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Using stochastic dynamic programming to support water resources management in the Ziya River basin

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Abstract

Water scarcity and rapid economic growth have increased the pressure on water resources and environment in Northern China causing decreasing groundwater tables, ecosystem degradation and direct economic losses due to insufficient water supply. We applied the water value method, a variant of stochastic dynamic programming, to optimize water resources management in the Ziya River basin. Natural runoff from the upper basin was estimated with a rainfall-runoff model auto-calibrated with in-situ measured discharge. The runoff serial correlation was described by a Markov Chain and used as input to the optimization model. This model was used to assess economic impacts of the middle route of South-North Water Transfer Project (SNWTP), ecosystem minimum flow constraints and...
limited groundwater pumping. A regional climate shift has exacerbated water scarcity and increased water values, resulting in stricter water management. Our results show that the SNWTP reduces the impacts of water scarcity and impacts optimal water management in the basin. The presented modelling framework provides an objective basis for development of tools to avoid over-pumping of groundwater resources at minimum costs.

Subject headings: Water resources management, China, Water shortage, River basins, Optimization models, Economic analysis, Stochastic models, Reservoir operation

Introduction

Population growth and rapid development of the Chinese economy have put water resources and water quality in Northern China under increasing pressure in recent decades (Liu and Xia 2004). In the North China Plain (NCP) water resources are vulnerable, and recent expansions of irrigation agriculture in combination with climatic variability have intensified the need for water in the area (Liu et al. 2001; Liu and Xia 2004; Mo et al. 2009). Rapidly decreasing groundwater tables, dry rivers and heavily polluted surface water bodies are some of the consequences of the human development in the area (Liu and Xia 2004; Mo et al. 2009; Zheng et al. 2010). Increasing focus on ecosystem protection, sustainable groundwater pumping and economic impacts of water scarcity complicate decision making in water resources management in Northern China. To reduce the impacts of water scarcity, China has invested in the South-to-North Water Transfer Project (SNWTP), which will transport water from south to the dry north (Yang and Zehnder 2005; Feng et al. 2007).

Reservoir management in water scarce environments with significant hydrologic uncertainty, such as the NCP, is challenging; suboptimal management can lead to economic
losses for water users during droughts or to water spills during floods. A number of robust, unbiased and rational tools for supporting water allocation decisions have therefore been reported in the literature during the last decades; Harou et al., (2009) provided a good overview. River basins often represent highly coupled management problems with different water sources, a mix of conflicting water users and multiple reservoirs. Whereas simulation models can deal with a high level of detail, optimization approaches have traditionally been kept simpler due to difficulties in expressing all the complexity of the decision problem mathematically and to keep the optimization problem computationally feasible (Loucks and van Beek 2005; Harou et al. 2009). The hydropower sector has historically been facing similar optimization problems, while trying to predict the management of reservoir systems yielding, for example, the highest hydropower benefits (Pereira and Pinto 1991; Wolfgang et al. 2009). The water value method, which is based on stochastic dynamic programming (SDP), is a widely used technique to optimize reservoir operation (Stage and Larsson 1961; Stedinger et al. 1984; Pereira and Pinto 1991). We present a more general application of the water value method in water resources economics and integrated water resources management.

This study demonstrates a method to support optimal management of scarce water resources at the basin scale. A rainfall-runoff model is used to estimate natural surface water availability for water users situated upstream a reservoir. The optimal water allocation problem is formulated as a cost minimization problem subject to a demand fulfillment constraint. The water users are characterized by water demands to be satisfied by different water sources at different costs. Each user is also characterized by a cost of curtailment, and the optimal management is defined as the reservoir operation that minimizes the total costs over the planning period. The water value method is applied in a general hydro-economic
context to optimize reservoir operation in the Ziya River basin on the NCP and used to assess
the potential benefit of the middle route of the SNWTP.

Materials and methods

We demonstrate our approach on the Ziya River basin, a separate sub-basin in the
highly exploited Hai River system, to illustrate the complexity of the decision problems faced
by water managers during extreme water scarcity and to highlight the impacts of the SNWTP
on optimal reservoir management. The basin is located south-west of Beijing in the semi-
arid/semi-humid Northern China (Figure 1) and includes a downstream area located on the
NCP. The precipitation (annual average 500 mm) is highly seasonal with 70 % falling in the
summer and large inter-annual variations from 300 mm/year in dry years to more than 900
mm in wet years (China Meteorological Administration 2009). The intensively irrigated
spring wheat of the wheat-maize double cropping system in the downstream basin is
therefore highly dependent on irrigation water availability (Sun et al. 2010). Runoff can be
stored in multiple reservoirs upstream the NCP and released when needed. However, the
uncertain reservoir inflows and high water demands complicate reservoir management and
increase the risk of economic losses due to water scarcity. The problem becomes more
complex with the 2-stage implementation of the middle route of the SNWTP. Since 2008,
water from Shijiazhuang to Beijing has been transferred along the middle route (SNWTP,
pre-2014 in Figure 1) (water-technology.net 2013). From 2014 and onwards, water will flow
from the Yangtze River in the south to the NCP and Beijing (SNWTP, post-2014 in Figure
1). Further, the decision makers have introduced minimum annual flow requirements to the
Baiyangdian Lake, which again decreases the amount of water available for irrigation.

Optimization model setup
The optimal reservoir operation rules for the multiple major reservoirs of the Ziya River basin were found using an SDP approach (see the section “Stochastic dynamic programming and decision support”). Including all of the 5 major reservoirs (the Huangbizhuang and Gangnan reservoirs on the Hutuo River north-west of Shijiazhuang and the Lincheng, Zhuzhuang and Dongwushi reservoirs south of Shijiazhuang) as separate states into the model would make the model computationally intractable due to the well-known curse of dimensionality. The reservoirs were therefore aggregated assuming that the releases from all reservoirs can be diverted to any point in the downstream basin. This assumption is realistic, as the main rivers of the downstream basin are highly linked with smaller canals. Conceptually, this single reservoir receives the combined runoff from the basin situated upstream the reservoirs. The water users of the upstream basin were divided into three groups; agricultural maize production, industry and domestic. These users can get their water demand satisfied with either river runoff or groundwater (no surface water storage).

Unused upstream runoff flows to the aggregated reservoir, where it is stored for the downstream water users which are grouped into agricultural wheat-maize production, domestic and industry. Reservoir releases generate hydropower up to a turbine capacity, and basin outlets flow to the Baiyangdian Lake and to the Bohai Gulf. The downstream users have also access to groundwater and water from the middle route of the SNWTP. Water from the reservoir can be diverted into the canal and sent to the city of Beijing. This setup makes it possible to test the impact of the new canal on optimal management of the reservoir.

**Rainfall-runoff model**

The natural runoff to the reservoirs at the western boundary of the NCP was estimated from the 7 sub-catchments shown in Figure 2. We used a simple conceptual water balance model based on the Budyko framework to simulate daily runoff (Zhang et al. 2008).
Hargreaves method was used to estimate daily evapotranspiration from daily maximum and minimum temperatures. The simple model is based on Budyko’s assumption that rainfall and available energy determine the long-term annual evapotranspiration from a catchment (Budyko 1958; Zhang et al. 2008). Budyko then derived a water balance model (the Budyko curve) based on this assumption. This empirical relationship describes runoff as the fraction of the precipitation not used to satisfy the evaporative demand (Zhang et al. 2008; Roderick and Farquhar 2011). Zhang et al. (2008) applied the Budyko framework for shorter time steps and allowed for water storage between time steps. A set of calibration parameters, including the evapotranspiration efficiency and the groundwater storage, controls the resulting discharge (Zhang et al. 2008).

The Yehe River tributary of the Hutuo River in the Taihang Mountains (grey shaded in figure 2) was used as a calibration sub-catchment, with in-situ measured discharge from the Pingshan station (no. 30912428) (MWR Bureau of Hydrology 2011). This catchment has a relatively low population density and small reservoirs, and the flow regime was therefore assumed to be close to natural. The runoff from this catchment was auto-calibrated with daily measured discharge from 1971-1980, 1983-1991 and 2006-2008 (MWR Bureau of Hydrology 2011) with the objective of maximizing the monthly Nash-Sutcliffe Efficiency (NSE). The resulting calibration parameters were applied to the other 6 mountainous sub-catchments. The calibrated rainfall-runoff model was forced with 51 years (1958-2008) of daily precipitation and maximum and minimum temperature measurements from 6 weather stations (China Meteorological Administration 2009). Spatial interpolation of weather station data was performed with Thiessen polygons.
The combined simulated daily runoff from all upstream sub-catchments (Figure 2) was aggregated to monthly time steps and normalized. Each monthly discharge was then assigned an inflow class \(\text{dry} (0 – 20^{th} \text{ percentile}), \text{normal} (20^{th} – 80^{th} \text{ percentile}), \text{wet} (80^{th} – 100^{th} \text{ percentile})\), and the transition probability matrix \(P_{kl}\) was determined by counting the number of transitions from each inflow class in month \(k\) to each inflow class in month \(l\).

This aggregated dataset was used to represent the stochastic properties of the natural reservoir inflow and hence used as input to the optimization model. The Markov Chain was validated to ensure second-order stationarity (Loucks and van Beek 2005). The Markov Chain was used to generate a synthetic runoff time series, which was tested against the measured runoff for stationary mean and variance.

**Stochastic dynamic programming and decision support**

For a system with \(M\) users denoted with index \(m\), the total costs \(tc\) of satisfying the demand of the users in each stage can be formulated as the cost \(c\) of allocating or curtailing \((ct)\) the user \(x\) amounts of water:

\[
tc = \sum_{m=1}^{M} \left( c_{sw} x_{sw} + c_{gw} x_{gw} + c_{sn} x_{sn} + c_{ct} x_{ct} \right)_{m}
\]  

(eq. 1)

In the Ziya River basin the water sources are surface water (sw), groundwater (gw) and the water from the SNWTP middle route (sn), and the supply costs arise from pumping, treatment and conveyance. Alternatively, the users can be curtailed, which leads to curtailment costs (see the section “Curtailment costs and water demands”). While surface water is often associated with the lowest direct cost to the users, the absence of surface water will force the users to switch to alternative, more expensive sources or curtailment. With scarce surface water resources and limited storage capacity combined with the large seasonal and annual precipitation variations, present releases will therefore decrease future surface
water availability. Thus, present costs should be balanced against future uncertain costs. These costs are coupled in time, as the reservoirs allow storage for future use (dynamic problem). The one-step ahead allocation problem for a given stage can therefore not be solved independently from the other stages. Incorporation of uncertain reservoir inflow adds stochasticity to the system.

We used SDP to develop rational reservoir operation rules in the uncertain environment, a method known as the water value method in the hydropower sector (Stage and Larsson 1961; Stedinger et al. 1984; Pereira et al. 1998; Loucks and van Beek 2005; Wolfgang et al. 2009). The backwards recursive SDP equation runs in monthly time steps (stages) and calculates the minimum of the sum of immediate and expected future costs using the classical Bellman formulation (eq. 2) for all discretized reservoir states (water levels). The objective is to minimize the total costs given by the optimal value function \( F^*_t(V_t, Q^k_t) \) while satisfying the water demands (eqs. 3-7):

\[
F^*_t(V_t, Q^k_t) = \min \left[ \sum_{m=1}^{M} \sum_{n=1}^{N} (c_{m,n} x_n)_{m,j} - r b_{kp} + \sum_{l=1}^{L} \left( p_{kl} F^*_{t+1} \left( V_{t+1}, Q^l_{t+1} \right) \right) \right] \quad \text{(eq. 2)}
\]

with \( V_t \) being reservoir storage at stage \( t \), \( n \) being the sources shown in (eq. 1), \( p_{kl} \) being the reservoir inflow serial correlation that describes the probability of a transition from a flow class \( k \) reservoir inflow \( Q^k_t \) in stage \( t \) to a flow class \( l \) reservoir inflow \( Q^l_{t+1} \) in stage \( t+1 \). Because the future cost function is convex, future costs can be constrained from below by a set of linear constraints derived from the discrete sampling of total costs \( F^*_{t+1} \) as described by Pereira and Pinto (1991). The optimal solution will have a future cost that falls on one of these linear constraints. The set of linear constraints on the future cost is integrated with the remainder of the optimization problem to form one single linear program for the one-step ahead optimization problem (eq. 8). We decided to define three flow classes for
every month, as described in the section “Rainfall-runoff model”, due to the length of the simulated runoff series. The benefits from hydropower production (reservoir releases $r$ times marginal production benefit $b_{hp}$) are subtracted from the immediate costs. The optimization problem is defined by the objective function (eq. 2) subject to constraints on water demand fulfillment (eq. 3), water balance of the reservoir (eq. 4), water balance of reservoir releases (eq. 5), upstream releases (eq. 6) and releases to Beijing (eq. 7):

$$sw_{m,t} + gw_{m,t} + sn_{m,t} + ct_{m,t} = d_{m,t} \quad \text{(eq. 3)}$$

$$V_t + Q_t - \sum_{u=1}^{U} sw_{u,t} = V_{t+1} + r_t + s_t \quad \text{(eq. 4)}$$

$$r_t + s_t = \sum_{d=1}^{D} sw_{d,t} + Q_{out,t} \quad \text{(eq. 5)}$$

$$\sum_{u=1}^{U} sw_{u,t} \leq Q_t \quad \text{(eq. 6)}$$

$$SW_{Beijing,t} + SN_{Beijing,t} \leq CP_{SNWTP} \quad \text{(eq. 7)}$$

$$FC \geq \lambda_h (V_{end} - V_h) + FC_h \quad \text{(eq. 8)}$$

where $sw_{m,t}$, $gw_{m,t}$, $sn_{m,t}$ are, respectively, the surface water, groundwater and SNWTP water allocations and $ct_{m,t}$ the water curtailment of user $m$ in stage $t$. Further, $d_{m,t}$ is the given demand of user $m$. The dynamics of the system is described by a water balance equation (eq. 4) linking reservoir storage in $t+1$ to reservoir storage in $t$ where $\sum_{u=1}^{U} sw_{u,t}$ is the sum of surface water allocations in stage $t$ to the upstream user $u$ ($U$ users). The total reservoir releases consist of release through the hydropower turbines, $r_t$ and spills $s_t$ exceeding the turbine capacity. The combined reservoir releases ($r_t + s_t$) must equal the combined surface water allocations to the $D$ downstream users (denoted $d$) and unused outflow $Q_{out}$ from the basin (eq. 5). The upstream water users are constrained by the upstream runoff (eq. 6) and the
combined allocations to the Beijing user (reservoir releases from Ziya River basin, $sw_{Beijing,t}$ and SNWTP water from Yangtze River, $sn_{Beijing,t}$) is constrained by the capacity of the middle route of the SNWTP, $c_{P_{SNWTP}}$ (eq. 7). The piecewise linear future cost function $FC$ was added as $h$ linear pieces as shown in (eq. 8) with slopes $\lambda_h$ being the shadow prices logged in t+1, $h$ being an index of the discrete reservoir storage levels and $FC_h$ being the future costs logged in t+1. The linear problem optimizer CPLEXLP (IBM 2013) was chosen due to its high efficiency.

The outcome of the optimization (eq. 2) is two [stages by states] matrices with minimum total costs (CNY) and shadow prices (CNY/m³) with CNY being 2005 Chinese Yuan. As alternative to logging $\lambda$ directly, the water values $\theta$ (CNY/m³) can also be found as the first derivative of the total costs with respect to the discretized reservoir volumes (Stage and Larsson 1961):

$$\theta = \frac{\partial F^*_l}{\partial V_{t+1}}$$  \hspace{1cm} (eq. 9)

To avoid the effect of the end condition (future cost = 0) the model is run to equilibrium by looping the annual input data until the inter-annual differences in the water values becomes insignificant. The initial year furthest from the end condition is used as the equilibrium water value table. The equilibrium water value tables, one for each inflow class, are now used to guide a forward moving simulation phase similar to the optimization phase. From a given reservoir storage at time t, the water values are used as future costs and determine the allocation of water between use now and storage for the future. A perfect foresight dynamic program (DP) with a single future cost function (similar setup as the SDP optimizer) is used to evaluate the performance. With perfect foresight, this test will show exactly how well it is
possible to manage the water resources and can be used to benchmark the performance of the SDP optimization.

**Curtailment costs and water demands**

A central input for the optimal value function (eq. 2) is the curtailment cost of the water users. This cost describes the marginal cost in monetary units \(\text{CNY} / m^3\) for not satisfying a user’s water demand. For *agricultural* users we based the calculations on literature estimates of the crop water use efficiency, *WUE* (see Table 1) in the lower part of the basin (Mo et al. 2009). The curtailment cost was estimated as:

\[
cc = WUE \cdot p
\]

(eq. 10)

where \(cc\) is the curtailment cost of the crop and \(p\) is the producer’s price of the crop, scaled to 2005 prices using the consumer price index (World DataBank 2013). The irrigation demands and irrigation schedule for the individual crops are based on field interviews from March 2013 of 22 farmers distributed within the Ziya River basin (see Table 1) and is in the same range as in the literature (Liu et al. 2001; Mo et al. 2009). The total irrigated areas were extracted as the land use classes "Dryland Cropland and Pasture" and "Irrigated Cropland and Pasture" in the USGS Euroasia Landcover Map (U.S.Geological Survey 2013). These land use classes were evaluated as being irrigated based on field observations.

Table 1

*Industrial* water demands were estimated from Hai River statistics and scaled with the upstream and downstream areas (Berkoff 2003; Moiwo et al. 2009). The industrial curtailment costs were based on a previous study of the industrial water value in the Hai River basin (World Bank 2001) and not differentiated between the upper and lower area (see Table 2).
Domestic demands were estimated from provincial per capita water consumption statistics as shown in Table 2 (NBSC 2011). The demands were scaled to the upper and lower basin with the 2007 Landscan population density map (Berkoff 2003; Bright et al. 2008). The curtailment costs were based on a previous study of the water scarcity damage costs for the domestic users in the Hai River basin (World Bank 2001). The water demand and the curtailment costs of the Beijing user were based on the same study.

The ecosystem water demands could have been included as regular water users in the optimization framework, but due to lack of ecosystem water values, ecosystem water requirements were added as demand constraints, based on an estimate of the deficit in the water balance of the Baiyangdian Lake as shown in Table 2 (The People's Government of Hebei Province 2012).

The supply costs of surface water and SNWTP water were set to zero. Benefits from hydropower production will favor surface water allocations over SNWTP allocations to the downstream users. A constant groundwater pumping price of 0.4 CNY/m³ based on field interviews were used. This price represents only the electricity costs for pumping. Pumping costs from irrigation canal to field were not included.

Table 2

The SNWTP water available for allocation to the Ziya River basin was estimated from the data in Table 2. Different expected water transfer rates for the middle route are reported in the literature, including 5 km³/year (Jia et al. 2012), 9 to 13 km³/year (Berkoff 2003) and the 9.5 km³/year presented in Table 2 (water-technology.net 2013). As boundary condition for the model, the fraction of water available to allocation has been defined as the 9.5 km³/year subtracted the 7.4 km³/year for the 100 major cities in the north (Wang and Ma 1999). The remaining 2.1 km³/year where distributed evenly to the arable land of the NCP.
and the share available to Ziya were found. The Beijing water deficit of 1 km$^3$/year (Ivanova 2011) were considered a part of the 7.4 km$^3$/year and added to the SNWTP water available in the model.

Monte Carlo simulations are used to assess the uncertainty of the economic model. The input uncertainties were initially estimated and a set of samples were generated with Latin-Hypercube sampling (LHS). The water demands and the curtailment costs are assumed to be normally distributed with standard deviations of 20% around the estimated value. The hydropower benefits are assumed to be uniformly distributed with 80% uncertainty. Each uncertain input is sampled once per sample. With 17 uncertain parameters (8 demands, 8 curtailment costs and the hydropower benefits) a sample size of $n = 50$ was found to be sufficient. The $n$ results are used to estimate standard deviations.

**Results**

**Rainfall-runoff model**

The rainfall-runoff model was auto-calibrated to measured runoff in the calibration catchment shown in Figure 2. Despite the absence of major reservoirs in the calibration catchment, the measured runoff included delayed peaks occurring in the dry winter months as shown for the early years in Figure 3. We expect these peaks to be a result of reservoir releases, as the timing fits the normal irrigation practices in the region. In some of the later years, peak summer discharge is very low, despite the occurrence of precipitation events similar to the early period. The highest achievable monthly NSE for all of the 7,700 overlapping days is 0.47 (calibration target), which increases to 0.64 if the winter months are not used in the calculation of the NSE. The water balance error $(\text{sim} - \text{obs})/\text{obs}$ is 10%. The calibration catchment contains multiple smaller reservoirs to serve irrigation agriculture and almost 2 million people. The observed discharge may therefore deviate significantly from
discharge under natural conditions. Before using the later presented results in actual decision making, the modelling framework should be updated with more realistic estimates of the natural water availability, preferably using observed river discharge time series.

The assumption of stable conditions in the basin is a prerequisite for reaching steady-state water value tables. However, the simulated runoff shows a decreasing tendency over the 51 years. Plotting the accumulated mean precipitation for the 3 weather stations used for the Shanxi Province (Figure 4) reveals that the precipitation has been decreasing over the period. This has previously been discussed in the literature (Chen 2010; Sun et al. 2010; Cao et al. 2013). Based on a simple manual fit, we decided to split the simulation into two climate periods with a shift in year 1980 where each period is assumed to have stationary precipitation.

The average flow of each inflow class can be seen in Figure 5 for. The timing of the peak flow is similar in the period 1980-2008, but the magnitude of the flow is lower. In particular the dry winter months from November to February are drier in the period 1980-2008.

**Stochastic dynamic programming**

The backwards recursive SDP algorithm (eq. 2) was run with a looped 10-year sequence of the annual input data to reach inter-annual equilibrium water value tables for each climate period. The resulting water value tables for three scenario runs can be seen in Figure 6. The water values are highest at low reservoir states and in the dry periods with water values above 0.3 CNY/m$^3$. In wet months and at high reservoir states the water value
drops below 0.2 CNY/m³. Comparing different inflow classes shows that a dry flow class results in higher water values (more conservative reservoir management) than in the normal or wet flow class. The lower reservoir inflow in the period 1980-2008 results in increased water values and thereby also more conservative reservoir management with lower reservoir releases. The large blue areas with water values around 0.4 CNY/m³ in the two scenarios with unlimited groundwater pumping are caused by the groundwater pumping price, which is lower than any of the users’ curtailment costs. In the scenario with the partly finished middle route of the SNWTP, the Beijing user is constrained to surface- and SNWTP water alone, as the groundwater in this area is already fully exploited. If no surface water is available, the user can only be curtailed. This increases the water value whenever the reservoir is close to empty, and the demand cannot be satisfied with the in-stage runoff alone. After the SNWTP middle route has been completed, the water diverted from the Yangtze River can satisfy the Beijing demand completely, and hence the water value at low states becomes lower. Based on the SNWTP data in Table 2, a 109 million m³/month limit was put on the SNWTP water from Yangtze River. In the last scenario, an annual average sustainable groundwater pumping limit for the NCP users is also introduced. A study has modelled the annual NCP groundwater recharge rate to be 17.77 km³/year (Liu et al. 2011), and this is scaled to the share of Ziya River basin of the NCP (3.43 km³/year) and distributed evenly to obtain a monthly limit. This groundwater pumping limit causes the users with the lowest curtailment costs (the farmers) to be curtailed and increases the water value to 2-2.5 CNY/m³.

Figure 6

Simulating water allocation

The expected equilibrium water values were used to drive a 51 years reservoir operation simulation phase. From a starting volume at a given stage with known reservoir
state and inflow class, the corresponding water value vector (all possible states in $t+1$) represents benefits of storing water for future use in a forward moving optimization algorithm. The resulting reservoir management and perfect foresight DP solutions are shown for the 3 scenarios in Figure 7. In general the SDP simulations show the same trends as the DP solution, but the apparent inter-annual cycles mainly after 1980 are not captured by the SDP simulation. The DP solution will save water for these sequences of dry years, whereas the simple Markov Chain runoff serial correlation will contain the same probabilities for each year. Therefore, the SDP solution releases more water in the beginning of the dry years and ends up with lower storage than the DP solution. Introducing a groundwater pumping limit (Figure 7, lower) will make the reservoir management more conservative as the higher water values cause more water to be stored for the highest value water uses. Also note the higher storage of the SDP solution compared to the DP solution. In Figure 7 a) and c), the SDP solution shows higher reservoir states relative to the DP solution. This is caused by non-zero transition probabilities to a low inflow state and the SDP model therefore rather saves water than curtail expensive users.

Figure 7

The constraints can be modified to enable evaluation of a variety of case setups and policy scenarios. In Table 3 the total costs with SDP and DP can be seen for 12 different scenarios. From the difference in total costs between the scenarios, it is possible to calculate the average shadow price of water allocated to ecosystems (ecosystem flow constraint as indicated in Table 2) or the SNWTP water. The standard deviations ($s$) of the results have been calculated from the Monte Carlo simulations. The water diverted from the Yangtze River along the SNWTP middle route will lower the total costs with an average of 4.6 CNY/m$^3$ ($s = 1.3$ CNY/m$^3$). Forcing a minimum ecosystem flow of 100 million m$^3$ to fill up
the Baiyangdian Lake in July will on average cost 0.41 CNY/m$^3$ ($s = 0.13$ CNY/m$^3$) if the current practice with unlimited groundwater pumping continues. This indicates that the water allocated to Baiyangdian Lake will be substituted with groundwater pumping, which is available at a fixed cost of 0.4 CNY/m$^3$. If an average groundwater pumping limit is introduced, the average shadow price of the ecosystem water will be 2.78 CNY/m$^3$ ($s = 1.04$ CNY/m$^3$) indicating that the diversion will cause curtailment of the farmers. The differences between the objective values of SDP and perfect foresight DP are between 0.3 % and 4.7 % (average 1.8 %) for scenarios without a groundwater limit and between 3.6 % and 5.7 % (average 4.3 %) for scenarios with a groundwater limit.

Table 3

The impact of describing the runoff serial correlation can be found by comparing to a model run based on average monthly runoff from the 51 years. For the 3 scenarios presented in Figure 6 and Figure 7, the total objective values with runoff serial correlation were 3.70 billion CNY/year ($s = 0.6$ billion CNY/year), 3.09 billion CNY/year ($s = 0.5$ billion CNY/year), and 11.39 billion CNY/year ($s = 3.7$ billion CNY/year), as shown in Table 3.

Using average monthly flows instead, these total costs become 3.70 billion CNY/year, 3.21 billion CNY/year and 12.02 billion CNY/year. The total costs with perfect foresight of 3.53 billion CNY/year, 3.06 billion CNY/year and 10.75 billion CNY/year for these scenarios show the direct gain of using the stochastic representation of the runoff. The trade-off for the higher accuracy of the SDP model is a 3 times longer computation time (66 seconds) than the model based on average flows (23 seconds).

**Discussion**

The purpose of this study is to demonstrate the potential use of SDP and the water value method in integrated water resources management on a complex management problem.
We found that the method can be used to assess the economic impact of changes in the hydraulic infrastructure and changes in water policies. The SNWTP greatly changes the optimal management of the basin; the intermediate emergency diversion to Beijing (2008-2014) increases the water value, which implies more conservative reservoir storage forcing more users to switch to groundwater pumping. Once completed, the middle route of the SNWTP will bring more water to the basin and reduce the total costs with 4.6 CNY/m$^3$ ($s = 1.3$ CNY/m$^3$). This is approximately half of a World Wildlife Fund estimate of 9.3 CNY/m$^3$ for SNWTP water delivered to the Hebei Province (Berkoff 2003). The shadow prices of the SNWTP water supplied to the users therefore indicate that the SNWTP is not sufficient to balance a necessary reduction of groundwater pumping. Introducing a monthly groundwater pumping limit greatly increases the water values as the lowest value users are curtailed. Even when fully operational, the middle route of the SNWTP will not provide enough water (at least in our setup) to avoid water curtailments of some users once the groundwater pumping limit is introduced. This is also in alignment with the findings of Ma et al. (2006), and the model results therefore suggests that a sustainable groundwater abstraction can only be reached in combination with initiatives such as water recycling, efficiency improvements, pricing policies, increased transfer capacity etc. The optimal reservoir management is greatly impacted by the limited groundwater pumping, and we see a new annual pattern with steadier water levels in the reservoir until a rapid release in a single month. With increased water scarcity, the economic consequence of a wrong decisions increases, which is reflected in larger differences between the SDP model and the DP model.

We found that SDP is a suitable and efficient method to determine optimal water management. The total costs found with the SDP model lie within a few percentages of the total costs of a situation with perfect foresight, and the SDP model can therefore be a
valuable tool for the decision makers. However, limits on the number of surface water reservoirs force aggregation of the multiple reservoirs to avoid high dimensionality of the optimization problem (see for example Pereira et al. 1998) and imply some highly simplifying assumptions of the hydraulic infrastructure. Also, the simple Markov Chain runoff serial correlation could be extended to capture the inter-annual wet-dry cycles, which seems to be present in the runoff time series. An example could be the hidden-state Markov Chain as applied in Fisher et al. (2012). This could make the reservoir management more conservative in the years following a wet year and therefore bring the SDP solution even closer to the DP solution. With a single reservoir setup, the present model is also limited to a simple representation of the groundwater pumping. Ideally, the groundwater should be included as another reservoir to assess actual impacts of management changes on the long term groundwater table. This would also make it possible to introduce head-dependent groundwater pumping costs, which would make the objective function non-linear. With such a scheme, it would be possible to analyze how different electricity prices affect the long term groundwater table. The current single-step optimization problems were solved with linear programming. Linearity is not strictly necessary and nonlinearities could be accommodated, however with increasing simulation time being a potential limitation. Howitt et al. (2002) demonstrated a solution to nonlinear optimization problems with GAMS but also other non-linear solvers such as LINGO or genetic algorithms could be used.

Time linked constraints, such as fixing the long term groundwater table or allowing the model to select the optimal timing of ecosystem water diversions, will introduce even more dimensions to the optimization problem. An alternative method such as stochastic dual dynamic programming, SDDP (Pereira and Pinto 1991) can be a better choice for this type of complex problems. SDDP will, however, only give one solution (the optimal) with the given
initial conditions. The SDP framework outputs the complete solution (water value tables),
which can be used for adaptive management. Moreover, the simulation could use a more
complex representation of the system such as multiple reservoirs and more users. The inter-
temporal trade-offs are determined from water value tables found in the optimization phase,
using a simpler system representation. The computation time of the forward moving
simulation phase is currently less than one second, and higher complexity can therefore be
accommodated. The optimization phase is also relatively fast, and it would be
computationally feasible to add another reservoir. As we are mainly interested in the
upstream-downstream conflicts, all upstream users are aggregated and have access to the
aggregated runoff. Thus, the Markov Chain is based on the aggregated runoff. If the upstream
basin is spatially disaggregated or if a second surface water reservoir is introduced, the
number of possible inflow states will be increased. If the data were available, an alternative
improvement could be to represent the users with demand curves. These could be
implemented in the SDP framework, but would result in non-linear one-step ahead
optimization problems. Thus, a non-linear global solver such as genetic algorithms is
required. To keep the one-step ahead optimization problem linear, the demand curves would
have to be approximated by segments of constant curtailment costs and demands. This would
increase the number of decision variables but would probably still be computationally
feasible for a low number of segments per user.

Lack of public available hydrological, economic and management data is also a great
challenge when executing a case study in China. Despite multiple field trips and extensive
online and onsite research, many rough assumptions were needed. Realistic curtailment costs
are essential for the model to output realistic estimates, but even more important is the
relative size of curtailment costs between the users, as this will decide which users to curtail
and which to supply. Additional data on the producer prices, costs and water demands for farmers and industries would reduce uncertainty of the curtailment costs and demand estimates. The standard deviations of the total costs are currently between 15% and 33%, and thus in the same range as the input uncertainty. This indicates that reduced uncertainty of the input data would lead to a proportional decrease in model output uncertainty.

The natural runoff was estimated with a simple hydrological model. The model was calibrated to a semi-natural sub catchment and applied to the entire upstream area. Assuming the same calibration parameters across the catchments is not critical, because the topography and vegetation across the catchments are very homogeneous. The uncertainty of the hydrological model was not evaluated, because the main focus of this study is to demonstrate the hydro-economic optimization and simulation framework. It is expected that decision makers, also in China, will have access to better calibration data or, ideally, measured natural runoff.

The results show the potential economic benefits if the system is managed according to the optimal solution. The results based on the best available data suggest that it is not possible to achieve sustainable use of the water resources without curtailing some users. The model can be used to identify the trade-offs between the users and, ideally, which supplied users should compensate the curtailed users. However, the actual implementation of these compensation payments is an unresolved issue and outside the scope of this paper.

**Conclusion**

The water value method, a variant of SDP, was found to be a suitable approach for solving complex single reservoir river basin management problems. The optimization problem was defined as a minimization of water supply costs subject to a water demand fulfillment constraint. The resulting water value tables are efficient and illustrative tools to
guide the decision makers and can help to obtain a better quantitative understanding of the
conflicts arising from water scarcity. Optimization runtimes are short and allow efficient
analysis of multiple scenarios.

The optimization model can explain the consistent groundwater table decline that has
been observed in the Ziya River basin. In the optimal solution, the water users of the basin
will keep pumping groundwater until their demands are fulfilled, unless groundwater access
is restricted. Without regulation, groundwater drawdown is expected to continue until the
pumping costs exceed the curtailment costs of the users. The scenario results show that the
middle route of the SNWTP will reduce water scarcity and impact optimal water resources
management in the basin. The best available data indicate that the SNWTP will be
insufficient to entirely avoid over-pumping the groundwater aquifer, as introduction of
average sustainable groundwater pumping limits greatly increased water values and caused
curtailment of several users. Drier climate and high water demands therefore remain
unresolved challenges in the area.

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Andersen from the China-EU Water Platform for sharing his extensive network in China; Y.
Song for his help digitizing the input data; Z. Lin for sharing data and experience from the
case study area; and J. Luchner and K. N. Marker for their critical review and quality
assurance of the optimization framework.

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Table 1: Model input data including water demands, water values and reservoir properties. All prices have been converted to 2005 CNY with the consumer price index (World DataBank 2013).

<table>
<thead>
<tr>
<th>Input data</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrial water demands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hai River basin</td>
<td>6.6</td>
<td>km³/year</td>
<td>(Berkoff 2003)</td>
</tr>
<tr>
<td>Area of Hai River basin</td>
<td>318,866</td>
<td>km²</td>
<td>(Moiwo et al. 2009)</td>
</tr>
<tr>
<td>Area of Ziya River basin</td>
<td>52,299</td>
<td>km²</td>
<td></td>
</tr>
<tr>
<td>Area upstream reservoirs</td>
<td>26,048</td>
<td>km²</td>
<td></td>
</tr>
<tr>
<td>Total water demand ²</td>
<td>1,083</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td>Downstream demand ²</td>
<td>543</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td>Upstream demand ²</td>
<td>539</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td><strong>Industrial water values (curtailment costs)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban ³</td>
<td>6.4</td>
<td>CNY/m³</td>
<td>(World Bank 2001)</td>
</tr>
<tr>
<td>Rural ³</td>
<td>4.3</td>
<td>CNY/m³</td>
<td>(World Bank 2001)</td>
</tr>
<tr>
<td>Average</td>
<td>5.3</td>
<td>CNY/m³</td>
<td></td>
</tr>
<tr>
<td><strong>Domestic water demands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hebei Province</td>
<td>123</td>
<td>l/person/day</td>
<td>(NBSC 2011)</td>
</tr>
<tr>
<td>Shanxi Province</td>
<td>106</td>
<td>l/person/day</td>
<td>(NBSC 2011)</td>
</tr>
<tr>
<td>Total population inside basin</td>
<td>25.0</td>
<td>M people</td>
<td>(Bright et al. 2008)</td>
</tr>
<tr>
<td>Upstream population</td>
<td>5.8</td>
<td>M people</td>
<td>(Bright et al. 2008)</td>
</tr>
<tr>
<td>Downstream demand</td>
<td>864</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td>Upstream demand</td>
<td>223</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td>Water demand Beijing ⁴</td>
<td>1,000</td>
<td>Mm³/year</td>
<td>(Ivanova 2011)</td>
</tr>
<tr>
<td><strong>Domestic water values (curtailment costs)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban ³</td>
<td>3.2</td>
<td>CNY/m³</td>
<td>(World Bank 2001)</td>
</tr>
<tr>
<td>Rural ³</td>
<td>3.2</td>
<td>CNY/m³</td>
<td>(World Bank 2001)</td>
</tr>
<tr>
<td>Average</td>
<td>3.2</td>
<td>CNY/m³</td>
<td></td>
</tr>
<tr>
<td>Curtailment cost Beijing ³</td>
<td>5.5</td>
<td>CNY/m³</td>
<td>(Berkoff 2003)</td>
</tr>
<tr>
<td><strong>South-North Transfer Project, middle route</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflow from Yangtze</td>
<td>9,500</td>
<td>Mm³/year</td>
<td>(water-technology.net 2013)</td>
</tr>
<tr>
<td>Water demand 100 cities</td>
<td>7,400</td>
<td>Mm³/year</td>
<td>(Wang and Ma 1999)</td>
</tr>
<tr>
<td>Arable land on the NCP</td>
<td>179,500</td>
<td>km²</td>
<td>(Liu et al. 2011)</td>
</tr>
<tr>
<td>Water for NCP users in Ziya ⁵</td>
<td>1,307</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td><strong>Ecosystem water demand</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum diversion ⁶</td>
<td>100</td>
<td>Mm³/year</td>
<td></td>
</tr>
<tr>
<td><strong>Reservoir storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dongwushi</td>
<td>152</td>
<td>Mm³</td>
<td>(HWCC 2012)</td>
</tr>
<tr>
<td>Gangnan</td>
<td>1,570</td>
<td>Mm³</td>
<td>(HWCC 2012)</td>
</tr>
<tr>
<td>Huangbizhuang</td>
<td>1,210</td>
<td>Mm³</td>
<td>(HWCC 2012)</td>
</tr>
<tr>
<td>Lincheng</td>
<td>180</td>
<td>Mm³</td>
<td>(HWCC 2012)</td>
</tr>
<tr>
<td>Zhuzhuang</td>
<td>436</td>
<td>Mm³</td>
<td>(HWCC 2012)</td>
</tr>
<tr>
<td>Aggregated reservoir storage</td>
<td>3,548</td>
<td>Mm³</td>
<td></td>
</tr>
<tr>
<td><strong>Hydropower production</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum turbine capacity ⁷</td>
<td>1,500</td>
<td>Mm³/month</td>
<td>(HEBWP 2013)</td>
</tr>
<tr>
<td>Electricity price ⁸</td>
<td>0.40</td>
<td>CNY/kWh</td>
<td>(China Daily 2012)</td>
</tr>
<tr>
<td>Installed turbine capacity</td>
<td>69</td>
<td>MW</td>
<td>Aggregate ⁹</td>
</tr>
<tr>
<td>Hydropower benefits ⁸</td>
<td>0.036</td>
<td>CNY/m³</td>
<td></td>
</tr>
</tbody>
</table>

²Converted to 2005 prices.
³Demands scaled with the areas.
⁵Based on plan described by The People’s Government of Hebei Province (2012).
⁶Remaining SNWTP water distributed evenly to NCP arable land and scaled to the downstream Ziya River basin.
⁷Capacities from Huangbizhuang, Zhuzhuang and Dongwushi Reservoirs scaled to the remaining reservoirs.
⁸Estimated from maximum production, maximum turbine capacity and current electricity price.
⁹(HEBWP 2013; HWCC 2013; Baidu Encyclopedia 2012; Baidu Encyclopedia 2013a; Baidu Encyclopedia 2013b)
Table 2: Irrigation schedule, water use efficiencies, producer’s prices and water values for wheat and corn agriculture in Hebei and Shanxi Provinces. All prices are in 2005 Chinese Yuan (CNY) calculated with the consumer price index (World DataBank 2013).

<table>
<thead>
<tr>
<th>Agricultural water user</th>
<th>Irrigation schedule(^a), mm</th>
<th>Water use efficiency(^b), kg/mm/ha</th>
<th>Producers prices(^c), CNY/kg</th>
<th>Curtailment cost(^d), CNY/m(^3)</th>
<th>Area(^e), km(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanxi, corn</td>
<td>50 50 ... 50 50</td>
<td>16</td>
<td>1.62</td>
<td>2.6</td>
<td>2,846</td>
</tr>
<tr>
<td>Hebei, corn(^e)</td>
<td>... ... ... 100</td>
<td>16</td>
<td>1.62</td>
<td>2.6</td>
<td>15,223</td>
</tr>
<tr>
<td>Hebei, wheat(^e)</td>
<td>100 100 100 100 ... 400</td>
<td>14</td>
<td>1.61</td>
<td>2.3</td>
<td>15,223</td>
</tr>
</tbody>
</table>

\(^a\) Based on field interviews of 22 farmers within the basin.

\(^b\) Estimated from Mo et al. (2009).

\(^c\) (USDA Foreign Agricultural Service 2012) converted from 2011.

\(^d\) Based on land use classes “Dryland Cropland and Pasture” and “Irrigated Cropland and Pasture” in (U.S. Geological Survey 2013).

\(^e\) Double cropping system so the same area is used for wheat in the spring and corn in the summer.
Table 3: Average annual benefits and costs with SDP and a perfect foresight benchmark for 12 different scenarios. The shadow prices (SP) of water to ecosystems and the water from the middle route of the SNWTP are indicated. Pre 2008 = before the SNWTP, 2008 - 2014 = SNWTP partly finished (emergency plan), Post 2014 = SNWTP finished (water from Yangtze to Beijing), E = minimum ecosystem flow constraint (to Baiyangdian Lake), GW = upper groundwater pumping constraint for the NCP users, ¥ = CNY, s = standard deviation, Bhp = benefits from hydropower production, TC = total costs, DP = dynamic programming with perfect foresight, + = constraint active. 1These scenarios are the ones presented in Figure 6 and Figure 7.

<table>
<thead>
<tr>
<th>SNWTP status</th>
<th>E</th>
<th>GW</th>
<th>SP SNWTP</th>
<th>s</th>
<th>SP E</th>
<th>s</th>
<th>Bhp SDP</th>
<th>s</th>
<th>TC SDP</th>
<th>s</th>
<th>Bhp DP</th>
<th>s</th>
<th>TC DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre 2008</td>
<td>+</td>
<td>+</td>
<td>0.34 0.07</td>
<td>74 41</td>
<td>8.69</td>
<td>1.9</td>
<td>72 8.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre 2008</td>
<td>+</td>
<td>+</td>
<td>2.57 0.72</td>
<td>86 39</td>
<td>17.30</td>
<td>4.2</td>
<td>89 16.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre 2008</td>
<td>+</td>
<td>+</td>
<td>0.60 0.25</td>
<td>81 39</td>
<td>3.70</td>
<td>0.6</td>
<td>82 3.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre 2008</td>
<td>+</td>
<td>+</td>
<td>3.26 1.77</td>
<td>87 40</td>
<td>13.60</td>
<td>3.9</td>
<td>89 13.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post 2014</td>
<td>+</td>
<td>+</td>
<td>-4.5 1.3</td>
<td>70 41</td>
<td>3.06</td>
<td>0.5</td>
<td>69 3.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post 2014</td>
<td>+</td>
<td>+</td>
<td>-4.5 1.3</td>
<td>71 41</td>
<td>3.09</td>
<td>0.5</td>
<td>70 3.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post 2014</td>
<td>+</td>
<td>+</td>
<td>-4.7 1.2</td>
<td>86 40</td>
<td>11.42</td>
<td>3.7</td>
<td>88 10.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post 2014</td>
<td>+</td>
<td>+</td>
<td>-4.7 1.2</td>
<td>86 39</td>
<td>11.39</td>
<td>3.7</td>
<td>88 10.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1: The Ziya River basin including main rivers, reservoirs, main cities and the SNWTP routes. The major reservoirs are indicated with: 1 Gangnan; 2 Huangbizhuang; 3 Lincheng; 4 Zhuzhuang; 5 Dongwushi. The rivers and canals were automatically delineated from the SRTM digital elevation map (Rabus et al. 2003) and manually verified and corrected with Google Earth (Google Inc. 2013) and the cover map in MWR Bureau of Hydrology (2011). The SNWTP routes were sketched in Google Earth and partly adopted from field observations and a map by Daxixianpipi (2011). The provincial boundaries were downloaded from the National Geomatics Center of China (NGCC, 2009).
Figure 2: The upstream sub-catchments extracted from the digital elevation maps (Rabus et al. 2003) in the rainfall-runoff model and the weather stations (China Meteorological Administration 2009).

Figure 3: Measured runoff, simulated runoff and precipitation time series for two periods in the calibration catchment (China Meteorological Administration 2009; MWR Bureau of Hydrology 2011).
Figure 4: Accumulated precipitation in the Shanxi Province with a manual linear fit to the first years (1958-1980). Average of the stations 53673, 53588 and 53782 (China Meteorological Administration 2009)

Figure 5: Monthly discharge for the three flow classes in the two regional climate periods
Figure 6: Equilibrium water value tables for 3 different case setups, 3 different inflow classes (dry, normal, wet) and 2 climate periods (before and after the climate shift in 1980).

a) Setup with partly completed SNWTP (from Ziya basin to Beijing) and with unlimited groundwater pumping. b) Setup with finished SNWTP and unlimited groundwater pumping. c) Setup with finished SNWTP and a groundwater pumping limited to the average monthly groundwater recharge. The y-axes are reservoir storage; E = empty, F = full.
Figure 7: Simulated reservoir storage using the SDP equilibrium water value table as rule curve along with the perfect foresight DP solution for the 3 different scenarios. a) Setup with partly completed SNWTP (from Ziya basin to Beijing) and with unlimited groundwater pumping. b) Setup with finished SNWTP and unlimited groundwater pumping. c) Setup with finished SNWTP and a groundwater pumping limited to the average monthly groundwater recharge.