Comparison of Recharge Estimation Methods Used in Minnesota

by Geoffrey Delin, Richard Healy, David Lorenz, and John Nimmo

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Take-Home Messages

- High-quality, long-term, continuous hydrologic and climatic data are important for accurate recharge estimation
- Use of multiple recharge estimation methods is beneficial
- Local and basin-scale recharge estimates can be regionalized using the regional regression recharge (RRR) model
- RRR map provides regional estimates for uses such as initial ground-water flow model calibration

USGS Study Objectives

- Quantify recharge to surficial materials in Minnesota:
  - (a) using multiple methods,
  - (b) representing different time and spatial scales
- Compare results of the methods
- Attempt to regionalize the site-specific or basin-scale estimates

Recharge Estimation Methods Used

Site-Specific Methods

- Unsaturated-zone water balance (UZWB)
- Water-table fluctuation (WTF)
- Age dating of ground water

Basin-scale Method

- RORA analysis of streamflow records using a recession-curve displacement technique

Other Methods Used to Estimate Recharge in Humid Regions

Local-Scale Methods

- Lysimeters (unsaturated zone)
- Chloride, isotopic, and environmental tracers
- Applied tracers
- Darcy flux (using Darcy's Law)
- Seepage meters
- Water-balance equations
- Numerical modeling

Basin-Scale and Regional Methods

- Streamflow hydrograph separation (baseflow)
- Water-balance equations
- Numerical modeling
- GIS techniques
- Remote sensing techniques

Scanlon et al. (2002)

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Unsaturated-Zone Water Balance (UZWB) Method

Spatial scale: *1 m^2*

Temporal scale: *Event based / seasonal*

Temporal variability in recharge

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Unsaturated-Zone Water Balance Method Assumptions

- Based on premise that soil water moves upward in response to ET above a boundary in the unsaturated zone and that
- Water below that depth moves downward to the water table as a result of each recharge period

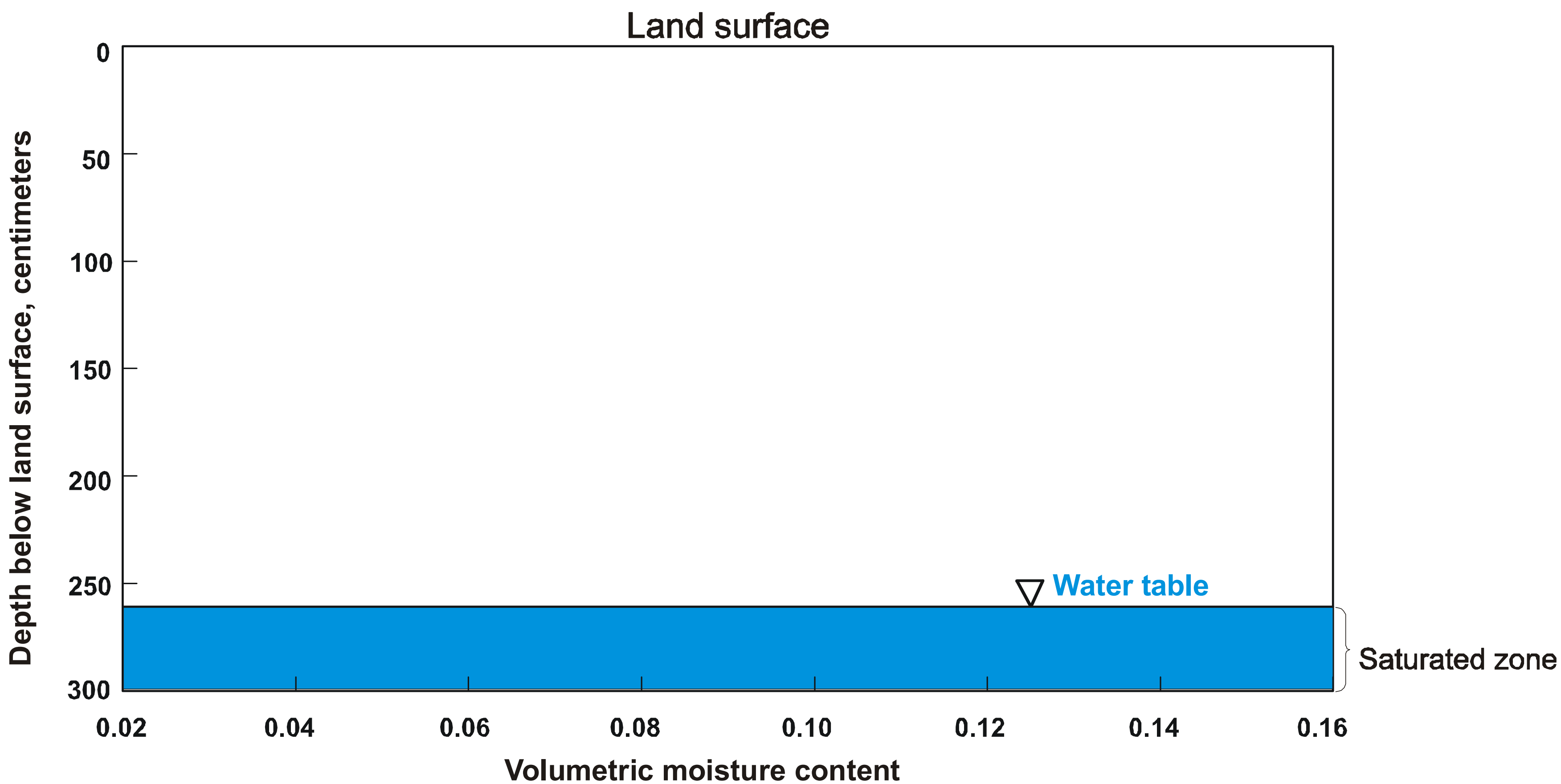
Delin and Herkelrath (2005)

USGS

UZWB Equipment Needs

- **Soil moisture and soil tension measured hourly at multiple depths in the unsaturated zone**

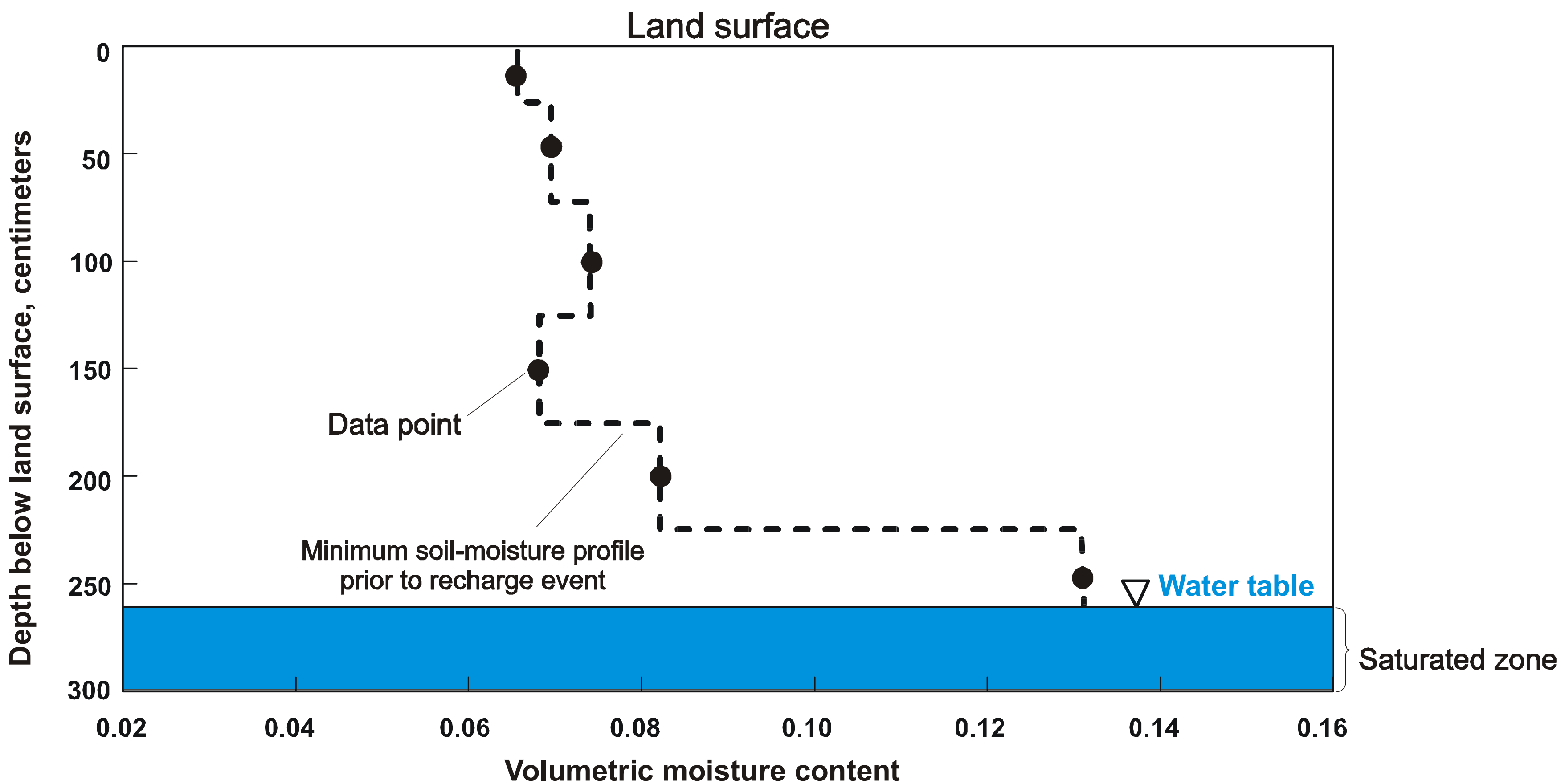
Unsaturated-Zone Water Balance



Conceptualized diagram

USGS

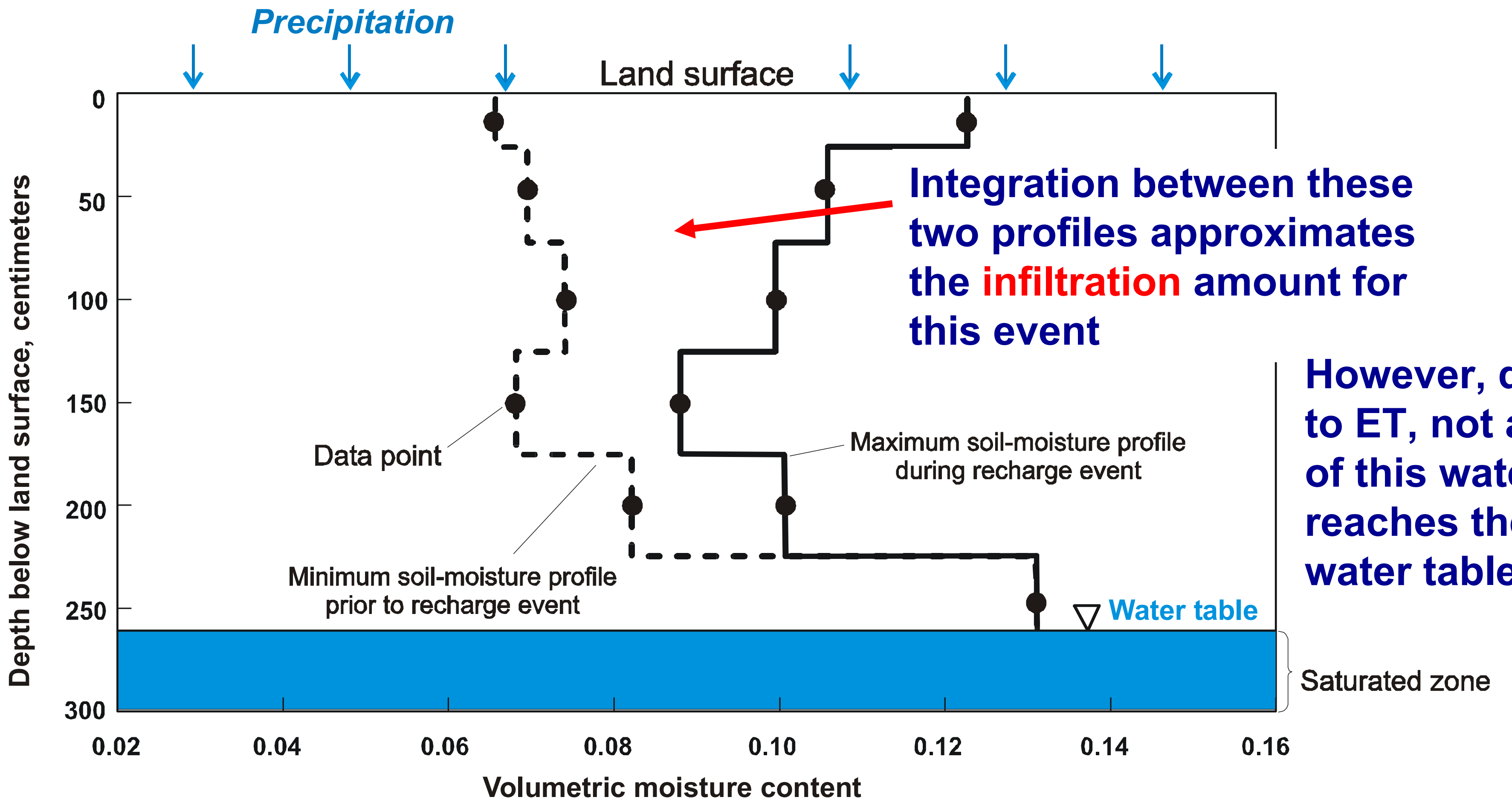
Unsaturated-Zone Water Balance



Conceptualized diagram

USGS

Unsaturated-Zone Water Balance



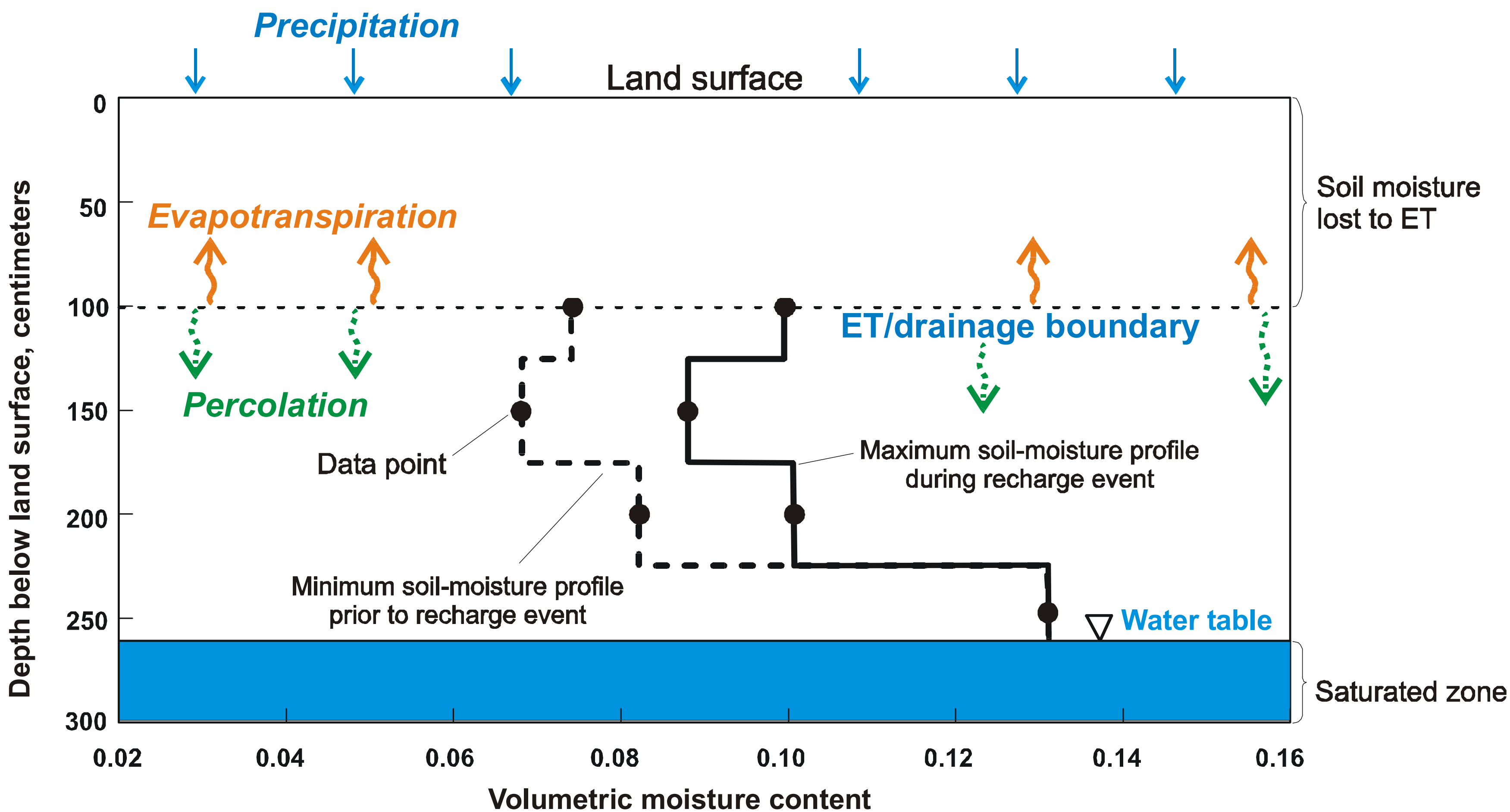
Integration between these two profiles approximates the infiltration amount for this event

However, due to ET, not all of this water reaches the water table

Conceptualized diagram

USGS

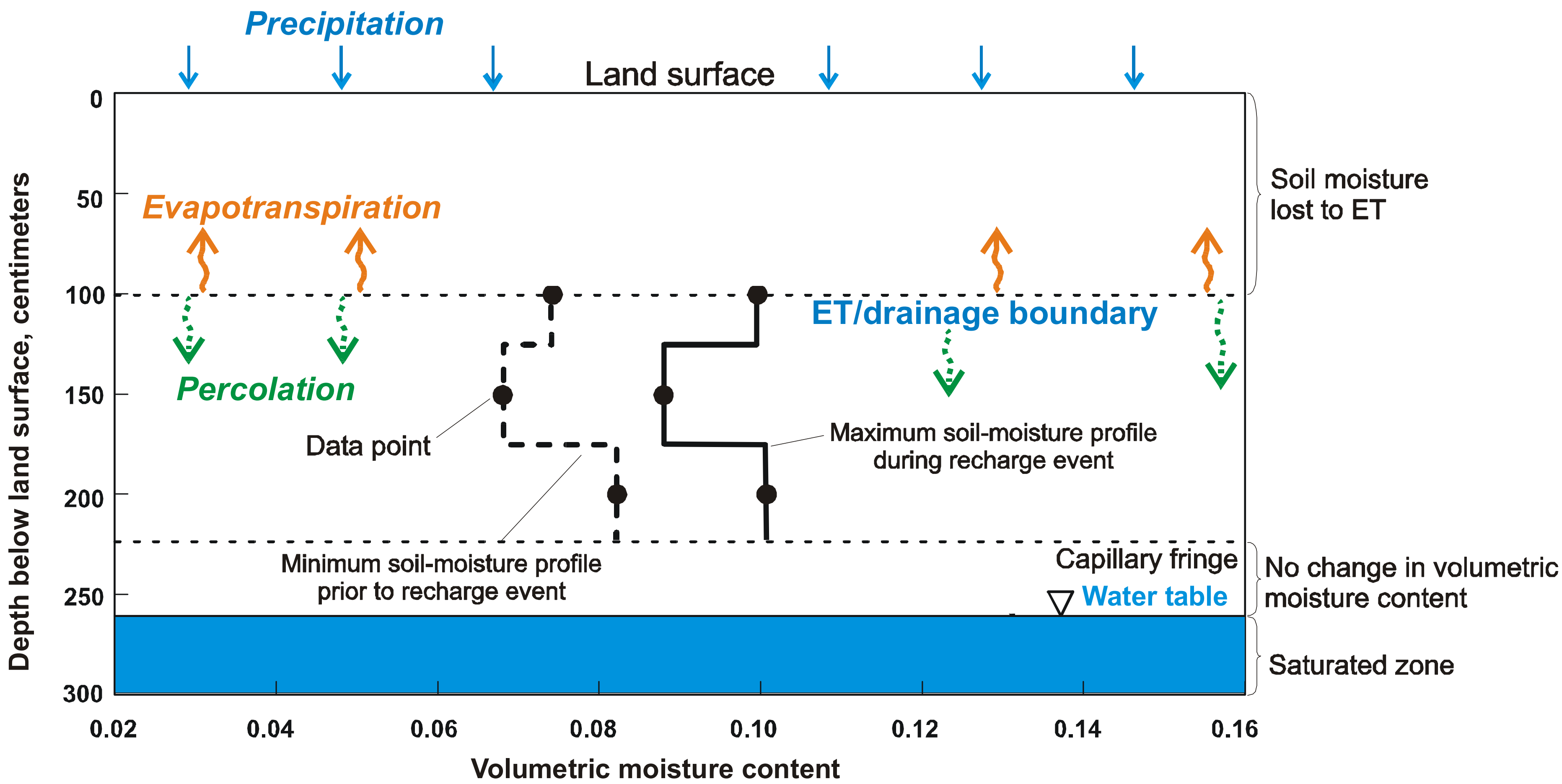
Unsaturated-Zone Water Balance



Conceptualized diagram

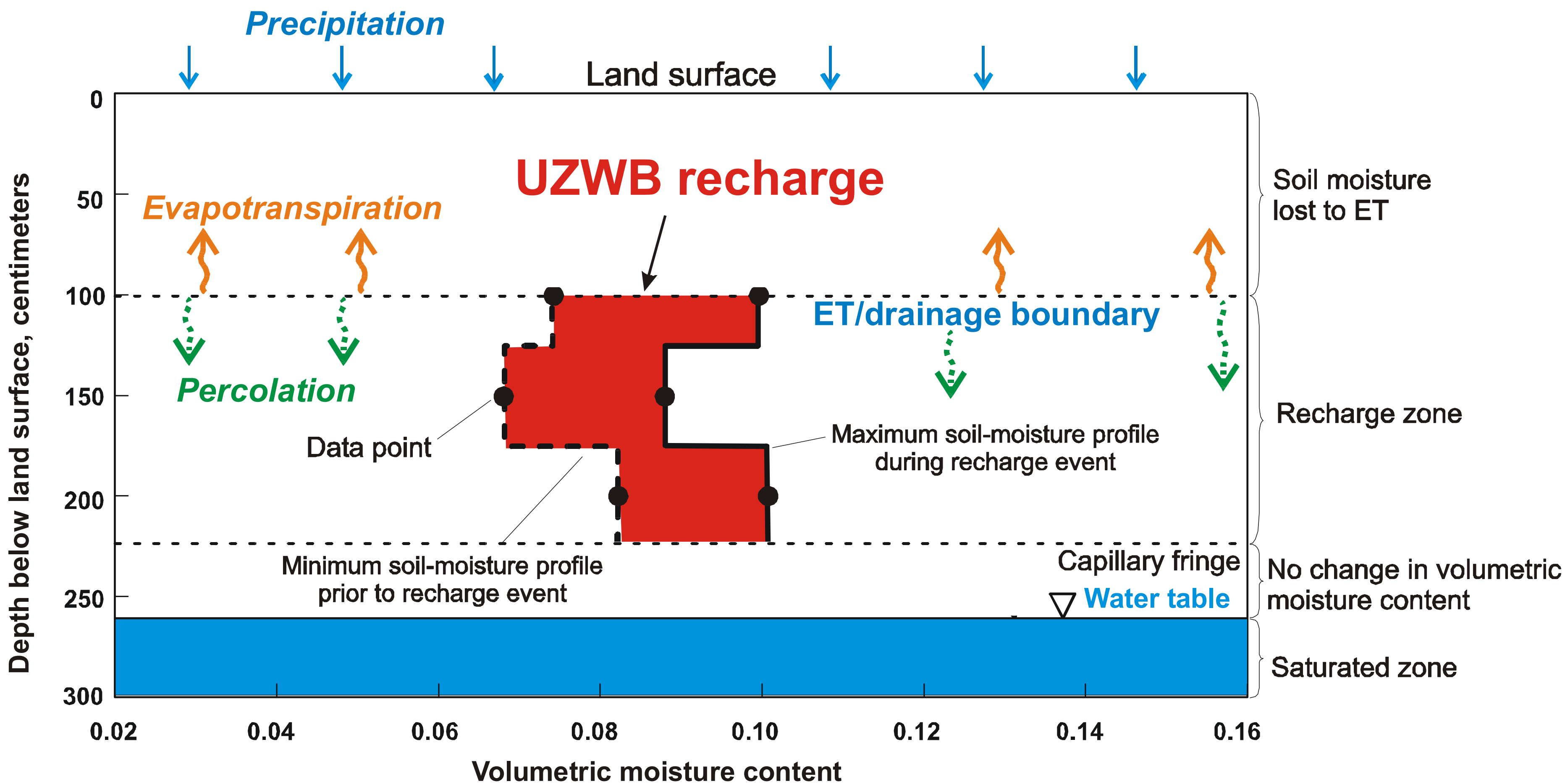
USGS

Unsaturated-Zone Water Balance



Conceptualized diagram

Unsaturated-Zone Water Balance



Conceptualized diagram

USGS

Limitations of UZWB Method

- Small scale of influence
- Intensive collection of soil-moisture and soil-pressure data is required
- Probes installed in wall of trench

Delin and Herkelrath (2005)

USGS

Water-Table Fluctuation (WTF) Method

Spatial scale*:** ***1 to 100s m^2

Temporal scale*: *Event based / seasonal

Temporal variability in recharge

WTF Method Assumptions

Based on premise that rises in ground-water levels in unconfined aquifers are due to recharge, calculated as:

Recharge = $Sy \times (dh_t)$

where Sy = specific yield,

dh_t = water-level rise (difference between peak rise and low point of extrapolated recession curve at the time of the peak)

Healy and Cook (2002)

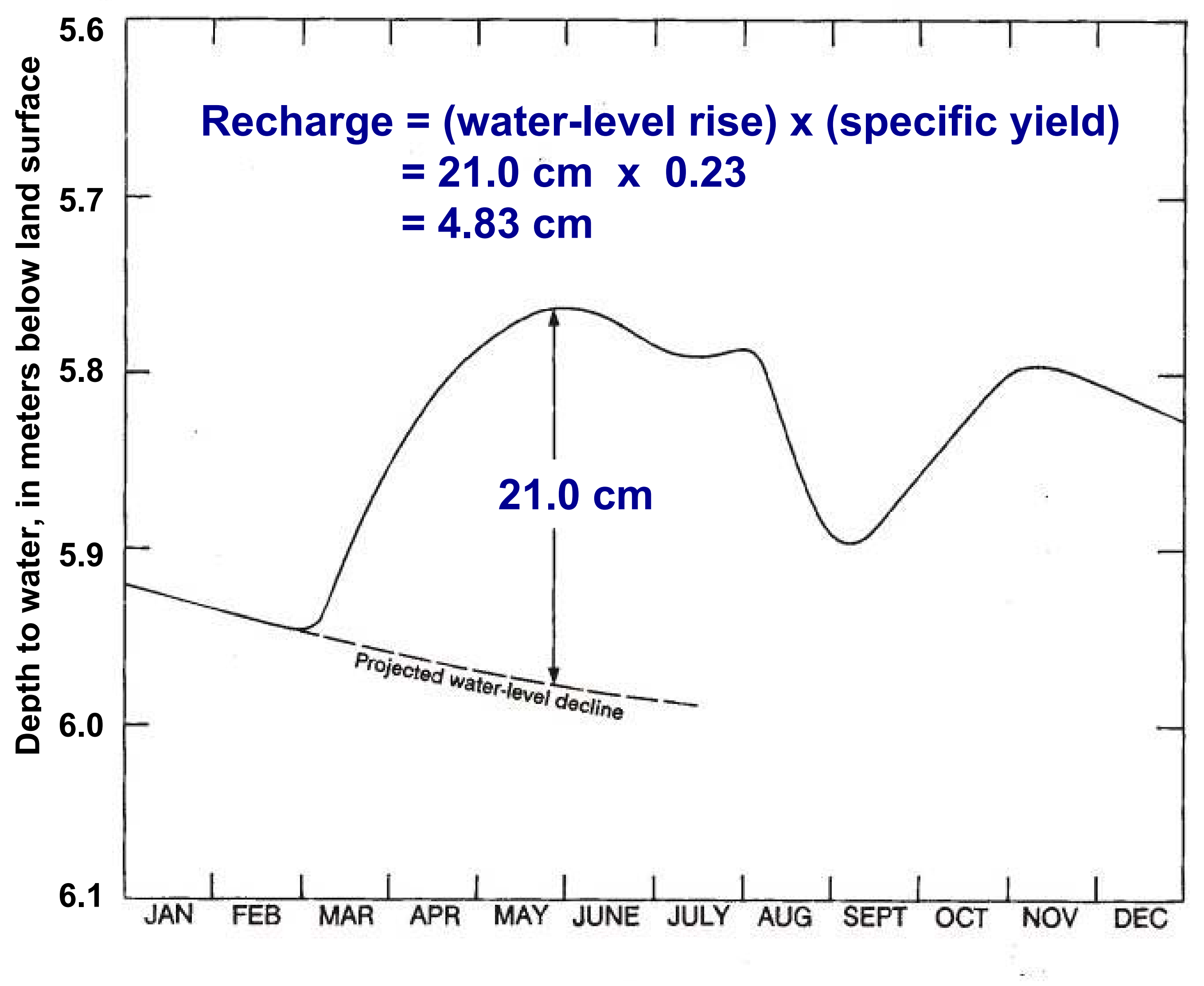
USGS

Three Approaches Used to Estimate dh_t for WTF Method

- Graphical extrapolation (manual)
- Master Recession Curve (MRC) (automated)
- RISE program (Rutledge, 2003)
  [does not account for hypothetical recession]

Delin et al. (2007)

Graphical Approach to Estimate dh_t



This approach involves more subjectivity than the other WTF approaches.

Different users would produce different results.

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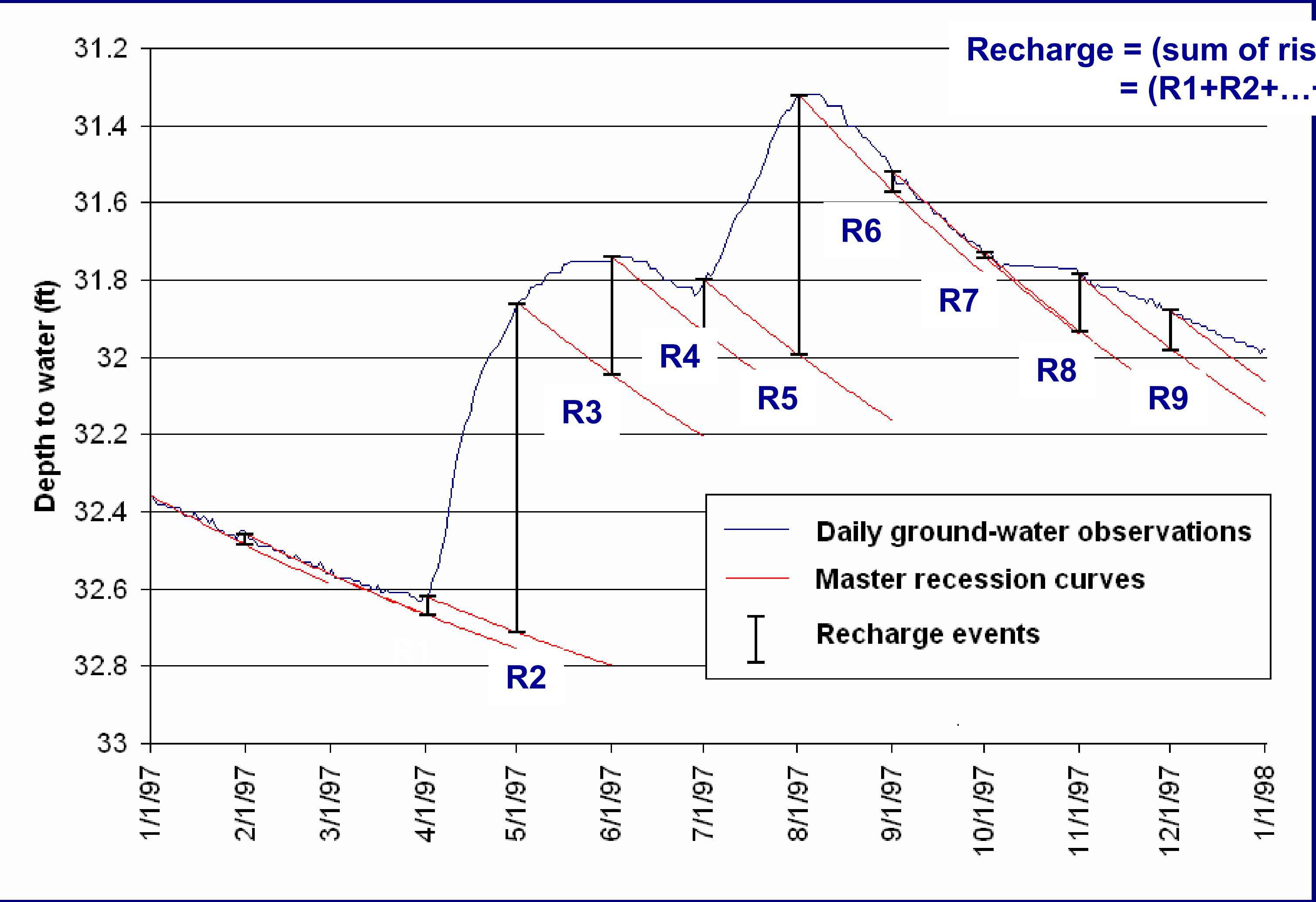
Example graph from Delin (1990)

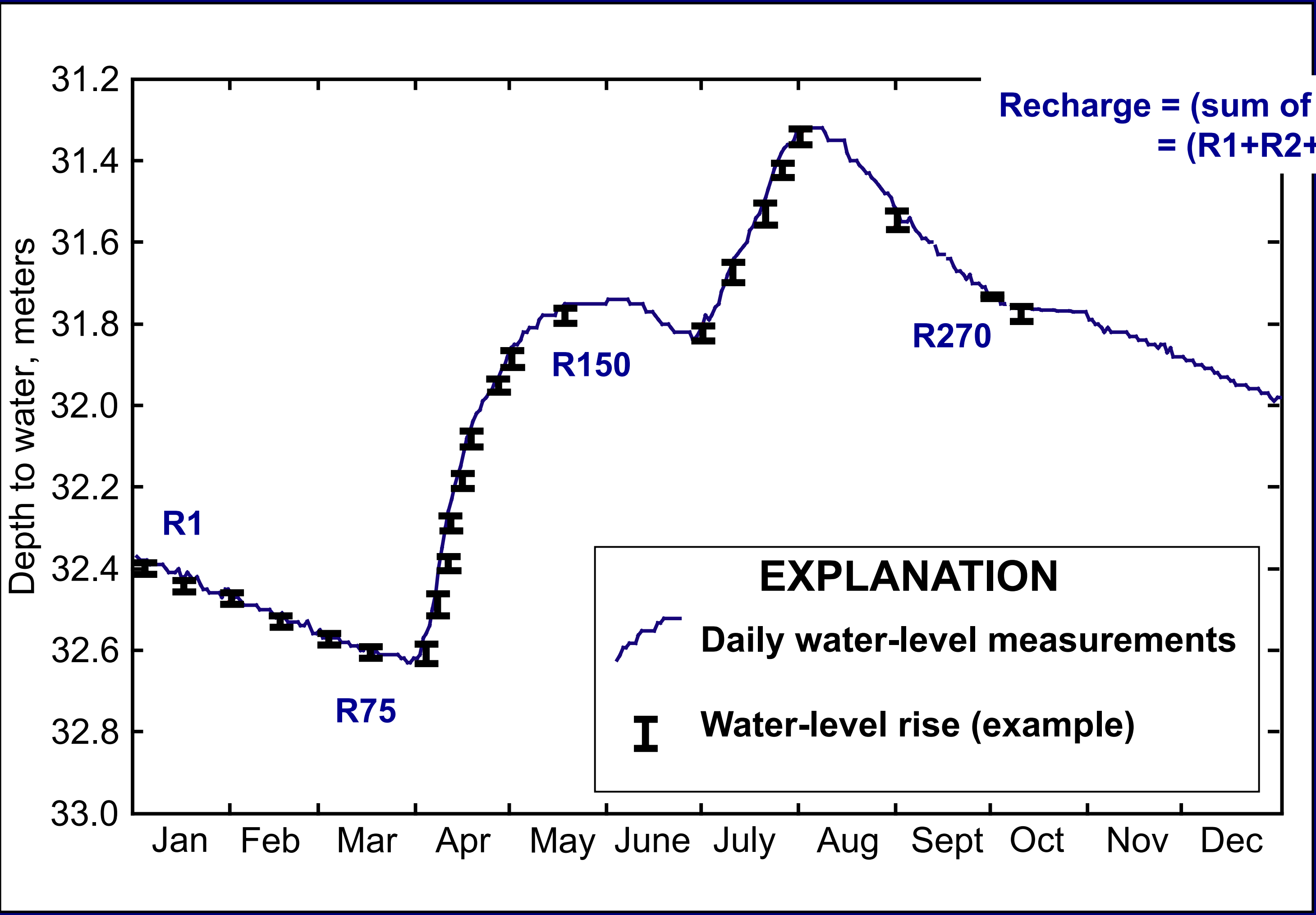
Master Recession Curve Approach



This approach: **involves multiple steps;** easy to apply; **avoids subjectivity;** but may include rises unrelated to recharge

Delin et al. (2007)

RISE Program Approach to Estimating *dh*$_t$



Recharge = (sum of rises) x (specific yield)
= ($R1+R2+\ldots+R_n$) x *Sy*

This approach:
simple,
avoids subjectivity;
easy to apply;
but makes no allowance for hydrograph recession

Al Rutledge, USGS, electronic communication, 2003

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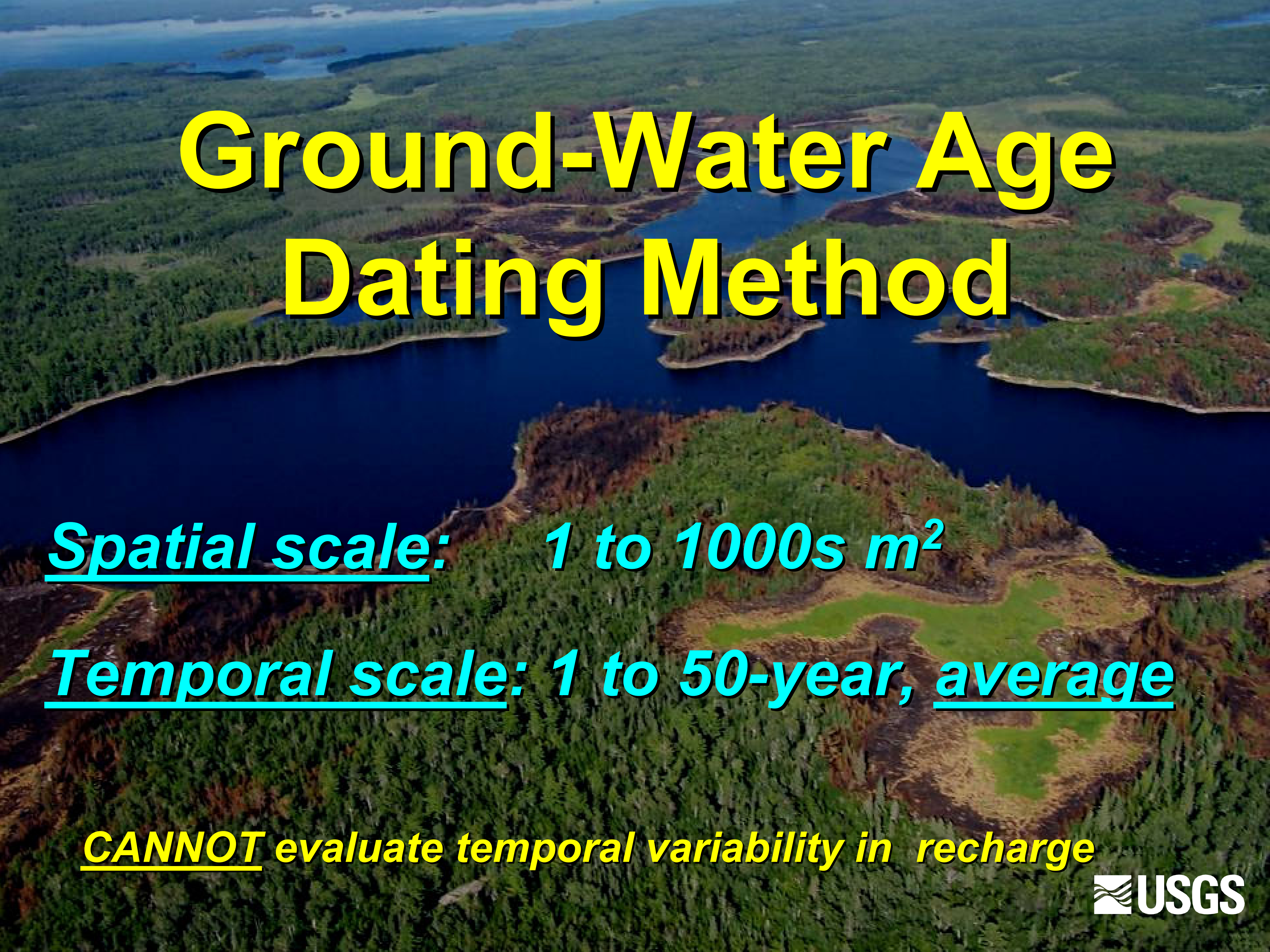
Limitations of WTF Method

- Small scale of influence
- ET, river fluctuations, or pumping may affect hydrograph
- Does not account for constant recharge
- Specific yield estimates uncertain



Ground-Water Age Dating Method

***Spatial scale*: 1 to 1000s m^2**

Temporal scale*: 1 to 50-year, *average

***CANNOT* evaluate temporal variability in recharge**

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Ground-Water Age Dating Method Assumptions

- Assumes ground-water age and well-depth information can be used to obtain a ground-water velocity (***V***)
- <u>Recharge</u> = ***V*** x ϕ
  where ***V*** = ground-water velocity, and
  ϕ = average saturated porosity
- Piston flow is assumed

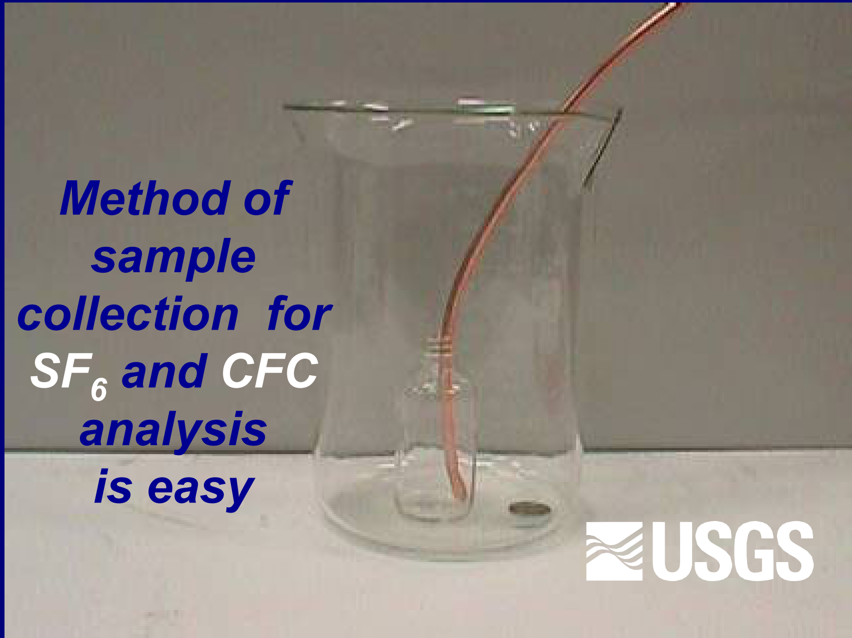
Delin et al. (2000)

USGS

Ground-Water Age Dating

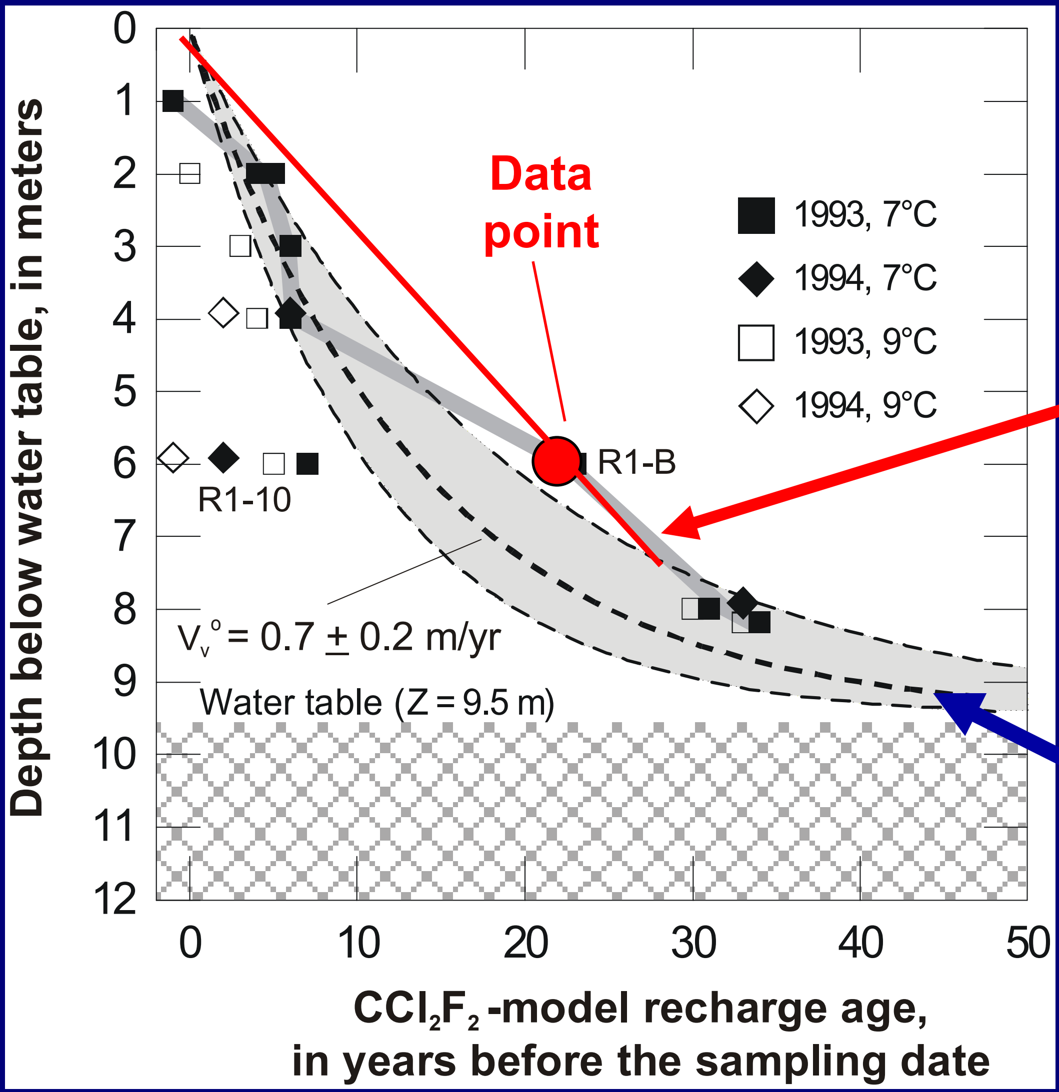
- Age must be determined to within about 1 year before present
- Estimated using chlorofluorocarbons (CFC's), sulfur-hexafluoride (SF_6), and tritium/helium (^3H-^3He) techniques (+ others)
- Ground-water age is defined as the time elapsed since water entered the aquifer as recharge

Equip. used in $^3H/^3He$ sampling



Method of sample collection for SF_6 and CFC analysis is easy

Vertical Velocity Determination – Ground-Water Age Dating Method



Linear age-depth profile used where only a single ground-water age is available

Exponential age-depth profile developed from multiple ages

Delin et al. (2000)

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Limitations of Ground-Water Age Dating Method

- Ignores horizontal movement below water table
- Analyses costly: $895 for ^{3}H-^{3}He; $112 ($CFCs$ & SF_6) per sample
- Specialized labs

Delin et al. (2000 and 2007)

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RORA Method

Spatial scale: *100 to 1000s km^2*

Temporal scale: *monthly to period of record*

Limited temporal variability in recharge

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RORA Method

- RORA is an automated method for estimating average recharge in a basin
- Analyze streamflow records using the recession-curve-displacement method of Rorabaugh (1960, 1964)
- RORA accounts for ET effects, underflow, and other losses following a precipitation event

Rutledge (1998 and 2000)

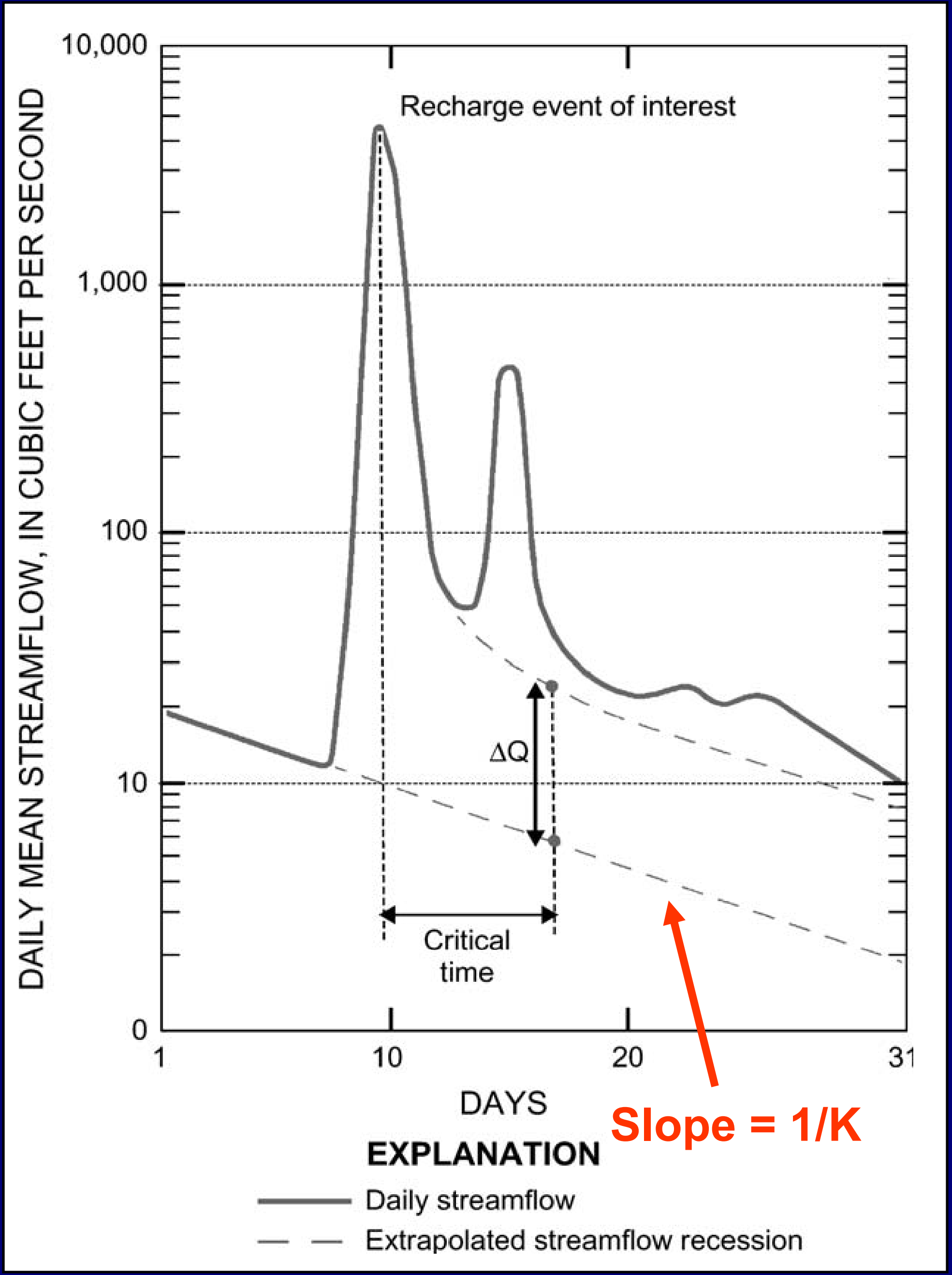
USGS

Gaging Station/Basin Selection for RORA Method

- **Primary Basin Selection Criteria:**
  - no missing data (1 year required),
  - basin size less than about 1,300 km^2 (500 mi^2)
  - flow not affected by control structures
- **For Minnesota study:**
  - basin size less than 5,000 km^2 (~2,000 mi^2)
  - 10+ years of record,
  - evaluated records from 340 basins,
  - 38 basins met our criteria

Rutledge (1998 and 2000)

USGS



RORA Recharge Estimate

Recharge = 2(ΔQ)K / 2.3026

where

ΔQ = difference in the theoretical flows at the critical time,

K = recession index, time required for ground water discharge to recede by one log cycle after recession becomes linear

Rutledge (1998 and 2000)

USGS

RORA Limitations

- Assumes that the streamflow recession is caused by ground-water discharge
- Slow runoff from snowmelt could be confused for ground-water discharge
- High-quality, daily streamflow data are required

Rutledge (1998 and 2000)

Regionalization of Recharge Estimates Using the Regional Regression Recharge (RRR) Model

Spatial variability of recharge

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RRR Model Assumptions

- Spatial variability in recharge can be estimated from:
  (1) climate,
  (2) local or basin-scale recharge rates, and
  (3) landscape characteristics
- Although local-scale recharge estimates could have been used…
- RORA recharge estimates are best suited to regionalization at a State scale

Lorenz and Delin (2007)

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RRR Methodology

- Regression equation developed based on:
  - precipitation data (*P*),
  - growing degree days (*GDD*)
  - recharge (*R*) from RORA analysis of streamflow,
  - specific yield (SY_{Rawls}) derived from STATSGO soils data, as the landscape characteristic

$$R = 14.2 + 0.6459P - 0.02231GDD + 7.63SY_{Rawls}$$

- Final step: create recharge map of Minnesota using GIS based on a regression analysis of the data sets

Lorenz and Delin (2007)

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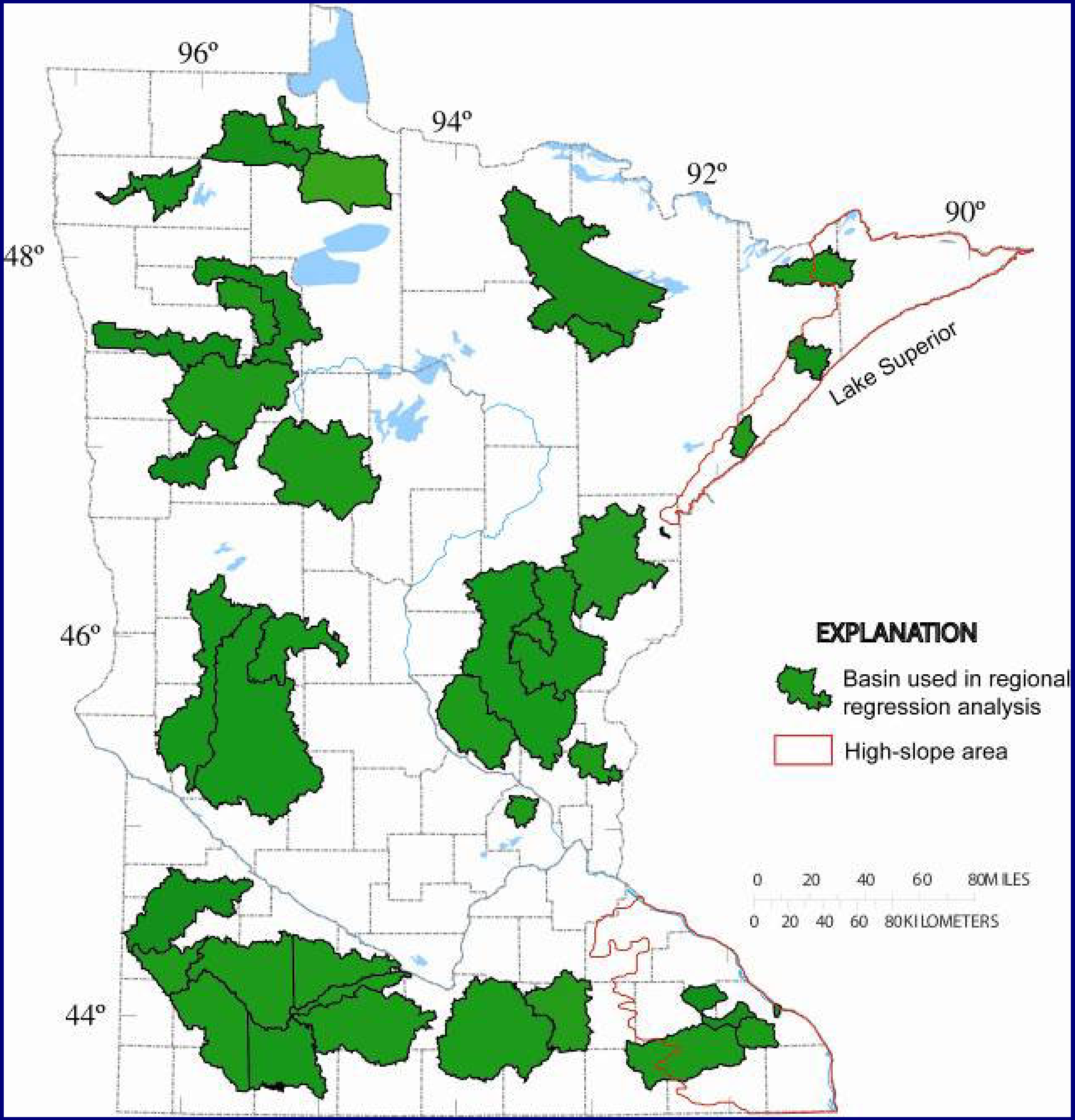
38 Basins met RORA Recharge Selection Criteria



Limited coverage imposes some uncertainty in the RRR recharge estimates

However, these basins were representative of variability in the State

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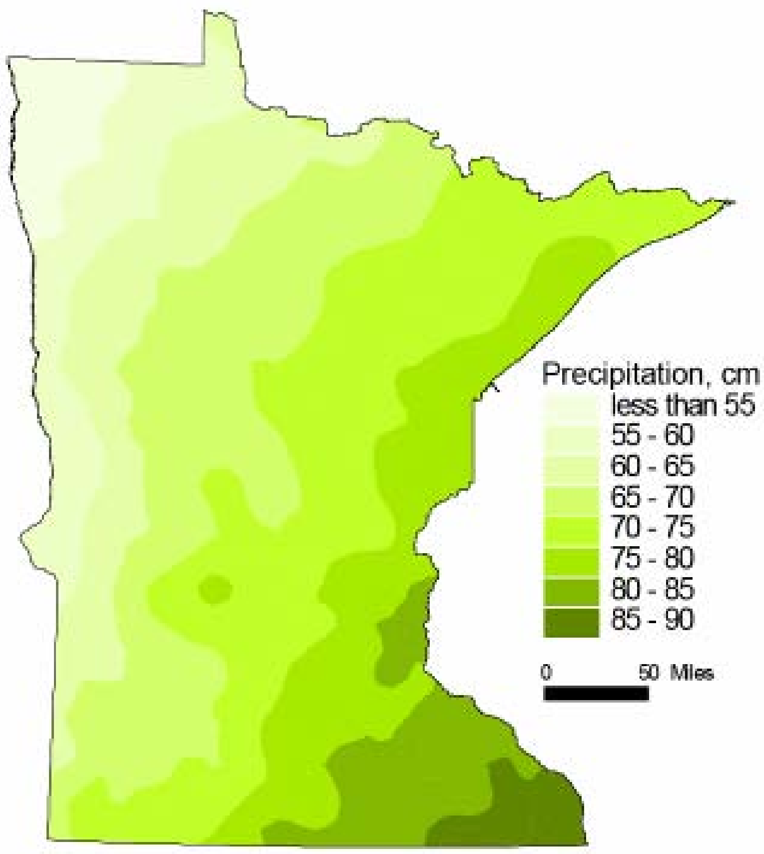
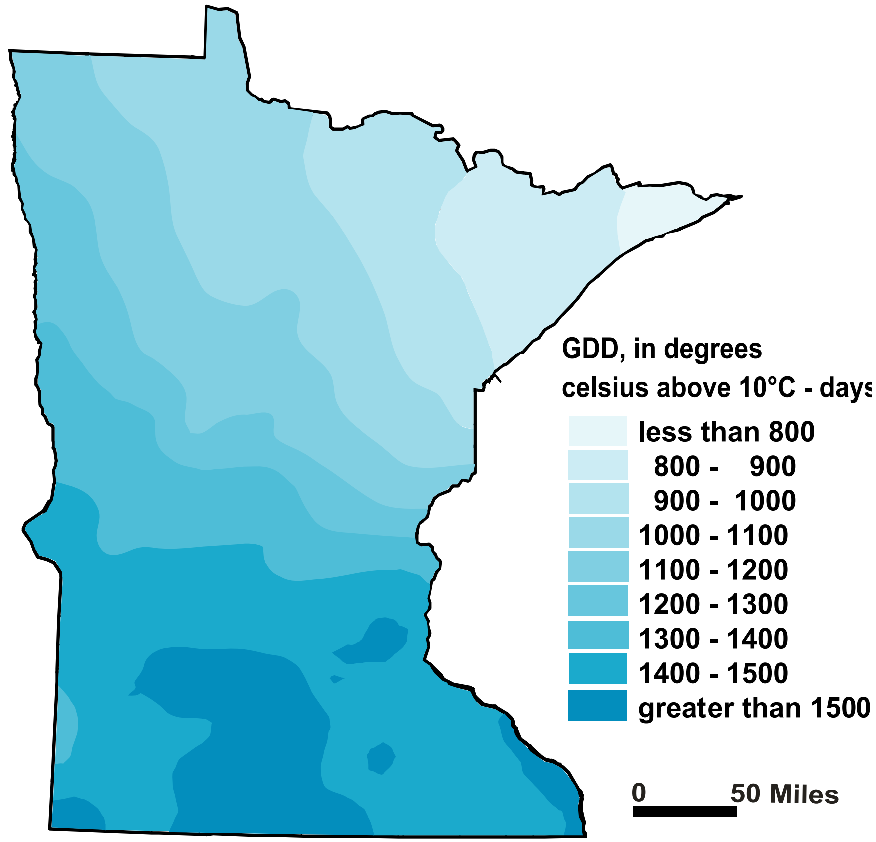
Climate Spatial Data Sets Used in RRR Analysis

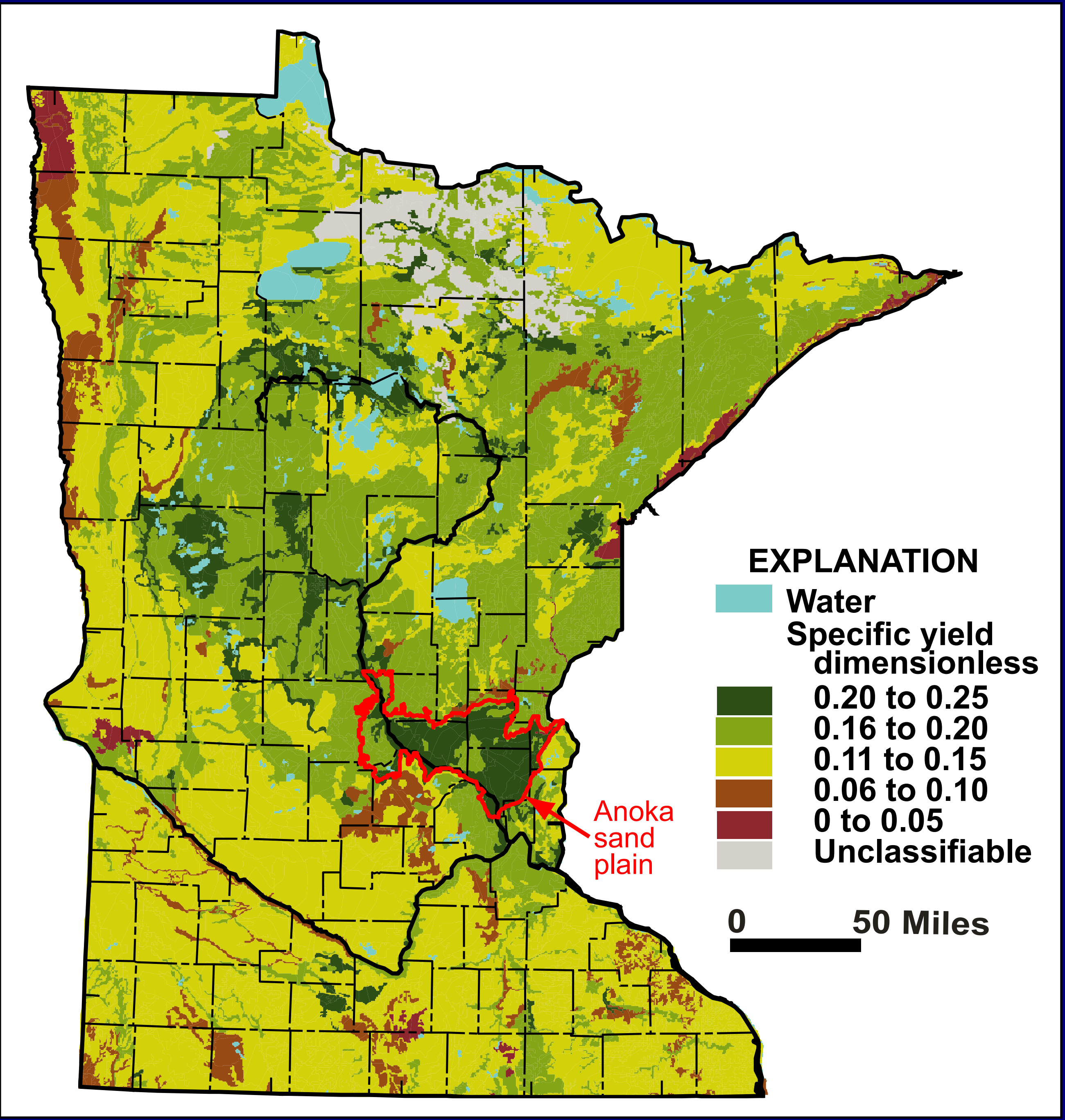


Average annual precipitation, 1971-2000



Average annual growing degree days, 1971-2000

Landscape Spatial Data Set Used in the RRR Analysis



Specific yield from RAWLS analysis of STATSGO soils data

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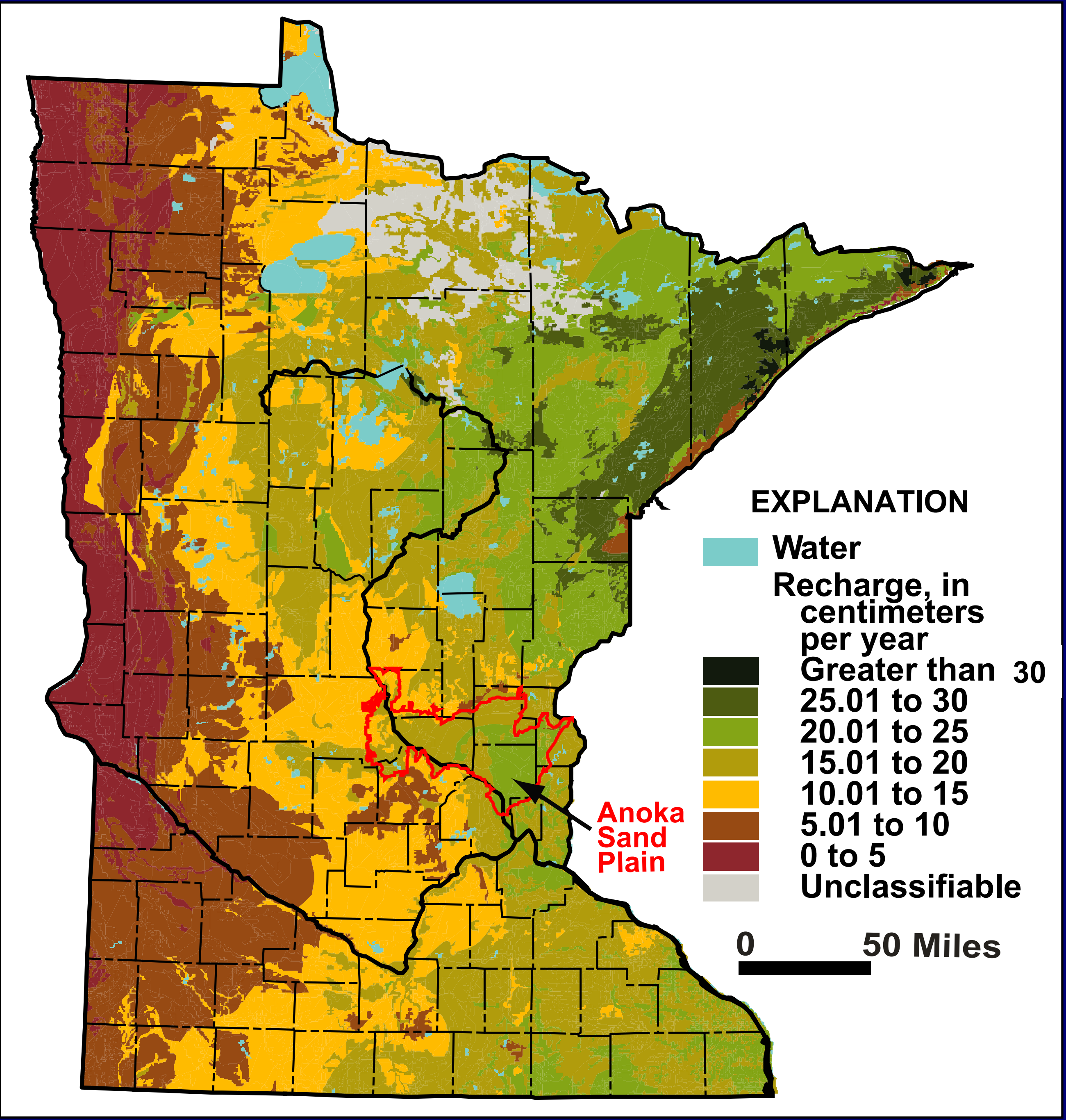
RRR Model

Average Annual Recharge to Surficial Materials



Lorenz and Delin (2007)

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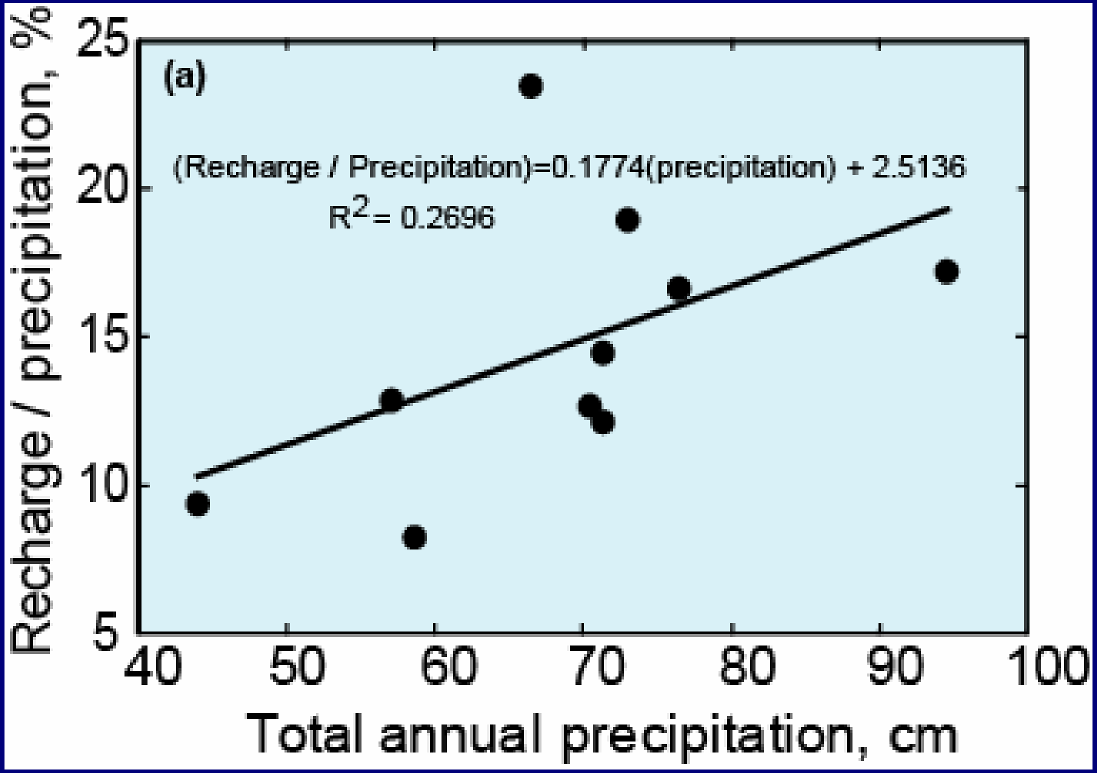
Results and Methods Comparison

Delin et al. (2007)

Ground-Water Recharge Normalized as a Percent of Precipitation

WTF RISE program results;

Bemidji well 310D



Fair correlation $R^2 = 0.2696$

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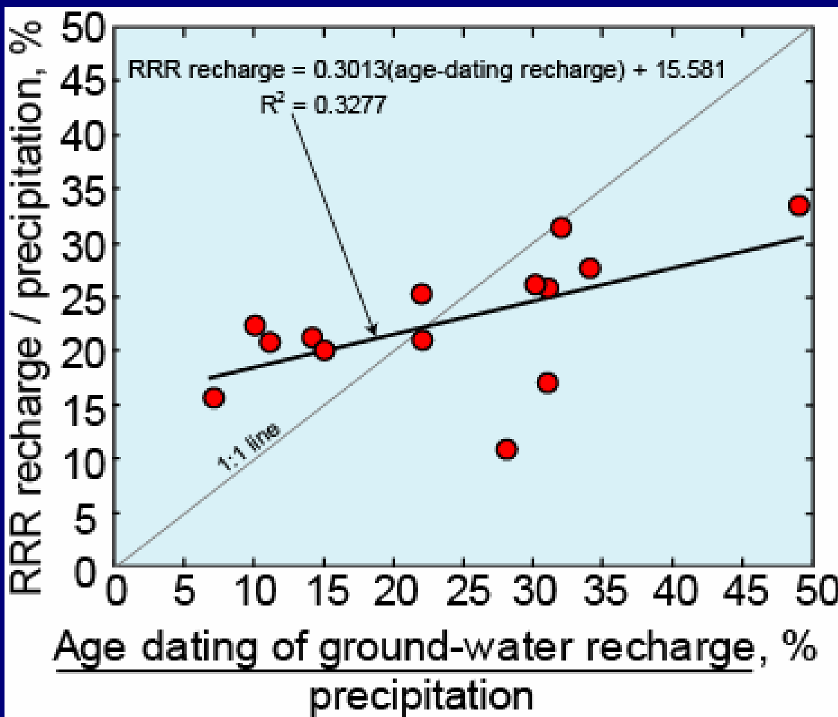
Delin et al. (2007)

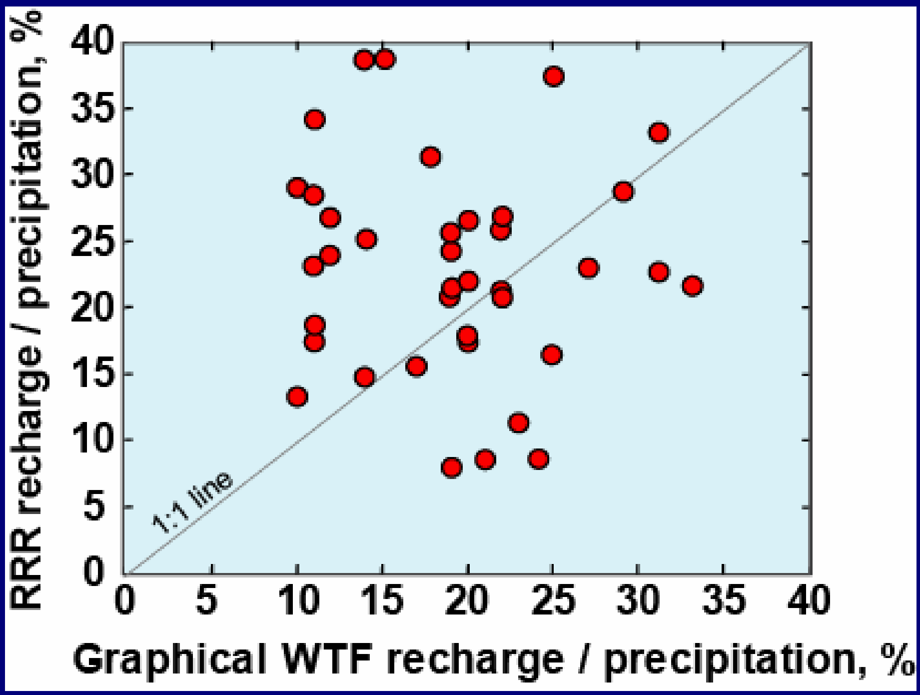
Relation of RRR to Other Recharge Rates

Age-Dating of Ground Water



Fair correlation R^2 = 0.3277

Water-Table Fluctuations



Very poor correlation R^2 = 0.0008

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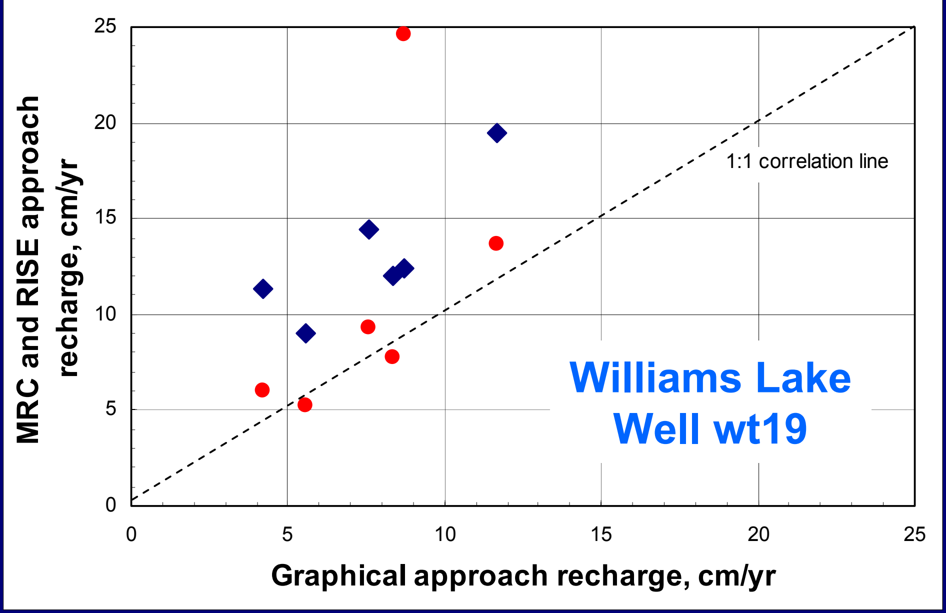
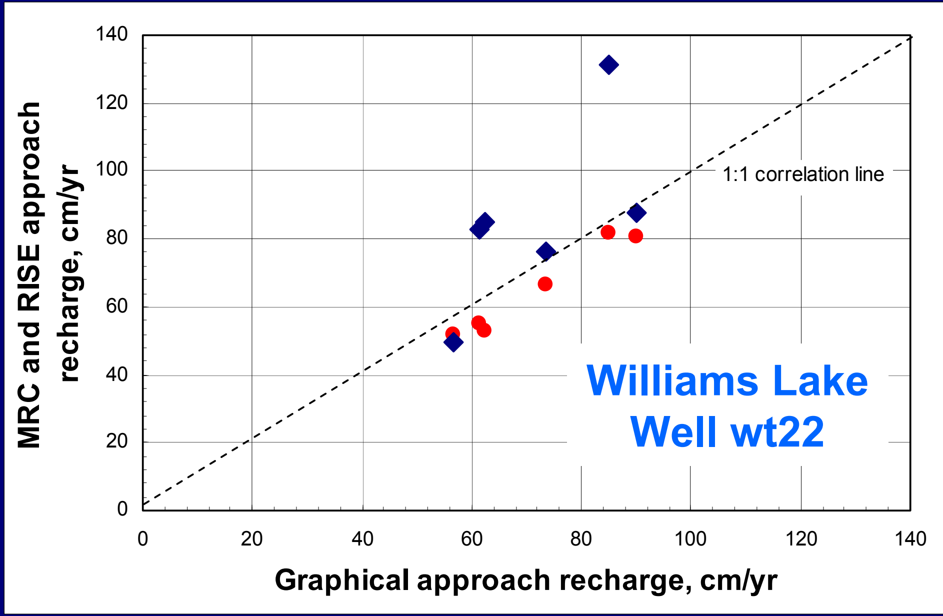
Delin et al. (2007)

WTF Method – Example Plots of Graphical vs. MRC and RISE Approaches





	Well wt19	Well wt22
Rech. % of precip:	15 %	~100 %
UZ Thickness:	5 m	2 m

• MRC method • RISE method

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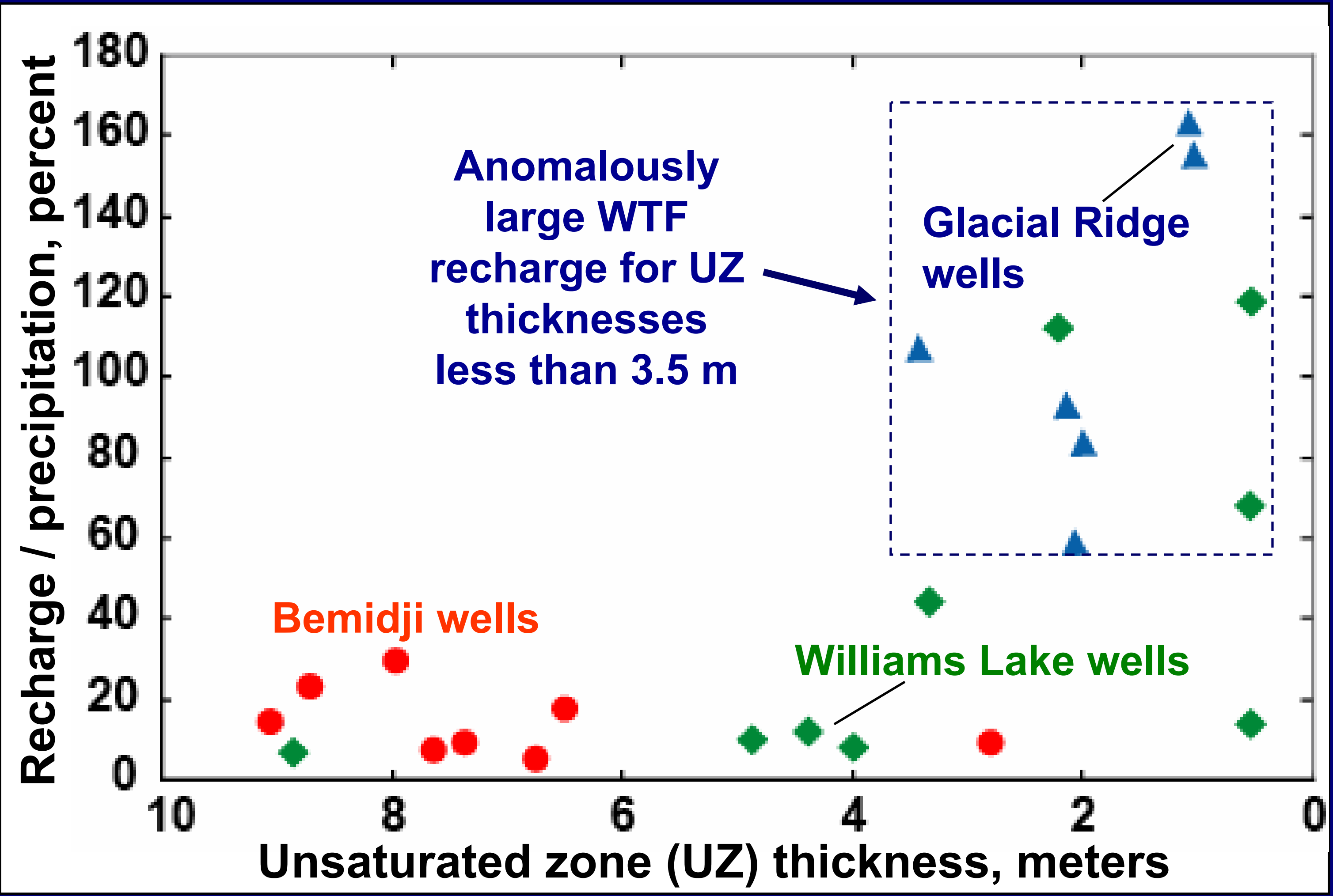
Relation Between WTF Recharge and UZ Thickness



2003 data

Graphical approach

23 wells total

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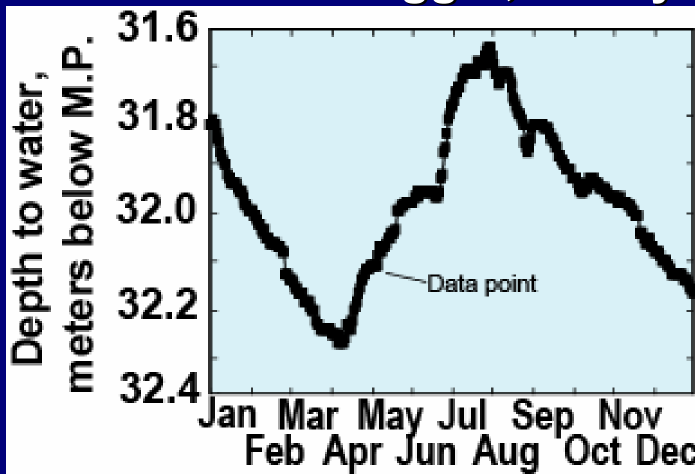
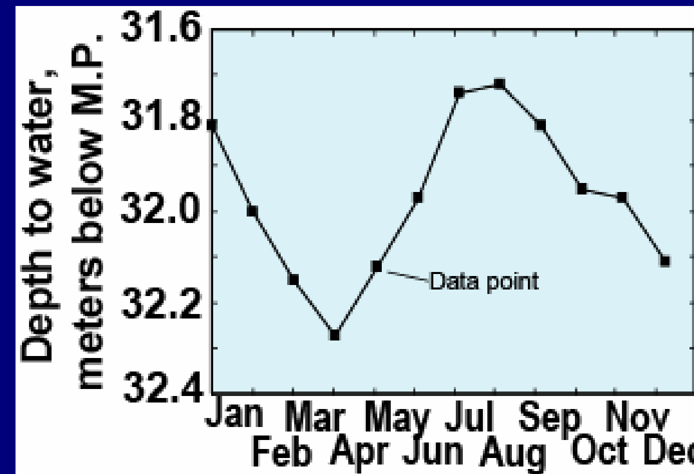
Delin et al. (2007)

Effects of Measurement Interval on WTF Recharge Estimates

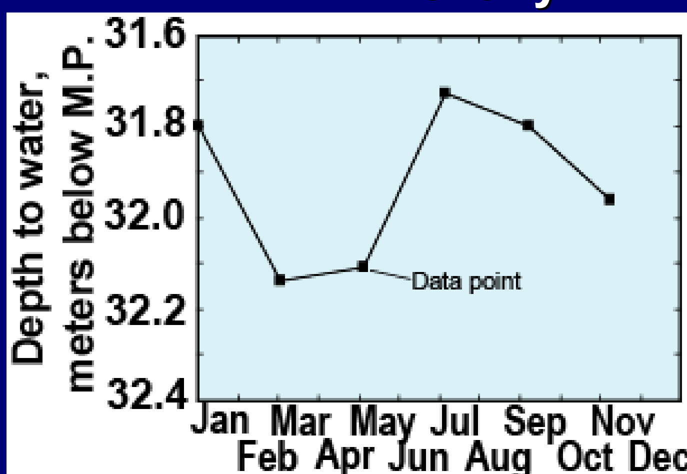
Datalogger, hourly



Monthly



Bi–Monthly



Question: How does reduced measurement frequency affect recharge estimates based on the WTF method?

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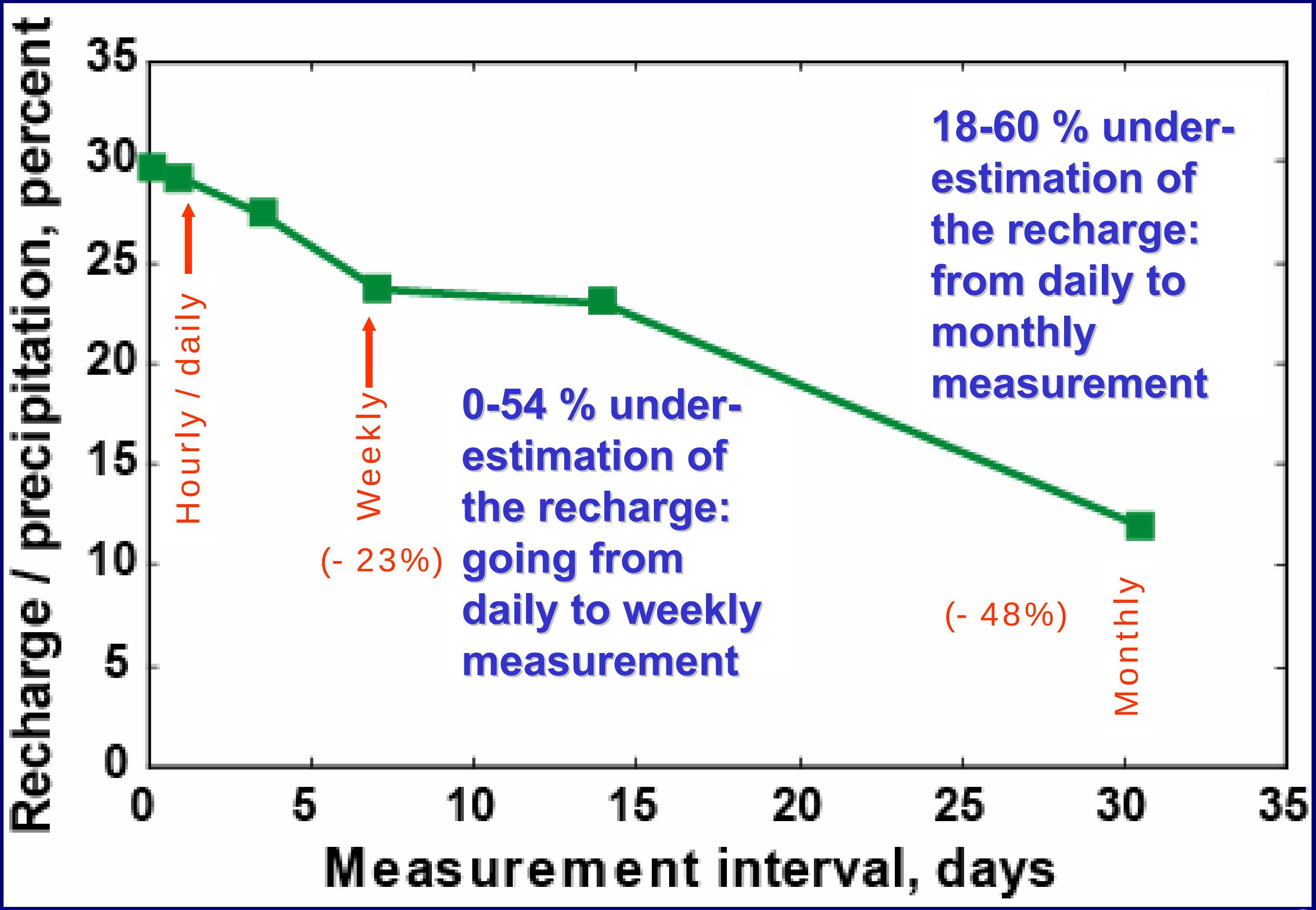
Delin et al. (2007)

Effects of Measurement Interval on WTF Recharge Estimates

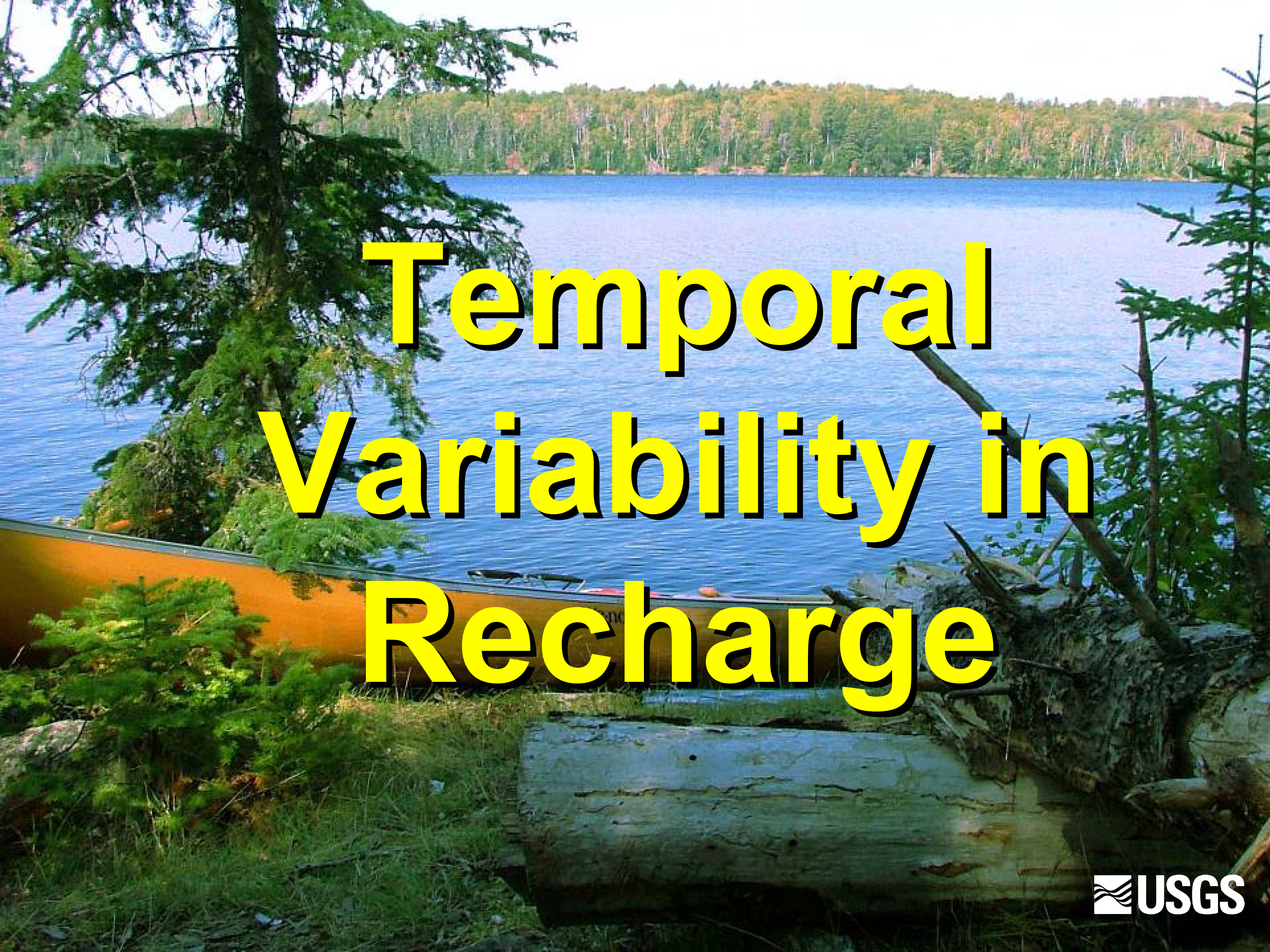
No change in estimated recharge going from hourly to daily measure



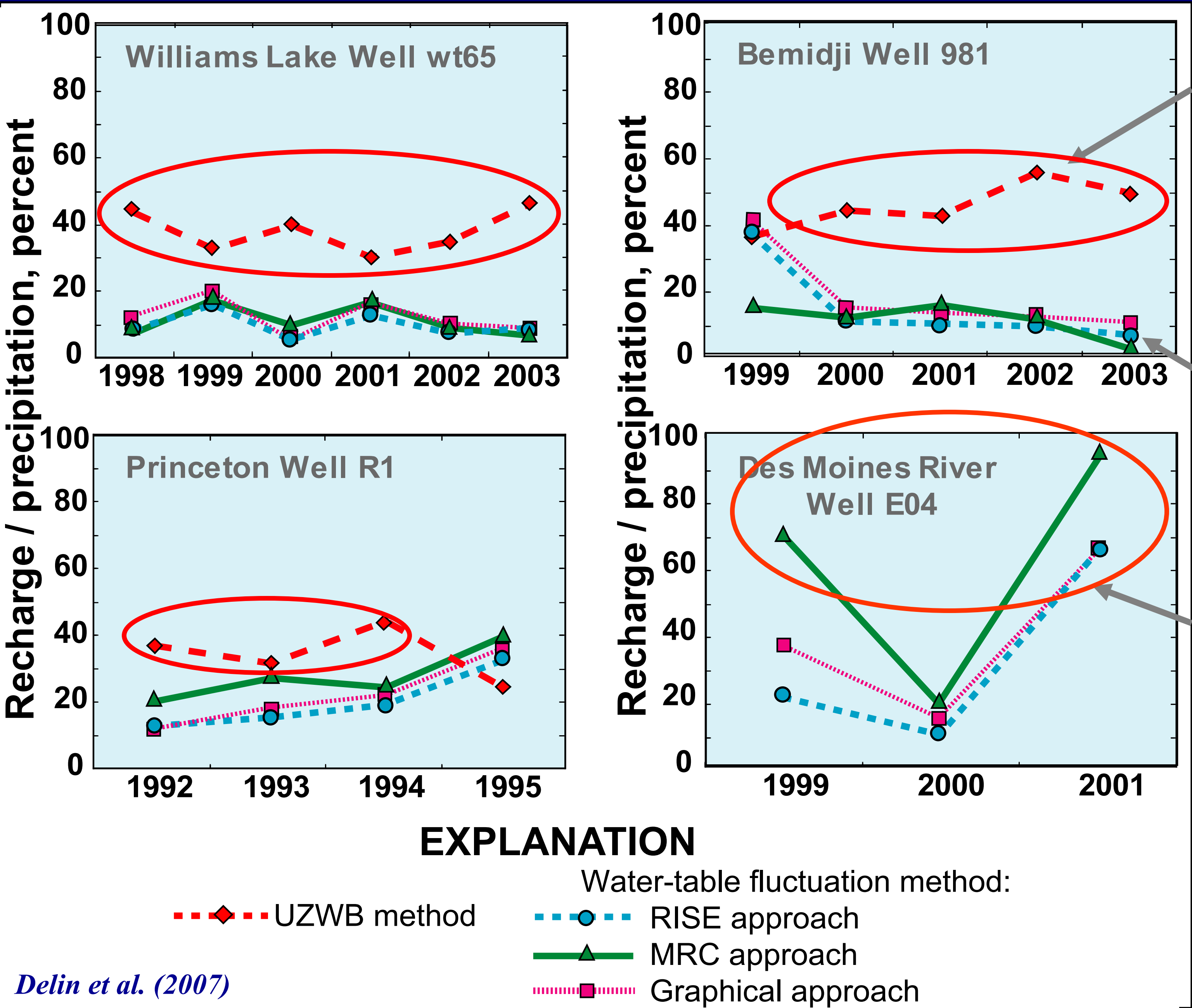
WTF graphical approach; 1993 datalogger data

Delin et al. (2007)

USGS


Temporal
Variability in
Recharge

Temporal Variability in Recharge, % of precip.



UZWB results anomalously large most years

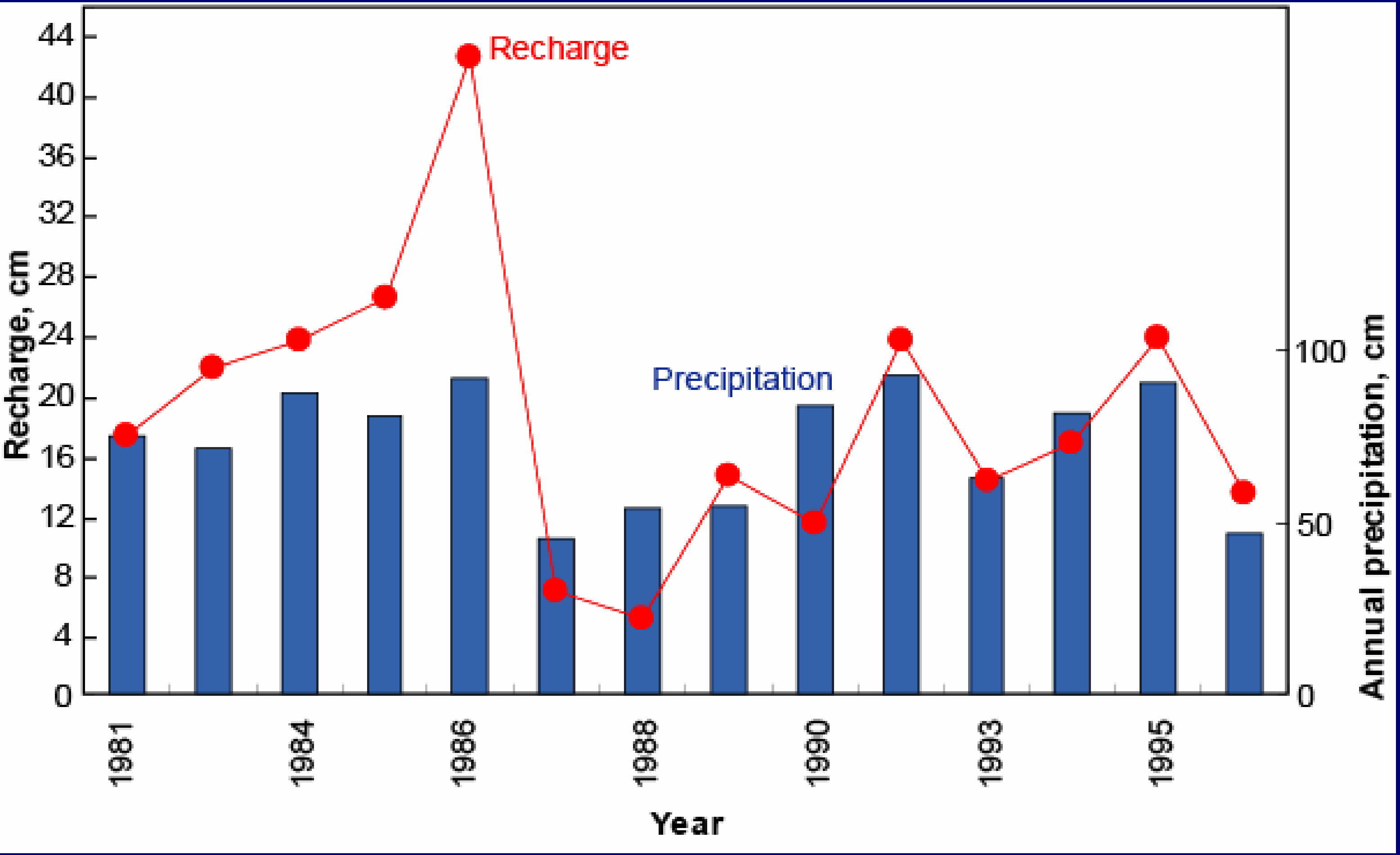
WTF results fairly consistent

Shallow depth to WT causes anomalously large recharge rates at some sites

Delin et al. (2007)

USGS

Temporal Variability in Annual RORA Recharge – Knife River near Mora



$R^2 = 0.52$

Delin et al. (2007)

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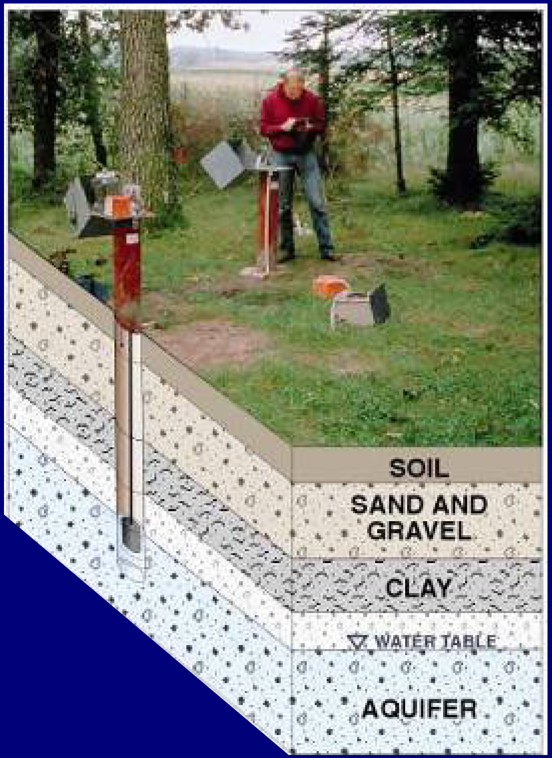
Summary

- Recharge rates to unconfined aquifers in Minnesota typically are about 10-35 % of precipitation
- Recharge based on the 3 water-table fluctuation (WTF) approaches are similar, however:
  - MRC estimates are generally greatest
  - RISE estimates are generally lowest
- Recharge estimation using the WTF method is challenging / inaccurate in areas of shallow depth to water table (< 3.5 m)

High-Quality, Long-Term, Continuous Data are Important

Climate

Streamflow



Ground-water levels

Use Multiple Methods

RORA

UZWB

Ground-water Age Dating

WTF

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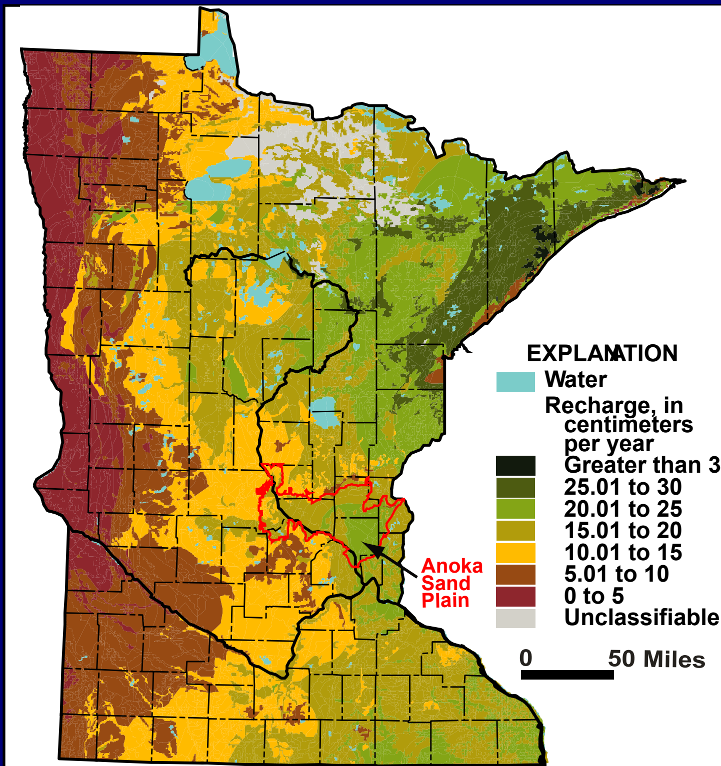
RRR Map



Valuable for regional analyses; e.g., – input for ground-water flow models

Not appropriate for use at local scales

RRR Model

Apply at different scales based on data availability:

(1) climate,

(2) <u>local</u> or basin-scale recharge rates, and

(3) landscape characteristics

USGS

Reports Summarizing this Research

http://mn.usgs.gov/publicationIndex.html

Delin, Healy, Lorenz, and Nimmo, 2007, Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA: *Journal of Hydrology*, v. 334, no. 1-2, p. 231-249.

Lorenz and Delin, 2007, A regression model to estimate regional ground-water recharge in Minnesota: *Ground Water*, v. 45, no. 2

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http://pubs.usgs.gov/fs/2007/3002/

Delin and Risser, 2007, Ground-water recharge in humid areas of the United States – A summary of ground-water resources program studies, 2003-06: USGS Fact Sheet 2007-3007.

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