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The cost of ending groundwater overdraft on the North China Plain

C. Davidsen[1,2,3], S. Liu[2], X. Mo[2], D. Rosbjerg[1], and P. Bauer-Gottwein[1]

[1]Technical University of Denmark, Department of Environmental Engineering, Kgs. Lyngby, Denmark
[2]Chinese Academy of Sciences, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Beijing, China
[3]Sino-Danish Center for Education and Research, Aarhus C, Denmark

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Correspondence to: C. Davidsen (clad@env.dtu.dk), S. Liu (liusx@igsnrr.ac.cn), P. Bauer-Gottwein (pbau@env.dtu.dk)

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Abstract

Over-exploitation of groundwater reserves is a major environmental problem around the world. In many river basins, groundwater and surface water are used conjunctively and joint optimization strategies are required. A hydroeconomic modelling approach is used to find cost-optimal sustainable surface water and groundwater allocation strategies for a river basin, given an arbitrary initial groundwater level in the aquifer. A simplified management problem with conjunctive use of scarce surface water and groundwater under inflow and recharge uncertainty is presented. Because of head-dependent groundwater pumping costs the optimization problem is non-linear and non-convex, and a genetic algorithm is used to solve the 1-step-ahead sub-problems with the objective of minimizing the sum of immediate and expected future costs. A real-world application in the Ziya River Basin in northern China is used to demonstrate the model capabilities. Persistent overdraft from the groundwater aquifers on the North China Plain has caused declining groundwater tables, salinization and infiltration of wastewater. The model maps the opportunity cost of water in different scenarios, and the cost of ending groundwater overdraft in the basin is estimated to be 5.47 billion CNY yr^{-1}. The model can be used to guide decision makers to ensure long-term sustainability of groundwater and surface water resources management in the basin in an economically optimal way.

1 Introduction

Groundwater aquifers are of high economic importance around the world and often act as buffers in the water supply system during droughts (Tsur and Graham-Tomasi, 1991; Tsur, 1990). On the North China Plain, persistent groundwater overexploitation over the past decades has caused decline of the shallow and deep groundwater tables (Liu et al., 2001). The immediate benefits of satisfying the water demands greatly exceed the costs of pumping, which highlights the problem of the present self-regulating management. As the groundwater resource is overexploited, the immediate benefits of the increased unsustainable supply have to be traded off against the long-term increase in pumping costs and reduced buffering capacity.

Optimal management of conjunctive use of surface water and groundwater has been addressed widely in the literature. Harou and Lund (2008) used a deterministic hydroeconomic optimization approach to examine the economic effects of ending long-term groundwater overdraft in California. The linear model was run under different scenarios and used to estimate the water users' willingness-to-pay, water scarcity costs and the benefits of conjunctive use facilities. Andreu et al. (1996) developed the deterministic AQUATOOL simulation software based on the Out-of-Kilter Algorithm to minimize deficits in demand and minimum flows in a coupled surface water–groundwater environment. This model was later applied in a hydroeconomic context by Pulido-Velázquez et al. (2006) to minimize the sum of scarcity costs and variable operating costs for a coupled setup with a distributed-parameter groundwater simulation. The integrated aquifer model allowed variable pumping costs in a forward moving, scenario-based framework but lacked the ability to give predictions in an uncertain real-time management environment. An alternative optimization approach was demonstrated by Riegels et al. (2013), who maximized welfare subject to ecosystem constraints by adjusting time-constant water prices.

While a high level of complexity can be accommodated in deterministic simulation models, the objective functions of stochastic optimization models are kept simpler to remain computationally feasible. Philbrick and Kitanidis (1998) applied Stochastic Dynamic Programming (SDP) to a multi-reservoir system to optimize conjunctive use of surface water and groundwater given stochastic inflow. The second order gradient dynamic programming method, a modification of the classical recursive SDP, was used to mitigate the well-known *curse of dimensionality*. Pumping costs were linked linearly to pumping rates but changes in pumping costs due to long-term depletion of the aquifer were not considered. Head-dependent pumping costs were included in the SDP model by Knapp and Olson (1995), who analyzed conjunctive use of groundwater with randomly generated runoff. Non-linearity arising from the head dependent pumping costs was overcome with lattice programming techniques in this qualitative model setup.

This study demonstrates how a hydroeconomic modeling approach can be used to identify the least-cost strategy to achieve sustainable groundwater abstraction. In this context, "sustainable" means that the long-term average abstraction does not exceed the long-term average recharge. A water management problem with conjunctive use of surface water and groundwater similar to Harou and Lund (2008) is addressed. Increased complexity is caused by uncertain surface water runoff and groundwater recharge and non-linearity arising from head and rate dependent groundwater pumping costs. The cost minimization problem is solved with the water value method, a variant of SDP (Pereira and Pinto, 1991; Stage and Larsson, 1961; Stedinger et al., 1984). The non-linear discrete sub problems are solved with a combined genetic algorithm and linear programming method similar to that used by Cai et al. (2001), but applied to a coupled groundwater-surface water management problem in an SDP framework.

2 Methods

2.1 Study area

Northern China and particularly the North China Plain (NCP) have experienced increasing water scarcity problems over the past 50 years due to population growth, economic development and reduced precipitation (Liu and Xia, 2004). The deficit in the water balance has historically been covered by overexploitation of the groundwater aquifer, causing a regional lowering of the groundwater table by up to 1 $\mathrm{m\,yr^{-1}}$ (Zheng et al., 2010).

The case study area is the Ziya River Basin, which is located in the Hebei Province on the NCP and with the upper catchment stretching through the Taihang Mountains into the Shanxi Province. The basin is subject to severe water scarcity, which causes multiple conflicts. The 52 300 $\mathrm{km^2}$ basin, shown in Fig. 1, is home to approximately

25 million people (data from 2007; Bright et al., 2008). A hydroeconomic study of the Ziya River by Davidsen et al. (2015) focused primarily on optimal management of the surface water resources. Five major reservoirs with a combined storage capacity of 3.5 km^3 are located in the basin. In this study, it is assumed that the full storage capacity can be managed flexibly without consideration of storage reserved for flood protection or existing management rules.

In Davidsen et al. (2015), the groundwater resource was included as a simple monthly upper allocation constraint, which prevents analysis of dynamic interactions between the groundwater and surface water resources and limits the decision space. In the present model setup, the groundwater is included as a simple dynamic aquifer box model with an upper storage capacity of 275 km^3. This allows for more flexible management with larger abstractions in dry years and increased recharge in wet years. The groundwater aquifer can thereby be used to bridge longer drought periods.

A conceptual sketch of the management problem is shown in Fig. 2. The water users are divided into groups of economic activities; irrigation agriculture, industrial and domestic water users. Each water user group is characterized by constant water demands (m^3) and constant curtailment costs of not meeting the demand (see Table 1), as also applied by Davidsen et al. (2015). The water demands are assumed to be deterministic and decoupled from the stochastic runoff. This is a reasonable assumption because the rainfall on the NCP normally occurs in the summer months, while irrigation water demands are concentrated in the dry spring. The irrigation schedule is centrally planned and typically the same every year. The water users upstream the surface water reservoir (u) have access to the runoff and a monthly limited volume of groundwater, X_{gw}. The water users located downstream the reservoir (d) have access to reservoir releases, water delivered through the South-to-North Water Transfer Project (SNWTP) and groundwater from the dynamic aquifer.

2.2 Optimization model formulation

An SDP formulation is used to find the expected value of storing an incremental amount of surface water or groundwater, given the month of the year, the available storage in surface and groundwater reservoirs and the inflow scenarios. The backward recursive equation calculates the sum of immediate and expected future costs for all combinations of discrete reservoir storage levels (states) and monthly time steps (stages). The immediate management costs (IC) arise from water supply and water curtailment, whereas the expected future costs (EFC) are the optimal value function in $t+1$ weighed by the corresponding transition probabilities. In the present setup, we decided to weighted the IC and EFC equally, but inclusion of discount rates other than zero is possible. Because of the head and rate dependent groundwater pumping costs, which will be described in detail later, the immediate cost depends non-linearly on the decision variables. The objective is to minimize the total costs over the planning period, given by the optimal value function $F_t^*\left(V_{\mathrm{gw},t}, V_{\mathrm{sw},t}, Q^k_{\mathrm{sw},t}\right)$ based on the classical Bellman formulation:

$$F_t^*\left(V_{\mathrm{gw},t}, V_{\mathrm{sw},t}, Q^k_{\mathrm{sw},t}\right) =$$

$$\min\left(\mathrm{IC}\left(V_{\mathrm{gw},t}, V_{\mathrm{sw},t}, Q^k_{\mathrm{sw},t}\right) + \sum_{l=1}^{L}\left(p_{\mathrm{kl}} F^*_{t+1}\left(V_{\mathrm{gw},t+1}, V_{\mathrm{sw},t+1}, Q^l_{\mathrm{sw},t+1}\right)\right)\right) \tag{1}$$

with IC being the immediate costs:

$$\mathrm{IC}\left(V_{\mathrm{gw},t}, V_{\mathrm{sw},t}, Q^k_{\mathrm{sw},t}\right) = \sum_{m=1}^{M}\left(c_{\mathrm{sw}} x_{\mathrm{sw}} + c_{\mathrm{gw}} x_{\mathrm{gw}} + c_{\mathrm{SNWTP}} x_{\mathrm{SNWTP}} + c_{\mathrm{ct}} x_{\mathrm{ct}}\right)_{m,t} - r_{\mathrm{sw},t} b_{\mathrm{hp}} \tag{2}$$

subject to:

$$x_{\mathrm{sw},t,m} + x_{\mathrm{gw},t,m} + x_{\mathrm{SNWTP},t,m} + x_{\mathrm{ct},t,m} = \mathrm{dm}_{m,t} \tag{3}$$

$$V_{\mathrm{sw},t} + Q_{\mathrm{sw},t} - \sum_{u=1}^{U} x_{\mathrm{sw},u,t} - r_{\mathrm{sw},t} - s_{\mathrm{gw},t} = V_{\mathrm{gw},t+1} \tag{4}$$

$$r_{\mathrm{sw},t} + s_{\mathrm{sw},t} = \sum_{d=1}^{D} x_{\mathrm{sw},d,t} + q_{\mathrm{E},t} \tag{5}$$

$$V_{\mathrm{gw},t} + Q_{\mathrm{gw},t} - \sum_{d=1}^{D} x_{\mathrm{gw},d,t} - s_{\mathrm{gw},t} = V_{\mathrm{gw},t+1} \tag{6}$$

$$\sum_{u=1}^{U} x_{\mathrm{sw},u,t} \leq Q_{\mathrm{sw},t} \tag{7}$$

$$\sum_{u=1}^{U} x_{\mathrm{gw},u,t} \leq X_{\mathrm{gw},t} \tag{8}$$

$$r_{\mathrm{t}} \leq R, x_{\mathrm{sw,Bei}} + x_{\mathrm{SNWTP,Bei}} \leq Q_{\mathrm{SNWTP}}, q_{\mathrm{E},t} \geq Q_{\mathrm{E}}, V_{\mathrm{sw},t} \leq V_{\mathrm{max,sw}}, V_{\mathrm{gw},t} \leq V_{\mathrm{max,gw}} \tag{9}$$

$$c_{\mathrm{gw}} = f\left(V_{\mathrm{gw}}, \sum_{d=1}^{D} x_{\mathrm{sw},d}\right) \tag{10}$$

(see Table 3).

Eqution (3) is the water demand fulfillment constraint, i.e. the sum of water allocation and water curtailments equals the water demand of each user. Eq. (4) is the water balance of the combined surface water reservoir, while Eq. (5) is the water balance of the reservoir releases. A similar water balance for the dynamic groundwater aquifer follows in Eq. (6). The upstream surface water allocations are constrained to the upstream runoff (Eq. 7), while the upstream groundwater allocations are constrained to a fixed sustainable monthly average (Eq. 8). In Eq. (9), the upper and lower hard constraints on the decision variables are shown. Last, Eq. (10) is the marginal groundwater pumping cost, which depends on the combined downstream groundwater allocations as described later.

A rainfall–runoff model based on the Budyko Framework (Budyko, 1958; Zhang et al., 2008) and previously applied by Davidsen et al. (2015) is used to estimate the near-natural daily surface water runoff into reservoirs. The 51 years (1958–2008) of simulated daily runoff are aggregated to monthly runoff and normalized. A Markov chain which describes the runoff serial correlation between three flow classes defined as dry (0–20th percentile), normal (20th–80th percentile), and wet (80th–100th percentile), is established and validated to ensure second order stationarity (Loucks and van Beek, 2005). The groundwater recharge is estimated from the precipitation data also used in the rainfall–runoff model. The average monthly precipitation ($\mathrm{mm\,month^{-1}}$) for each runoff class is calculated, and a simple groundwater recharge coefficient of 17.5 % of the precipitation (Wang et al., 2008) is used.

The SDP loop is initiated with EFC set to zero and will propagate backward in time through all the discrete system states as described in the objective function. For each discrete combination of states, a cost minimization sub-problem will be solved. A sub-problem will have the discrete reservoir storage levels ($V_{\mathrm{gw},t}$ and $V_{\mathrm{sw},t}$) as initial conditions, and reservoir inflow is given by the present inflow class in the Markov chain. The optimization algorithm will search for the optimal solution, given the costs of the immediate management (water allocations and water curtailments, including reservoir releases and groundwater pumping) which have to be balanced against the expected future costs. As the SDP algorithm is propagating backward in time, the future costs will be equal to the minimum total costs from $t+1$, weighted by the Markov chain transition probabilities. The algorithm will continue backward in time until equilibrium is reached, i.e. until the shadow prices (marginal value of storing water for future use) in two successive years remain constant. The SDP model is developed in MATLAB (MathWorks Inc., 2013) and uses the fast *cplexlp* (IBM, 2013) to solve the linear sub-problems.

The sets of equilibrium shadow prices, referred to as the water value tables, can subsequently be used to guide optimal water resources management forward in time with unknown future runoff. In this study, the available historic runoff time series are used to demonstrate how the derived water value tables should be used in real time operation. The simulation will be initialized from different initial groundwater aquifer storage levels thereby demonstrating which pricing policy should be used to bring the NCP back into a sustainable state.

2.3 Dynamic groundwater aquifer

The groundwater aquifer is represented as a simple box model (see Fig. 2) with recharge and groundwater pumping determining the change in the stored volume of the aquifer (Eq. 6). The pumping is associated with a pumping cost determined by the energy needed to lift the water from the groundwater table to the land surface (Eq. 10):

$$P = (\rho g \Delta h)/\varepsilon \tag{11}$$

where P is the specific pump energy ($\mathrm{J\,m^{-3}}$), ρ is the density of water ($\mathrm{kg\,m^{-3}}$), g is the gravitational acceleration ($\mathrm{m\,s^{-2}}$), Δh is the head difference between groundwater table and land surface (m) and ε is the pump efficiency (–). The marginal pumping cost c_{gw} ($\mathrm{CNY\,m^{-3}}$) is found from the average electricity price c_{el} ($\mathrm{CNY\,Wh^{-1}}$) in Northern China:

$$c_{\mathrm{gw}} = c_{\mathrm{el}} P \tag{12}$$

Hence this cost will vary with the stored volume in the groundwater aquifer. The present electricity price structure in China is quite complex, with the users typically paying between 0.4 and 1 $\mathrm{CNY\,kWh^{-1}}$ depending on power source, province and consumer type (Li, 2012; Yu, 2011). In this study a fixed electricity price of 1 $\mathrm{CNY\,kWh^{-1}}$ is used. The immediate costs of supplying groundwater to a single user follow:

$$c_{\mathrm{gw},t} x_{\mathrm{gw},t} = \rho g \Delta h \varepsilon^{-1} c_{\mathrm{el}} x_{\mathrm{gw},t} \tag{13}$$

where Δh is found as the mean depth from the land surface to the groundwater table (see Fig. 2) between t and $t+1$:

$$\Delta h = \Delta h_{\text{top}} + \left(V_{\max,\text{gw}} - \frac{V_{\text{gw},t} + V_{\text{gw},t+1}}{2} \right) S_y^{-1} A^{-1} \tag{14}$$

where Δh_{top} is the distance from the land surface to the top of the aquifer at full storage (m), S_Y is the specific yield (–) of the aquifer and A is the area of the aquifer (m^2). Here $V_{\text{gw},t+1}$ is a decision variable and once substituted into Eq. (13), it is clear that the problem becomes non-linear.

In Eq. (14) the drawdown is assumed uniform over the entire aquifer. This simplification might be problematic as the local cone of depression around each well could contribute significantly to the pumping cost and thereby the optimal policy. Therefore, the steady state Thiem drawdown (Thiem, 1906) solution is used to estimate local drawdown at the pumping wells. Local drawdown is then added to Eq. (15) to estimate total required lift:

$$\Delta h_{\text{Thiem}} = \frac{Q_{\text{w}}}{2\pi T} \ln \left(\frac{r_{\text{in}}}{r_{\text{w}}} \right) \tag{15}$$

where Q_{w} is the pumping rate of each well (m^3 month^{-1}), T is the transmissivity (m^2 month^{-1}), r_{in} is the radius of influence (m) and r_{w} is the distance from origin to the point of interest (m), here the radius of the well. The transmissivity is based on a hydraulic conductivity of 1.3×10^{-6} m^2 month^{-1} for silty loam (Qin et al., 2013) which was tested to be realistic in a MIKE SHE model of the Ziya River Basin (Marker, 2013). Field interviews revealed that the wells typically reach no deeper than 200 m below surface, which results in a specific yield of 5 %. The thickness of the aquifer Q_{w} is defined as the total allocated groundwater within the stage (m^3 month^{-1}), distributed evenly to the number of wells in the catchment:

$$Q_\mathrm{w} = \frac{\sum_{d=1}^{D} x_{\mathrm{gw},d,t}}{n_\mathrm{w}} = \frac{V_{\mathrm{gw},t} - V_{\mathrm{gw},t+1} + Q_{\mathrm{gw},t} - s_{\mathrm{gw},t}}{n_\mathrm{w}} \tag{16}$$

where n_w is the number of wells in the downstream basin. Erlendsson (2014) estimated the well density in the Ziya River Basin from Google Earth to be 16 wells km^{-2}. Assuming that the wells are distributed evenly on a regular grid and that the radius of influence r_in is 500 m, overlapping cones of depression from 8 surrounding wells are included in the calculation of the local drawdown. This additional drawdown is included using the principle of superposition as also applied by Erlendsson (2014).

2.4 Solving non-linear and non-convex sub-problems

In the previous study by Davidsen et al. (2015), the optimization problem was strictly linear and strictly convex. The individual sub-problems of the SDP scheme could therefore be solved with a fast linear programming algorithm. In this study however, with non-linearity from the head-dependent groundwater pumping costs, the expected future cost function is no longer strictly convex.

Non-linear optimization problems can be solved with evolutionary search methods, a sub division of global optimizers. A widely used group of evolutionary search methods is genetic algorithms (GA), which have been found to be efficient tools to get the approximate solution to complex non-linear optimization problems (see, e.g., Goldberg, 1989; Reeves, 1997). GAs use a random search approach inspired by natural evolution and have been applied to the field of water resources management by, e.g., Cai et al. (2001), McKinney and Lin (1994) and Nicklow et al. (2010). Cai et al. (2001) used a combined genetic algorithm and linear programming (LP) approach to solve a highly non-linear surface water management problem. By fixing some of the complicating decision variables, the remaining objective function became linear and thereby solvable with LP. The GA was used to test combinations of the fixed parameters while looking for the optimal solution. The combination yielded faster computation time than if the GA was used to estimate all the parameters.

This study uses a genetic algorithm implemented in MATLAB to solve the cost minimization sub problems. This GA function will initially generate a set of candidate solutions known as the *population*. Each of the candidate solutions contains a set of decision variables (sampled within the decision space), which will yield a feasible solution to the optimization problem. In MATLAB, a set of options specifies: the *population size*, the stopping criteria (*fitness limit*, *stall limit*, *function tolerance* and others), the *crossover fraction*, the *elite count* (number of top parents to be guaranteed survival) and the *generation function* (how the initial population is generated). The options were adjusted to achieve maximum efficiency of the GA for the present optimization problem.

The computation time for one single sub-problem is orders of magnitude larger than solving a simple LP. As the optimization problem becomes computationally heavier with increasing number of decision variables, a hybrid version of GA and LP, similar to the method used by Cai et al. (2001), was developed (see Fig. 3). Decision variables that cause non-linearity are identified and chosen by the GA. Once these complicating decision variables are chosen, the remaining objective function becomes linear and thereby solvable with LP. In the present optimization problem (Eq. 1) the non-linearity is caused by the head-dependent pumping costs as explained in Eqs. (13) and (14). Both the regional lowering of the groundwater table and the Thiem local drawdown cones depend on the decision variable for the stored volume in $t+1, V_{\mathrm{gw},t+1}$. If $V_{\mathrm{gw},t+1}$ is pre-selected, the regional drawdown is given and the resulting groundwater pumping rate Q_{w} can be calculated from the water balance. The groundwater pumping price is thereby also given, and the remaining optimization problem becomes linear.

The SDP framework is subject to the *curse of dimensionality*. With two state variables and non-linearity, the computation time is significant and is a limiting factor when choosing model discretization. With a low number of discrete states, the discretization error increases, particularly if the end storages $V_{\mathrm{gw},t+1}$ and $V_{\mathrm{sw},t+1}$ are kept discrete.

Piecewise linear interpolation of the future cost function (Pereira and Pinto, 1991) allows for free end storages but requires strict convexity. With two state variables, interpolation between the future cost points will yield a hyper-plane in three dimensions. In our problem, the EFC is no longer strictly convex and therefore both $V_{\mathrm{gw},t+1}$ and $V_{\mathrm{sw},t+1}$ are chosen by the GA. For a given combination of stages, discrete states and flow classes, the objective of the GA is to minimize the total costs, TC, with the free states $V_{\mathrm{gw},t+1}, V_{\mathrm{sw},t+1}$ being the decisions:

$$\mathrm{TC}\left(V_{\mathrm{gw},t+1}, V_{\mathrm{sw},t+1}\right) = \min\ \left(\mathrm{IC}\left(V_{\mathrm{gw},t+1}, V_{\mathrm{sw},t+1}\right) + \mathrm{EFC}\right)\left(V_{\mathrm{gw},t+1}, V_{\mathrm{sw},t+1}\right) \tag{17}$$

with EFC being the expected future costs. Given initial states and once the GA has chosen the end states, the immediate cost minimization problem becomes linear and hence solvable with LP (see Fig. 3). The IBM CPLEX linear programming solver (IBM, 2013) is used to solve the linear programs. The expected future costs are found by cubic interpolation of the discrete neighboring future cost grid points in each dimension of the matrix. The GA approaches the global optimum until a fitness limit criteria is met. The total costs are stored, and the algorithm continues to the next state. To reduce the computation time, the outer loop through the groundwater states is parallelized.

The performance of the GA-SDP model is compared to a deterministic Dynamic Program (DP), which finds the optimal solution given perfect knowledge about future inflows and groundwater recharge. The DP model uses the same algorithm as the SDP model and 1-dimensional state transition matrices with $p = 1$ between the deterministic monthly runoff data. For low storage capacity and long time scales, the effect of the end storage volume becomes negligible. Similar to the SDP model, the DP model was looped and run until the end of period condition does not affect the present management.

3 Results

Without any regulation or consideration of the expected future costs arising from overexploitation of the groundwater aquifer, the water users will continue maximizing immediate profits (producers) or utility (consumers). Because there are only electricity costs for groundwater, the users will continue pumping groundwater until the marginal groundwater cost exceeds the curtailment costs. At 1 CNY kWh^{-1} the marginal cost of lifting groundwater 200 m (typical depth of wells observed in the study area) can be found with Eqs. (13) and (14) to be 0.8 CNY m^{-3} and thereby less than the lowest curtailment cost at 2.3 CNY m^{-3}. It requires an electricity price higher than 2.8 CNY kWh^{-1} before the lowest-value user stops pumping from 200 m below surface.

The backward recursive SDP algorithm was run with a looped annual dataset until equilibrium water values, i.e. no inter-annual changes, were obtained. The water values increase fastest during the first years, and after approximately 100 years the annual increases become small. Due to the large storage capacity of the groundwater aquifer, equilibrium is however not achieved until after 150–180 years. These marginal water values represent the true values of storing a unit volume of water for later use and vary with reservoir storage levels, runoff flow class and time of the year. A sample of the resulting equilibrium water value tables are presented in Fig. 4. This figure shows the temporal variations of water values as a function of one state variable, keeping the other state variable at a fixed value. The state variables are fixed at empty, half full and full storage respectively. During the rainy season from June to August, high precipitation rates reduce water scarcity, resulting in lower surface water values. Because the groundwater storage capacity is much larger, increased recharge can easily be stored for later use, and groundwater values are therefore not affected. The water values after 1980 are clearly higher than in the period before 1980 due increased water scarcity caused by a reduction in the regional precipitation. In contrast, the groundwater value tables are uniform, with variation only with groundwater storage. The detailed water value tables are included as Supplement.

We simulate management using the equilibrium water value tables as decision rules and force the system with 51 years of simulated historical runoff. Time series of the simulated storage levels can be seen in Fig. 5 for the dynamic groundwater aquifer. The groundwater aquifer approaches an equilibrium storage level around 260 km^3 (95 % full). If the storage in the aquifer is below this level, the average recharge will exceed average pumping until the equilibrium storage is reached. If the storage level is above equilibrium, average pumping will exceed average recharge, and over time equilibrium storage is reached.

The surface water reservoir storage level varies over time, and in contrast to the findings by Davidsen et al. (2015) the storage capacity now becomes close to zero almost every year. This can be explained by the increased groundwater availability in the model, which allows increased groundwater allocation in multi-annual dry periods. To demonstrate the business-as-usual solution, the simulation model is run for a 20 year period with the present water demands and curtailment costs and with a discount rate set to infinity (= zero future costs). The resulting groundwater table is continuously decreasing as shown in Fig. 5.

In the simulated management runs, water will be allocated to the users up to a point where reductions in immediate cost are compensated by increases in expected future costs. The user's price, which can be applied in an opportunity cost pricing scheme, is the marginal value of the last unit of water allocated to the users. The user's price is the sum of the actual pumping cost (electricity used) and the additional opportunity cost given by the equilibrium water value tables. In Fig. 6, the user's prices for groundwater and surface water are shown for the 51 year simulation at and below the long-term sustainable groundwater storage level. When the groundwater storage level is close to equilibrium, the user's prices of groundwater and surface water are equal during periods with water scarcity. In wet months with reduced water scarcity, the model switches to surface water allocation only, and the groundwater user's price is undefined (gaps in the time series in Fig. 6). If the groundwater storage level is below the equilibrium, the groundwater user's price will be higher causing an increase in water curtailments and increasing storage level as shown in Fig. 5. Under these circumstances the surface water user's price increases up to a point where the two prices meet.

At the equilibrium groundwater storage level, the user's prices shown in Fig. 6 indicate frequent curtailment of wheat agriculture in the downstream Hebei Province, which has a willingness to pay of 2.3 CNY m^{-3}. The allocation pattern to this user is shown in Fig. 7: the model switches between high curtailment and high allocations, depending on water availability and storage in the reservoirs. Groundwater allocations fluctuate between satisfying 0 and 80 % of the demand. Inclusion of the steady state Thiem drawdown cones in the optimization model increases the marginal groundwater pumping cost with increased pumping rates. Groundwater allocations are distributed more evenly over the months, which results in less local drawdown. The total curtailments remain constant, while 1 % of the total water abstraction is shifted from groundwater to surface water, if the stationary Thiem drawdown is included.

The average total costs of the 51 years simulation for different scenarios can be seen in Table 1. A simple local sensitivity analysis is used to assess the uncertainty of the model. Davidsen et al. (2015) used Monte Carlo simulations based on 50 samples to estimate the uncertainty of the model outputs. However, the inclusion of an additional state variable has increased the optimization time significantly and made such an approach infeasible. Approximately 4000 CPU hours per climate period are needed to reach equilibrium in the present model, equivalent to two weeks, if the maximum of 12 parallel processors are used in MATLAB R2013a. The analysis was focused on the local sensitivity related to the water demands and water curtailment costs used directly in the objective function (Eq. 1) and the transmissivity used to estimate the local drawdown (Eq. 14). The uncertain input parameters were increased by 10 % and the sensitivity evaluated based on the simulation results. The resulting total costs can be seen in Table 1. A 10 % increase in the curtailment costs is returned as a 6.0 % increase in the total costs, while a similar increase of the demands generates a 2.1 % increase in costs. The transmissivity can vary over many orders of magnitude because it is a log-normally distributed variable. The sensitivity of $\log(T)$ is high: a 1.3 % change of $\log(T)$ from the baseline value results in a 1.5 % change in the cost.

4 Discussion

This study presents a hydroeconomic optimization approach that provides economic decision rules in terms of water values for joint surface water–groundwater management. The method was used to demonstrate how the water resources in the Ziya River Basin should be priced over time to reach a sustainable situation at minimum cost. We believe that the presented modelling framework has great potential use as a robust decision support tool in real-time water management. However, a number of limitations and simplifications need to be discussed.

A great advantage of the SDP-based water value method is the capability to obtain optimal decision rules for any combination of system states. A first limitation of the SDP-approach is, however, the *curse of dimensionality* as previously mentioned. The number of sub-problems to be solved in the backward moving SDP scheme increases exponentially with the number of state variables. In our case we are therefore limited to 2–3 inter-linked storage facilities and higher dimensional management problems will not be computationally feasible today. This limit on the number of surface water reservoirs and groundwater aquifers requires strongly simplified representation of the real world situation in the optimization model. These requirements can be relaxed in the simulation phase that follows the optimization. While the *curse of dimensionality* applies to the backward moving SDP scheme, the forward moving simulation is not limited to the same extent as just one single sub-problem is solved at each stage. The water values determined by the SDP scheme can thus be used to simulate management using a much more spatially resolved model with a high number of users. The advantage of SDP is that it provides a complete set of decision rules that can be applied in adaptive management, provided that the system can be simplified to a computationally feasible level. An alternative approach known as stochastic dual dynamic programming (SDDP, Pereira and Pinto, 1991; Pereira et al., 1998) has shown great potential for multi-reservoir river basin water management problems. However, because SDDP only samples around the optimal decisions, this method will not be able to provide the complete set of shadow prices for all state combinations and is therefore less suitable for adaptive management.

Computation time was a major limitation in this study, and the transition from the previous much simpler linear single state SDP model (Davidsen et al., 2015) to the presented non-linear SDP model with two state variables proved to require around 50 000 times more CPU hours. We used the high performance cluster (HPC) at the Technical University of Denmark to solve the SDP, and as the optimization can be run offline, the resulting optimization time of 2 weeks on 12 cores is acceptable.

Replacement of the hard upper groundwater pumping constraint used by Davidsen et al. (2015) with a dynamic groundwater aquifer, lowered the total costs from 11.39 billion CNY yr^{-1} to 8.47 billion CNY yr^{-1}. This difference highlights the problem of defining realistic boundaries to optimization problems and shows that simple hard constraints, here fixed groundwater pumping limits, can highly limit the optimal decision space. With inclusion of a dynamic groundwater aquifer, the model can use the large groundwater storage capacity as a buffer to the system, which significantly stabilizes the user's price of surface water as shown in Fig. 6. Finally, policies like minimum ecosystem flow constraints can be satisfied with less impact on the expensive users, which results in reductions in the respective shadow prices.

Another addition to the modelling framework was the Thiem stationary drawdown. The long time steps (monthly) make stationarity a realistic assumption. Inclusion of well drawdown significantly changed the simulated management but resulted in only slightly increased computation time. While addition of the Thiem stationary drawdown has only a small effect on total costs and total allocated water, it is clear from Fig. 7 that the additional Thiem drawdown highly impacts the allocation pattern to some of the water users. High groundwater pumping rates result in larger local drawdown and thus in higher pumping costs. This mechanism leads to a more uniform groundwater pumping strategy, which is clearly seen in Fig. 7 and results in much more realistic management policy.

From any initial groundwater reservoir storage level, the sustainable management brings the groundwater table to an equilibrium storage level at approximately 95 % of the aquifer storage capacity. Only small variations in the aquifer storage level are observed after the storage level reaches equilibrium. Intuitively, one would expect the equilibrium groundwater storage level to be as close as possible to full capacity while, still ensuring that any incoming groundwater recharge can be stored. Finding the exact equilibrium groundwater storage level would require a very fine storage discretization, which, given the size of the groundwater storage, is computationally infeasible. Therefore the equilibrium groundwater storage level is subject to significant discretization errors.

In the previous study by Davidsen et al. (2015), total costs, without restrictions on the groundwater pumping, were estimated to 3.09 billion CNY yr^{-1}. The present study estimates an increase to 8.56 billion CNY yr^{-1} for a comparable setup but with sustainable groundwater pumping and groundwater storage at equilibrium. This increase of 5.47 billion CNY yr^{-1} reflects the expected cost of ending the groundwater overdraft in the basin once the groundwater aquifer is at equilibrium storage. The cost of recharging the aquifer from the present storage level below the equilibrium is significantly higher. In Table 1, the scenario with initial groundwater storage below equilibrium (LGW) shows that the average cost of sustainable management from an initial storage at 100 km^3 (one third full) is 13.32 billion CNY yr^{-1}.

The difference between total costs with SDP and with DP (perfect foresight) is surprisingly small (1 %). While this difference indicates a very good performance of SDP, the model setup also simulates small economic consequences of wrong decisions. With the SNWTP in operation (post-2014) the most expensive user (Beijing) will always have enough water, and the remaining users have access to groundwater. The large downstream groundwater aquifer serves as a buffer to the system and eliminates the economic consequences of a wrong decision. If too much water is allocated to a user in month 1, the same user will simply receive a bit less water in a following time step. Wrong decisions are therefore not punished with curtailment of expensive users as observed by Davidsen et al. (2015) but will shift allocations in time and between the users with curtailment costs close to the long-term equilibrium water price (in this study the farmers). The inclusion of a dynamic groundwater aquifer thereby makes the model self-regulate, as periods with too strict policy will be compensated by periods with a more unrestrained policy. The robustness is also supported by the simple local sensitivity analysis. The impact of changes in the input parameters on the total costs is small, as it is mainly the timing and not the amount of curtailment being affected. Inclusion of the large groundwater aquifer reduces the effect of wrong timing, which is reflected in small differences between the total costs with and without perfect foresight.

The derived equilibrium groundwater value tables in Fig. 4 (and the Supplement detailed water value tables) show that that the groundwater values vary with groundwater storage alone and are independent of time of the year, the inflow scenario and the storage in the surface water reservoir. This finding is important for future work, as a substitution of the groundwater values with a simpler cost function could greatly reduce the number of states and thereby the computation time. The equilibrium groundwater price, i.e. the groundwater values around the long-term equilibrium groundwater storage, can possibly be estimated from the total renewable water and the water demands ahead of the optimization, but further work is required to test this. Further work should also address the effect of discounting of the future costs on the equilibrium water value tables and the long-term steady state groundwater table. In the present model setup, the large groundwater aquifer storage capacity forces the backward moving SDP algorithm to run through 200–250 model years, until the water values converge to the long-term equilibrium. Another great improvement, if data allow, would be to replace the constant water demands with elastic demand curves in the highly flexible GA-LP setup.

A significant impact of including groundwater as a dynamic aquifer is the more stable user's prices shown in Fig. 6. The user's price of groundwater consists of two parts: the immediate groundwater pumping costs (electricity costs) and the expected future costs represented by the groundwater value for the last allocated unit of water. As the model is run to equilibrium, the user's prices converge towards the long-term equilibrium at approximately 2.2 CNY m^{-3}. This long-term equilibrium is not affected by the actual electricity price, as increasing electricity prices will be offset by a similar reduction in the opportunity costs. A constant electricity price can therefore be used as a policy tool to internalize the user's prices of groundwater shown in Fig. 6. Stable water user's prices will ease the implementation of e.g. an opportunity cost pricing (OCP) scheme, which is one of the available policy options to enforce long-term sustainability of groundwater management.

5 Conclusion

This study presented how a hydroeconomic optimization approach can be used to derive a pricing policy to bring an overexploited groundwater aquifer back to a long-term sustainable state. The model quantifies potential savings of joint water management of a complex river basin in China. Surface water and groundwater management was optimized in a SDP framework based on a coupled GA-LP setup. The derived equilibrium water value tables represent the shadow prices of surface and groundwater for any combination of time, inflow class and reservoir storage. The groundwater values at equilibrium were found to be almost constant at 2.2 CNY m^{-3}, independent of the time of the year, the surface water storage and the inflow class. Non-convexity caused by the groundwater reservoir could be accommodated with the use of a GA and was further extended to include stationary Thiem local drawdown cones. Inclusion of a dynamic groundwater aquifer greatly reduced the total costs of water scarcity, compared to a setup with fixed monthly pumping limits. The sustainable management will recharge the aquifer until the equilibrium storage level is reached. From an initial storage at one third of the aquifer capacity, the average costs of ending groundwater overdraft are estimated to be 13.32 billion CNY yr^{-1}. After equilibrium is reached, the average costs are estimated to be 5.47 billion CNY yr^{-1}. The aquifer serves as buffer and allows for overexploitation in dry years, and this mechanism stabilizes the user's water prices. These stable user's prices are suitable for use in an OCP scheme. While the representation of the management problem must be kept simple in the optimization model, the OCP prices can be used to drive a much more detailed simulation model, which includes a detailed physical representation of the system.

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References

Andreu, J., Capilla, J., and Sanchís, E.: AQUATOOL, a generalized decision-support system for water-resources planning and operational management, J. Hydrol., 177, 269–291, 1996.

Berkoff, J.: China: the South–North Water Transfer Project – is it justified?, Water Policy, 5, 1–28, 2003.

Bright, E. A., Coleman, P. R., King, A. L., and Rose, A. N.: LandScan 2007, available at: http://www.ornl.gov/landscan/ (last access: 15 June 2015), 2008.

Budyko, M.: The Heat Balance of the Earth's Surface, US Department of Commerce, Washington, 1958.

Cai, X., McKinney, D. C., and Lasdon, L. S.: Solving nonlinear water management models using a combined genetic algorithm and linear programming approach, Adv. Water Resour., 24, 667–676, doi:10.1016/S0309-1708(00)00069-5, 2001.

Davidsen, C., Pereira-Cardenal, S., Liu, S., Mo, X., Rosbjerg, D., and Bauer-Gottwein, P.: Using Stochastic Dynamic Programming to Support Water Resources Management in the Ziya River Basin, China, J. Water Resour. Plann. Manage., 141, 04014086, doi:10.1061/(ASCE)WR.1943-5452.0000482, 2015.

Deng, X.-P., Shan, L., Zhang, H., and Turner, N. C.: Improving agricultural water use efficiency in arid and semiarid areas of China, Agr. Water Manage., 80, 23–40, doi:10.1016/j.agwat.2005.07.021, 2006.

Erlendsson, L. B.: Impacts of local drawdown on the optimal conjunctive use of groundwater and surface water resources in the Ziya River basin, China, Thesis, B.Sc. in engineering, Technical University of Denmark, Kongens Lyngby, Denmark, 18–19, 2014.

Goldberg, D. E.: Gentic Algorithms in Search, Optimization, and Machine Learning, Addison-Wesley Publishing Company, Inc., North China Plain, China, 1989.

Google Inc.: Google Earth, (version 7.1.2.2041), Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA, 2013.

Harou, J. J. and Lund, J. R.: Ending groundwater overdraft in hydrologic-economic systems, Hydrogeol. J., 16, 1039–1055, doi:10.1007/s10040-008-0300-7, 2008.

Honge, M.: N. China drought triggers water disputes, GOV.cn, Chinese Gov. Off. Web Portal, available at: http://www.gov.cn/english/2006-05/24/content_290068.htm (last access: 15 Jue 2015), 2006.

IBM: ILOG CPLEX Optimization Studio v. 12.4, 2013.

Ivanova, N.: Off the Deep End – Beijing's W ater Demand Outpaces Supply Despite Conservation, Recycling, and Imports, Circ. Blue, available at: http://www.circleofblue.org/waternews/2011/world/off-the-deep-end-beijings-water-demand-outnumbers-supply-despite-conservation-recycling-and-imports/ (last access: 18 July 2013), 2011.

Knapp, K. C. and Olson, L. J.: The economics of conjunctive groundwater management with stochastic surface supplies, J. Environ. Econ. Manag., 28, 340–356, doi:10.1006/jeem.1995.1022, 1995.

Li, V.: Tiered power bill debated, Shenzhen Dly., 17 May, 1, available at: http://szdaily.sznews.com/html/2012-05/17/content_2046027.htm (last access: 5 August 2014), 2012.

Liu, C. and Xia, J.: Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China, Hydrol. Process., 18, 2197–2210, doi:10.1002/hyp.5524, 2004.

Liu, C., Yu, J., and Kendy, E.: Groundwater exploitation and its impact on the environment in the North China Plain, Water Int., 26, 265–272, 2001.

Loucks, D. P. and van Beek, E.: Water Resources Systems Planning and Management and Applications, UNESCO PUBLISHING, Paris, France, 2005.

Marker, K. N.: Optimizing surface water and groundwater allocation in the Ziya River basin (China) with stochastic dynamic programming, M.Sc. thesis, Technical University of Denmark, Department of Environmental Engineering, Kongens Lyngby, Denmark, 2013.

MathWorks Inc.: MATLAB (R2013a), v. 8.1.0.604, including the Optimization Toolbox, Natick, Massachusetts, 2013.

McKinney, D. C. and Lin, M.-D.: Genetic algorithm solution of groundwater management models, Water Resour. Res., 30, 1897–1906, doi:10.1029/94WR00554, 1994.

Moiwo, J. P., Yang, Y., Li, H., Han, S., and Hu, Y.: Comparison of GRACE with in situ hydrological measurement data shows storage depletion in Hai River basin, Northern China, Water South Africa, 35, 663–670, 2010.

National Bureau of Statistics of China: Statistical Yearbook of the Republic of China 2011, The Chinese Statistical Association, available at: http://www.stats.gov.cn/tjsj/ndsj/2011/indexeh.htm (last access: 15 June 2015), 2011.

NGCC: Shapefile with provincial boundaries in China, Natl. Geomatics Cent. China, 1 Baishengcun, Zizhuyuan, Beijing, China, 100044, 2009.

Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., Karamouz, M., Minsker, B., Ostfeld, A., Singh, A., and Zechman, E.: State of the art for genetic algorithms and beyond in water resources planning and management, J. Water Resour. Plan. Manag., 136, 412–432, doi:10.1061/(ASCE)WR.1943-5452.0000053, 2010.

Pereira, M., Campodónico, N., and Kelman, R.: Long-term Hydro Scheduling based on Stochastic Models, EPSOM'98, Zurich, 1–22, available at: http://www.psr-inc.com/psr/download/papers/pereira_epsom98.pdf (last access: 29 October 2012), 1998.

Pereira, M. V. F. and Pinto, L. M. V. G.: Multi-stage stochastic optimization applied to energy planning, Math. Program., 52, 359–375, 1991.

Philbrick, C. R. and Kitanidis, P. K.: Optimal conjunctive-use operations and plans, Water Resour. Res., 34, 1307–1316, doi:10.1029/98WR00258, 1998.

Pulido-Velázquez, M., Andreu, J., and Sahuquillo, A.: Economic optimization of conjunctive use of surface water and groundwater at the basin scale, J. Water Resour. Plan. Manag., 132, 454–467, doi:10.1061/(ASCE)0733-9496(2006)132:6(454), 2006.

Qin, H., Cao, G., Kristensen, M., Refsgaard, J. C., Rasmussen, M. O., He, X., Liu, J., Shu, Y., and Zheng, C.: Integrated hydrological modeling of the North China Plain and implications for sustainable water management, Hydrol. Earth Syst. Sci., 17, 3759–3778, doi:10.5194/hess-17-3759-2013, 2013.

Reeves, C. R.: Feature article – genetic algorithms for the operations researcher, Informs J. Comput., 9, 231–250, doi:10.1287/ijoc.9.3.231, 1997.

Riegels, N., Pulido-Velazquez, M., Doulgeris, C., Sturm, V., Jensen, R., Møller, F., and Bauer-Gottwein, P.: Systems analysis approach to the design of efficient water pricing policies under the EU water framework directive, J. Water Resour. Plan. Manag., 139, 574–582, doi:10.1061/(ASCE)WR.1943-5452.0000284, 2013.

Stage, S. and Larsson, Y.: Incremental cost of water power, Power Appar. Syst. Part III. Transactions Am. Inst. Electr. Eng., 80, 361–364, 1961.

Stedinger, J. R., Sule, B. F., and Loucks, D. P.: Stochastic dynamic programming models for reservoir operation optimization, Water Resour. Res., 20, 1499–1505, doi:10.1029/WR020i011p01499, 1984.

The People's Government of Hebei Province: Water diversion project will benefit 500 million people, available at: http://www.chinadaily.com.cn/china/2012-12/27/content_16062623.htm (last access: 19 April 2013), 2012.

Thiem, G.: Hydrologische Methoden, Gebhardt, Leipzig, 56 pp., 1906.

Tsur, Y.: The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development, Water Resour. Res., 26, 811–818, doi:10.1029/WR026i005p00811, 1990.

Tsur, Y. and Graham-Tomasi, T.: The buffer value of groundwater with stochastic surface water supplies, J. Environ. Econ. Manag., 21, 201–224, doi:10.1016/0095-0696(91)90027-G, 1991.

USDA Foreign Agricultural Service: Grain and Feed Annual 2012, GAIN Rep. Number CH12022, available at: http://gain.fas.usda.gov/RecentGAINPublications/GrainandFeedAnnual_Beijing_China-PeoplesRepublicof_3-2-2012.pdf (last access: 15 June 2015), Peoples Republic of China, 2012.

USGS: Shuttle Radar Topography Mission, 1 Arc Second scenes, Unfilled Unfinished 2.0, Univ. Maryland, College Park, Maryland, 2004.

USGS: Eurasia land cover characteristics database version 2.0, USGS land use/land cover scheme, United States Geological Survey, available at: http://edc2.usgs.gov/glcc/tablambert_euras_as.php (last access: 18 July 2013), 2013.

Wang, B., Jin, M., Nimmo, J. R., Yang, L., and Wang, W.: Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers, J. Hydrol., 356, 209–222, doi:10.1016/j.jhydrol.2008.04.011, 2008.

World Bank: Agenda for Water Sector Strategy for North China, Volume 2, Main Report, Report No. 22040-CHA CHINA, available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2005/11/23/000012009_20051123104326/Rendered/PDF/220400rev00WHITE0Volume121Main1Report.pdf (last access: 15 June 2015), 2001.

Yu, H.: Shanxi to raise electricity price, Chinadaily, available at: http://www.chinadaily.com.cn/business/2011-04/15/content_12335703.htm (last access: 5 August 2014), 2011.

Zhang, L., Potter, N., Hickel, K., Zhang, Y., and Shao, Q.: Water balance modeling over variable time scales based on the Budyko framework–model development and testing, J. Hydrol., 360, 117–131, doi:10.1016/j.jhydrol.2008.07.021, 2008.

Zheng, C., Liu, J., Cao, G., Kendy, E., Wang, H., and Jia, Y.: Can China cope with its water crisis? – Perspectives from the North China Plain, Groundwater, 48, 350–354, doi:10.1111/j.1745-6584.2010.00695_3.x, 2010.

Table 1. Annual water demands and curtailment costs for the users in the Ziya River Basin.

	Upstream	Downstream	
Water demands (10^6 m^3 month^{-1})			
Industries	539	543	[a]
Domestic	223	864	[b]
Maize	569	1522	[c]
Wheat	–	6089	[c]
Beijing	–	1000	[d]
Ecosystems	–	100	[e]
Total	1331	10 119	
Curtailment costs (CNY m^{-3})			
Industries	5.3	5.3	[f]
Domestic	3.2	3.2	[f]
Maize	1.8	2.8	[g]
Wheat	–	2.1	[g]
Beijing	–	5.5	[h]

[a] Demands scaled with area, (Berkoff, 2003; Moiwo et al., 2010; World Bank, 2001).

[b] Based on daily water demand (National Bureau of Statistics of China, 2011) scaled with the 2007 population from Landscan (Bright et al., 2008).

[c] Based on the land cover (USGS, 2013) and irrigation practices collected in the field. The wheat irrigation demand is evenly distributed in Mar, Apr, May and Jun. Maize is irrigated in July.

[d] Based on plan by The People's Government of Hebei Province (2012), (Ivanova, 2011).

[e] Estimated deficit in the Baiyangdian Lake (Honge, 2006).

[f] Estimate by World Bank (2001).

[g] Based on the water use efficiency (Deng et al., 2006) and producers' prices (USDA Foreign Agricultural Service, 2012).

[h] Estimate by Berkoff (2003).

Table 2. Average total costs, hydropower benefits and shadow prices for different scenario runs. Pre 2008 = before the SNWTP, 2008–2014 = SNWTP partly finished (emergency plan), Post 2014 = SNWTP finished (water from Yangtze to Beijing), LGW are results from a run with initial groundwater storage below equilibrium (100 km^3, all other scenarios are initiated at equilibrium groundwater storage), (dm) are the results with higher demands, (ct) are with 10 % higher curtailment costs and (T) with 10 % higher transmissivity, TD = Thiem steady state drawdown included, E = minimum ecosystem flow constraint (to Baiyangdian Lake), TC = minimum total costs over the planning period (51 years tested), b_{hp} = marginal hydropower benefits, DP = dynamic programming (perfect foresight), SP = shadow price.

SNWTP scenario	Scenario settings			TCSDP	b_{hp}SDP	TCDP	b_{hp}DP	SP E	SP SNWTP
	Special run	TD	E	10^9 CNY y^{-1}	10^6 CNY y^{-1}	10^9 CNY y^{-1}	10^6 CNY y^{-1}	CNY m^{-3}	CNY m^{-3}
pre-2008		+	+	14.87	103.6				
2008–2014		+	+	11.69	103.5				3.2
post-2014				8.43	103.5				5.0
post-2014		+		8.47	103.6				4.9
post-2014		+	+	8.56	104.3	8.46	101.5	0.91	4.9
post-2014	LGW	+	+	13.32	99.2				1.2
post-2014	T	+	+	8.69	103.5				4.8
post-2014	dm	+	+	8.74	103.3				4.7
post-2014	ct	+	+	9.08	103.1				4.5

Table 3. Nomenclature.

F_t^*	optimal value function in stage t (2005 Chinese Yuan, CNY)
$V_{\mathrm{gw},t}$	stored volume in the groundwater aquifer, decision variable (m^3)
$V_{\mathrm{sw},t}$	stored volume in the surface water reservoir, decision variable (m^3)
$V_{\mathrm{max,sw}}$	upper storage capacity, surface water reservoir (m^3)
$V_{\mathrm{max,gw}}$	upper storage capacity, groundwater aquifer (m^3)
$Q_{\mathrm{sw},t}$	river runoff upstream reservoirs, stochastic variable ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
$Q_{\mathrm{gw},t}$	groundwater recharge, assumed to be perfectly correlated with $Q_{\mathrm{sw},t}$ ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
m	indicates the M water users
gw	groundwater
sw	surface water
ct	water curtailments
x	allocated volume, decision variable ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
c	marginal costs ($\mathrm{CNY\,m^{-3}}$). The costs are all constants, except from c_{gw} which is correlated to the specific pump energy (see Eqs. 11–16)
r_{t}	reservoir releases through hydropower turbines, decision variable ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
R	upper surface water reservoir turbine capacity ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
s_{sw}	reservoir releases exceeding R, decision variable ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
b_{hp}	marginal hydropower benefits ($\mathrm{CNY\,m^{-3}}$)
k	indexes the K inflow classes in stage t
l	indexes the L inflow classes in $t+1$
p_{kl}	transition probability from k to l
dm_m	water demand for user m ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
u	indexes the U upstream users
d	indexes the D downstream users
s_{gw}	spills from aquifer when $V_{\mathrm{gw},t}+Q_{\mathrm{sw},t}-x_{\mathrm{gw},t}>V_{\mathrm{max,sw}}$ ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
X_{gw}	maximum monthly groundwater pumping in the upstream basin ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
$q_{\mathrm{E},t}$	unused surface water available to ecosystems, decision variable ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
Q_{E}	minimum in-stream ecosystem flow constraint ($\mathrm{m}^3\,\mathrm{month}^{-1}$)
Bei	Beijing user
Q_{SNWTP}	maximum capacity of the SNWTP canal ($\mathrm{m}^3\,\mathrm{month}^{-1}$)

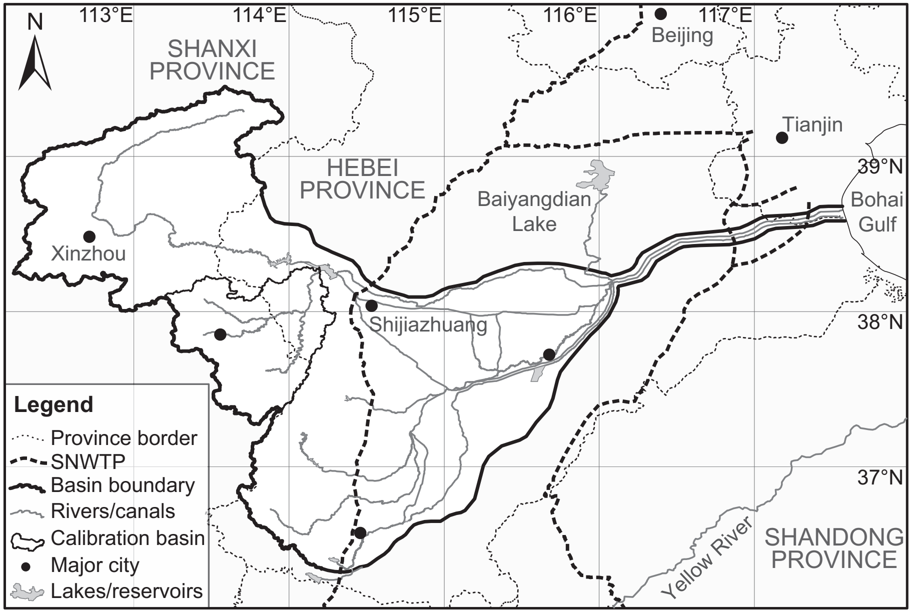

Figure 1. The Ziya River Basin. Watershed and rivers automatically delineated from a digital elevation map (USGS, 2004) and manually verified and corrected with Google Earth (Google Inc., 2013). The SNWTP routes (Central and Eastern) were sketched in Google Earth and verified with field observations. Provincial boundaries from (NGCC, 2009).

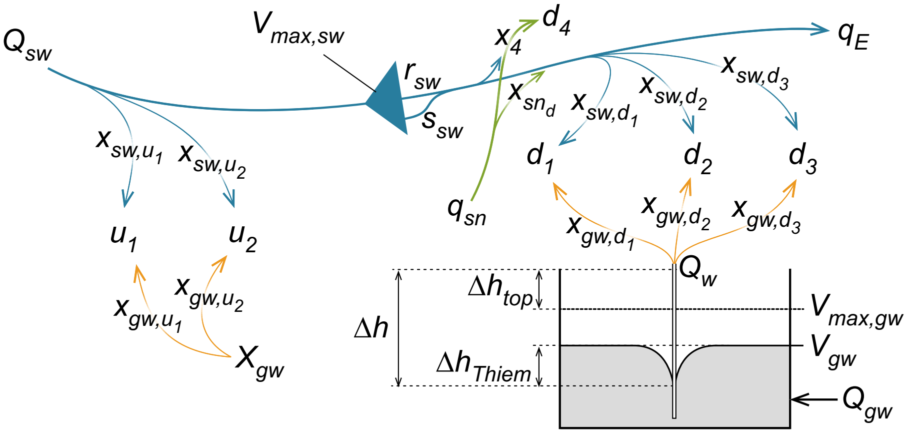

Figure 2. Conceptual sketch of the Ziya River Basin management problem with water users located upstream (u) and downstream (d) the surface water reservoir. Allocation decision variables are indicated for surface water (blue), SNWTP water (green) and groundwater (orange). A conceptual sketch of the downstream dynamic aquifer is included and show how the total lift (Δh) is composed of the top layer + the regional groundwater lowering + the local Thiem steady state groundwater drawdown.

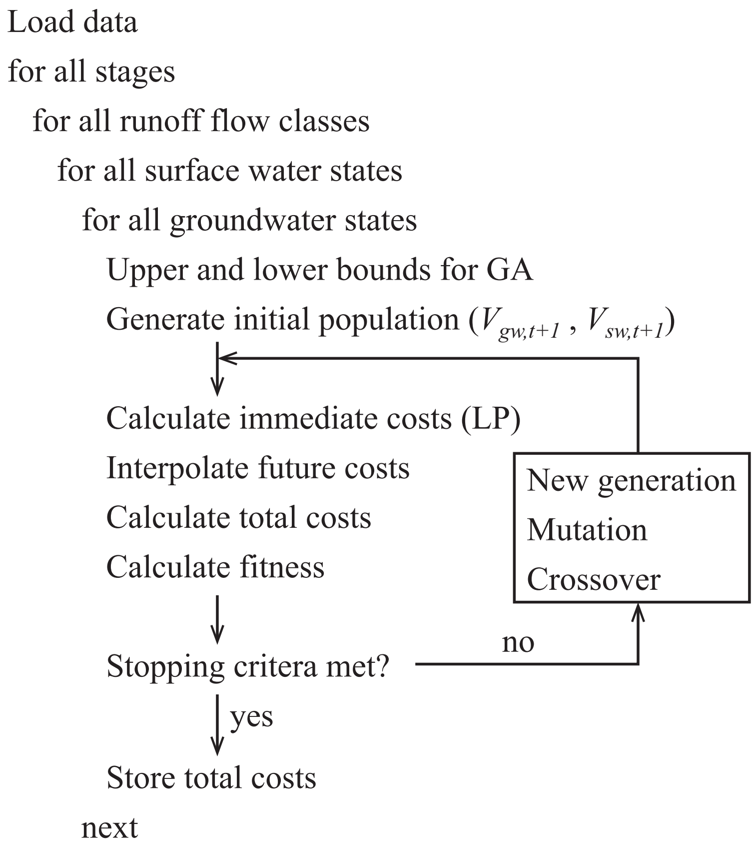

Figure 3. SDP optimization algorithm design.

HESSD
12, 5931–5966, 2015

The cost of ending groundwater overdraft on the North China Plain

C. Davidsen et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

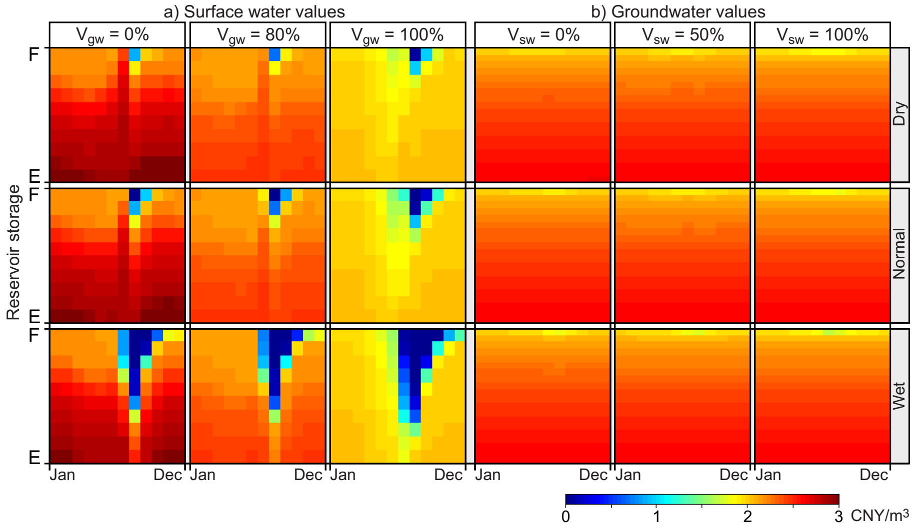

Figure 4. Temporal changes of the water values (CNY m^{-3}) for the climate period before 1980. The marginal water value is the true value of storing a unit volume of water for later use, and varies with reservoir storage levels, runoff flow class and time of the year. **(a)** Surface water values at fixed [0, 50, 100 %] groundwater aquifer storage. **(b)** Groundwater values over time at fixed [0, 50, 100 %] surface reservoir. The reservoir storage is shown from E (empty) to F (full).

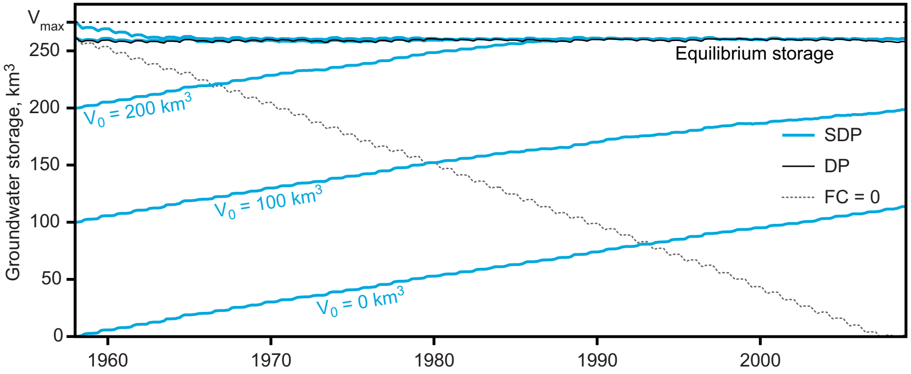

Figure 5. Simulated groundwater aquifer storage levels for 51 years of historical runoff with different initial groundwater storage(0, 100, 200, 258 and 275 km^3). The perfect foresight DP and management without consideration of the future (FC = 0) are also shown.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

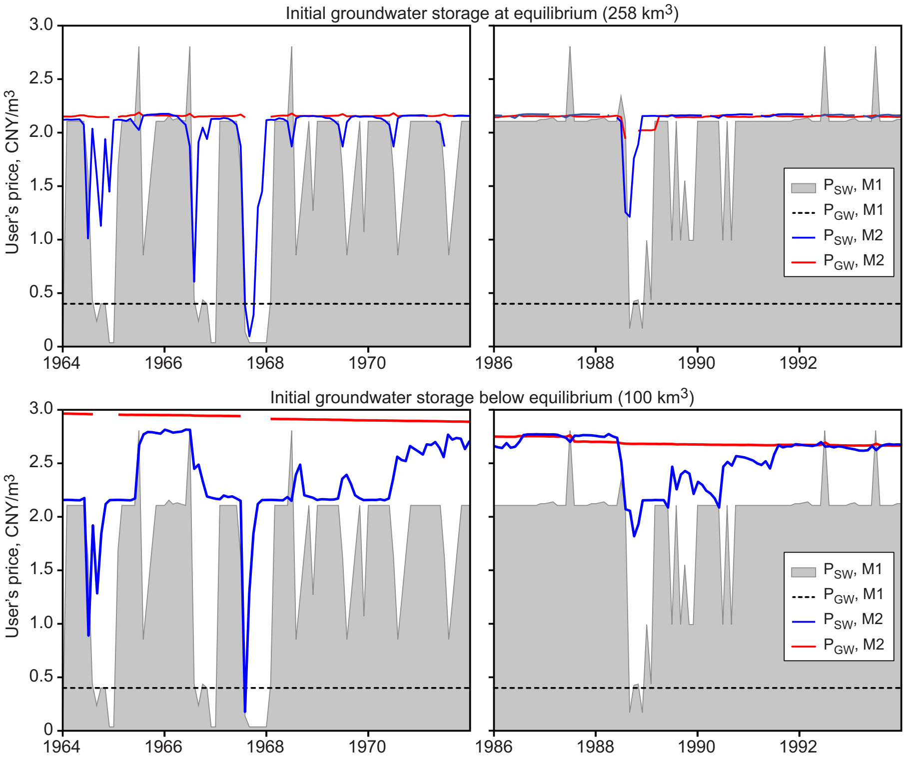

Figure 6. User's price for groundwater and surface water through for a 51 year simulation based on simulated historical runoff for two initial groundwater storages. P = user's price, M1 = results from Davidsen et al. (2014) with a single combined surface water reservoir and constant groundwater costs, M2 = results from the presented model framework with a combined surface water reservoir and a dynamic groundwater aquifer. The user's price for groundwater in M2 is the immediate pumping costs added the opportunity costs from the water value tables.

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The cost of ending groundwater overdraft on the North China Plain

C. Davidsen et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

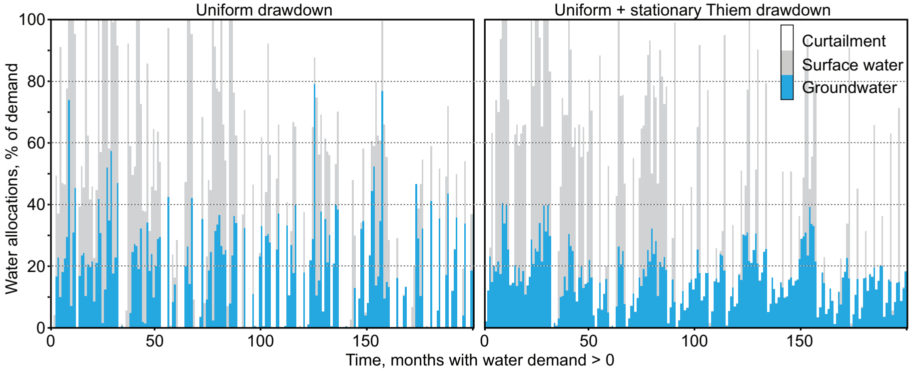

Figure 7. Composition of allocations and curtailments to wheat agriculture in the Hebei Province for the months March, April, May and June through 51 years simulation from an initial groundwater storage at equilibrium (258 km^3). The results are shown for a simple drawdown model with uniform regional lowering of the groundwater table, and a more realistic drawdown model which includes the stationary Thiem local drawdown cones.