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 $\rightarrow$ rainfed agriculture, ↑ recharge

• Natural ecosystems $\rightarrow$ 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 km²
Temporal resolution: monthly

Terrestrial water storage
High Plains
750,000 km² area

Irrigation circles (pivots)

- Grassland: 56%
- Shrubland: 3%
- Irrigated: 12%
- Rainfed: 28%
- Other: 1%

Map of the High Plains region showing the distribution of land use types.
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
Outline

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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

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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)

\[ 500 \quad - \quad 490 \quad = \quad 100 \]

Uncertainty

\[ 500 \pm 50 \quad - \quad 490 \pm 49 \quad = \quad 10 \pm 100 \]
High Plains
750,000 km² area

Irrigation circles (pivots)

- Grassland: 56%
- Irrigated: 12%
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- Shrubland: 3%
- Other: 1%

Map showing the High Plains region with a breakdown of land use and irrigation methods.
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: \( V \times \theta \)
= 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)

Groundwater Level Change

GW level decline
40 m over 10,000 km²

Groundwater level rise: 7 m over 3,500 km²
Recharge ~ 24 mm/yr
≈ 5% of rainfall
Chloride Profile beneath Irrigated Cropland

Deficit irrigation
Soil salinization
No recharge
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

Recharge 100 mm/yr (median, 20% of precipitation)
Plantations: decrease recharge to 0 mm/yr \(\rightarrow\) dec. runoff by 60%
Typical Terracing, Loess Plateau
Land Clearance in Australia, Early 1900s
Impact of Rainfed Agriculture on Water Resources, Australia

A. Before clearing

Perennial Native Vegetation

Rate of groundwater recharge is very slow

\[ R \leq 0.1 \text{ mm/yr} \]

Slow flow of saline groundwater into river

B. Shortly after clearing

Annual Crops or Pastures

Extra drainage moves slowly towards watertable.
Groundwater recharge remains unchanged

Saline groundwater flow remains unchanged

C. Later

Land salinisation develops in low-lying areas

Groundwater recharge increases

\[ R \leq 50 \text{ mm/yr} \]

Increased flow of saline groundwater into river

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

[Diagram showing groundwater level change and land area over time]
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