

1 The cost of ending groundwater overdraft on the North 2 China Plain

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12 Abstract

13 Over-exploitation of groundwater reserves is a major environmental problem around the
14 world. In many river basins, groundwater and surface water are used conjunctively and joint
15 optimization strategies are required. A hydroeconomic modelling approach is used to find
16 cost-optimal sustainable surface water and groundwater allocation strategies for a river basin,
17 given an arbitrary initial groundwater level in the aquifer. A simplified management problem
18 with conjunctive use of scarce surface water and groundwater under inflow and recharge
19 uncertainty is presented. Because of head-dependent groundwater pumping costs the
20 optimization problem is non-linear and non-convex, and a genetic algorithm is used to solve
21 the 1-step-ahead subproblems with the objective of minimizing the sum of immediate and
22 expected future costs. A real-world application in the water-scarce Ziya River Basin in
23 northern China is used to demonstrate the model capabilities. Persistent overdraft from the
24 groundwater aquifers on the North China Plain has caused declining groundwater levels. The
25 model maps the marginal cost of water in different scenarios, and the minimum cost of ending
26 groundwater overdraft in the basin is estimated to be 5.58 billion CNY/year. The study shows
27 that it is cost-effective to slowly recover the groundwater aquifer to a level close to the
28 surface while gradually lowering the groundwater value to the equilibrium at 2.15 CNY/m³.
29 The model can be used to guide decision makers to economic efficient long-term sustainable
30 of groundwater and surface water resources management.

31 **1 Introduction**

32 Groundwater aquifers are of high economic importance around the world and often act as
33 buffers in the water supply system during droughts (Tsur and Graham-Tomasi, 1991; Tsur,
34 1990). On the North China Plain, persistent groundwater overexploitation over the past
35 decades has caused decline of the shallow and deep groundwater tables (Liu et al., 2001). The
36 immediate benefits of satisfying the water demands greatly exceed the costs of pumping,
37 which highlights the problem of the present self-regulating management. As the groundwater
38 resource is overexploited, the immediate benefits of the increased unsustainable supply have
39 to be traded off against the long term increase in pumping costs and reduced buffering
40 capacity. Optimal allocation of the water resources should address coordinated use of the
41 water resources by considering the long term total costs while utilizing the groundwater as a
42 buffer. This is in line with the 2011 Chinese No. 1 Policy Document, which targets
43 improvement of the water use efficiency and reduction of water scarcity (CPC Central
44 Committee and State Council, 2010).

45 Optimal management of conjunctive use of surface water and groundwater has been
46 addressed widely in the literature (e.g Booker et al., 2012; Burt, 1964; Knapp and Olson,
47 1995; Labadie, 2004; Noel and Howitt, 1982). While control-based methods, such as Model
48 Predictive Control (MPC, e.g. Morari and Lee, 1999; Mayne et al., 2000) and Reinforcement
49 Learning (RL, Lee and Labadie 2007), focus on deriving real-time optimal control policies,
50 this study will focus on planning oriented optimization techniques. Deterministic optimization
51 problems for a given time horizon allow a detailed representation of the groundwater system
52 using spatially distributed groundwater models (Andreu et al., 1996; Harou and Lund, 2008;
53 Marques et al., 2006; Pulido-Velázquez et al., 2006). Stochasticity is commonly represented
54 in scenarios where a regression analysis is used to formulate operation rules, see e.g. the
55 Implicit Stochastic Optimization (ISO) approaches reviewed by Labadie (2004). Singh (2014)
56 reviewed the use of simulation-optimization (SO) modeling for conjunctive groundwater and
57 surface water use. In SO-based studies, efficient groundwater simulation models are used to
58 answer “what if”-questions while an optimization model is wrapped around the simulation
59 model to find “what is best”. Groundwater aquifers have been represented as simple
60 deterministic box or “bathtub” models (e.g. Cai et al., 2001; Riegels et al., 2013) and as
61 spatially distributed models (e.g. Maddock, 1972; Siegfried et al., 2009) with stochasticity

62 (Reichard, 1995; Siegfried and Kinzelbach, 2006). While the results obtained from these
63 methods are rich in detail, they yield only a single solution to the optimization problem.

64 Dynamic Programming (DP, Bellman 1957) based methods have been used extensively been
65 to demonstrate the dynamics of conjunctive groundwater – surface water use for both
66 deterministic (e.g. Buras, 1963; Provencher and Burt, 1994; Yang et al., 2008) and stochastic
67 (SDP, e.g. Burt, 1964; Philbrick and Kitanidis, 1998; Provencher and Burt, 1994; Tsur and
68 Graham-Tomasi, 1991) optimization problems. In DP-based methods, the original
69 optimization problem is decomposed into subproblems which are solved sequentially over
70 time. The entire decision space is thereby mapped, enabling use of the results as dynamic
71 decision rules. However, the number of subproblems grows exponentially with the number of
72 state variables and this *curse of dimensionality* has frequently limited the use of DP and SDP
73 (Labadie, 2004; Provencher and Burt, 1994; Saad and Turgeon, 1988). Although it causes loss
74 of detail and inability to disaggregate the results, reservoir aggregation has been suggested as
75 one solution strategy (Saad and Turgeon, 1988).

76 This study aims to answer the following two macro-scale decision support questions for
77 conjunctive groundwater and surface water management for the Ziya River Basin in North
78 China: 1) *what are the minimum costs of ending groundwater overdraft?* and 2) *what is the*
79 *cost-efficient recovery strategy of the over-pumped aquifer?* A hydroeconomic modeling
80 approach is used to identify the least-cost strategy to achieve sustainable groundwater
81 abstraction, defined as the long term average abstraction not exceeding the long term average
82 recharge. To overcome the management problem similar to Harou and Lund (2008) with
83 increased complexity caused by uncertain surface water runoff and groundwater recharge, the
84 surface water reservoirs are aggregated. This is adequate at macro-scale (Davidsen et al.,
85 2015) and allow use of dynamic programming based approaches. The cost minimization
86 problem is solved with the water value method, a variant of SDP (Stage and Larsson, 1961;
87 Stedinger et al., 1984) which produces dynamic tables of marginal costs linked to states,
88 stages and water source. Head and rate dependent pumping costs introduce non-linearity in
89 the discrete subproblems. This nonlinearity is handled with a hybrid Genetic Algorithm (GA)
90 and Linear Programming (LP) method similar to that used by Cai et al. (2001), here applied in
91 a coupled groundwater-surface water management problem within an SDP framework.

92 **2 Methods**

93 **2.1 Study area**

94 Northern China and particularly the North China Plain (NCP) have experienced increasing
95 water scarcity problems over the past 50 years due to population growth, economic
96 development and reduced precipitation (Liu and Xia, 2004). The deficit in the water balance
97 has historically been covered by overexploitation of the groundwater aquifer, causing a
98 regional lowering of the groundwater table by up to 1 m/year (Zheng et al., 2010).

99 The Ziya River Basin, a part of the Hai River Basin, was selected as case study area (see
100 Figure 1). The upper basin is located in the Shanxi Province, while the lower basin is located
101 in the Hebei Province on the NCP. The 52,300 km² basin has approximately 25 million
102 inhabitants (data from 2007, Bright et al., 2008), and severe water scarcity is causing multiple
103 conflicts. Five major reservoirs with a combined storage capacity of 3.5 km³ are located in the
104 basin. While reservoir rule curves and flood control volumes can easily be accommodated,
105 policies applied in practical management today were not accessible for the case area. Instead
106 it is assumed that the full storage capacity can be managed flexibly without consideration of
107 storage reserved for flood protection or existing management rules. Incorporating flood
108 storage volumes will reduce the available storage and increase water scarcity in the long dry
109 season. In the present model setup, we therefore find the lower limit on water scarcity costs,
110 assuming that the entire storage capacity is available for storing water. Reservoir spills will
111 cause an economic loss, and the model tends to avoid spills by entering the rainy season with
112 a low reservoir storage level.

113 A previous hydroeconomic study of the Ziya River Basin was a traditional implementation of
114 SDP on a single-reservoir system (surface water reservoir) and showed optimal water
115 management, while disregarding dynamic groundwater storage and head-dependent
116 groundwater pumping costs (Davidsen et al., 2015). Instead, the groundwater resource was
117 included as a simple monthly upper allocation constraint.

118 In the present study, the groundwater resource is included as a dynamic aquifer box model
119 with a storage capacity of 275 km³. The river basin has two aquifers (upstream and
120 downstream) which are only connected by the river. Ideally, each aquifer should be modelled
121 as a box model, but this extra state variable would be computationally challenging within the
122 SDP framework. We therefore set up a box model for the downstream and most important

123 aquifer only and abstraction from the upstream aquifer is only bounded by an upper pumping
124 limit corresponding to the average monthly recharge. The box model for the downstream
125 aquifer is formulated as *Infiltration + Storage = Pumping + Overflow*. The groundwater
126 overflow is only used in extreme cases, where the total pumping and available storage is less
127 than the infiltration. The spills will go to the spill variable and leave the system, as baseflow
128 to the rivers (unavailable for allocation). The aquifer is so heavily over-exploited that no
129 significant baseflow is being created or will be created in any foreseeable future. The box
130 model allows for more flexible management with large abstractions in dry years and increased
131 recharge in wet years. The groundwater aquifer can thereby be used to bridge longer drought
132 periods. Except from the groundwater box model, the conceptual model is identical to the one
133 used by Davidsen et al. (2015).

134 A conceptual sketch of the management problem is shown in Figure 2. The water users are
135 divided into groups of economic activities; irrigation agriculture, industrial and domestic
136 water users. Ideally, each water user group should be characterized by flexible demand
137 curves, but due to poor data availability a constant water demand (m^3) and a constant
138 curtailment cost of not meeting the demand were used for each group (see Table 1). The water
139 demands are assumed to be deterministic and decoupled from the stochastic runoff. This is a
140 reasonable assumption because the rainfall on the NCP normally occurs in the summer
141 months, while irrigation water demands are concentrated in the dry spring. The irrigation
142 schedule is centrally planned and typically unchanged from year to year. The upstream (u)
143 users have access to runoff and are restricted to an upper pumping limit X_{gw} corresponding to
144 the average monthly upstream recharge, while the downstream users (d) have access to
145 reservoir releases, water delivered through the South-to-North Water Transfer Project
146 (SNWTP) and groundwater from the downstream aquifer.

147 **2.2 Optimization model formulation**

148 An SDP formulation is used to find the expected value of storing an incremental amount of
149 surface water or groundwater, given the month of the year, the available storage in surface
150 and groundwater reservoirs and the inflow scenarios. The backward recursive equation
151 calculates the sum of immediate and expected future costs for all combinations of discrete
152 reservoir storage levels (states) and monthly time steps (stages). The immediate management
153 costs (IC) arise from water supply and water curtailment, whereas the expected future costs

154 (EFC) are the optimal value function in $t+1$ weighed by the corresponding transition
 155 probabilities. In the present setup, we decided to weigh the IC and EFC equally, but inclusion
 156 of discount rates other than zero is possible. Because of the head and rate dependent
 157 groundwater pumping costs, which will be described in detail later, the immediate cost
 158 depends non-linearly on the decision variables. The objective is to minimize the total costs
 159 over the planning period, given by the optimal value function $F_t^*(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k)$ based on
 160 the classical Bellman formulation:

$$161 \quad F_t^*(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) = \min \left(IC(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) + \sum_{l=1}^L (p_{kl} F_{t+1}^*(V_{gw,t+1}, V_{sw,t+1}, Q_{sw,t+1}^l)) \right) \quad (1)$$

162 with IC being the immediate costs:

$$163 \quad IC(V_{gw,t}, V_{sw,t}, Q_{sw,t}^k) = \sum_{m=1}^M (c_{sw} x_{sw} + c_{gw} x_{gw} + c_{SNWTP} x_{SNWTP} + c_{ct} x_{ct})_{m,t} - r_{sw,t} b_{hp} \quad (2)$$

164 subject to:

$$165 \quad x_{sw,m,t} + x_{gw,m,t} + x_{SNWTP,m,t} + x_{ct,m,t} = dm_{m,t} \quad (3)$$

$$166 \quad V_{sw,t} + Q_{sw,t} - \sum_{u=1}^U x_{sw,u,t} - r_{sw,t} - s_{gw,t} = V_{gw,t+1} \quad (4)$$

$$167 \quad r_{sw,t} + s_{sw,t} = \sum_{d=1}^D x_{sw,d,t} + q_{E,t} \quad (5)$$

$$168 \quad V_{gw,t} + Q_{gw,t} - \sum_{d=1}^D x_{gw,d,t} - s_{gw,t} = V_{gw,t+1} \quad (6)$$

$$169 \quad \sum_{u=1}^U x_{sw,u,t} \leq Q_{sw,t} \quad (7)$$

$$170 \quad \sum_{u=1}^U x_{gw,u,t} \leq X_{gw,t} \quad (8)$$

$$171 \quad r_t \leq R, \quad x_{sw,Bei} + x_{SNWTP,Bei} \leq Q_{SNWTP}, \quad q_{E,t} \geq Q_E, \quad V_{sw,t} \leq V_{\max,sw}, \quad V_{gw,t} \leq V_{\max,gw} \quad (9)$$

$$172 \quad c_{gw} = f \left(V_{gw}, \sum_{d=1}^D x_{sw,d} \right) \quad (10)$$

173 See Table 2 for nomenclature.

174 Eq. (3) is the water demand fulfillment constraint, i.e. the sum of water allocation and water
 175 curtailments equals the water demand of each user. Eq. (4) is the water balance of the

176 combined surface water reservoir, while Eq. (5) is the water balance of the reservoir releases.
177 A similar water balance for the dynamic groundwater aquifer follows in Eq. (6). The upstream
178 surface water allocations are constrained by the upstream runoff as shown in Eq. (7), while
179 the upstream groundwater allocations are constrained to a fixed sustainable monthly average
180 as shown in Eq. (8). In Eq. (9), the upper and lower hard constraints on the decision variables
181 are shown. Last, Eq. (10) is the marginal groundwater pumping cost, which depends on the
182 combined downstream groundwater allocations as described later.

183 A rainfall-runoff model based on the Budyko Framework (Budyko, 1958; Zhang et al., 2008)
184 has in a previous study been used to estimate the near-natural daily surface water runoff into
185 reservoirs (Davidsen et al., 2015). The resulting 51 years (1958-2008) of simulated daily
186 runoff was aggregated to monthly runoff and normalized. A Markov chain, which describes
187 the runoff serial correlation between three flow classes defined as dry (0 – 20th percentile),
188 normal (20th – 80th percentile), and wet (80th – 100th percentile), was established and validated
189 to ensure second order stationarity (Davidsen et al., 2015; Loucks and van Beek, 2005). The
190 groundwater recharge is estimated from the precipitation data also used in the rainfall-runoff
191 model. The average monthly precipitation (mm/month) for each runoff class is calculated, and
192 a simple groundwater recharge coefficient of 17.5% of the precipitation (Wang et al., 2008) is
193 used.

194 The SDP loop is initiated with EFC set to zero and will propagate backward in time through
195 all the discrete system states as described in the objective function. For each discrete
196 combination of states, a cost minimization subproblem will be solved. A subproblem will
197 have the discrete reservoir storage levels ($V_{gw,t}$ and $V_{sw,t}$) as initial conditions and reservoir
198 inflow is given by the present inflow class in the Markov chain The optimization algorithm
199 will search for the optimal solution, given the costs of the immediate management (water
200 allocations and water curtailments, including reservoir releases and groundwater pumping),
201 which have to be balanced against the expected future costs. As the SDP algorithm is
202 propagating backward in time, the future costs will be equal to the minimum total costs from
203 $t+1$, weighted by the Markov chain transition probabilities. The algorithm will continue
204 backward in time until equilibrium is reached, i.e. until the shadow prices (marginal value of
205 storing water for future use) in two successive years remain constant. The SDP model is
206 developed in MATLAB (MathWorks Inc., 2013) and uses the fast *cplexlp* (IBM, 2013) to
207 solve the linear subproblems.

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

214 **2.3 Dynamic groundwater aquifer**

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

$$219 \quad P = (\rho g \Delta h) / \varepsilon \quad (11)$$

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

$$224 \quad c_{gw} = c_{el} P \quad (12)$$

225 Hence this cost will vary with the stored volume in the groundwater aquifer. The present
 226 electricity price structure in China is quite complex, with the users typically paying between
 227 0.4 and 1 CNY/kWh depending on power source, province and consumer type (Li, 2012; Yu,
 228 2011). In this study a fixed electricity price of 1 CNY/kWh is used. The immediate costs of
 229 supplying groundwater to a single user follow:

$$230 \quad c_{gw,t} x_{gw,t} = \rho g \Delta h \varepsilon^{-1} c_{el} x_{gw,t} \quad (13)$$

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

$$233 \quad \Delta h = \Delta h_{top} + \left(V_{\max, gw} - \frac{V_{gw,t} + V_{gw,t+1}}{2} \right) S_y^{-1} A^{-1} \quad (14)$$

234 where Δh_{top} is the distance from the land surface to the top of the aquifer at full storage (m),
 235 S_y is the specific yield (-) of the aquifer, and A is the area of the aquifer (m^2). Here $V_{gw,t+1}$ is

236 a decision variable, and once substituted into Eq. (13) it is clear that the problem becomes
 237 non-linear.

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

$$243 \quad \Delta h_{Thiem} = \frac{Q_w}{2\pi T} \ln\left(\frac{r_{in}}{r_w}\right) \quad (15)$$

244 where Q_w is the pumping rate of each well (m³/month), T is the transmissivity (m²/month),
 245 r_{in} is the radius of influence (m), and r_w is the distance from origin to the point of interest
 246 (m), here the radius of the well. The transmissivity is based on a hydraulic conductivity of
 247 $1.3 \cdot 10^{-6}$ m/s for silty loam (Qin et al., 2013). The hydraulic conductivity is lower than the
 248 expected average for the NCP to provide a conservative estimate of the effect of drawdown.
 249 Field interviews revealed that the wells typically reach no deeper than 200 m below surface,
 250 which results in a specific yield of 5%. The groundwater pumping Q_w is defined as the total
 251 allocated groundwater within the stage (m³/month) and assumed evenly distributed to the
 252 number of wells in the catchment:

$$253 \quad Q_{w,t} = \frac{\sum_{d=1}^D x_{gw,d,t}}{n_w} = \frac{V_{gw,t} - V_{gw,t+1} + Q_{gw,t} - s_{gw,t}}{n_w} \quad (16)$$

254 where n_w is the number of wells in the downstream basin. The even pumping distribution is a
 255 fair assumption, as field investigations showed that 1) the majority of the groundwater wells
 256 are for irrigation, 2) the timing of irrigation, crop types and climate is homogeneous and 3)
 257 the groundwater wells have comparable capacities. Erlendsson (2014) estimated the well
 258 density in the Ziya River Basin from Google Earth to be 16 wells/km². Assuming that the
 259 wells are distributed evenly on a regular grid and that the radius of influence r_{in} is 500 m,
 260 overlapping cones of depression from 8 surrounding wells are included in the calculation of
 261 the local drawdown. This additional drawdown is included using the principle of
 262 superposition as also applied by Erlendsson (2014).

263 2.4 Solving non-linear and non-convex subproblems

264 With two reservoir state variables and a climate state variable, the number of discrete states is
265 quickly limited by the *curse of dimensionality*. A very fine discretization of the groundwater
266 aquifer to allow discrete storage levels and decisions is computationally infeasible. A low
267 number of discrete states increases the discretization error, particularly if both the initial and
268 the end storages $V_{gw,t+1}$ and $V_{sw,t+1}$ are kept discrete. The discrete volumes of the large aquifer
269 become much larger than the combined monthly demands, and storing all recharge will
270 therefore not be sufficient to recharge to a higher discrete storage level. Similarly, the
271 demands will be smaller than the discrete volumes, and pumping the remaining water to reach
272 a lower discrete level would also be infeasible. Allowing free end storage in each subproblem
273 will allow the model to pick e.g. the optimal groundwater recharge and pumping without a
274 requirement of meeting an exact discrete end state. With free surface water and groundwater
275 end storages, the future cost function has three dimensions (surface water storage,
276 groundwater storage and expected future costs). Pereira and Pinto (1991) used Benders'
277 decomposition approach, which employs piecewise linear approximations and requires
278 convexity. With head and rate dependent pumping costs and increasing electricity price, we
279 observed that the future cost function changes from strictly convex (very low electricity price)
280 to strictly concave (very high electricity price). At realistic electricity prices, we observed a
281 mix of concave and convex shapes. An alternative is to use linear interpolation with defined
282 upper and lower bounds. However, with two state variables, interpolation between the future
283 cost points will yield a hyperplane in three dimensions, which complicates establishment of
284 boundary conditions for each plane.

285 Non-linear optimization problems can be solved with evolutionary search methods, a sub
286 division of global optimizers. A widely used group of evolutionary search methods are
287 genetic algorithms (GAs), which are found to be efficient tools for getting approximate
288 solutions to complex non-linear optimization problems (see, e.g., Goldberg, 1989; Reeves,
289 1997). GAs use a random search approach inspired by natural evolution and have been
290 applied to the field of water resources management by, e.g., Cai et al. (2001), McKinney and
291 Lin (1994) and Nicklow et al. (2010). Cai et al. (2001) used a combined GA and LP approach
292 to solve a highly non-linear surface water management problem. By fixing some of the
293 complicating decision variables, the remaining objective function became linear and thereby
294 solvable with LP. The GA was used to test combinations of the fixed parameters while

295 looking for the optimal solution. The combination yielded faster computation time than if the
296 GA was used to estimate all the parameters.

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

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

319 For a given combination of stages, discrete states and flow classes, the objective of the GA is
320 to minimize the total costs, TC , with the free states $V_{gw,t+1}$, $V_{sw,t+1}$ being the decisions:

$$321 \quad TC(V_{gw,t+1}, V_{sw,t+1}) = \min IC(V_{gw,t+1}, V_{sw,t+1}) + EFC(V_{gw,t+1}, V_{sw,t+1}) \quad (17)$$

322 with EFC being the expected future costs. Given initial states and once the GA has chosen
323 the end states, the immediate cost minimization problem becomes linear and hence solvable
324 with LP (see Figure 3). The expected future costs are found by cubic interpolation of the

325 discrete neighboring future cost grid points in each dimension of the matrix. The GA
326 approaches the global optimum until a fitness limit criteria is met. The total costs are stored,
327 and the algorithm continues to the next state. To reduce the computation time, the outer loop
328 through the groundwater states is parallelized.

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

336 **3 Results**

337 Without any regulation or consideration of the expected future costs arising from over-
338 exploitation of the groundwater aquifer, the water users will continue maximizing immediate
339 profits (producers) or utility (consumers). Because there are only electricity costs for
340 groundwater, the users will continue pumping groundwater until the marginal groundwater
341 cost exceeds the curtailment costs. At 1 CNY/kWh the marginal cost of lifting groundwater
342 200 m (typical depth of wells observed in the study area) can be found with Eq. (13)-(14) to
343 be 0.8 CNY/m³ and thereby less than the lowest curtailment cost at 2.3 CNY/m³. It requires
344 an electricity price higher than 2.8 CNY/kWh before the lowest-value user stops pumping
345 from 200 m below surface.

346 The backward recursive SDP algorithm was run with a looped annual dataset until
347 equilibrium water values, i.e. no inter-annual changes, were obtained. The water values
348 increase fastest during the first years, and after approximately 100 years the annual increases
349 become small. Due to the large storage capacity of the groundwater aquifer, equilibrium is
350 however not achieved until after 150-180 years. These marginal water values represent the
351 true values of storing a unit volume of water for later use, and vary with reservoir storage
352 levels, runoff flow class and time of the year. A sample of the resulting equilibrium water
353 value tables are presented in Figure 4. This figure shows the temporal variations of water
354 values as a function of one state variable, keeping the other state variable at a fixed value. The
355 state variables are fixed at empty, half full and full storage respectively. During the rainy
356 season from June to August, high precipitation rates reduce water scarcity, resulting in lower

357 surface water values. Because the groundwater storage capacity is much larger, increased
358 recharge can easily be stored for later use, and groundwater values are therefore not affected.
359 Addition of stream-aquifer interactions to the model is expected to affect this behavior, but
360 since the flow in rivers/canals in the case study area is small most of the year, and since most
361 areas are far from a river, it is a reasonable assumption to ignore these dynamics. The water
362 values after 1980 are clearly higher than in the period before 1980 due to increased water
363 scarcity caused by a reduction in the regional precipitation. In contrast, the groundwater value
364 tables are uniform, with variation only with groundwater storage. The detailed water value
365 tables are included as supplementary information.

366 We simulate management using the equilibrium water value tables as pricing policy and force
367 the system with 51 years of simulated historical runoff. Time series of the simulated
368 groundwater storage can be seen in Figure 5 for different initial storage scenarios. The
369 groundwater aquifer approaches an equilibrium storage level around 260 km³ (95% full). If
370 the storage in the aquifer is below this level, the average recharge will exceed average
371 pumping until the equilibrium storage is reached. If the storage level is above equilibrium,
372 average pumping will exceed average recharge until equilibrium is reached. In Figure 6, the
373 surface water and groundwater storages are shown for a situation with equilibrium
374 groundwater storage. In most years, the surface water storage falls below 1 km³, leaving space
375 in the reservoir for the rainy season. The potential high scarcity costs of facing a dry scenario
376 with an almost empty reservoir is avoided by pumping more groundwater. These additional
377 pumping costs seem to be exceeded by the benefits of minimizing spills in the rainy season.
378 To demonstrate the business-as-usual solution, the simulation model is run for a 20 year
379 period with the present water demands and curtailment costs and with a discount rate set to
380 infinity (= zero future costs). The resulting groundwater table is continuously decreasing as
381 shown in Figure 5.

382 In the simulated management runs, water will be allocated to the users up to a point where
383 reductions in immediate cost are compensated by increases in expected future costs. The
384 user's price, which can be applied in a marginal cost pricing (MCP) scheme, is the marginal
385 value of the last unit of water allocated to the users. The user's price is the sum of the actual
386 pumping cost (electricity used) and the additional marginal cost given by the equilibrium
387 water value tables. In Figure 7, the user's prices for groundwater and surface water are shown
388 for the 51 year simulation at and below the long term sustainable groundwater storage level.

389 When the groundwater storage level is close to equilibrium, the user's prices of groundwater
390 and surface water are equal during periods with water scarcity. In wet months with reduced
391 water scarcity, the model switches to surface water allocation only, and the groundwater
392 user's price is undefined (gaps in the time series in Figure 7). If the groundwater storage level
393 is below equilibrium, the groundwater user's price will be higher causing an increase in water
394 curtailments and increasing storage level as shown in Figure 5. Under these circumstances the
395 surface water user's price increases up to a point where the two prices meet. With an initial
396 aquifer storage at one third of the aquifer capacity (100 km^3), the groundwater value is 3
397 CNY/ m^3 (see Figure 7). As the aquifer slowly recovers, the groundwater price decreases
398 gradually.

399 At the equilibrium groundwater storage level, the user's prices for groundwater is stable
400 around $2.15 \text{ CNY}/\text{m}^3$ as shown in Figure 7. This indicates curtailment of wheat agriculture in
401 the downstream Hebei Province, which has a willingness to pay of $2.12 \text{ CNY}/\text{m}^3$ (see Table
402 1). The allocation pattern to this user is shown in Figure 8: the model switches between high
403 curtailment and high allocations, depending on water availability and storage in the reservoirs.
404 Groundwater allocations fluctuate between satisfying 0% and 80% of the demand. Inclusion
405 of the steady state Thiem drawdown cones in the optimization model increases the marginal
406 groundwater pumping cost with increased pumping rates. Groundwater allocations are
407 distributed more evenly over the months, which results in less local drawdown. The total
408 curtailments remain constant, while 1% of the total water abstraction is shifted from
409 groundwater to surface water, if the stationary Thiem drawdown is included. Inclusion of well
410 drawdown significantly changed the simulated management but resulted in only slightly
411 increased computation time.

412 The average total costs of the 51 years simulation for different scenarios can be seen in Table
413 3. The average reduction in the total costs, associated with the introduction of the SNWTP
414 canal can be used to estimate the expected marginal economic impact of the SNWTP water.
415 The minimum total costs after the SNWTP is put in operation are compared to the scenario
416 without the SNWTP (pre-2008) and divided by the allocated SNWTP water. The resulting
417 marginal value of the SNWTP water delivered from Shijiazhuang to Beijing (2008-2014
418 scenario) is $3.2 \text{ CNY}/\text{m}^3$, while the SNWTP water from Yangtze River (post-2014 scenario)
419 reduces the total costs with $4.9 \text{ CNY}/\text{m}^3$. Similarly, a comparison of the total costs for the

420 post-2014 scenarios shows a marginal increase of 0.91 CNY/m^3 as a consequence of
421 introducing a minimum in-stream flow constraint.

422 A local sensitivity analysis focused on the water demands and curtailment costs used directly
423 in the objective function (Eq. (1)) and the transmissivity used to estimate the local drawdown
424 (Eq. (14)). The uncertain input parameters were increased by 10% and the sensitivity
425 evaluated based on the simulation results. The resulting total costs can be seen in Table 3. The
426 benchmark DP run was run for the post-2014 scenario with Thiem drawdown and minimum
427 ecosystem flow constraint. The minimum total costs of this run is $8.46 \cdot 10^9 \text{ CNY/year}$. This is
428 1.3% lower than the equivalent SDP run ($8.56 \cdot 10^9 \text{ CNY/year}$).

429 The minimum total costs were lowered from 10.50 billion CNY/year (Davidsen et al., 2015)
430 to 8.56 billion CNY/year (18% reduction) by allowing the groundwater aquifer to be utilized
431 as a buffer instead of a fixed monthly volume. This difference highlights the problem of
432 defining realistic boundaries to optimization problems and shows that simple hard constraints,
433 here fixed groundwater pumping limits, can highly limit the optimal decision space. With a
434 dynamic groundwater aquifer, the model can mitigate dry periods and stabilize the user's
435 price of surface water as shown in Figure 7. Finally, policies like minimum in-stream
436 ecosystem flow constraints can be satisfied with less impact on the expensive users. The total
437 costs without restrictions on the groundwater pumping have been estimated to 2.98 billion
438 CNY/year (Davidsen et al., 2015). To end the groundwater overdraft in the basin, the present
439 study thus estimates a cost increase of 5.58 billion CNY/year, once the groundwater aquifer is
440 at equilibrium storage. The cost of recharging the aquifer from the present storage level below
441 the equilibrium is significantly higher. In Table 3, the LGW scenario shows that the average
442 cost of sustainable management from an initial storage at 100 km^3 (one third full) is 13.32
443 billion CNY/year.

444 From any initial groundwater reservoir storage level, the model brings the groundwater table
445 to an equilibrium storage level at approximately 95% of the aquifer storage capacity. Only
446 small variations in the aquifer storage level are observed after the storage level reaches
447 equilibrium as shown in Figure 6. While addition of the Thiem stationary drawdown has only
448 a small effect on total costs and total allocated water, it is clear from Figure 8 that the
449 additional Thiem drawdown highly impacts the allocation pattern to some of the water users.
450 High groundwater pumping rates result in larger local drawdown and thus in higher pumping

451 costs. This mechanism leads to a more uniform groundwater pumping strategy, which is
452 clearly seen in Figure 8 and results in much more realistic management policy.

453 **4 Discussion**

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

461 A first limitation of the approach is the high level of simplification needed. There are two
462 main reasons for the high level of simplification: Limited data availability and the limitations
463 of the SDP method. The *curse of dimensionality* limits the approach to 2-3 inter-linked
464 storage facilities and higher dimensional management problems will not be computationally
465 feasible with SDP today. This limit on the number of surface water reservoirs and
466 groundwater aquifers requires a strongly simplified representation of the real world situation
467 in the optimization model. The simulation phase following the optimization is not limited to
468 the same extent, since only a single subproblem is solved at each stage. The water values
469 determined by the SDP scheme can thus be used to simulate management using a much more
470 spatially resolved model with a high number of users; this was not demonstrated in this study.
471 The advantage of SDP is that it provides a complete set of pricing policies that can be applied
472 in adaptive management, provided that the system can be simplified to a computationally
473 feasible level. An alternative approach known as stochastic dual dynamic programming
474 (SDDP, Pereira and Pinto, 1991; Pereira et al., 1998) has shown great potential for multi-
475 reservoir river basin water management problems. Instead of sampling the entire decision
476 space with the same accuracy level, SDDP samples with a variable accuracy not pre-defined
477 in a grid, focusing the highest accuracy around the optimal solution. This variable accuracy
478 makes SDDP less suitable for adaptive management. Despite the highly simplified system
479 representation, we believe that the modeling framework provides interesting and non-trivial
480 insights, which are extremely valuable for water resources management on the NCP.

481 Computation time was a limitation in this study. Three factors increased the computational
482 load of the optimization model: 1) inclusion of the groundwater state variable resulted in an

483 exponential growth of the number of subproblems; 2) the non-convexity handled by the
484 slower GA-LP formulation caused an increase in the computation time of 10-100 times a
485 single LP; and 3) the SDP algorithm needed to iterate through more than 200 years to reach
486 steady-state. A single scenario run required 4,000 CPU hours and was solved in two weeks
487 using 12 cores at the high performance cluster (HPC) at the Technical University of Denmark.
488 This is 50,000 times more CPU hours than a single reservoir SDP model (Davidsen et al.,
489 2015). Since the water value tables can be used offline in the decision making, this long
490 computation time can be accepted.

491 The long computation time made the use of, e.g., Monte Carlo-based uncertainty analysis
492 infeasible. The local sensitivity analysis showed that a 10% increase in the curtailment costs
493 is returned as a 6.0% increase in the total costs, while a similar increase of the demands
494 generates a 2.1% increase in costs. The transmissivity can vary over many orders of
495 magnitude because it is a log-normally distributed variable. The sensitivity of $\log(T)$ is high:
496 a 1.3% change of $\log(T)$ from the baseline value results in a 1.5% change in the cost. At the
497 same time, the simple system representation needed in SDP required assumptions of inflow
498 and storage discretization, aggregation of the surface water reservoirs, generalized estimates
499 of pumping cost and a lumped groundwater model which all contribute to the uncertainty.
500 Further, poor data availability for the case study area required some rough estimates of the
501 natural water availability, single-point demand curves and perfect correlation between rainfall
502 and groundwater recharge. The method-driven assumptions generally limit the decision
503 support to basin-scale, while the simple estimates caused by poor data availability contribute
504 to raising the general uncertainty of the model results. Given the computational challenges
505 and the diverse and significant uncertainties, the model results should be seen as a
506 demonstration of the model capabilities rather than precise cost estimates. Better estimates
507 will require access to a more comprehensive case dataset and involve a complete sensitivity
508 analysis.

509 Intuitively, one would expect the equilibrium groundwater storage level to be as close as
510 possible to full capacity, while still ensuring that any incoming groundwater recharge can be
511 stored. Finding the exact equilibrium groundwater storage level would require a very fine
512 storage discretization, which, given the size of the groundwater storage, is computationally
513 infeasible. Therefore the equilibrium groundwater storage level is subject to significant

514 discretization errors. The long time steps (monthly) make the stationarity required for using
515 the Thiem stationary drawdown method a realistic assumption.

516 The difference between total costs with SDP and with DP (perfect foresight) is small (1.3%).
517 Apart from Beijing, which has access to the SNWTP water, the remaining downstream users
518 have unlimited access to groundwater. The large downstream groundwater aquifer serves as a
519 buffer to the system and eliminates the economic consequences of a wrong decision. The
520 model almost empties the reservoir every year as shown in Figure 6, and wrong decisions are
521 not punished with curtailment of expensive users as observed by Davidsen et al. (2015). The
522 groundwater aquifer reduces the effect of wrong decisions by allowing the model to minimize
523 spills from the reservoir without significant economic impact of facing a dry period with an
524 empty reservoir. A dynamic groundwater aquifer thereby makes the decision support more
525 robust, since it is the timing and not the amount of curtailment being affected.

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

541 A significant impact of including groundwater as a dynamic aquifer is the more stable user's
542 prices shown in Figure 7. The user's price of groundwater consists of two parts: the
543 immediate groundwater pumping costs (electricity costs) and the expected future costs
544 represented by the groundwater value for the last allocated unit of water. As the model is run
545 to equilibrium, the user's prices converge towards the long term equilibrium at approximately

546 2.2 CNY/m³. The electricity price can be used as a policy tool to internalize the user's prices
547 of groundwater shown in Figure 7. Stable water user's prices will ease the implementation of
548 e.g. a MCP scheme, which is one of the available policy options to enforce long-term
549 sustainability of groundwater management.

550 **5 Conclusions**

551 This study describes development and application of a hydroeconomic approach to optimally
552 manage conjunctive use of groundwater and surface water. The model determines the water
553 allocation, reservoir operation and groundwater pumping that minimizes the long-term sum of
554 head and rate dependent groundwater pumping costs and water curtailment costs. The model
555 is used to quantify potential savings of joint water management of the Ziya River Basin in
556 Northern China, but the model can be applied to other basins as well. Estimates of natural
557 runoff, groundwater recharge, water demands and marginal user curtailment costs are cast
558 into a SDP-based optimization framework. Regional and Thiem stationary drawdown is used
559 to estimate rate and head dependent marginal groundwater pumping costs. The resulting
560 optimization subproblems become nonlinear and non-convex and are solved with a hybrid
561 GA-LP setup. A central outcome from the SDP framework is tables of shadow prices of
562 surface and groundwater for any combination of time, inflow class and reservoir storage.
563 These tables represent a complete set of pricing policies for any combination of system states
564 and can be used to guide real-time water management. Despite a significant computational
565 demand to extract the water value tables, the method provides a suitable approach for basin-
566 scale decision support for conjunctive groundwater and surface water management.

567 The model provides useful insight to basin-scale scarcity-driven tradeoffs. The model outputs
568 time series of optimal reservoir storage, groundwater pumping, water allocation and the
569 marginal economic value of the water resources at each time step. The model is used to derive
570 a pricing policy to bring the overexploited groundwater aquifer back to a long-term
571 sustainable state. The economic efficient recovery policy is found by trading off the
572 immediate costs of water scarcity with the long term additional costs of a large groundwater
573 head. From an initial storage at one third of the aquifer capacity, the average costs of ending
574 groundwater overdraft are estimated to be 13.32 billion CNY/year. The long-term cost-
575 effective reservoir policy is to slowly recover the groundwater aquifer to a level close to the
576 surface by gradually lowering the groundwater value from an initial level of 3 CNY/m³. Once
577 at this sustainable state, the groundwater values are almost constant at 2.15 CNY/m³ which

578 suggests that wheat agriculture should generally be curtailed under periods with water
579 scarcity. The dynamic groundwater aquifer serves as a buffer to the system and is used to
580 bridge the water resources to multiple years. The average annual total costs are reduced with
581 18% to 8.56 billion CNY compared to a simpler formulation with fixed monthly pumping
582 limits. The stable user's prices are suitable to guide a policy scheme based on water prices
583 and the method has great potential as basin-scale decision support tool in the context of the
584 China No. 1 Policy Document.

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774

775 Table 1: Annual water demands and curtailment costs for the users in the Ziya River Basin.
 776 *Based on the dataset from Davidsen et al. (2015).*

	Upstream	Downstream	
Water demands (10⁶ m³/year)			
<i>Industries</i>	539	543	^a
<i>Domestic</i>	223	864	^b
<i>Maize</i>	569	1,522	^c
<i>Wheat</i>	-	6,089	^c
<i>Beijing</i>	-	1,000	^d
<i>Ecosystems</i>	-	100	^e
<i>Total</i>	1,331	10,119	
Curtailment costs (CNY/m³)			
<i>Industries</i>	5.3	5.3	^f
<i>Domestic</i>	3.2	3.2	^f
<i>Maize</i>	1.8	2.8	^g
<i>Wheat</i>	-	2.1	^g
<i>Beijing</i>	-	5.5	^h

777 ^a*Demands scaled with area, (Berkoff, 2003; Moiwo et al., 2010; World Bank, 2001)*

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

780 ^c*Based on the land cover (USGS, 2013) and irrigation practices collected in the field. The wheat irrigation demand*
 781 *is evenly distributed in March, April, May and June. Maize is irrigated in July.*

782 ^d*Based on plan by The People's Government of Hebei Province (2012), (Ivanova, 2011)*

783 ^e*Estimated deficit in the Baiyangdian Lake (Honge, 2006)*

784 ^f*Estimate by World Bank (2001)*

785 ^g*Based on the water use efficiency (Deng et al., 2006) and producers' prices (USDA Foreign Agricultural Service,*
 786 *2012)*

787 ^h*Estimate by Berkoff (2003)*

788

789 Table 2: Nomenclature.

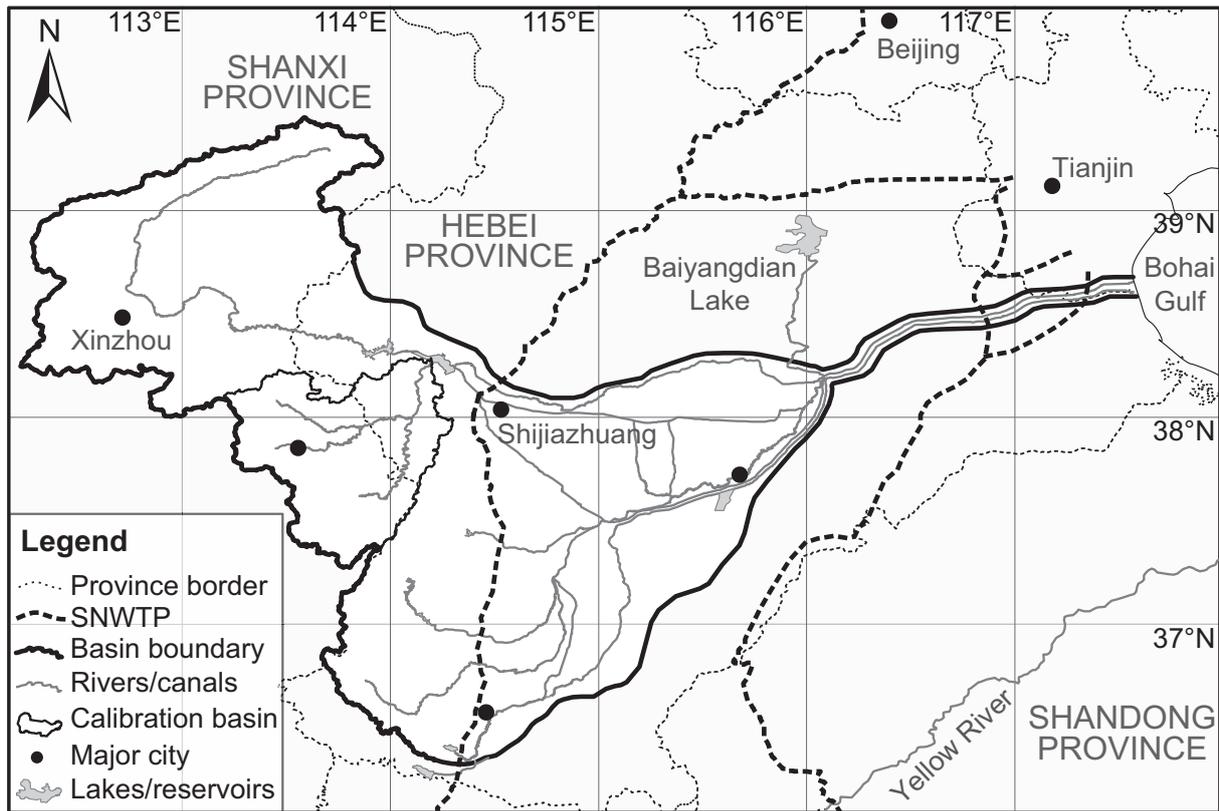
790	F_t^*	optimal value function in stage t (2005 Chinese Yuan, CNY)
791	$V_{gw,t}$	stored volume in the groundwater aquifer, decision variable (m^3)
792	$V_{sw,t}$	stored volume in the surface water reservoir, decision variable (m^3)
793	$V_{\max,sw}$	upper storage capacity, surface water reservoir (m^3)
794	$V_{\max,gw}$	upper storage capacity, groundwater aquifer (m^3)
795	$Q_{sw,t}$	river runoff upstream reservoirs, stochastic variable (m^3/month)
796	$Q_{gw,t}$	groundwater recharge, assumed to be perfectly correlated with $Q_{sw,t}$ (m^3/month)
797	m	indicates the M water users
798	gw	groundwater
799	sw	surface water
800	ct	water curtailments
801	x	allocated volume, decision variable (m^3/month)
802	c	marginal costs (CNY/ m^3). The costs are all constants, except for c_{gw} which is
803		correlated to the specific pump energy. See Eq. (11)-(16)
804	r_t	reservoir releases through hydropower turbines, decision variable (m^3/month)
805	R	upper surface water reservoir turbine capacity (m^3/month)
806	s_{sw}	reservoir releases exceeding R , decision variable (m^3/month)
807	b_{hp}	marginal hydropower benefits (CNY/ m^3)
808	k	indexes the K inflow classes in stage t
809	l	indexes the L inflow classes in $t+1$
810	p_{kl}	transition probability from k to l
811	dm_m	water demand for user m (m^3/month)
812	u	indexes the U upstream users
813	d	indexes the D downstream users
814	s_{gw}	spills from aquifer when $V_{gw,t} + Q_{sw,t} - x_{gw,t} > V_{\max,sw}$ (m^3/month)
815	X_{gw}	maximum monthly groundwater pumping in the upstream basin (m^3/month)
816	$q_{E,t}$	unused surface water available to ecosystems, decision variable (m^3/month)
817	Q_E	minimum in-stream ecosystem flow constraint (m^3/month)
818	Bei	Beijing user
819	Q_{SNWTP}	maximum capacity of the SNWTP canal (m^3/month)

820

821 Table 3: Average minimum total costs (TC) and hydropower benefits (HP) over the 51 year
 822 planning period for different scenario runs. SNWTP scenarios: pre 2008 = before the canal,
 823 2008 - 2014 = canal from Shijiazhuang to Beijing, post 2014 = canal from Yangtze River to
 824 Beijing. Scenarios: **LGW** is initial groundwater storage at 100 km³ (all other scenarios are
 825 initiated at equilibrium groundwater storage); **dm** is 10 % higher water demands; **ct** is 10%
 826 higher curtailment costs ; **T** is 10% higher transmissivity; **TD** is Thiem steady state
 827 drawdown; **E** is minimum ecosystem flow constraint; “+” is active and “-” is inactive.

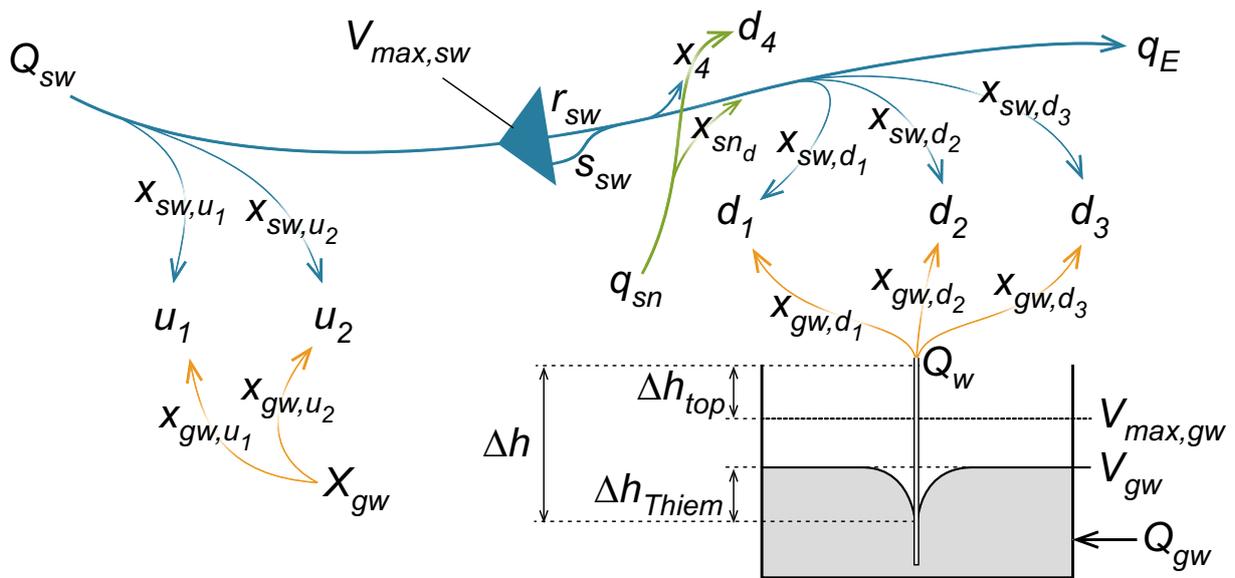
SNWTP scenario	Scenario settings			TC SDP	HP SDP
	Special run	TD	E	10 ⁹ CNY/y	10 ⁶ CNY/y
pre-2008	-	+	+	14.87	103.6
2008-2014	-	+	+	11.69	103.5
post-2014	-	-	-	8.43	103.5
post-2014	-	+	-	8.47	103.6
post-2014	-	+	+	8.56	104.3
post-2014	LGW	+	+	13.32	99.2
post-2014	T	+	+	8.69	103.5
post-2014	dm	+	+	8.74	103.3
post-2014	ct	+	+	9.08	103.1

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 829
 830



831
 832 Figure 1: The Ziya River Basin. Watershed and rivers automatically delineated from a digital
 833 elevation map (USGS, 2004) and manually verified and corrected with Google Earth (Google
 834 Inc., 2013). The SNWTP routes (Central and Eastern) were sketched in Google Earth and
 835 verified with field observations. Provincial boundaries from (NGCC, 2009).

836



837

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

844

845

846

Load data

for all stages

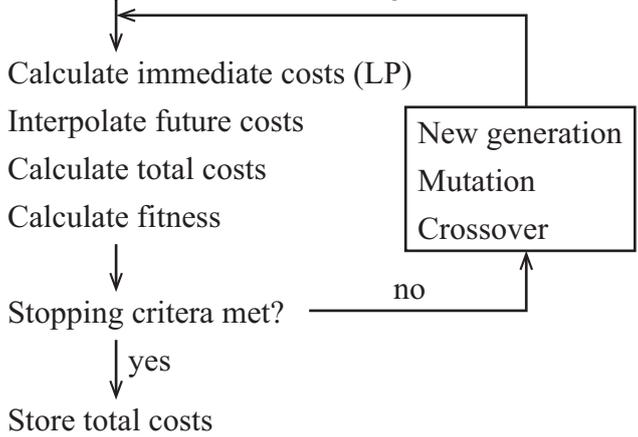
for all runoff flow classes

for all surface water states

for all groundwater states

Upper and lower bounds for GA

Generate initial population ($V_{gw,t+1}$, $V_{sw,t+1}$)



847

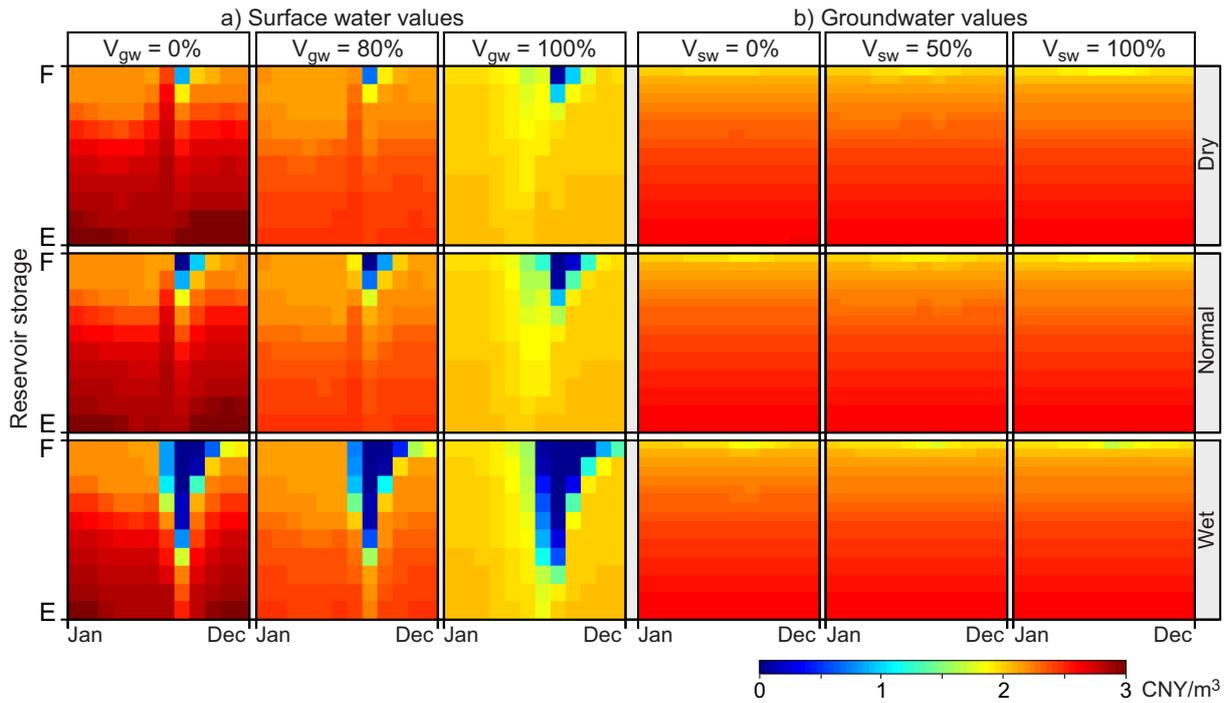
next

848 Figure 3: SDP optimization algorithm design.

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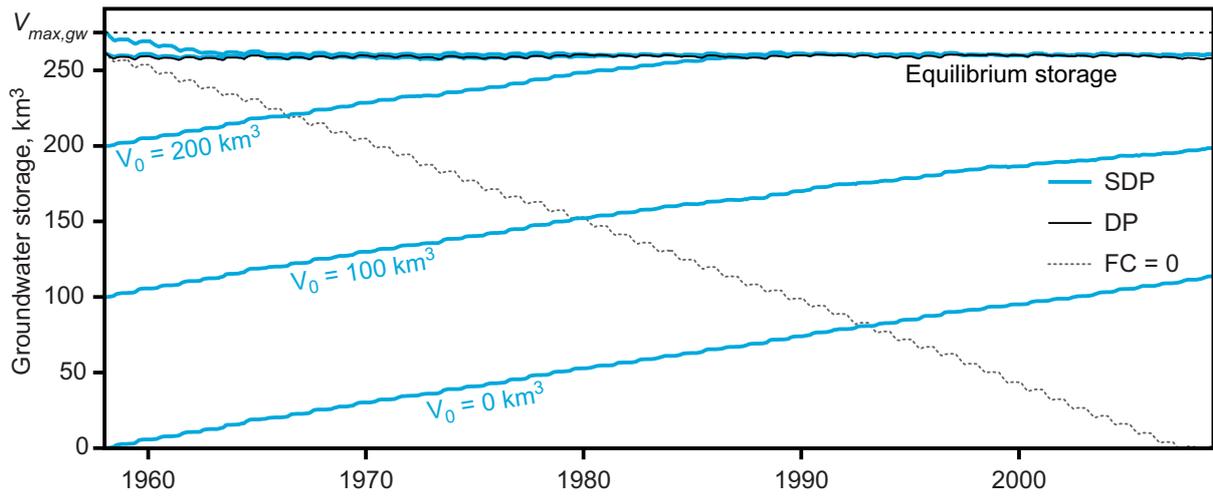
852

853 Figure 4: Temporal changes of the water values (CNY/m³) for the climate period before 1980.
 854 The marginal water value is the true value of storing a unit volume of water for later use and
 855 varies with reservoir storage levels, runoff flow class and time of the year. a) Surface water
 856 values at fixed [0%, 80%, 100%] groundwater aquifer storage. b) Groundwater values over
 857 time at fixed [0%, 50%, 100%] surface reservoir. The reservoir storage is shown from E
 858 (empty) to F (full).

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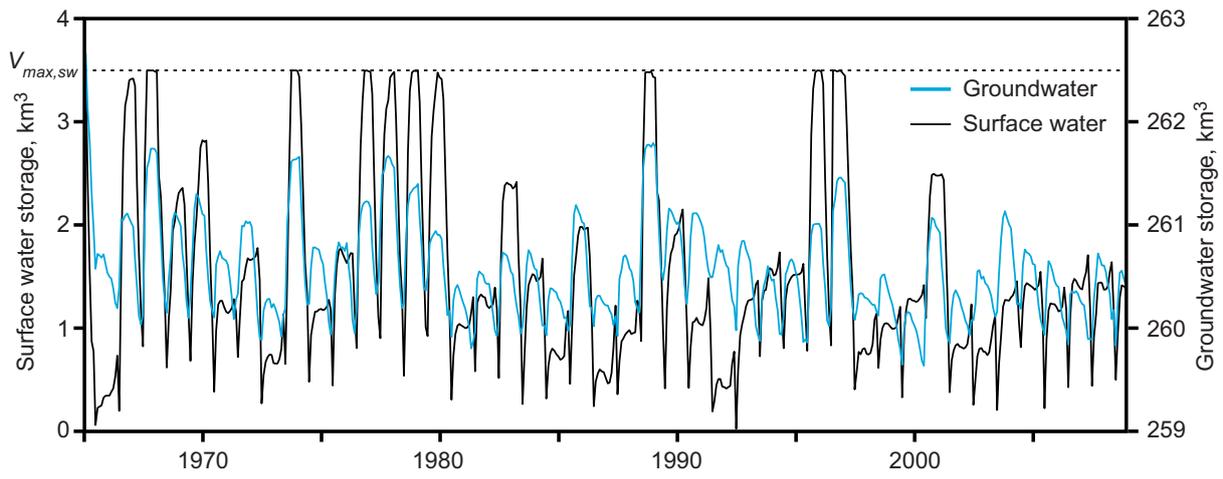


862

863 Figure 5: Simulated groundwater aquifer storage levels for 51 years of historical runoff with
864 different initial groundwater tables (0, 100, 200, 258 and 275 km³). The perfect foresight DP
865 and management without consideration of the future (FC = 0) are also shown.

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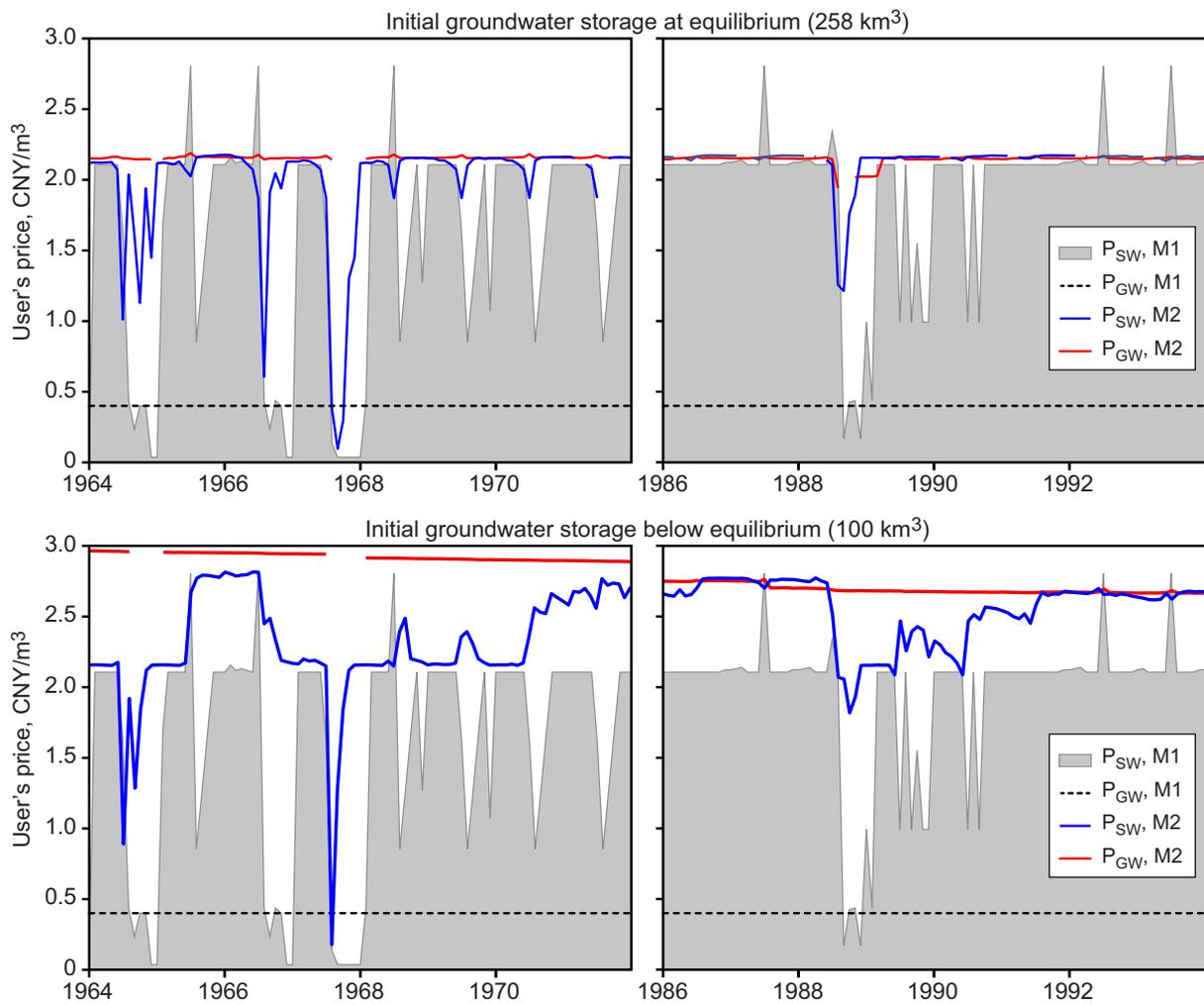
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869 Figure 6: Simulated storage levels in the surface water reservoir and the groundwater aquifer
 870 at equilibrium groundwater storage.

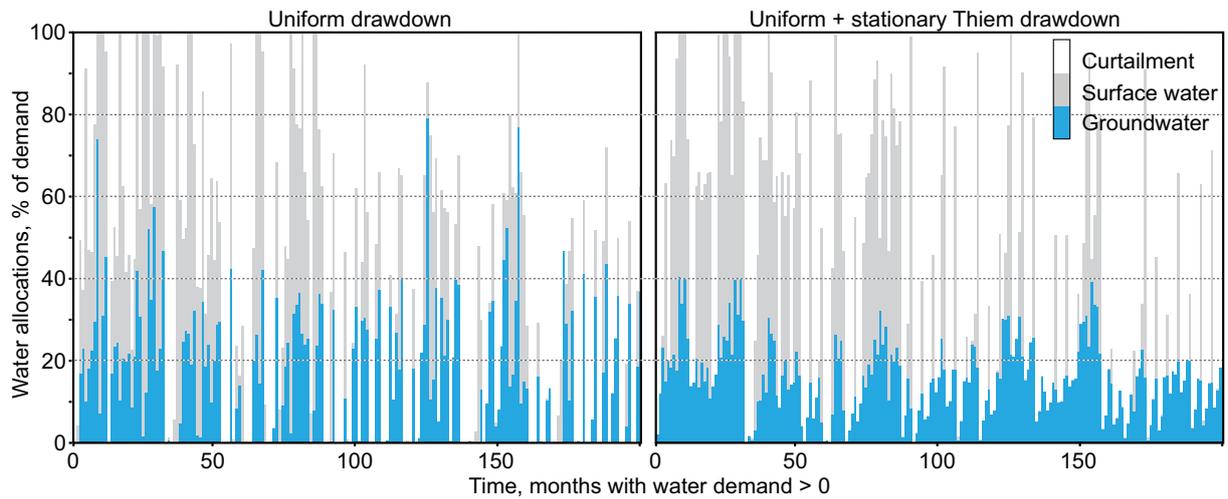
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872

873 Figure 7: User's price for groundwater and surface water through for a 51 year simulation
 874 based on simulated historical runoff for two initial groundwater storages. P = user's price. M1
 875 = results for a single surface water reservoir with a constant groundwater costs (Davidsen et
 876 al., 2015). M2 = results from the presented model framework with an additional dynamic
 877 groundwater aquifer. The user's price for groundwater in M2 is the immediate pumping costs
 878 added the marginal costs from the water value tables.

879



880

881 Figure 8: Composition of allocations and curtailments to wheat agriculture in the Hebei
 882 Province for the months March, April, May and June through 51 years simulation from an
 883 initial groundwater storage at equilibrium (258km³). The results are shown for a simple
 884 drawdown model with uniform regional lowering of the groundwater table, and a more
 885 realistic drawdown model, which includes the stationary Thiem local drawdown cones.