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Introduction to Environmental Isotopes

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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
It is Getting Warmer!

The context – ONE
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

\[ P = Q + E + \frac{dS}{dt} \]

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:** \[ P = Q + E + \frac{dS}{dt} \]

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

Where:

\[
\left( \frac{dS_I}{dt} + E_I \right) \quad \text{Interception processes}
\]

\[
\left( \frac{dS_s}{dt} + E_s + Q_s \right) \quad \text{Surface water processes}
\]

\[
\left( \frac{dS_u}{dt} + E_T + E_u + Q_f \right) \quad \text{Root zone moisture processes}
\]

\[
\left( \frac{dS_g}{dt} + Q_g \right) \quad \text{Groundwater processes}
\]

**Possible changes in all variables due to climate and/or land changes!!**
How can Environmental Isotopes help??
Environmental Isotope – Basics

- Protons and neutrons in the nucleus have approximately the same weight
- Electrons (negative charge) are lighter and are located in electron shells
- 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

\[ P = Q + E + \frac{dS}{dt} \]

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
- Evaporation is the driving factor in isotopic fractionation

- Transpiration and Percolation do not cause fractionation

- Quantification between fractionating and non-fractionating losses

- Conservation of mass and isotopes

\[ m_i - m_f = m_p - m_t - m_v - m_z \]

\[ p \cdot X_i + i \cdot X_t + z \cdot X_v + t \cdot X_t = f \cdot X_t + f \cdot X_f \]

with:

\[ m_i = \delta m_i = m_t = m_v = m_z \]

(e.g. Robertson et al. 2006, J. of Hydrol.)
Isotope Depths Profiles and Evaporation Line

\[ y = 3.8x - 18.6 \]

\[ R^2 = 0.95 \]
New way to estimate evaporation fluxes?!

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

\[ P = Q + E + \frac{dS}{dt} \]

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

Precipitation [mm]

Discharge [l/s]

Event 1
Event 2
Event 3

Spring A
Spring B

Hydrochemical Dynamics: Dissolved Silica

Spring A

Spring B

Standardized concentrations [%]

Discharge [l/s]
Hydrochemical Dynamics: Deuterium

Spring A

Spring B

![Graph showing δD and discharge for Spring A and Spring B over the dates 23.10.99 to 31.10.99. The graphs include data points for deuterium, precipitation, and discharge.](image-url)
Results of Hydrograph Separation at both Springs/Hillslopes

Spring A

Discharge [l/s] over time from 24.10.99 to 01.11.99. Graph showing direct runoff and deep & shallow GW discharge.

Spring B

Discharge [l/s] over time from 24.10.99 to 30.10.99. Graph showing direct runoff, deep GW, and shallow GW discharge.
Example: Interpretation of Dominant Processes at the Hillslope Scale

(Picture: P. Mosley)

(McDonnell, 1990, WRR)
“... all nice, but we need measurements at catchment scale!”

Event (new) and prevent (old) water!
Tracer-based Hydrograph Separation in the Weatherley Catchment, South Africa

Investigation of different compartments of the water cycle using environmental isotopes

\[ P = Q + E + \frac{dS}{dt} \]

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

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: 0.1-40a
- CFC/SF₆: (4)10-40a
- ⁸⁵Kr: 1-40a
- Tritium: 1-40a (admixture only)
- δD, δ¹⁸O: 0.1-4a
- ¹⁴C: 2ka-40ka
- ⁴⁰Ar: >100 000a
- ³⁶Cl: >100 000a
- ³⁹Ar: 50-2000a
- ⁴He: 50- >100 000a (age estimates)
- ³⁶Ar: 50-2000a
- ⁴⁰Ar: >100 000a
Tritium, $^3$H
Tritium input into the water cycle

(From: IAEA, 2005)
Tritium input function: Radioactive decay

Already very low again!
Estimation of Residence Times

Use environmental isotopes: $^{18}\text{O}$, $^2\text{H}$, $^3\text{H}$, CFCs, …
Example for Estimating of Residence Times at a Spring

Using environmental isotope: $^{18}\text{O}$

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

(Uhlenbrook et al. 2002, WRR)
CFCs for dating groundwater

confirmation of $^3$H results

(Uhlenbrook et al., 2002; WRR)
Sub-basin Brugga (40 km$^2$)

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

Investigation of different compartments of the water cycle using environmental isotopes

\[ P = Q + E + \frac{dS}{dt} \]

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

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)
Validating catchment models

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