity, \( m(x) \) is the saturated aquifer depth obtained from \( m(x) = h(x,t) - b \) with \( b \) being the aquifer bottom. \( q(L,t) \) are source and sink terms such as pumping rates at specific locations \( L \). \( S \) is the spatially variable storage coefficient and \( h(x,t) \) the piezometric level at a certain time \( t \) and location. Equation (3) is a second-order partial differential equation for the unknown head distribution as a function of time and location. It is defined in a domain \( \Omega \) with boundary \( \Gamma \) and subject to the initial conditions
\[ h = h_0 \quad \text{in} \quad \Omega \quad \text{at} \quad t = t_0 \]  
(4)
and boundary conditions
\[ T \frac{\partial h(x,t)}{\partial n} = c(h - h(x,t)) + Q \quad \text{on} \quad \Gamma \]  
(5)
where \( H \) is the prescribed head of an external source such as a stream or lake. Finally, \( Q \) is a prescribed flux on the boundary.

[18] In order to find a solution of equation (3) for a particular problem, the relevant physical coefficients (i.e., \( S \) and \( T \)), the domain geometry as well as initial and boundary conditions have to be provided. Except for very simple geometries, analytical solutions are difficult to obtain. Therefore numerical methods are applied to approximate such solutions [De Marsily, 1986]. One such approach is the finite difference method in which the continuous system is replaced by a regular grid of discrete points in space and time and the partial derivatives are replaced by terms calculated from the differences in head values at these points. The process leads to a coupled system of linear algebraic equations and their solution yields the head values at specific locations and times.

[19] The drawdown calculated by the finite difference method in a regional model is an averaged value over the cell and does not correspond to the actual drawdown that is observed around actual wells. Therefore the piezometric heads were corrected by a term derived from the Thiem formula [Prickett and Lonnquist, 1971].

3.3. Economic Model

[20] The objective function is a \((M \times 1)\) vector \( f(\cdot) \) of discounted present costs with \( 1 \leq m \leq M \). More precisely, the \( m \)-th entry of \( f(\cdot) \) can be expressed as
\[ f_m = \sum_{n(m)} f_n = \sum_{n(m)} \sum_{i} \frac{1}{(1 + \delta)^{t - t_0}} g(q^m_{n}(t), h^m_{n}, t) \]  
(6)
and denoting the summed present costs over all directed networks \( n(m) \) that are within the control of the \( m \)-th decision maker. \( t_{end} \) is the planning horizon. Note that \( g(q^m_{n}(t), h^m_{n}, t) \) are current costs. \( \delta \) is the discount rate. \( t' \) is the time of construction of a particular borehole \( r_{m} \) together with its associated conveyor. Hence, if \( t' = 0 \), then that particular borehole is in operation from the beginning of the simulation. Conveyor costs were related to pumping wells \( r_{m} \) in a simple manner. These costs were added to the corresponding borehole costs of the installations that are located at the origin of each corresponding conveyor in flow direction.

[21] For each decision maker, the costs \( g(\cdot, t) \) are composed of fixed costs and running costs (see Appendix A for a definition of \( g(\cdot, t) \)). The former occur at time \( t' \) and are proportional to the conveying distance and the borehole drilling depth. The latter are the costs of the energy required to lift and convey water to the final sinks. These costs vary nonlinearly in dependence of the well pumping rates \( q^m_{n}(t) \) and the conveyed water volumes. As functions of particular location, running costs might be noncontinuous because of possible constraint infringements and the switching on and off of pumps.

3.4. Conveyance Infrastructure Model

[22] Evolutionary stochastic optimization methods work on a population of realizations, also called individuals (see section 4). Each feasible realization \( r \) consists of a given number of demand locations \( D^m_n \) with \( n = 1 \ldots N \) and \( n \geq m \) and an arbitrary spatial configuration \( L \) of an arbitrary number \( I \) of pumping wells situated within the catchment domain \( \Omega \). If \( n = m \) each decision maker has to provide water to exactly 1 demand center. It is assumed that water is conveyed from individual wells to demand centers by directed networks. Each such network is described by a set of arcs \( a^m_n \). Hence, for each realization \( r \), \( \Sigma_m n(m) \) directed networks have to be identified. Subsequently, pumping is randomly distributed over the wells so that the quantity constraints for each demand center are fulfilled.

[23] An algorithm for the determination of the conveyance infrastructure contains the following steps.

[24] 1. Network membership identification, \( L \rightarrow \mathcal{L}^m_n \).

[25] 2. Creation of network topology \( a^m_n \) for each \( n(m) \) \( \forall m \).  

[26] 3. Determination of \( q^m_n(t) \) for each \( \mathcal{L}^m_n \) \( \forall m \).  

[27] Given that each well can only serve one demand center, \( \mathcal{L}^m_n \) is determined by \( k \) means clustering which partitions the set of wells into \( \Sigma_m n(m) \) mutually exclusive clusters. Each cluster in the partition is defined by its member objects and by its centroid \( c^m_n \). The centroid for each cluster is the point to which the sum of distances from all objects (including the distance \( D^{m}_{n} c_{n}^{m} \) in that cluster is minimal.

3.5. Constraint Handling

[28] An infrastructural change in existing well configurations at a certain point in time may be necessary because of drawdown, quality or capacity constraint violations and installation failures at certain locations. One possible way to deal with constraint violation are methods based on penalty functions. Approaches incorporating these penalties suffer from two problems. First, the optimal set of solutions \( \Theta^* \) depends on the magnitude of the penalty. Users normally have to try different penalty magnitudes to find a value which steers the search toward the feasible region. Second, the inclusion of a penalty term may critically distort the
objective function. In order to avoid such problems, an adaptive pumping heuristics is implemented here that does not necessitate penalties.

Let us denote boreholes where a constraint violation occurs at time \( t \) with \( \mathcal{L}_{m,i}(t) \). In such cases, the affected boreholes have to be switched off so that the drawdown constraints as defined by equation (1) are no longer violated. After such a termination of operation, however, the demanded quantity \( Q_{m,i}(t), t > t \) has to be redistributed over the remaining pumping stations \( \mathcal{L}_{m,i}(t) \) with \( i \neq i \). Unless offset by decreasing overall demand, pumping rates at boreholes in operation consequently rise as more and more wells have to be switched off because of the lowering of the piezometric levels at increasingly fewer places. In the most extreme case, this would lead to a final concentration of pumping at one particular place while \( t \leq T_{\text{end}} \). Converse to that, any real-world allocation policy would allow for constraint violating wells to be temporarily switched off and replaced by alternative pumping locations. These are installed to backup lacking supply. We refer to this replacement as moving wells.

The constraint handling heuristics has two aspects. First, it relocates pumping at a particular location \( \mathcal{L}_{m,i} \) once a specific constraint is no longer fulfilled there. Relocation takes place in the direction of the steepest ascent, \( \nabla h(x, t) \). The displacement distance is assumed to be proportional to \( |\nabla h(x, t)| \) which also defines the range \( r \) of the Moore neighborhood within which displacement is possible. If the direction of steepest ascent is ambiguous, the decision with regard to direction is randomly taken ensuring that the displacement distance is minimal within the given Moore neighborhood. After relocation, the new boreholes will be conveying water to the switched off parent location and from there on route the water into the existing conveyance network. Second, deactivated boreholes can become active again if constraints are no longer violated, that is, head recovery at \( t_{\text{end}} \) is observed (see Wang and Ahlfeld [1994] for a different implementation of such well relocation).

The dynamic expansion of the pumping and conveyance infrastructure of a particular realization is portrayed in Figure 2 which shows a sample run over 50 years of pumping in a confined aquifer.

### 3.6. Characterization of Allocation Policies

Dimensionless analysis can be used to characterize spatial network configurations and the state of the aquifer at

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**Figure 2.** Simulated piezometric contour lines from \( t = 1 \) year to \( t = T_{\text{end}} = 50 \) years in a sample aquifer domain and (bottom right) development of \( \zeta \) (equation (9)). The drawdown patterns emerge from a random initial well placement and the subsequent relocation of pumping during simulation forced by drawdown constraint violations. Note that formerly switched off boreholes can become active again after drawdown recovery (indicated by the arrows).
a certain time $t$. Equations (7)–(9) define a set of such possible numbers.

\begin{align}
\zeta_1 &= \frac{\lambda_n m}{\sigma m} \\
\zeta_2 &= \frac{A_m d_m}{q_{tot}t} \\
\zeta &= \frac{\zeta_1}{\zeta_2} = \frac{\lambda_n m q_{tot}t}{A_m d_m^2}
\end{align}

where $\lambda_n m$ is the sum of all $\frac{(j-1)i}{2}$ distances between the $i$ boreholes that are members of a pumping cluster $m(m)$ and are pumping at a certain time $t$, $A_m$ is the area inside the convex hull defined by the active boreholes within a cluster, $d_m$ is the average drawdown in the pumping cells of the cluster compared to steady state, $q_{tot} = \sum_i \sum_q q_n(t)$ is the volume of water pumped from $t_0$ to $t$. $\zeta_1$ relates the network length to an average observed (or computed) drawdown over the cluster. The area spanned by the convex hull divided by an averaged measure of the spread of the drawdown cone defines $\zeta_2$. It is straight forward to define a third dimensionless number $\zeta$ that contains information of both, $\zeta_1$ and $\zeta_2$.

[33] For the sake of illustration, let us design 50 random pumping network realizations in the same aquifer domain. The number of operating boreholes, their location as well as pumping may vary, the overall pumped quantity $q_{tot}$ being fixed. Looking at the statistics of such ensemble, the average borehole to borehole distances within the clusters vary from a minimal 5.82 km to a maximal 57.53 km with a standard deviation of $\sigma = 10.11$ km. Similarly, the average drawdown at the pumping locations varies between 7.9 m in the case of a lot of active boreholes and 67.4 m in the case of few pumping wells with $\sigma = 10.33$ m.

[34] Figure 3 shows the corresponding configurations for minimal and maximal values of $\zeta_1$, $\zeta_2$ and $\zeta$. Generally, a low $\zeta$ means few boreholes start in a spatially concentrated configuration and cause a local drawdown cone of considerable depth. Similarly, a big $\zeta$ indicates a widespread allocation pattern with low pumping intensity at the wells, causing the piezometry to fall more homogeneously over the extent of the cluster. Since $\zeta$ contains information from both, $\zeta_1$ and $\zeta_2$, we utilize $\zeta$ as a descriptive of allocation policies.

[35] With $\zeta$, the dynamics of a particular network cluster and the associated development of the aquifer state can be conveniently described. An abrupt change of $\zeta$ indicates configuration changes in the number of operating wells from one time step to the next. With the spread of the spatial extent of the drawdown cone $A_m$ over time, $\zeta$ increases correspondingly (see bottom right plot in Figure 2).

4. Optimization Method

[36] The EA models the evolution of a population of individuals through successive generations using three probabilistic operators: reproduction, crossover, and mutation. We refer to these as variation. The reproduction process serves to retain those policies with high fitness (i.e., favorable objective $f(q, h, \cdot)$) whereas the cross over operator seeks to improve the design by combining the high-fitness policies. The mutation operator finally protects against convergence to a local minimum by adding random noise. The effect of these operators is that designs with high fitness will persist as the management policies evolve from one generation to the next.

[37] For the approximation of the set of policies $\Theta^*$, we utilize the recent multiobjective elitist EA SPEA2 [Zitzler et al., 2002]. SPEA2 works on a fixed population size of individuals. Their characteristics are stored in an archive and subject to change according to the individual’s quality or ‘fitness’ as calculated by the EA as function of $f(q, h, \cdot)$. SPEA2 uses a fine-grained fitness assignment strategy which incorporates density information so as to avoid crowding on the Pareto surface. Figure 4 shows the structure of the EA in a schematic fashion. The variation creates new offspring individuals out of the set of parent individuals $\xi$ that were chosen for mating during the process of mating selection. Subsequently, according to the offspring’s pumping policies, the state, that is, the development of the piezometric head $h$, and the objective vectors are calculated. On the basis of that, the environmental selection then determines whether offspring individuals will be stored in the archive or discarded. This process is repeated until a termination criterion is met.

[38] The mutation operator for the problems discussed can be implemented in many different ways [see Dougherty and Marryott, 1991, and references therein]. Mutation, as understood here, has 2 aspects: (1) mutation of the spatial location of selected wells and (2) mutation in time of the pumping rates of selected wells. The principle of location mutation is the following. The easting and northing ($x, y$) of a set of randomly chosen wells get mutated according to $(x', y') = (x, y) + (\Delta x, \Delta y)$ if $(x', y') \in \Omega$ with $\Delta x(\mu = x, \sigma^2)$ and $\Delta y(\mu = y, \sigma^2)$ being random numbers. The standard deviation $\sigma^2$ is a user specified measure of the magnitude of mutation.

[39] Mutation in the pumping rate adds random disturbance to the distribution of pumping within a directed network at a certain time $t$. Wells are randomly chosen for mutation if $p_{mu}(t) < p_{mu}$, where $p_{mu}(t) \in [0, 1]$ is a random number assigned to each active well $L_{n,i}$ at time $t$ and $p_{mu}$ is a user defined mutation threshold. If for all wells and all times $p_{mu}(t) > p_{mu}$ and if there is no crossing over, then
variation becomes a simple reproduction. The change in pumping rate at a particular well needs to be counterbalanced by a corresponding change in the remaining locations chosen for mutation so as not to violate the demand constraint \( S_i q_n \). Therefore, if the list of well locations to experience pumping rate mutation contains less than two entries, no such mutation takes place.

The crossover operator is a method for sharing information between individuals; it combines the features of two parent individuals to form two offspring with the possibility that good individuals may generate better ones. The type of the problem suggests the implementation of a simple crossover algorithm which has been proposed by Wright [1991].

If two realizations, that is, parent individuals \( r_1 \) and \( r_2 \), have been selected for crossing over, they swap randomly chosen directed networks. More precisely, they interchange selected supply infrastructure \( K_m \) for similar demand centers \( D_n \). Swapping occurs if \( p(K_m) \geq p_{so} \) where \( p(K_m) \) is a random number between 0 and 1 assigned to each demand center \( D_n \) and \( p_{so} \) is a user specified crossing over probability.

The coupling of the simulation part with the EA is conforming to the platform and programming language independent PISA standards [Bleuler et al., 2003]. This implementation allows the problem-independent selection to interact with the problem-specific variation with minimal overhead.

5. Application

Of the 4,300,000 km² that Algeria, Tunisia and Libya cover together, only 2% receive enough rainfall to sustain agriculture without irrigation. They are located along the coast line which is subject to a moderate Mediterranean climate. More than 80% of the 48.2 million inhabitants of the three countries live within this so-called green belt. The remaining, sparsely populated area is under the influence of the arid/hyperarid Saharan climate. This is characterized by very hot summers, extreme diurnal temperature variations and highly irregular precipitation both in time and space. In the desert and on its fringes, economic activity solely relies on production from irrigated agriculture [World Bank, 2002].

The irrigated area in the Saharan environment has tripled proportionally to the development of the population from 1950 to 2000. In the year 2000, it extended over an area of more than 14,000 km². This extension was made possible by technological transition, that is, the gradual progression from traditional groundwater abstraction by hand dug wells or springs to high-volume abstraction by motor pumps and deep artesian wells.

Agricultural policy in Algeria, Tunisia and Libya, in the last fifty years was largely determined by considerations of food security, self-sufficiency and import substitution practices. In an attempt to avert large-scale migration to urban centers, irrigated desert agriculture which is the economic backbone of the population living in desert stretches was promoted.

Water abstraction from the NWSAS has increased more that fivefold over the last 50 years, from an estimated 15 m³/s in 1950 to approximately 80 m³/s in the year 2000 (48 m³/s in Algeria, 17 m³/s in Tunisia and 15 m³/s in Libya). More than 90% of that quantity pumped is consumptively used for irrigation. Mainly because of these irrigation measures, Algeria and Tunisia increased their...
share of total agricultural output as percentage of total GDP from a marginal 2% in the sixties to more than 15% at the turn of the century. In Libya, it accounted for 5% of the total GDP during the nineties (Food and Agricultural Organization of the United Nations, FAOSTAT agricultural statistical database, 2004, available at http://faostat.fao.org/). All three countries have seen considerable growth of their economy since independence.

[47] Supported by all three countries, a joint NWSAS management program was launched in 1999 under the auspices of the international organization Observatoire du Sahara et du Sahel (OSS). One of the main achievements of the program was the development of a finite difference groundwater model of the NWSAS. However, the above mentioned NWSAS resource model has not been made publicly available. For our purpose and on the basis of published data by the OSS, a finite difference groundwater model of the system was therefore developed (Sahara and Sahel Observatory, Modèle mathématique, unpublished report, 2002, hereinafter referred to as Sahara and Sahel Observatory, unpublished report, 2002). A detailed description of the model development and its calibration can be found in work by Beck [2002].

5.1. NWSAS Finite Difference Model

[48] The two layers, the IC and TC, were modeled. Both are sedimentary aquifers separated by a complex sequence of clay-rich, semipervious layers of the Cenomanian. The structures were formed by clastic and then carbonate deposition that occurred throughout the Cretaceous over much of central North Africa. Both reservoirs were filled with freshwater during the wet Quaternary Period. The IC and the TC are continuous between Algeria, Libya and Tunisia covering an area of more than 106 km² (A. Mamou and A. Hlaimi, Les nappes phréatiques de la Nefzaoua: Caractéristiques et exploitation, unpublished report, 1999). Figure 1 shows their extension. Extensive knowledge of the Algerian and Tunisian part of the system was obtained for the first time 1972 within the scope of an international resource assessment study coordinated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [1972].

[49] In the finite difference aquifer model, the initial cell discretization was chosen to be 25 × 25 km. For later use in the simulation-optimization calculations, a coarser model with cell size 50 × 50 km, which was abstracted from the detailed one, was utilized. Discretization is shown in Figure 5. The aquifer layers were modeled to be partially convertible between confined and unconfined, transmissivity being constant throughout simulation. The incorporation of layer geometry allowed representing the change in storage in case of aquifer conversion from confined to phreatic due to pumping. Aquifer geometry was derived from geological cross sections published by UNESCO [1972] and Pallas and Salem [2000]. Hydrogeological data of the Libyan part of the basin was generally difficult to obtain. It was assumed that the topography corresponds to the top of the TC. The topography was determined by the establishment of a digital terrain model based on GTopo30 images (U.S. Geological Survey GTopo30 Global Digital Elevation Model, 2001, available at http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

[50] A leakage term depending on rock properties and thickness of the separating Cenomanian establishes hydraulic contact between the IC and TC. Drain cells were used to represent the Algerian-Tunisian Chotts, the Fogggaras of the Adrar region in western Algeria and the Libyan spring Ain Tawargha because they adequately reproduce the physical nature of the sinks dewatering the system. At the same time they become inactive once the piezometric heads fall below the drain level.

[51] Leakage and transmissivity zones were determined according to geological aquifer properties. A total of 9 parameters (transmissivity, leakage and drain conductance) were calibrated for the steady state model using data from 1950 (Sahara and Sahel Observatory, Système aquifère du Sahara septentrional: Analyse globale des données hydrogéologiques du SASS, unpublished report, 2000). For the calibration of the transient flow model parameters (storage coefficient and specific yield), data from 1950 to 1970 were available. The comparison of observed versus calculated heads as well as drain yields of springs were used as quality measures. Generally, a satisfactory calibration with no systematic errors resulted with a standard deviation of about 22 m over a head range of approximately 500 m. The reproduction of observed spring yields by the model was generally satisfactory [Beck, 2002].

[52] The nature of the management problem suggests that 2 kinds of constraints are relevant, drawdown and gradient constraints. The former were implemented by setting an absolute drawdown limit. The limited pumping depth reflects the restrictions given by the well screen interval depth. It was, however, difficult to obtain detailed data for...
each region. On the basis of oral communications with the regional as well as national water authorities, we established an average well screen interval depth of 200 m in the TC aquifer. Drawdown restrictions in the IC were chosen similarly except for the central basin where the top of the IC is located at an average of 1000 m below ground. This figure was chosen as restriction there. Gradient restricted cells are only implemented in the TC surrounding potential sources of salinity, that is, the Chotts in the central basin and the Mediterranean sea in the Libyan part of the basin [Siegfried, 2004].

[53] Recent recharge to the system has been recognized in both aquifers, the bulk of it taking place south of the Saharan Atlas in Algeria as well as in the Dahar Mountains in Tunisia [Edmunds et al., 1997]. Those fluxes, estimated at approximately 30 m$^3$/s, are of some importance in the recharge areas with regard to local resource management. However, they are negligible on a basin-wide scale considering the enormous size of the resources stored in relation to the limited spatial extension of the recharge zones. Thence we decided not to incorporate present day recharge which causes our calculations to be conservative.

5.2. Economic Model Data

[54] Depending on location, technology of infrastructure and the market prices of energy, the cost coefficients $C_{IP}$, $C_{IC}$, $c_L$ and $c_T$ can vary spatially and temporarily. For this study, spatially varying per drilling meter tube installation costs $C_{IP}$ have been implemented. They account for the fact that it is more costly to tap the deeper IC aquifer. Figure 5c and 5d show the spatial distribution of the per drilling meter costs and their corresponding values. These are rule of thumb values that have been taken from drilling experiences in Southern Tunisia [Y. Ben Salah and F. Horriche, Direction Générale des Ressources en Eau (DGRE), personal communication, 2002]. Boreholes and conveyors located in remote desert areas such as the Grand Erg Oriental, Grand Erg Occidental or the Hamada el Hamra in Libya are costlier to realize than infrastructure nearby already existing one or easily accessible areas. No rule of thumb values could be obtained from North African water experts for an estimation of per meter conveyance system costs $C_{IC}$. However, a great part of the Saharan desert is difficult to access. In order to penalize solutions in the outback, the values of $C_{IC}$ have been arbitrarily chosen to be one magnitude of order higher in the inaccessible areas (see Figure 5b). Furthermore, it is supposed that the conveying system is uniformly built with regard to material and operational properties and that energy prices do not change over the simulated time horizon $T_{end}$. The latter implies that no technical progress is assumed to take place.

[55] The cost of energy $p_E$ that is related to the terms $c_L$ and $c_T$ is assumed to be constant throughout simulation (see Appendix A). On the basis of price data from Tunisia, it has been chosen to equal 0.1 $/(kWh)$ and to be uniform throughout the basin (see DGRE, Direction etudes et planification, tariffs and statistics, Centrale Eolienne, Sidi Daoud/Cap-Bon, Tunisia, 2001). For all optimization runs, a constant discount rate of $\delta = 3\%$ was assumed.

5.3. Strategic Models

[56] Up to now, no trinational treaty exists that could frame cooperative resource management. Water related legislation in Algeria and Tunisia is largely based on laws introduced by the colonial forces in the first half of the twentieth century and has been continuously developed in response to emerging needs and dangers of growing exploitation. Contrary to that, the colonial legislative heritage in Libya was renounced with the 1969 revolution and a new legislation based on the islamic law, the Shari’ah, was established. In the three countries, groundwater is state owned (O. Salem, Groundwater legislation in Libya, unpublished report, 1996; D. El Batti, Inventaire et analyse de la législation sur les eaux souterraines en Tunisie, unpublished report, 1996; A. Adoum, Législation et réglementation des eaux en Algérie, unpublished report, 1996). However, a joint NWSAS management program was launched in 1999 under the auspices of the international organization Observatoire du Sahara et du Sahel (OSS). As a result, the three countries launched a nonbinding consultation mechanism on the future management of the common property NWSAS resource.

[57] The question now to be answered is, whether gains from the pursuit of cooperative strategies to allocation, given a specific demand, exist and, if so, what these imply in terms of policy recommendations. For this purpose, an alternative strategy is investigated and subsequently ranked against the status quo allocation. For all calculations, the exogenously driven development of demand is similar. Figure 5a shows the water demand locations and Table 1 shows the demand projections. All calculations are carried out over the time horizon of 50 years from the year 2000 to 2050.

[58] The status quo allocation is one where decision makers follow their declarations of intent about the distribution and magnitude of future pumping within national territories over the next fifty years. Starting from the year 2000, development of regional water demand over the next

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Table 1. Development of the Future Regional Demand in the Corresponding Agricultural Centers$^{a}$

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<td>4 and 10: Libyan Coast (TC/IC)</td>
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$^{a}$Values are countrywise projections (Sahara and Sahel Observatory, unpublished report, 2002) and are given in m$^3$/s.
where the left-hand side difference denotes the \( n \)-moving average between the last two entries of the sequence \( S = \{ s_u \}_{u=1}^{N-n+1} \) with

\[
\bar{s}_u = \frac{1}{n} \sum_{i=1}^{u+n-1} g_v(i)
\]

Figure 6. Development of the generational mean present costs \( f_i \) during optimization: \( f_1 \), mean summed present costs for Algeria; \( f_2 \), mean summed present costs for Libya; \( f_3 \), mean summed present costs for Tunisia; \( f_{total} = f_1 + f_2 + f_3 \). 50 years is given in Table 1 for each major agricultural center within the basin. During simulation, each finite difference pumping cell has a predetermined pumping quantity. No infrastructural costs occur at \( t = t_0 \) since pumping and conveyance infrastructure already exist. The development of the overall costs as well as any later change in the system configuration due to constraint violation and subsequent relocation of affected wells is accounted for.

[60] The alternative, subsequently called perpetuation strategy, describes a particular cooperative transboundary management strategy. On the basis of the existing infrastructure, Pareto-optimal allocation policies of pumping are sought. For that purpose, optimization is carried out upon an archive of individuals. Each one of these individuals has a random distribution of \( q_{n,p}^m(t) \) with demand constraints applying as defined by equation (1). Boreholes are allowed to be moved all over the basin irrespective of national borders. Existing infrastructure causes no additional costs at \( t = t_0 \). Only if the random initial pumping quantity assigned to a finite difference cell exceeds the maximum yield of the already built wells, additional borehole construction costs proportional to the number of new wells and \( C_{IP} \) occur.

[61] Sensitivity analysis showed convergence of the objective function and Pareto surface population diversity to be crucially dependent on the archive and mating pool size. A good trade-off between computational demand and optimization quality has been achieved with the following parameter values for the archive size \( \varepsilon = 300 \) and for the mating pool size \( \xi = 4 \).

6. Discussion of Results

6.1. Comparative Analysis

[62] The optimization result proposes a pumping schedule based on locations and aquifers. Pareto-optimal policies of both optimized strategies are characterized by lower mean terminal present values of the objective compared to the status quo (see Figure 8). In average, total present costs of allocation policies under the perpetuation strategy are 78 ± 2% lower (77% for Algeria, 90% for Tunisia and 85% for Libya) compared to the status quo. The mean current prices of 1 m³ of water relative to the status quo are shown in Table 2 for the corresponding years.

[63] Significant capital gains can be achieved by all three countries while following the perpetuation strategy. On average, in the case of the status quo, the costs in the year 2050 for providing one unit of pumped groundwater would be more than 30 times higher than in the year 2000. Contrary to that, the provision costs in the case of the optimized allocation would only rise by a factor of 7 (see Table 3). Quite obviously, this finding should provide a strong incentive to embark on cooperative allocation policies.

[64] Note that absolute costs as provided in Table 3 have to be considered with care for the following two reasons. First, input prices are not well known and absolute costs clearly depend on them. Second, neither depreciation nor failure of infrastructure have been taken into account which are likely to increase absolute costs. The relative cost comparison remains, however, valid.

[65] Benefits can be achieved mainly from intelligent scheduling upon the existing pumping and conveying...
system. For the set of Pareto-optimal policies, Figure 9 shows a cross-generational density plot of the pumping locations. In the TC aquifer, solutions are similar in character in as far as they all feature the same pumping location set. Even with gradient restrictions in place, no spatial relocation of pumping is proposed. Two reasons are responsible. First, the TC gets unconfined at pumping locations. The drainage of the effective porosity causes less deep increases in drawdown cones. Second, once a gradient constraint of the TC is hit, pumping can be increased in the IC until recovery is observed. This again confirms the basic understanding of the IC as backstop in an economic sense. Contrary to that, relocation of IC wells is observed in the Pareto-optimal policies. IC boreholes in the central basin region around the Chott get gradually switched off. Reddish to yellow and green finite difference cells appear in the IC in Figure 9. This is just an indication of the diversity of the nondominated, optimized allocation policies.

6.2. Transboundary Water Transfer

As shown in the case of the perpetuation strategy, intelligent scheduling of pumping pays off for each of the three nations. So far, however, it has not been stated more precisely whether transboundary cooperation is a necessary prerequisite for the achievement of such benefits. Remember that cooperation in our case implies the notion of a transboundary institution that determines basin-wide allocation, irrespective of national boundaries. Because of the considerable size of the resource, it is conceivable that the cost savings can be realized entirely by the optimal location allocation of pumping within each national territory without the need for further transnational cooperation, at least over the optimization time horizon of 50 years.

Figure 11 shows for each country how much of the demand it should cover from foreign territory according to the best policy under the perpetuation strategy. Algeria has no incentive to pump in Libya because of the great distances of its demand centers from the Libyan territory. The commonly shared Chott region between Algeria and Tunisia (see Figure 1) is critical with regard to Chott induced salination. There, the gradient criteria require Tunisia to shift part of its TC pumping to the nearby Algerian side. Clearly, Tunisia could provide its demand from the IC. However, it appears to be more cost efficient to convey water from the nearby Algerian infrastructure than to invest in IC boreholes, at least in the beginning. Remember that

| Table 2. Unit Groundwater Prices Per Square Meter in the Years 2000 and 2050 As Well As Their Ratios<sup>a</sup> |
|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
|                | Status Quo      | Perpetuation    | Status Quo      | Perpetuation    |                |
| 2000            | 2050            | Ratio           | 2000            | 2050            | Ratio           |
| Algeria         | 3.1E-02         | 2.8E+00         | 35.0            | 2.1E-02         | 6.5E-01         | 8.0             |
| Tunisia         | 5.7E-02         | 1.8E+00         | 31.3            | 5.8E-03         | 1.8E-01         | 7.2             |
| Libya           | 6.5E-02         | 1.9E+00         | 28.8            | 1.9E-02         | 2.8E-01         | 4.3             |
| Average         | 7.3E-02         | 2.5E+00         | 34.4            | 1.7E-02         | 5.2E-01         | 7.1             |

<sup>a</sup>All countries experience a significantly lower price-rise ratio when they follow the perpetuation strategy.

<sup>b</sup>Read 3.1E-02 as 3.1 × 10⁻².

| Table 3. Current Provision Costs Per Meter Cube of Water for Algeria (A), Tunisia (T), and Libya (L) in Selected Years Relative to the Status Quo<sup>a</sup> |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SQ(A/T/L)       | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             |
| PER(A)          | 25              | 13              | 11              | 12              | 16              | 16              | 16              | 16              | 16              | 16              | 16              |
| PER(T)          | 10              | 4               | 4               | 4               | 4               | 5               | 5               | 4               | 4               | 4               | 4               |
| PER(L)          | 29              | 162             | 69              | 38              | 38              | 35              | 35              | 35              | 35              | 35              | 35              |

<sup>a</sup>Values are given in percent; mean values over last generation allocation policies are given for the PER strategy. SQ is status quo and PER is perpetuation strategy.

Figure 8. Development of cumulative present costs for each country according to strategies chosen (mean over last generation). On the average, the perpetuation strategy compares favorably to the status quo strategy (see also Table 2).
the IC in Tunisia is more than 1000 m deep and boreholes therefore expensive to drill. Furthermore, optimization proposes that Tunisia gets part of its water to supply the Nezawa oases from the southern Ghadames well field in Libya where the three countries join near the oasis of Ghadames. The Ghadames well field serves the western branch of the Great Man Made River with groundwater from the IC.

Libya finally should spread pumping of the Ghadames well field over a greater area than initially planned. However, we do believe that the Libyan authorities planned the well field in the Ghadames region on the basis of detailed knowledge about the resource and its properties. It is not conceivable that a well field installation of this size with an estimated maximum yield of 20 m$^3$/s would require relocation after that short a time of less than 20 years in operation (see IC plots in Figure 9). In fact, a lifetime of approximately 40 years of the Libyan well field infrastructure has been assumed by Libyan authorities (personal communication, O. Salem and L. Madi, 2002). The borehole dynamics in that region proposed by our modeling results might be related to a locally wrong conceptualization of our finite difference NWSAS model.

Compared to the overall quantity pumped, the share of transboundary water transfer as proposed by this best allocation policy is marginal as proposed by the optimized location allocation schemes. In other words, benefits result from intelligent pumping scheduling within the countries. This is mainly because of the immense resource size and the transnational distances between the demand centers. As optimization results show, only the Chott region could profit from transboundary management and it seems beneficial to

![Figure 9. Density plot of the well locations as proposed by the last-generation individuals. The dark blue cells indicate that all of the nondominated solutions propose pumping at this location. Red to light colors indicate that only parts of the solutions propose pumping at the corresponding finite difference cells. A shifting in the location of the IC pumping activity over time is visible in the central basin. This shift is induced by deep cones of depressions developing in the confined IC indicating an economic scarcity depth.]
establish a transnational institution that would regulate resource allocation in this area. For this, the establishment of the trinational consultation mechanism with regard to transboundary groundwater issues has laid a promising foundation.

7. Conclusions

[71] Traditional, gradient-based optimization techniques overly restrict the allowed complexity of the optimization problem. The development of recent multiobjective evolutionary optimization algorithms and their capability of successfully handling complex simulation optimization models motivated the development of a multiobjective groundwater management tool. The model is tested on a real-world supply problem where three countries have to decide upon their distribution of pumping over a given time horizon so as to minimize their corresponding costs. Consequently, a cooperative strategy is ranked against a noncooperative status quo strategy.

[72] The cooperative perpetuation strategy allows free distribution of demand over existing infrastructure, irrespective of national borders. Model results show that average per unit water provision prices in the year 2050 are 7 times smaller for the perpetuation strategy compared to the status quo. Therefore it appears to be individually rational for the

Figure 10. Optimal scheduling showing intermittent pumping within clusters and between the two aquifers, TC and IC. The lower peak of \( \zeta \) for network cluster \( K_2 \) (light green) vanishes in period \( t = 12 \), that is, in the year 2012, which indicates collapse of pumping within one finite difference cell. Note that the cluster numbers refer to the individual provision networks that serve the corresponding demand centers as shown in Figure 5.

Figure 11. Percentage of pumping in foreign countries compared to total country demand for each country.
Northern African decision makers to implement cooperative allocation policies. We believe that these findings provide valuable input to the recently established trinational consultation mechanism with regard to the issues related to transboundary resource management. For each country, the calculated monetary gains from optimal management provide a strong incentive for cooperation.

[73] Gains result from intelligent scheduling, that is, intermittent pumping between boreholes and aquifers, upon existing and required future infrastructure and limited transboundary water transfer. Over the optimization time horizon of 50 years, demand can be covered without the large-scale renewal of groundwater provision infrastructure. Because of the threat of salination in the Chott region of the central NWSAS basin, transboundary cooperation between Algeria and Tunisia would be beneficial. However, big volume transboundary water transfers do not result from optimization because of the large spatial extent of the resource. Each country has enough options to cover its demand under cost-minimizing behavior on its own territory during the next 50 years. This finding does not discard the necessity for transboundary management. On the contrary, any policy deemed optimal for one country is only optimal as long as the others follow their corresponding optimal policies in the realization because of the stock effect given by the aquifer piezometry. This becomes even more true over the long time horizon.

[74] Without doubt, the role of desalinated seawater in substituting the increasingly expensive fossil groundwater will increase in the foreseeable future. When Libya started to plan the Great Man Made River in the late seventies, the cost of 1 m³ of desalinated seawater was approximately 5.5 US$. At that time, the per meter cube cost figures resulting from the Great Man Made River project were by large competitive with less than 1 US$ [Alghariani, 2004]. Because of technical progress in the development of new membranes, the average price of desalinated seawater nowadays has fallen to less than 0.5 US$. If the desert oases’ agriculture are to be preserved by the governments in the long run, it can be sustained with this new infinite resource. For it to be developed, capital saved by the implementation of cooperative and intelligent groundwater management policies could be used to invest in the necessary desalination infrastructure to allow for a gradual technological transition.

Appendix A: Definition of Current Costs

[75] The current costs $g(\cdot, t)$ are defined as

$$g(q_{m,n}^m(t), h_{n,t}^m) = (C_{IP} + C_{IC} \cdot I_{n,t})_0 + \Delta t (c_I q_{m,n}^m(t) \Delta h_{n,t}^m + c_{LT} L_{n,t}^m \Delta q_{m,n}^m(t))^T \quad (A1)$$

where $C_{IP}$ are the total present installation costs of borehole infrastructure. $C_{IC}$ is the associated present per conveyor meter installation costs of the conveyance system. These two cost components incur only at the time of construction of the corresponding infrastructure, that is, at $t = t'$. $q_{m,n}^m(t)$ refers to the pumped quantity of water at $L_{n,t}$ whereas $q_{n,t}$ denotes the conveyed quantity of water at this particular location. Hence, for $L_{n,t}^m$, $q_{n,t}^m(t) = q_g(t)$ whereas for $L_{n,t}^*, q_{n,t}^m(t) = \sum_{i \neq j} q_g^j(t)$. $L_{n,t}^m$ is the distance over which water is conveyed. $\Delta h_{n,t}^m(t)$ is the head difference between the level to which the volume of water $q_m^m(t)$ $\Delta t$ has to be raised at time $t$ in order to be conveyed and the actual groundwater level $h_{n,t}^m$. $c_I$ and $c_{LT}$ are factors of proportionality which account for pumping plant efficiency $\eta$ and hydraulic losses in the pipe. More specifically, $c_I \propto P_E^\eta \rho$ with $g$ being the gravitational constant and $\rho$ the average density of water. $c_{LT} \propto L_{n,t}^m \rho g$ being the Moody friction factor [see, e.g., Glover et al., 1992; Munson et al., 1990]. In both cases, $P_E$ denotes the energy price. Depending on location, technology of infrastructure and the market prices of energy, the cost coefficients $C_{IP}, C_{IC}, c_I$ and $c_{LT}$ can vary spatially and temporarily.

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References


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