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Role of Models in Sustainable Groundwater Management

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- **Test for sustainability using a groundwater model**
- **Example: the mid-reach basin of Heihe, China**
  - Setting up the model
  - Process of calibration
  - Taking into account uncertainty
  - Using the model for management decision support
- **Conclusions**

Definition of sustainability

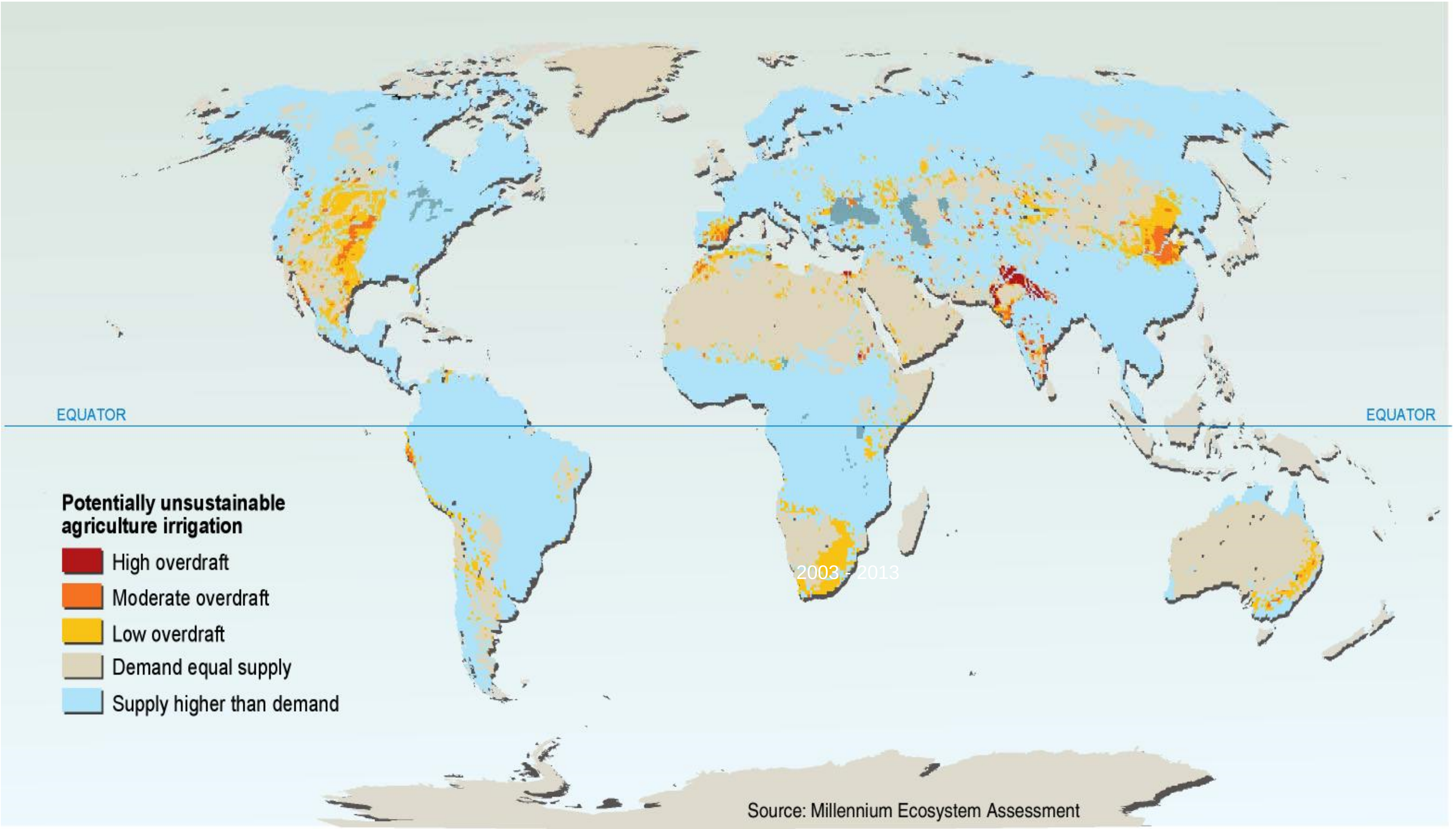
- Difficult task involving environmental, economic and social aspects

- Easier to define: What is non-sustainable?

- Unsustainable practices in the context of groundwater, which eventually lead to a crisis
    - Overpumping of an aquifer
    - Draining of a wetland or stream
    - Salinization due to irrigation–induced high groundwater tables
    - Groundwater pollution with non-degradable pollutants
    - Violent conflict between users e.g. on international aquifers

Overpumping of aquifers

Estimate for year 2000: Out of 1000 km^3/yr groundwater abstracted 280 km^3 are not replenished *(Wada et al. 2010)*



Main cause: Agricultural irrigation

Externalities of overpumping

- Drying up of streams and wetlands
- Die-off of phreatophytic vegetation and desertification
- Soil subsidence
- Irreversible decrease of storativity
- Salt water intrusion
- Increase in pumping cost
- **Depletion of storage (Loss of resilience against climate change)**

Source: Wu Aimin 2013

Drying up of wetlands

⬅ **Wetland park in Zhangye, Gansu**

Pop. Euphratica forests, West China
⬇

Global wetland area decreased by 50% between 1900 and 2000. Trend is unbroken.

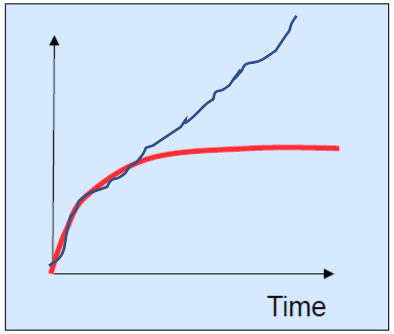
Soil Salinization

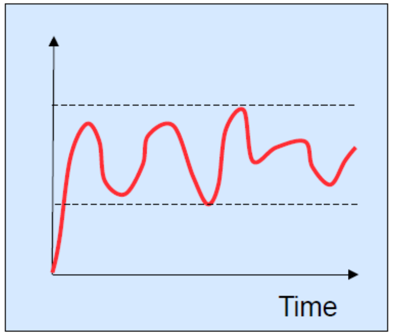
Consequence of high phreatic evaporation from a groundwater table close to groundsurface

80 Mio. of 260 Mio. ha irrigated land are affected globally

How to check for sustainablility

1. Build a model of the system
2. Insert future drivers





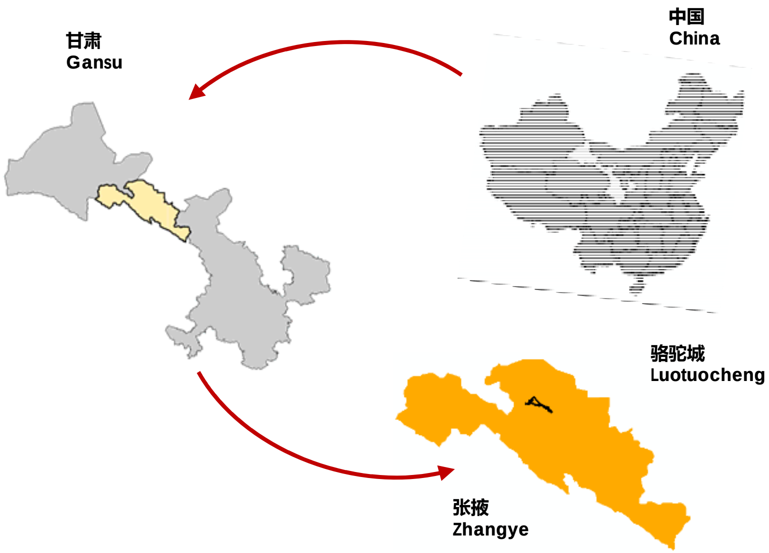
3. Run the model to the limit of large times
4. Check whether results are acceptable in view of environmental, economic and social aspects
5. Sustainability can be enhanced if groundwater is used conjunctively with surface water as a large storage, which buffers stochasticity of surface water hydrology

Steps in building and using a model

1. Choose the model domain
2. Do a water balance (0-D) — If not feasible, **STOP !**
3. Set up properties and drivers
   - Over discretized domain
4. Calibration and validation
   - choose your calibration strategy
   - calibrate/verify output against observations of heads and fluxes
5. Analyze uncertainty
6. Explore sustainability
   - for present management practice
   - for other possible management alternatives
7. Determine robust management strategy

Example: Heihe Mid-reach

Heihe Basin: Zhangye, Gansu, China

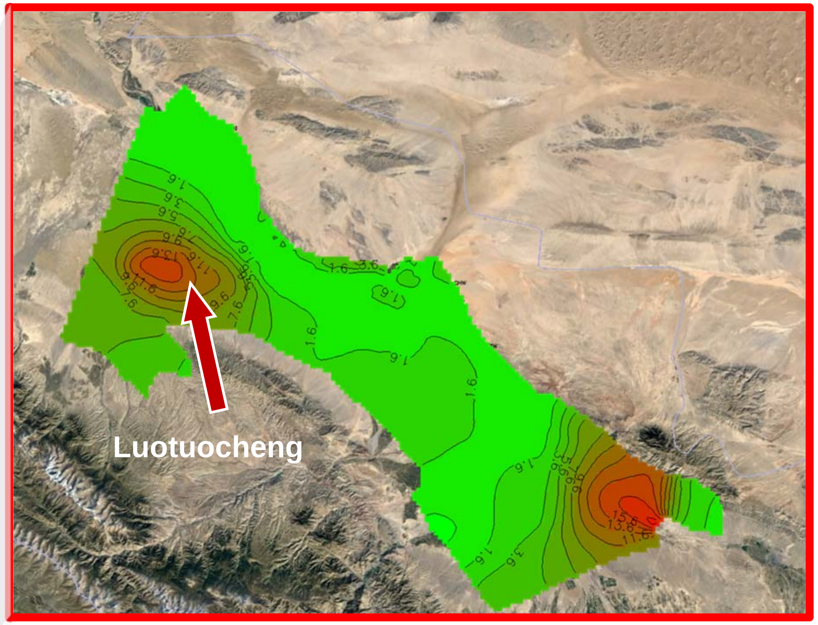


- Arid climate
- Full irrigation by river water and groundwater
- Highly productive agriculture

Problems

East Juyuan Lake

Heihe Mid-reach

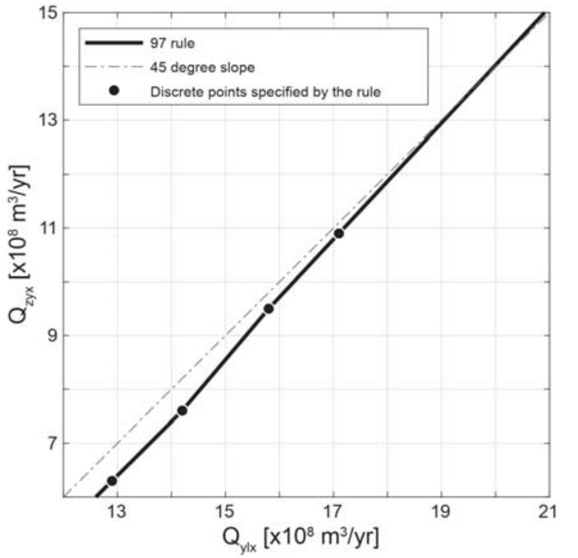


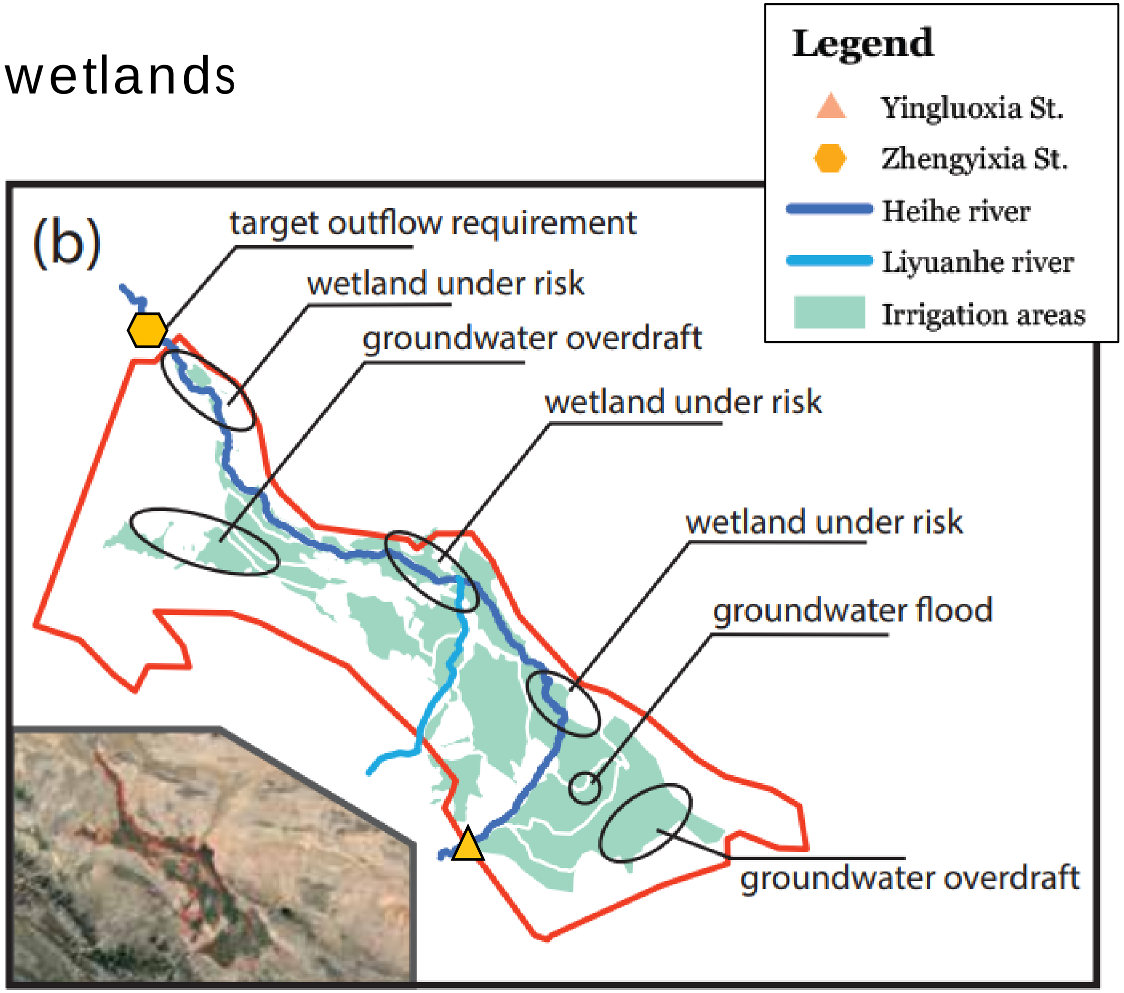
- **Overuse of water** led to drying up of terminal lake and degradation of tugai forests
- 2 large cones of depression developed from pumping near Luotuocheng/Sunan and Daman

What does “sustainable” mean here?

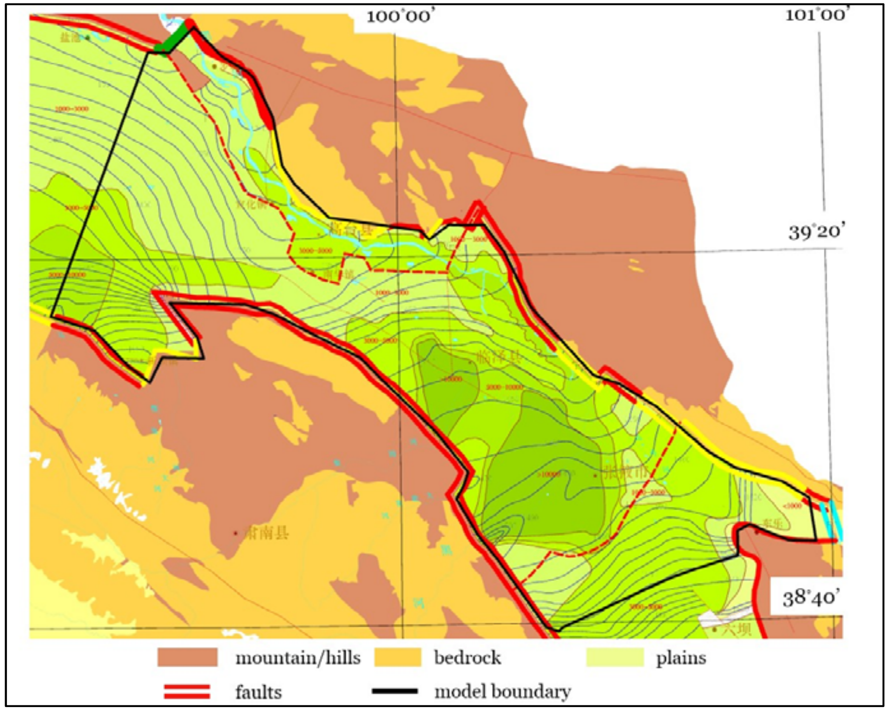
- Satisfying minimal outflow
  (97-rule; about half of inflow sent to downstream)
- Preventing deep cones of depression
- Preventing salinization
- Preventing drying up of wetlands

“97 water allocation scheme”
(Nr. 496, 1997, Minister of Water Resource)

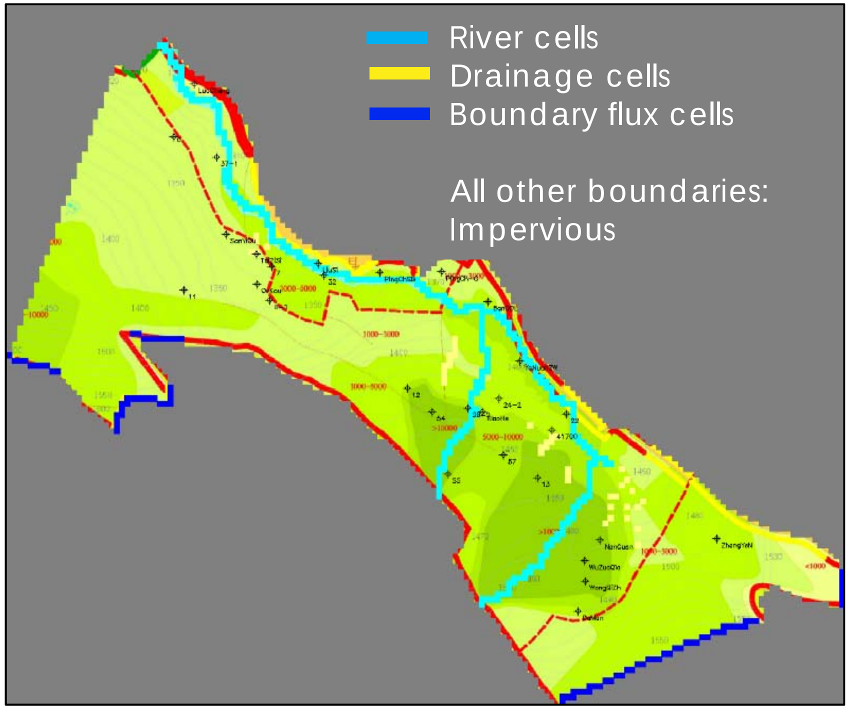




Define model domain

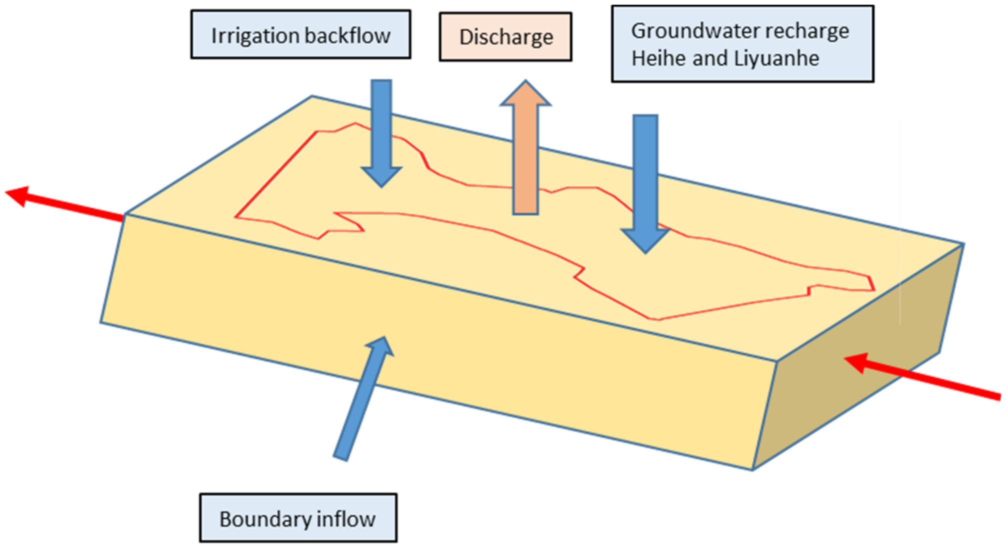


Hydrogeological map 2018



Discretization 1 km × 1 km， 2-D horizontal

The 0-D (box) model (pre-1990 situation)



Total In: 12.1	Units 10^8 m^3/a
Boundary inflow	1.5
GW recharge Heihe and Liyuanhe	5.6
Net recharge by irrigation backflow	4.8

Total Out: 12.1	Units 10^8 m^3/a
Drainage to river including springs and other drainage	8.2
Phreatic evaporation	3.8
Pumping negligible in 1990	0

River inflow : 18.7×10^8 m^3/a

River outflow : 8.2×10^8 m^3/a

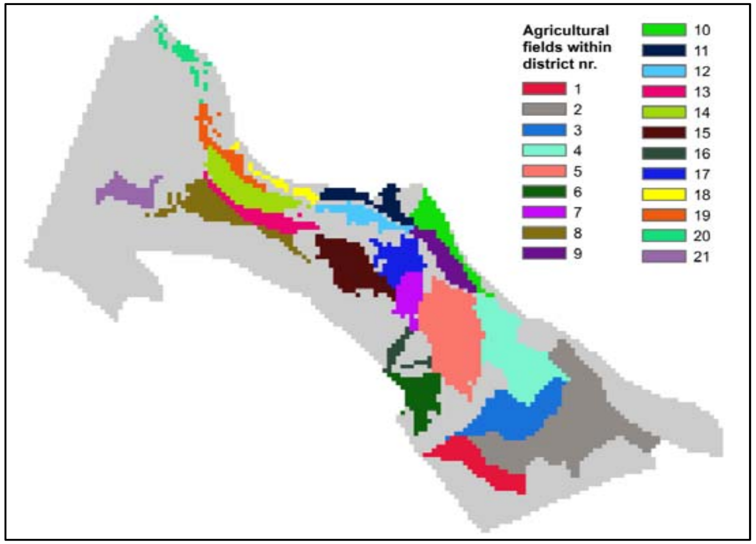
Assumptions:

- Steady state
- Irrigation backflow 30%

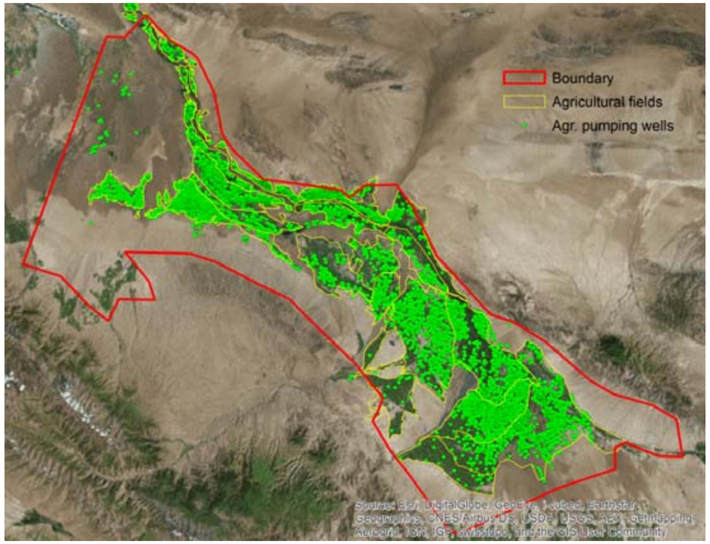
phreatic evaporation backed out

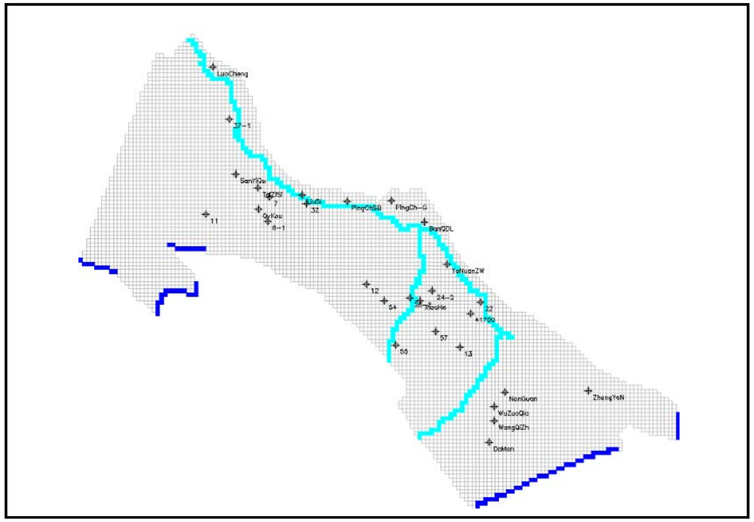
The distributed model: Some other inputs

Irrigation districts

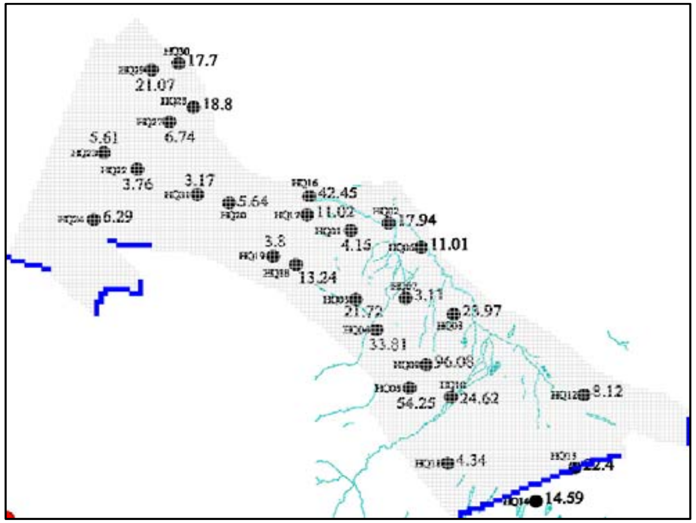


Pumping wells



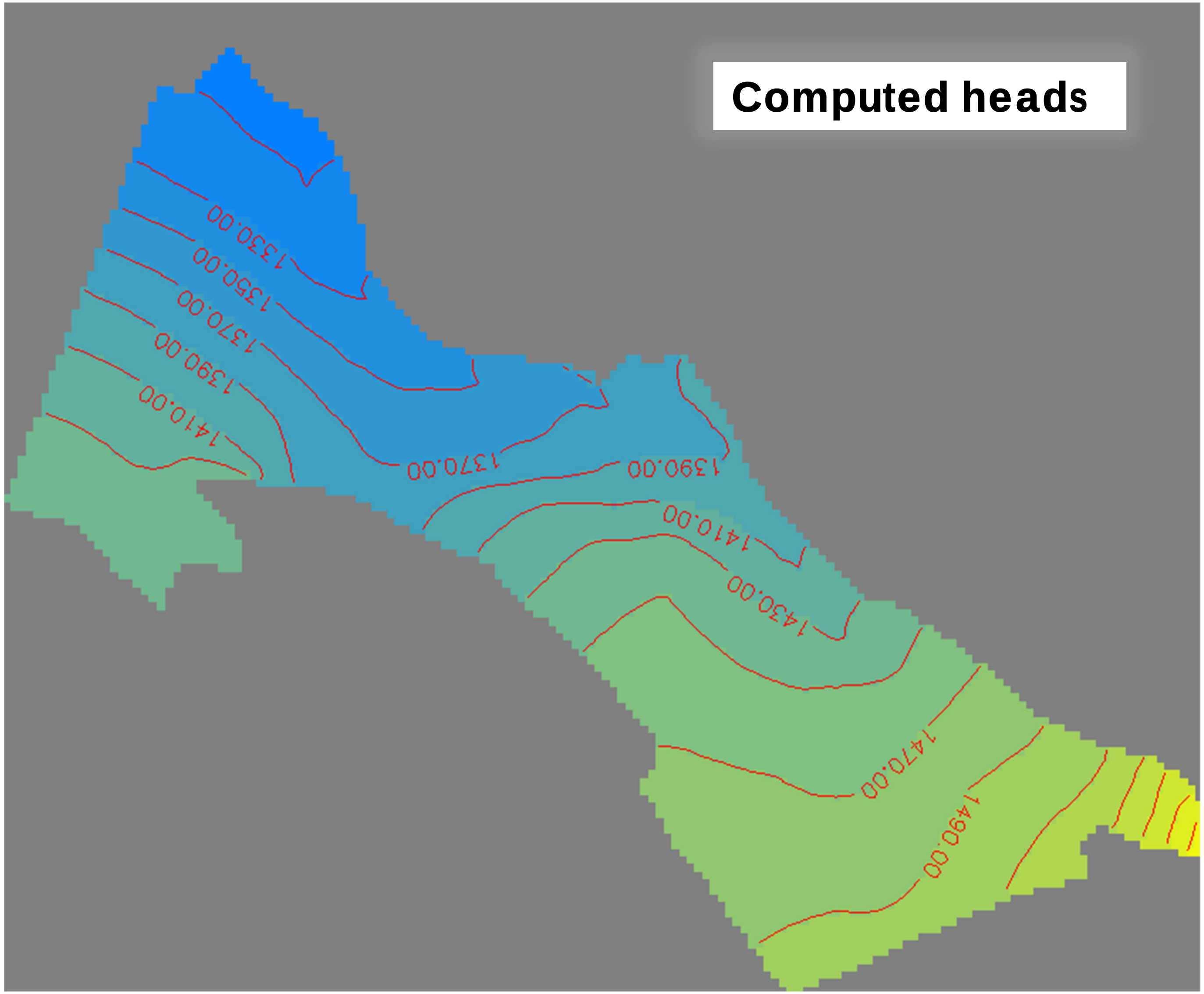


Observation wells



Pumping test results

Head distribution steady state



Calibration: Steady state (1986-1989)

Rules and strategy

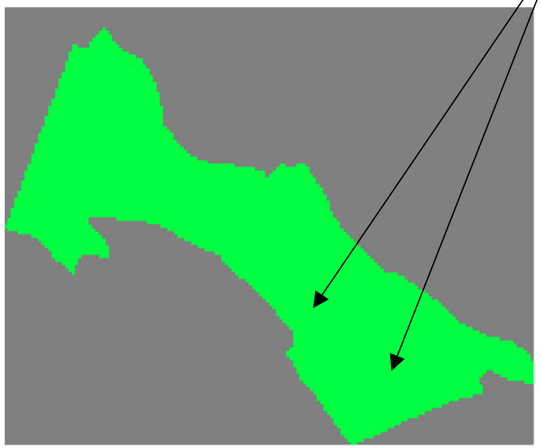
- Calibration strategy here: Keep estimated fluxes from box model and adjust K-values
- Simultaneous calibration of fluxes and K-values leads to non-unique results!
- Number of parameters to be estimated should be much smaller than number of head-observations
- Zoning of K-values according to geological map and prior knowledge from pumping test data
- Always check parameter covariance matrix for correlations (+ or -) between parameters

First try: 1 zone homogeneity assumption

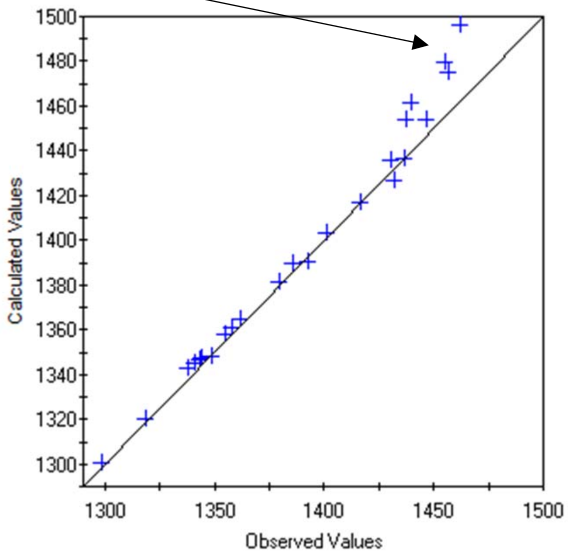
calibrated K-value (m/d)

Parameter	Estimated value	95% confidence limit	
	(m/d)	Lower limit	Upper limit
K1	5.6	4.2	7.3

systematic deviation for high heads



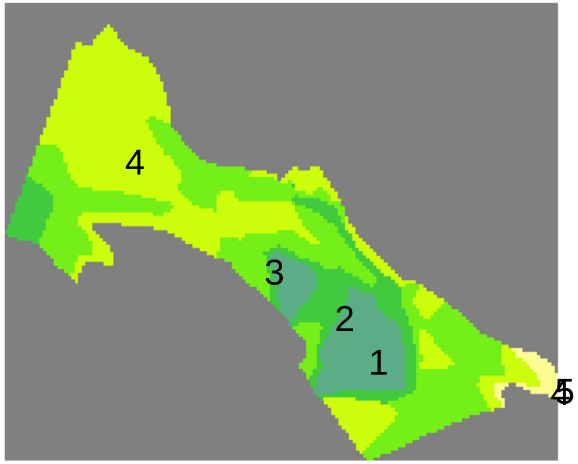
K-zones

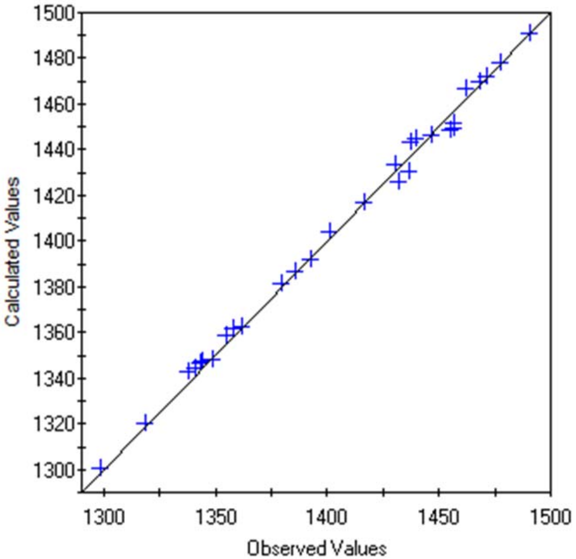


Variance: 719 m^2

Obvious choice: 5 zones of geological map

Parameter	Estimated value	95% confidence limit	
	(m/d)	Lower limit	Upper limit
K1	85.9	63.8	115.7
K2	9.5	3.1	29.3
K3	15.1	8.7	6.0
K4	4.7	4.4	5.1



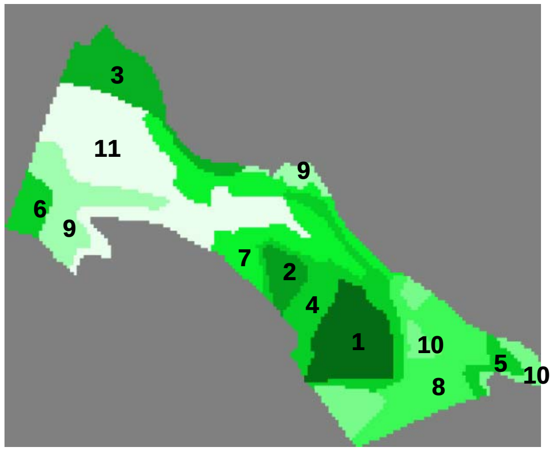


Variance: 13.7 m^2

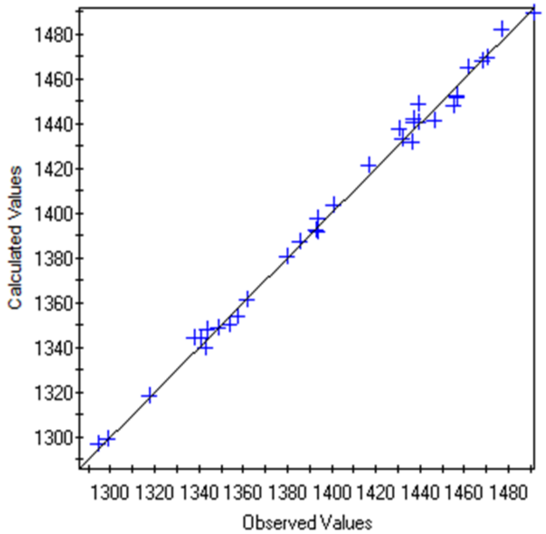
K5 is not identifiable! ➔ Change to unique 4 zone model by setting K5 = K4

Final choice: 11 zones
(6 fixed with pumping test results)

Parameter	Estimated value	95% confidence limit	
	(m/d)	Lower limit	Upper limit
K1	83.61	68.66	101.83
K2	23.82	8.87	63.99
K3	20	fixed	
K4	15	fixed	
K5	15	fixed	
K6	15	fixed	
K7	13.00	9.39	18.45
K8	13.16	8.74	19.77
K9	7	Fixed	
K10	7	Fixed	
K11	4.70	4.56	4.94



Closer to pumping test results



Variance: 10.9 m^2

Summary steady-state calibration

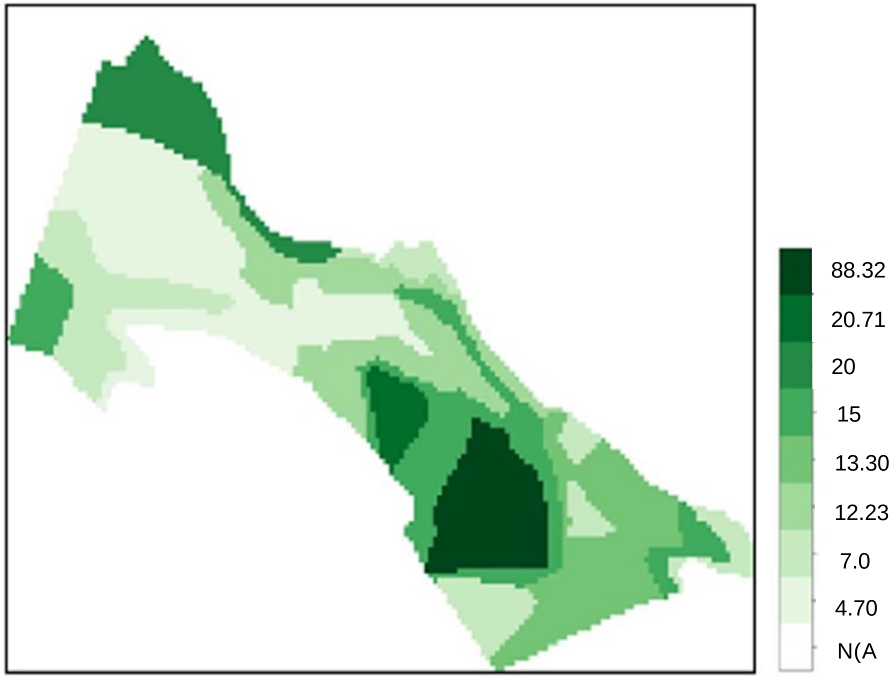
Nr. of zones	Fit (σ^2 in m^2)	Uniqueness	Correlation matrix	Remarks
11	10.5	No	Normal matrix singular	Can be made unique by fixing 6 zonal values
5	10.9	Yes	No off-diagonal matrix elements > 0.5	From 11 zone model by fixing 6 zonal values with values from pumping tests
4	13.7	Yes	No off-diagonal matrix elements > 0.5	From 5 zone geological model by setting zone 5 value = zone 4 value
1	719	Yes	NA	Good fit except for high end

Time-dependent model

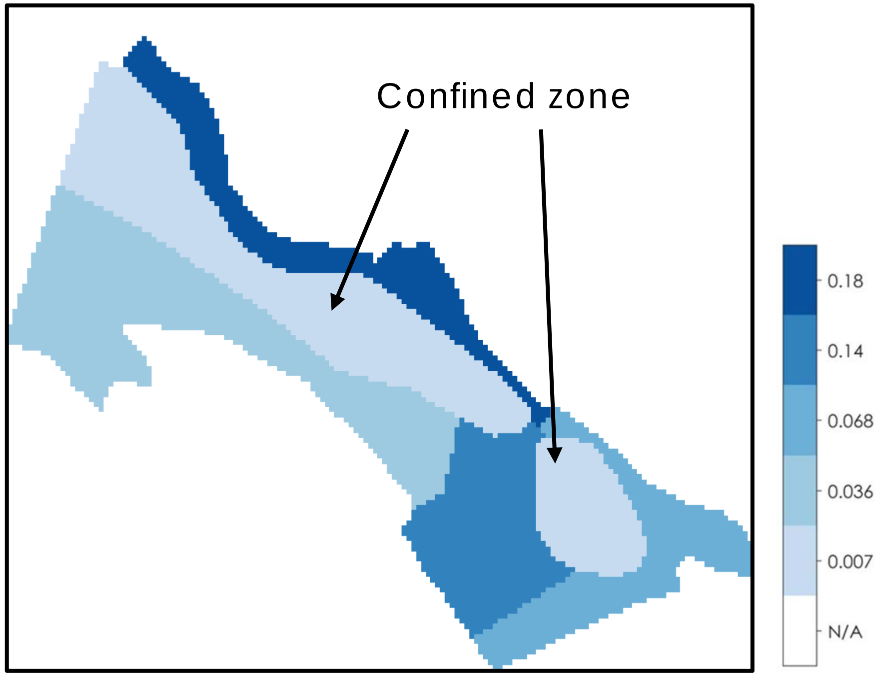
- Zoning of storage coefficients
  (taking into account confined part of aquifer according to geological map)
- Iterative improvement of hydraulic conductivities
- Steady state 1986-1989 to define initial condition
- Simulation in yearly time periods using yearly average data
  (net-recharge and river seepage through 1990-2012)
- Determine long-term steady state with average future drivers

Time-dependent calibration results

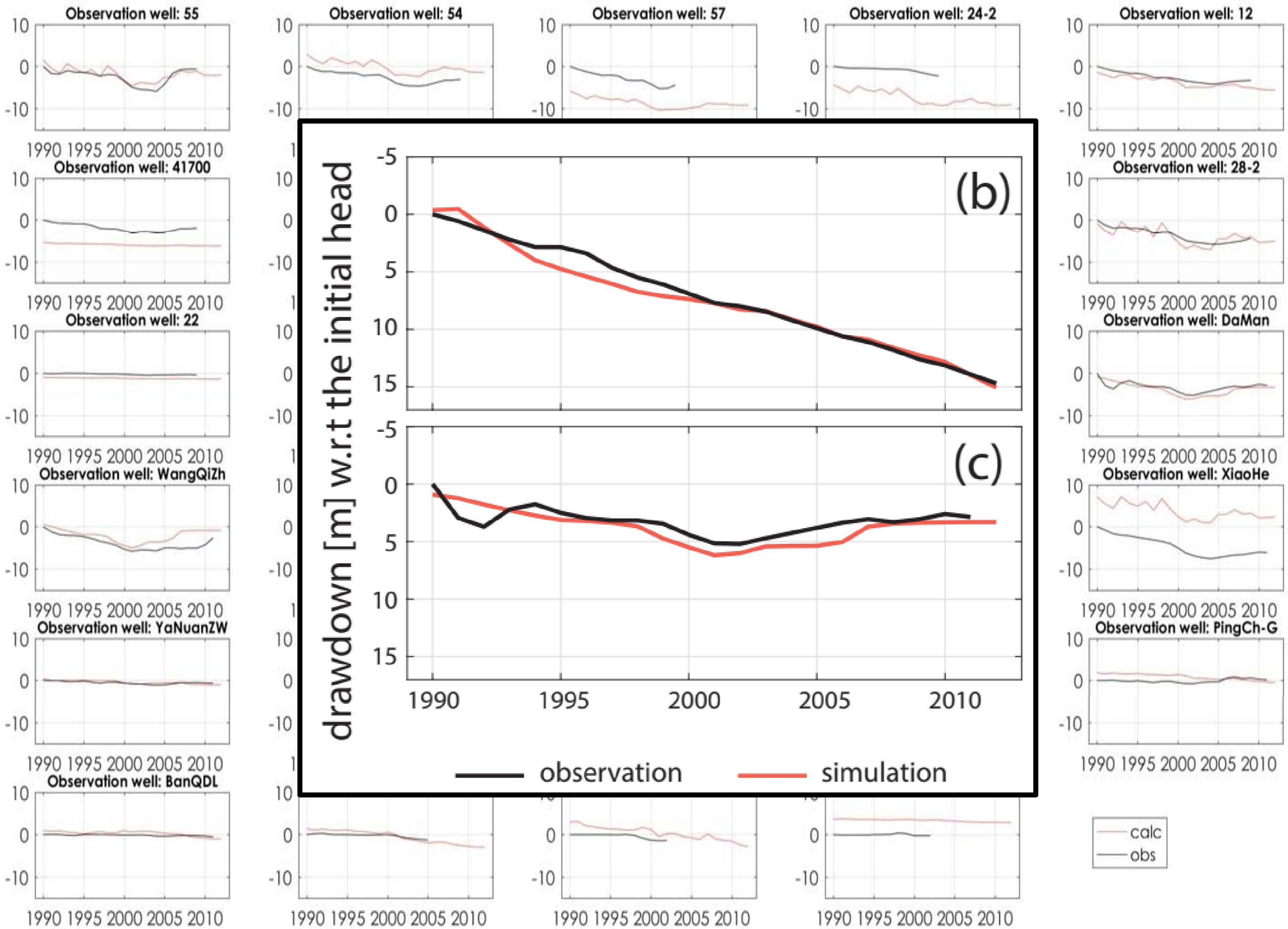
Hydraulic conductivity **K** (m/d)



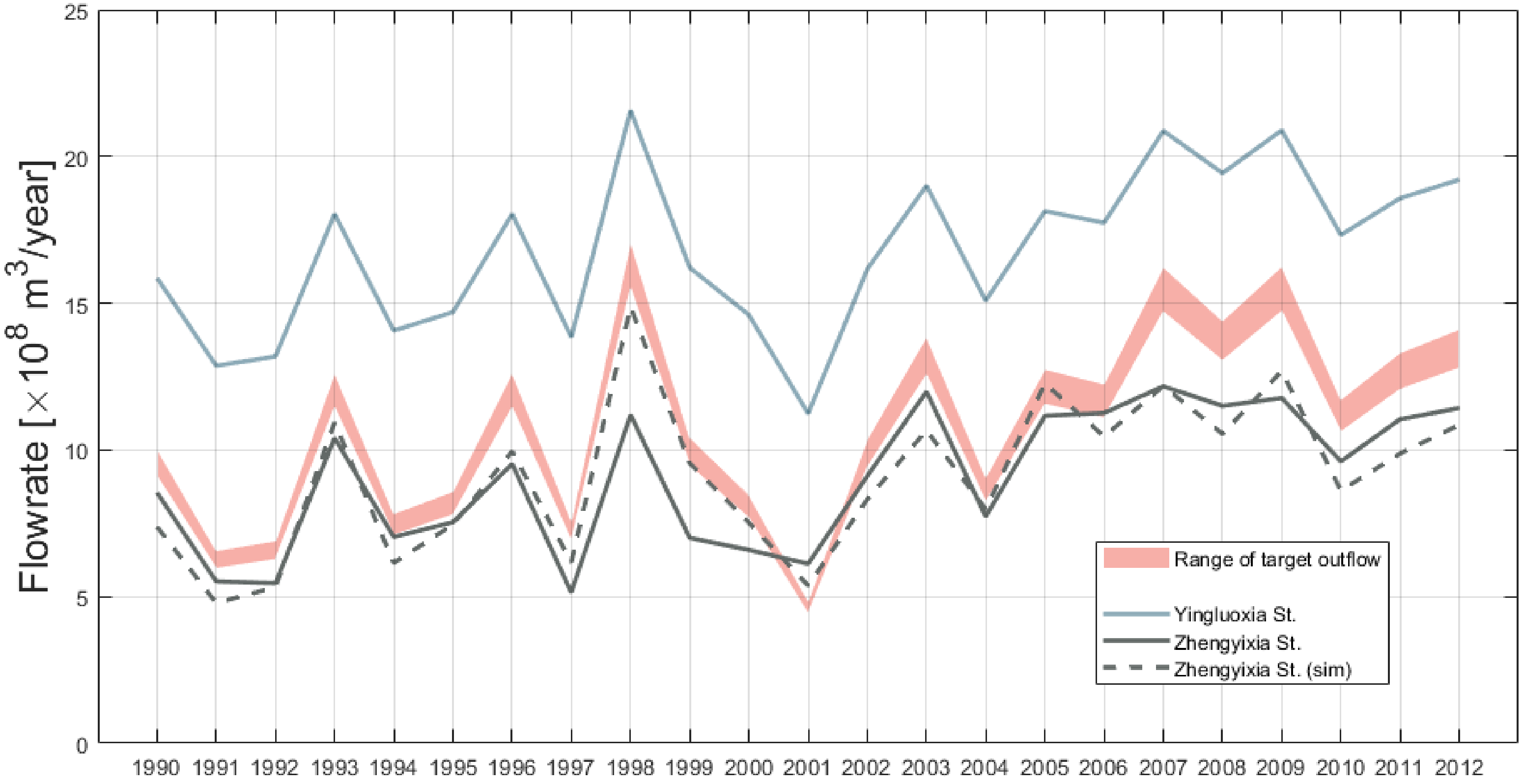
Specific yield (-)



Calibrated heads of time-varying model (1990-2012)



Verification of the model with river fluxes



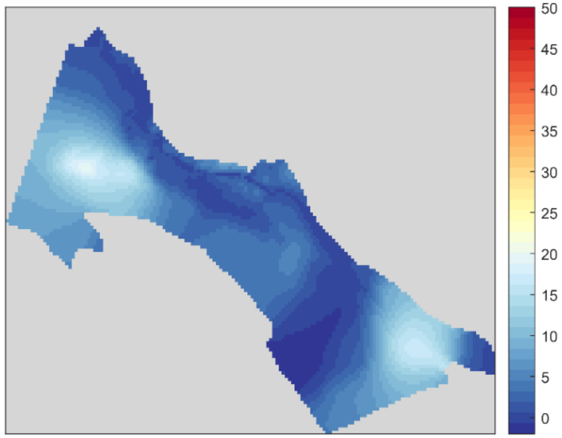
Non-compliance paradoxically occurs in water rich years:
While agricultural demand is almost constant, phreatic evaporation and evaporation by wetlands is higher in water rich years

Running the model to infinity

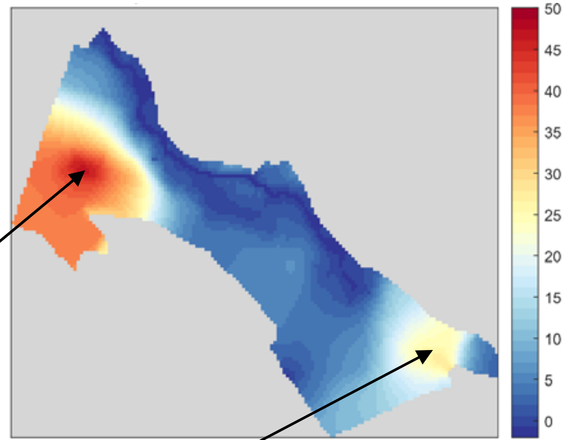
(with river flow rate and water allocation of 2012)

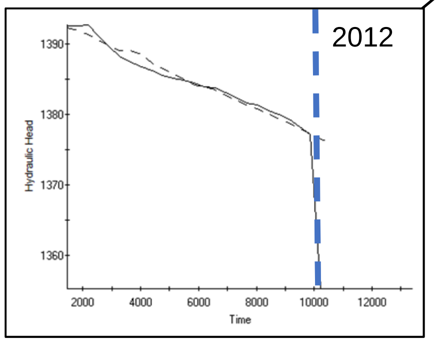
water table change [m]

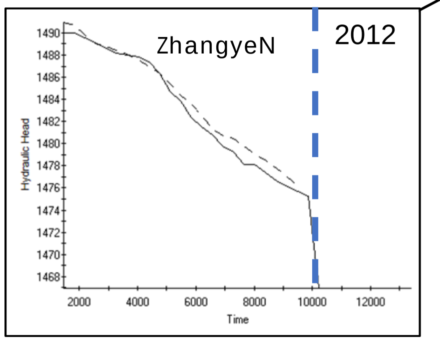
between 1990 and 2012



between 1990 and ∞







Water table change at two critical piezometers in the cones of depression

Conclusions with regards to sustainability

Running model to steady state:

Heads will stabilize at lower levels: Further decline by **up to 23** m in Luotuocheng/Sunan irrigation districts and **up to 9** m in Daman compared to 2012

97-rule **cannot be fulfilled** without decrease in total water use, i.e. decrase in agricultural GDP

Reduced phreatic evaporation in the new equilibrium state: About 1.3×10^8 m^3/year less compared to 1990, increasing the available resource by that amount

Apart from that change, in steady state 1 m^3 of irrigation water diverted from the river has about the same impact on downstream flow as 1 m^3 abstracted from the aquifer

However, this result is subject to uncertainty

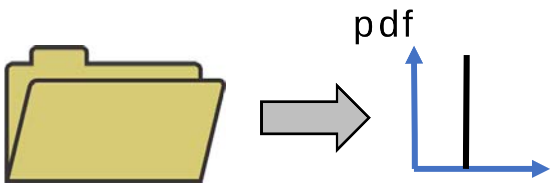
Capturing uncertainty

- Uncertain hydraulic conductivities
- Uncertain specific yields
- Uncertain initial conditions
- Uncertain boundary flux
- ...

→ Use **ensemble of realizations** instead of one realization In a Monte-Carlo approach

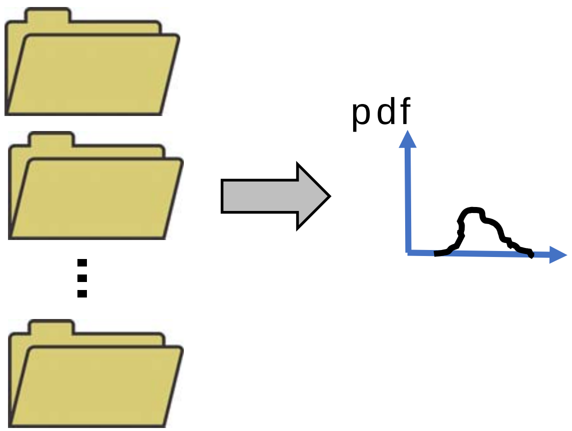
Deterministic model

1 input data set → 1 result



Stochastic model

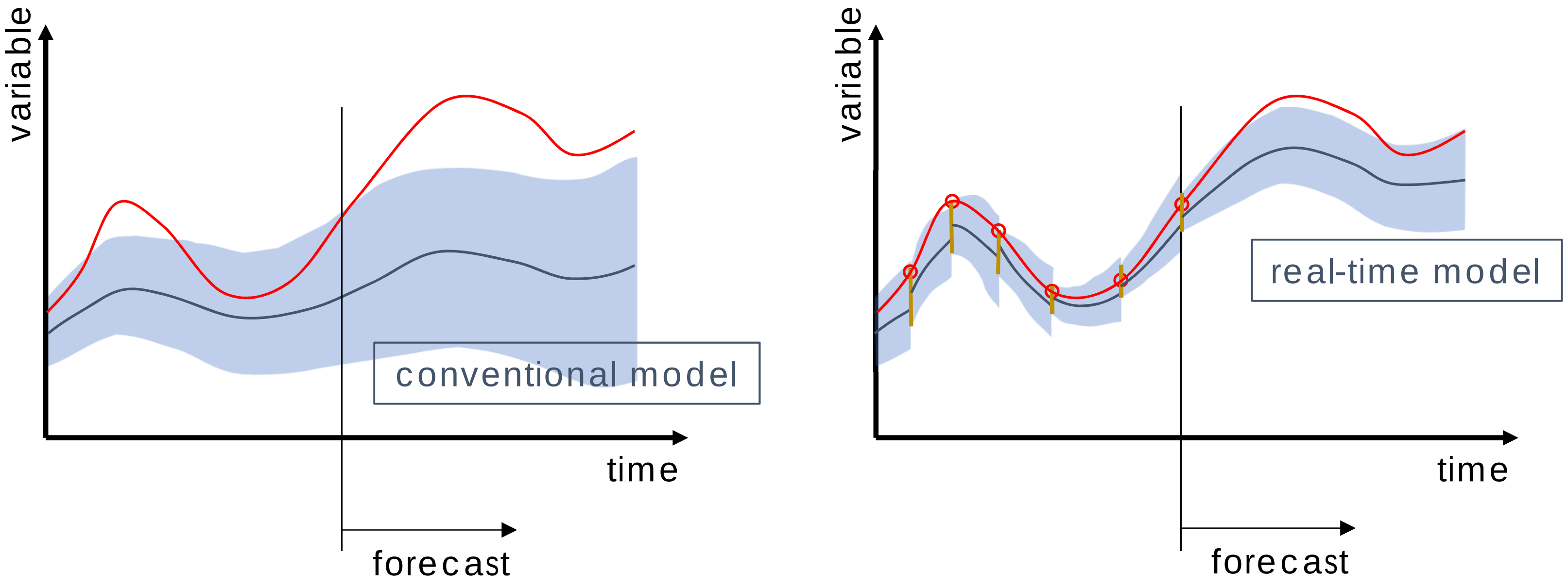
N equally likely input data sets → a distribution of results



Improving prediction power by assimilation

Incorporating uncertainty in conventional model

Real-time model with data assimilation using Ensemble Kalman Filter (EnKF)



Legend

reality

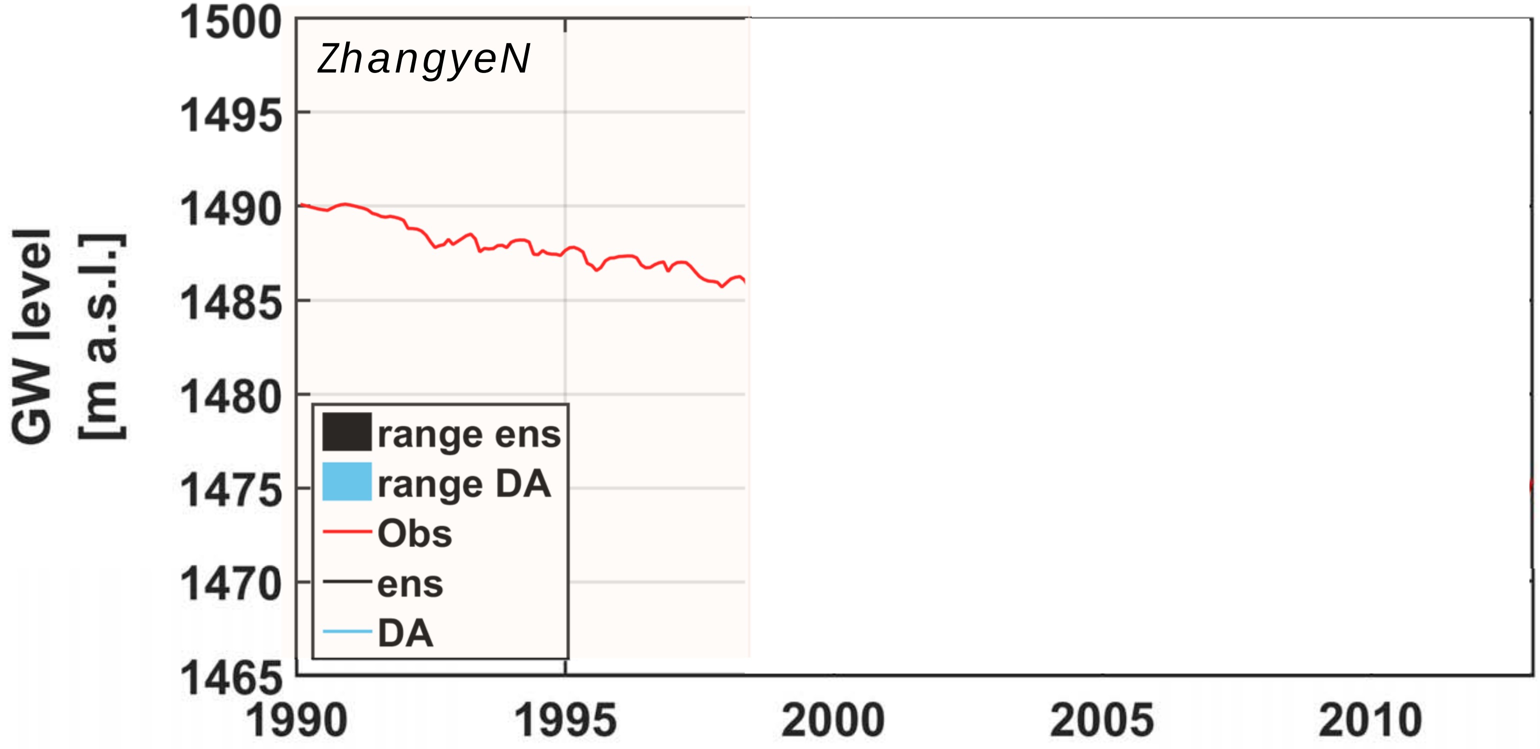
ensemble

ensemble mean

Time steps with data assimilation

Forecast quality of the Heihe real-time model

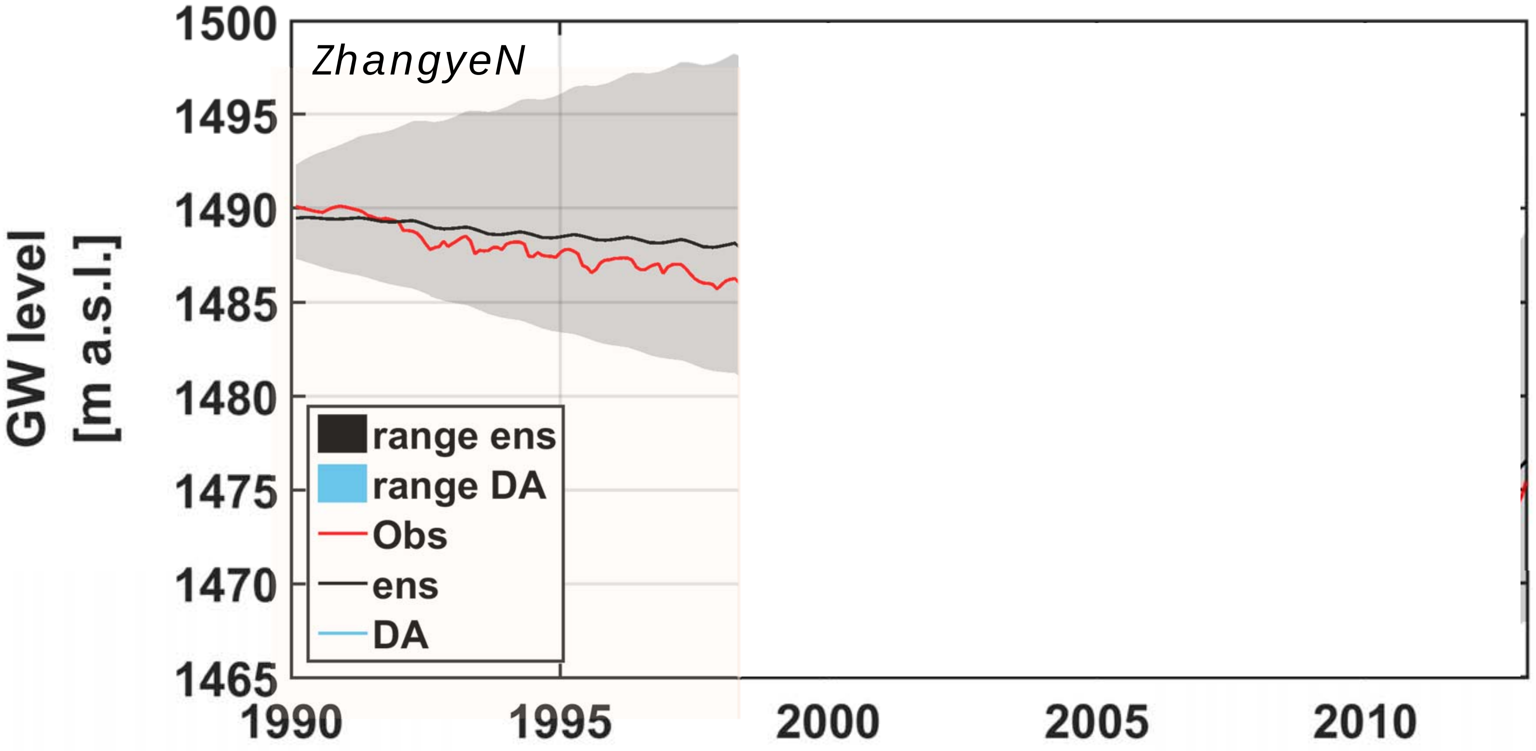
(Monthly steps)



Observed groundwater levels

Forecast quality of the Heihe real-time model

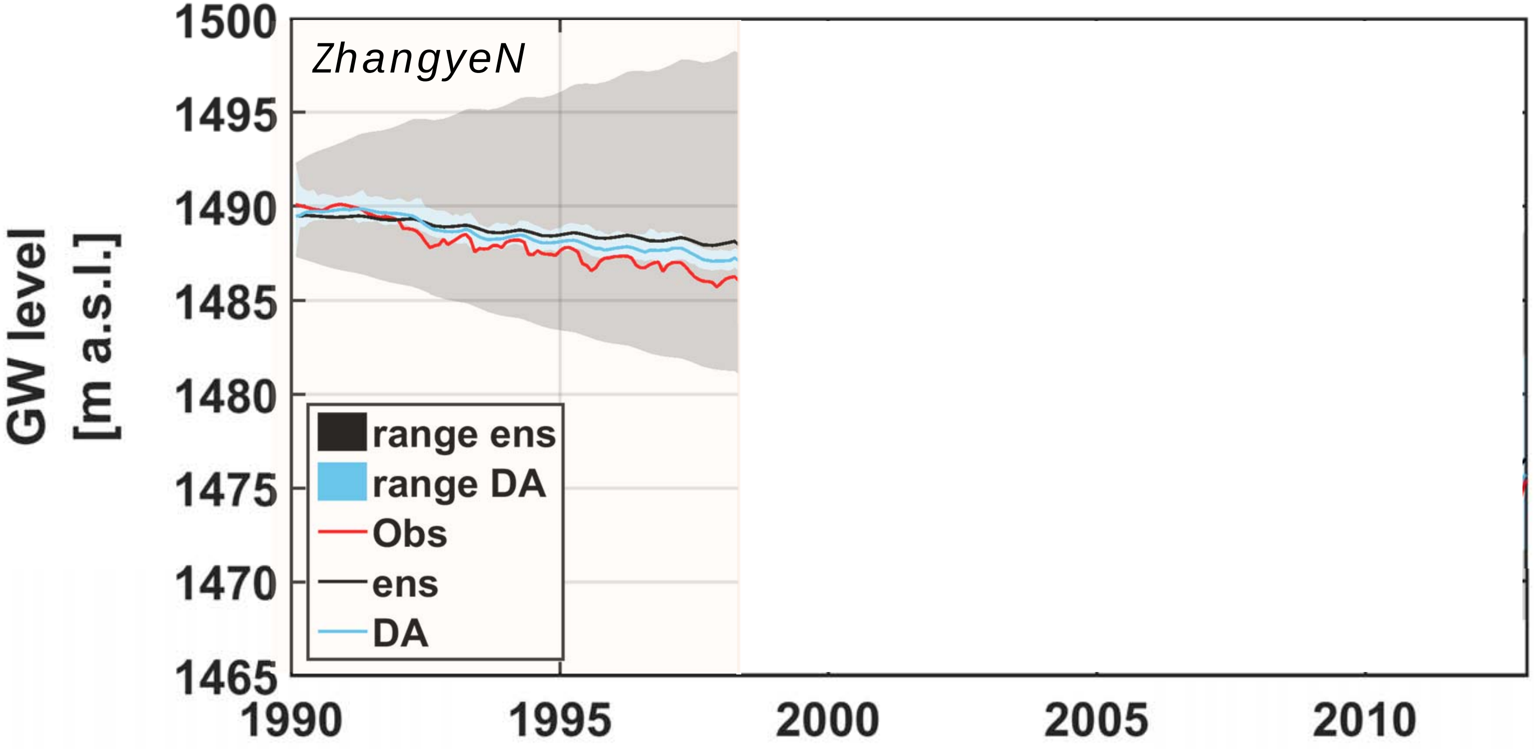
(Monthly steps)



Ensemble simulation

Forecast quality of the Heihe real-time model

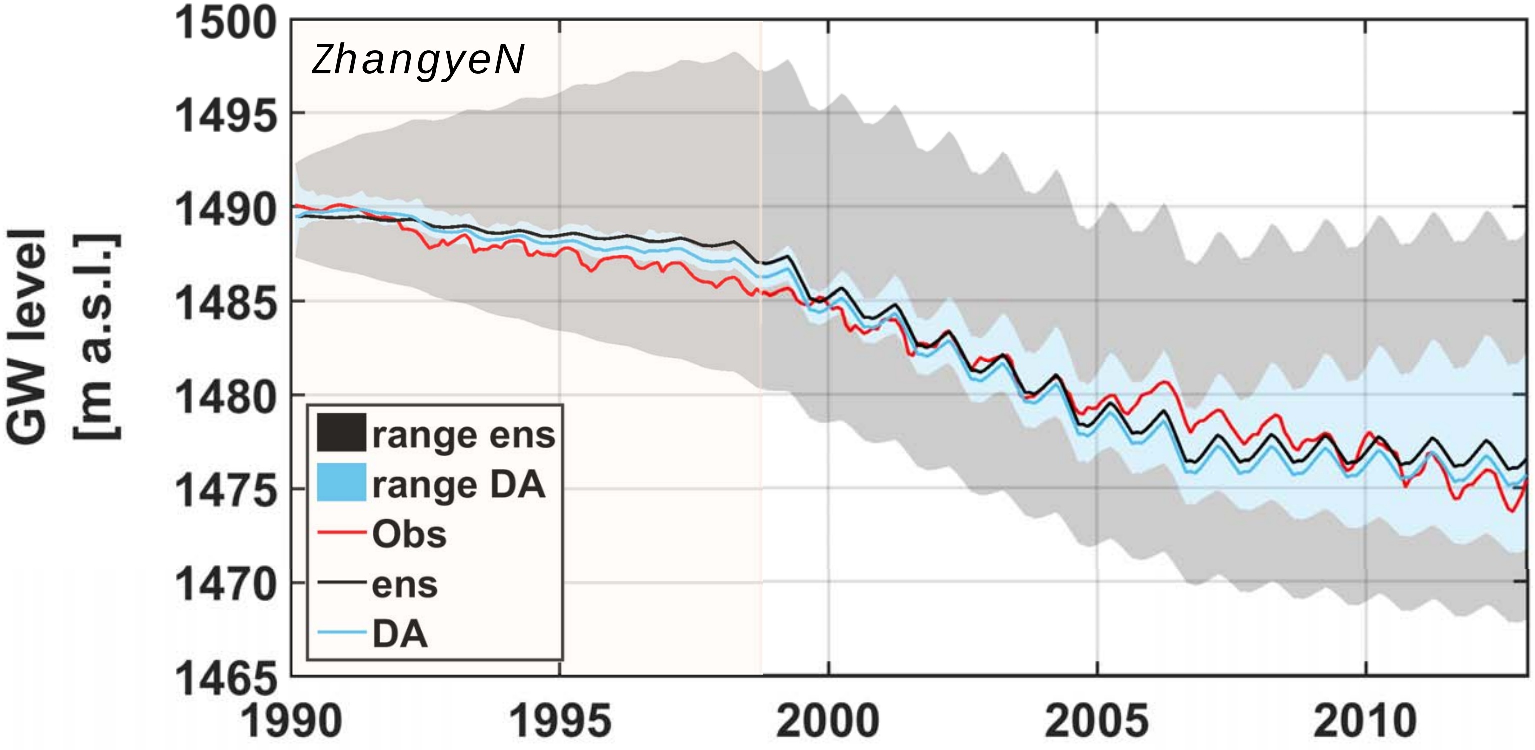
(Monthly steps)



Data assimilation: correcting the model on the go (in real-time),
Filtering out inappropriate realizations with EnKF

Forecast quality of the Heihe real-time model

(Monthly steps)

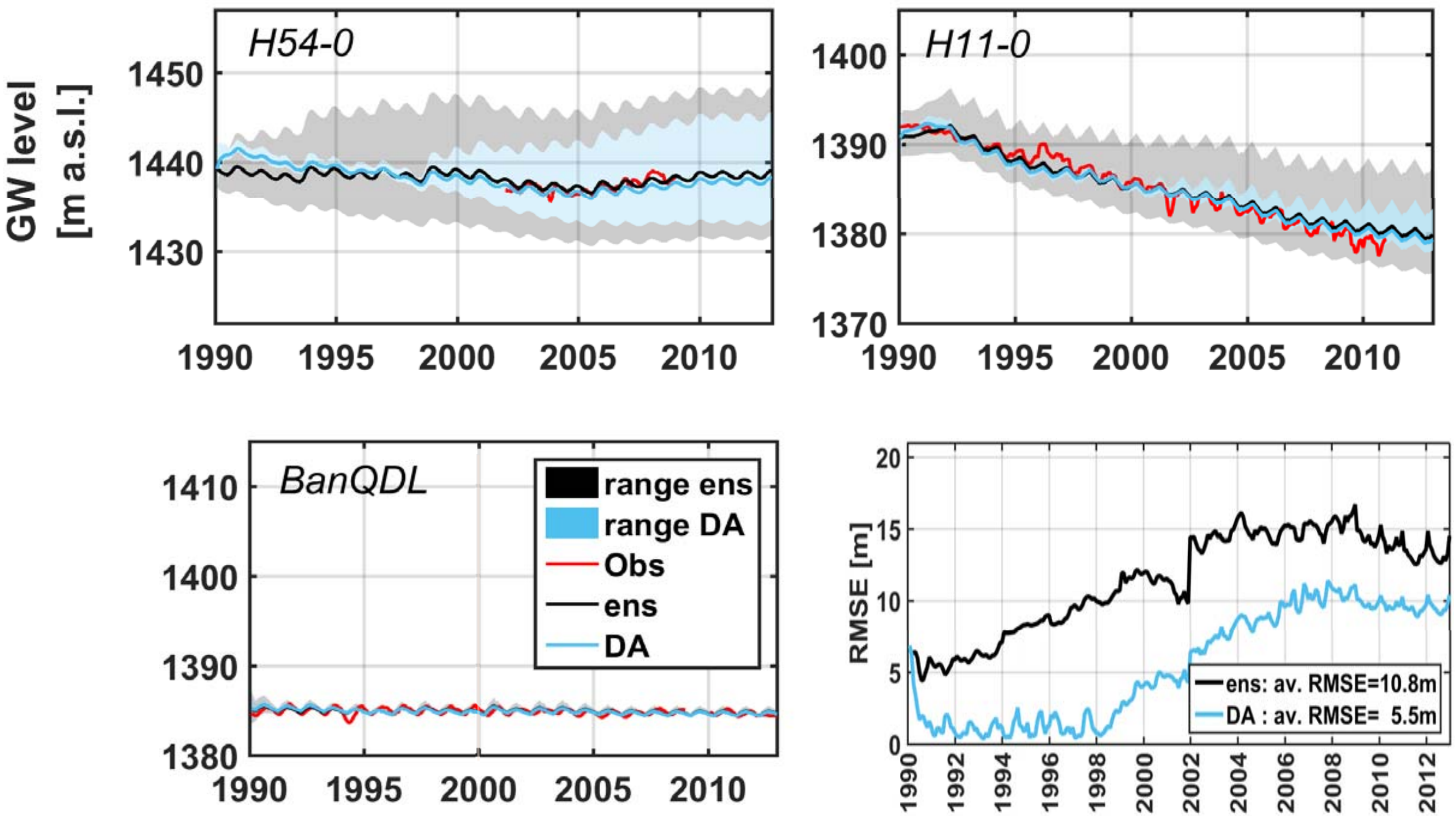


Switch to forecast: Reduction of uncertainty compared to ensemble prediction

Forecast quality of the Heihe real-time model

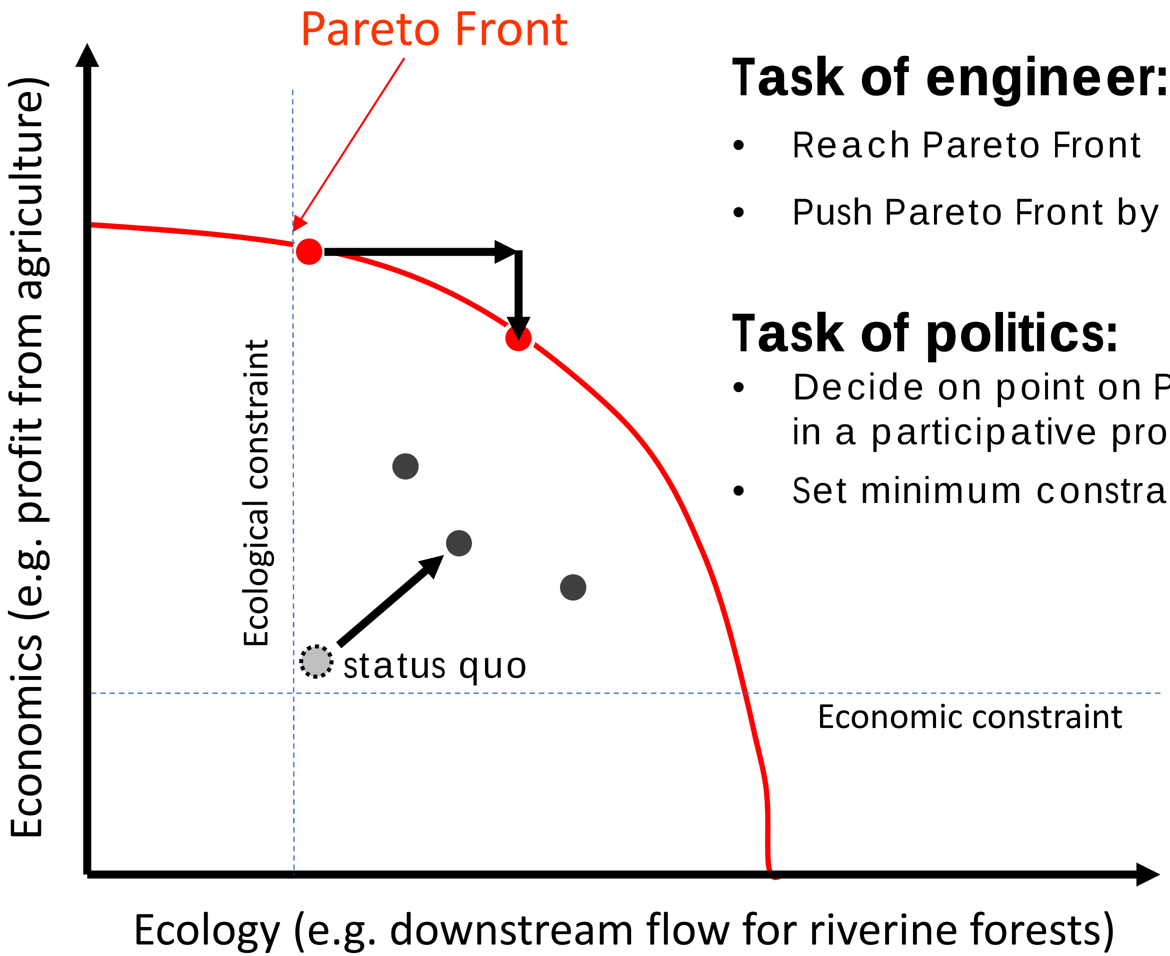
Some more piezometers

Black: Ensemble simulation
Blue: Data assimilation
Red Observed groundwater levels



Improved overall RMSE (by almost 50%)

Multi-objective optimization using model



Task of engineer:

- Reach Pareto Front
- Push Pareto Front by new technology

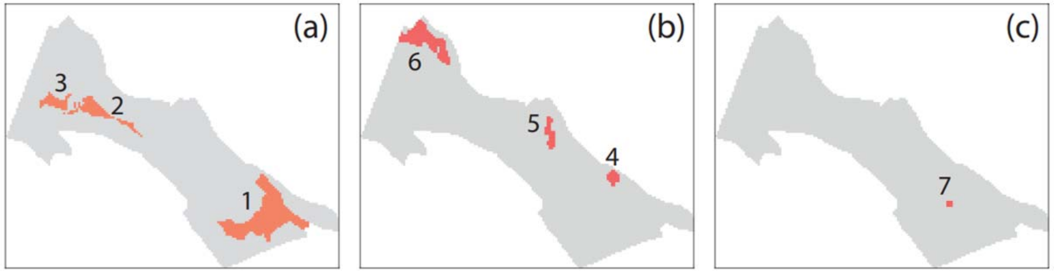
Task of politics:

- Decide on point on Pareto front in a participative process between stakeholders
- Set minimum constraints

But in real world, many stakeholders with usually more than 2 objectives

Multi-objective optimization in the Heihe

- Problem formulation as minimization of all objectives
  - **Decision variables**: [%] of total water use supplied by groundwater extraction
  - **Objectives:** 7 objectives computed from groundwater head

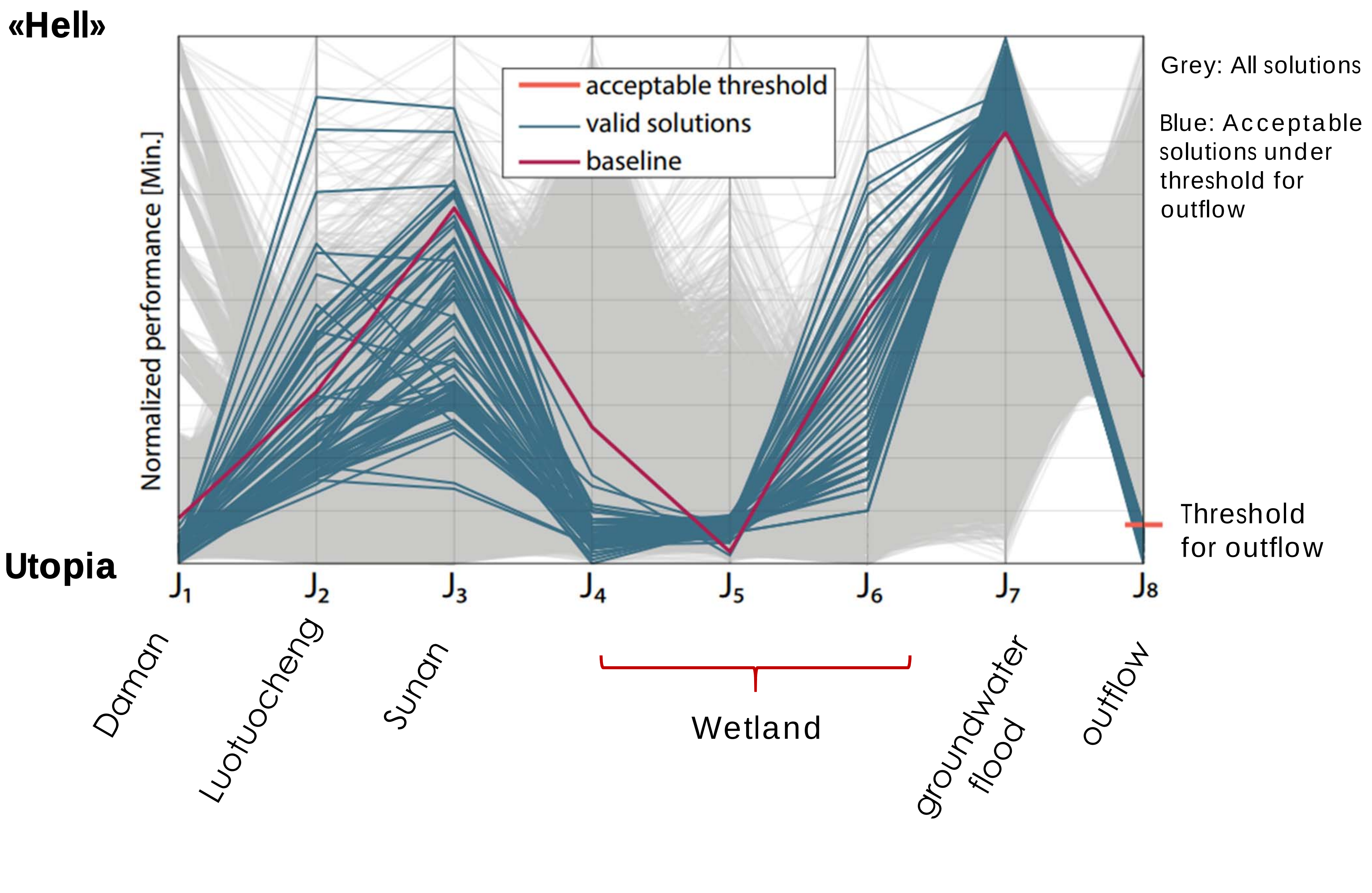


masks of the area of interests

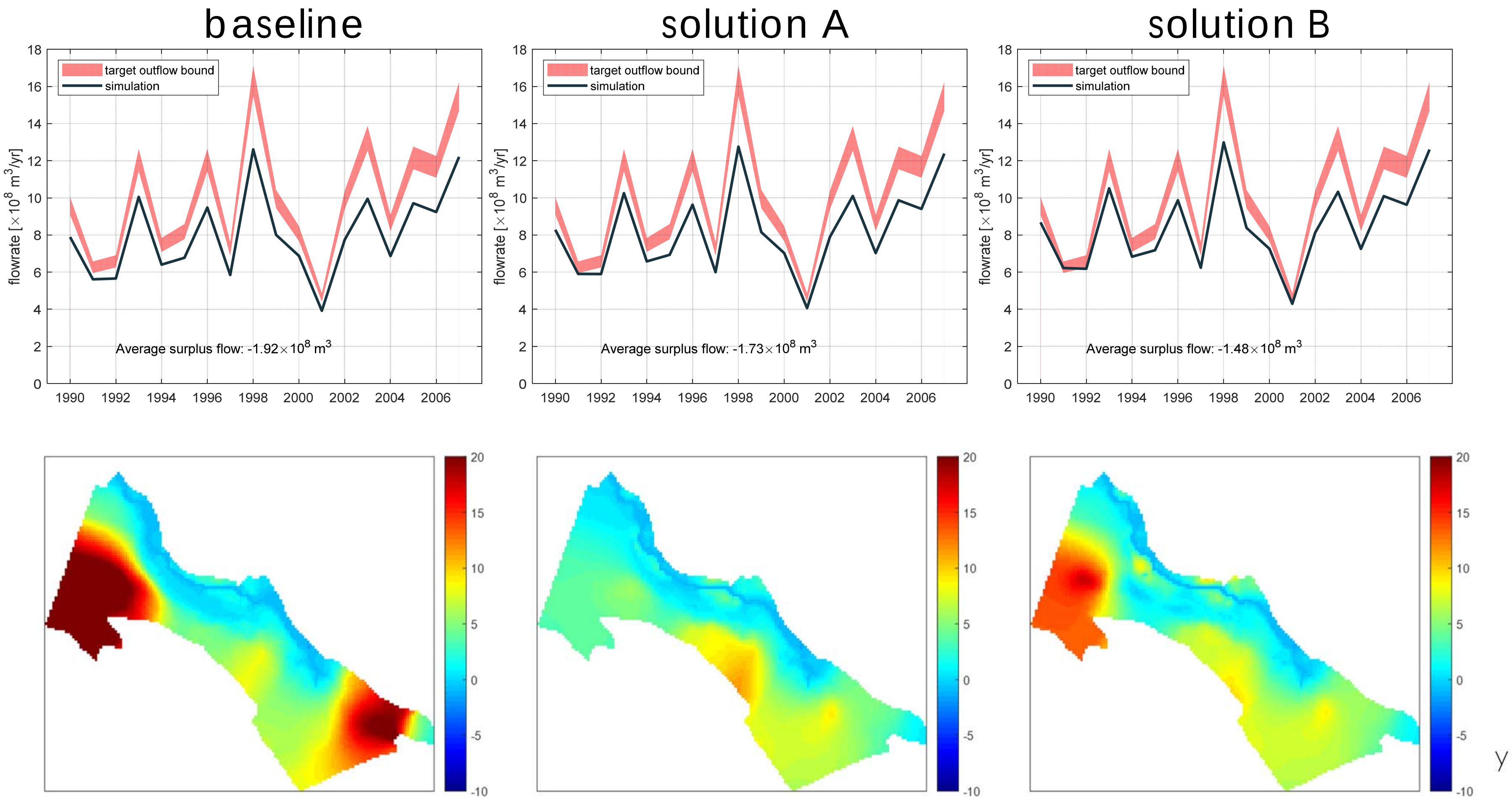
and 8th objective to maximize total outflow (= minimize its negative) computed from groundwater balance

Optimization method use to determine approximate Pareto frontier: multiple-objective evolutionary algorithm (Borg-MOEA)

Pareto front: Parallel bar representation



Water balance and heads for 3 solutions

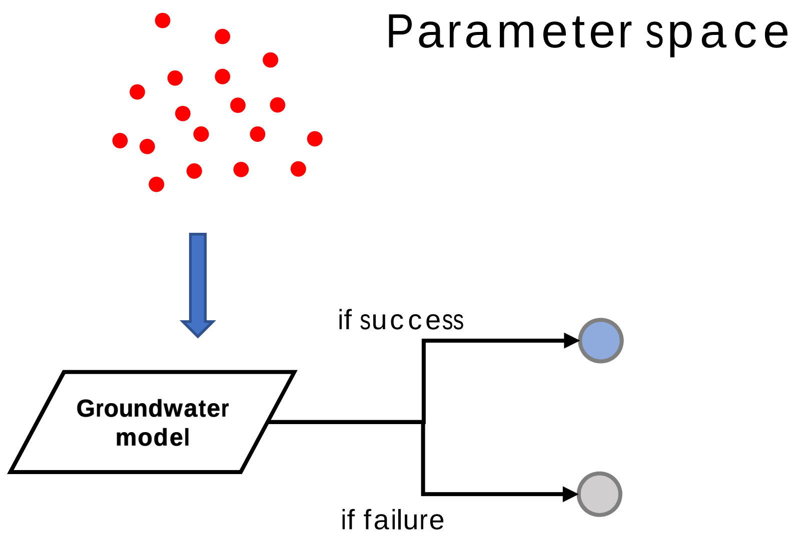


Robust decision analysis

Uncertain driving force

- inflow
- total water consumption

Factor	Lower bound	Upper bound
Inflow	0.5	1.5
Total water consumption	0.8	1.2



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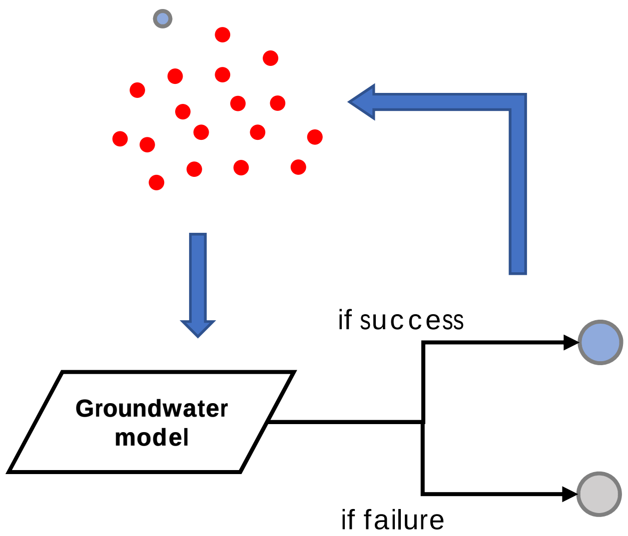

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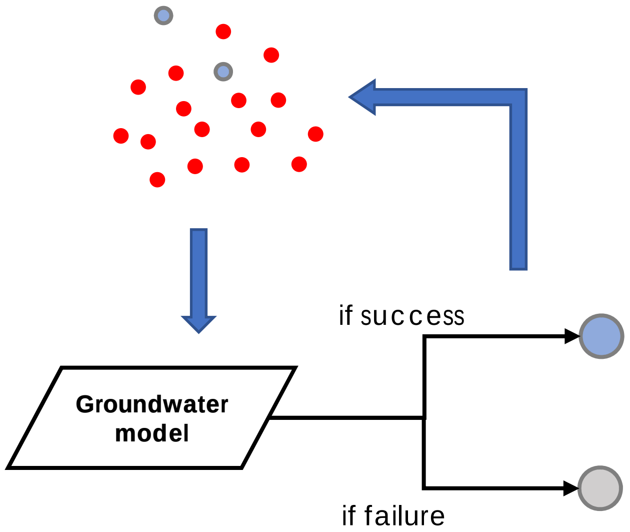

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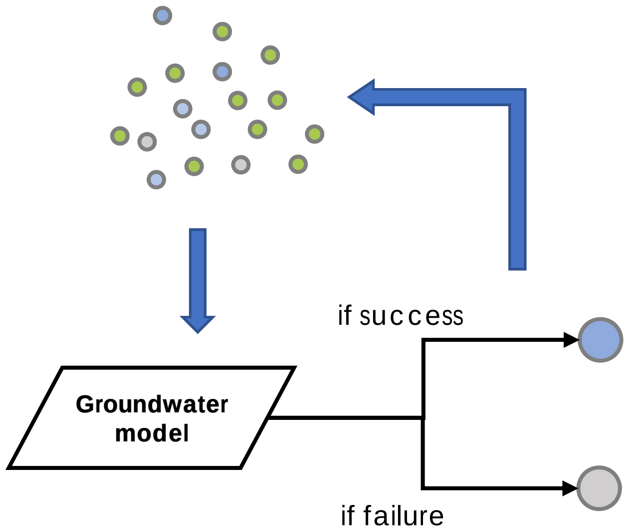
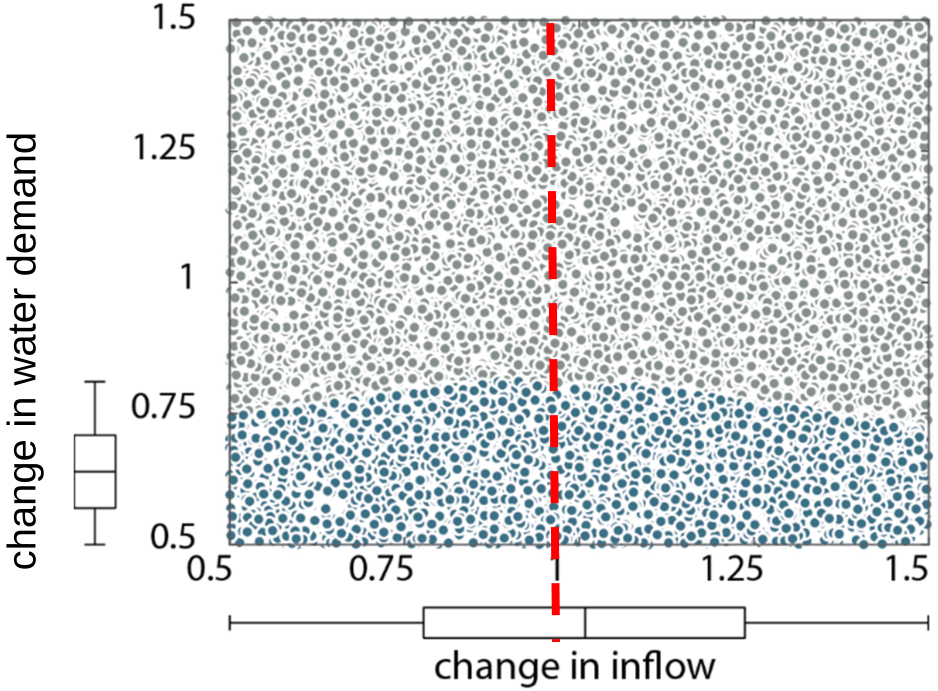
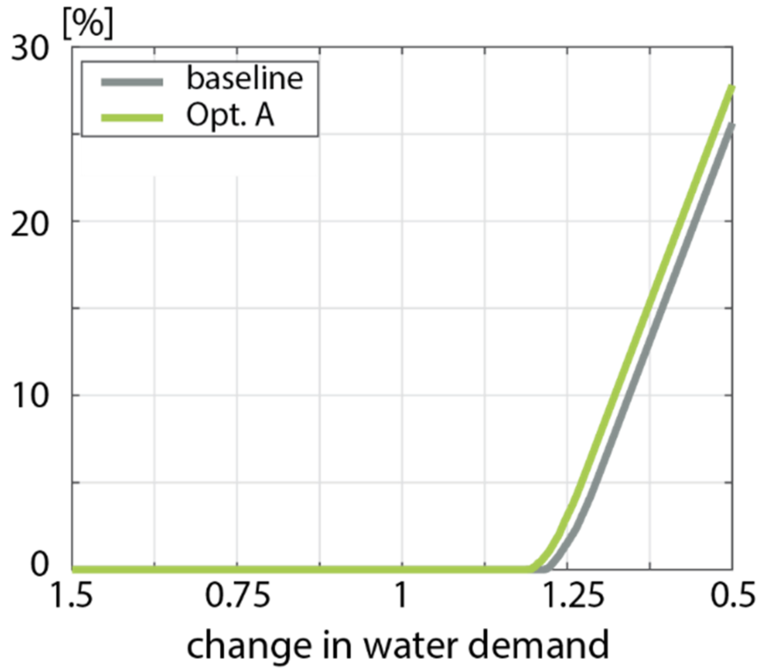


Results for option A

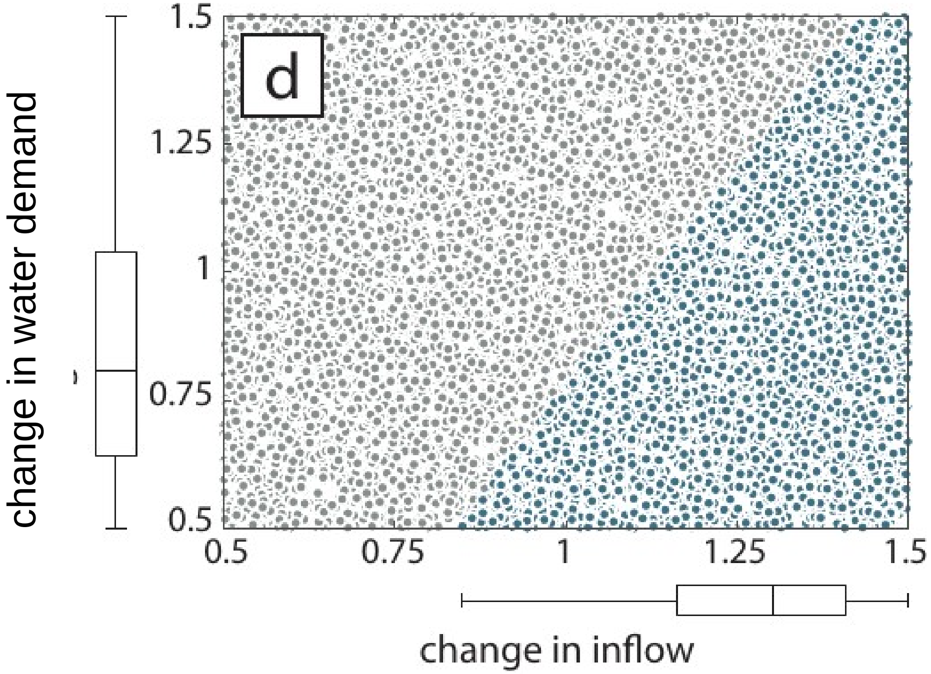




Note: if future inflow increases, sustainable water demand must decrease due to the peculiarity of the 97-rule. Our suggestion: change rule!

New rule: minimum downstream flow independent of inflow = $9.5x10^8$ m^3/year

Results for new rule in expectation of higher inflows



New rule: minimum downstream flow independent of inflow = $9.5x10^8$ m^3/year
Advantages: easier to administer as no yearly forecast of flow is needed and better for irrigation in wet years, while average flow to the downstream is not changing much.

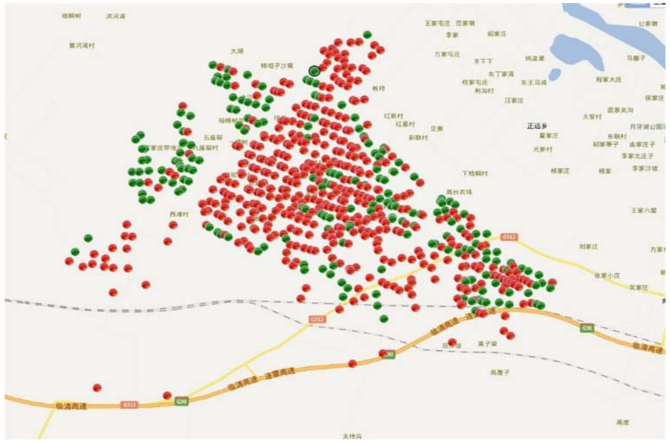
Conclusions

- Groundwater models have a role in groundwater management
- They allow to identify sustainability of a management practice
- When assessing a model, a reconstruction of the interplay of the most relevant processes is more important than the goodness of fit
- The best model still contains uncertainty, which should be quantified
- Uncertainty can be controlled by identifying robust solutions

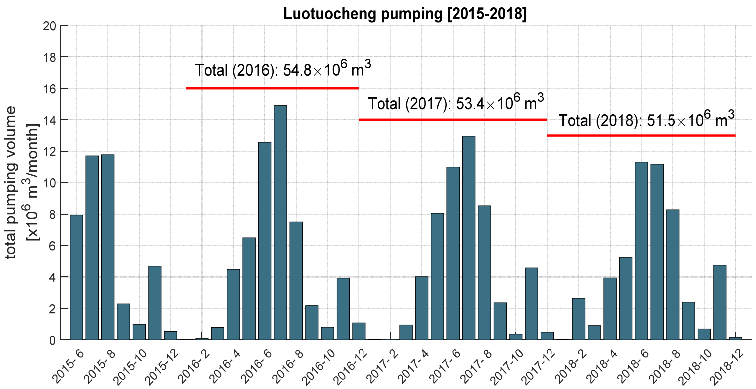
Postscript

The overpumping issue will be solved. How?

Smart metering and control of pumping



Luotuocheng irrigation district



Withdrawals of **667** monitored wells **from June 2015**

Smart meter and IC card allowing control of large number of wells (IoT)

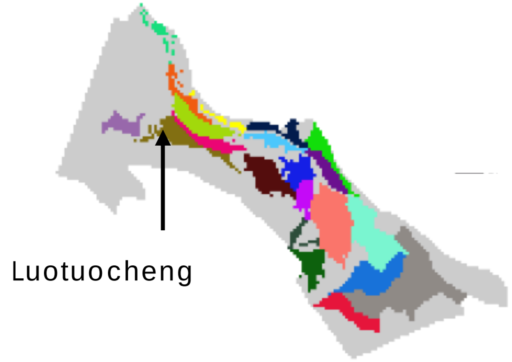
No tampering

Indicators for effectiveness

1 mu = 1/15 ha

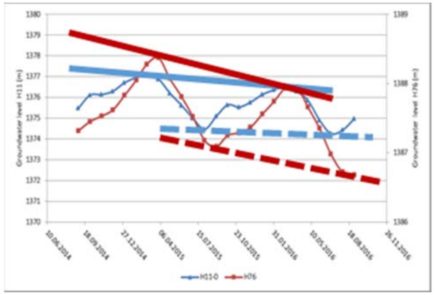
- Amount of water used per mu decreased

  from 480 m³/mu/year to 420 m³/mu/year within two years



- Speed of water level decline in Luotuocheng reduced

  from 0.5 m/year to 0.2 m/year



- Number of applications for government-subsidized drip irrigation increased

  by 5 times

Acknowledgments

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Chinese Ministry of Water Resources

China Geological Survey

Chinese Academy of Sciences


Thank you for your attention !