Sustainable Groundwater Resources in Semiarid Regions

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SW US; Niger, Africa; Israel; Rajasthan and W. Bengal, India;
Loess Plateau and North China Plain, China;
Murray Basin, AU

Background

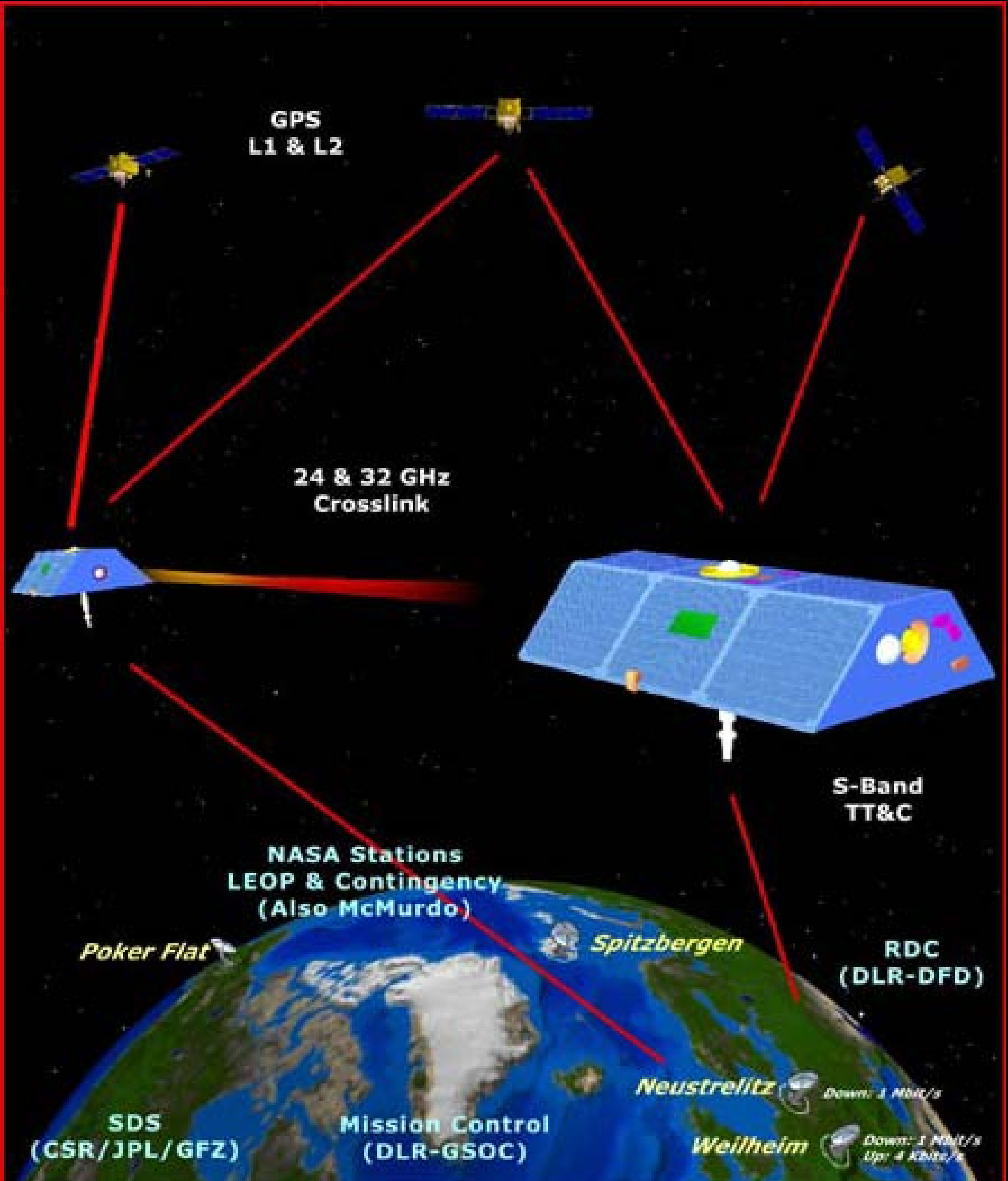
- Irrigated agriculture consumed 90% of global fresh water resources in the last century (Shiklomanov, 2000)
- Increasing emphasis on groundwater resources for irrigation e.g. irrigation North China Plain, W. India
- What techniques can we use to assess water sustainability?
- How much groundwater production is sustainable?

Results

- Land use change has large scale impacts on groundwater resources in semiarid regions
- Should be able to use land use to manage water resources
- Natural ecosystems: little or no recharge
- Natural ecosystems → rainfed agriculture, ↑ recharge
- Natural ecosystems → irrigated agriculture, variable impact. Deficit irrigation no recharge, soil salinization

Outline

- Techniques with examples from SW US
  - Remote sensing (GRACE satellite data)
  - Soil sampling (environmental tracers):
- Natural ecosystems → rainfed agriculture → irrigated agriculture
- Examples SW US, Australia, Niger, Loess Plateau
- Summary



GRACE
Gravity Recovery and Climate Expt.

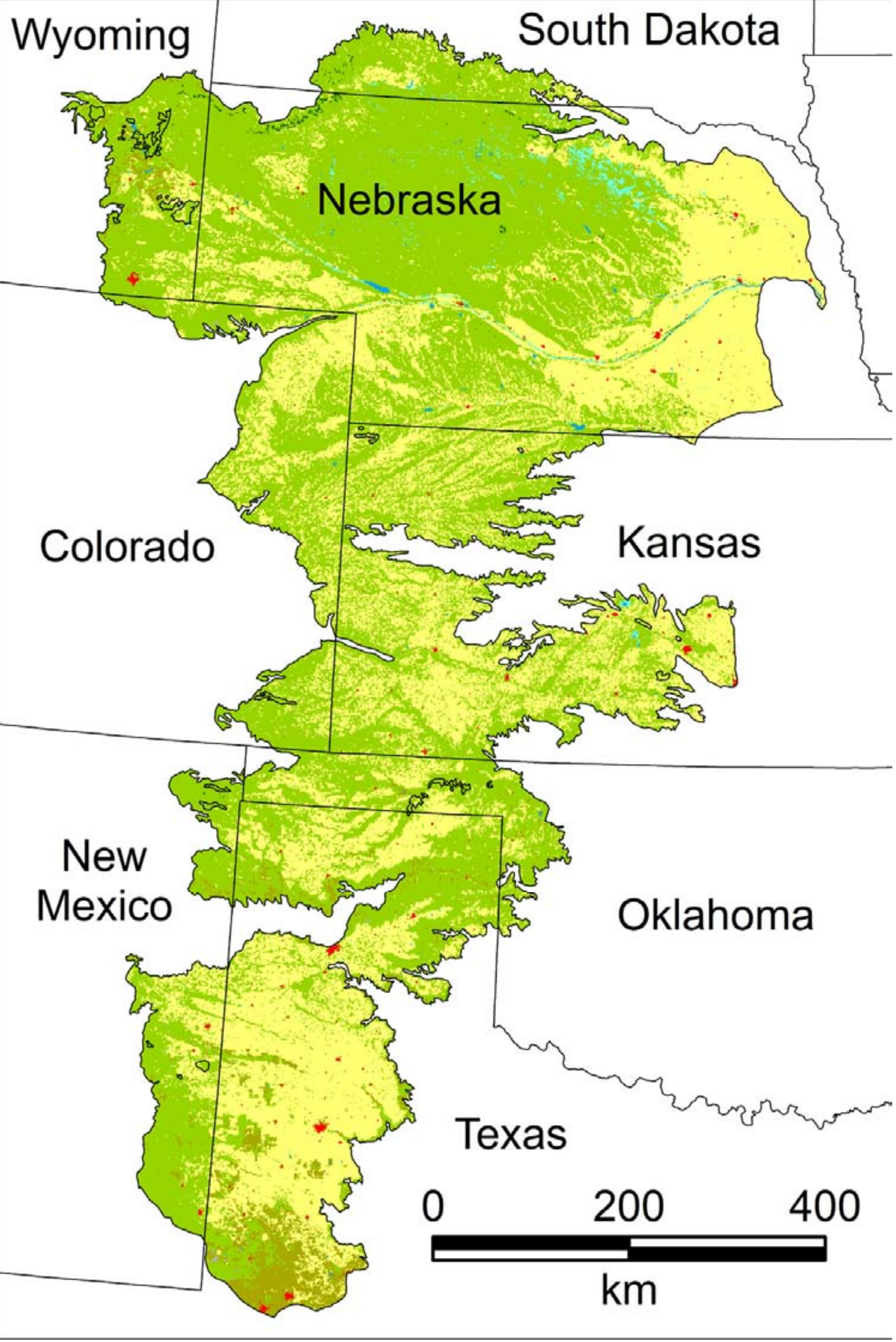
Launched March 2002

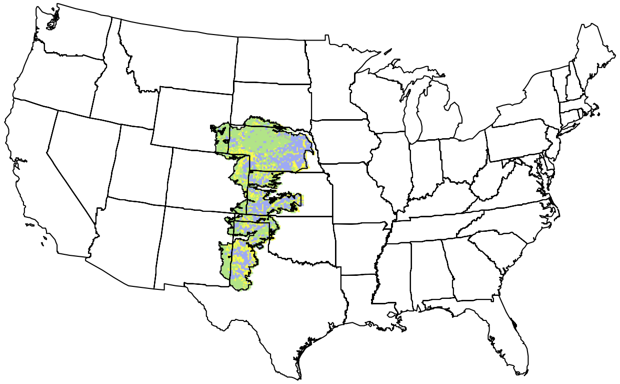
Spatial resolution:
~ 200,000 km^2
Temporal resolution:
monthly

Terrestrial water storage

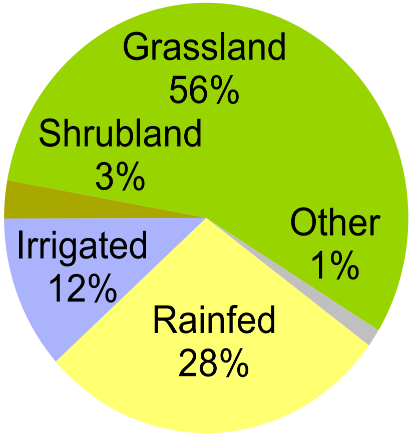
High Plains

750,000 km^2 area

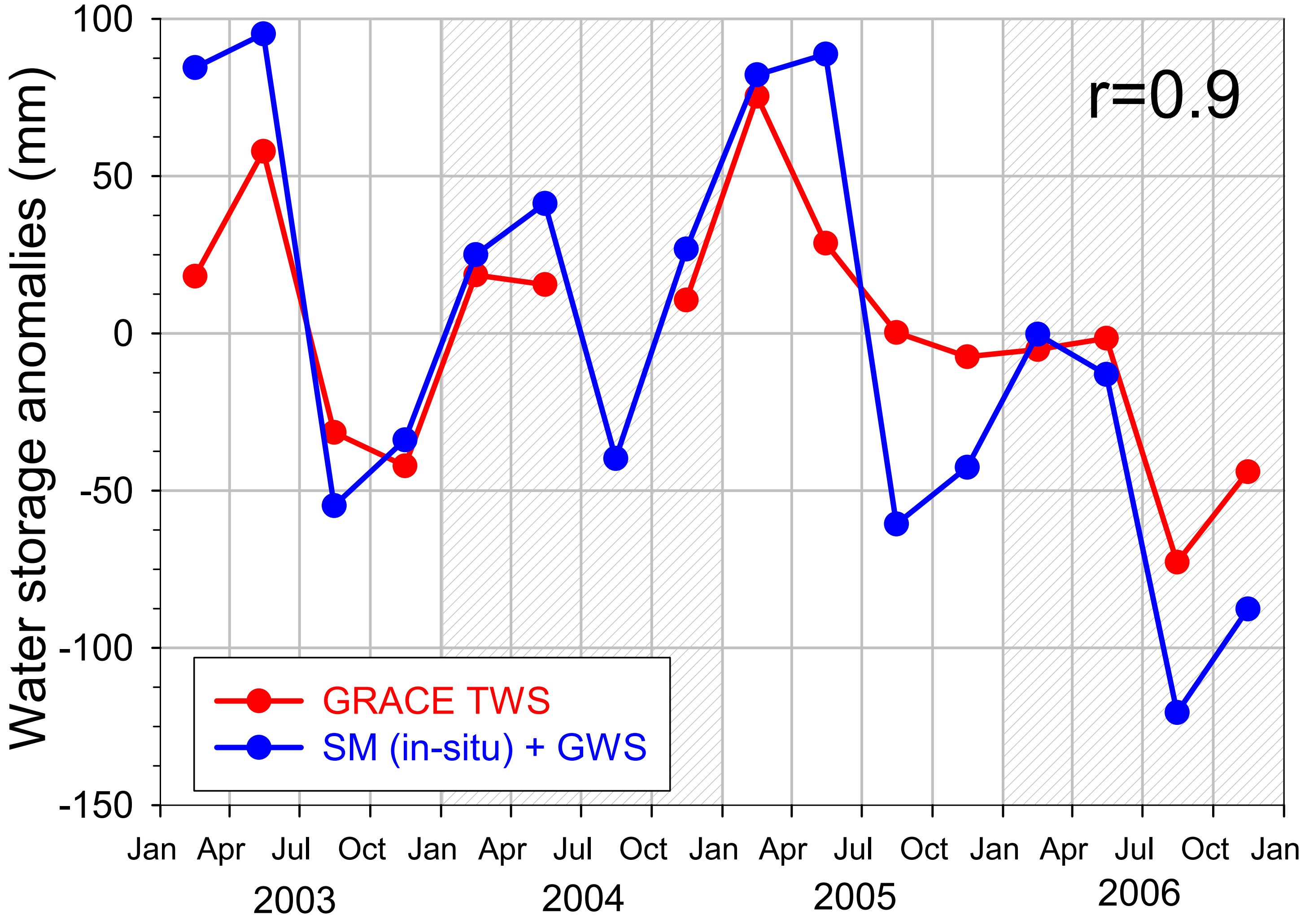




Irrigation circles (pivots)

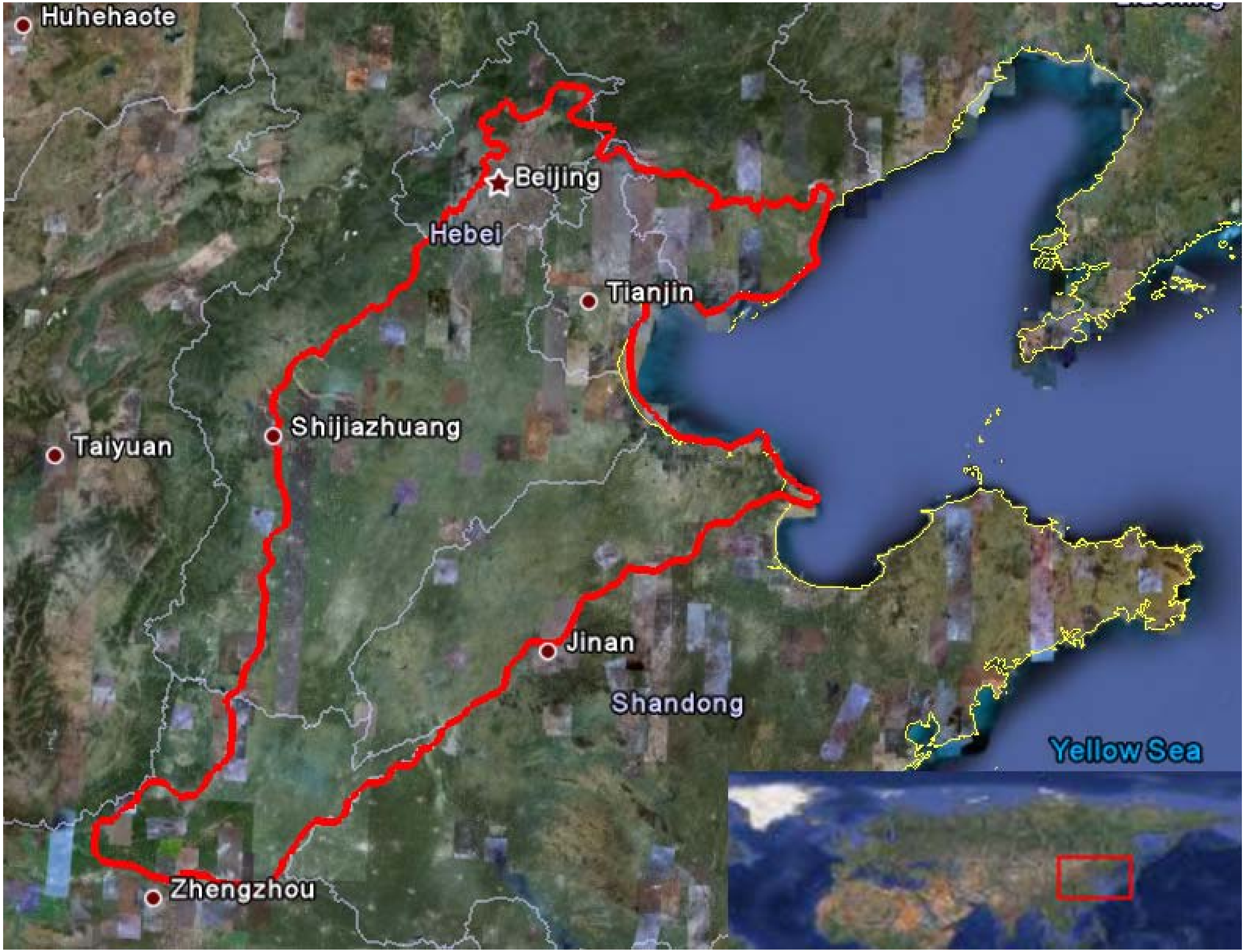


Comparison of GRACE Seasonal Terrestrial Water Storage with Measured Data



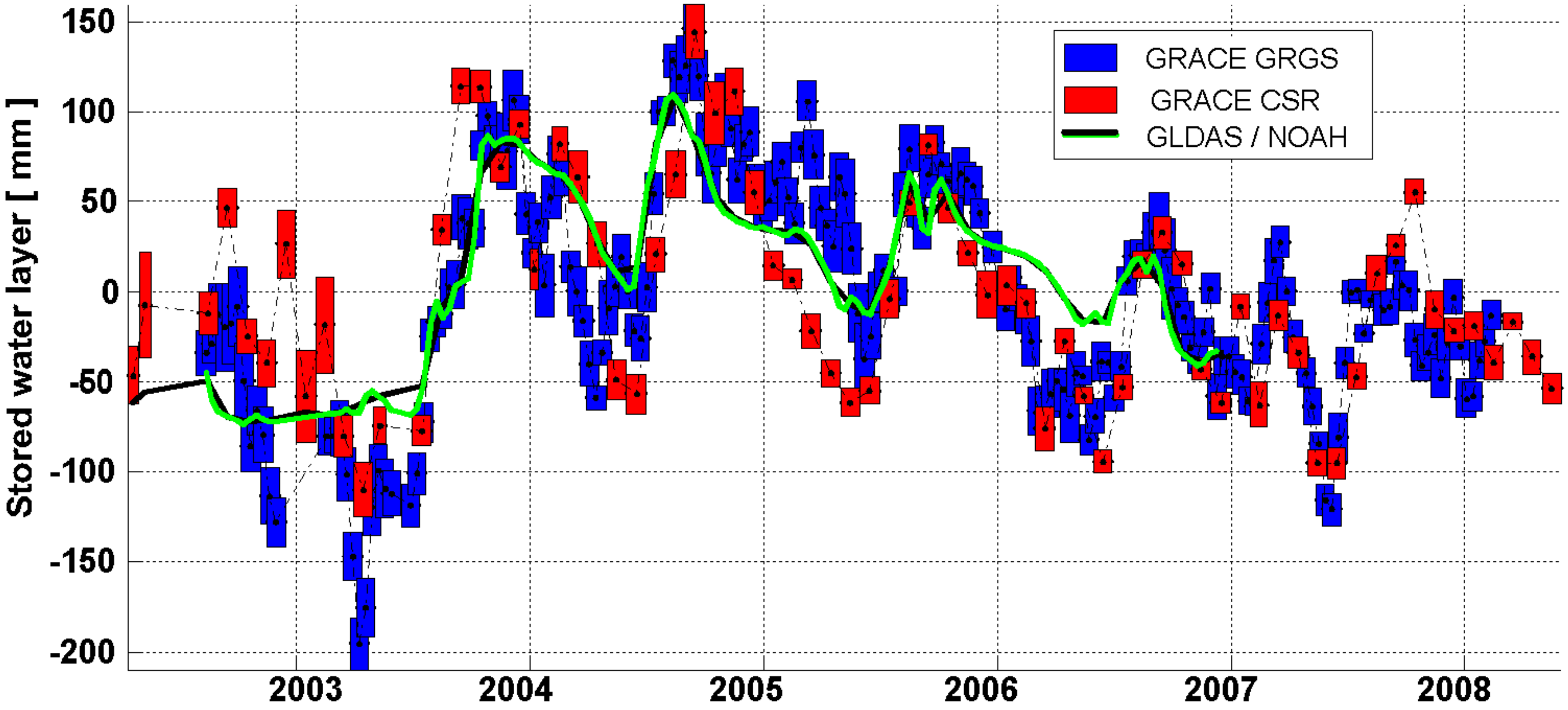
Strassberg et al., 2007

North China Plain



Laurent Longuevergne, BEG

Comparison of Water Storage from GRACE and GLDAS



GLDAS: Global Land Data Assimilation System, NOAH model
CSR: Center for Space Research, Univ. Texas Austin
GRGS: Groupe de Recherches de Geodesie Spatiale

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Recharge Estimation Using Water Balance Approaches

Precipitation – Evapotranspiration = Recharge (mm/yr)

500 mm/yr – 450 mm/yr = 50

Recharge Estimation Using Water Balance Approaches

Precipitation – Evapotranspiration = Recharge (mm/yr)

500 mm/yr – 450 mm/yr = 50

Uncertainty

500 ± 50 – 450 ± 45 = 50 ± 95

Recharge Estimation Using Water Balance Approaches

Precipitation – Evapotranspiration = Recharge (mm/yr)

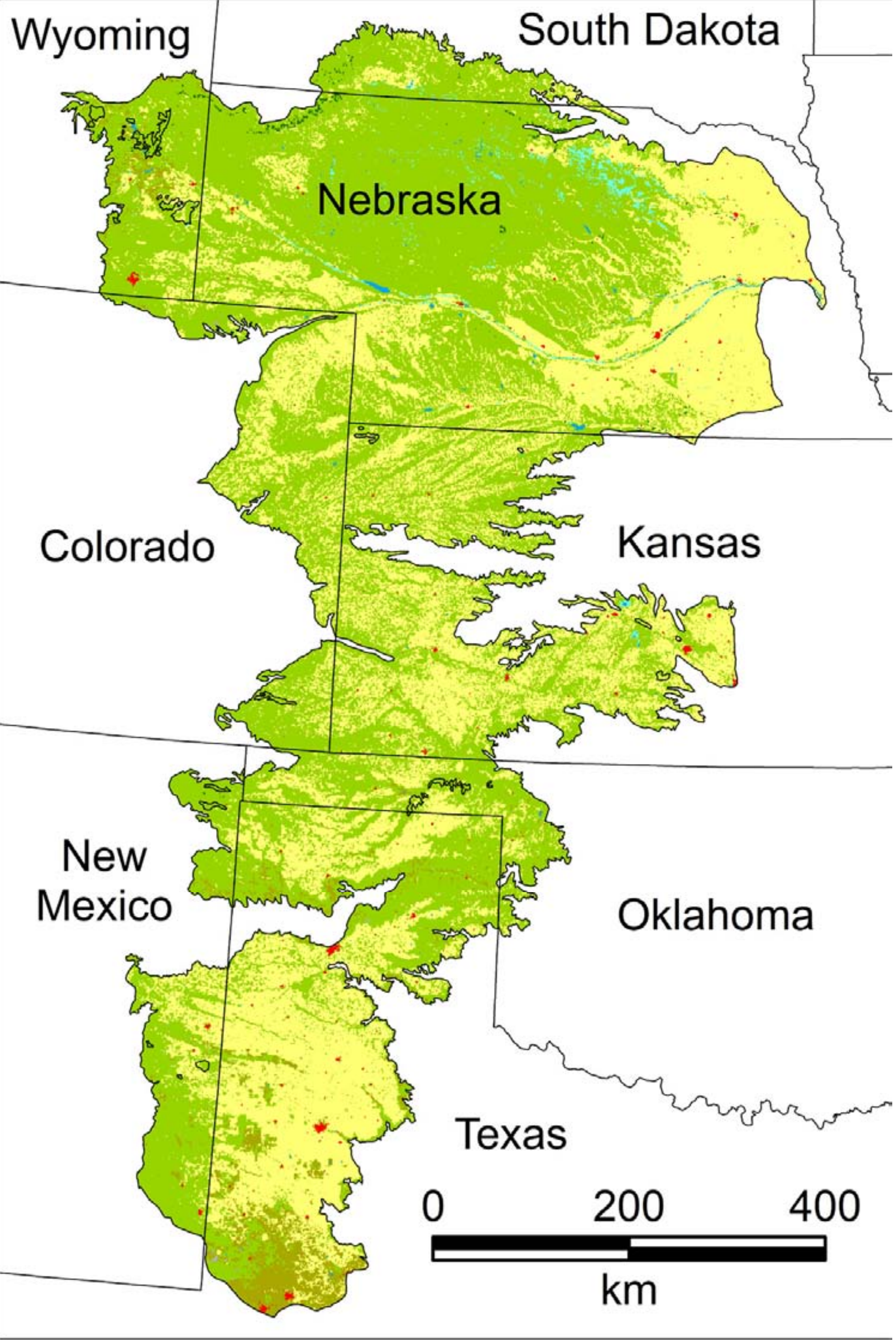
500 – 490 = 100

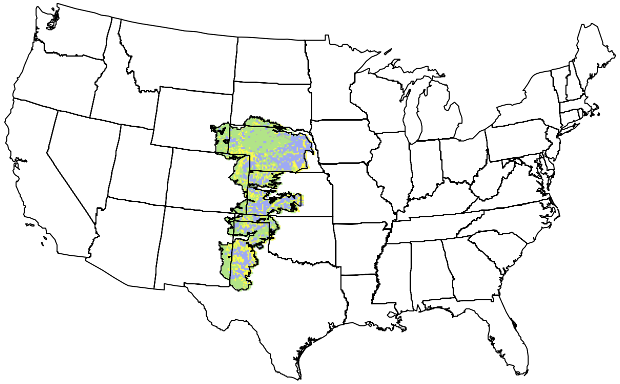
Uncertainty

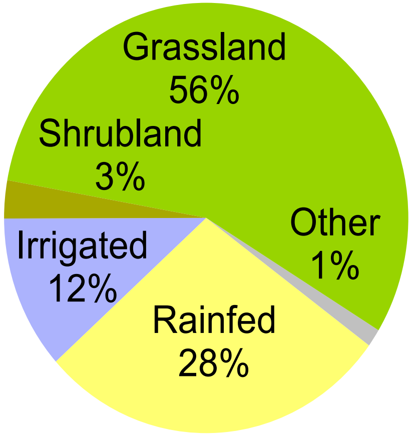
500 ± 50 – 490 ± 49 = 10 ± 100

High Plains

750,000 km^2 area

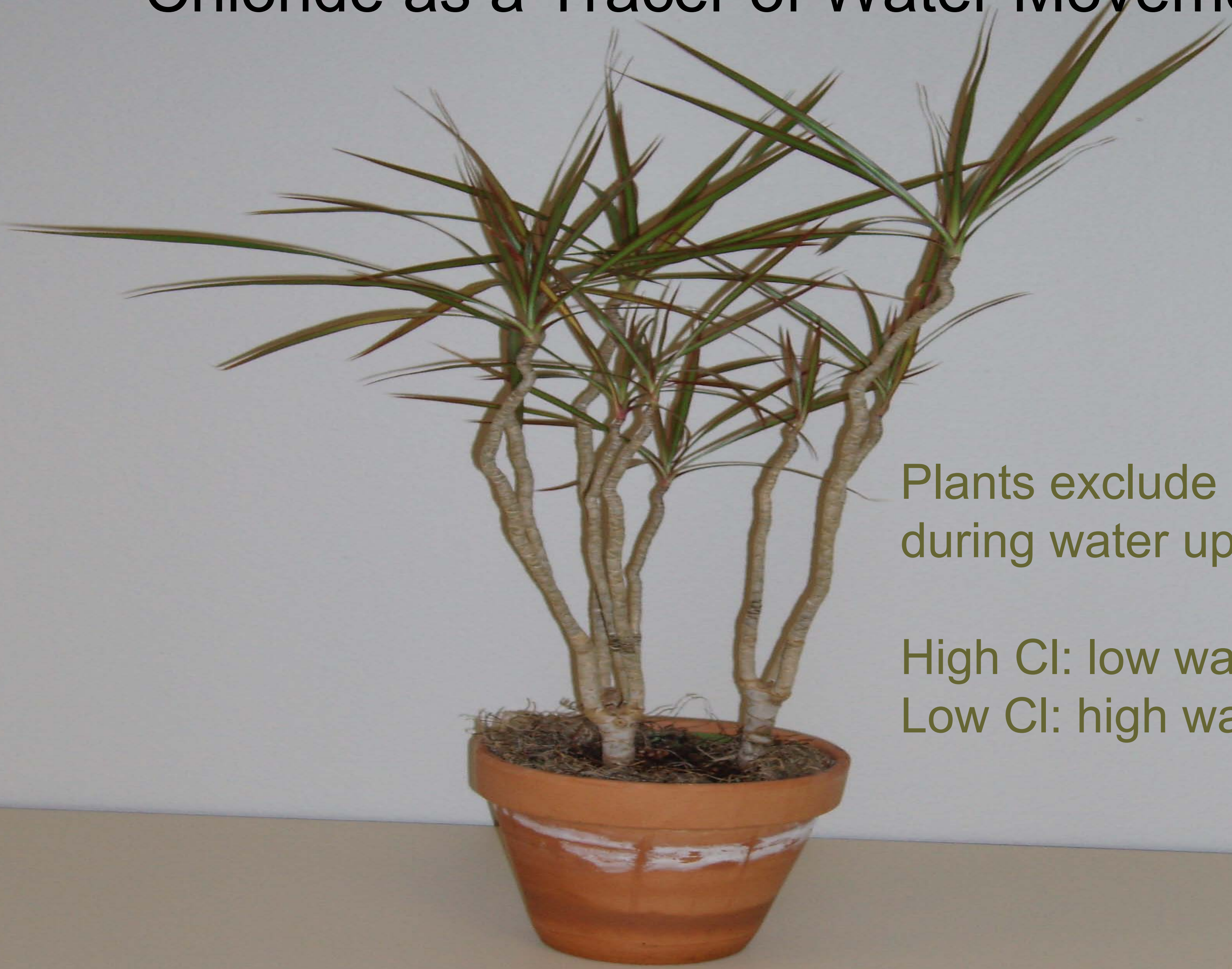






Irrigation circles (pivots)

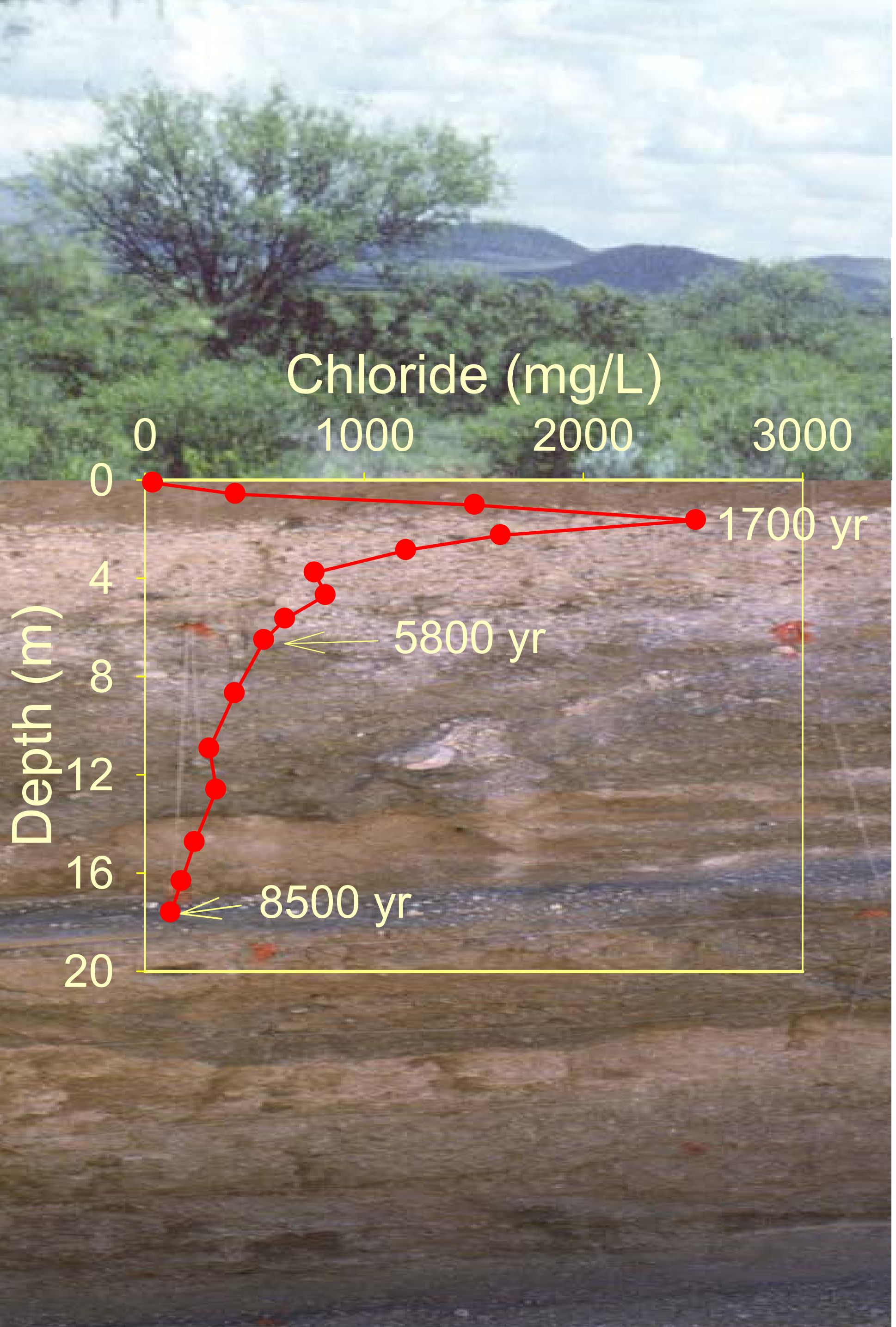
Chloride as a Tracer of Water Movement



Plants exclude chloride during water uptake

High Cl: low water flux
Low Cl: high water flux

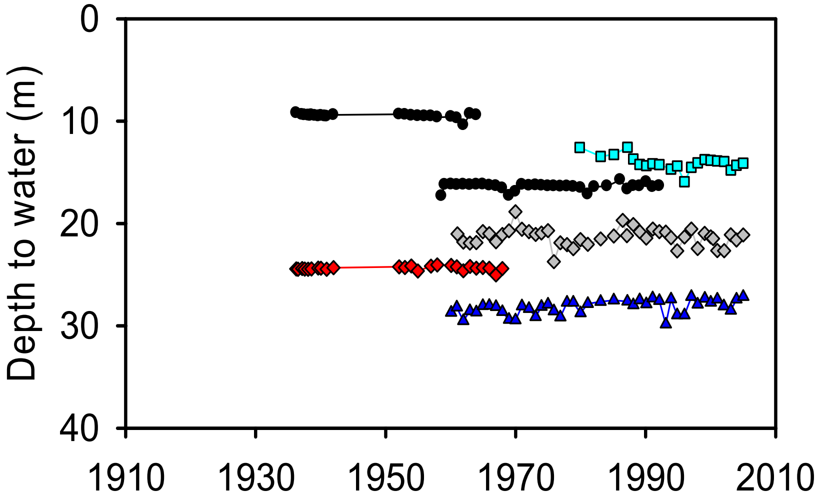
Chloride bulge shape: upward water flux



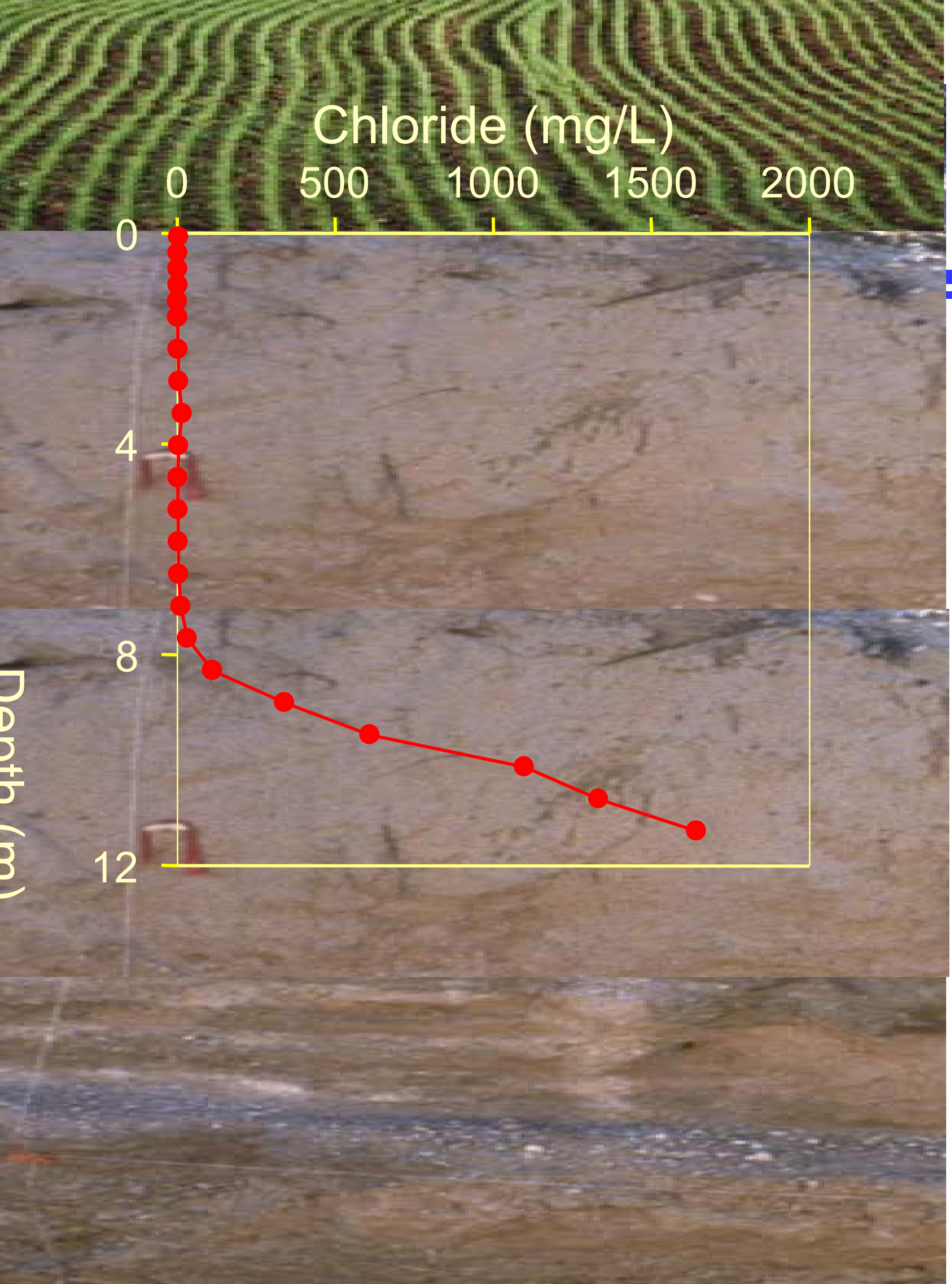
Southwestern US:
Natural vegetation,
Semiarid regions
NO RECHARGE

The only recharge is focused beneath streams and playas

Groundwater Level Hydrographs Natural Ecosystems



Chloride Profile beneath Rainfed Cropland



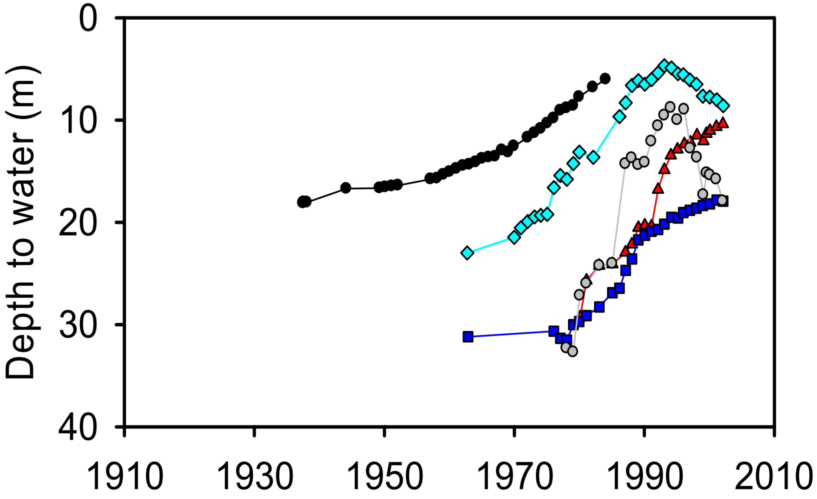
Velocity: 8 m/80 yr
=0.01 m/yr

Recharge rate: V x θ
=0.1 m/yr x 10%
=0.01 m/yr = 10 mm/yr

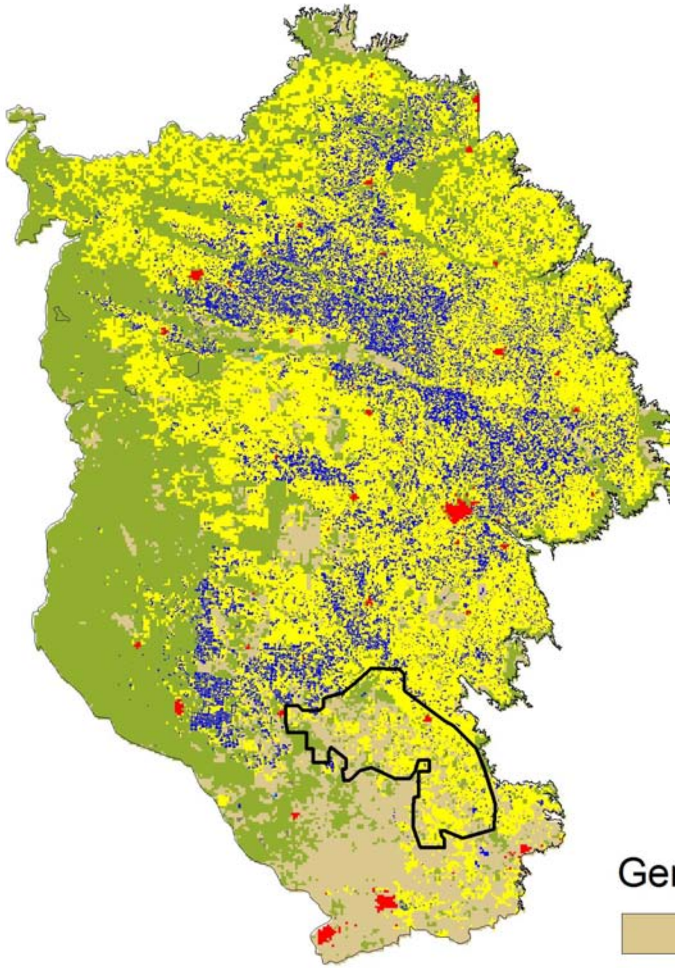
Regional average recharge
25 mm/yr
Precipitation 500 mm/yr
Recharge = 5% of precip

Scanlon et al., 2007, WRR

Groundwater Level Hydrographs
Rainfed Agriculture



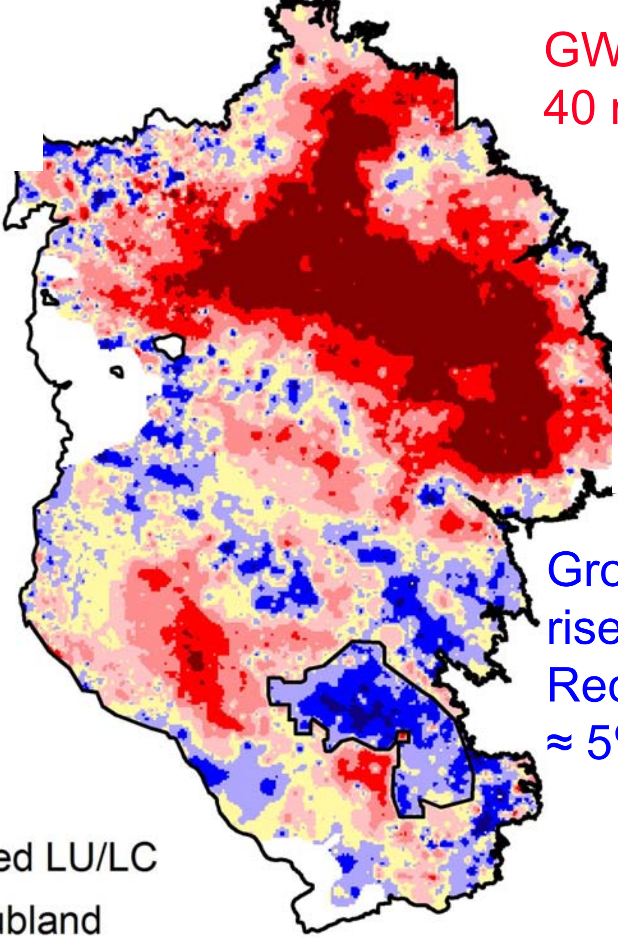
Land Use (1992)



Generalized LU/LC

- 🟫 Shrubland
- 🟩 Grasslands
- 🟨 Cultivated
- 🟦 Irrigated
- 🟥 Urban

Groundwater Level Change



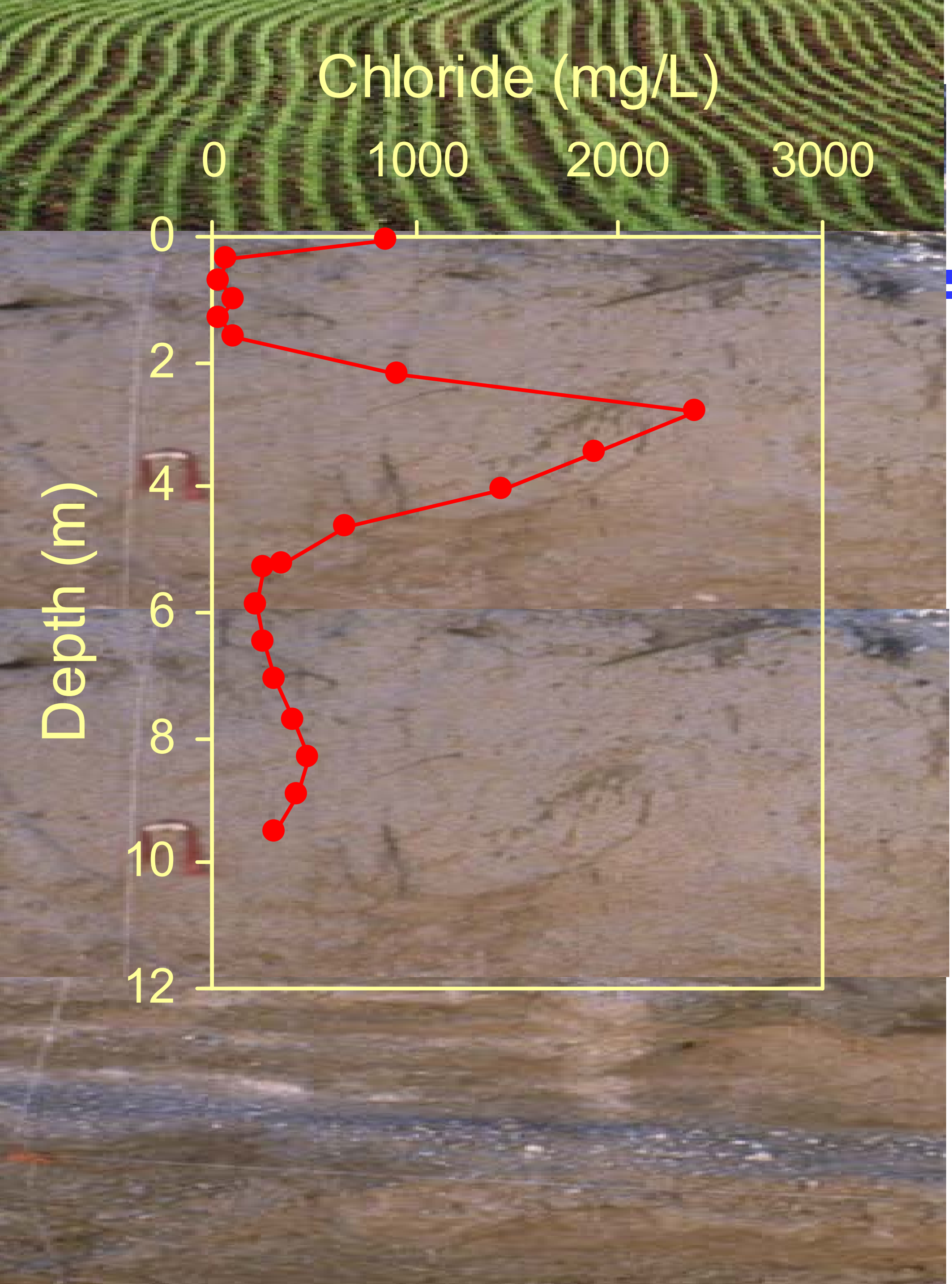
GW level decline
40 m over 10,000 km^2

Groundwater level
rise: 7 m over 3,500 km^2
Recharge ~ 24 mm/yr
≈ 5% of rainfall

Water Level Change

- ■ -76 - -30
- ■ -30 - -15
- ■ -15 - -6
- ■ -6 - -1.5
- ■ -1.5 - 1.5
- ■ 1.5 - 6
- ■ 6 - 15
- ■ 15 - 30

Chloride Profile beneath Irrigated Cropland

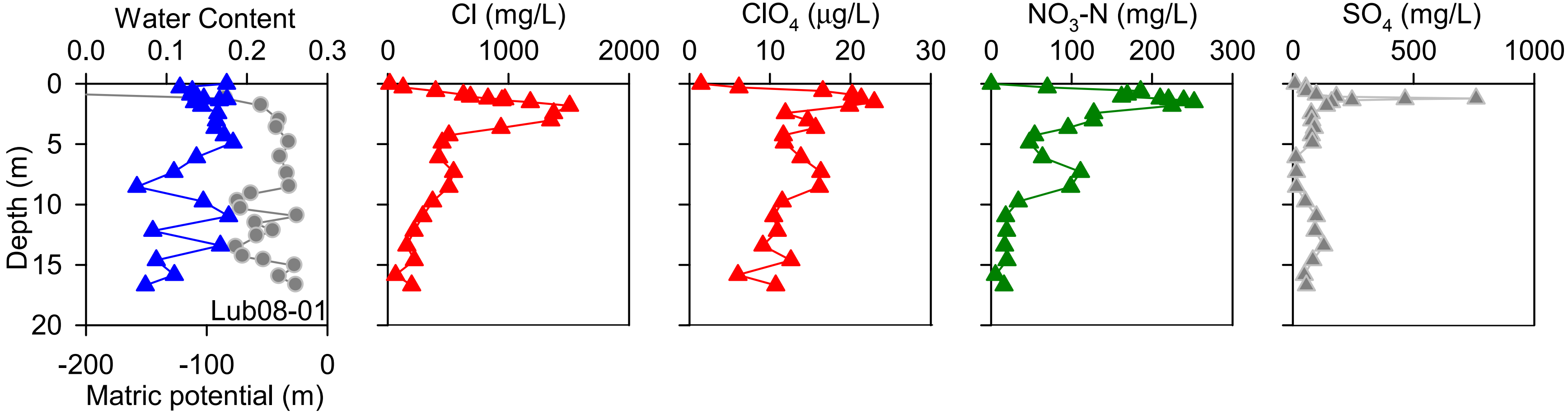


Deficit irrigation

Soil salinization

No recharge

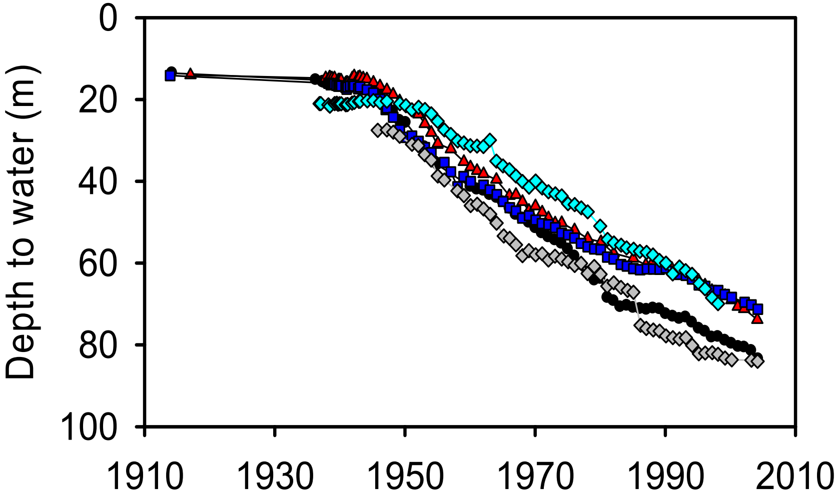
Salt Buildup under Deficit Irrigation



Chloride would require 13000 yr to accumulate if precipitation was only input.

N inventories below root zone represent 90% of total N in the profile

Groundwater Level Hydrographs
Irrigated Agriculture



Water Conservative Irrigation

- Irrigate at 75% of PET, often 0.3 m/yr of irrigation water
- 70% of precipitation in summer
- Irrigation water moderately saline (TDS 500 – 1000)
- No flushing of salts…soil salinization
- NO RECHARGE
- No reduction in irrigation pumpage because irrigate larger area
- NOT SUSTAINABLE

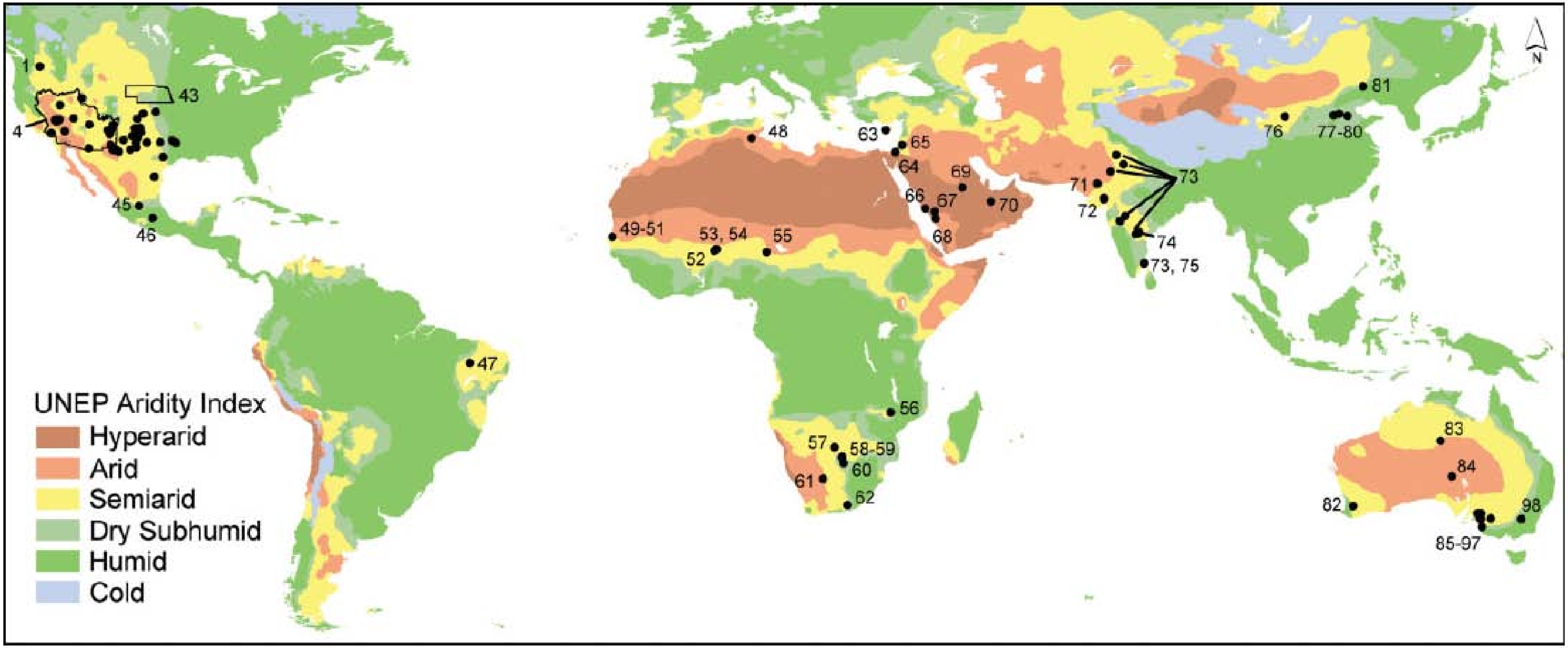
What is Sustainable in the Southern High Plains

- Rainfed agriculture: recharge 25 mm/yr
- Irrigated agriculture: currently 0 recharge
- If irrigating with 250 mm/yr,
  - could irrigate 10% of cultivated area
  - or could irrigate all cultivated area 10% of the time

Global Analysis of Sustainability Natural Ecosystems

- Little or no recharge:
- Australia
  - Murray Basin: < 0.01 mm/yr; eucalyptus, chloride accumulating 30,000 yr
- SW US:
  - 0 mm/yr; large bulge shaped chloride profiles, 10,000 – 30,000 yr accumulation
- Africa:
  - SW Niger: 2 mm/yr, 0.4 % of precipitation)
  - Senegal: sand dunes, 30 mm/yr (10% of precipitation)
- India
  - Rajasthan: sand dunes 3 - 6 mm/yr (2 – 4% of precipitation)

Global Synthesis of Groundwater Recharge in Semiarid and Arid Regions

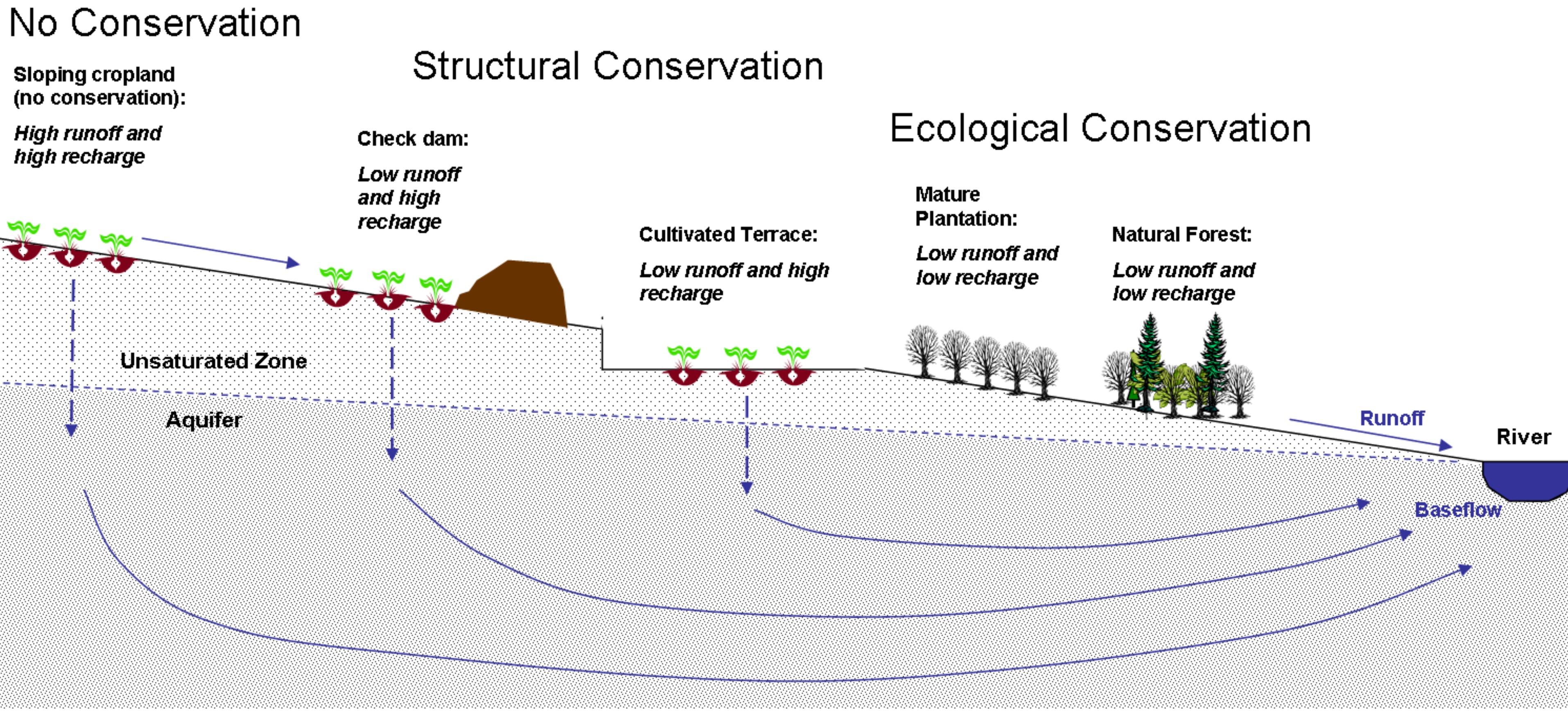


Scanlon et al., Hydrol. Proc. 2006

Natural Ecosystems → Rainfed Cropland

- Decrease ET
- Increase recharge
- SW US: 0 → 25 mm/yr; Precip. 480 mm/yr
- China: Loess Plateau; ? → 47 – 245 mm/yr; Precip. 500 mm/yr
- Australia: Murray Basin: < 0.1 → 10 mm/yr; Precip. 300 – 500 mm/yr
- Niger: 2 → 25 mm/yr; Precip. 566 mm/yr
- India: Rajasthan; 3 → 46 – 104 mm/yr; Precip. 600 mm/yr

Impact of Erosion Control on Recharge



No Conservation

Sloping cropland (no conservation):
High runoff and high recharge

Structural Conservation

Check dam:
Low runoff and high recharge

Cultivated Terrace:
Low runoff and high recharge

Ecological Conservation

Mature Plantation:
Low runoff and low recharge

Natural Forest:
Low runoff and low recharge

Recharge 100 mm/yr (median, 20% of precipitation)
Plantations: decrease recharge to 0 mm/yr → dec. runoff by 60%

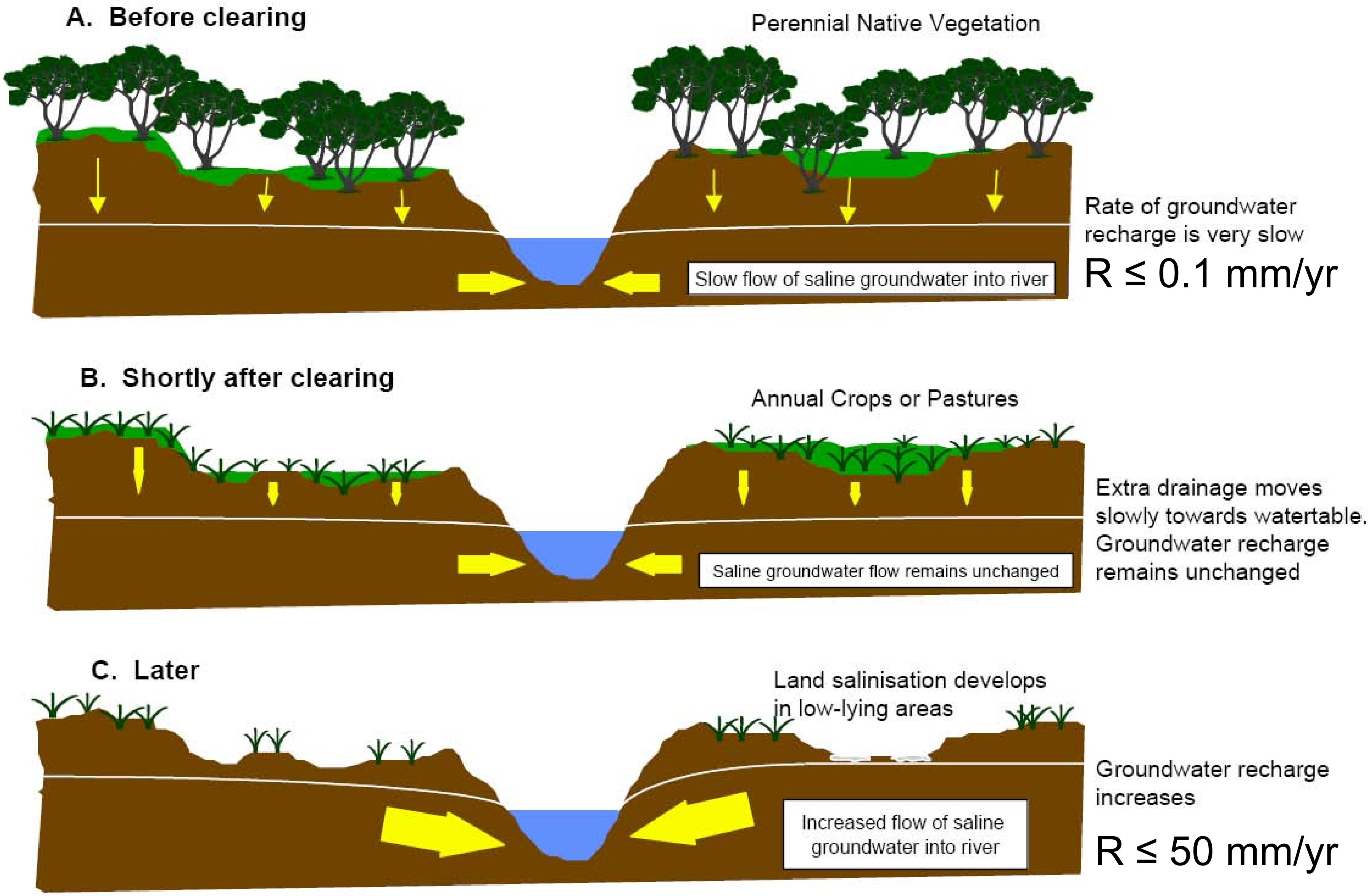
Gates, 2009

Typical Terracing, Loess Plateau

Land Clearance in Australia, Early 1900s

© CSIRO Land and Water
Photography by John Coppi

Impact of Rainfed Agriculture on Water Resources, Australia



A. Before clearing

Perennial Native Vegetation

Slow flow of saline groundwater into river

Rate of groundwater recharge is very slow

$R \leq 0.1$ mm/yr

B. Shortly after clearing

Annual Crops or Pastures

Saline groundwater flow remains unchanged

Extra drainage moves slowly towards watertable. Groundwater recharge remains unchanged

C. Later

Land salinisation develops in low-lying areas

Increased flow of saline groundwater into river

Groundwater recharge increases

$R \leq 50$ mm/yr

Cook et al., 2001, CSIRO

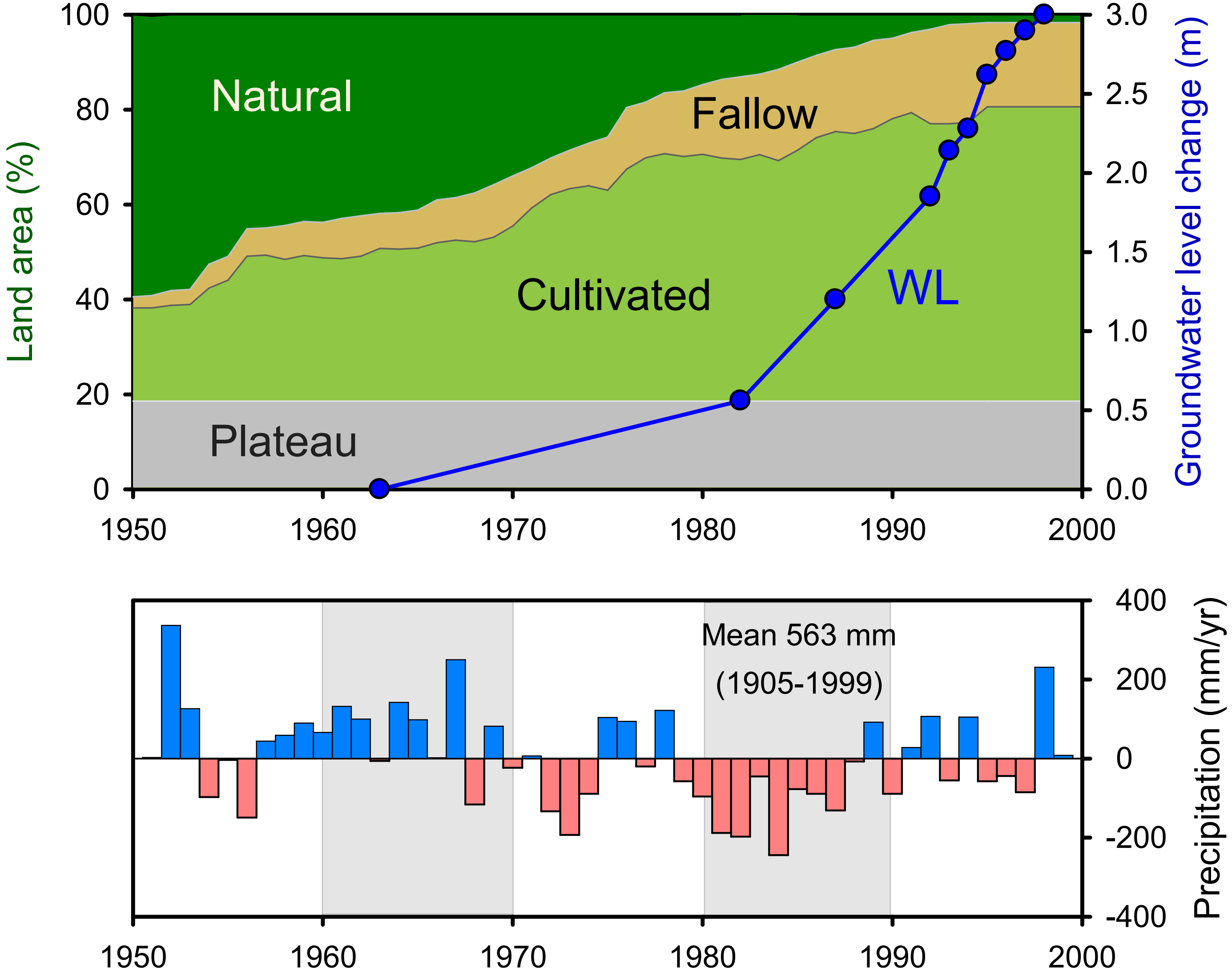
Impact of Land Use Change and Climate Variability in Water Resources in Niger

Studied since 1990s

Hapex-Sahel

Af. Monsoon Multidiscip. Analysis

Groundwater Level Rises Caused by Cultivation, Niger



Favreau et al.,
2002, GW

Sustainable Water Resources in Niger

- Savannah →millet cropland, crusting of soil, ↑runoff, focused recharge beneath ephemeral lakes
- Lot of nitrate beneath natural ecosystems, flushed into groundwater beneath lakes
- Need to do some irrigation in rainfed areas to lower the groundwater table
- Recharge 25 mm/yr, 4% of precipitation
- If irrigating with 250 mm/yr, could irrigate 10% of cultivated land or irrigate 10% of the time.
- Irrigate with high nitrate groundwater
- Use low nitrate groundwater away from ephemeral lakes for villages

Sustainable Water Resources Management

- Rainfed agriculture … not sustainable…water level rises, dryland salinity e.g. Australia, US, Niger
- Irrigated agriculture, groundwater depletion, salt accumulation
- Need to integrate rainfed and irrigated agriculture to develop sustainable water resources management
- Linkages between land use and water resources indicate that we can use land use to manage water resources

Estimate of Groundwater Storage Change, NCP from GRACE