5 November 2009, Dutch Hydrology Meeting to receive the Darcy Lecture 2009, by Dr. Peter Cook, VU Amsterdam

Introduction to Environmental Isotopes

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Institute for Water Education

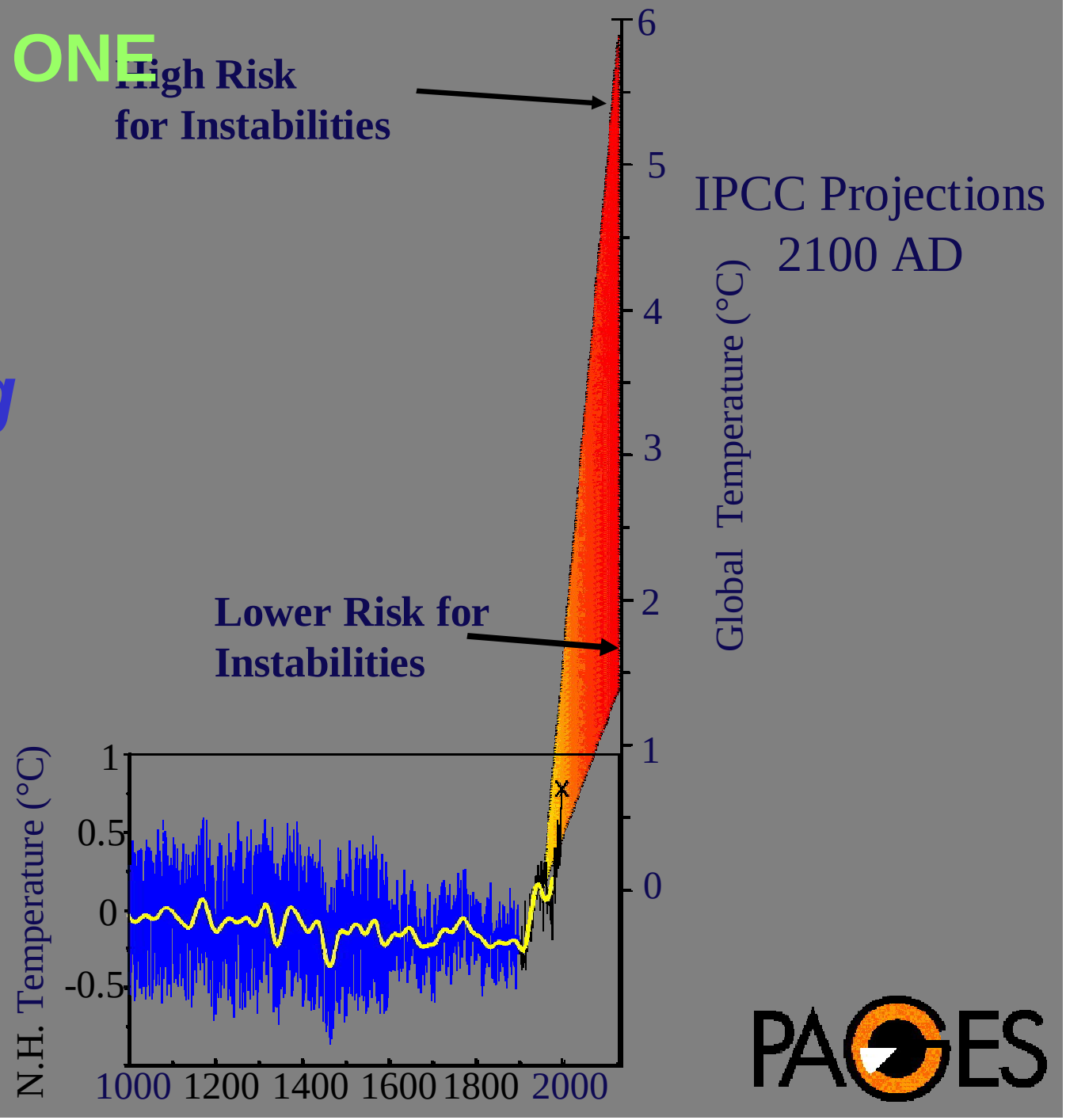
TU Delft
Delft University of Technology

Outline of This Lecture

1. Introduction
2. How can environmental isotopes help to detect and quantify global change impacts on water?
   - Evaporation
   - Runoff generation
   - Groundwater
   - Precipitation
3. Concluding Remarks

The context – ONE

It is Getting Warmer!



The context – TWO

- *A massive land-grabbing scramble in Africa as foreign companies - some with foreign aid money support - rapidly establish enormous monoculture fields in tropical countries.*

  ⇒***Prof Seif Madoffe, SUA***

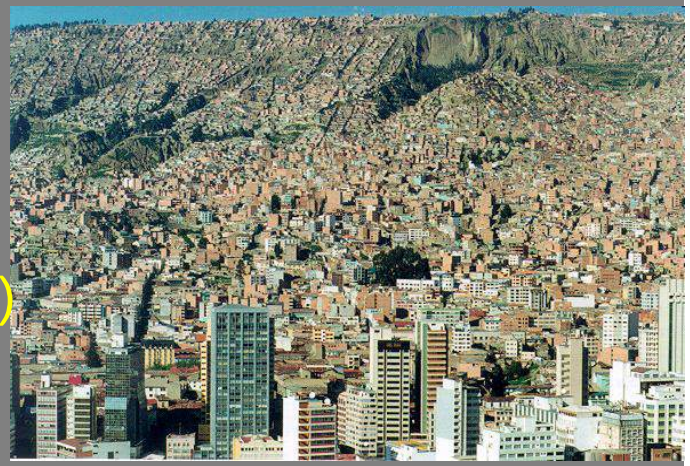
'climate colonialism'

Sugar Cane – Kilombera Basin, Tanzania

Global Changes

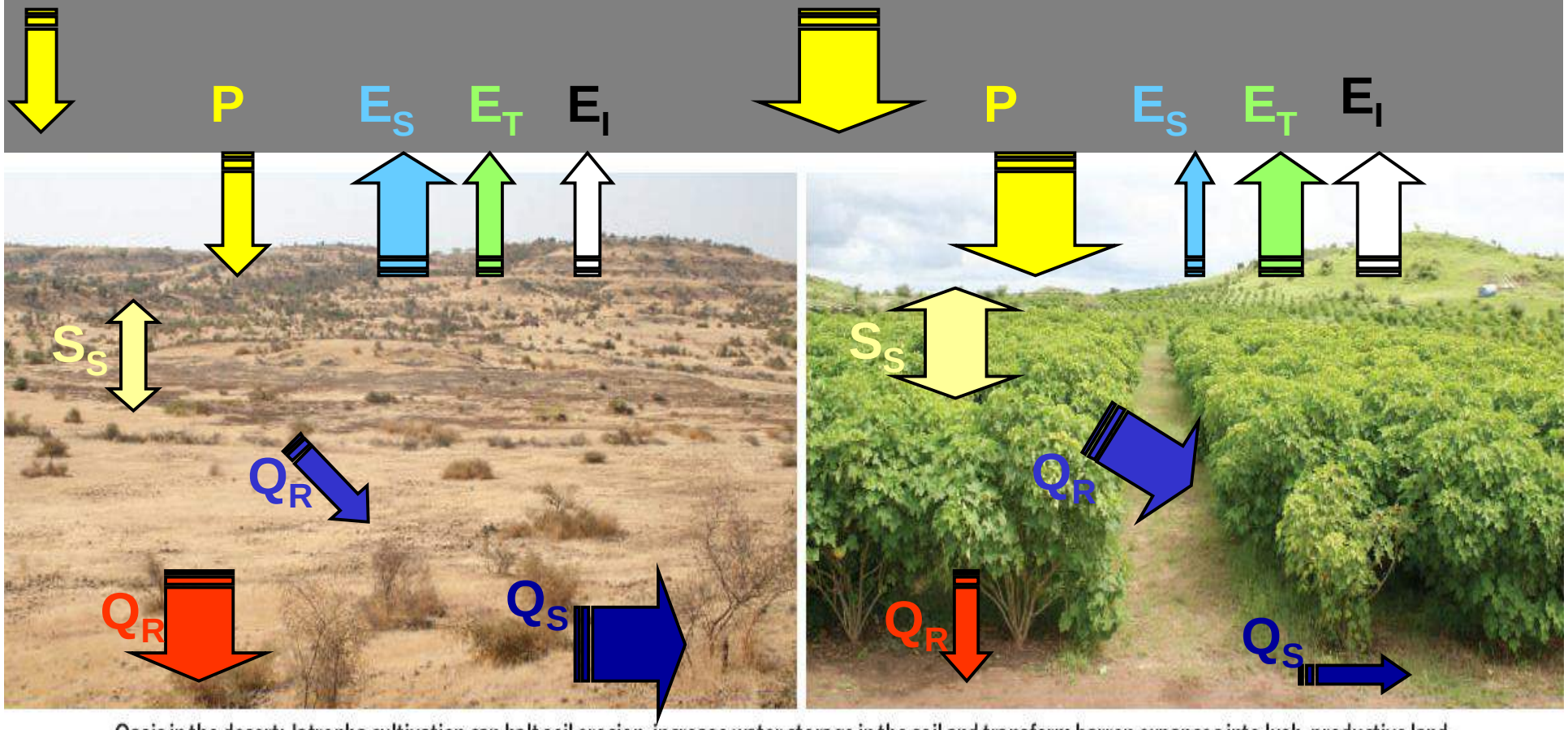
- Climate (temperature, precipitation, radiation …)
- Land use, land cover
  - ⇒ De-forestation / re-forestation
  - ⇒ Urbanisation
  - ⇒ Etc.
- Population (amount, density, structure, …)
- Water use in space and time
- Economic development
- Change of diet (more meat => more water)
- N- and P-fluxes to water bodies
- Pollution (new substances etc.)
- Change in composition of species
- etc. etc. etc.

…. and many interdependencies/feedbacks!



Impacts of land use change on hydrological processes

$P = Q + E + dS/dt$



Oasis in the desert: Jatropha cultivation can halt soil erosion, increase water storage in the soil and transform barren expanses into lush, productive land.

Short-term dynamics (e.g. interception, flood generation) *vs.* long-term dynamics (e.g. groundwater recharge, base flow)

Picture from Fairless, 2007, *Nature*

Water Balance Equation: **P=Q+E+dS/dt**

$$\left(\frac{dS_I}{dt} + E_I\right) + \left(\frac{dS_s}{dt} + E_s + Q_s\right) + \left(\frac{dS_u}{dt} + E_T + E_u + Q_f\right) + \left(\frac{dS_g}{dt} + Q_g\right) = P$$

Where:

$$\left(\frac{dS_I}{dt} + E_I\right)$$ Interception processes

$$\left(\frac{dS_s}{dt} + E_s + Q_s\right)$$ Surface water processes

$$\left(\frac{dS_u}{dt} + E_T + E_u + Q_f\right)$$ Root zone moisture processes

$$\left(\frac{dS_g}{dt} + Q_g\right)$$ Groundwater processes

Possible changes in <u>all</u> variables due to climate and/or land changes!!

How can Environmental Isotopes help??

CLIMATE CHANGE www.sciencemag.org SCIENCE VOL 319 1 FEBRUARY 2008

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1*] Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It

that has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natu-

uth Africa

Environmental Isotope – Basics

$^{16}_{8}O$

Mass number (= protons + neutrons)

8 protons (positive), 8 electrons (negative), 8 neutrons (neutral)

Atomic number (= protons)

- Protons and neutrons in the nucleus have approximately the same weight

- Electrons (negative charge) are lighter and are located in electron shells

$^{18}_{8}O$

8 protons, 8 electrons, 10 neutrons

- Nuclides with same atomic number (i.e. an element) but different mass number are called isotopes

- 92 natural elements have more than 1000 stable and radioactive isotopes

Some common environmental isotopes

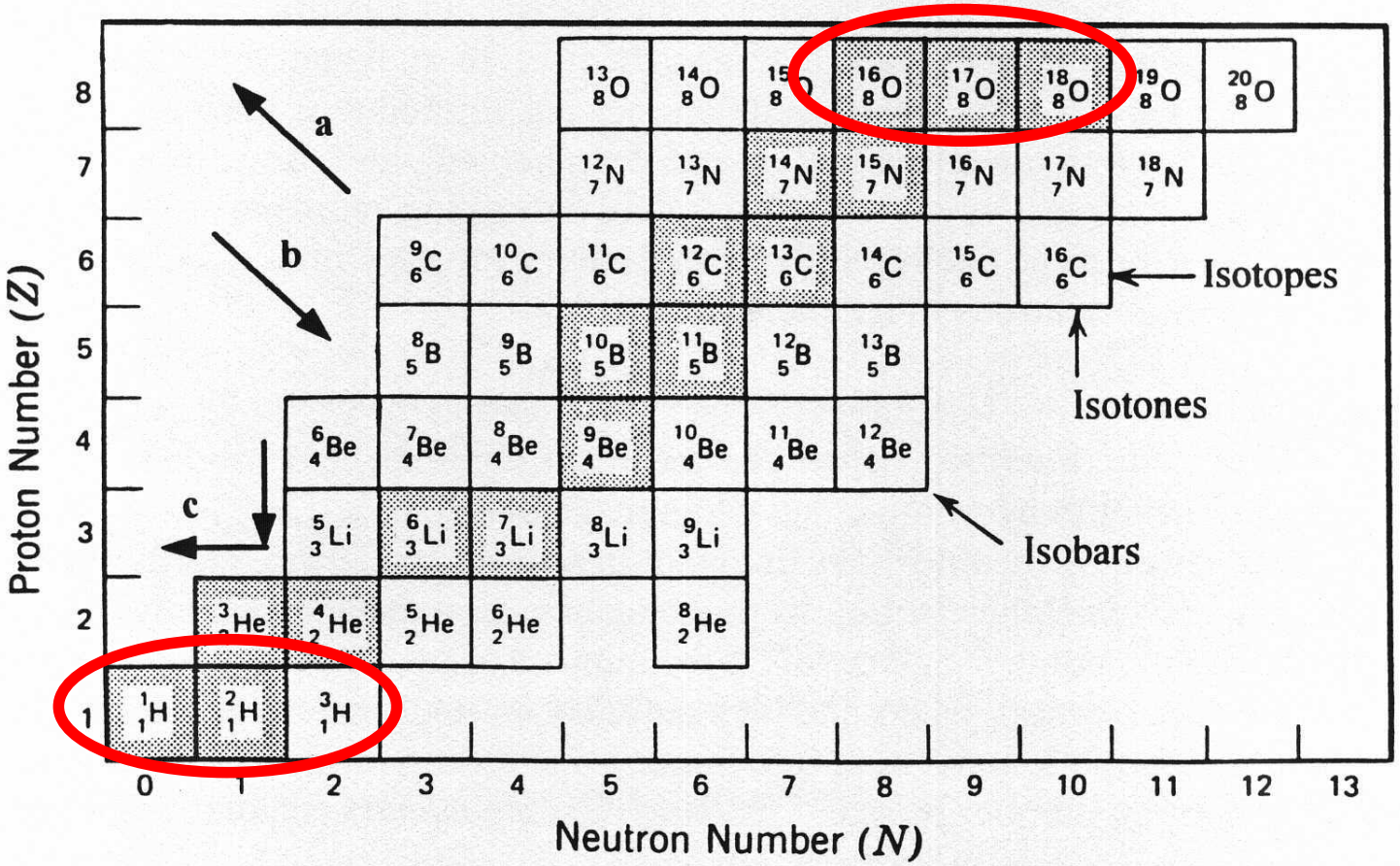
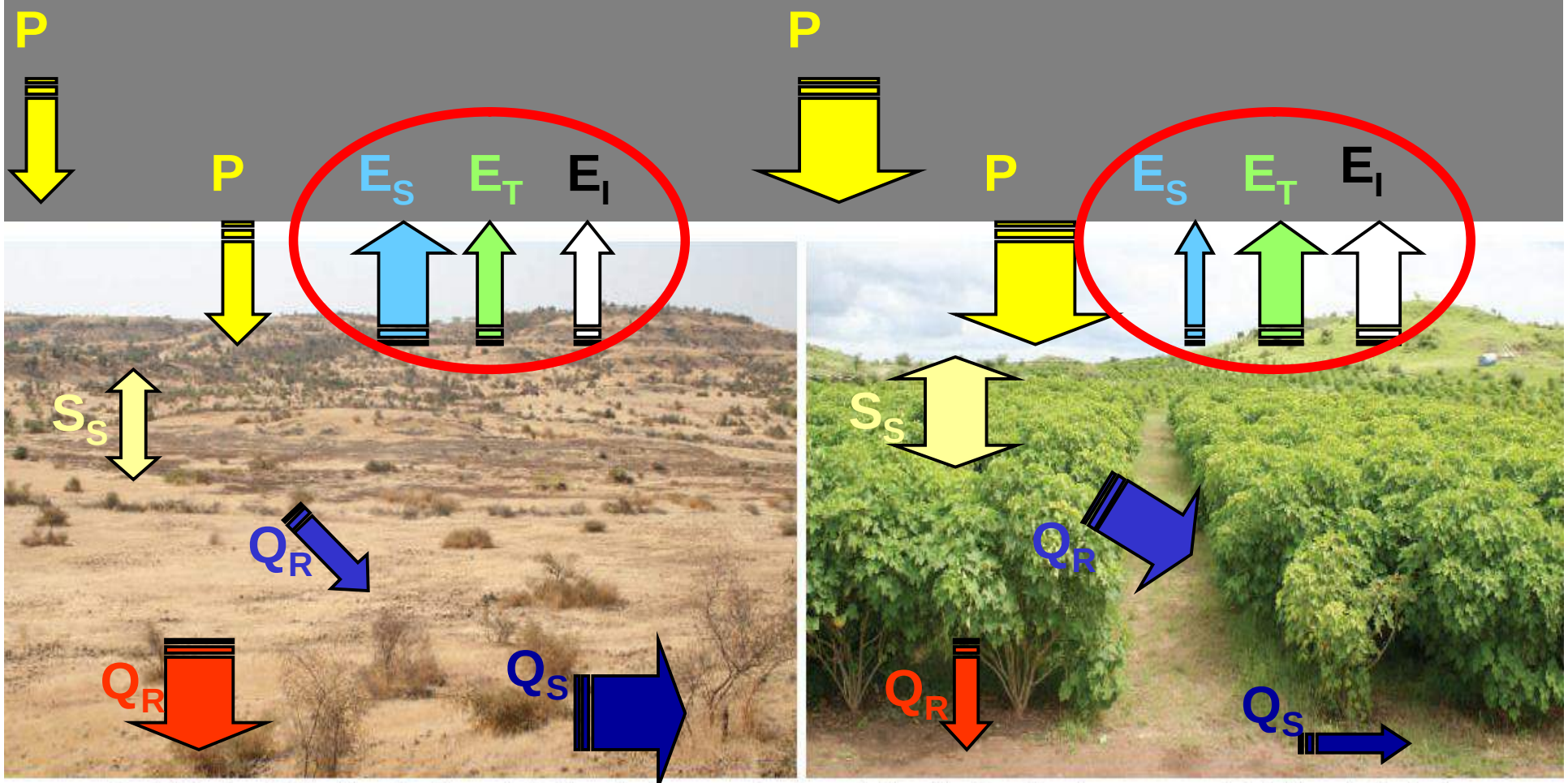


Figure 2.1. Partial chart of the elements. Each square represents a particular nuclide. The shaded squares are stable atoms and the unshaded squares are unstable or radioactive nuclides. Arrows at the left side of the diagram show the shifts in proton and neutron number caused by different decay mechanisms: beta decay (a), positron decay and beta capture (b), and alpha decay (c). Modified from Faure (1986).

Source: Kendall, 1998

Investigation of different compartments of the water cycle using environmental isotopes

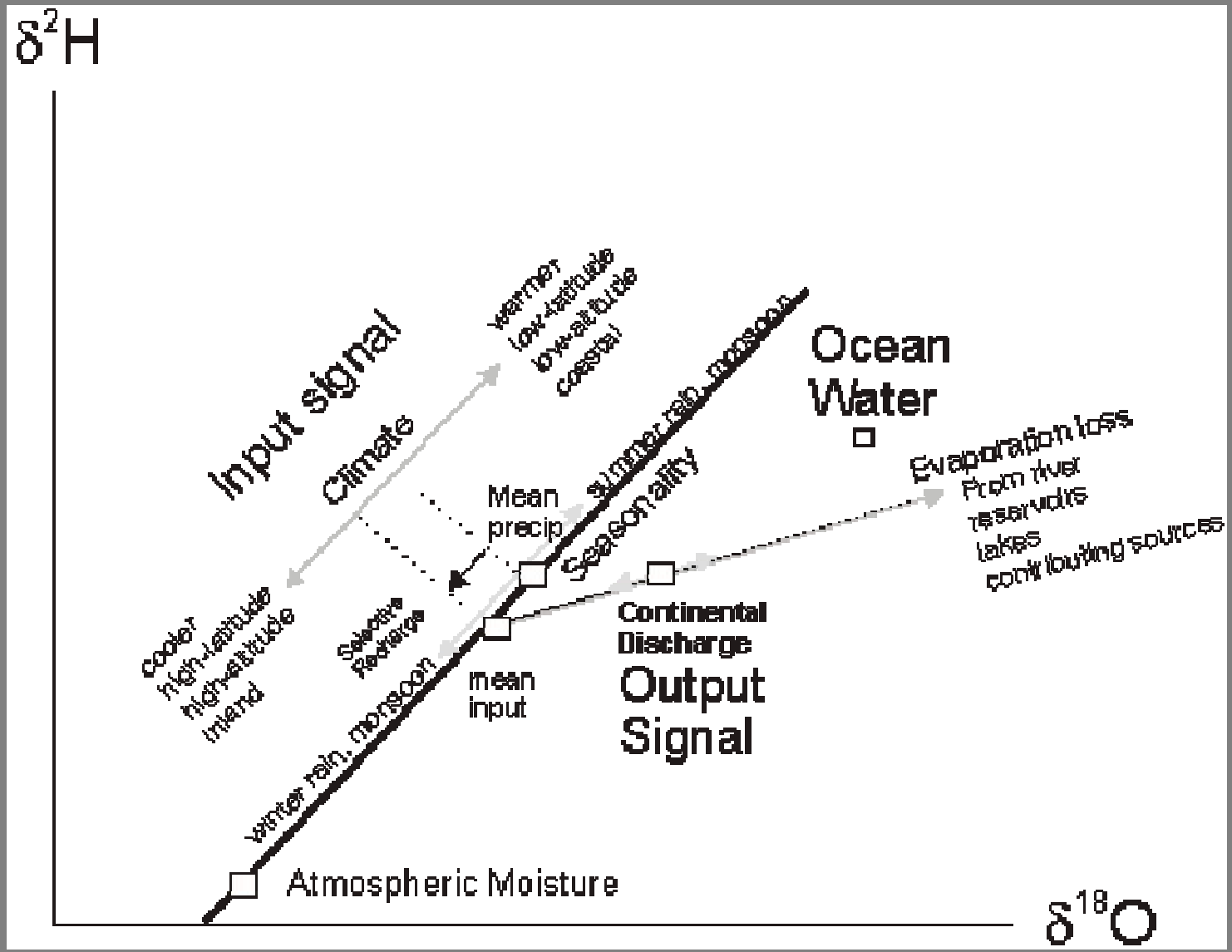
$$P=Q+E+dS/dt$$



Oasis in the desert: Jatropha cultivation can halt soil erosion, increase water storage in the soil and transform barren expanses into lush, productive land.

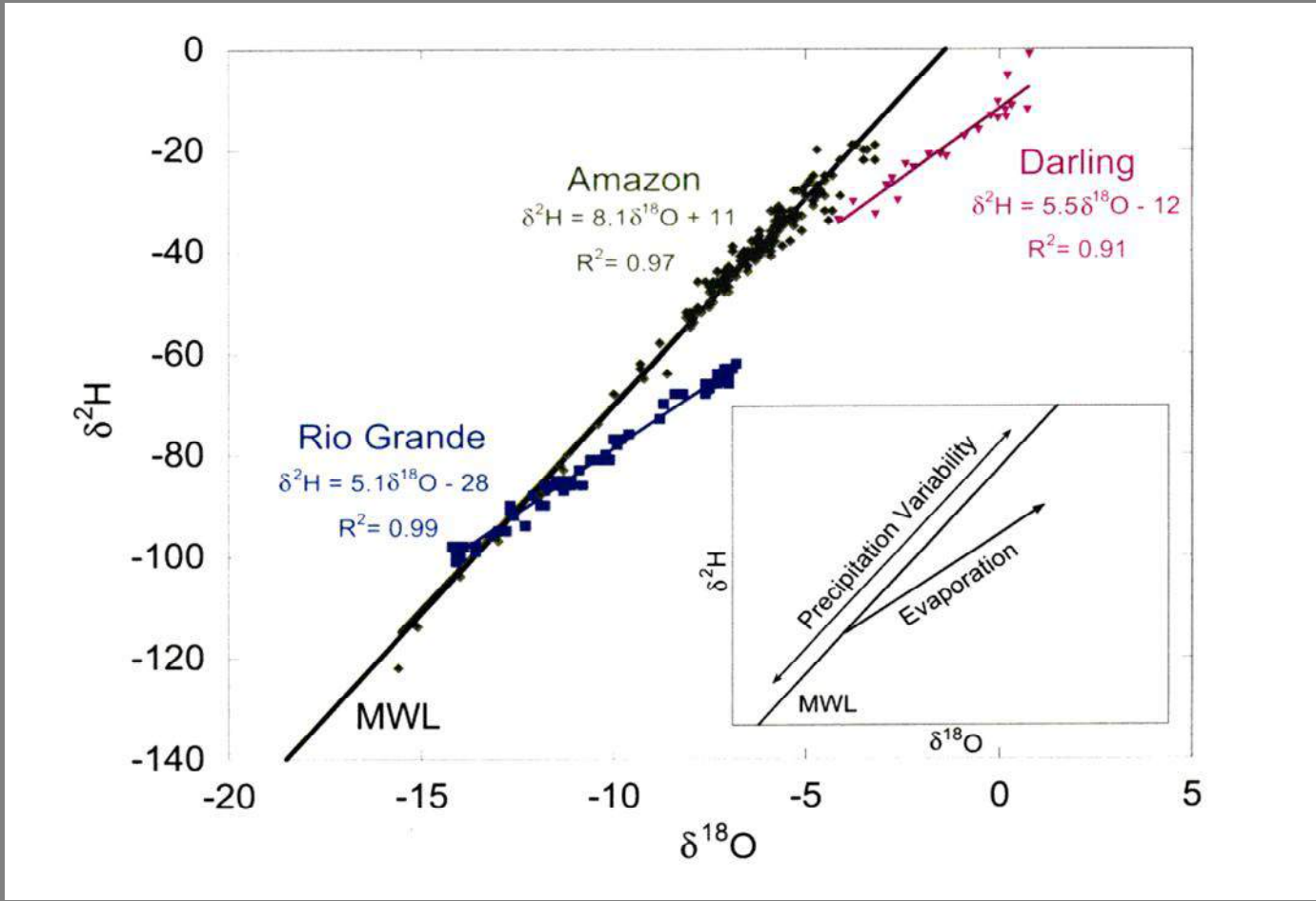
Picture from Fairless, 2007, *Nature*

Meteoric Water Line (MWL): The Concept



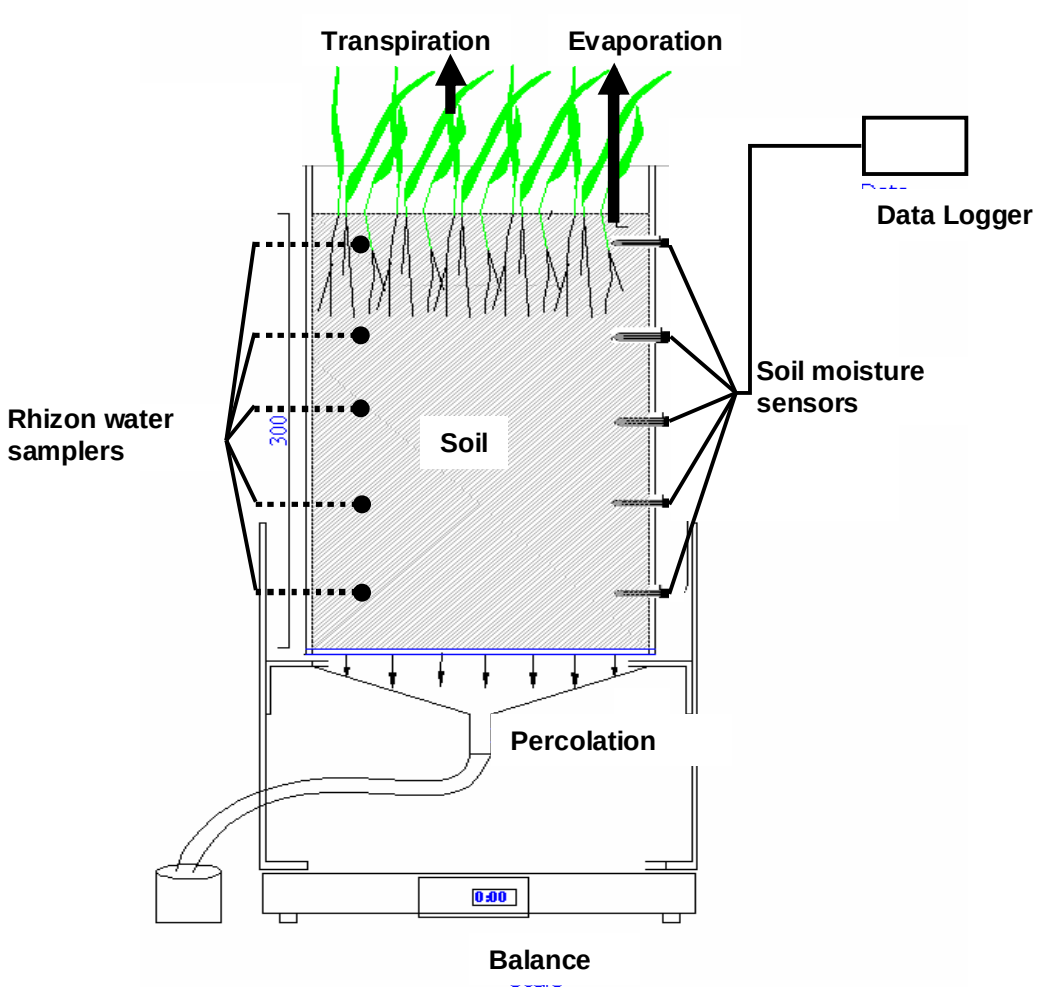
Source: IAEA

Observing evaporation using environmental isotopes in big systems



Agarwaal et al., 2002

Better Understanding of *Evaporation Fluxes* using Environmental Isotopes



Wenninger et al., in preparation

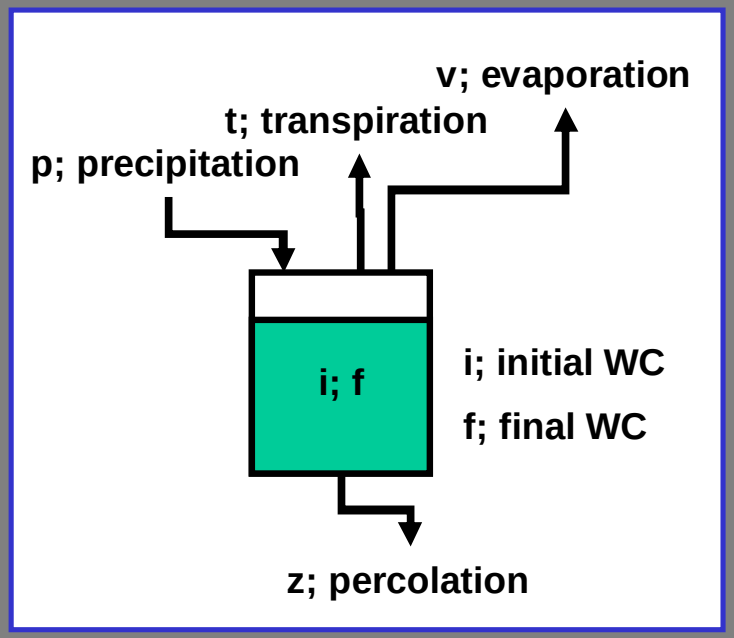
Isotope Mass Balance

- Evaporation is the driving factor in isotopic fractionation
- Transpiration and Percolation do <u>not</u> cause fractionation
- Quantification between fractionating and non-fractionating losses
- Conservation of mass and isotopes

$$m_f - m_i = m_p - m_v - m_t - m_z$$

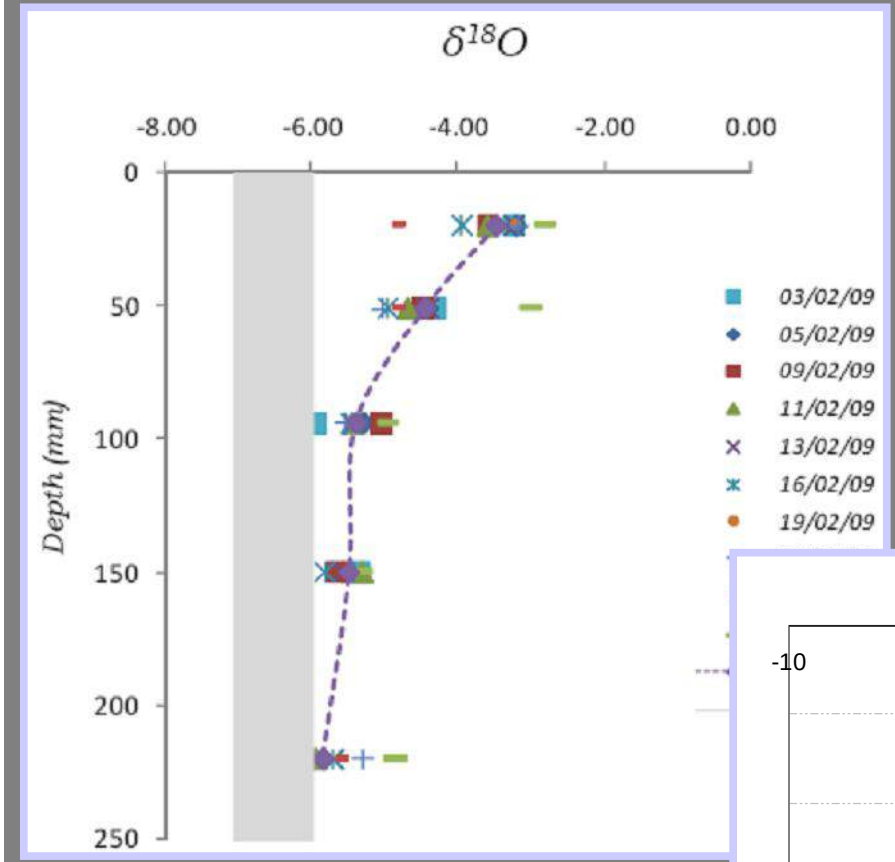
$$\delta_f x_f + \delta_v x_v + \delta_t x_t + \delta_z x_z = \delta_i x_i + \delta_p x_p$$

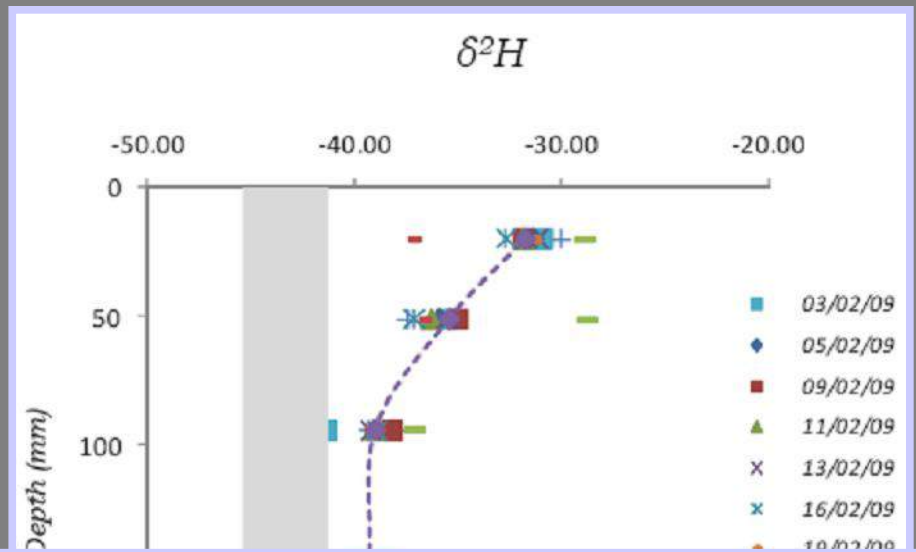
with: $x_j = m_j / m_{Total}$ $\quad m_{Total} = m_i + m_p$

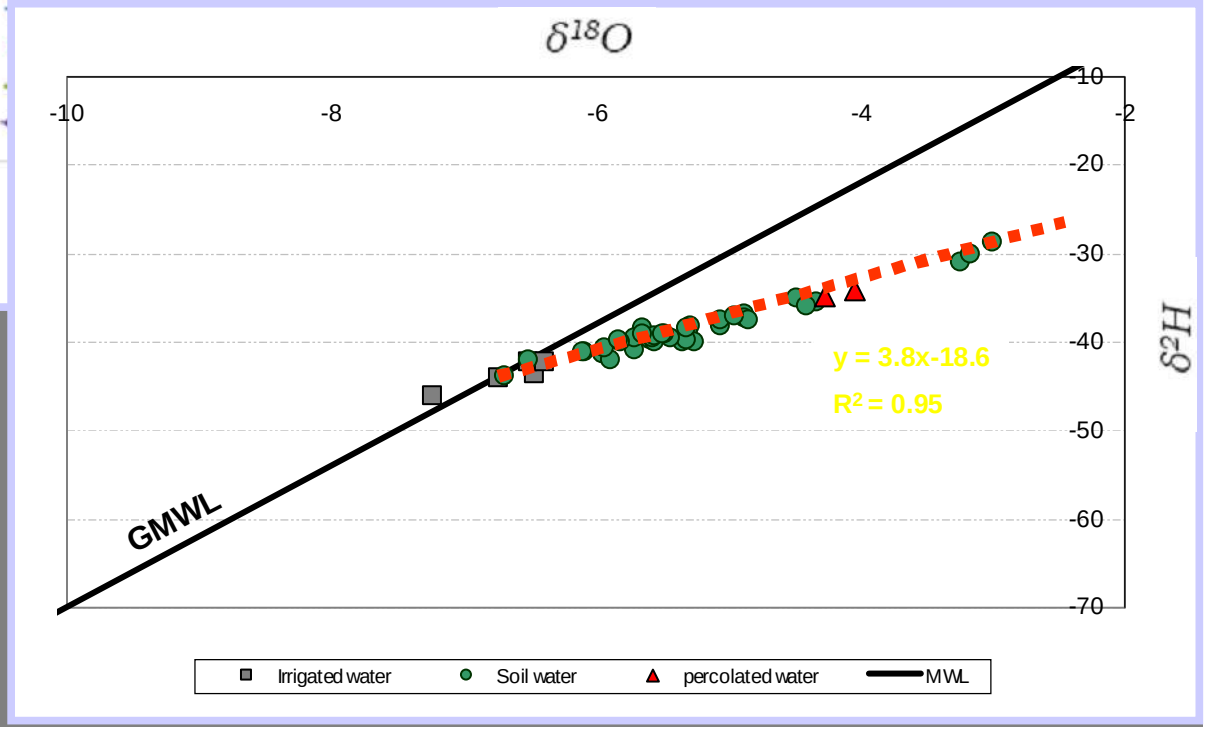


(e.g. Robertson et al. 2006, J. of Hydrol.)

Isotope Depths Profiles and Evaporation Line

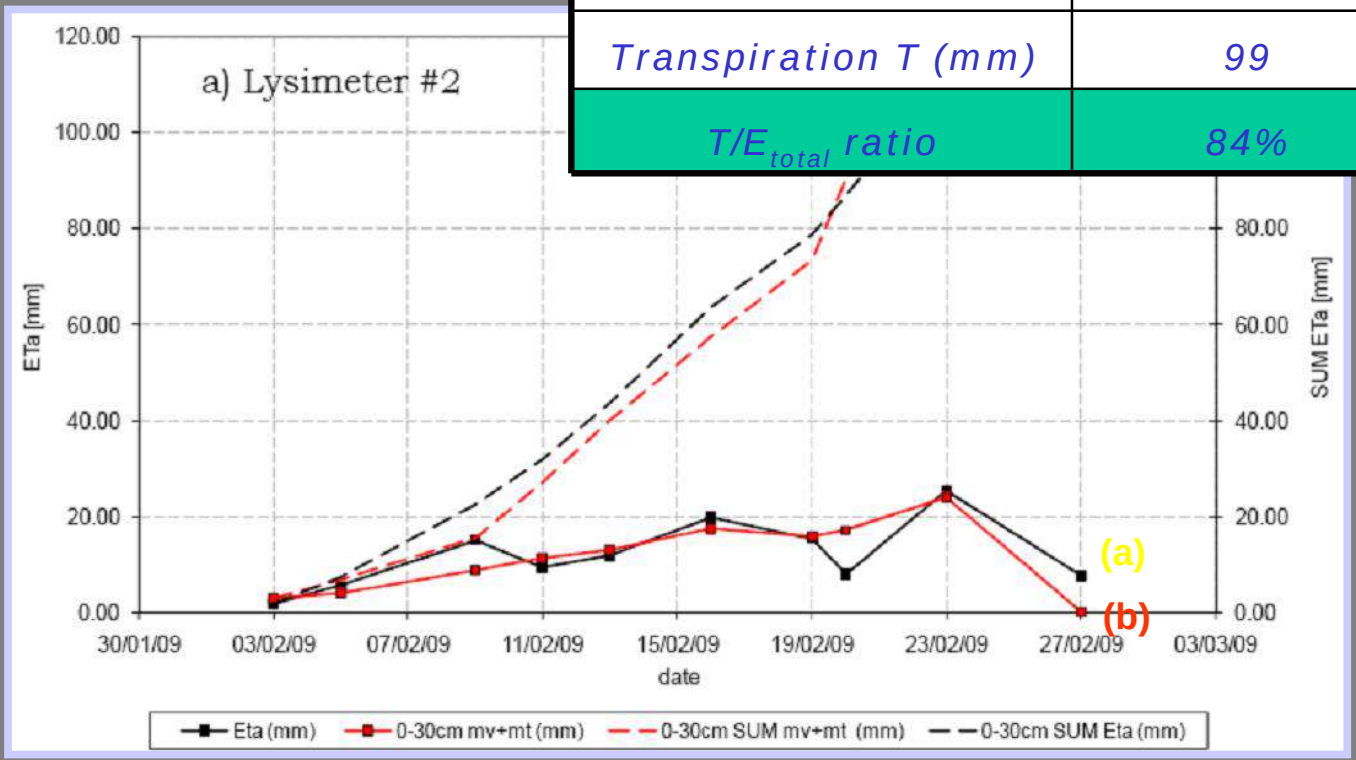






New way to estimate evaporation fluxes?!

	Lysimeter A	Lysimeter B
Evaporation E (mm)	19	77
Transpiration T (mm)	99	0
T/E_{total} ratio	84%	0



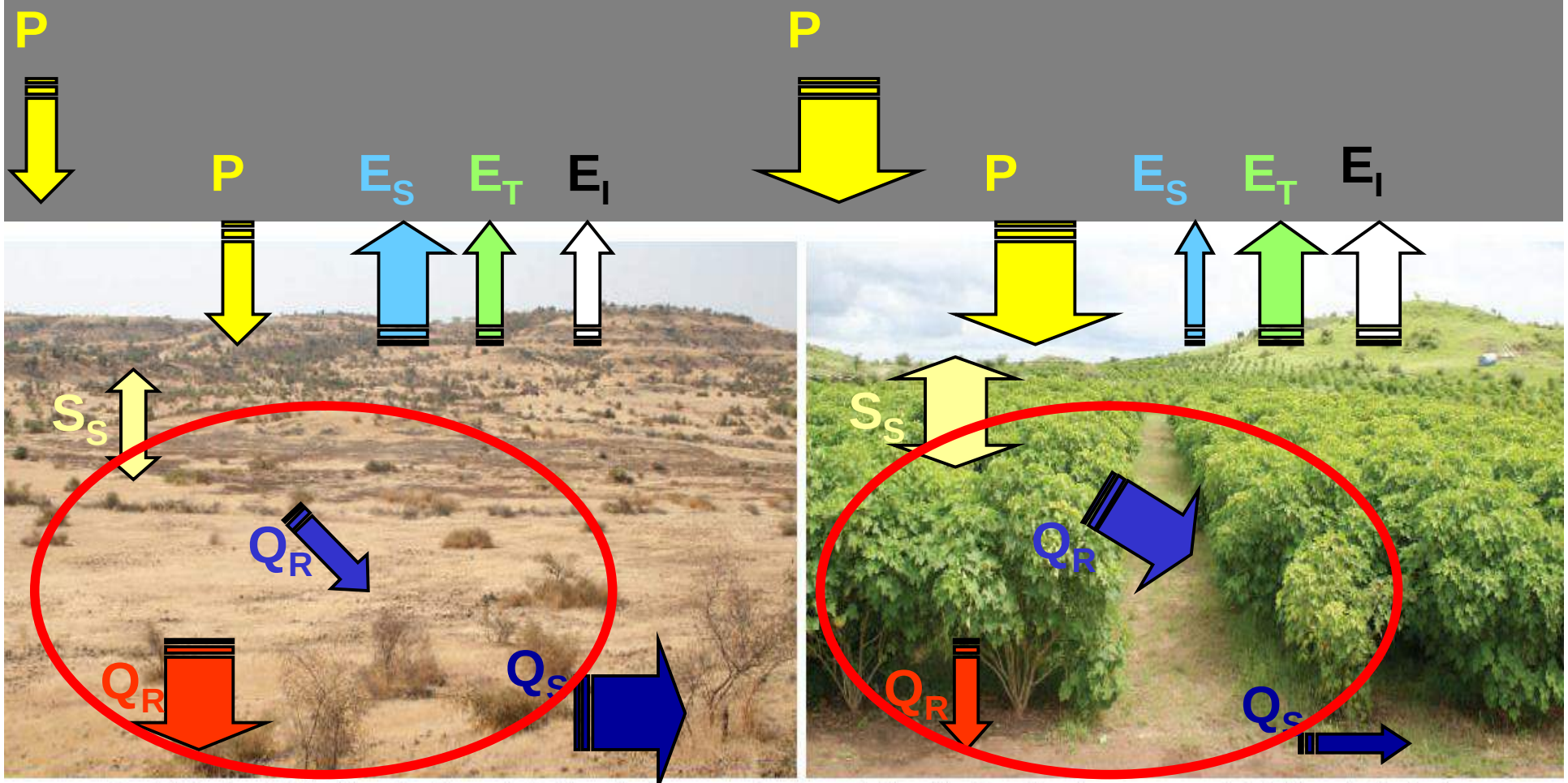
Comparison between different evaporation estimations:

(a) measured using hydrometric data and HYDRUS 1D, and

(b) calculated using isotope mass balance.

Investigation of different compartments of the water cycle using environmental isotopes

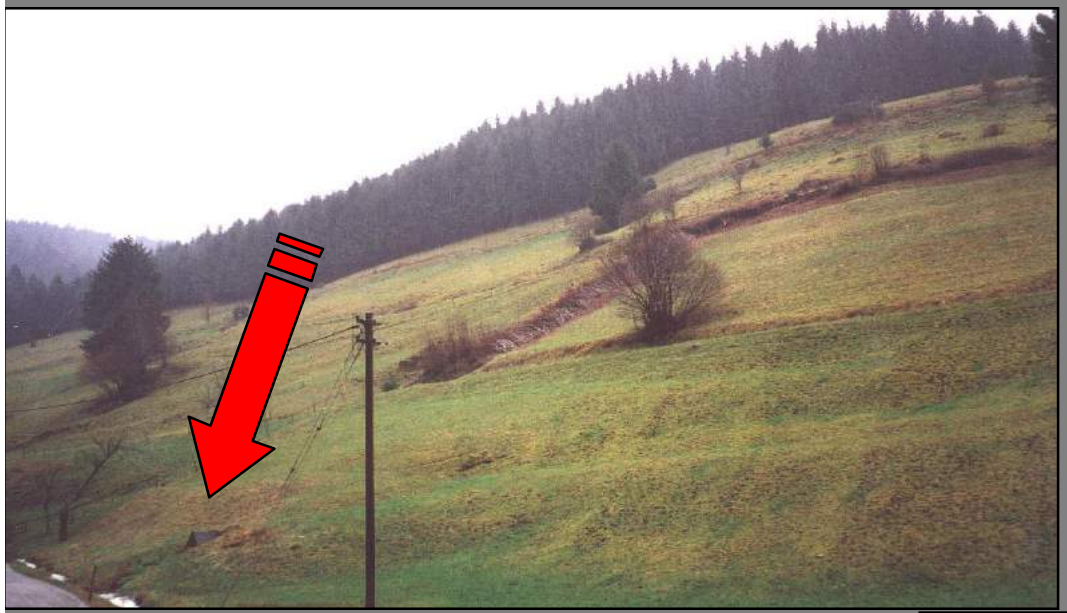
$$P=Q+E+dS/dt$$



Oasis in the desert: Jatropha cultivation can halt soil erosion, increase water storage in the soil and transform barren expanses into lush, productive land.

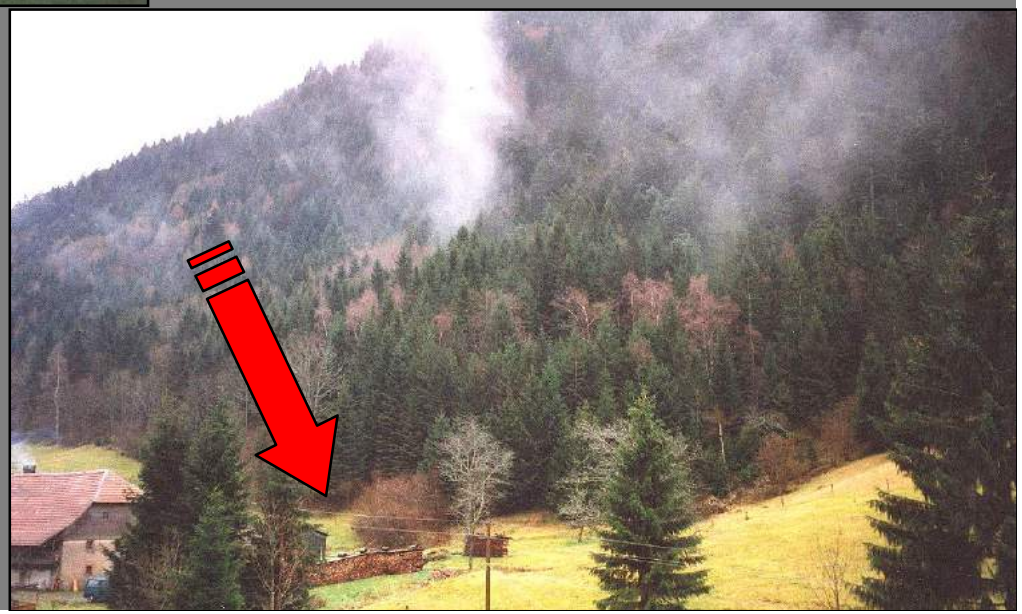
Picture from Fairless, 2007, *Nature*

Studying hillslope processes with environmental isotopes

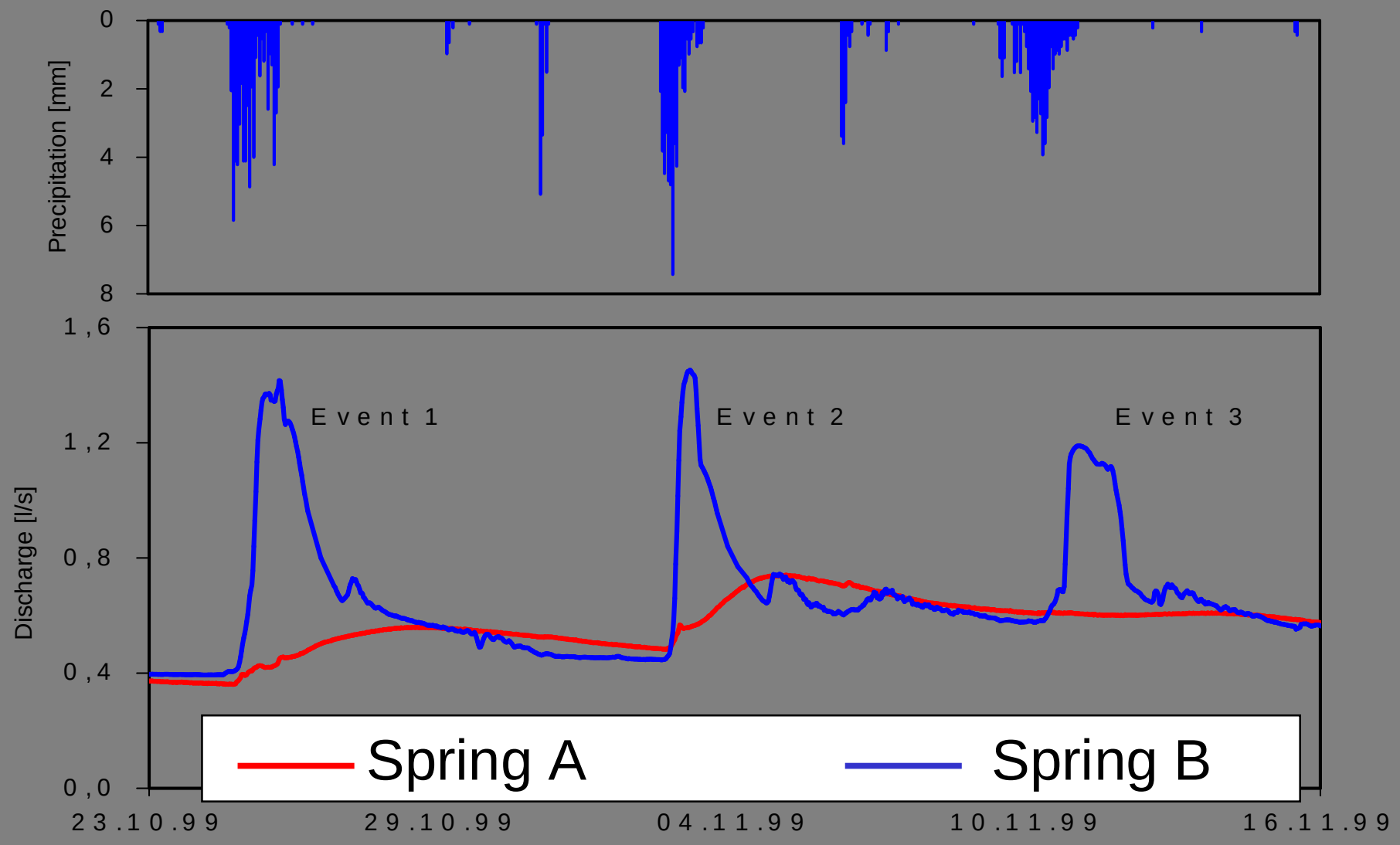


Spring A (Zipfeldobel)

Spring B (Zängerlehof II)



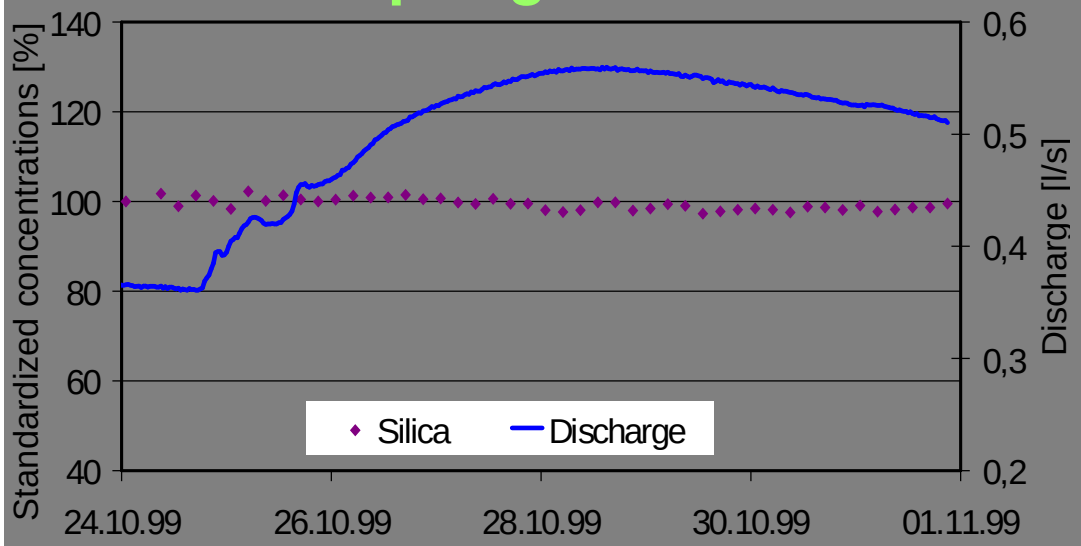
Investigation Period



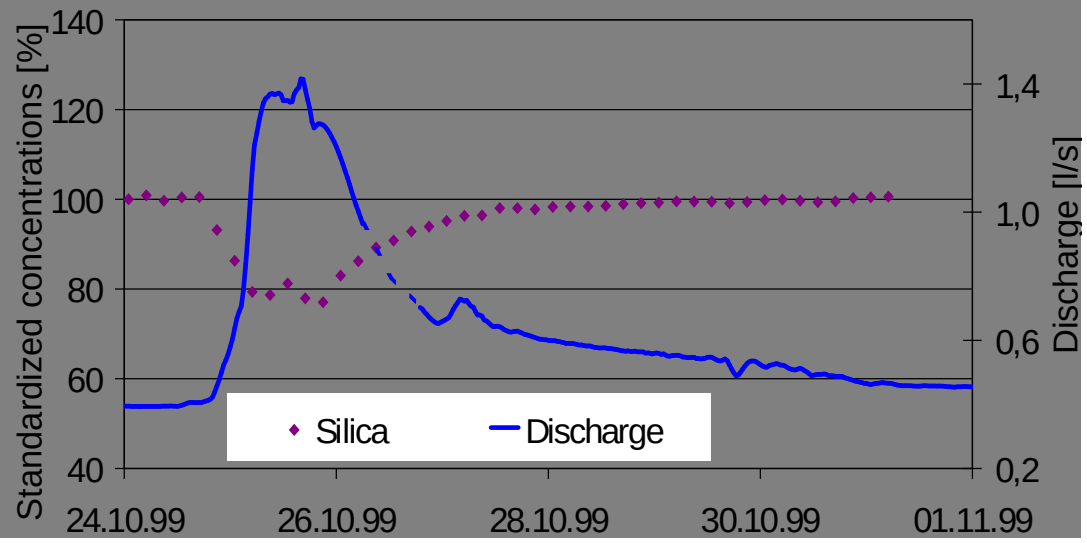
(Uhlenbrook, Didszun, Wenninger, 2008, Hydr. Sci. Journal)

Hydrochemical Dynamics: Dissolved Silica

Spring A

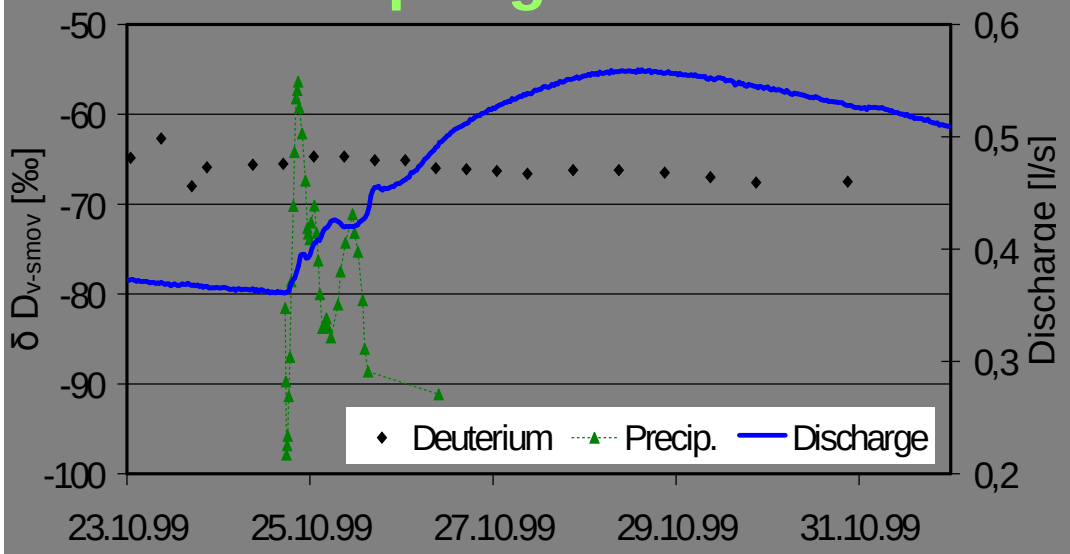


Spring B

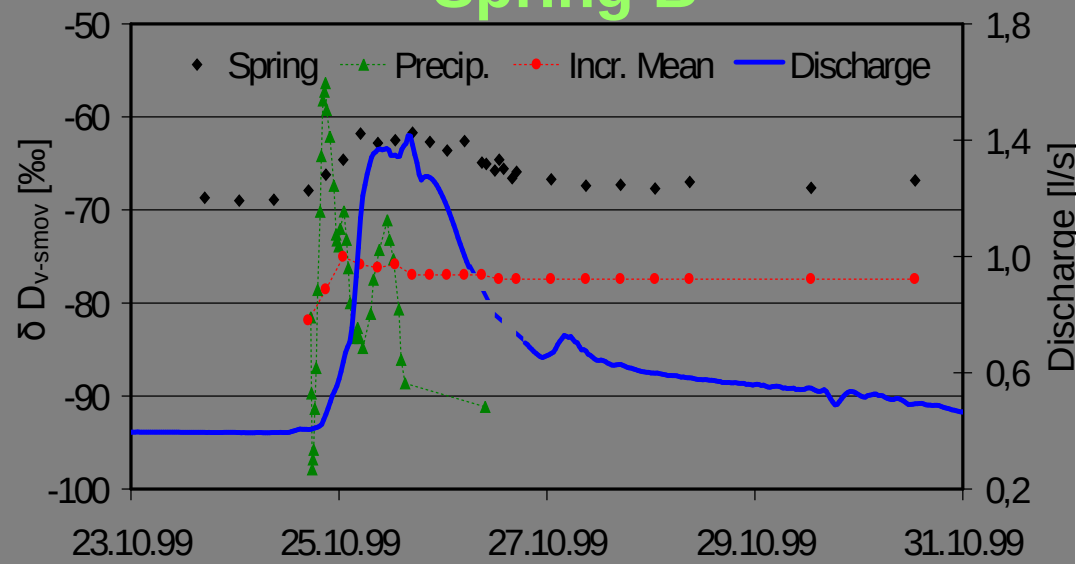


Hydrochemical Dynamics: Deuterium

Spring A

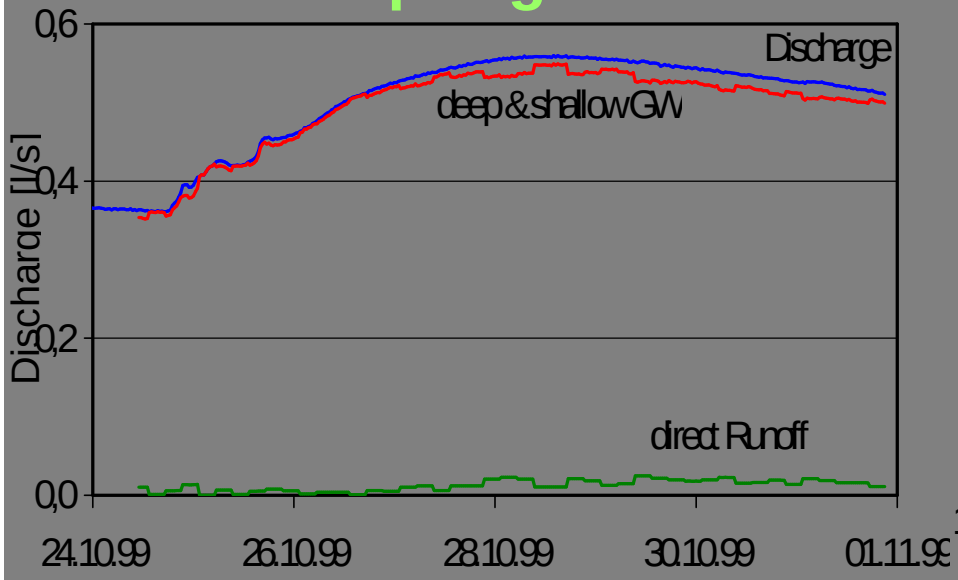


Spring B

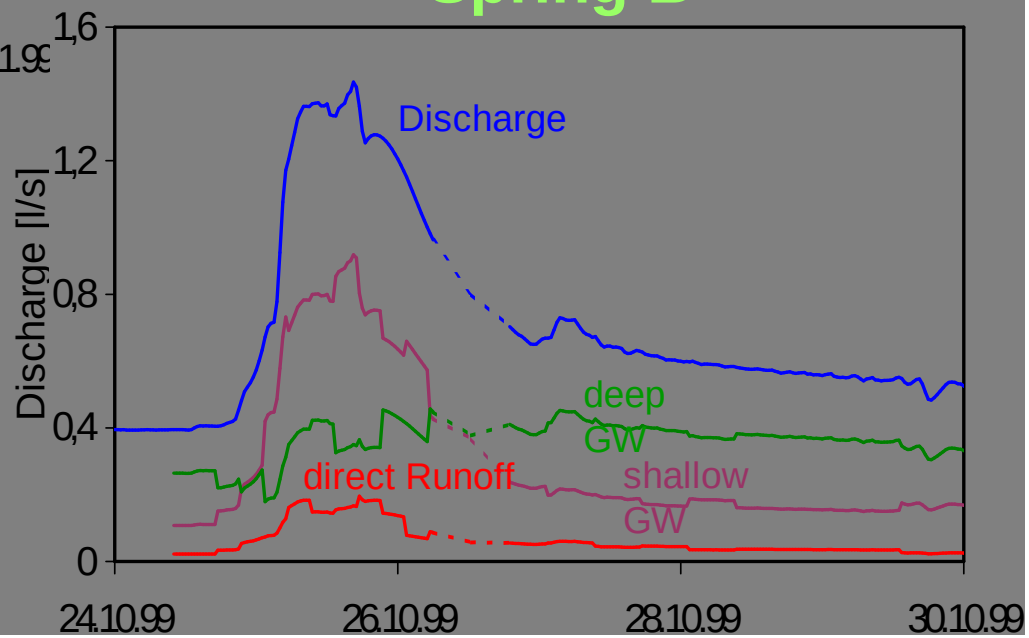


Results of Hydrograph Separation at both Springs/Hillslopes

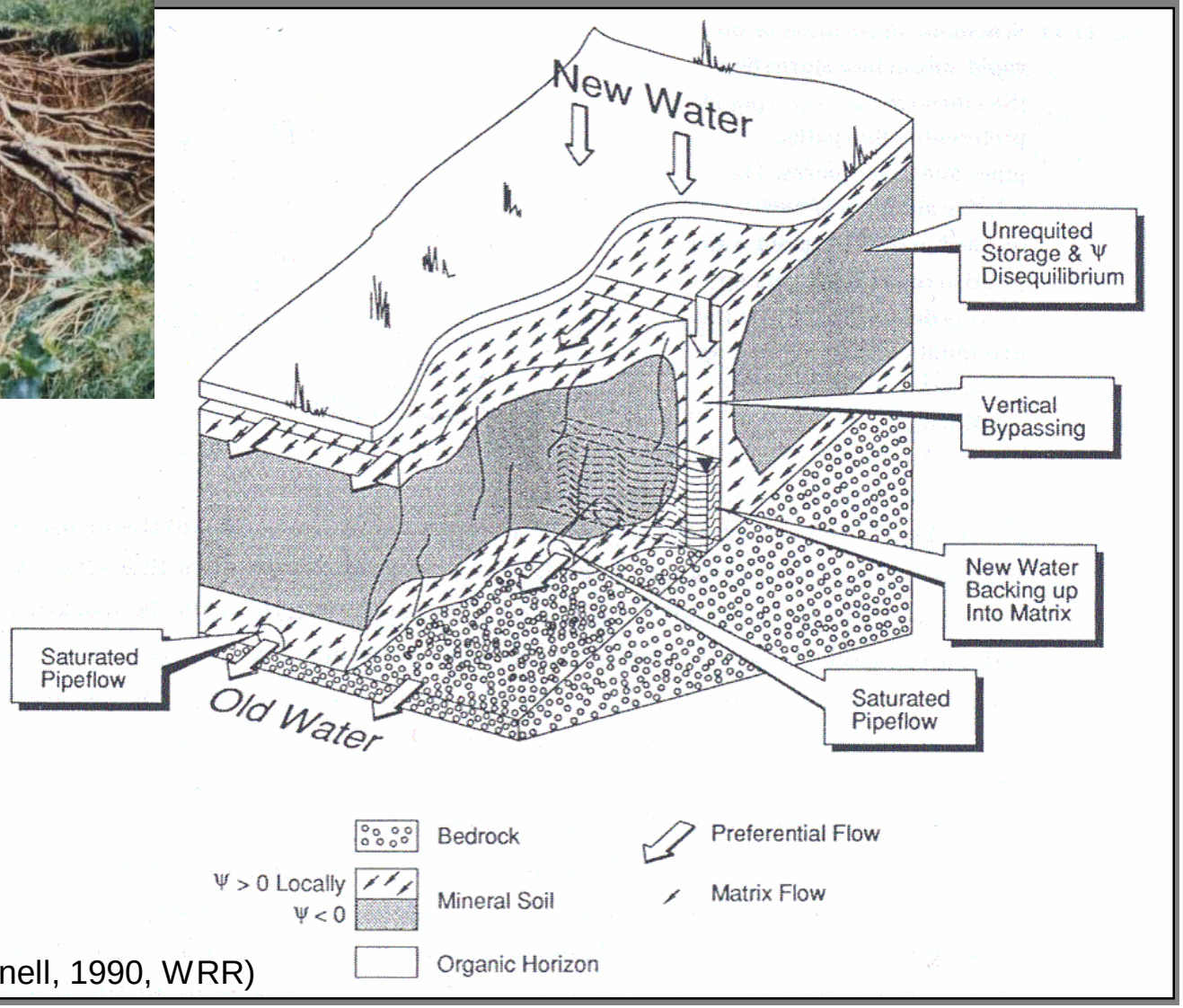
Spring A



Spring B

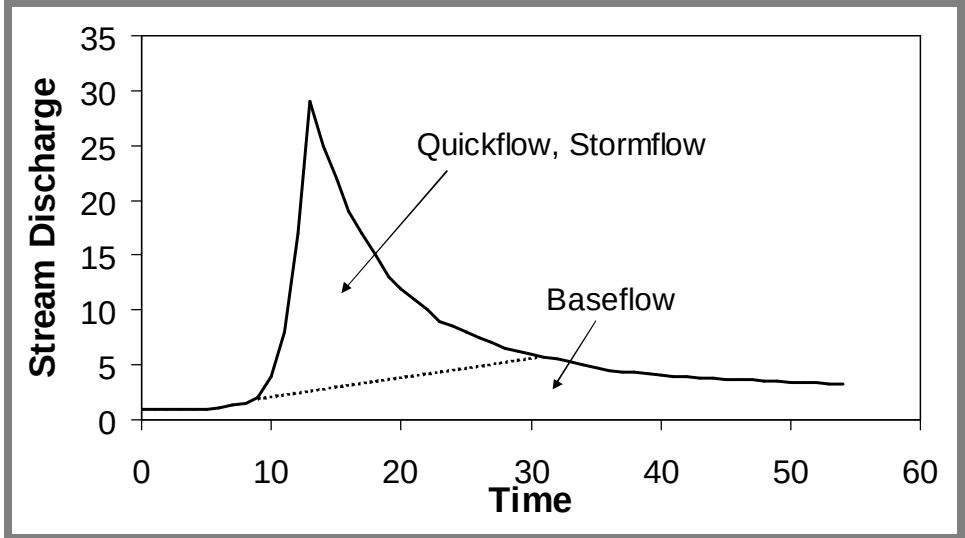


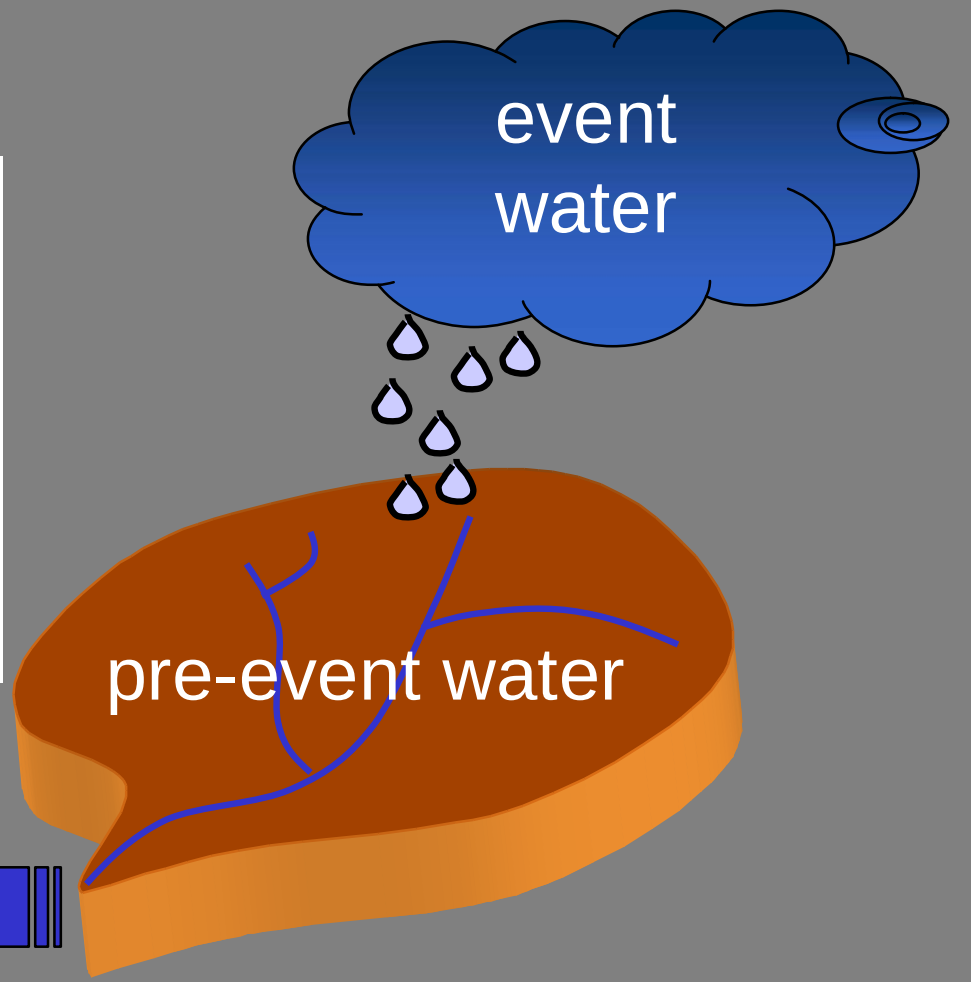
Example: Interpretation of Dominant Processes at the Hillslope Scale



(Mc Donnell, 1990, WRR)

" … all nice, but we need measurements at catchment scale!"

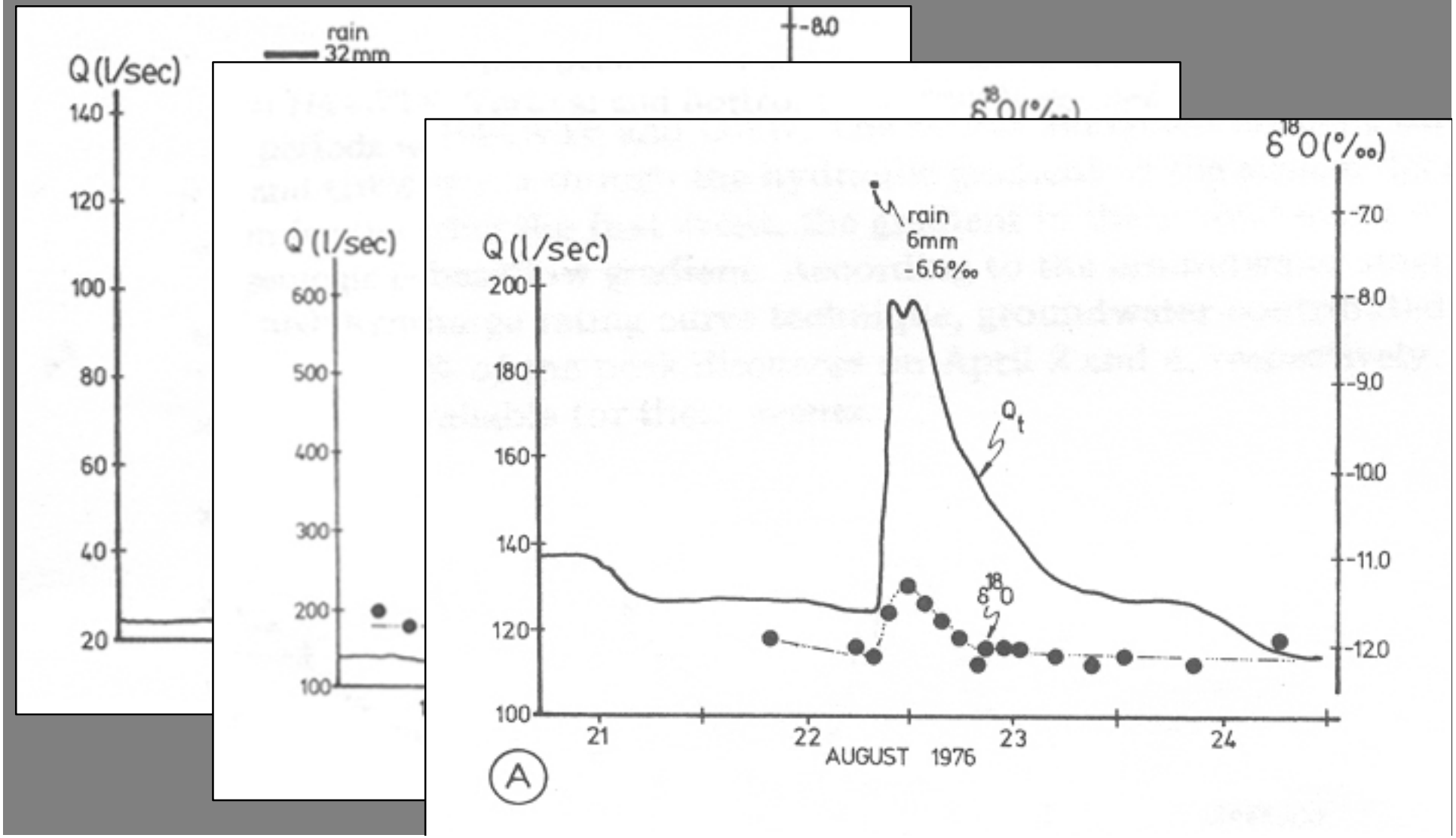




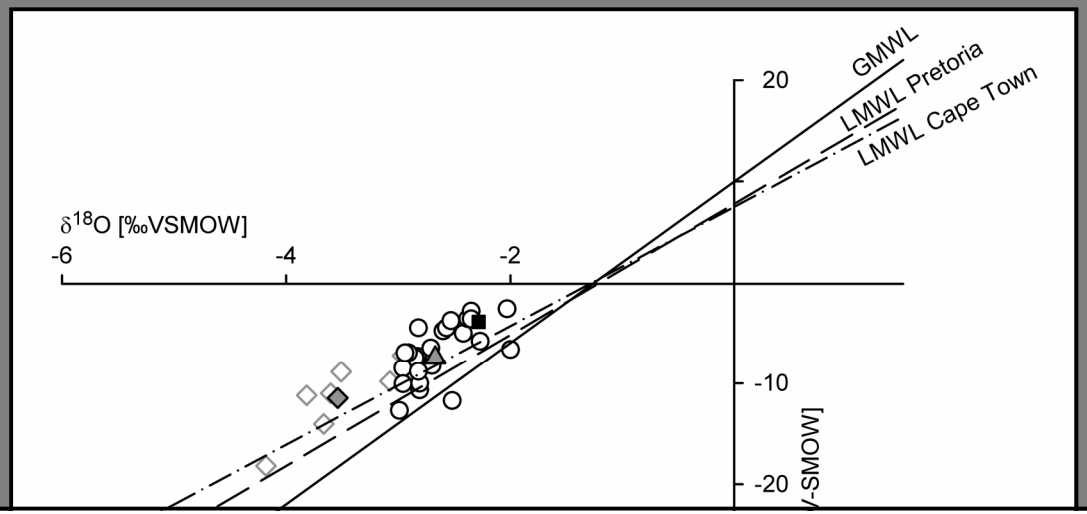
Event (new) and prevent (old) water!

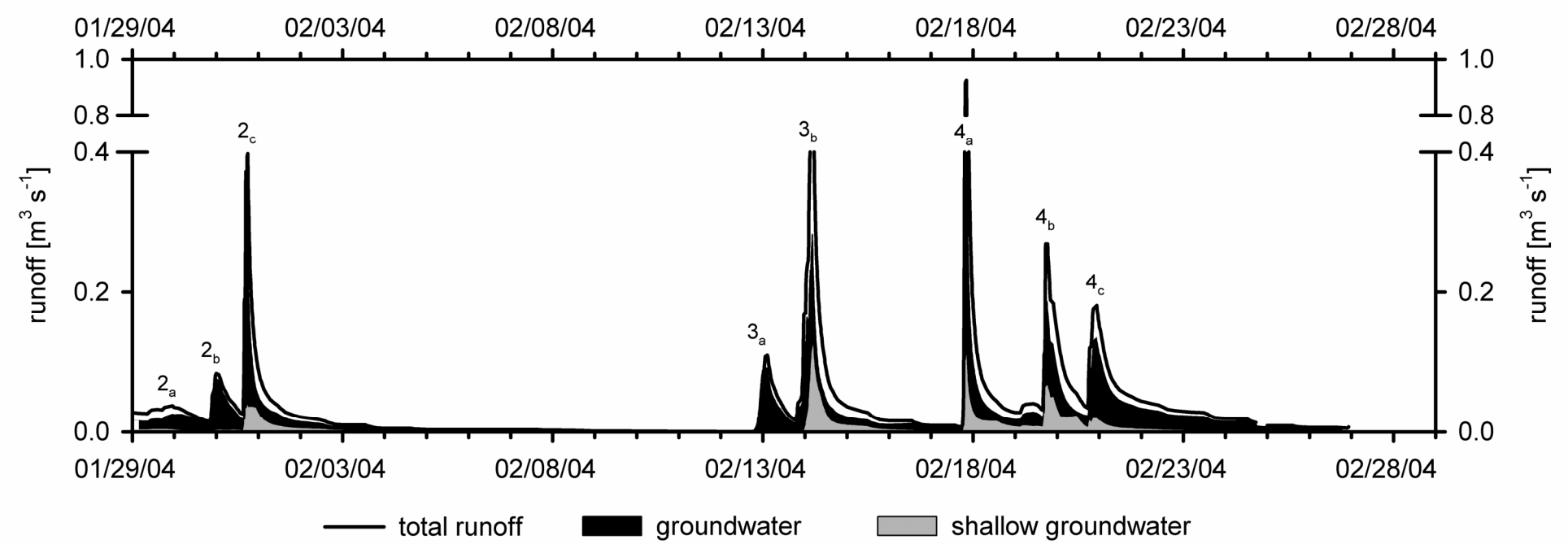
The bench mark paper:

Sklash & Farvolden, 1979: The role of ground-water in storm runoff. *Water Resources Research.*



Tracer-based Hydrograph Separation in the Weatherley Catchment, South Africa

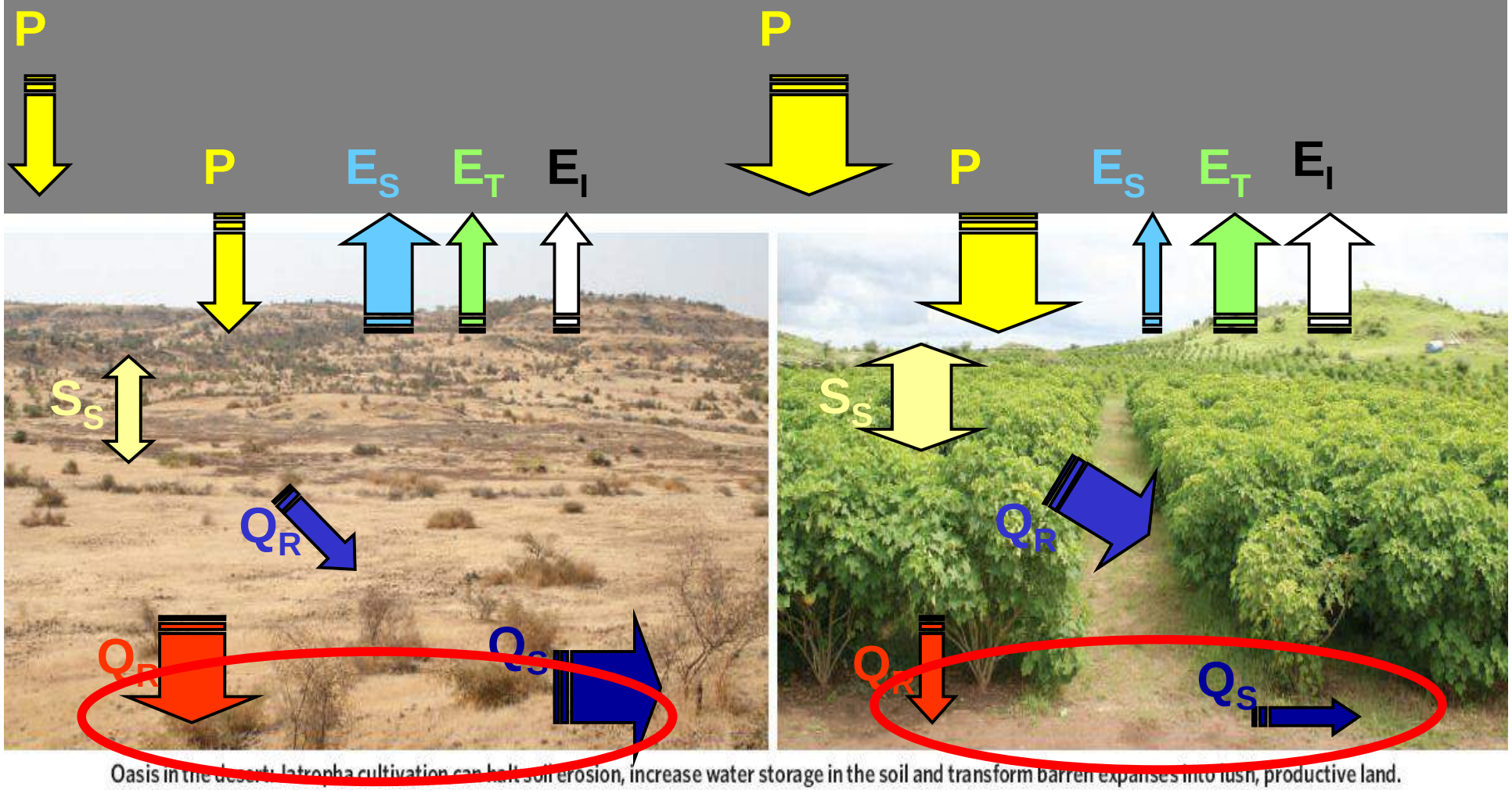




Wenninger, Uhlenbrook, Lorentz, 2008, *Hydr. Sci. Journal*

Investigation of different compartments of the water cycle using environmental isotopes

$$P=Q+E+dS/dt$$

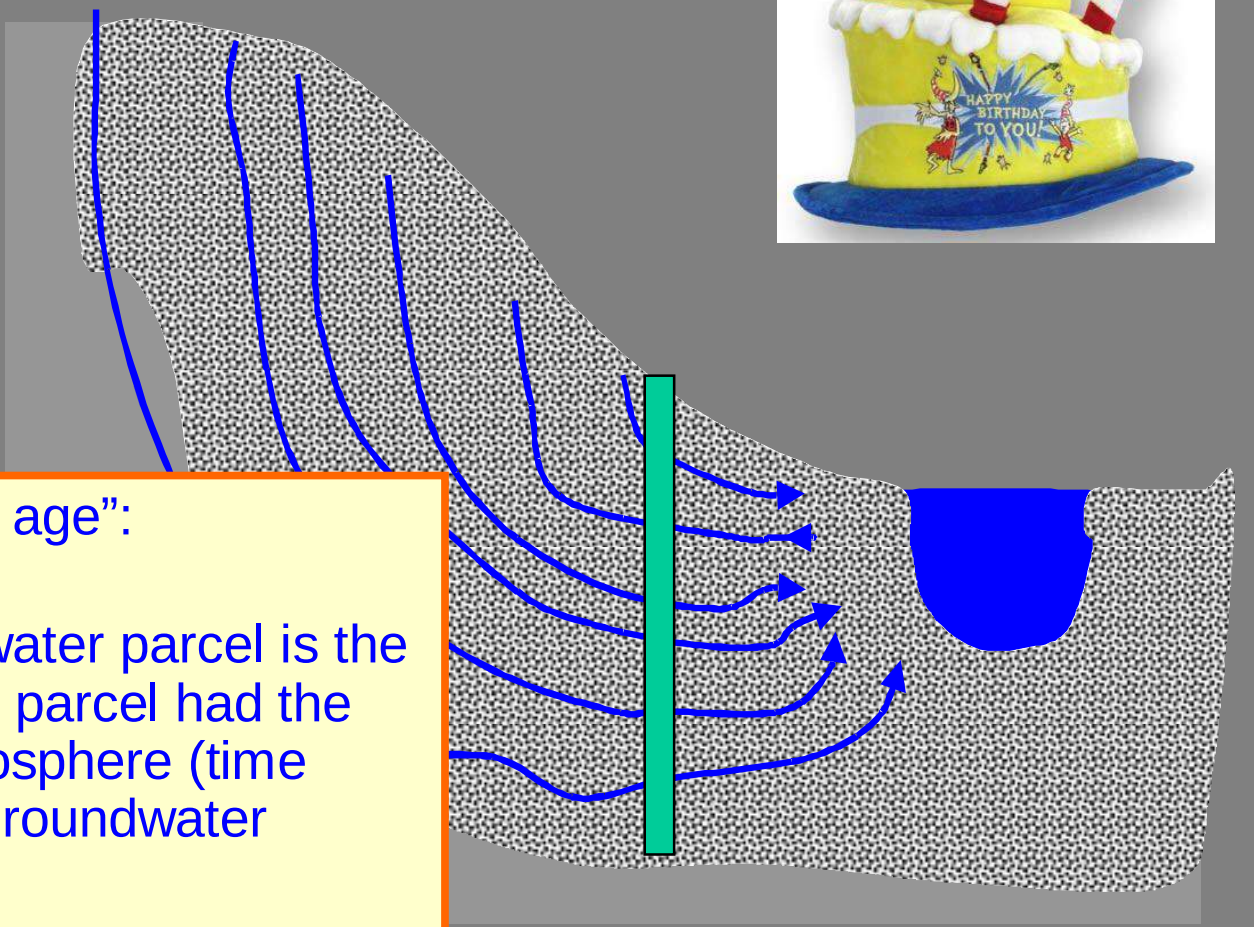


Oasis in the desert: Jatropha cultivation can halt soil erosion, increase water storage in the soil and transform barren expanses into lush, productive land.

Picture from Fairless, 2007, *Nature*

Estimation of Residence Times of Water

Groundwater and surface waters are a mixture of different ages

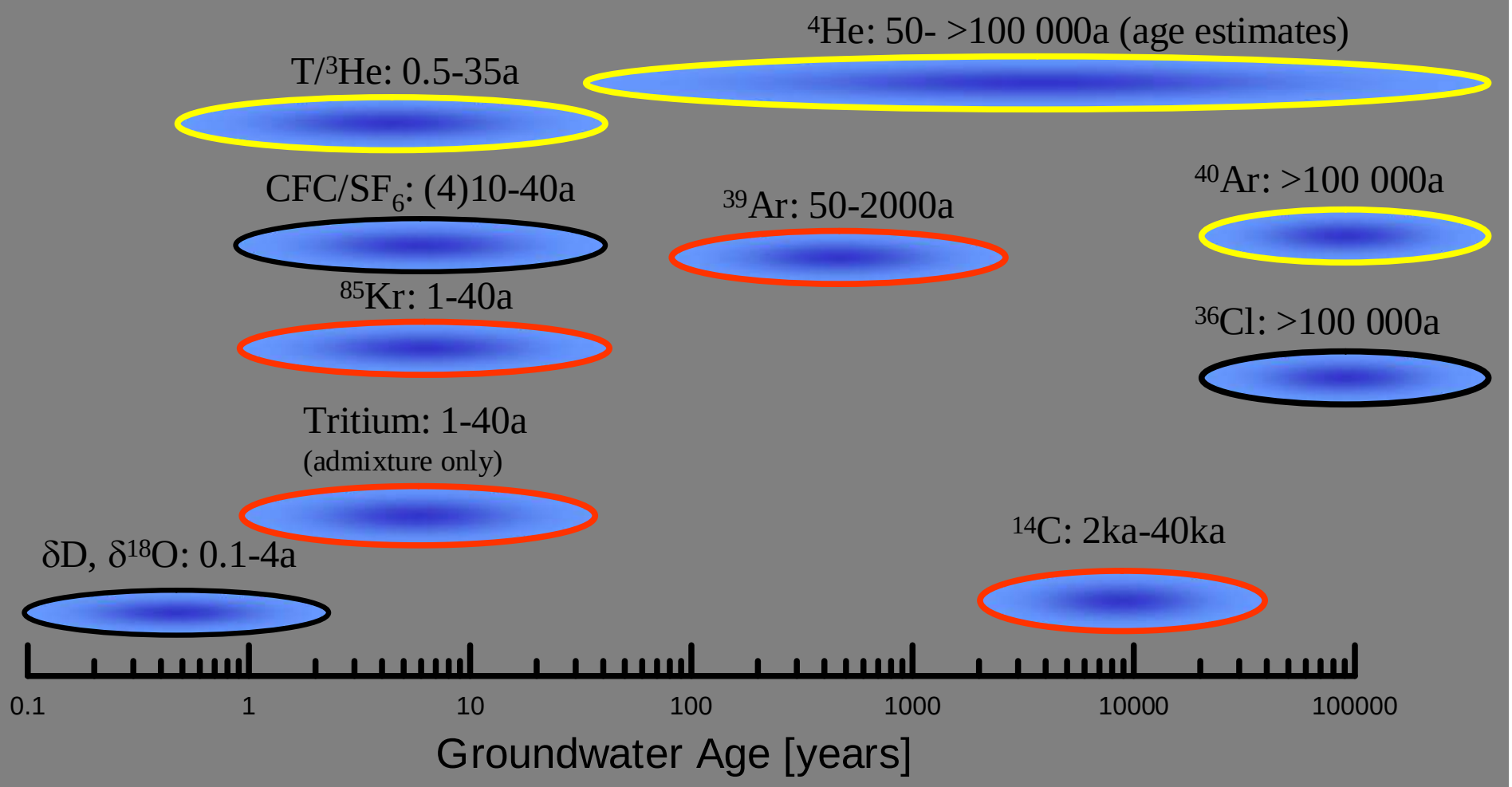


Definition of “groundwater age”:

The “age” of a groundwater parcel is the time elapsed since this parcel had the last contact to the atmosphere (time since recharge at the groundwater surface).

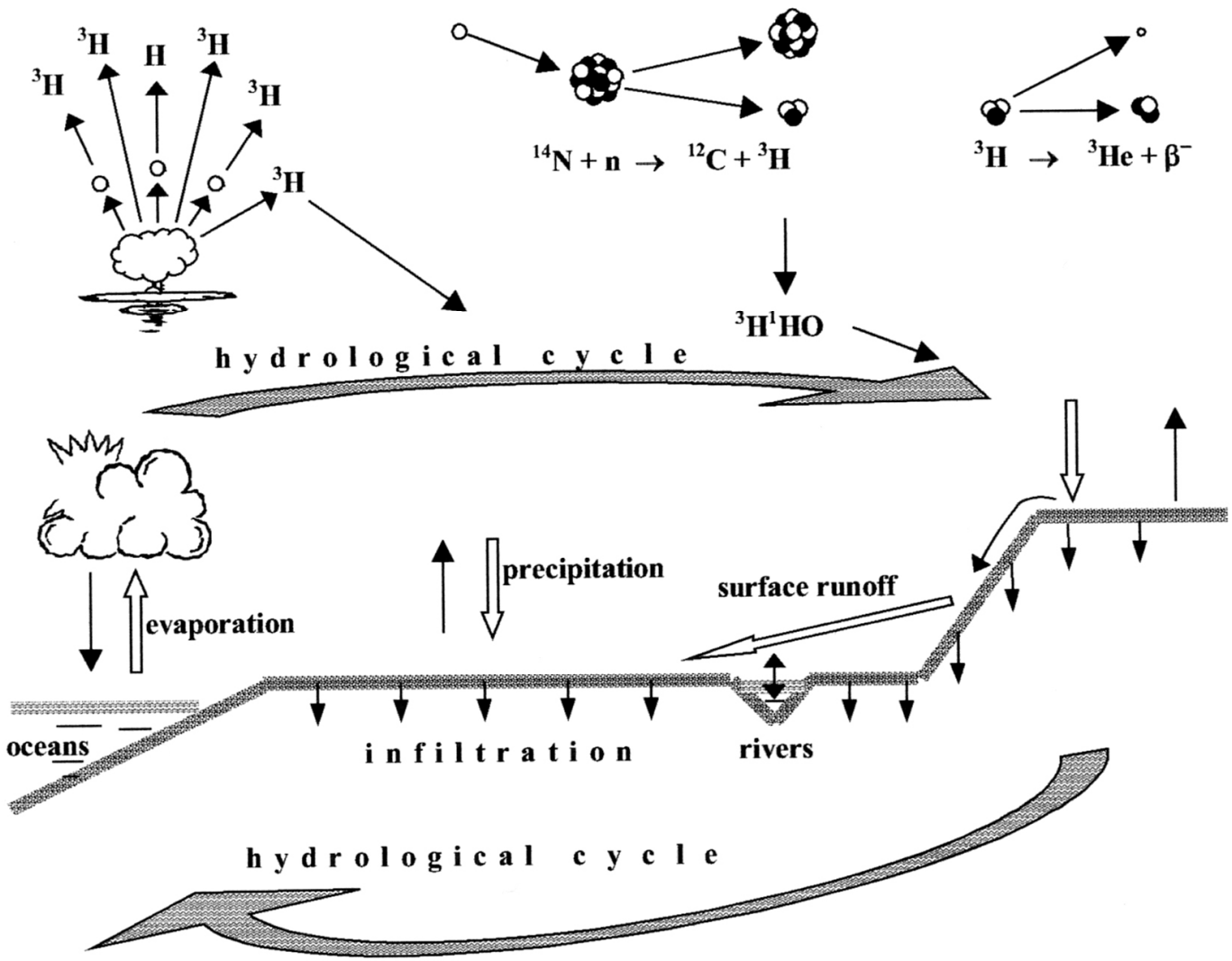
(from: A. Suckow, 2004, IAEA)

Groundwater Residence Time Estimation
('age dating')
Which tracer is useful for which time scales?



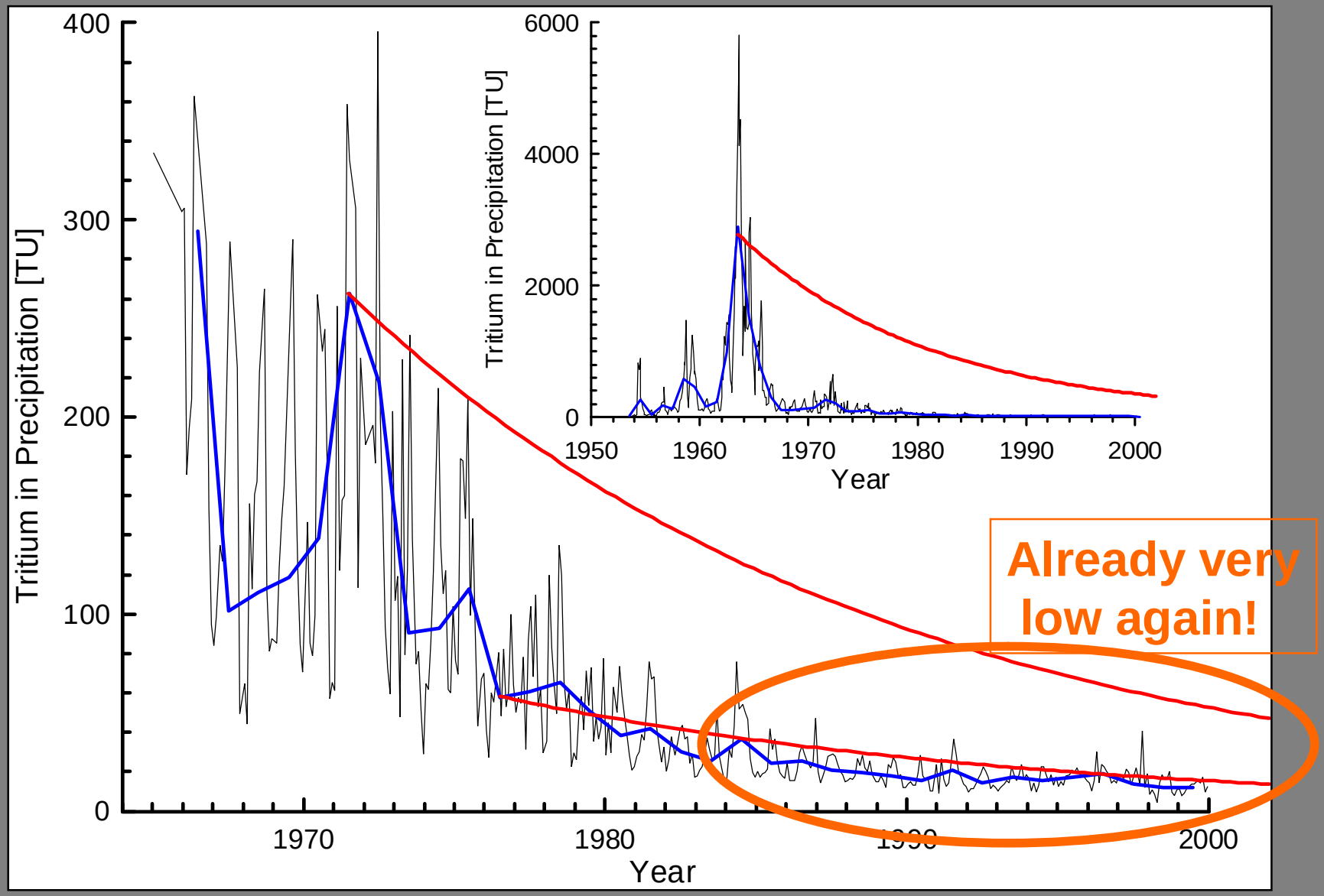
Tritium, ^{3}H

Tritium input into the water cycle



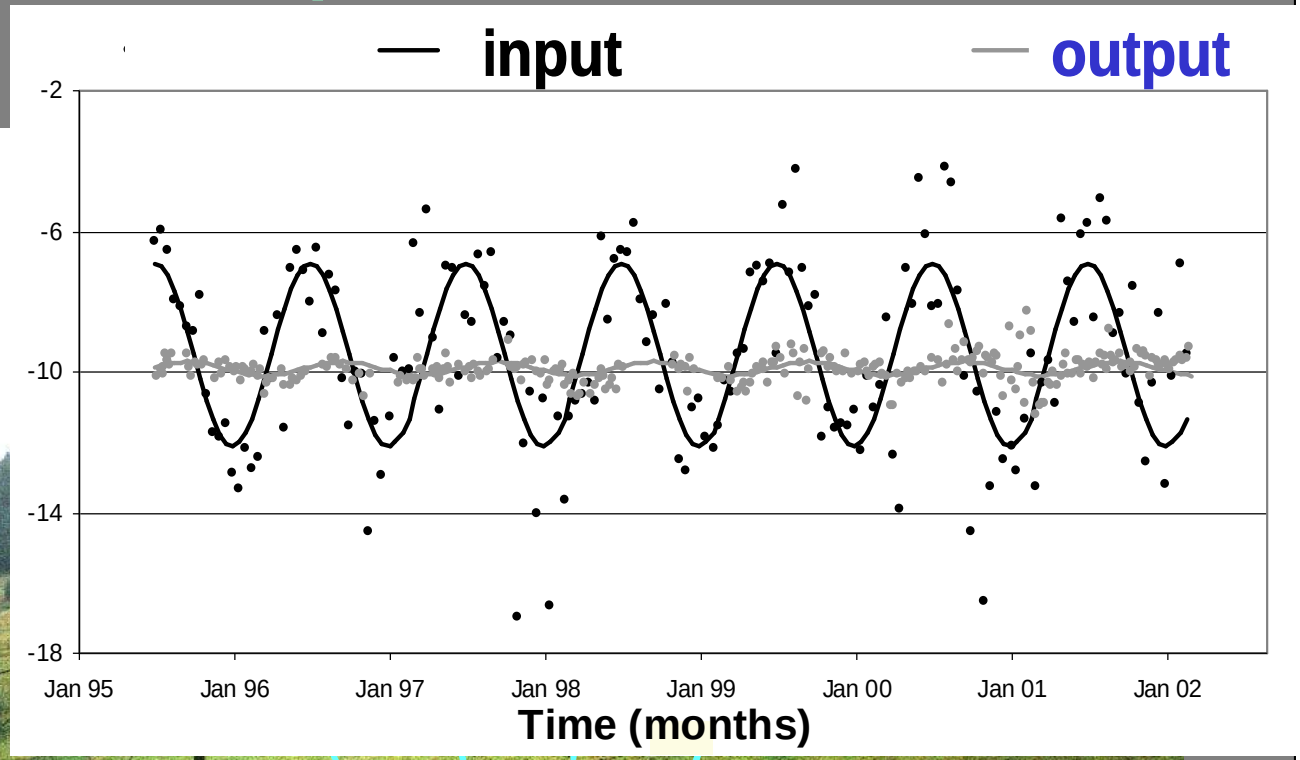
(From: IAEA, 2005)

Tritium input function: Radioactive decay



Estimation of Residence Times

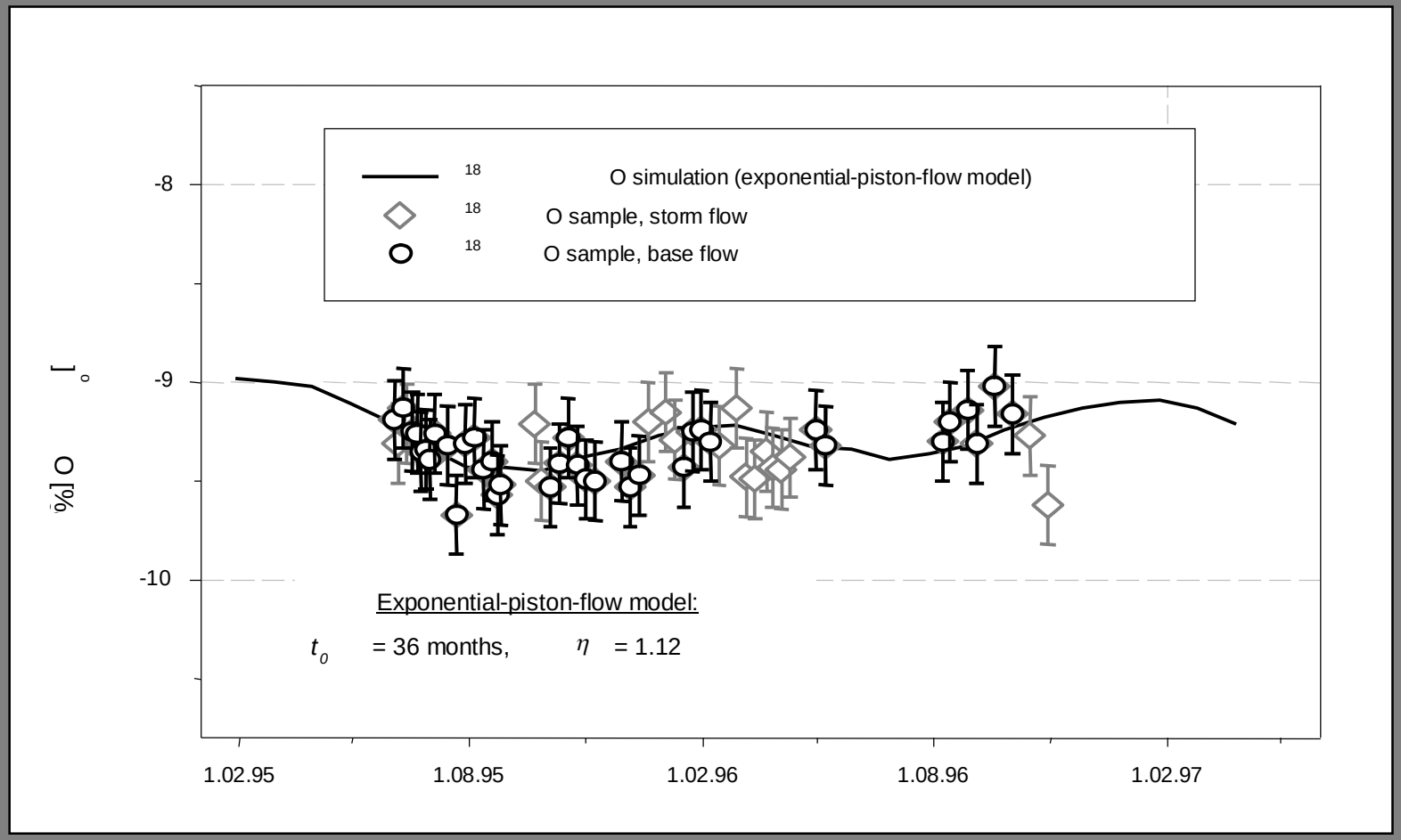
Use environmental isotopes: ^{18}O, ^{2}H, ^{3}H, CFCs ….



spring for water supply

Example for Estimating of Residence Times at a Spring

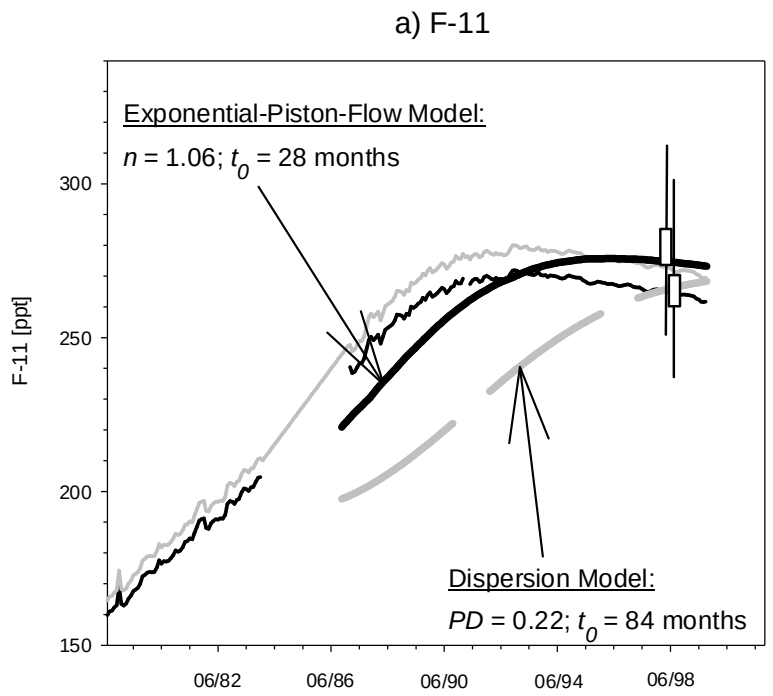
Using environmental isotope: ^{18}O

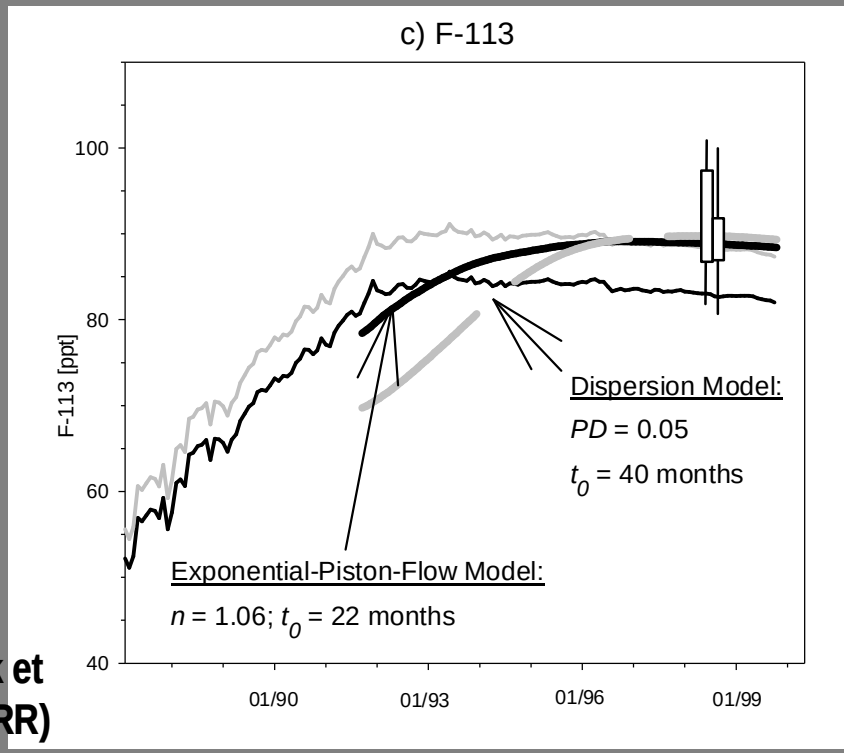


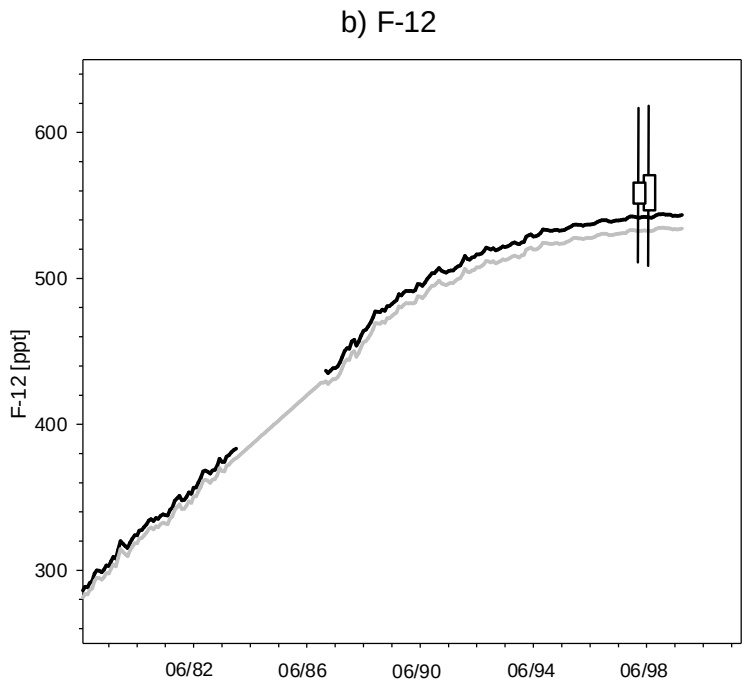
Mean residence time: **26-36 mon**

(Uhlenbrook et al. 2002, *WRR*)

CFCs for dating groundwater -> confirmation of ^3H results



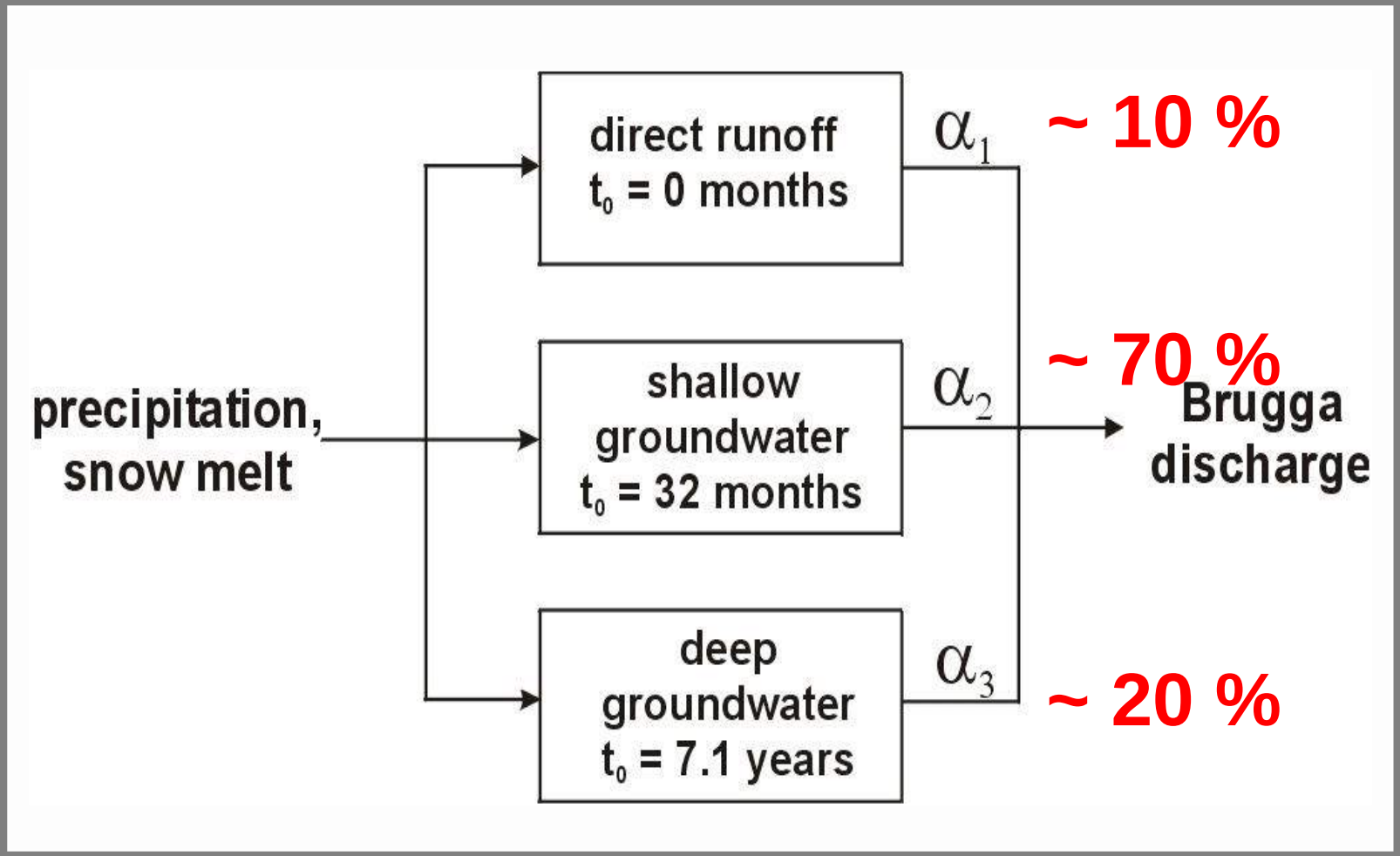




(Uhlenbrook et al., 2002; WRR)

Sub-basin Brugga (40 km²)

Three main flow systems with different residence times and contributions on a seasonal time scale



(Uhlenbrook et al. 2002, *Wat. Resour. Res.*)

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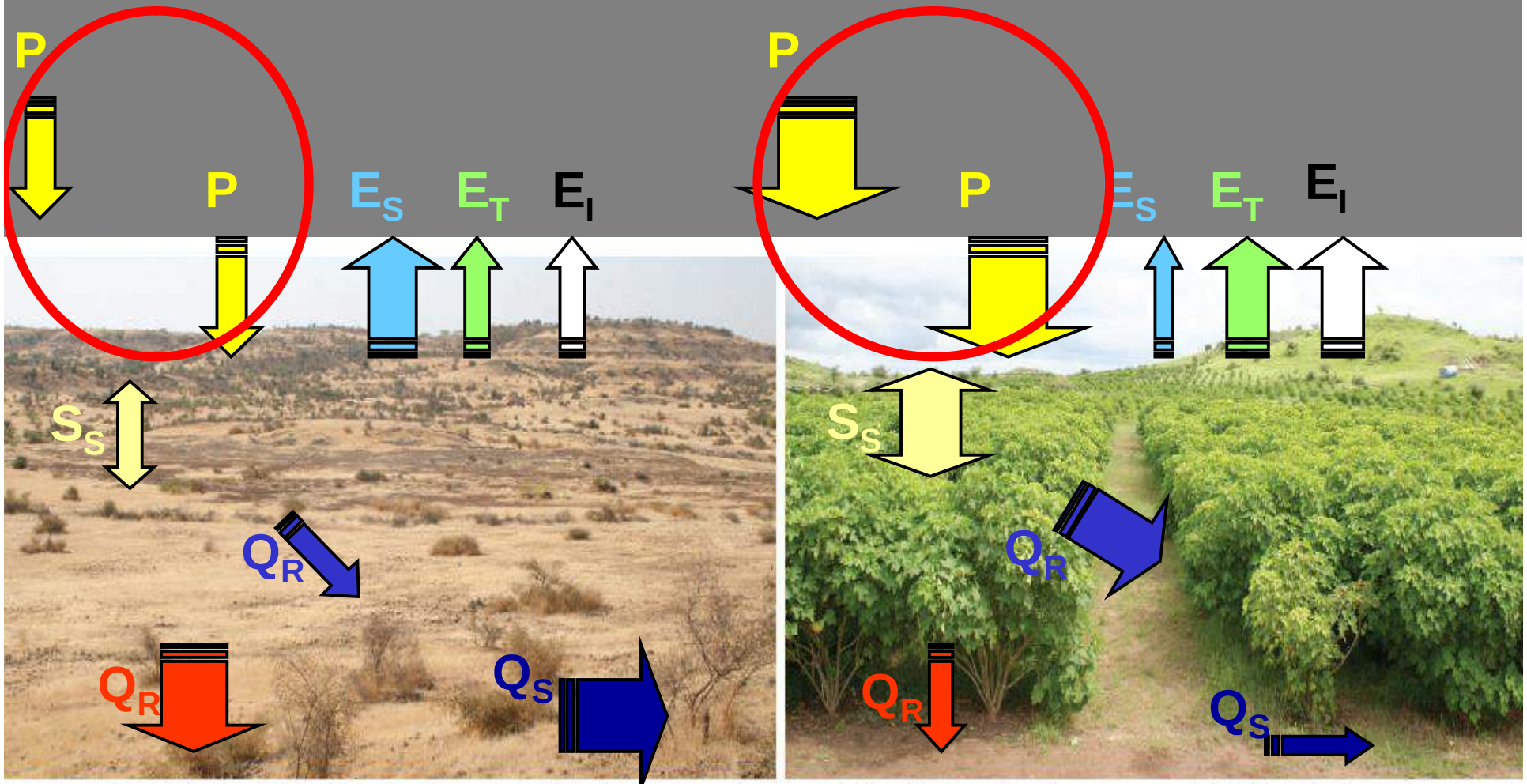

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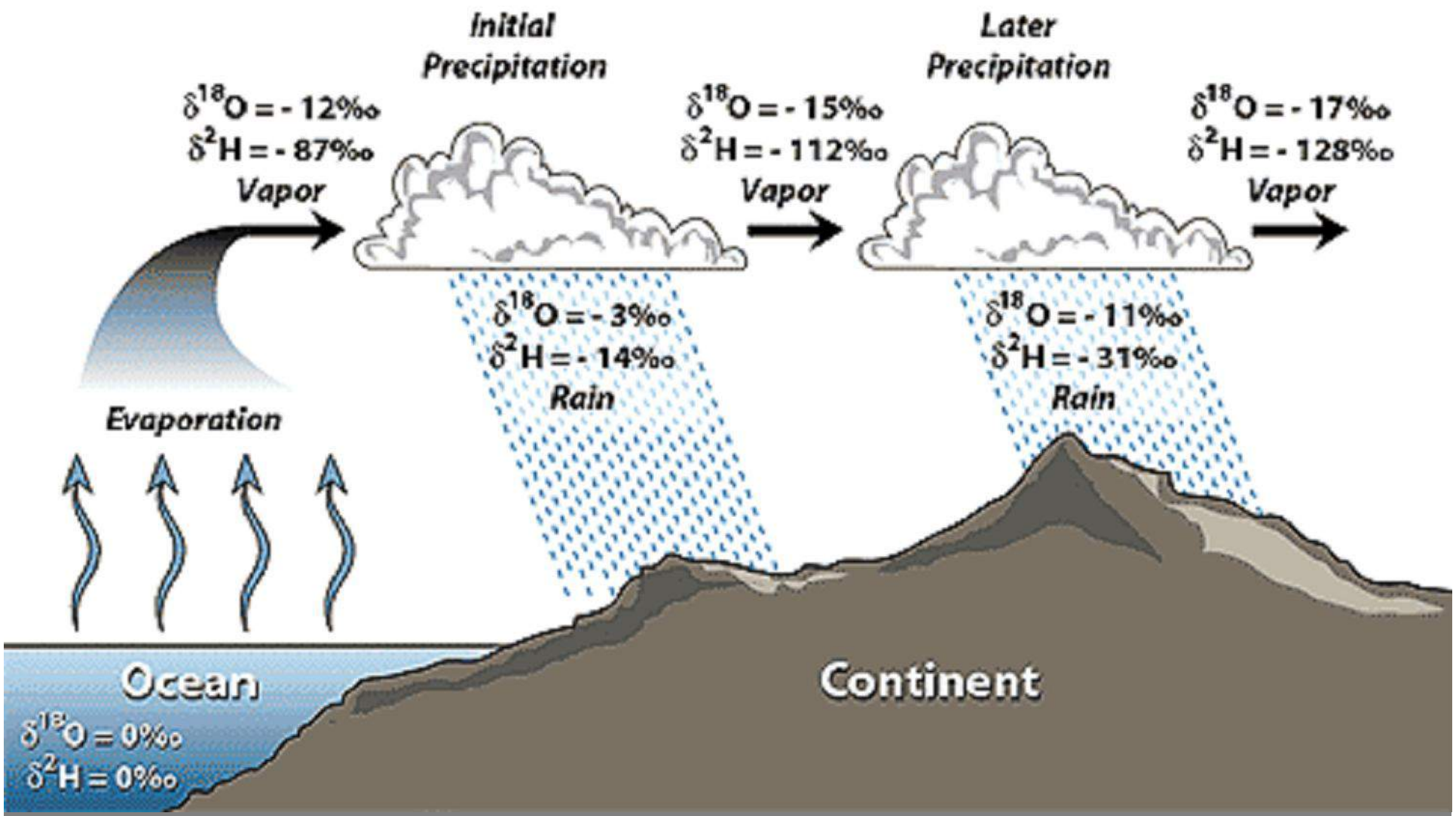
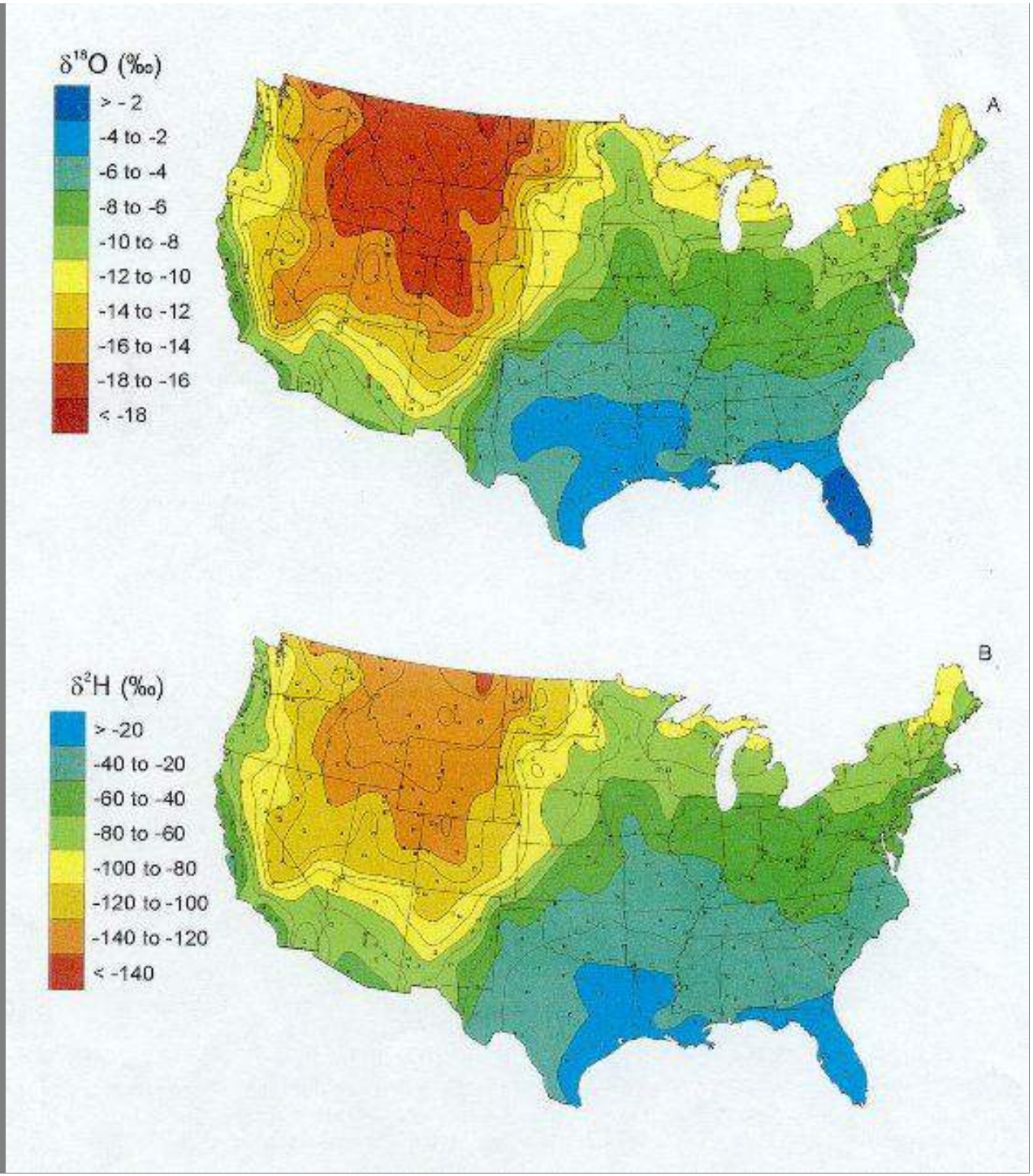
Picture from Fairless, 2007, *Nature*

Changes in Isotopic Composition of Precipitation



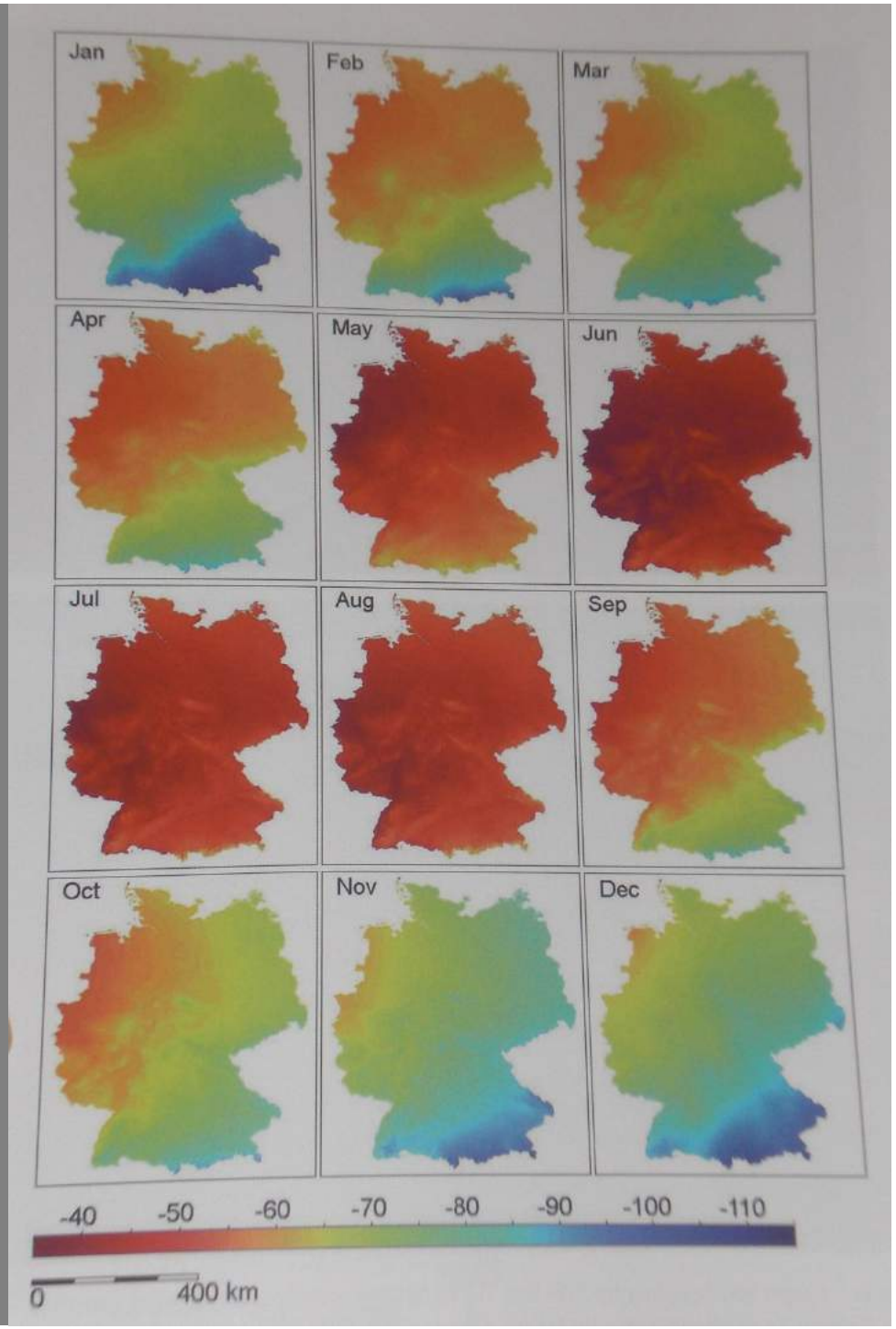
http://www.sahra.arizona.edu/programs/isotopes/oxygen.html

Spatial variations of isotopes in the USA

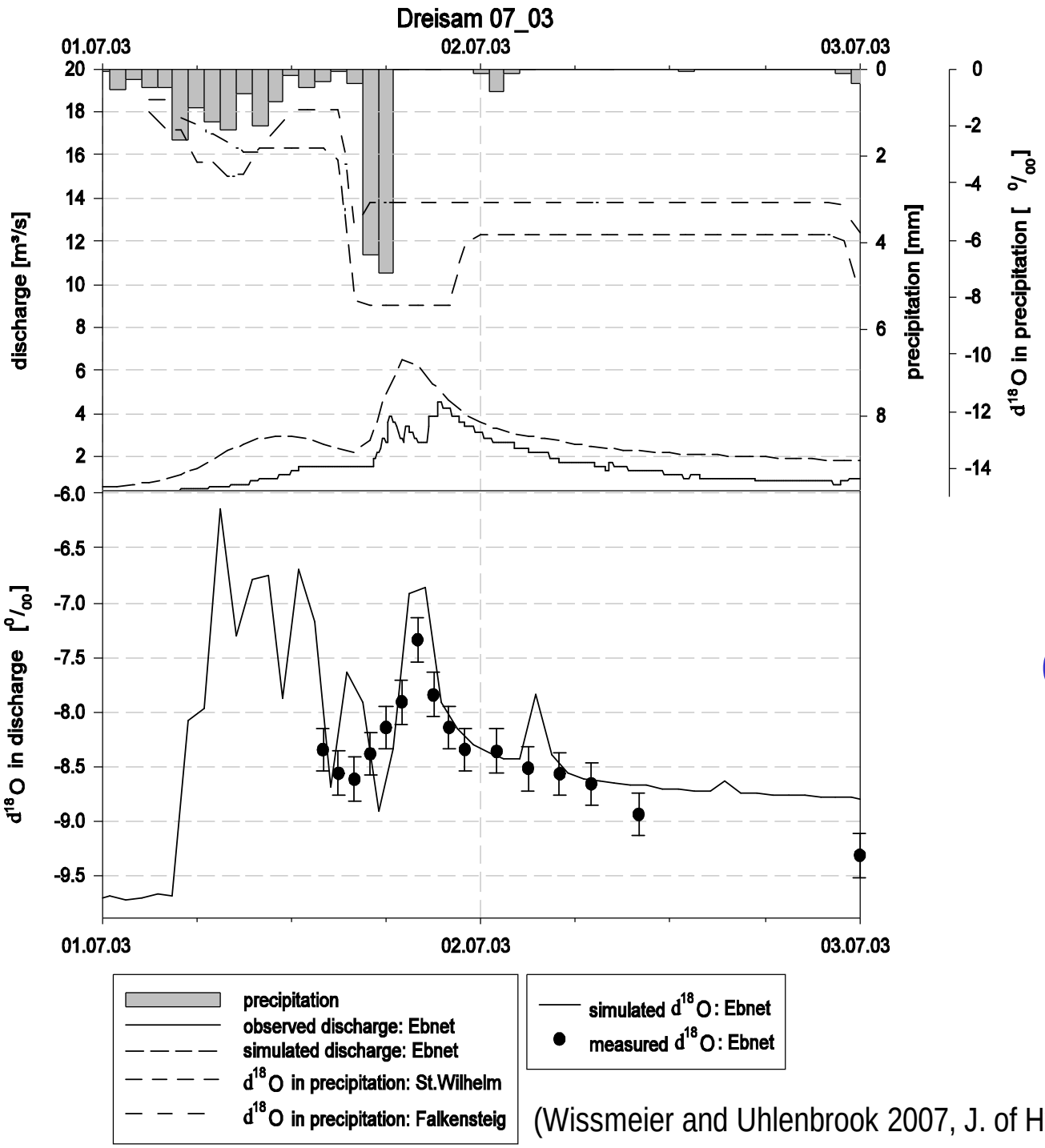


Source: Kendall and Coplen, 2001

Spatial and temporal variations of deuterium in Germany

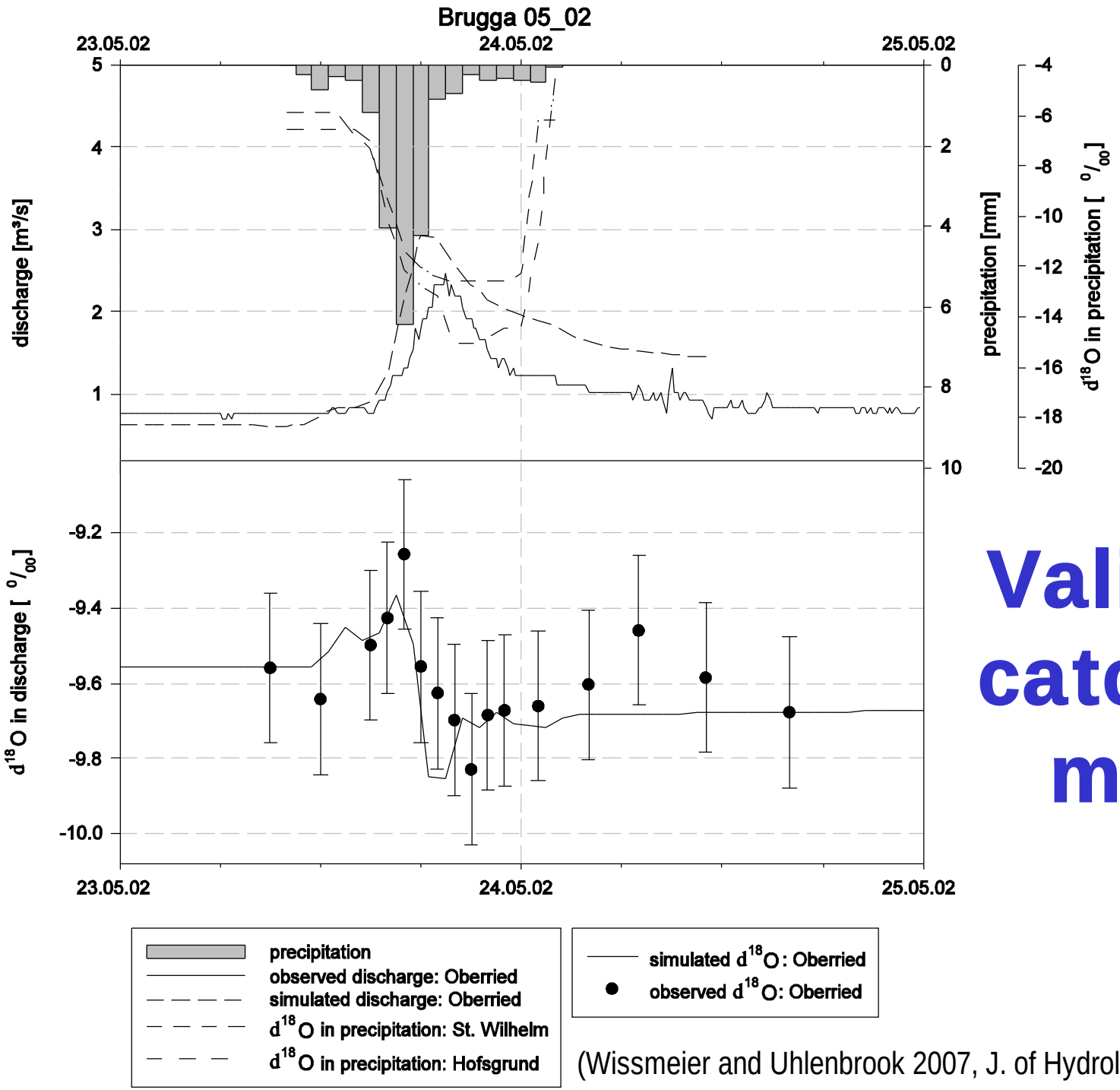


(Source: Leibundgut et al., 2009)



(Wissmeier and Uhlenbrook 2007, J. of Hydrol.)

Validating catchment models



Validating catchment models

(Wissmeier and Uhlenbrook 2007, J. of Hydrol.)

Concluding Remarks – Introduction to Environmental Isotopes

(1) The world is changing – Hydrology too ('stationary is dead')

(2) How can environmental isotopes help us to understand changes and their impacts?

(3) Innovative ways to observe hydrological processes, in particular in combination with other methods (geophysics, model etc.)

(4) Today: Isotope Hydrology using ^{18}O, ^{2}H, ^{3}H, components of the water molecule

(5) Next time: Isotope Biogeochemistry using ^{15}N, ^{13}C and ^{34}S, or other dating techniques noble gases, metals, etc.