Groundwater depletion in North China from GRACE satellites, ground-based monitoring network and groundwater modeling

FENG Wei[1,2], **ZHONG Min**[1], **XU Hou-Ze**[1],
Jean-Michel LEMOINE[2], **Richard BIANCALE**[2], **XIA Jun**[3],
ZHENG Chun-Miao[4], **Cao Guo-Liang**[4] & **Tang Qiu-Hong**[5]

[1]Institute of Geodesy and Geophysics, Chinese Academy of Sciences, China
[2]CNES/GRGS, GET/OMP, Toulouse, France
[3]Research Institute of Water Security, Wuhan University, China
[4]Center for Water Research, Peking University, China
[5]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, China

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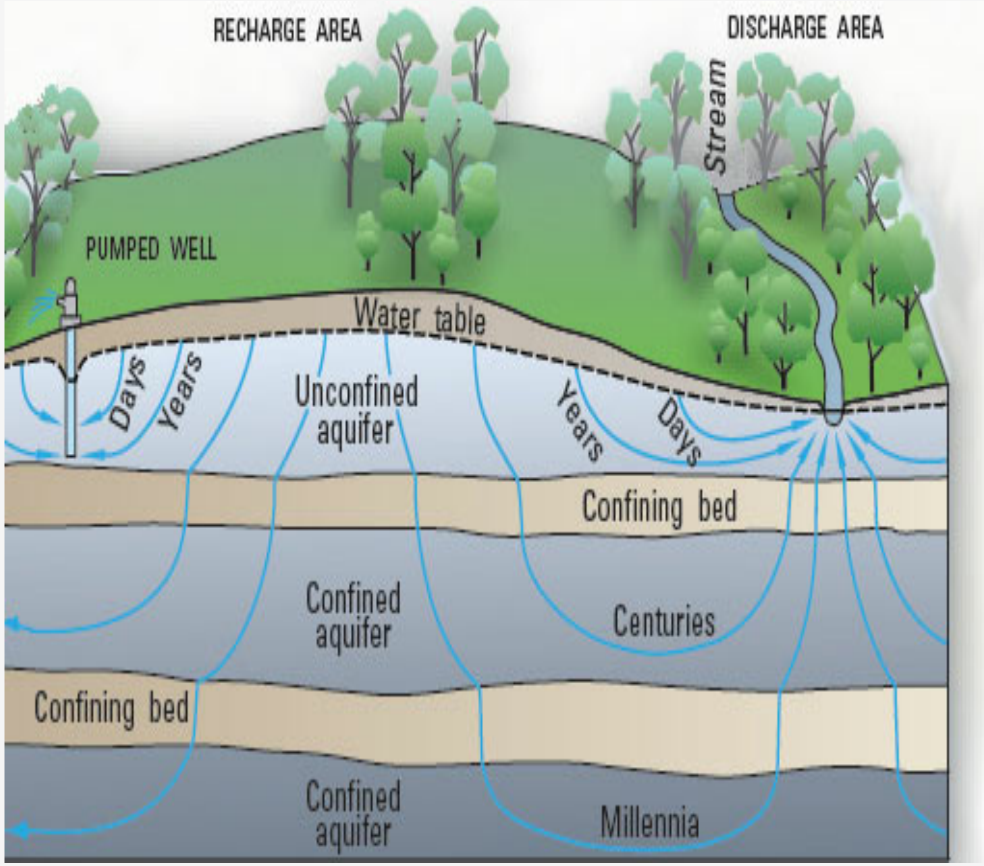
Terrestrial water storage change (TWS)



Δ TWS (GRACE)

=

Δ Canopy
(negligible)

+

Δ Surface water
(potential significant: flooded areas, dams, wetland)

+

Δ Soil moisture
(significant)

+

Δ Unconfined & confined aquifers
(potential significant: groundwater pumping)

credit: USGS

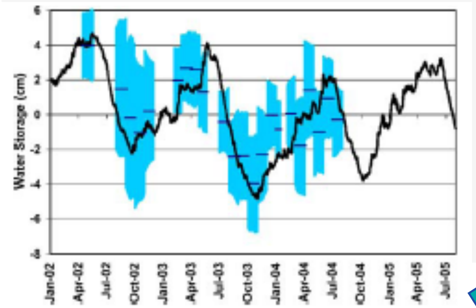
Groundwater storage (GWS)

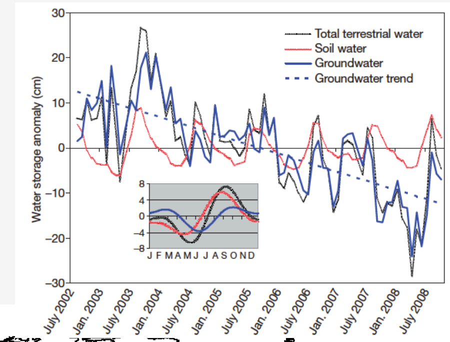
Monitoring methods:

- **Direct observations from monitoring wells (time consuming, limited spatial distribution,…)**
- **Groundwater models (e.g., MODFLOW)**
- **Remote sensing (GRACE)**
  - **To estimate the groundwater storage change using GRACE, we need to subtract soil moisture (SM) and other components from total water storage change.**
  - **SM can be estimated from models (GLDAS, CPC, WGHM,…) or from ground-based soil moisture measurements.**

Globally, irrigation has caused groundwater depletion (by groundwater pumping) in many parts of the world.

Background





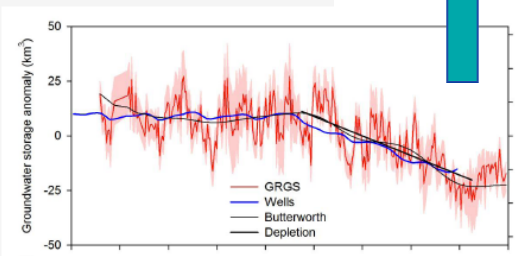
17.7 km³/yr, 54 km³/yr

North India and Pakistan
Rodell [2009]
Tiwari [2009]

North China??

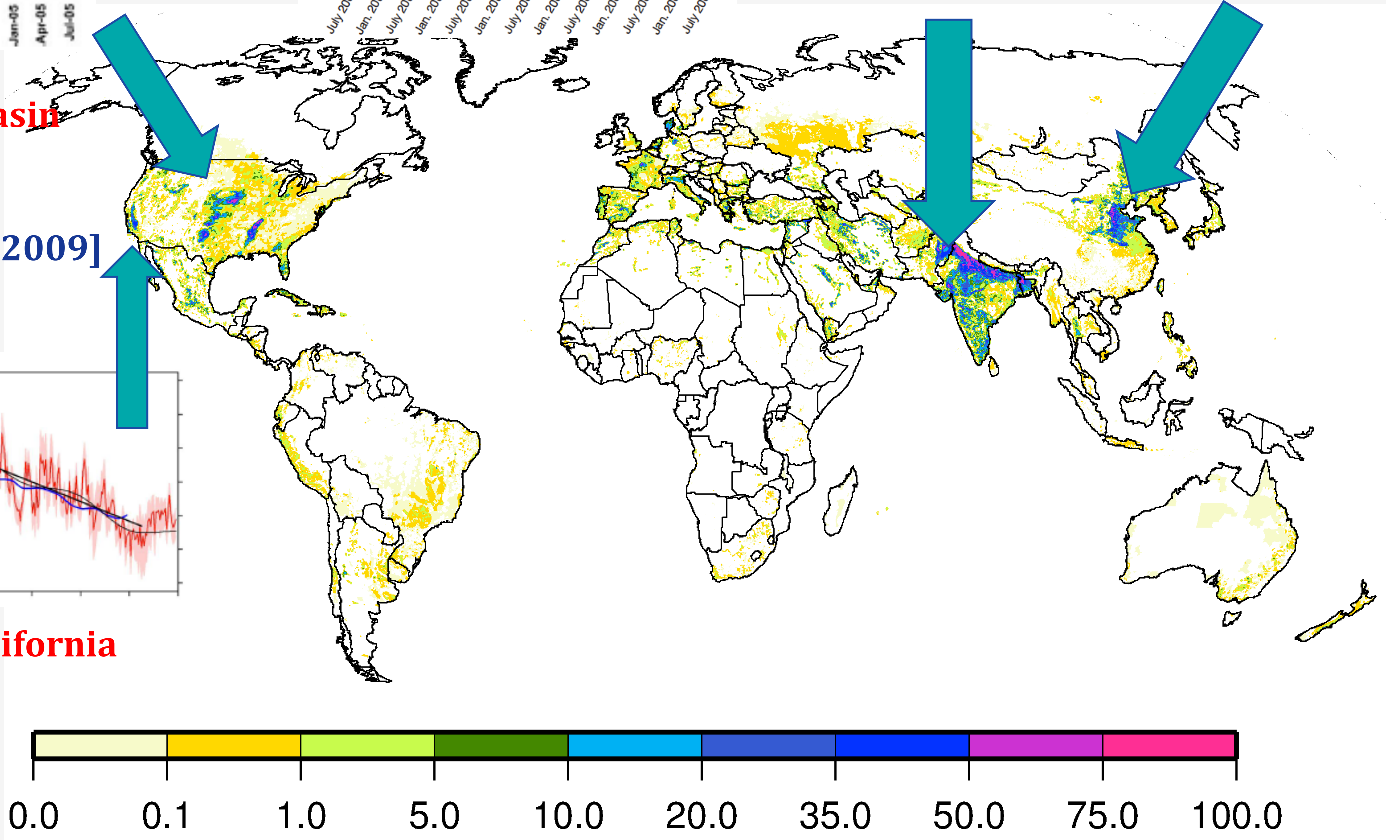
Mississippi rive basin
Rodell [2007],
High Plains
Strassberg [2007, 2009]

~9 km³/yr



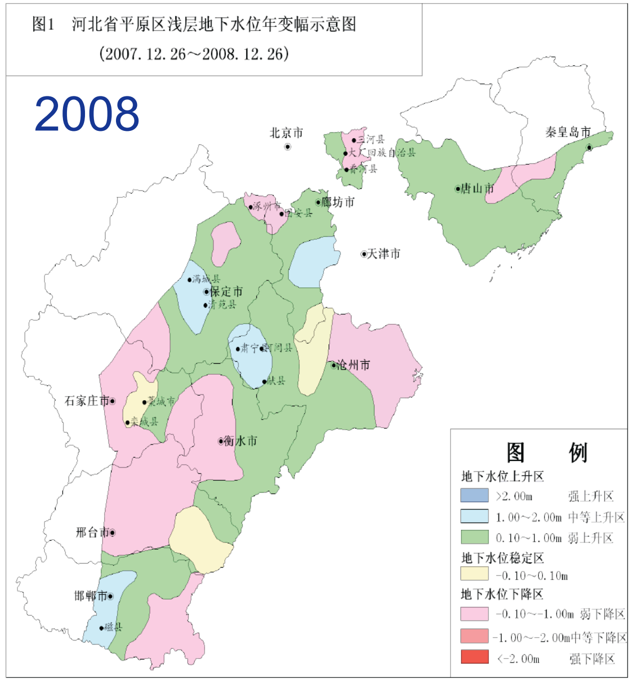
Central Valley, California
Famiglietti [2011]
Scanlon [2012]

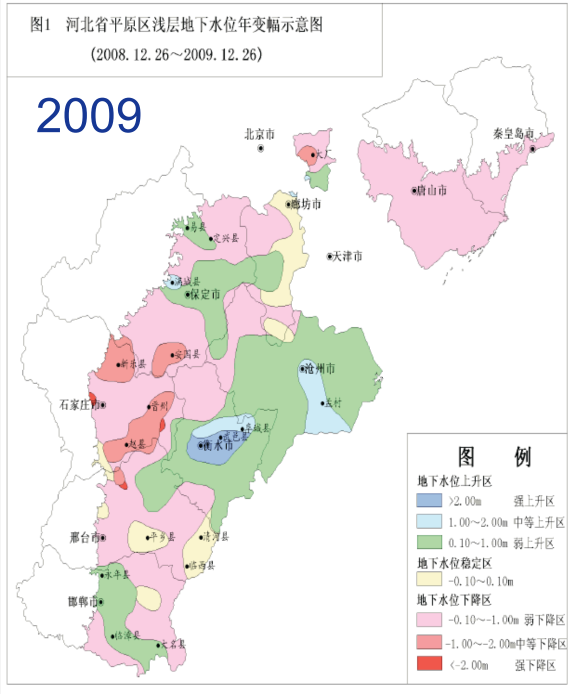
8.9 km³/yr

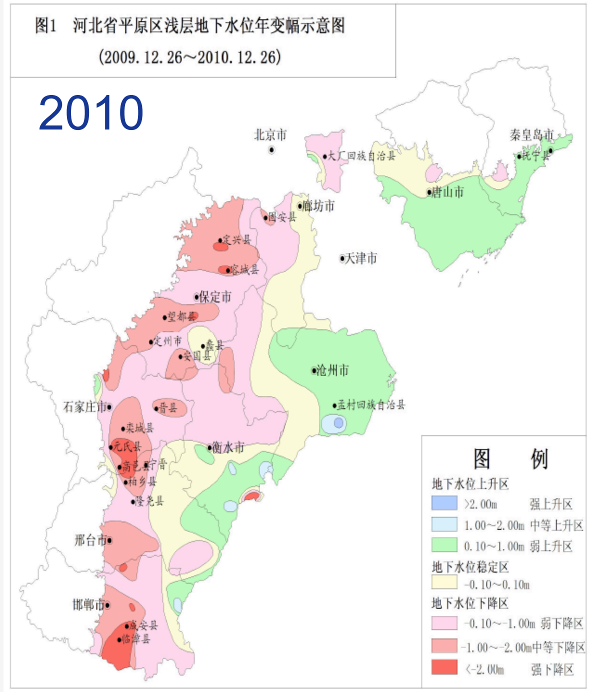


Percentage of grid cell area equipped for irrigation with groundwater, *Siebert [2010]*

Groundwater depth changes in Hebei







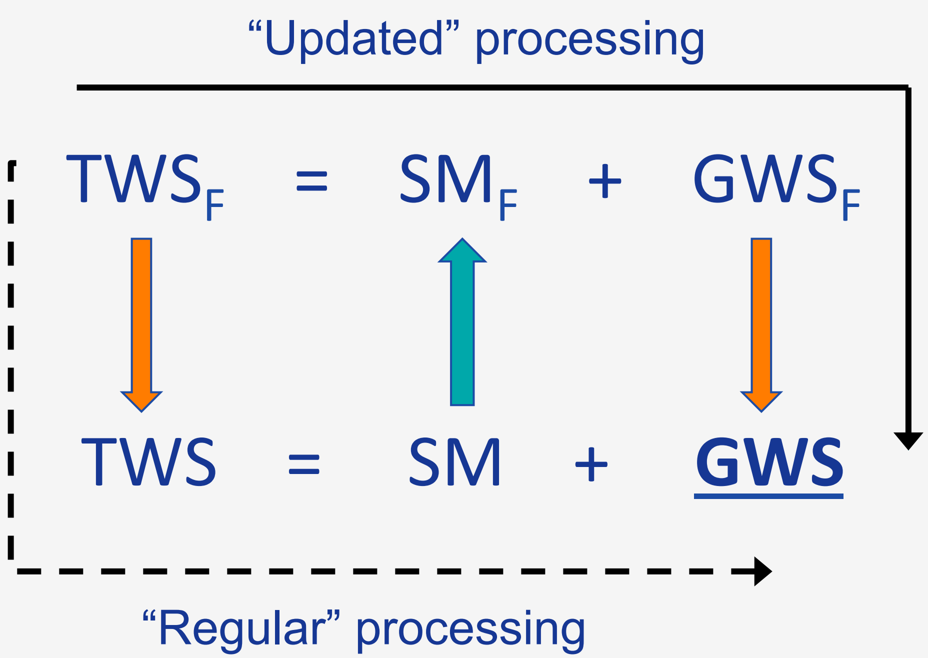
Whether GRACE can observe the groundwater depletion here?

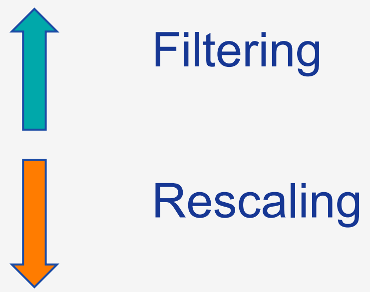
Groundwater Bulletin of Hebei Plain

Data

- **GRACE products:**
  - CSR, GFZ, JPL（Swenson's destriping, 200km Gaussian filter ）
  - GRGS
- **Hydrological models: GLDAS** (Noah, Mosaic and Vic), **CPC**
- **In-situ observations: 40 daily monitoring well observations**
- **Government reports: Groundwater Bulletin of China Northern Plains (GBCNP), Groundwater Bulletin of Hebei Plain**
- **Groundwater model output of North China Plain**

GRACE Data processing





TWS: terrestrial water storage
SM: soil moisture
GWS: groundwater storage

Estimation of scaling factor in "Regular" processing:

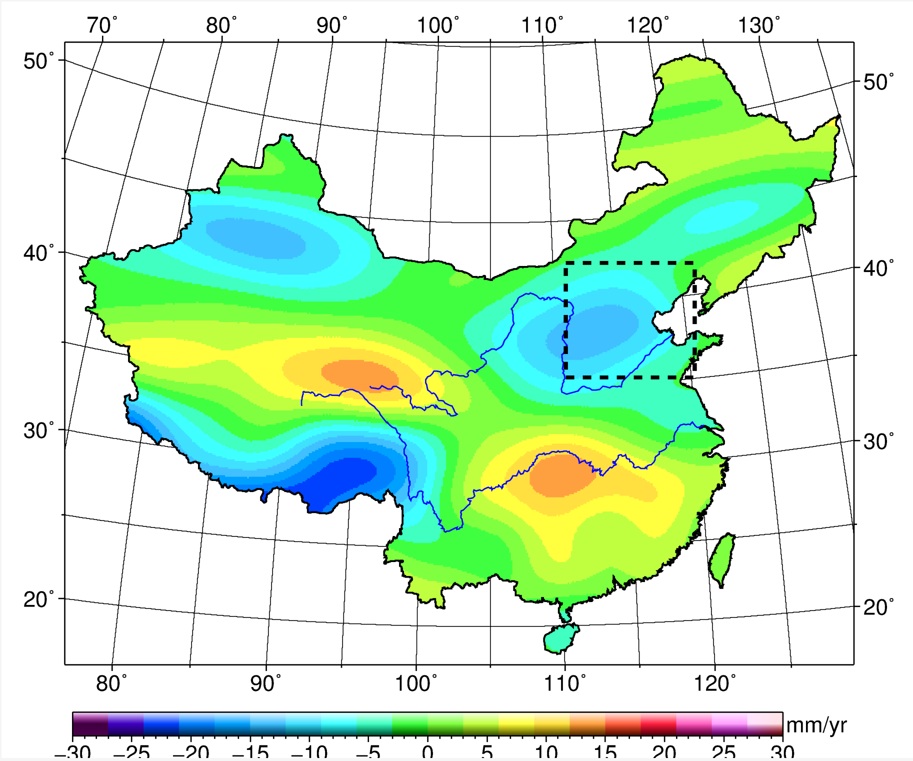
method1 : assuming the signal over the study region is uniform (1 inside, 0 outside)
method2 : assuming the hydrology model can assimilate the TWS in the region

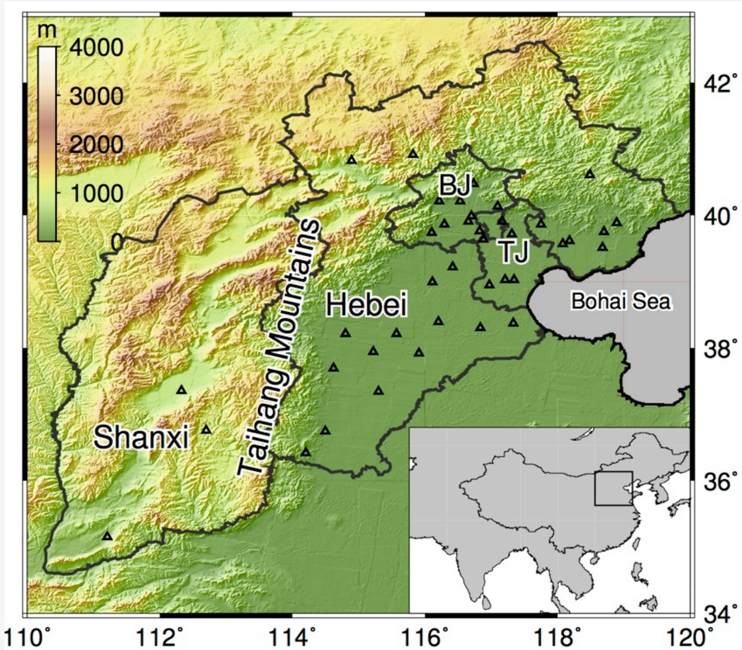
Estimation of scaling factor in "Updated" processing:

using a prior groundwater model or groundwater observations of GWS

Scanlon et al. 2012

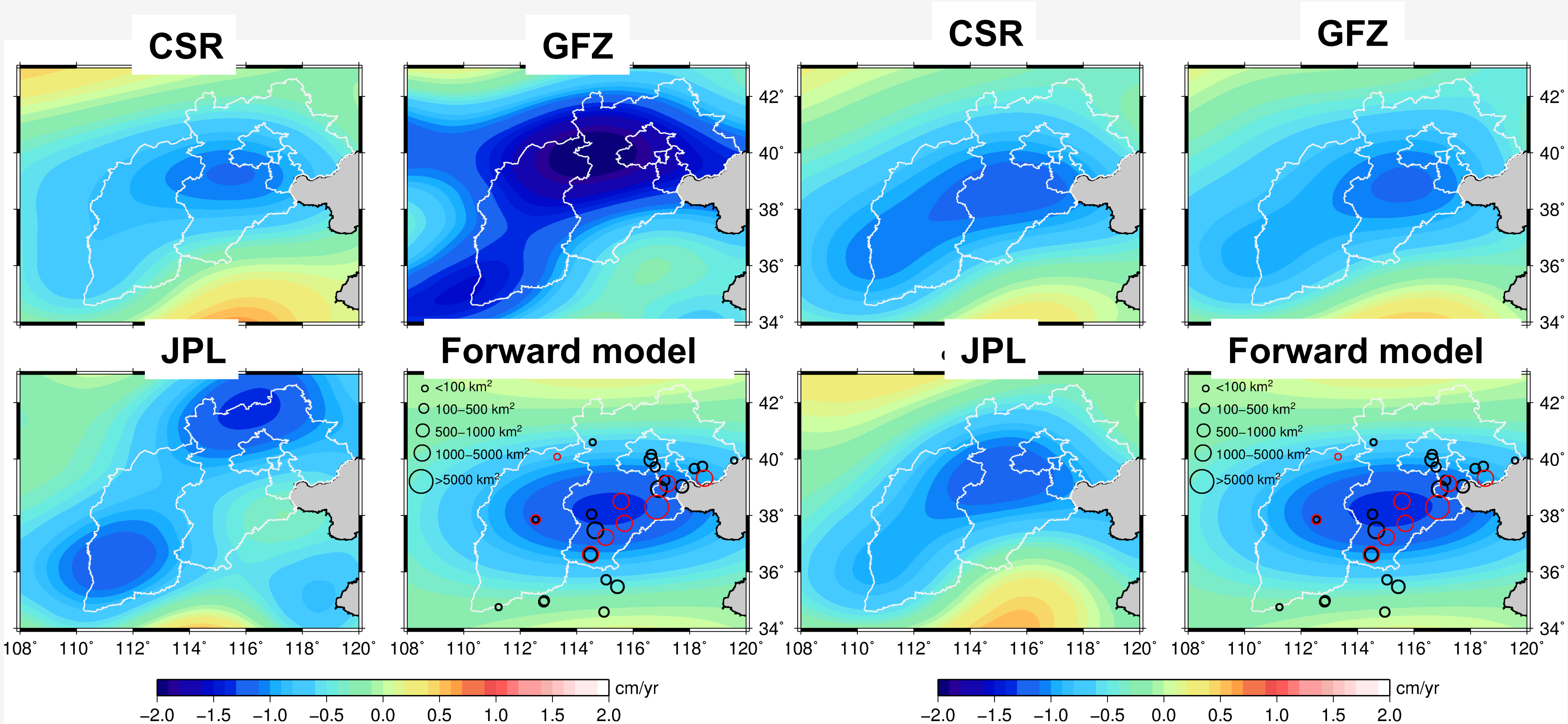
Terrestrial water storage changes in China





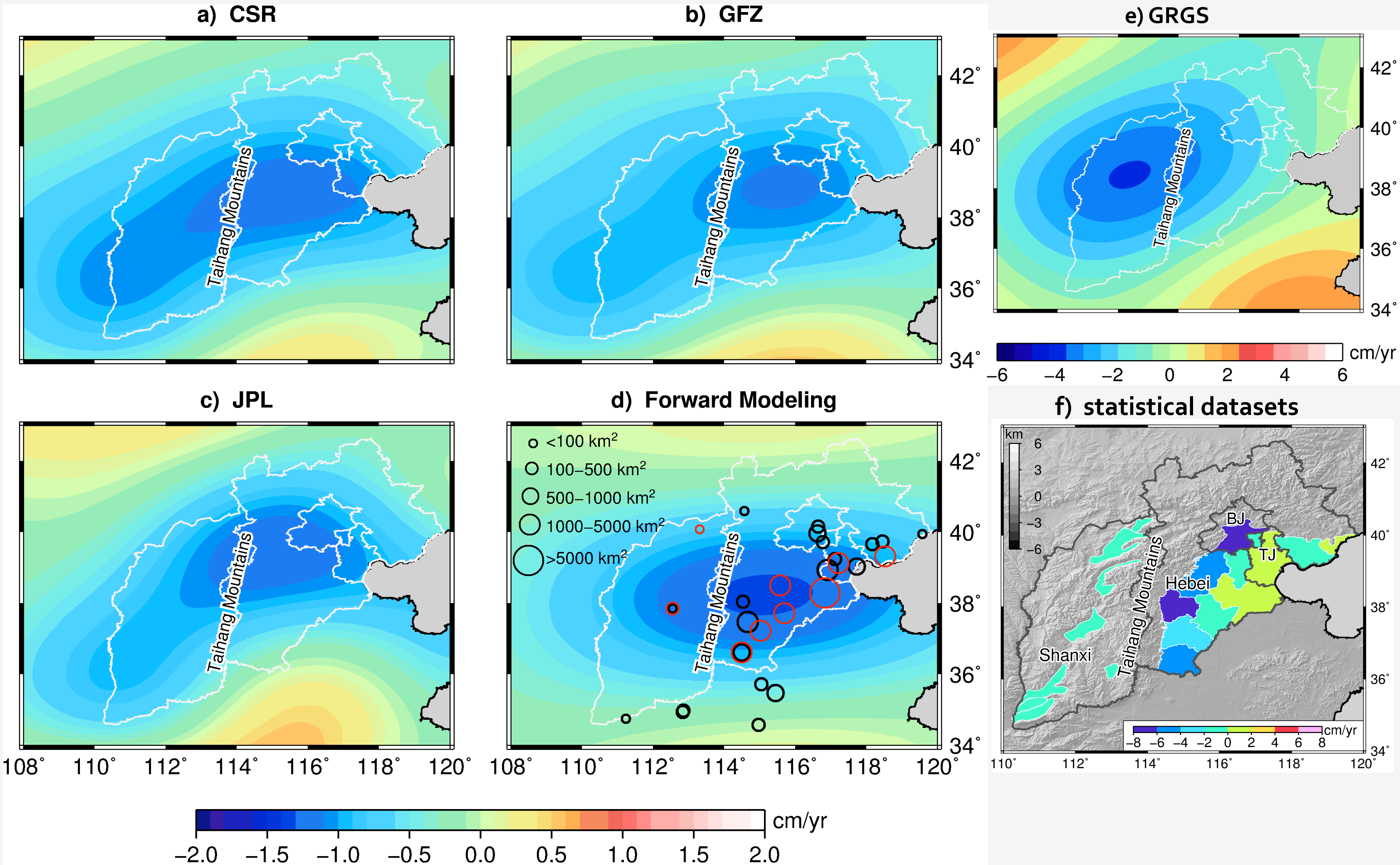
- the largest wheat/maize production zone in China
- Since 1970s, the very rapid development of agriculture and industry has resulted in great demand for water resources
- In 2009, groundwater accounted respectively for 61%, 26%, 80% and 58% of total water supply in Beijing, Tianjin, Hebei and Shanxi.

Groundwater storage trends in North China

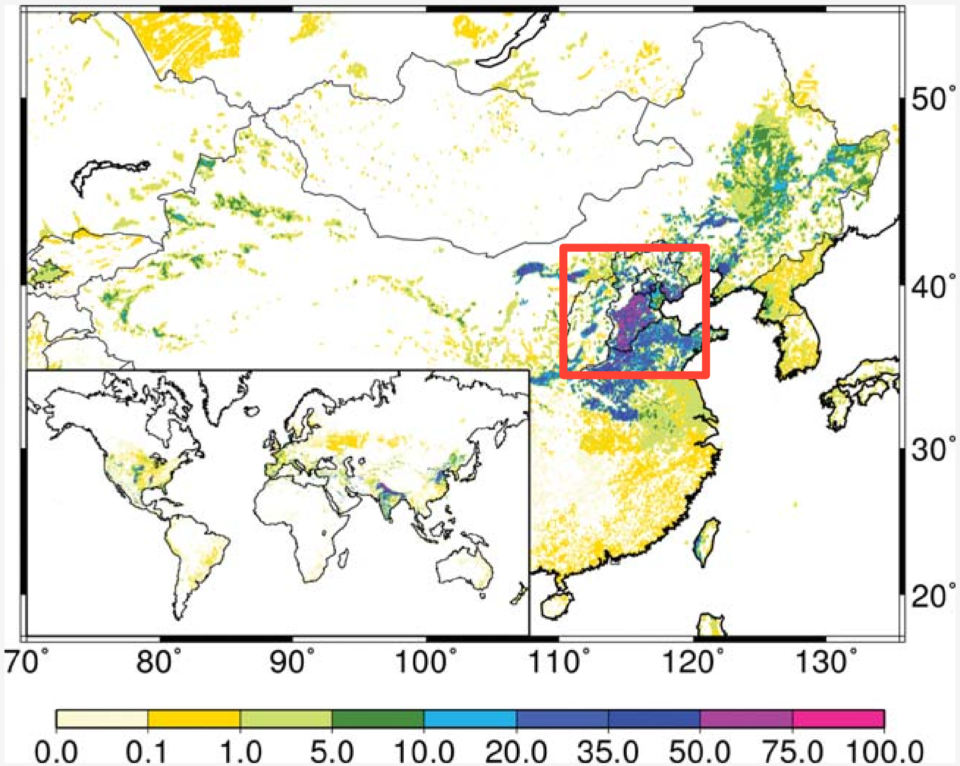


GRACE RL04 **GRACE RL05**

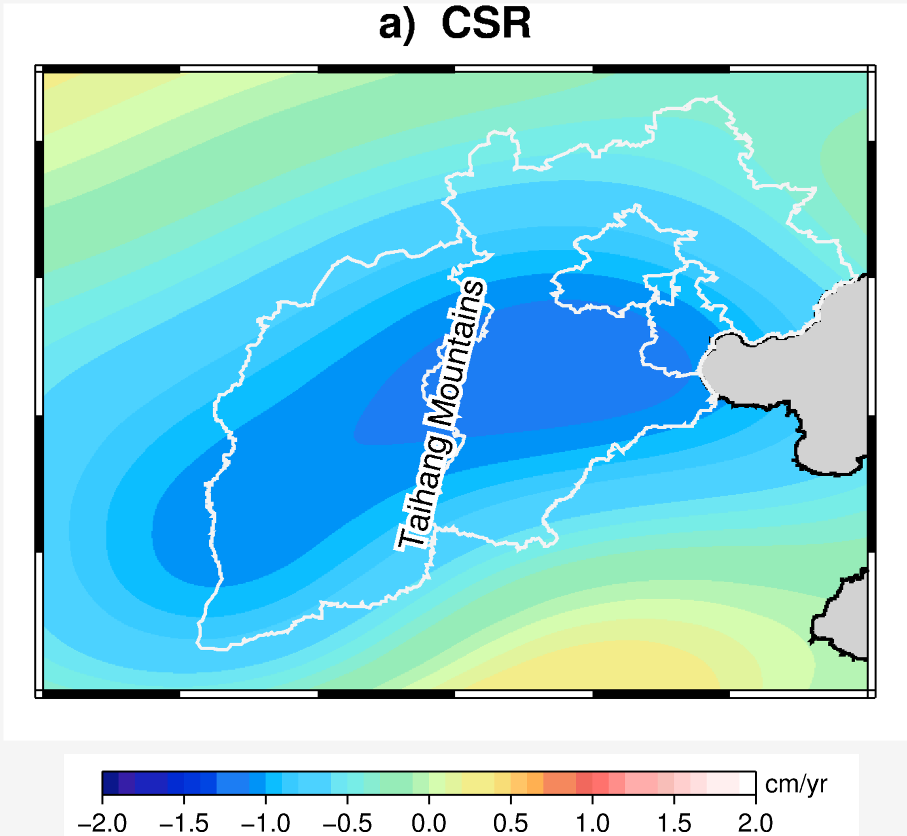
Groundwater storage trends in North China



Groundwater storage trends in North China



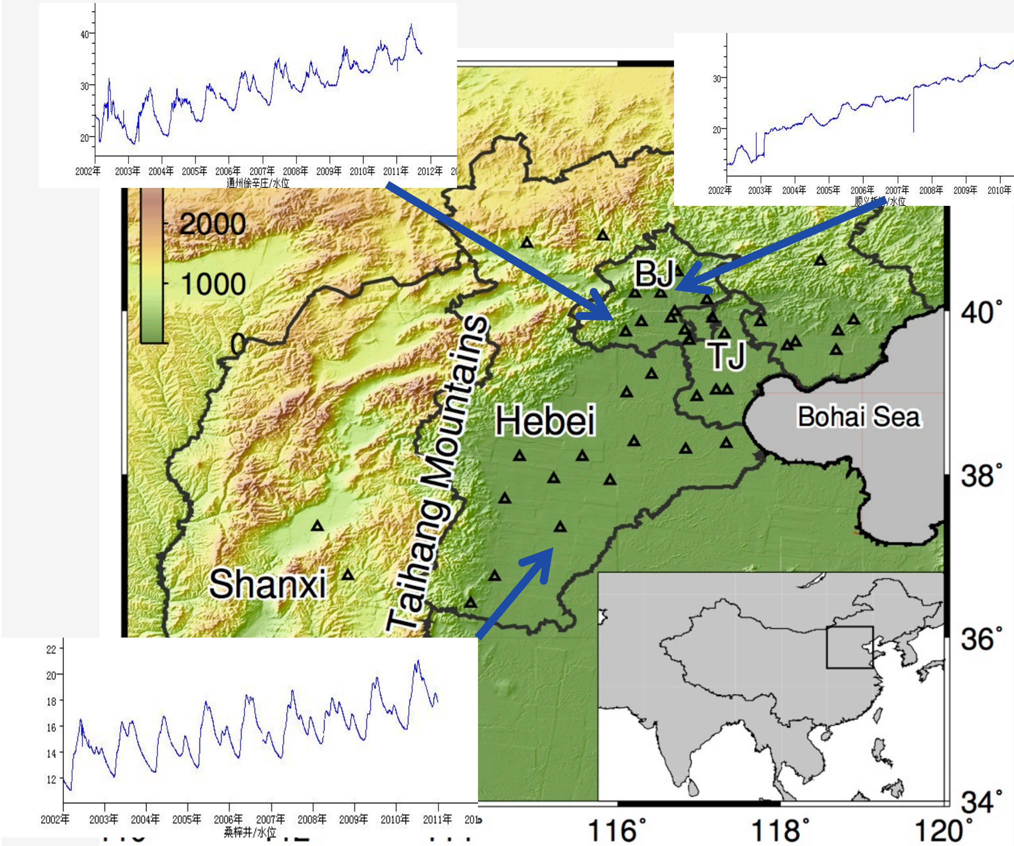
Percentage of grid cell area equipped for irrigation with groundwater, *Siebert [2010]*



Trend map of groundwater storage changes from GRACE-SM

Groundwater storage trends in North China

Groundwater storage changes = Groundwater table changes * Specific yield

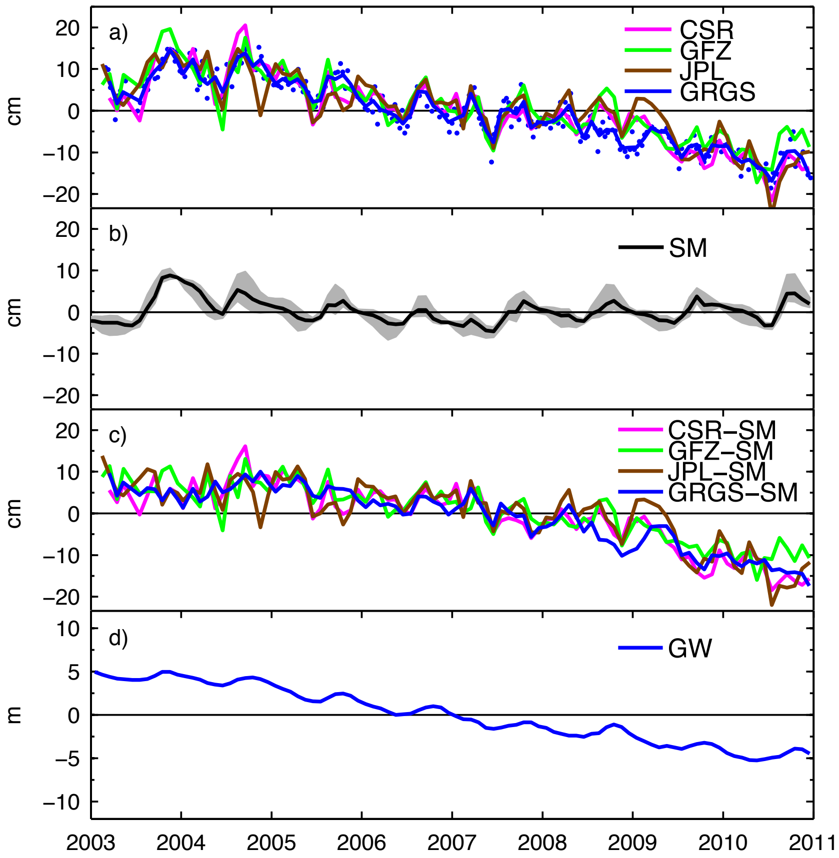


spatial distribution of monitoring wells

spatial distribution of specific yields

courtesy: Fei & Zhang

Groundwater storage trends in North China



Groundwater depletion rates in North China estimated from different methods and data

	km³/yr	cm/yr
CSR - SM	8.3 ± 1.1	2.2 ± 0.3
GFZ - SM	7.6 ± 1.4	2.0 ± 0.4
JPL - SM	7.9 ± 1.3	2.1 ± 0.4
GRGS - SM	9.2 ± 0.8	2.4 ± 0.2
monitoring well	7.5~10.6	2.0 ~ 2.8

Groundwater storage trends in North China

- Different error components in the error budget of monthly GWS estimates and the trend

		monthly (cm)	trend (cm/yr)
TWS (GRACE)	measurement error	3.54	0.16
	leakage ($k\Delta S_{leakage}$)	2.61	0.12
	scaling factor (Δk^*S_0) ($\Delta k^*S_{leakage}$)	<0.58 <0.22	0.03 0.01
	Processing error	--	0.12
	GIA	--	0.06
	total	4.87	0.24
SM	Hydrological model	3.98	**0.18**
GWS	GRACE - SM	5.96	**0.30**

Groundwater storage trends in North China（Groundwater Bulletins）

	Beijing	Tianjin	Hebei	Shanxin	Total (10^8 m^3/yr)
2003-2004	-3.90	-0.75	-12.75	-1.25	-18.65
2004-2005	-6.39	+0.04	-28.44	-4.78	-39.57
2005-2006	-6.87	+0.25	-29.74	-3.19	-39.55
2006-2007	-6.42	-0.16	-23.62	-0.85	-31.05
2007-2008	-0.67	+1.16	+5.89	-2.06	+4.32
2008-2009	-5.28	-0.14	-12.09	-3.26	-20.77
2009-2010	-4.26	-0.20	-26.07	-2.54	-33.07

Shallow groundwater storage changes in plain areas of Beijing, Tianjin, Hebei and Shanxi. The data are based on *Groundwater Bulletin of China Northern Plains (GBCNP)* issued by the Ministry of Water Resources of China.

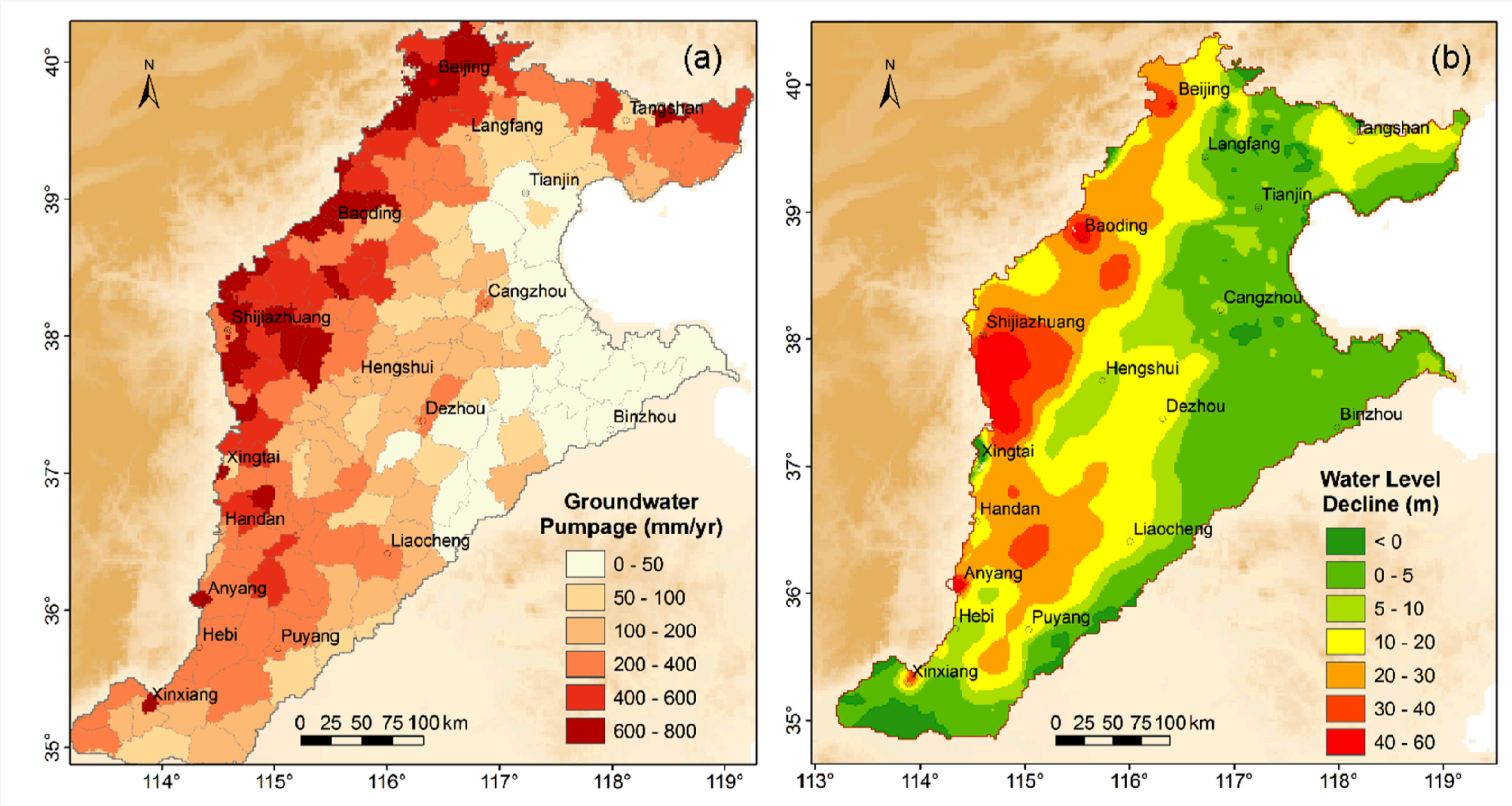
The estimate from GBCNP is about 2.5 km^3/yr, which is far smaller than our GRACE-based estimates (CSR: 8.3 ± 1.1 km^3/yr)

GRACE vs. Groundwater Bulletins

- One of the main reasons is that the estimate from GBCNP only includes the groundwater information in shallow aquifers of China northern plains.
- High groundwater depletion rate estimated by GRACE indicates the important contribution of **groundwater depletion in deep aquifers** of North China.
- Some studies show that the deep groundwater table also decreases intensively in the piedmonts of Taihang Mountains and the central plain areas of Hebei province [*World Bank*, 2001; *Foster et al.*, 2004; *Tamanyu et al*, 2009].

Groundwater storage trends in North China

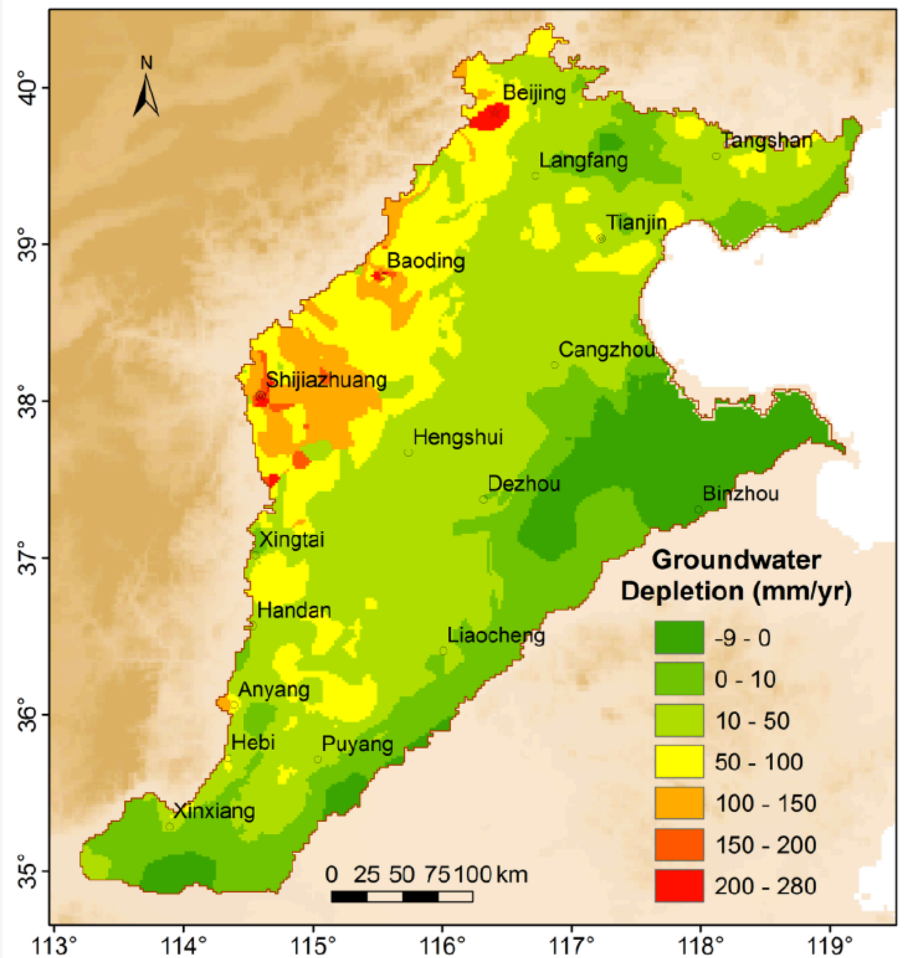
➢ **Groundwater model of North China Plain**



Spatial distribution of (a) annual groundwater withdral, i.e., pumping rate per unit area and (b) water level change over 1970 – 2008

Groundwater storage trends in North China

- Groundwater model of North China Plain

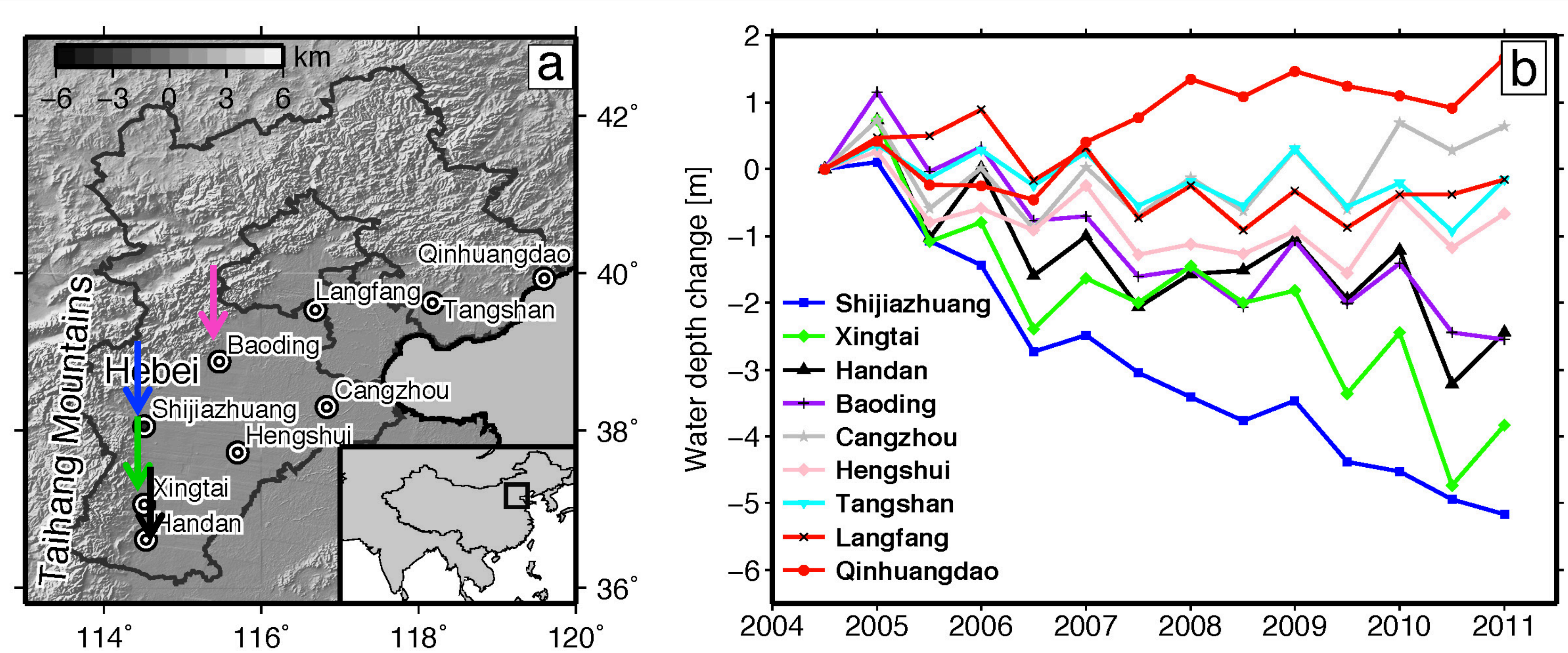


Model-derived GWS trend:
2002-2008 : **4.0** km^3/yr

GRACE-based GWS trend:
2003-2008 : **3.9** km^3/yr

Spatial distribution of average groundwater storage depletion rate estimated from the groundwater model over 1970 – 2008

Groundwater storage trends in North China



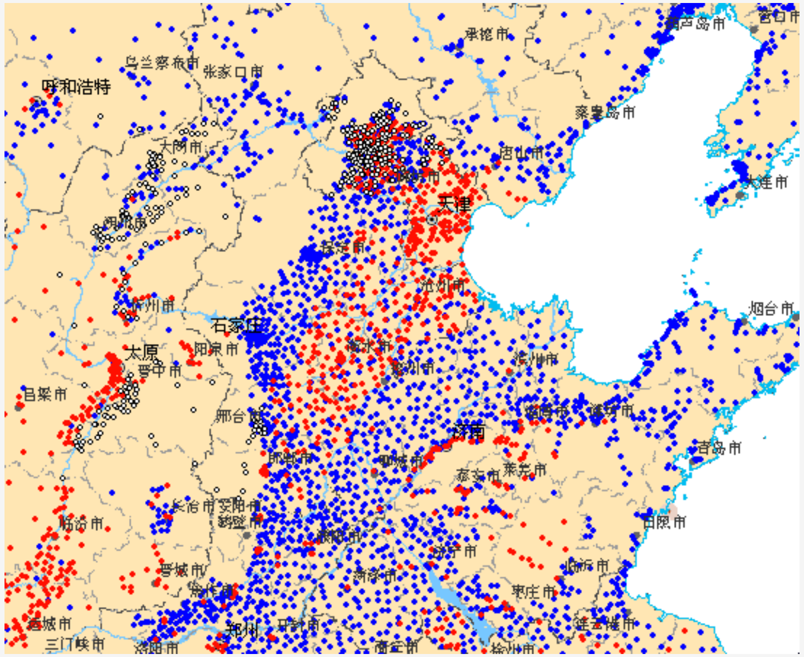
Shallow water table depth changes in nine main cities of Hebei province from 2004 to 2010 (data from Groundwater Bulletin of Hebei Plain)

Summary

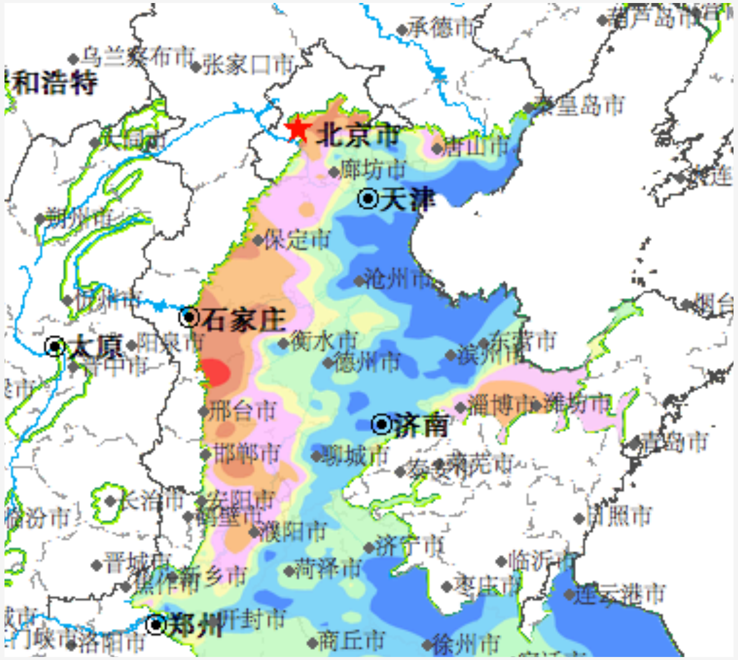
- Based on the GRACE-derived TWS and simulated SM estimates, the groundwater depletion rate in North China is 8.3 ± 1.1 km^3/yr, which is about three times higher that the official estimate from the GBCNP (2.5 km^3/yr). The study region lost approximately 50 km^3 of groundwater from 2003 to 2010, which is greater than the capacity of China's Three Gorges Dam, the largest power station in the world.
- The largest groundwater depletion is located in the piedmont regions of the Taihang Mountains.

Future work

- Groundwater model of North China (2003-2012)
- Comparison of different GRACE solutions
- Spatial and temporal variations of groundwater level changes from the monitoring network



Distribution of monitoring wells in North China



Water table depth in North China (monthly)

AGU fall meeting 2013 presentations: H51S-05, G23A-0772


Thank you!
North China Plain