A Path Towards Sustainable Use of Overpumped Aquifers

Wolfgang Kinzelbach, Yu Li, Lu Wang, Ning Li
IfU, ETH Zurich

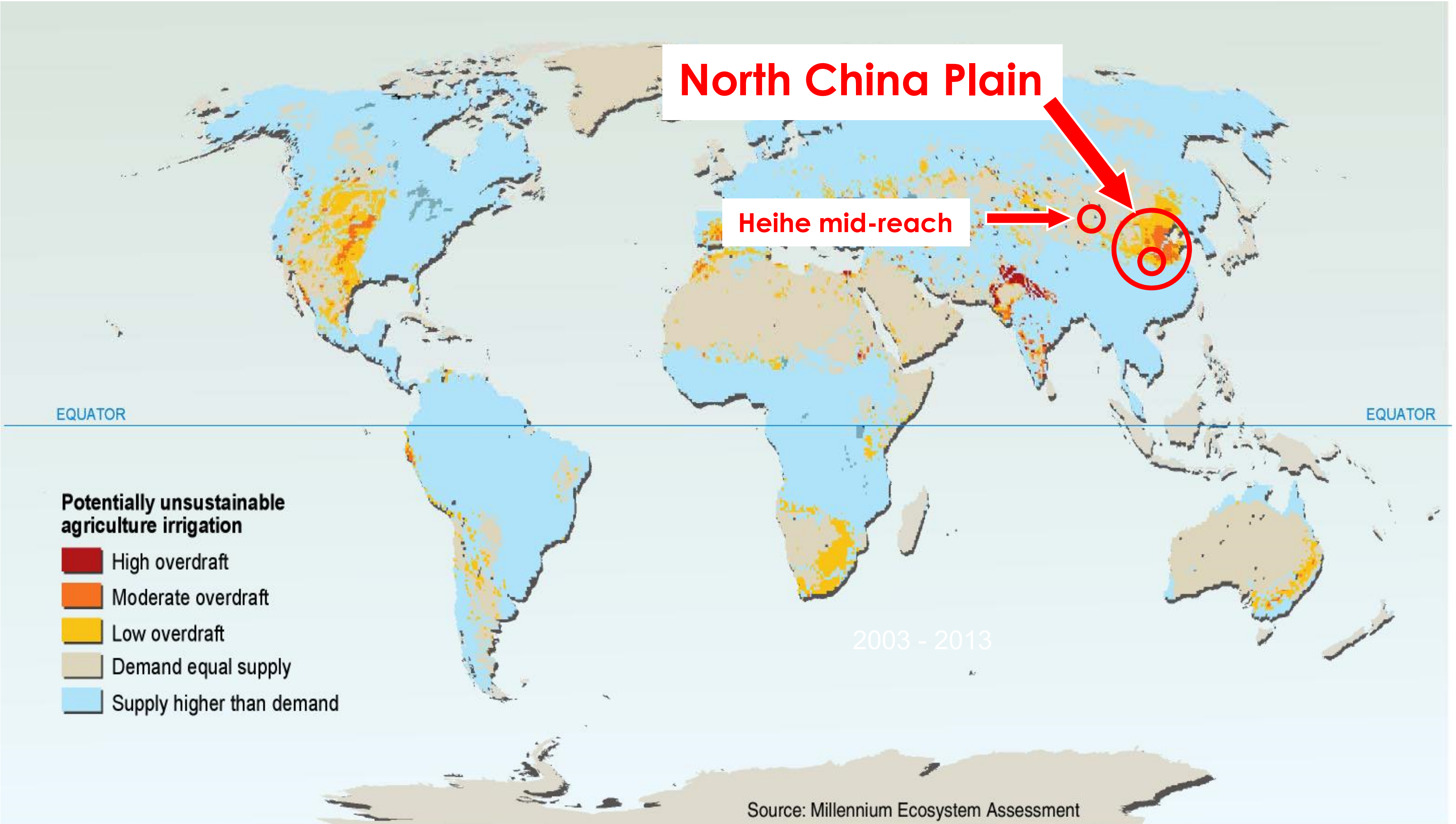
Haijing Wang, Beatrice Marti, Silvan Ragettli, Tobias Siegfried
hydrosolutions, Zurich

Contents

- Overpumping of aquifers: Why bother?
- Groundwater management
- Two case studies
  - 1st case: Heihe mid-reach in Gansu Province
  - 2nd case: Guantao in North China Plain
- Conclusions

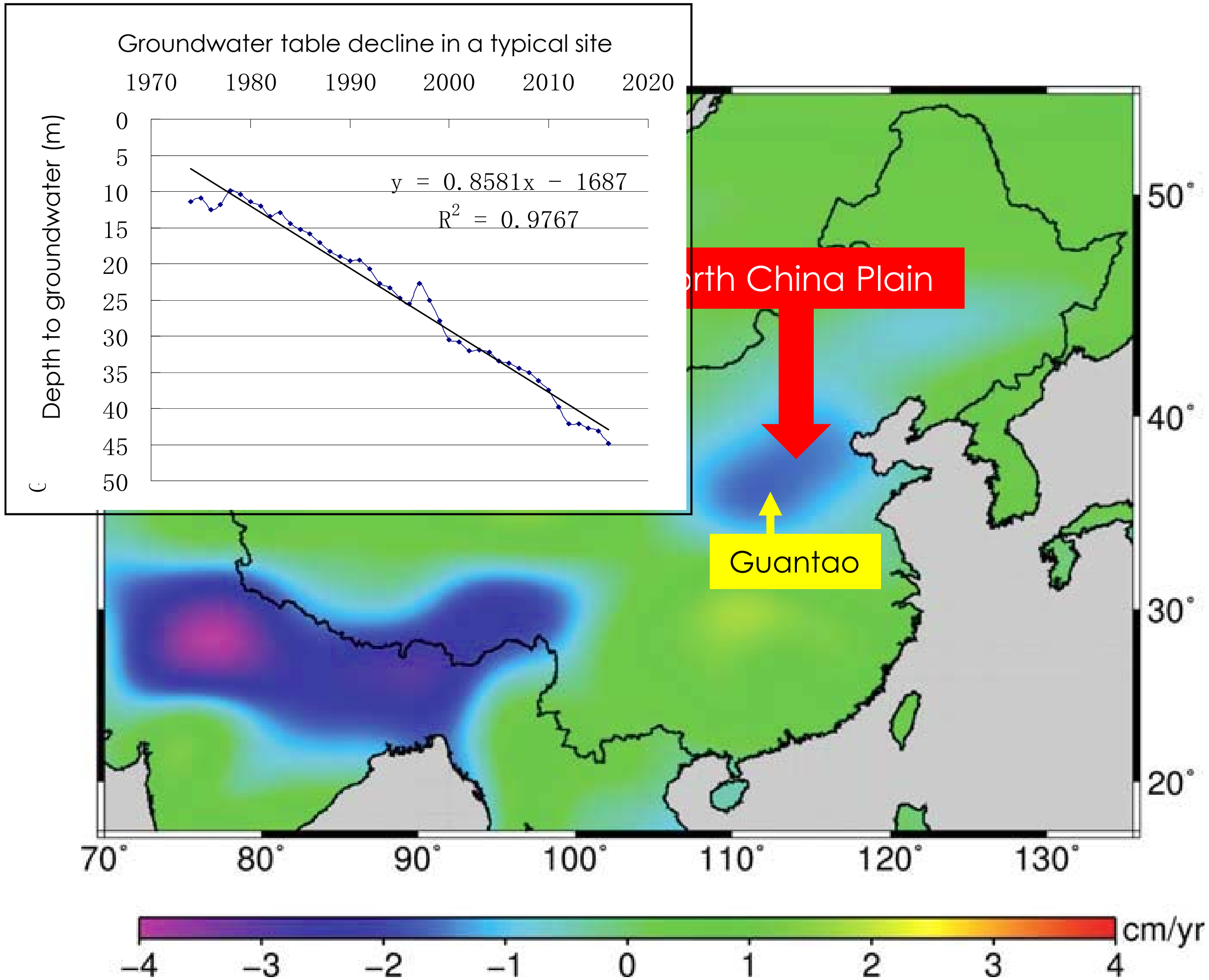
Overpumping of aquifers

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

Overpumping in NCP as seen by GRACE



From 2003 - 2012

Depletion ≈
6-8 Bio. m³/yr

Recharge ≈
40 Bio. m³/year

Overpumping is
15-20 % of average
recharge

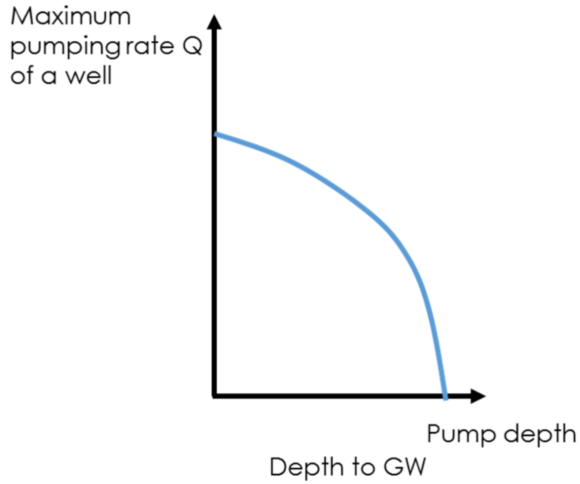
Source: Feng Wei et al, 2013

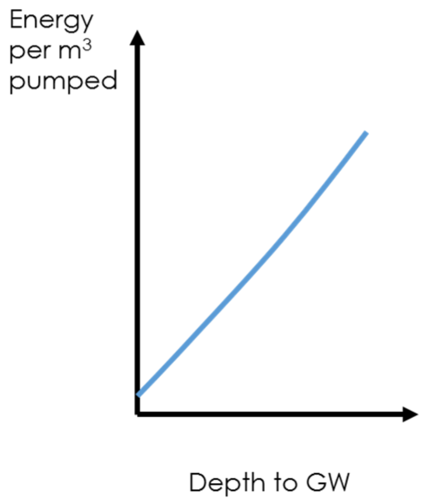
Why bother?

- Overpumping contains an inherent self-regulating mechanism

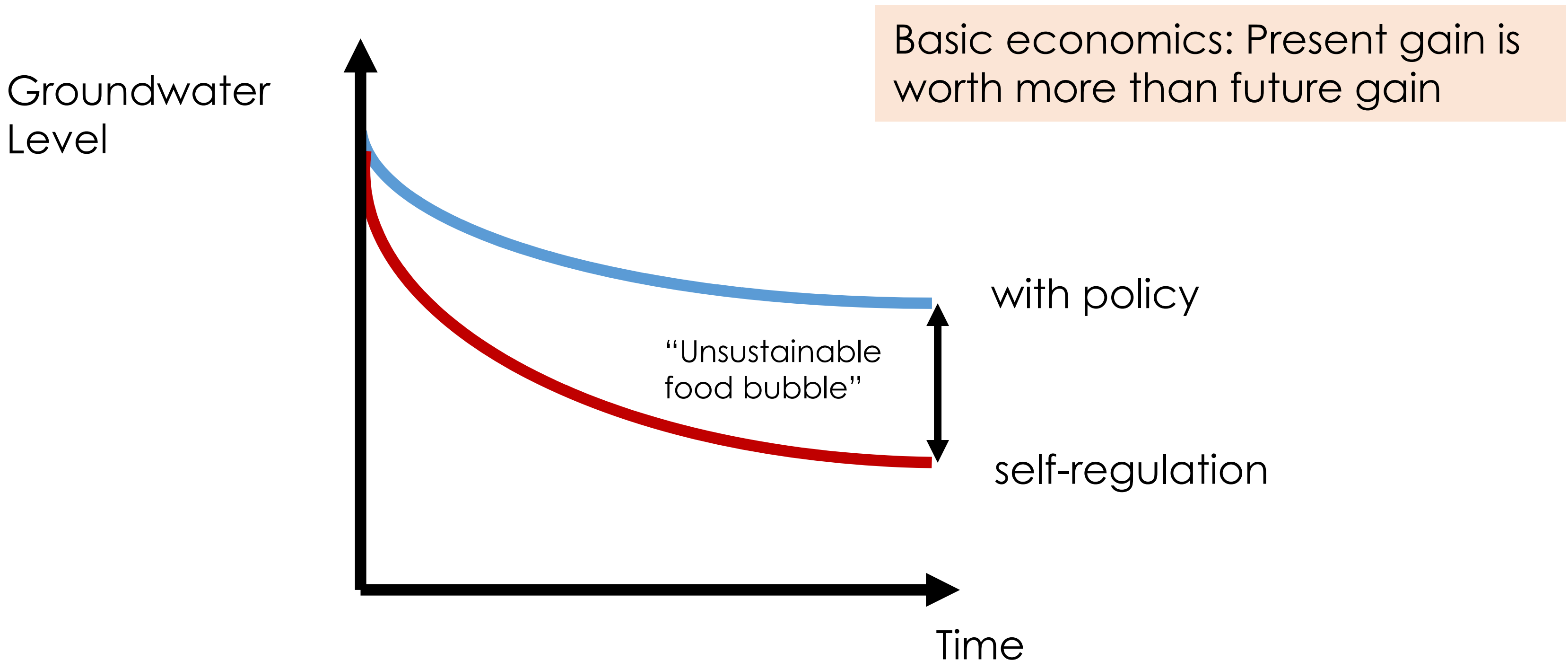
- With declining water levels, well yields decrease and pumping becomes increasingly expensive or infeasible

- Eventually a balance with recharge may be restored, however at a much lower groundwater table





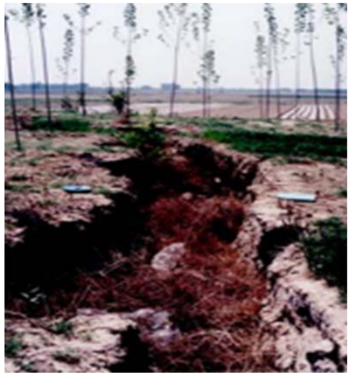
Is self-regulation the best we can do?



- Same final equilibrium between recharge and discharge, but different final groundwater levels and different impacts regarding environment and system resilience

Consequences of overpumping (in Hebei)

- Drying up of streams and wetlands (reduction by 90%)
- Die-off of phreatophytic vegetation above all in NW China
- Soil subsidence (up to 2.5 m under cities, more than 50 crevices of more than1km length)
- Salt water intrusion (up to 50 km inland)
- **Depletion of storage and loss of resilience against drought**

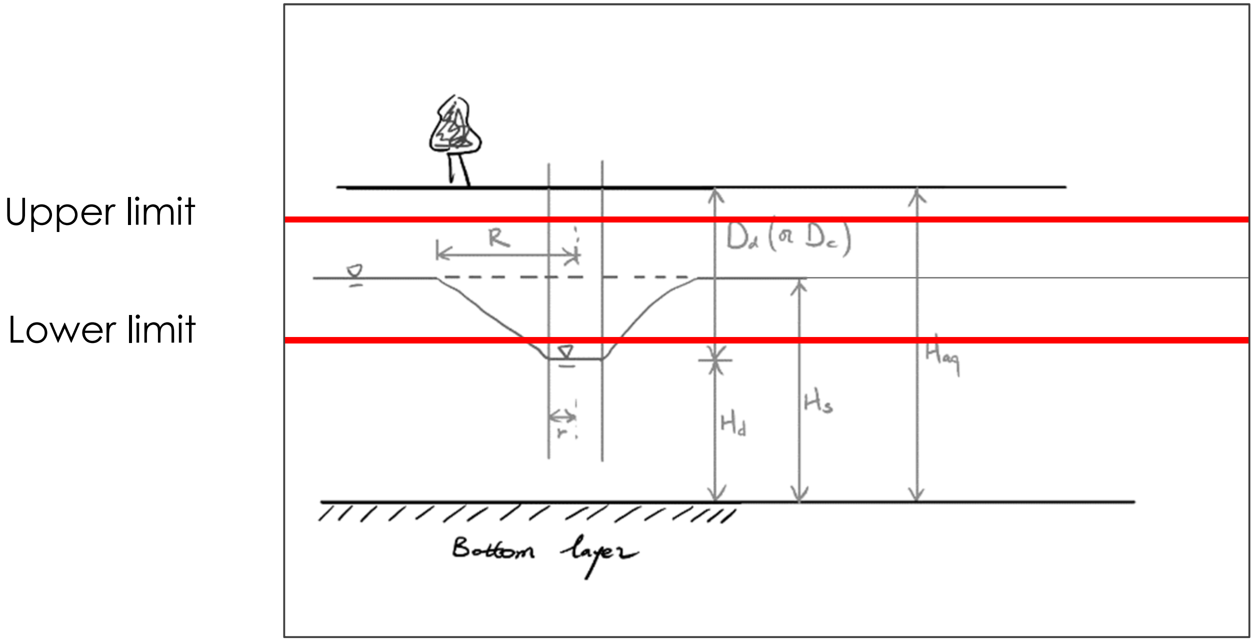


Source: Wu Aimin 2013

Sustainable use: the red line concept

Taking into account

- Ecologically required levels
- Economically required levels
- Storage needed for weathering a design drought
- Longterm equilibrium between inflows and outflows



Deal: Produce less, but uniformly, irrespective of precipitation

Elements needed for a management system:

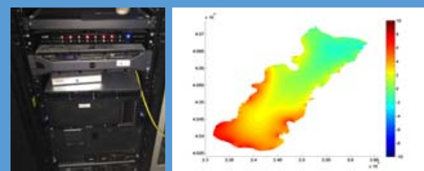
monitoring, modelling and control

Monitoring

- groundwater heads
- pumped volumes
- pumping electricity
- landuse by RS
- precipitation

Connection between abstraction and groundwater table

Data bank and decision support



- groundwater model/box model
- optimization of water allocation

Choose policy

Policy implementation

- cap or price
- subsidies for fallowing
- surface water import etc.

Assessment of success

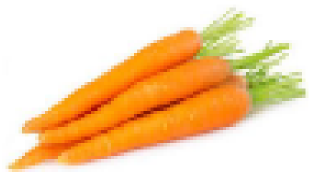
Policy instruments

(Vedung, 1989)

Water rights/Quota

Sticks - regulatory instruments

Laws and administrative regulations that formulate some rules and directives of behaviours



Price/Subsidies

Carrots - economic instruments

Measures either handing out or taking away of material resources if people perform certain actions

Technical advice

Sermons - informational instruments

Interventions that affect people through transferring knowledge, communicating reasoned argument, and persuasion

Quota and volumetric pricing require metering

Methods for abstraction monitoring

~~Traditional water meter~~

~~Problem: Tampering~~

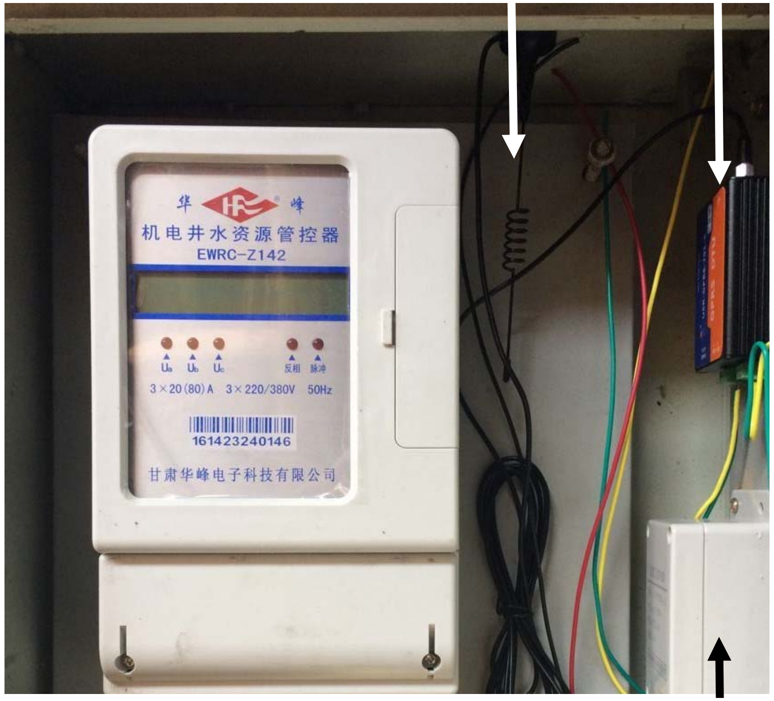
Smart water meter

Operation via swipe card

Real-time to guarantee functioning

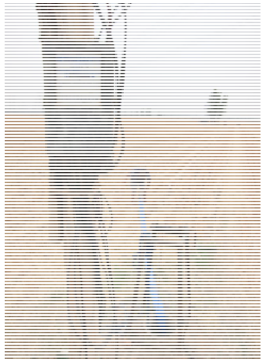
Data transfer every 8 hours

Problem: investment cost, operating cost, maintenance



Many brands available with different principles of measurement

Other methods - using proxies



Monitoring via electricity consumption

Problem: Conversion factor required
Advantage: New smart electricity meters allow real-time reading from utility offices

Monitoring via use-time

Oldest method, especially in surface water allocation

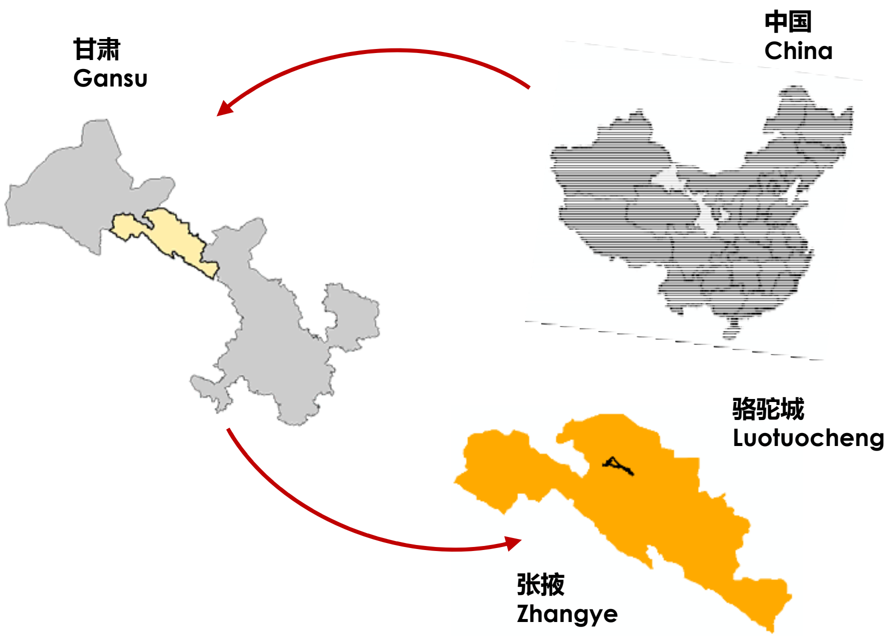
Monitoring via land use and irrigation norms

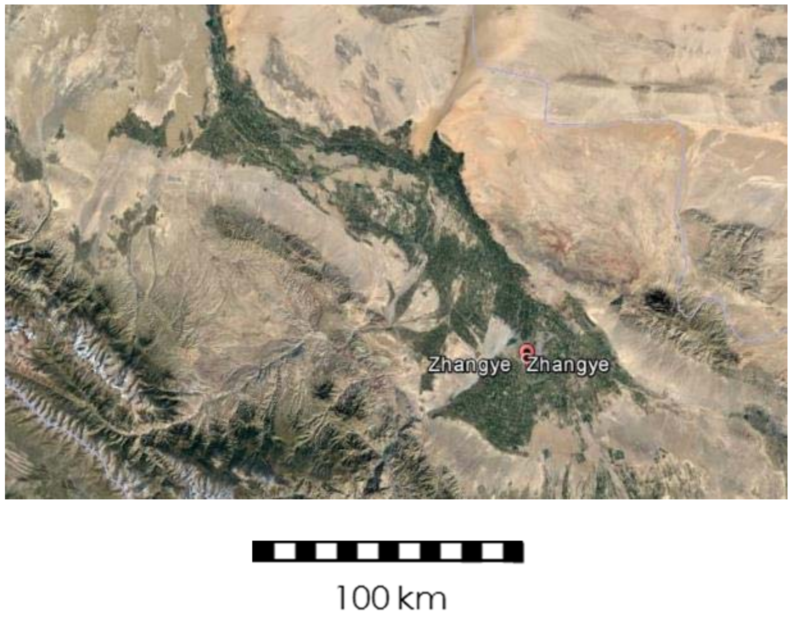
Facilitated through advances in remote sensing, especially in arid and semi-arid environments

Subtract surface water use!

First case: Heihe mid-reach

Heihe Basin: Zhangye, Gansu



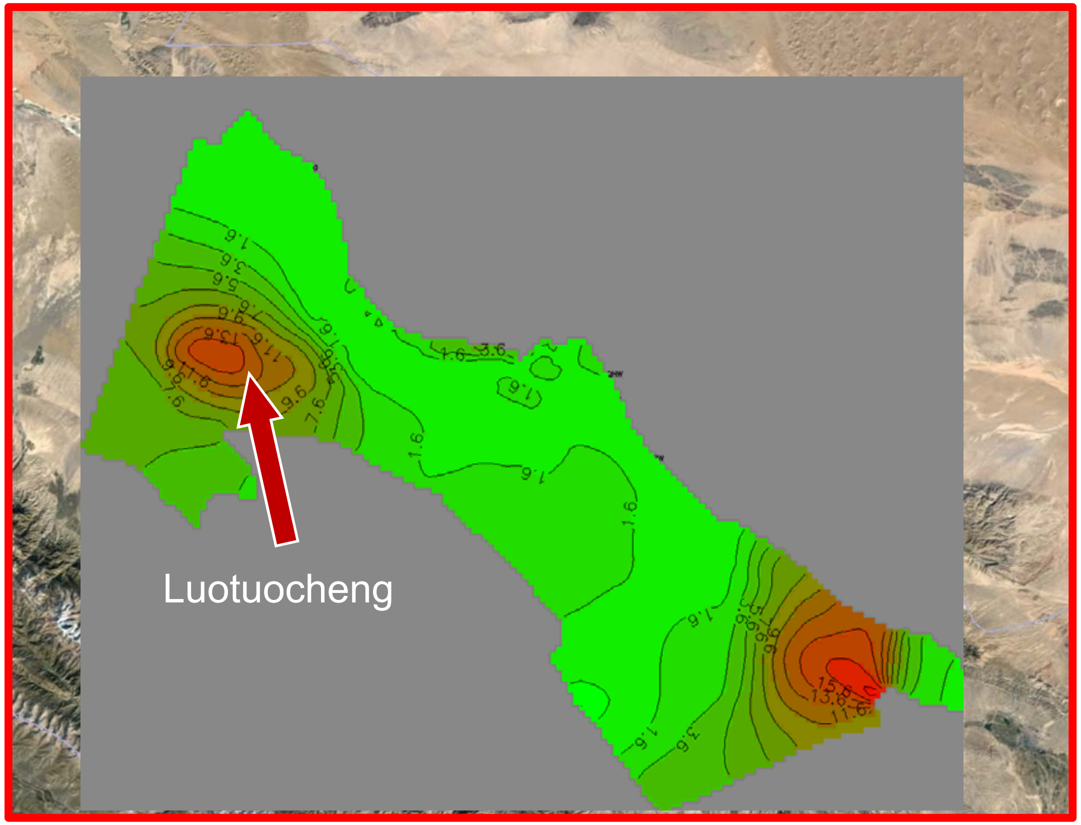


Arid climate, full irrigation by river water and groundwater, creating river oasis with very high agricultural productivity.
Speciality: seed maize

Problems of Heihe Mid-reach

Drying up of East Juyan Lake

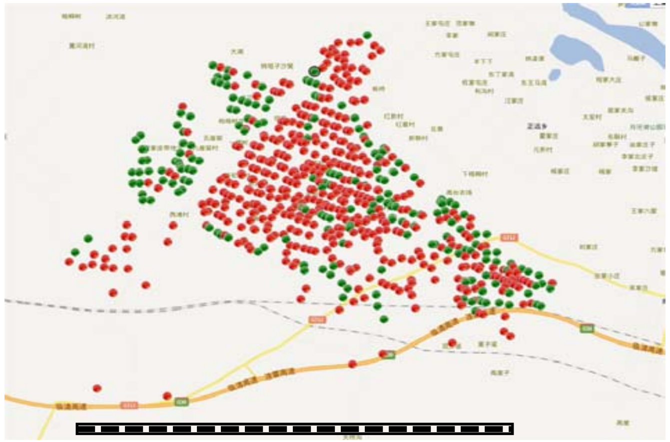
Degradation of *populus euphratica* forests



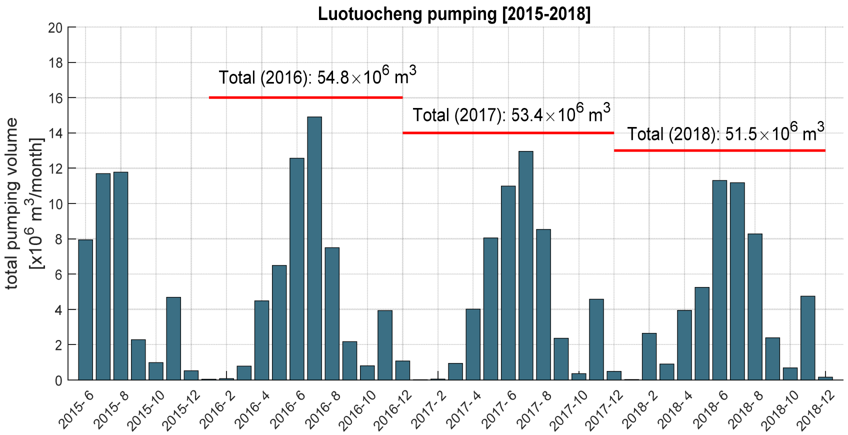
- 97 rule: about half the inflow to the Zhangye basin has to be released to the downstream ecosystems.
- Executed since 2001.
- Replacement of river water by groundwater led to two deep cones of depression

The local problem: Control of pumping

Luotuocheng irrigation district



20 km



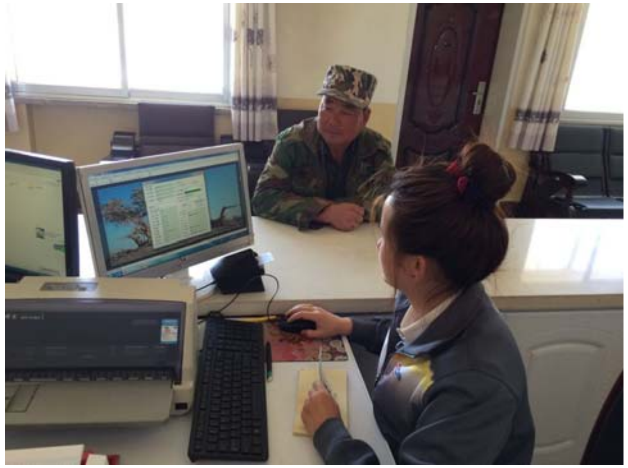
Withdrawals of 667 monitored wells since June 2015

Smart meters and IC card for control of each single well

Management rules in Luotuocheng

- Water rights assigned to individuals (814 m^3/mu/yr)
  Much too large! In reality about 500 m^3/mu/yr
- Pricing reform carried out (1 m^3 of groundwater: 0.11 CNY water fee + electricity fee ≈ 0.24 CNY)
  Accepted by farmers, about 10% of input cost
- Income from water fee sufficient to maintain the smart meter system (repayment of investment and maintenance in PPP)
  Each well supplies 150’000 m^3/a
- Trading of water rights permitted
  Not much used
- Protection of water meters from vandalism

  Inclusion into rural electric equipment

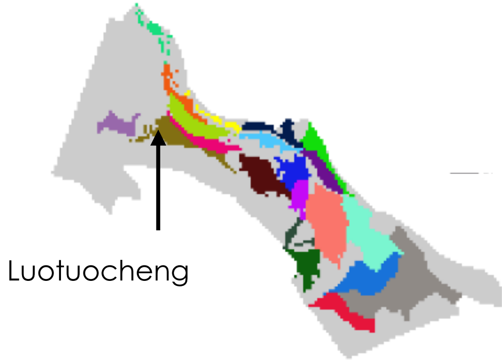


1 mu = 1/15 ha

Indicators for effectiveness

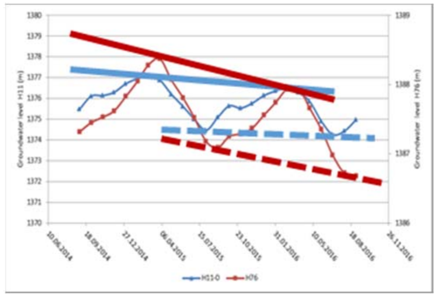
- Yearly amount of groundwater used per mu decreased

  from 480 m^3/mu/year to 420 m^3/mu/year within two years



- Speed of water level decline in Luotuocheng is reduced

  from 0.5 m/year to 0.2 m/year



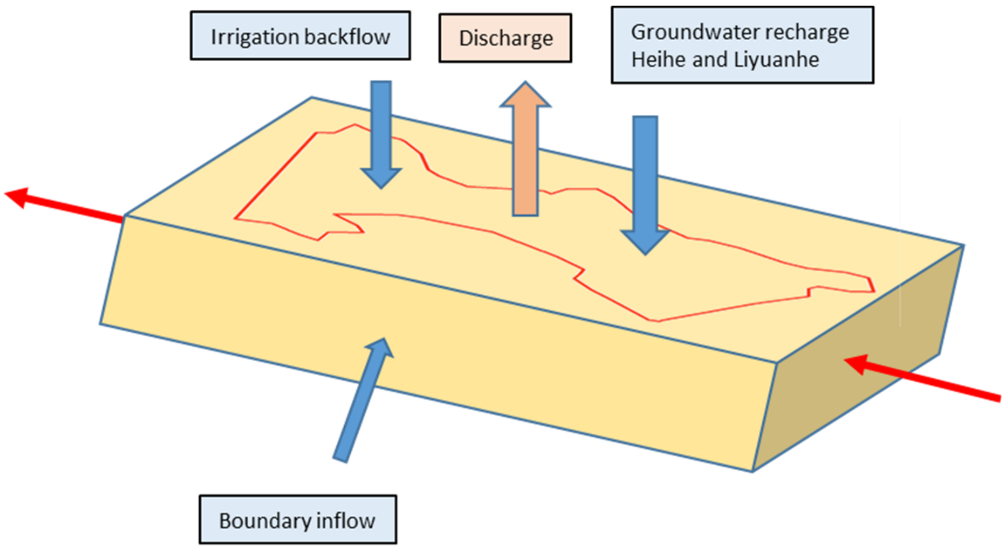
- Number of applications for government-subsidized drip irrigation increased

  by 5 times

1 mu = 1/15 ha

The global problem: Requirements of the downstream

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

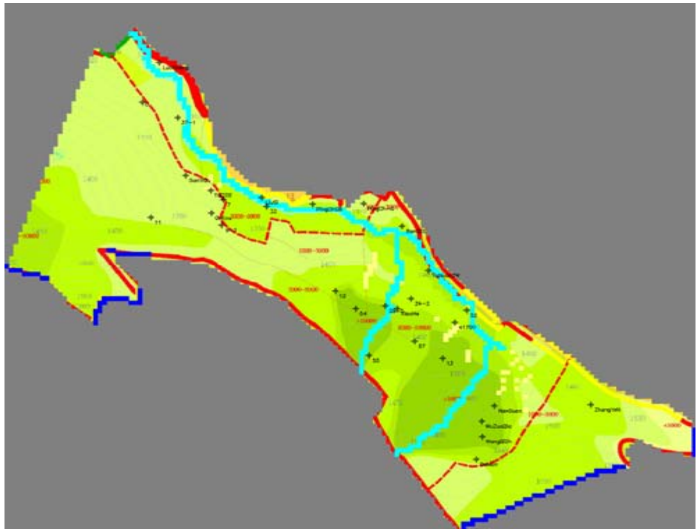
Outflow to downstream : 8.2×10^8 m^3/a

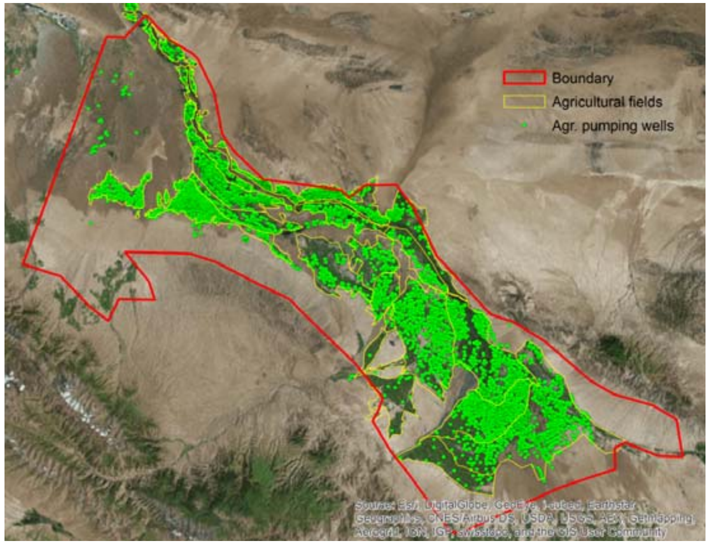
Required outflow : 9.6×10^8 m^3/a

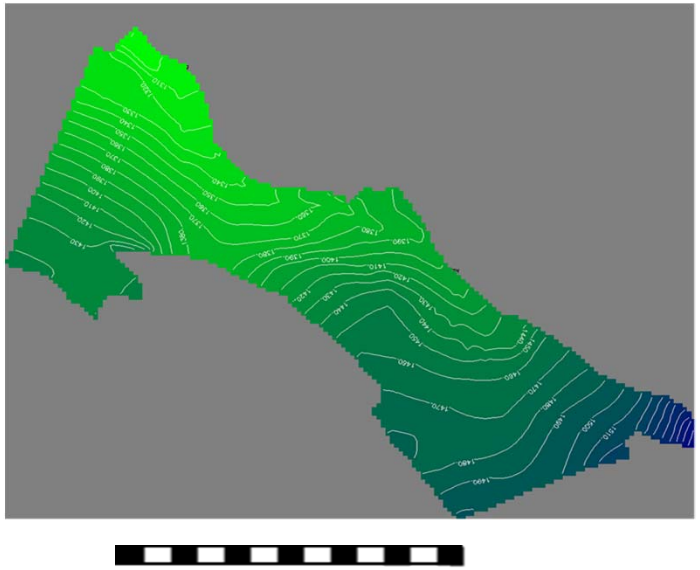
Assumptions:

- Steady state, phreatic evaporation backed out
- Irrigation backflow 30%

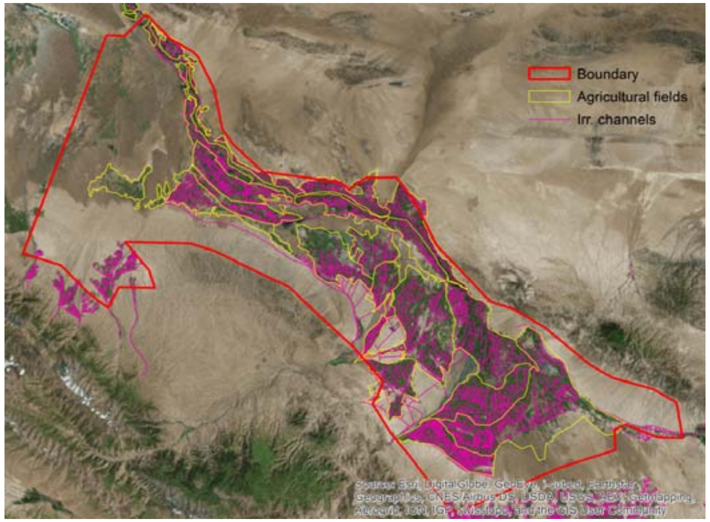
The groundwater model of Heihe mid-reach







100 km

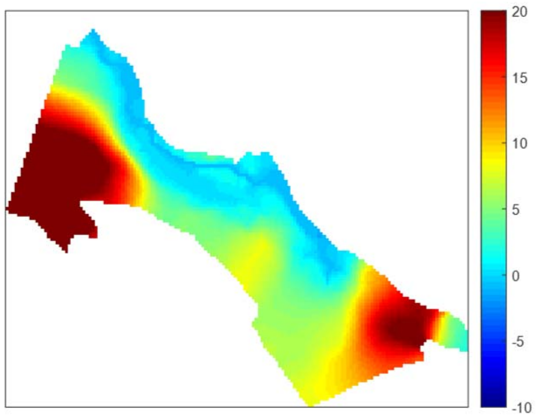


Findings

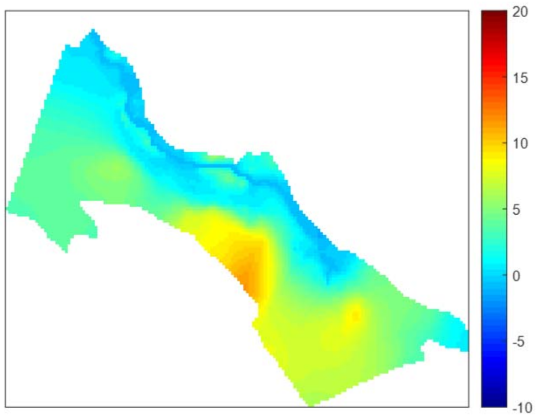
- In steady state 1 m^3 of irrigation water diverted from the river has about the same impact on downstream flow as 1 m^3 abstracted from the aquifer (Slight difference due to decrease of phreatic evaporation for GW-abstraction)

- To fulfil the 97 allocation rule, total water use has to be reduced by about 20%

- Avoidance of local deep cones of depression is feasible through optimization of allocation of surface water

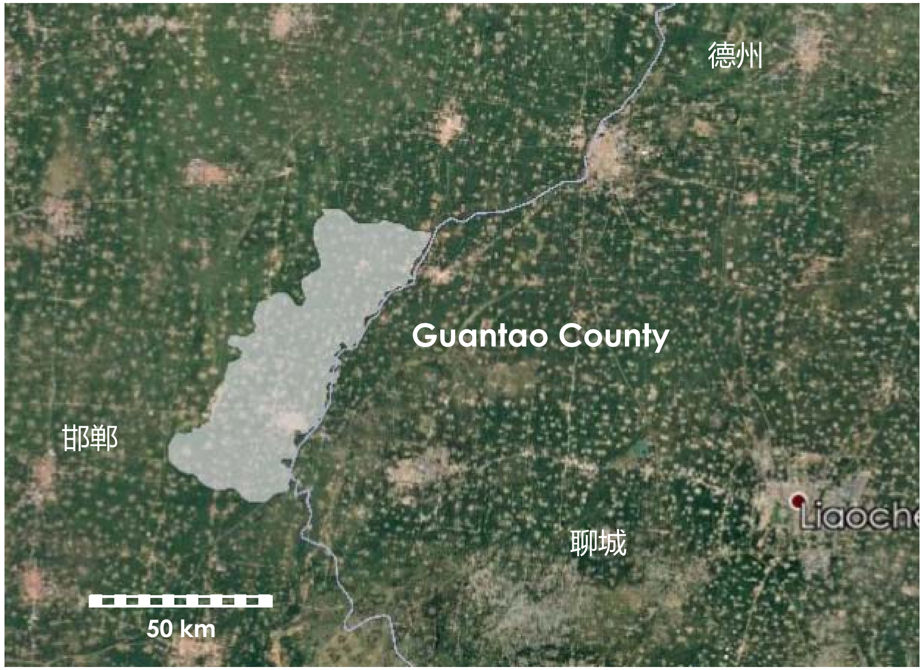


Baseline



Optimized solution

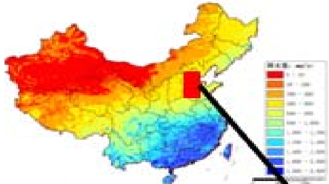
Second case: Guantao County in NCP



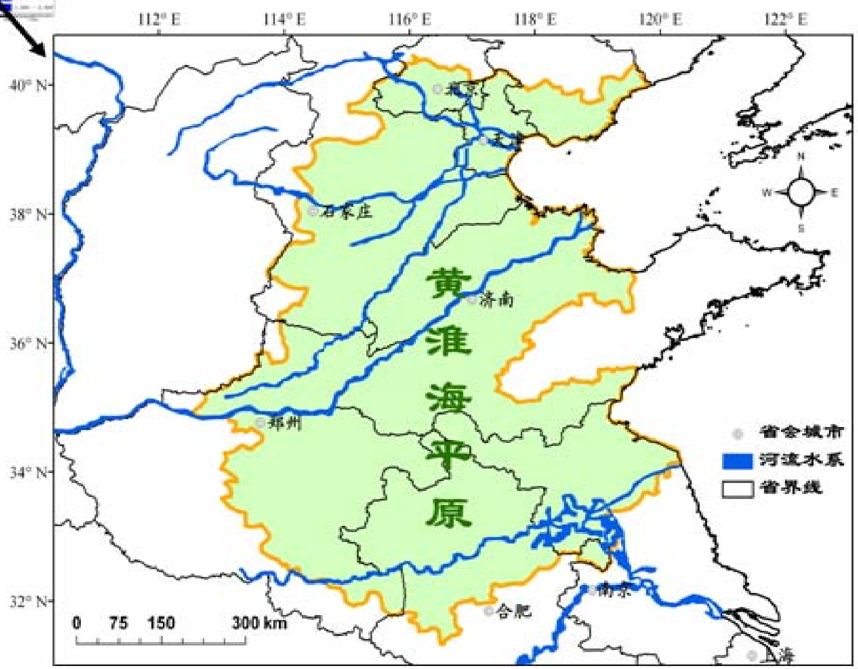
Problem:

- Present agricultural production level is not sustainable, because of declining groundwater levels caused by double cropping practice
- Control of pumping difficult due to large number of small family farms

The importance of NCP in grain production in China



Winter wheat:
60% of national output

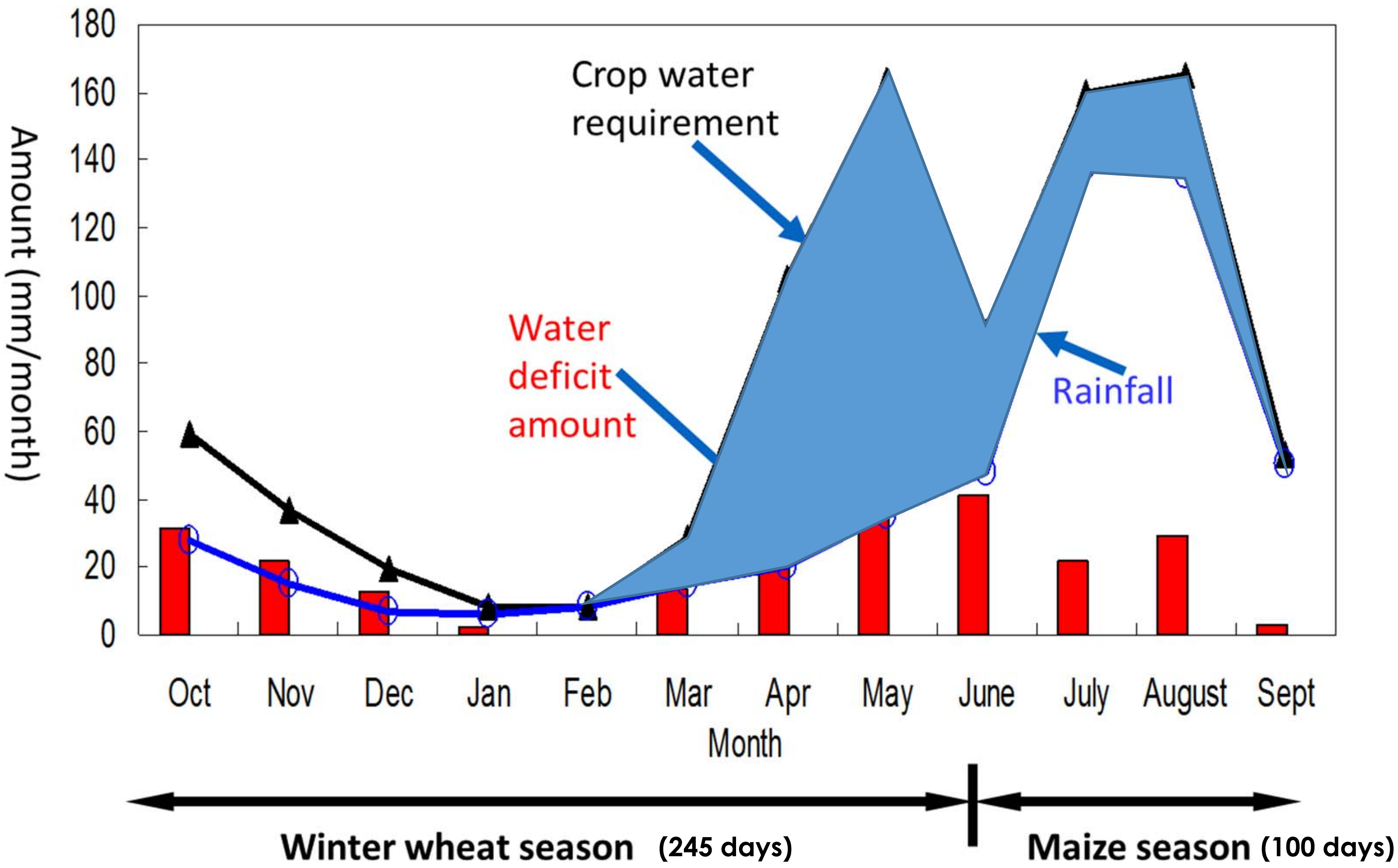


North China Plain (NCP)

Maize:
45% of national output

Major cropping system:
winter wheat + summer maize
double cropping

Main reason for overpumping



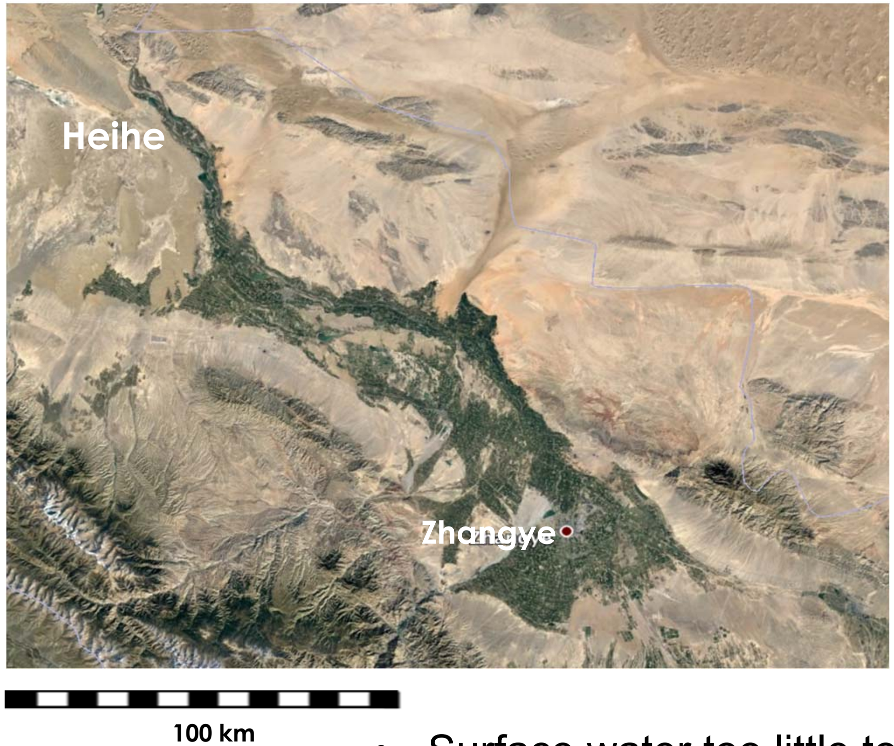
Water consumption: Winter wheat: 400-450mm; Maize: 300-400mm

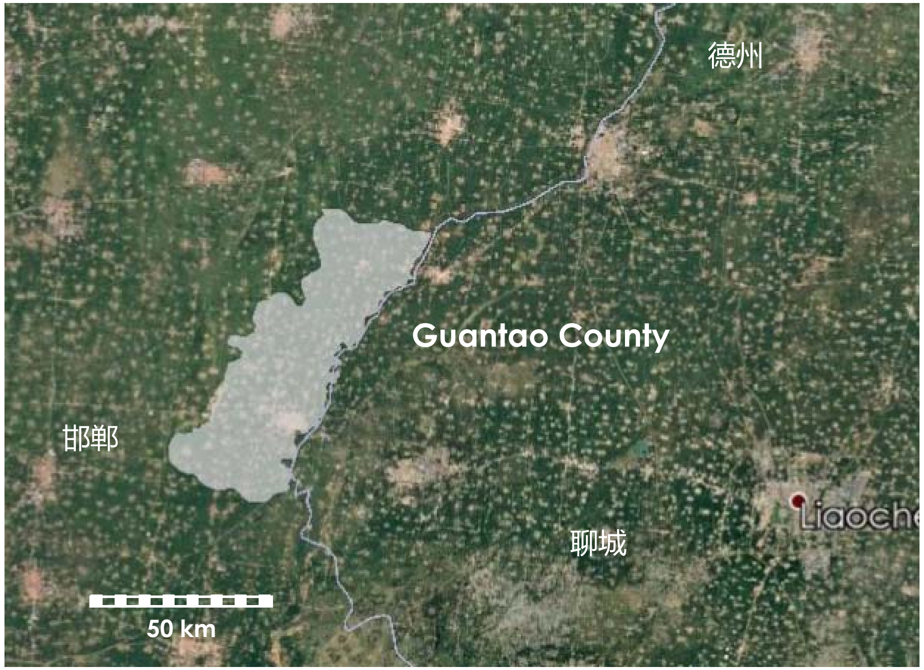
Annual average rainfall: 450-550 mm

Annual irrigation requirement: 200-400mm

Source: Prof. Xiying Zhang

Differences to Heihe





- Surface water too little to close gap
- Wells small and primitive
- Area per person: 1.3 mu, one fifth of Heihe
- Area per shallow well: 20 - 80 mu, 1/10 – 1/3 of Heihe
- Only supplementary irrigation

1 mu = 1/15 ha

Groundwater abstraction monitoring

Only few wells are sufficiently well equipped for installation of a smart water meter

For the majority of wells installation and maintenance of a smart water meter are technically and economically infeasible

→ Clue to monitoring in NCP: Electricity consumption by pumps as proxy

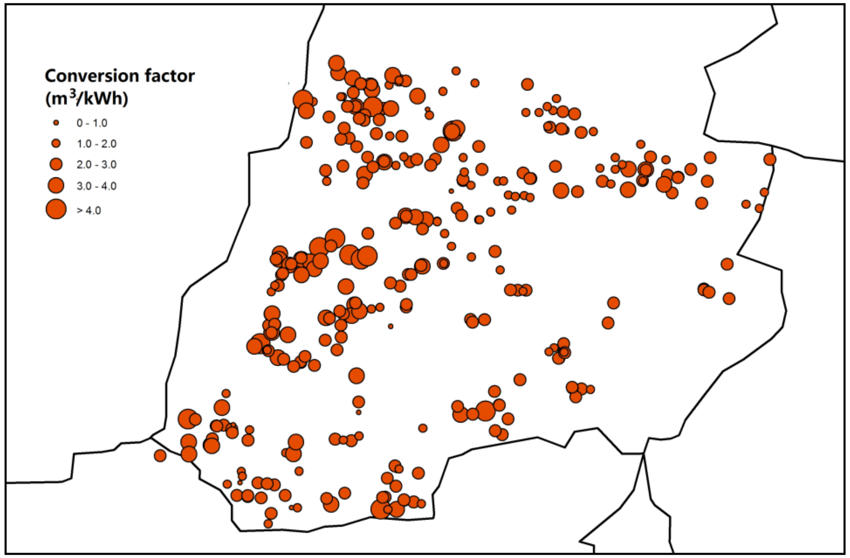
Smart water meter

Smart electricity meter

Conversion factor determined by pumping tests

- Power (*N*: kW)
  - Read electricity meter and time
- Flow rate (*Q*: m^3/h)
  - Portable ultrasonic flow meter
  - Volumetric method
- Depth to water table (H: m)

➢ Conversion factor: $c_f = \frac{Q}{N}$ (m^3/kWh)

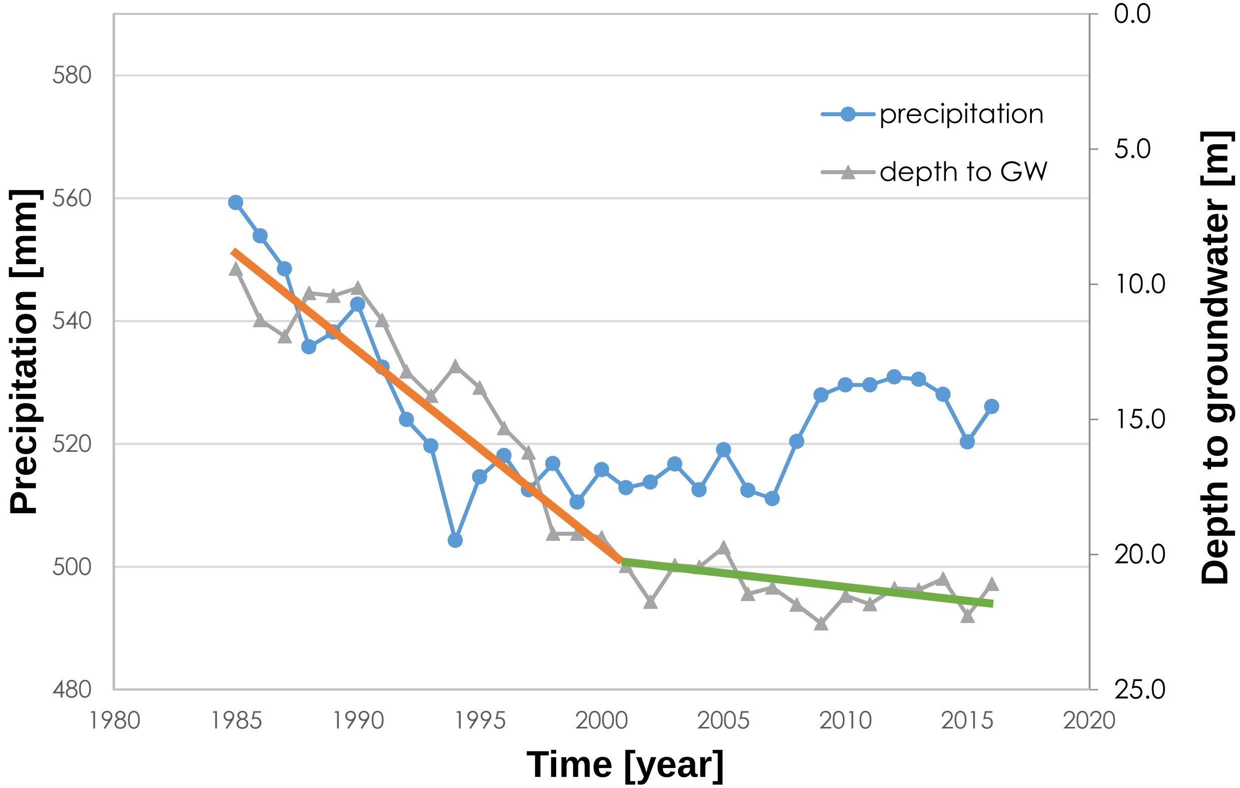


Lu Wang, 2017

Roughly 2.75 m^3/kWh in shallow aquifer and 1.32 m^3/kWh in deep aquifer

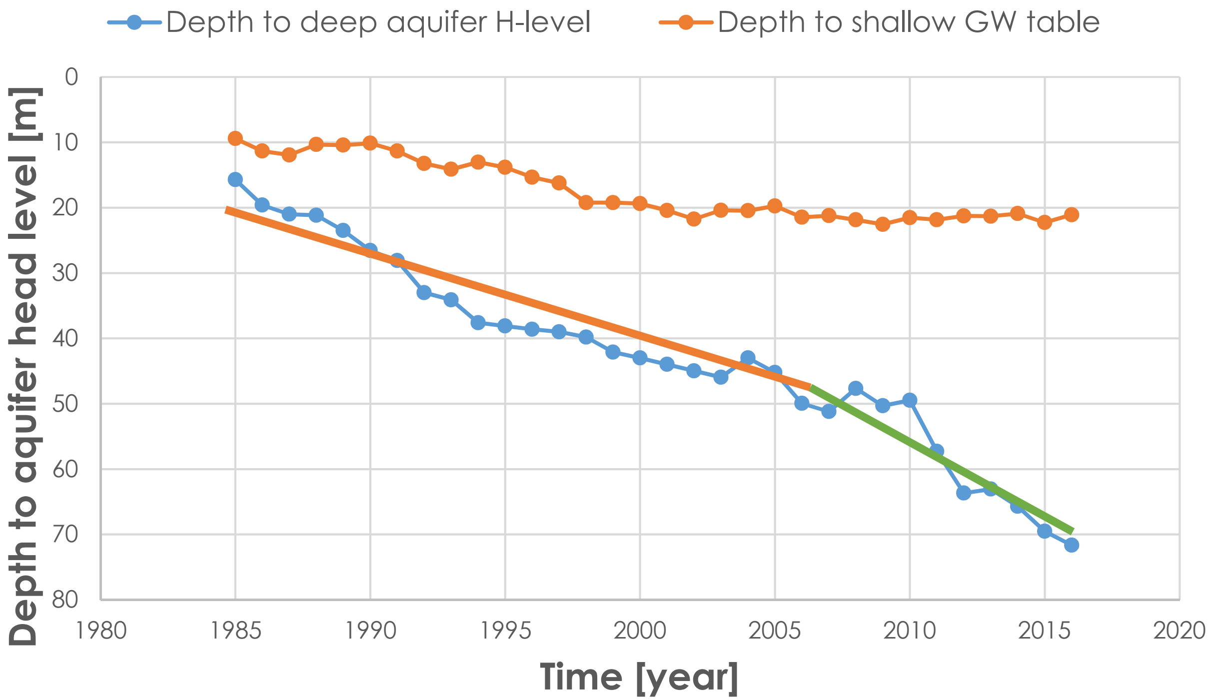
Development of overpumping in Guantao: Shallow aquifer

- Data: Average of three long-term observation wells
- 30-year moving average of precipitation
- Observation: Rate of water table decline decreased from 0.8 m/a to 0.15 m/a



Development of overpumping in Guantao: Deep aquifer

- Data: Average of 10 long-term observation wells
- Observation: Rate of water table decline increased from 1.0 m/a to 2.2 m/a



Difference in heads between shallow and deep aquifer still increasing!
Risk of attracting saline water from shallow aquifer

Water ≠ Water

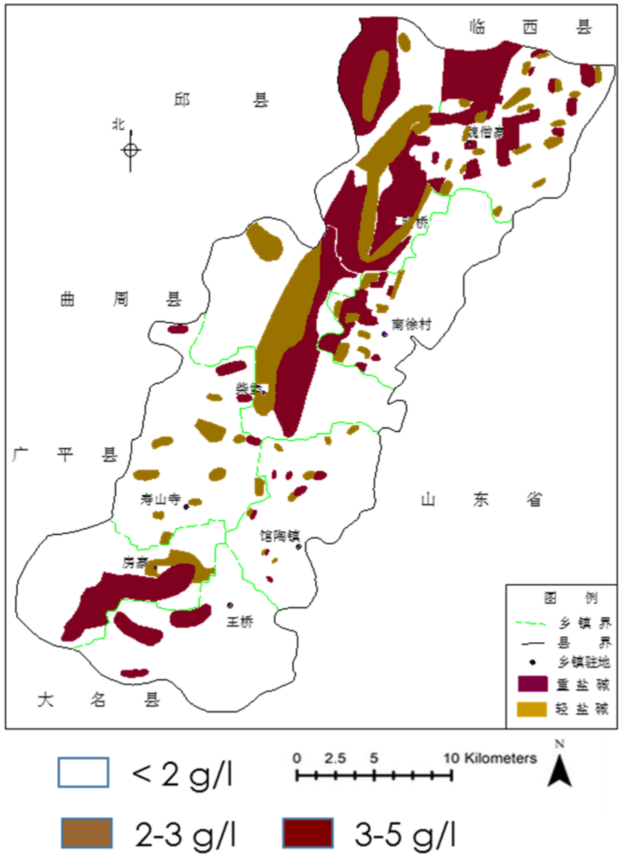
Shallow aquifer

- Not of drinking water quality
- Locally too saline for irrigation
- Recharge about 20% of precipitation

Deep aquifer

- Drinking water quality
- No recharge
- Household and industry use partially replaced by water from NSWT
- Agriculture still strong user due to salinity constraints (dilution and green houses)

Salinity in shallow aquifer



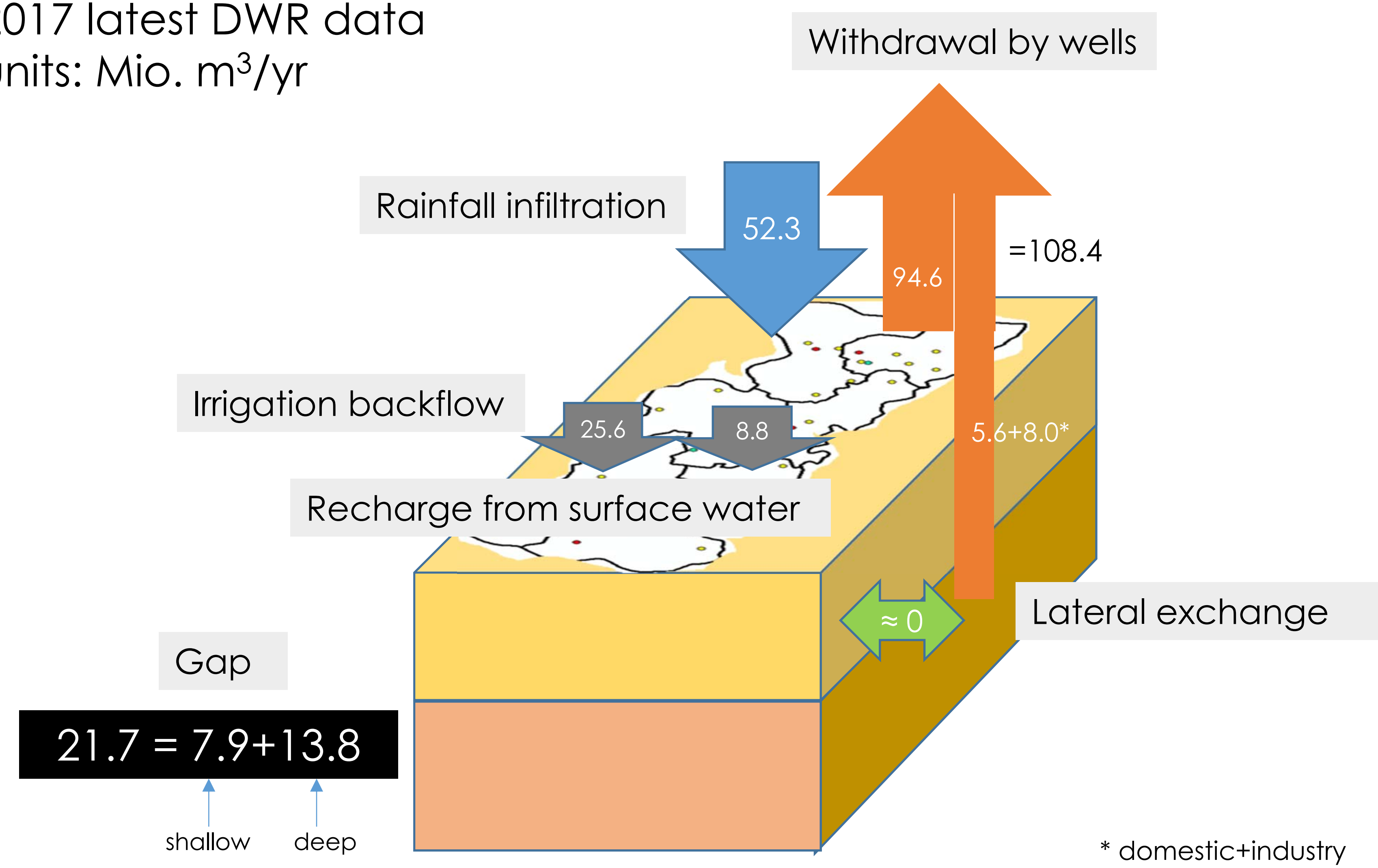
Options to stop pumping from deep aquifer

- Measures for reduction of groundwater use preferably in high salinity areas

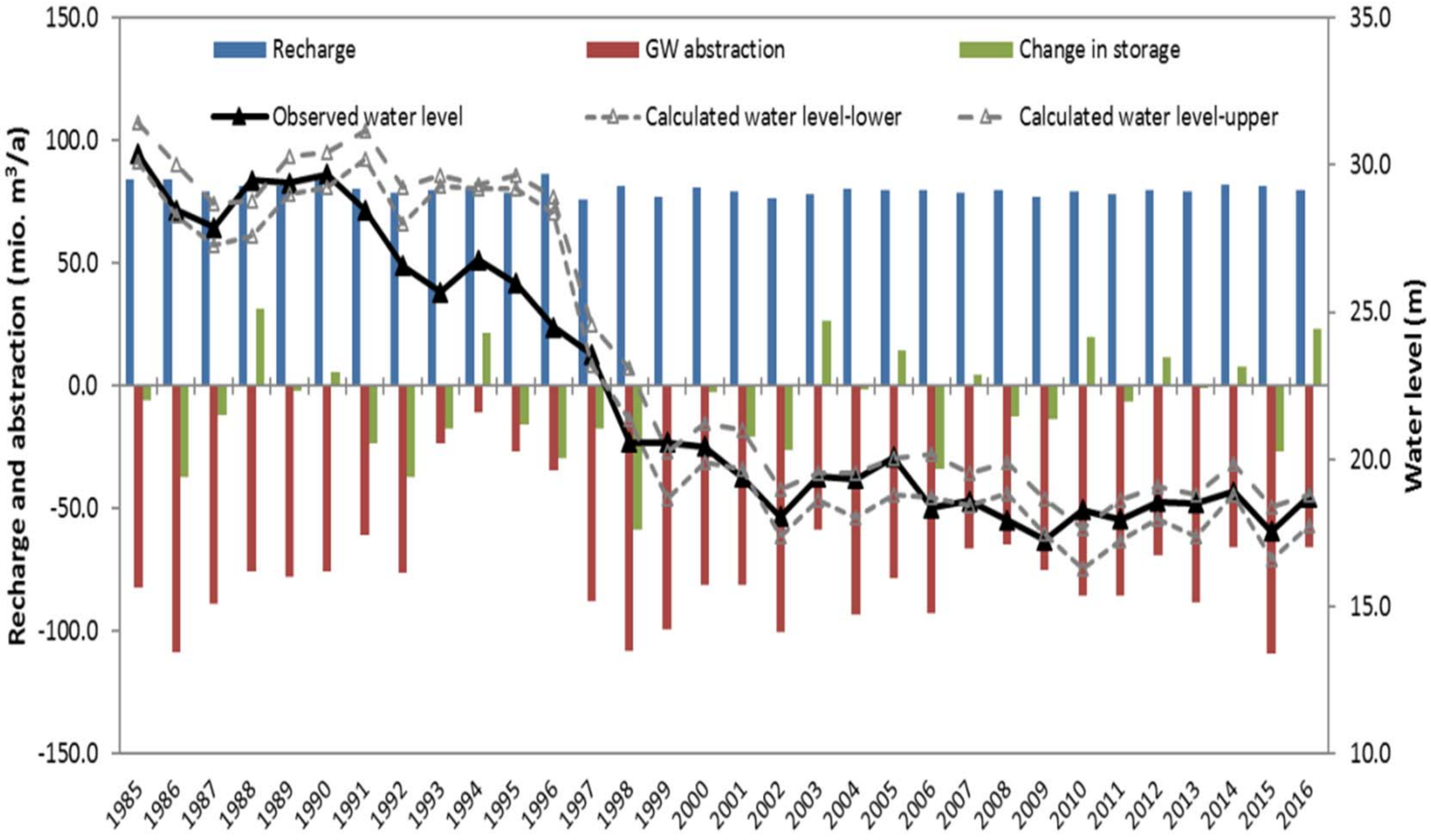
Water balance Guantao

Assumption: Lateral fluxes in shallow aquifer negligible with respect to vertical fluxes (confirmed by numerical model)

2017 latest DWR data
units: Mio. m^3/yr



History of water balance Guantao



Reconstruction of shallow aquifer water balance and comparison with average heads

How to close the gap in Guantao?

Measure	Max. amount Mio. m^3/a	Cost CNY/m^3
Water saving (small fields and pipes)	?	0.56
Conservation tillage	?	1.0
Water saving (drip irrigation vegetables + greenhouses)	7	2.0
No winter wheat irrigation	64	2.5
Yellow river and reservoir water	?	0.15
SN-transfer water	5	7.00

- Agricultural water supply-demand gap of 20-30 Mio. m^3/yr identified
- Demand and supply side options to fill the gap
- All demand side options are subsidized
- All supply side options are too small and unreliable, depending on availability of water
- Remaining potential for water saving irrigation is low
- Treated waste water is not considered, as it does not have the required quality
- Most reliable method: Reduction of winter wheat. To fill gap, a reduction by about 30 % is required

Policy and economic instruments

- Personal water right ✓
- Quota solution for management (2 block scheme)
- Red line to protect well yield and keep reserve for prolonged drought
- Change in planting structure:
  - subsidy for fallowing ✓
  - subsidy for planting water saving crops and trees ✓

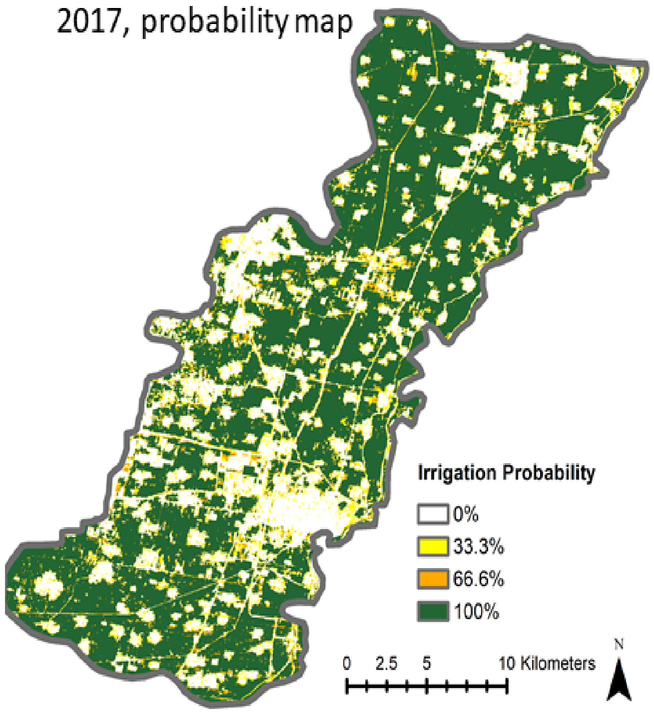
Water price or cap?

- **Water fee proportional to volume (our favorite)**
  - Price as signal for scarcity
  - Price elasticity of water demand could be small
  - Easily collected together with electricity fee
  - Effect felt immediately while pumping, not at end of year
- **Quota (adopted by Hebei province)**
  - Generally preferable method as rationale of punishing overdraft is sound
  - Implementation more difficult than implementation of fee as accounting is done end of the year
  - Farmers will rather pay penalty than lose harvest
- **Combination (experimental with some success)**
  - 一提一补 Reimbursing water fee up to quota
  - Credit for paying water fee from first cubic meter up to quota (Worldbank)
  - Buy-back of water rights

No fees have been collected in Guantao up to now due to resistance by the farmers!

Most successful measure: Fallowing

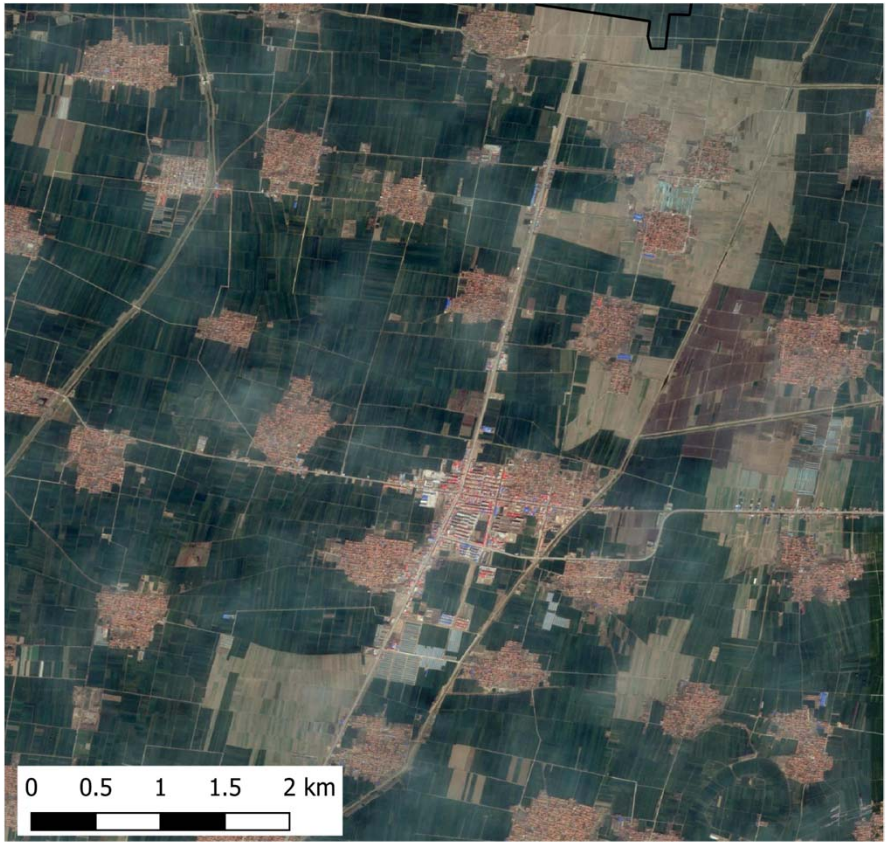
- Only real solution to overpumping is the adaptation of cropping structure to water resources available
- Subsidy for fallowing is generally welcomed by farmers as income from winter wheat is very low (lower than subsidy)
- Fallowing can be monitored by remote sensing
- Amount of subsidy available is the limiting element
- Subsidy of 500 CNY/mu/season corresponds to about 2.5 CNY/m^3 of water saved (in comparison: subsidy for high-end water saving 2 CNY/m^3)



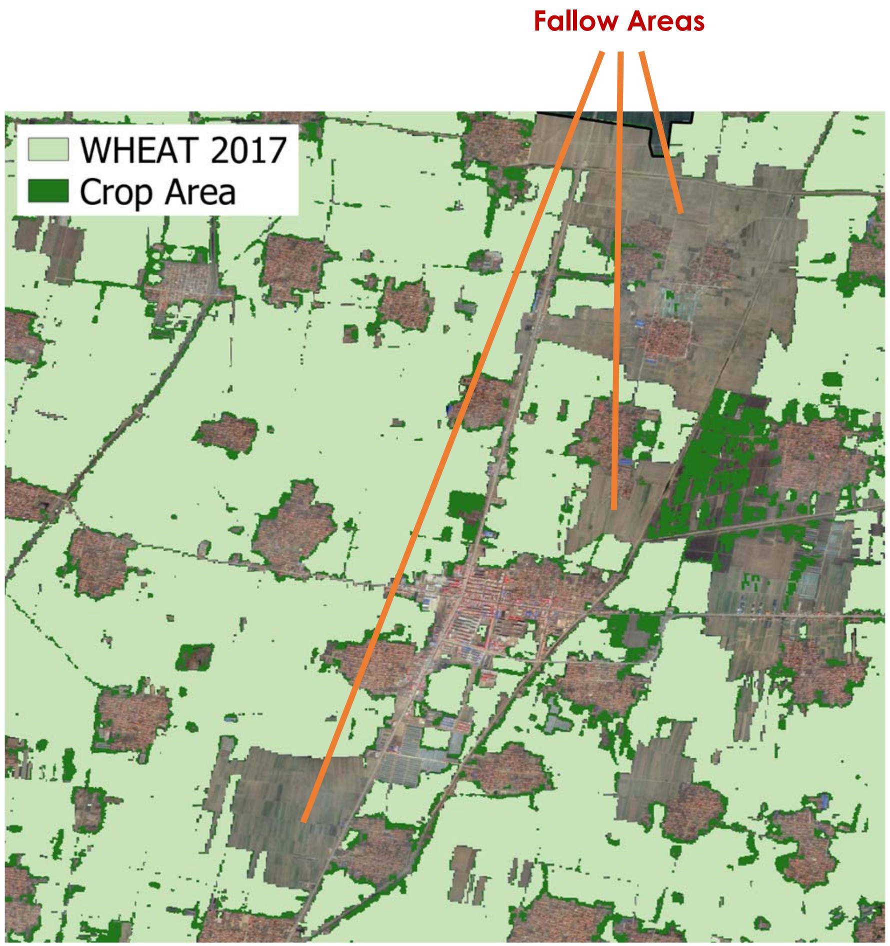
13th 5-year plan requires: Planting according to water availability. Not yet achieved!

1 mu = 1/15 ha

Control by land use monitoring: Winter wheat



Weisengzhai Township

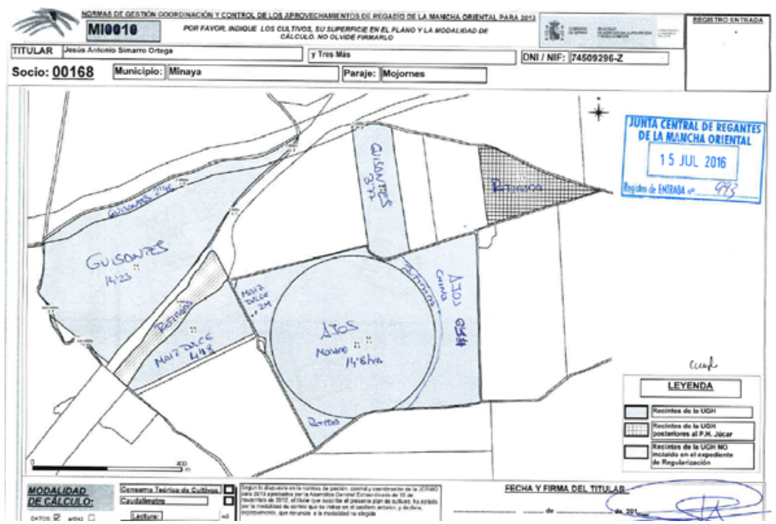


By comparison to 2016 image

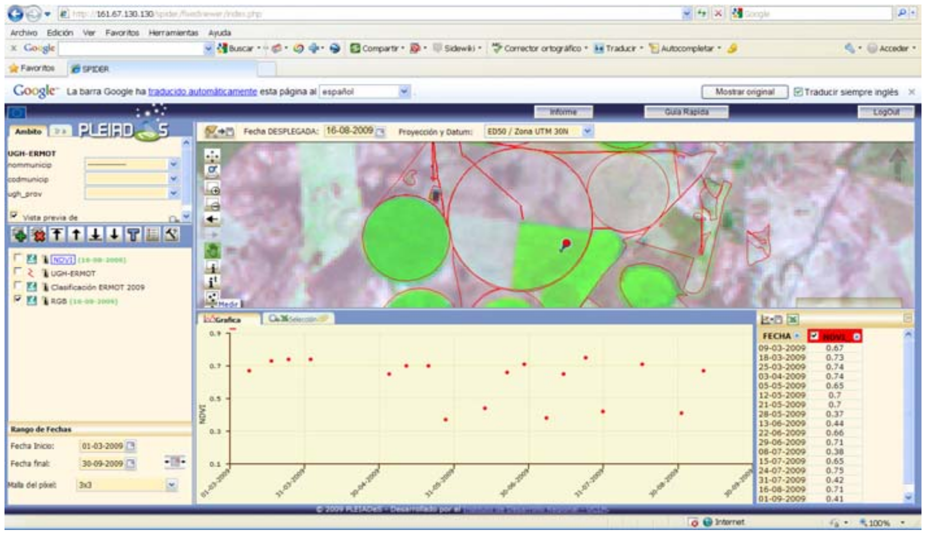
Ragettli, hydrosolutions, Zurich

Successful example of overpumping control without pricing of water

- **Eastern La Mancha, Spain**
  - Irrigation Management Units have a water right
  - Crops and areas are declared before the irrigation season with summed demands ≤ water right
  - They are verified by remote sensing
  - Non-compliance is sanctioned by reduction of water allocation in the following season (Monetary fining useless)



Self-declaration of crops according to water right



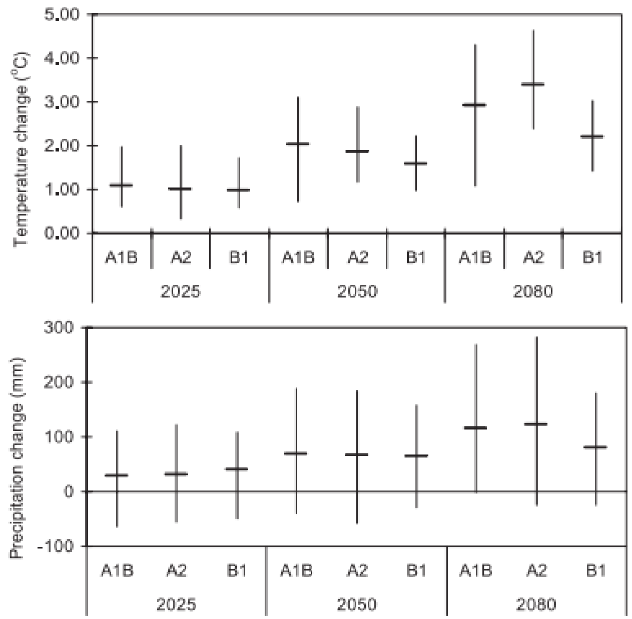
Verification by remote sensing

Some recent observations from Guantao

- Farmers who have received subsidy for not growing winter wheat for 3 years, stop to plant winter wheat even without subsidy
- In areas with more saline groundwater farmers shift from double cropping of winter wheat/summer maize to cotton even without subsidy due to higher earnings
- Tree plantations only involve subsidy for 5 years
- Percentage of small-holder family income from farming is decreasing due to off-farm jobs and remittances of family members working in town

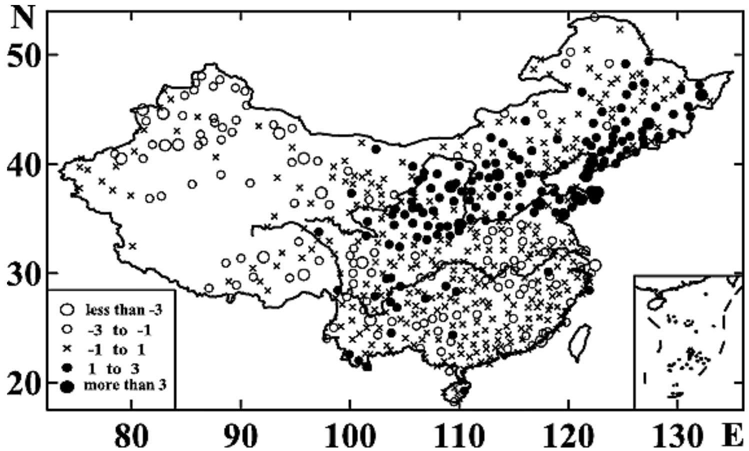
What about climate change?

- A warmer and, with less confidence, slightly wetter climate in the future
- Decrease in streamflow
  - Will surface water imports be available in the amounts needed according to present plans?
- Larger variability
- How will drought cycles change?
- Increase in heat spells requires more irrigation water for cooling the crop



Annual temperature and precipitation changes over the ensemble of GCM simulations for NCP.

(Guobin Fu et al. 2008)



The difference of the annual mean number of drought months (PDSI < −1.0) between two periods: 1977–2003 minus 1951–1976.

(Zou et al. 2005)

Conclusions

- Trend to larger farms and precision agriculture will lead to more efficient water use, but effect may be reduced by heat waves
- Water saving potential is insufficient to stop overpumping in NCP. Surface water import is unreliable. Remaining gap has to be closed by change in cropping system
- For the whole of Hebei province this translates to a loss of 5% of China's wheat production.
- Change in grain policy needed (e.g. import of meat to decrease feed grain production, but guarantee food grain)
- Yield gap can be addressed via new cultivars and Integrated Soil-Crop System Management
- In the very long term demography will help

Acknowledgments

Support through the Swiss Agency for Development and Cooperation, the Chinese Ministry of Water Resources, the Chinese Academy of Sciences and the China Geological Survey is gratefully acknowledged.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

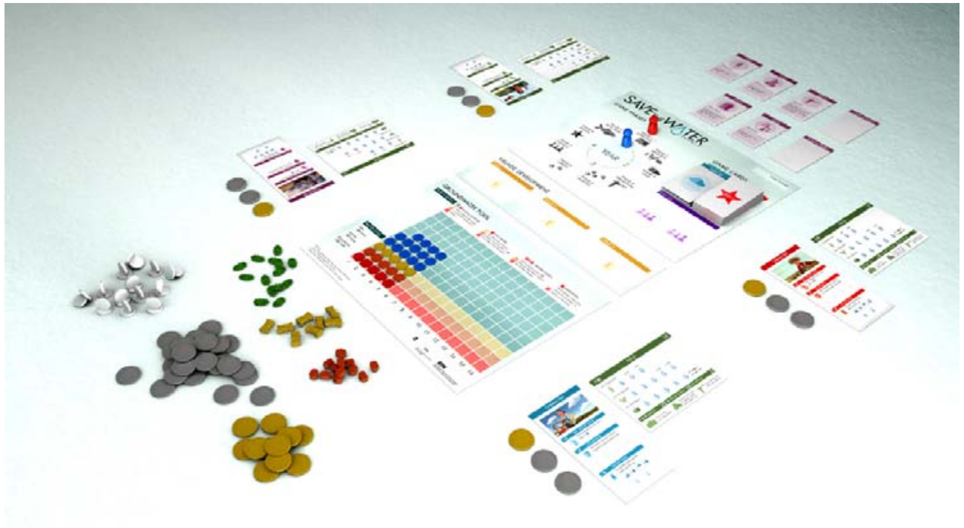
Chinese Ministry of Water Resources

China Geological Survey

Chinese Academy of Sciences

Awareness through groundwater game

- Complex serious game developed by ZhdK (Lunin et al.)
- Goals
  - Raising awareness
  - Test of policy impact
  - Learn about farmers' preferences



Played with great success by many people! You are welcome to test app version!

Awareness through groundwater game

- Complex serious game developed by ZhdK (Lunin et al.)
- Goals
  - Raising awareness
  - Test of policy impact
  - Learn about farmers' preferences

https://savethewater-game.com/game

Played with great success by many people! You are welcome to test app version!

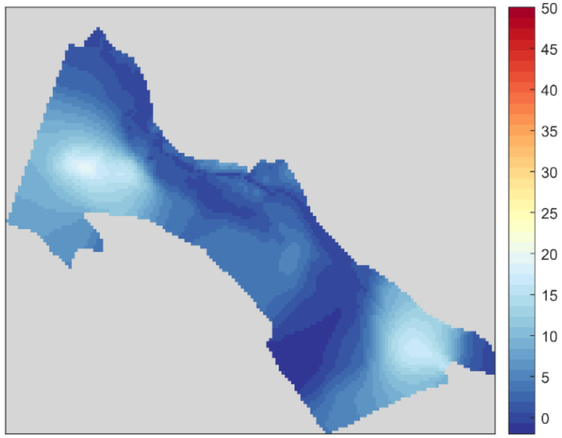
Is a new quasi-steady state feasible?

(with river flow rate and water allocation of 2012)

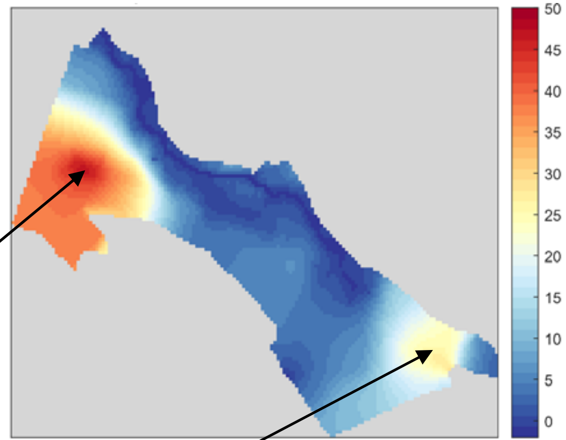
Not every decrease of the groundwater level means overpumping
If a new steady state can be reached, sustainable abstraction is still possible

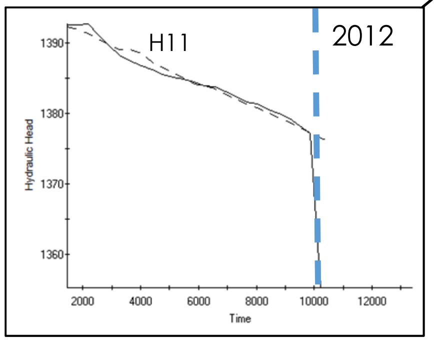
water table change [m]

between 1990 and 2012

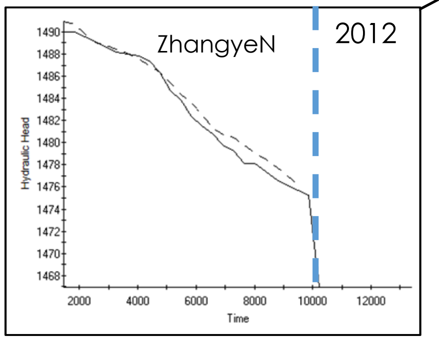


between 1990 and steady state





Another 28 m of decline

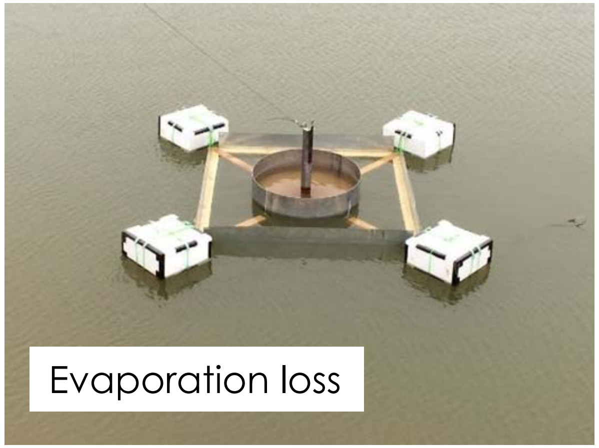


Another 9 m of decline

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

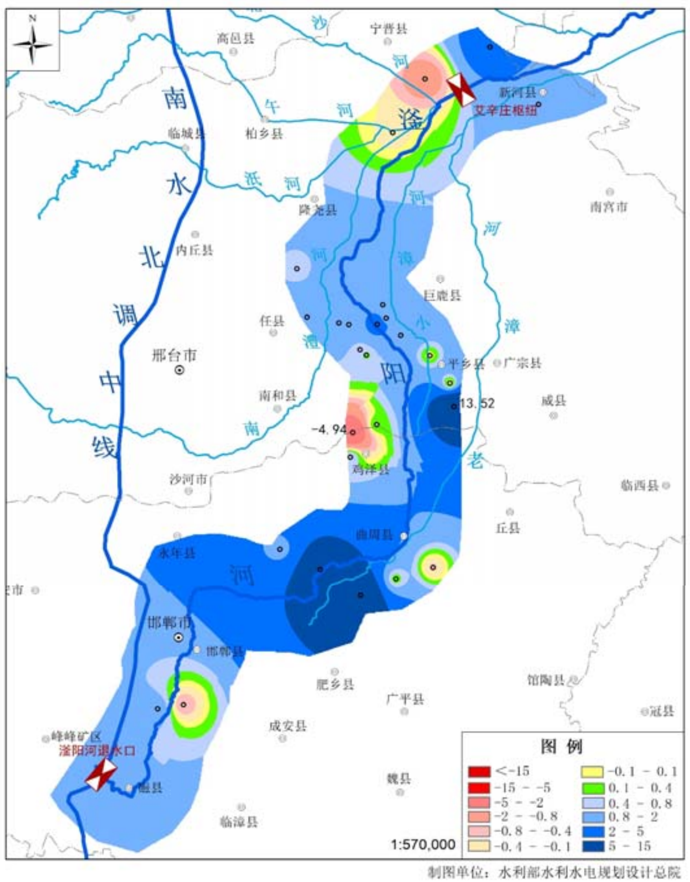
Artificial aquifer recharge

Infiltration basins Guantao



Net infiltration of lake of 35’900 m^2 area: 110’000 m^3 per filling
Low efficiency, but at point of use

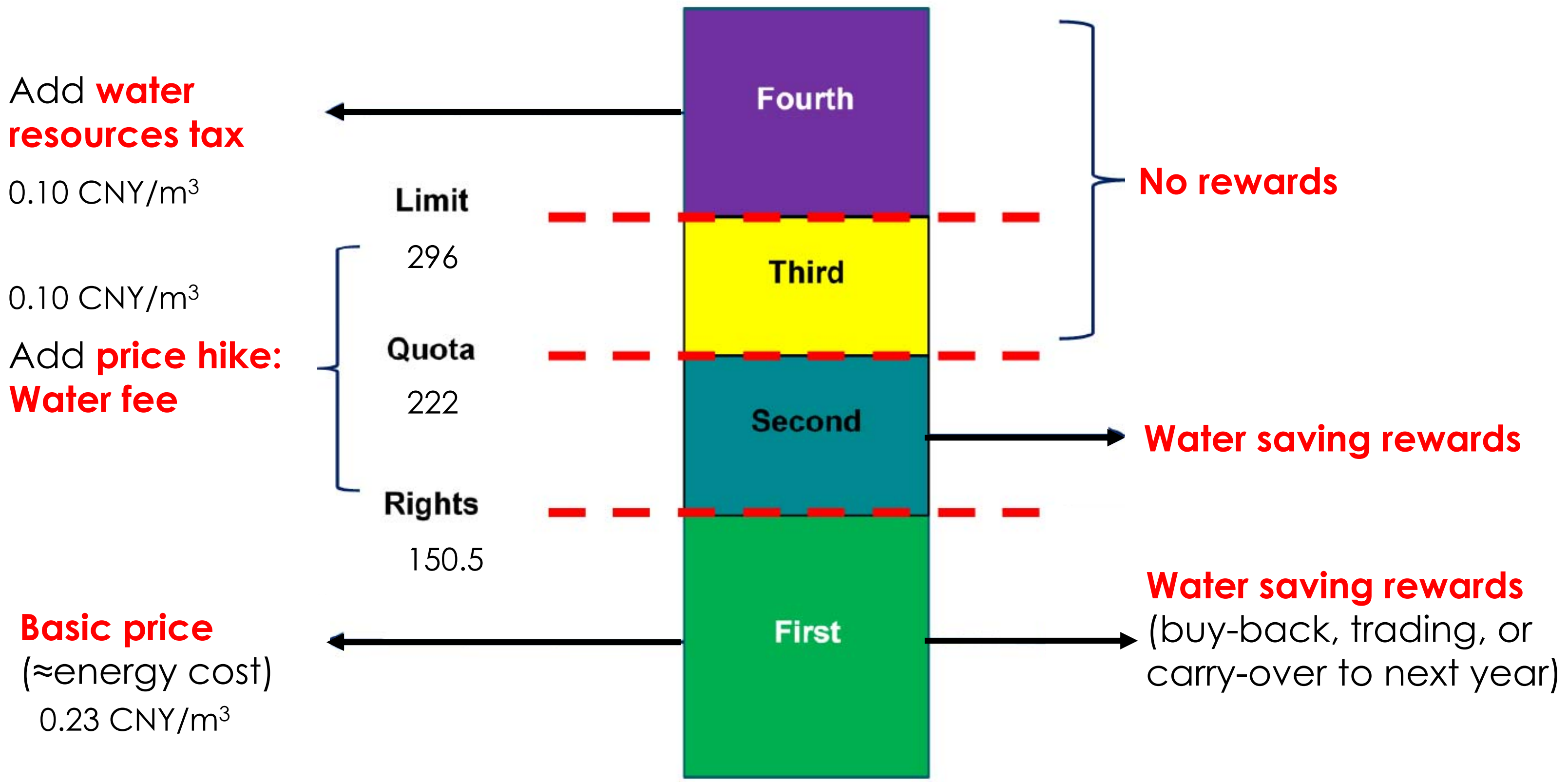
Infiltration in river beds: Example Fuyang River



MWR, 2019

Using water from NSWT and upstream reservoirs
High efficiency, but only in vicinity of river

The Hebei provincial rules



Three lines and four ladder steps scheme (Values for Guantao in m^3/mu/year)
Basic question: What is the rationale for water fees?

1 mu = 1/15 ha