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Optimizing conjunctive use of surface water and groundwater resources with stochastic dynamic programming

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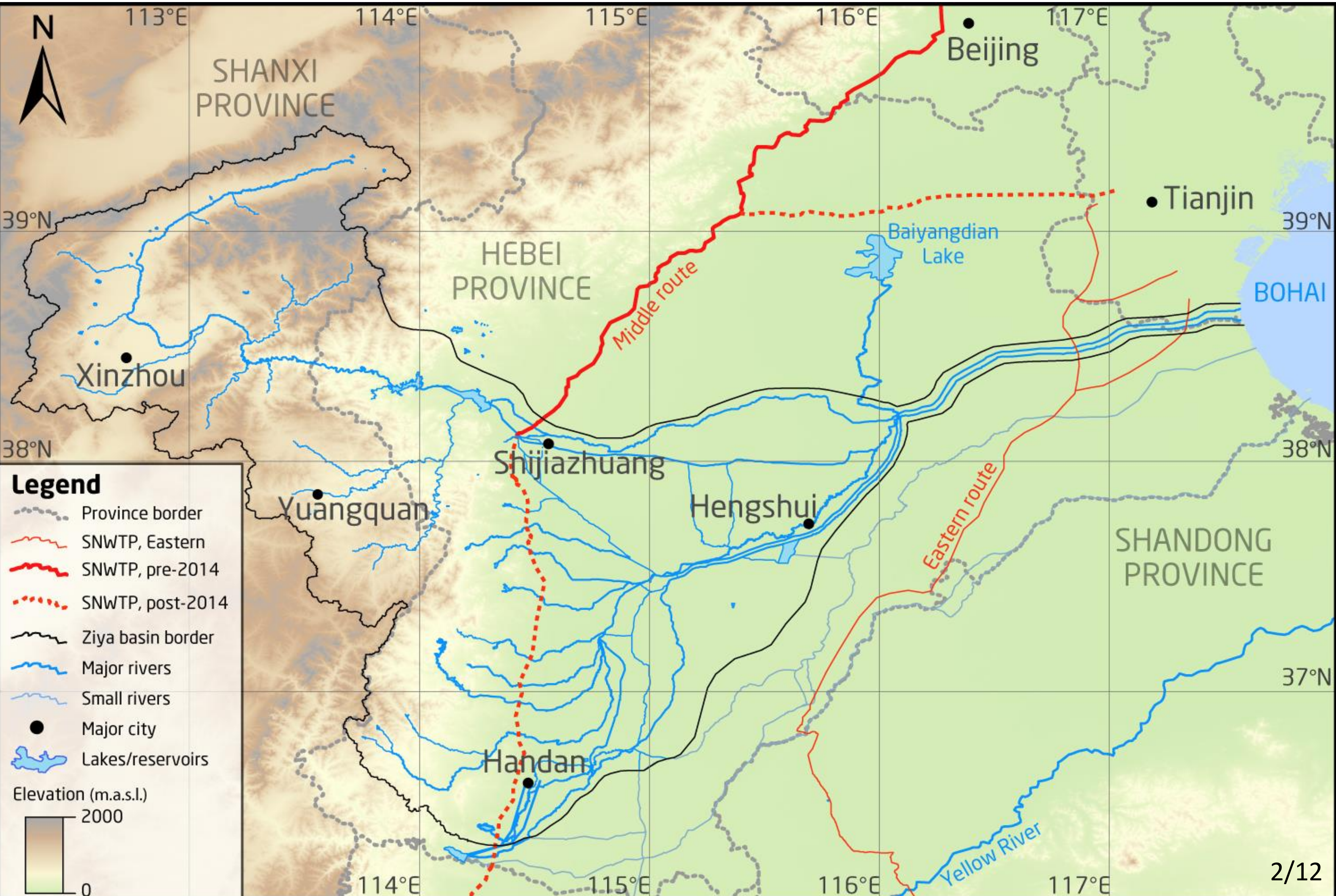
Background water scarcity conflicts

- Water scarcity causes multiple conflicts about water, e.g.
  - upstream ↔ downstream
  - irrigation ↔ ecosystems

- Previous study: optimal surface water management.
  - Stochastic Dynamic Programming (SDP) to investigate optimal management.
  - combined surface water reservoir (state variable).
  - groundwater at fixed pumping costs and with volume constraints.

- Current study: optimal conjunctive use of surface and groundwater.
  - Stochastic Dynamic Programming (SDP) to investigate optimal management.
  - two state variables.
    - a combined surface water reservoir.
    - a dynamic groundwater aquifer.
  - non-linearity (head-dependent pumping costs).

Case Ziya River Basin, Northern China



Method optimization problem

Objective: Meet water demands at minimum cost over the planning period.

- Water sources: Surface water (sw), groundwater (gw), SNWTP water (sn) or water curtailment (ct).

Find expected value of storing a marginal amount of water for later use.

- Solved with Stochastic Dynamic Programming (SDP).
- Minimize the sum of *immediate* and *future* costs of meeting demands.

$$F_t^*\left(V_{gw,t}, V_{sw,t}, Q_t^k\right) = min\left[\sum_{m=1}^{M}\sum_{n=1}^{N}\left(c_n x_n\right)_{m,t} - r_t b_{hp} + \sum_{l=1}^{L}\left(p_{kl} F_{t+1}^*\left(V_{gw,t+1}, V_{sw,t+1}, Q_{t+1}^l\right)\right)\right]$$

Subject to:

Demand fulfillment

$$x_{sw,t,m} + x_{gw,t,m} + x_{\text{sn},t,m} + x_{\text{ct},t,m} = d_{m,t}$$

Upstream users (no storage)

$$\sum_{u=1}^{U} x_{sw,t} \leq Q_t$$

Water balances

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

$$r_{sw,t} + s_{sw,t} = \sum_{d=1}^{D} x_{sw,t} + Q_{out,t}$$

$$V_{gw,t} + rch_t - \sum_{m=1}^{M} x_{gw,t} - s_{gw,t} = V_{gw,t+1}$$

F^*	optimal value function
V	reservoir storage
Q	reservoir inflow (runoff)
m	user index (agri., dom., ind., Beijing)
n	water source (sw, gw, sn, curtail)
c	cost of n
x	allocated quantity of n
r	surface water reservoir releases
b_{hp}	hydropower benefits
p_{kl}	transition probability from Q_t to Q_{t+1}
k	inflow scenario in month t
l	inflow scenario in month t+1
t	time index, monthly steps used
dmd	water demand
s_{sw}	spills around turbines
s_{gw}	groundwater spills
Q_{out}	non-used discharge to the sea
U	users upstream the reservoir
D	users downstream the reservoir
rch	groundwater recharge

Method optimization problem

Water users

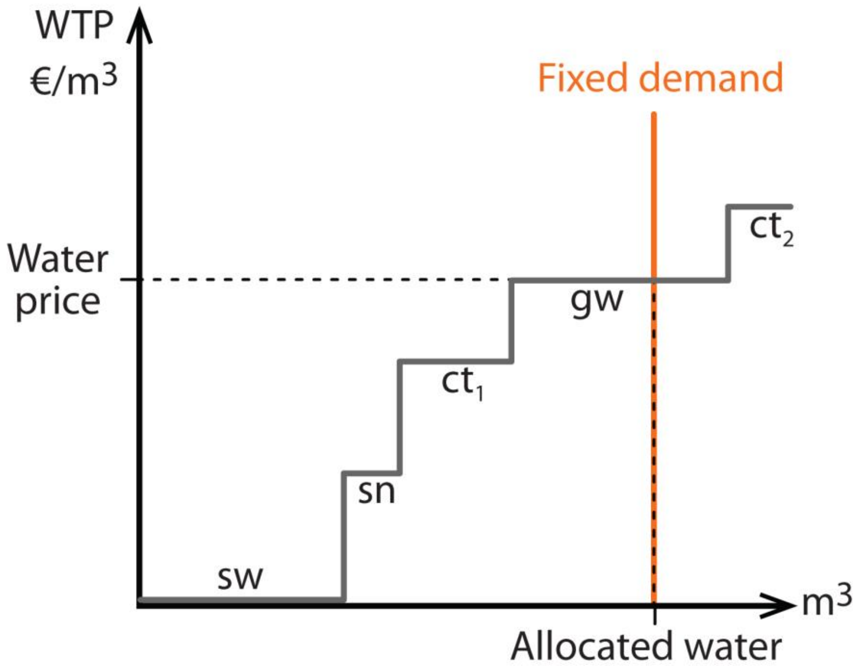
- Agriculture, industries, domestic, Beijing.

Water demand

- Inelastic, estimated from provincial statistics and field interviews.

Willingness to pay (WTP) / curtailment costs

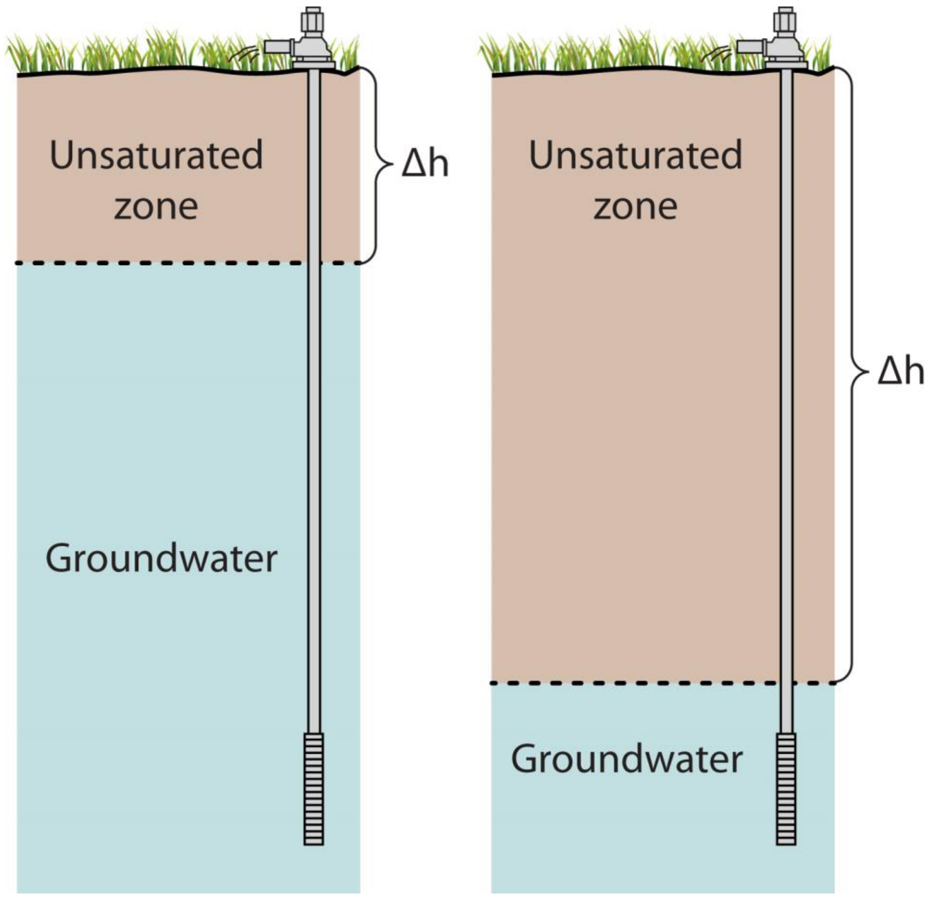
- Estimated from provincial statistics, literature review and field interviews.
- Agriculture: based on water use efficiency.



Rough annual water balance

Demands:	11 km^3
Runoff:	3 km^3
Groundwater recharge:	2 km^3
Water deficit:	6 km^3

Method head-dependent pumping costs



Low pumping cost High pumping cost

$$P_{pump} = (\rho g \Delta h) / \varepsilon$$ Specific pump energy (J/m³)

$$c_{gw} = P_{pump} c_{electricity}$$ Pump cost (Yuan/m³)

Method optimization algorithm

Genetic algorithm

Decisions:

SW end storage, V_{SW}
GW end storage, V_{GW}

Minimize total costs, TC

$TC = IC + FC$

Present regulation

Immediate costs, IC

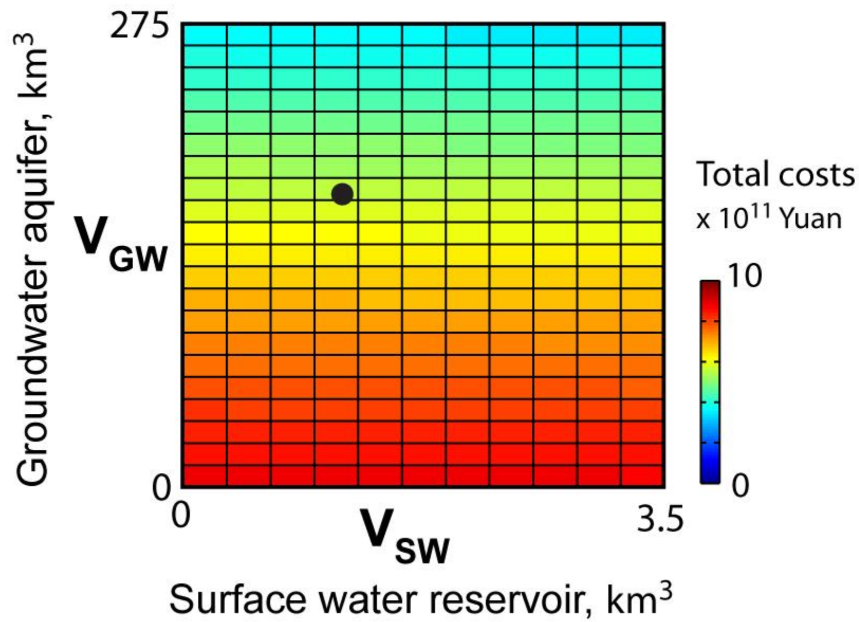
Solve linear program

$IC(V_{SW}, V_{GW})$

Future costs, FC (total costs, t+1 → end)

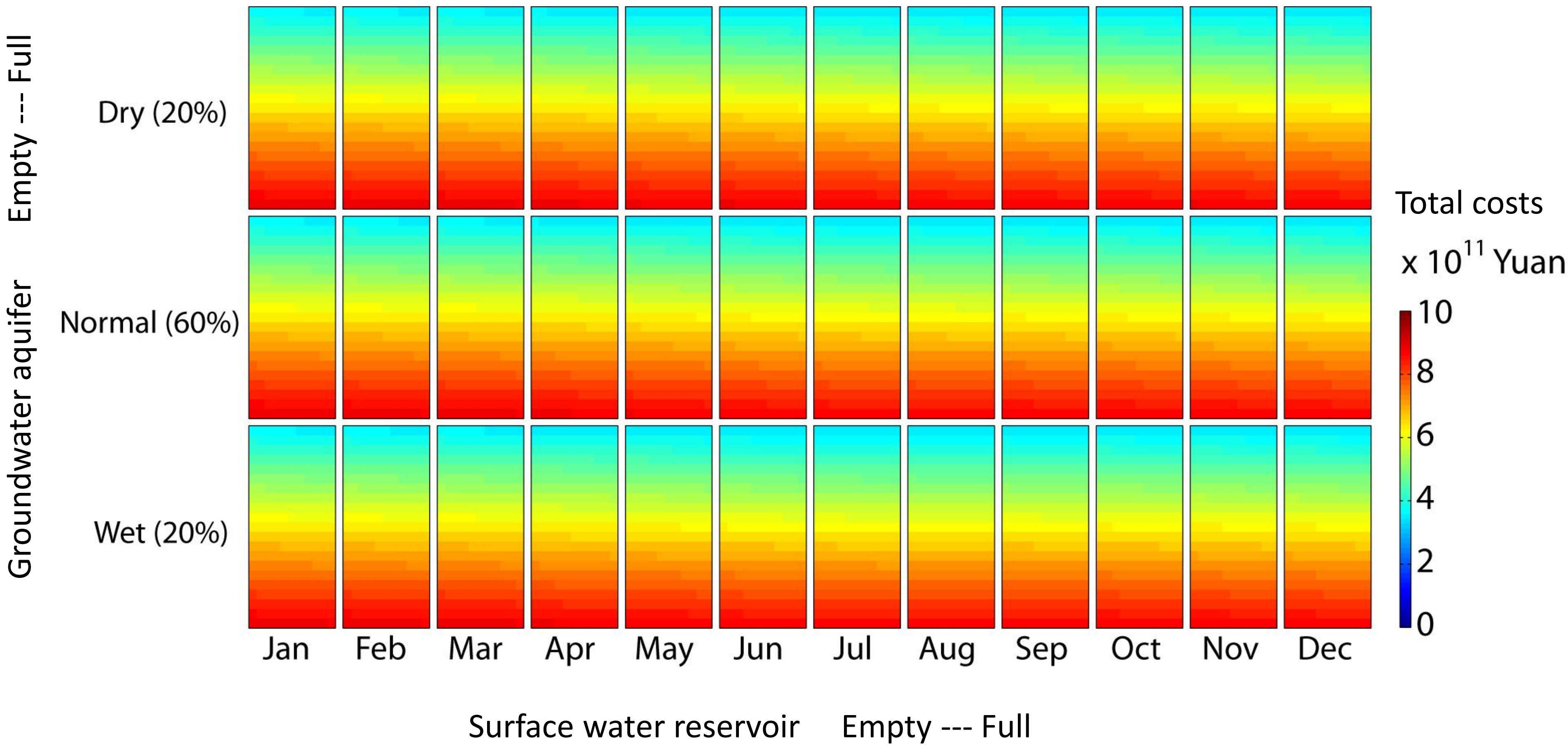
Interpolate FC matrix

$FC(V_{SW}, V_{GW})$



Results total costs

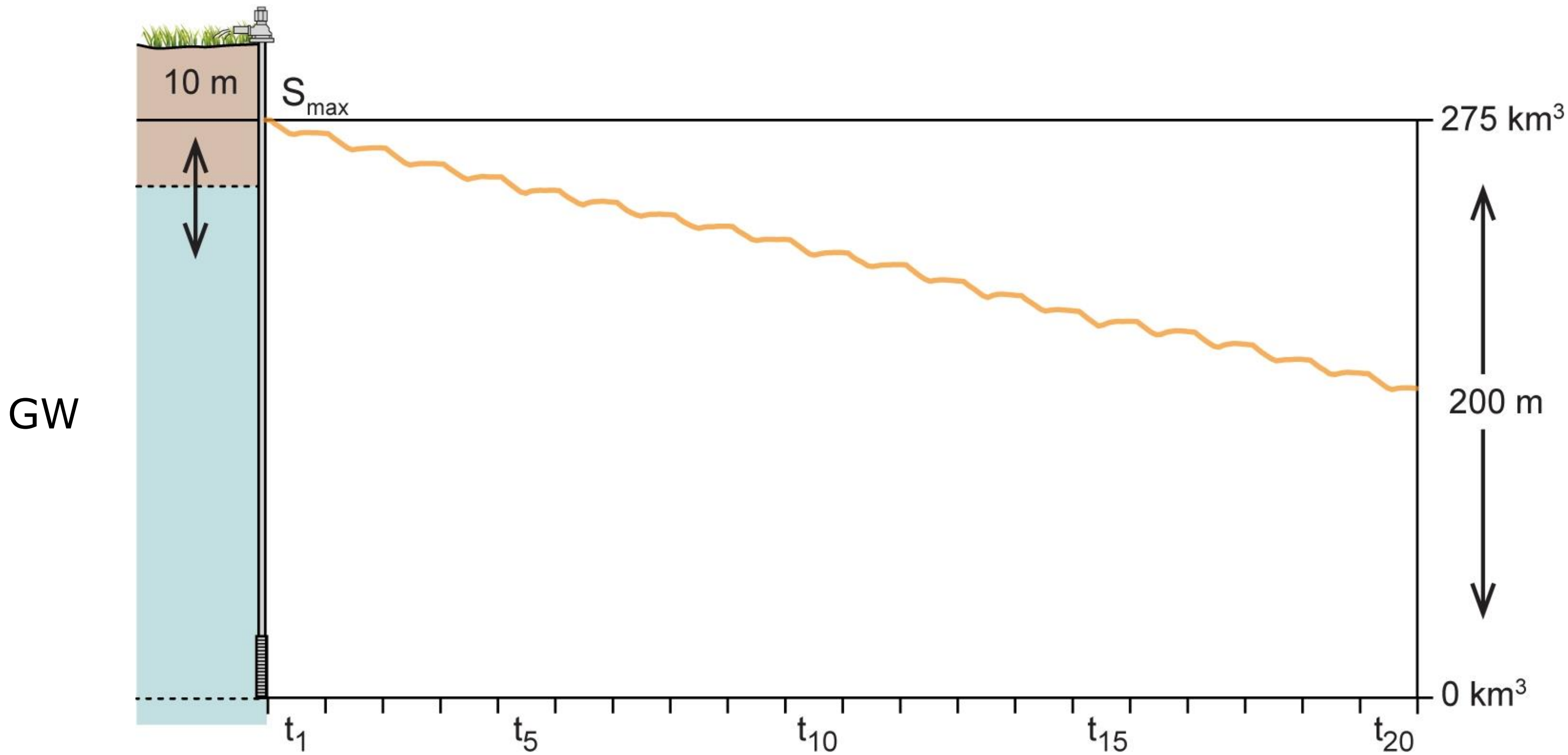
- Model run until water values remain constant between the years (60-70 years).
- 12 cores and IBM CPLEX ==> 4 days computation time.



Results application in policy support

Today on the North China Plain

- Individual users profit maximize individually
- The users pay only pumping costs
- Pumping costs not high enough to stop pumping until > 200m below surface



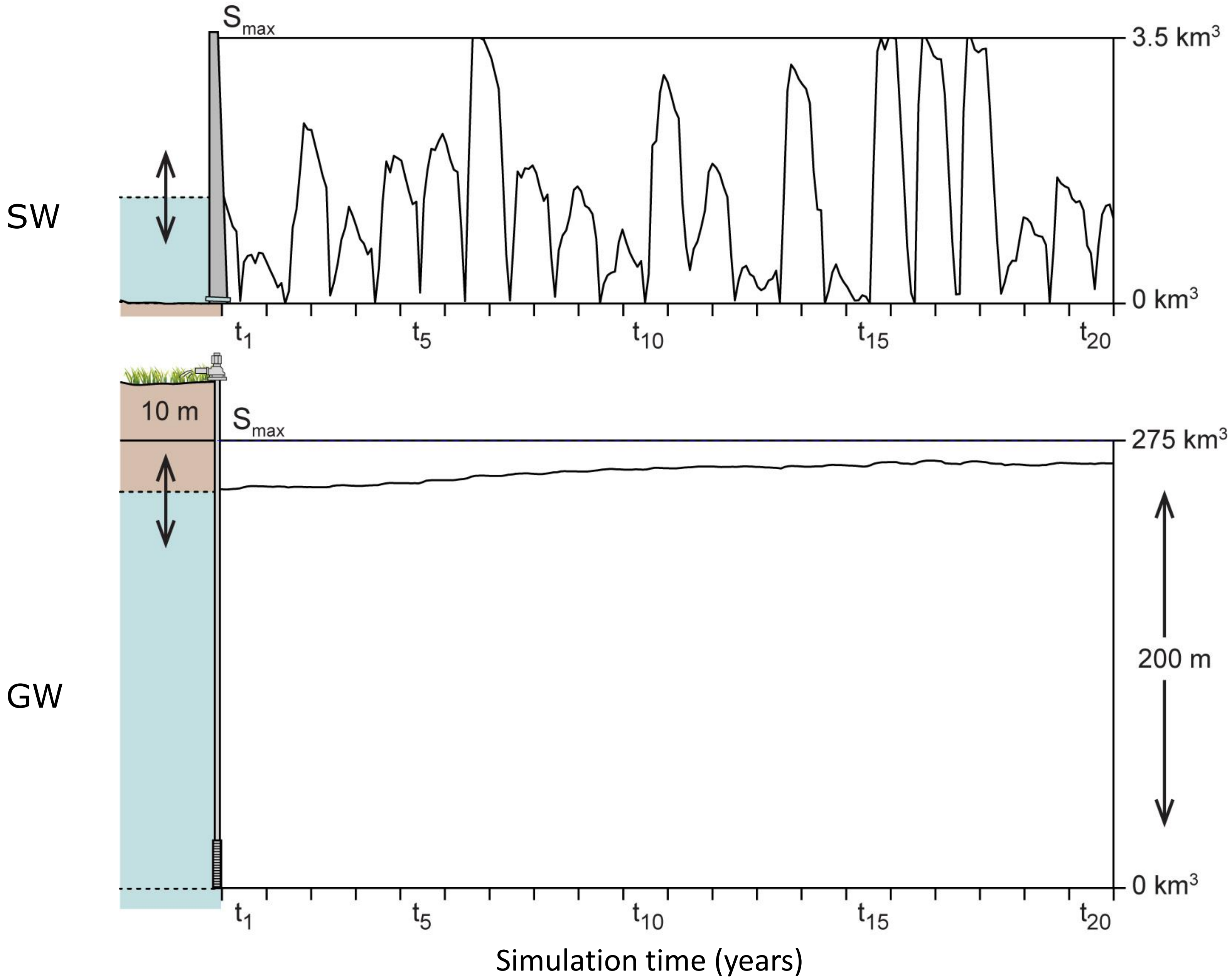
Results application in policy support

Our model -- long term lowest costs

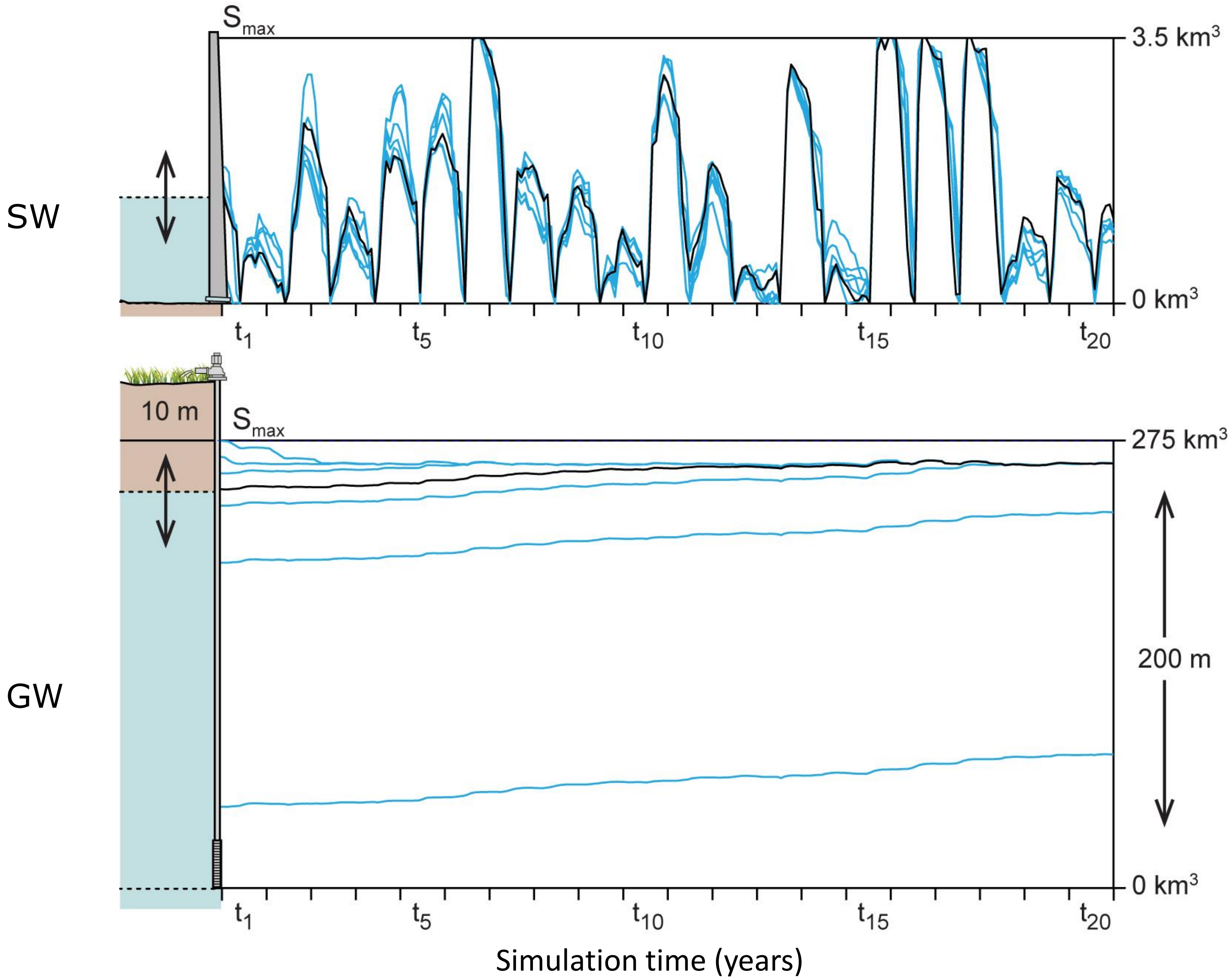
- Dynamic true groundwater and surface water value that depends on:
  - time
  - flow class
  - surface water storage
  - groundwater storage
- The optimization reveals the shadow price of both groundwater and surface water.
- The users should pay the head-dependent pumping costs + an additional tax equal to the shadow price.

  Pumping cost + shadow price = users' groundwater price

Results application in policy support



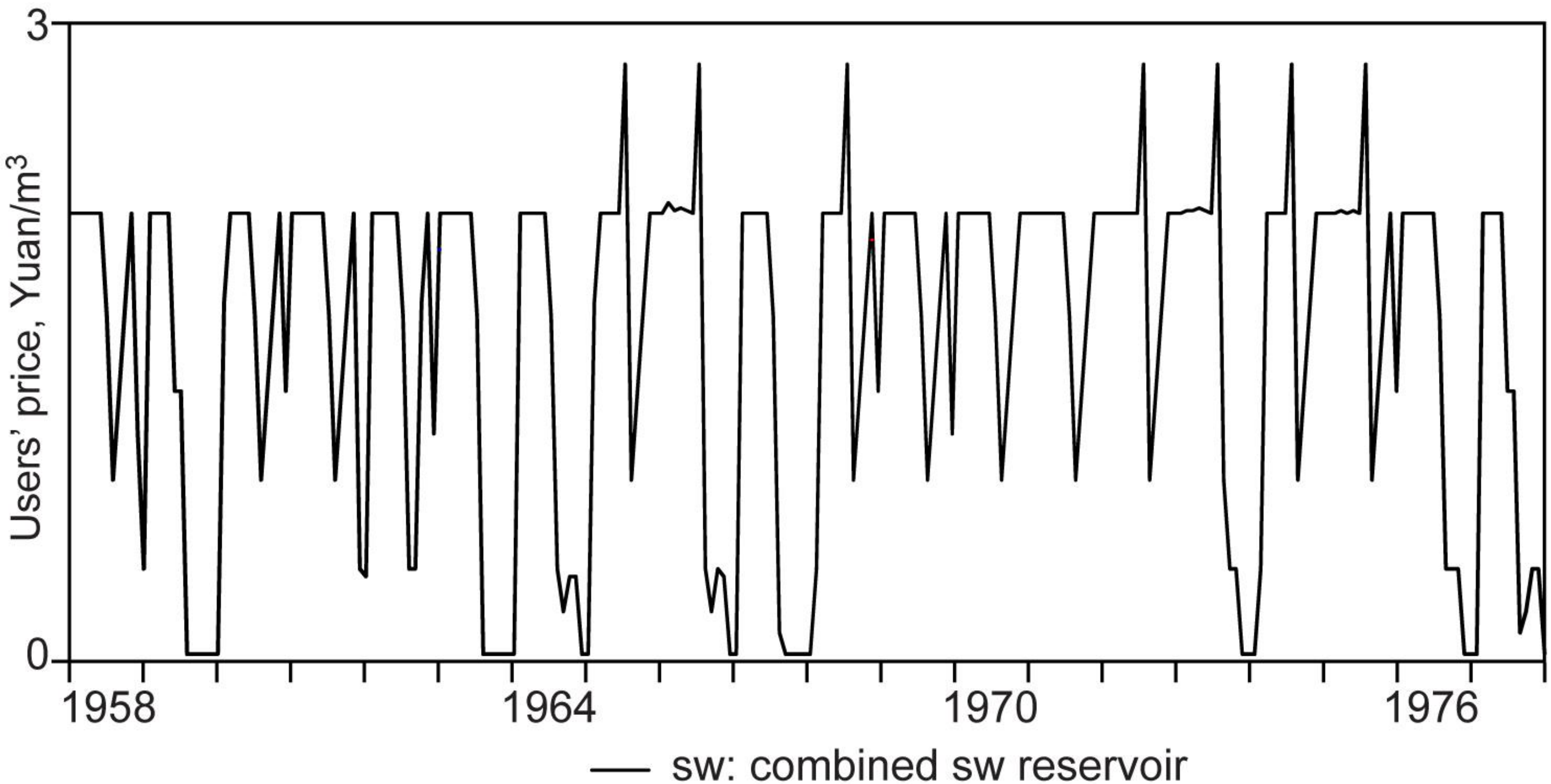
Results application in policy support



Results application in policy support

Users' water price

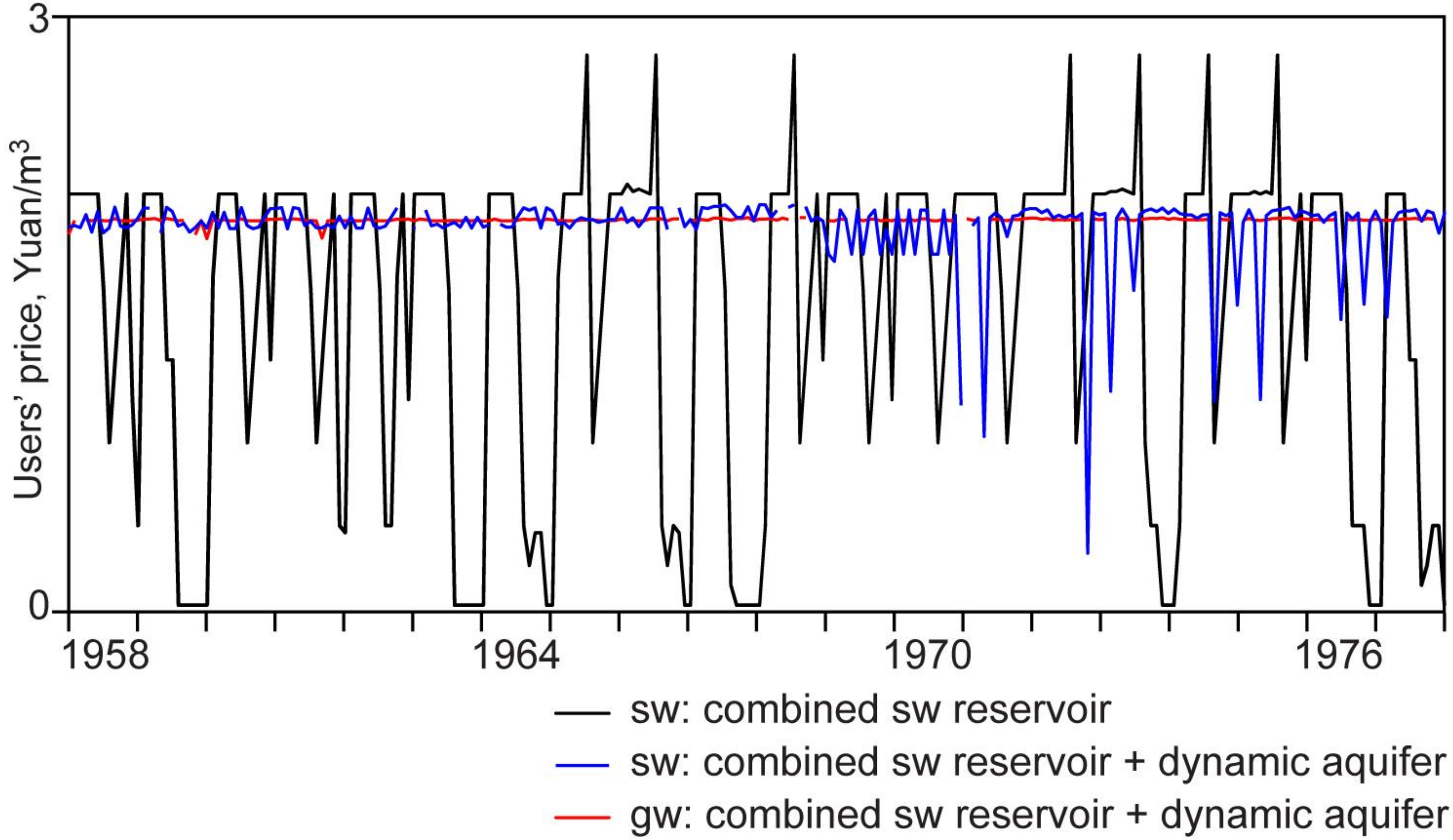
- Large variations with a single combined surface water reservoir



Results application in policy support

Users’ water price

- Large variations with a single combined surface water reservoir
- The dynamic groundwater aquifer serves as a buffer and keeps the users’ price more stable (= easier to regulate for decision makers)



Conclusions

Stochastic dynamic programming for dual-reservoir optimization.

- Optimal surface water management is linked to optimal groundwater management.
  - Shadow price for all combinations of time, flow classes, sw storage and gw storage
- Long term sustainable groundwater management found.
  - The dynamic groundwater aquifer serves as a buffer and stabilizes the water price
- Brute force method with high computational demand.
- Non-linear nature of head dependent pumping costs can be accommodated.

Future work

- Effect of local drawdown (cone of depression at each well).
- Discounting of future costs.
- Sensitivity analysis.

Questions

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