## Hydrological Measurements

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Hydrograph separation





## **Hydrograph Separation**

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- ... sorry, but my references are sometimes incomplete!!

### Objectives of this lecture

- 1. Why isotope hydrograph separations?
- 2. Difference to graphical hydrograph separations and hydrograph separations using hydrochemical tracers
- 3. Classical 2-component separation and 3component separation
- 4. Brief introduction to the complexity of runoff generation processes
- 5. Case studies

### **Moldau River at Prague**



Photo © Czech Hydrometeorological Institute

(From: Dr. Tomas Vitvar, IAEA)

### Hudson River Tributary, New York





(From: Dr. Doug Burns, USGS)

### **Runoff Processes ??**

- Direct precipitation on stream channel
- Overland flow
  - 1. Infiltration excess (Horton-type overland flow)
  - 2. Saturation excess return or direct precipitation on saturated areas
- Subsurface storm flow (see fig.); i.e., macropore flow, groundwater ridging, transmissivity feedback, piston-flow mechanisms *Complex and NOT*

fully understood!!!







# Brief history of hydrograph separation techniques

- Graphical hydrograph separation was the dominant method from the 1930s through 1960s
- Solute tracers were used to separate hydrographs in the 1960s (still used today)
- Natural isotope tracers were used to separate hydrographs beginning in the 1970s



The bench mark paper: Sklash & Farvolden, 1979: The role of groundwater in storm runoff. WRR.





# Why do we separate hydrographs using tracers?

- We hope to learn something about the age and sources of stream flow as well as about the stream flow generation processes
- Usually we need physical hydrologic data (e.g. groundwater levels, soil moisture, surface runoff, artificial tracers) in addition to a separation based on tracers to deduce stream flow generation processes and hydrologic flow paths
- Two principally different separations using tracers:
  - Time-source separation: divide the hydrograph into new and old water, or event and pre-event water

#### isotope tracers

 Geographic-source separation: divide the hydrograph in terms of contributions from different landscape position (e.g. groundwater in the riparian zone, saturated hillslope hollows, organic horizon of the soil)

hýdrochemical (and isotope) tracers

### Some important terms

- **Component** or **end-member:** part of the hydrograph separated based on tracers, doesn't necessarily have physical meaning
- Hydrologic flow paths: pathway through the landscape by which water reaches the stream (e.g. shallow groundwater flow through the soil organic horizon, overland flow from hillslope hollows)
- Component not the same as hydrologic flow path
- Component could represent water that has largely traveled to the stream via a hydrologic flow path, but not necessarily Example: shallow soil water identified as important component of runoff in many watersheds, but quantifying the contribution of soil water to the stream tells nothing about how soil water arrived at the stream

#### Hydrograph separation Solution of simple mass balance calculations

- Simplest approach is a two-component separation where:
   Storm flow = "new" water + "old" water
   New water = rain or melting snow; event water
   Old water = groundwater, soil water etc.; pre-event water
- New water sometimes called "event" water, old water sometimes called "pre-event" water
- Hydrograph separation only works when the isotopic composition of new and old water are significantly different (greater than analytical precision)

#### Hydrograph separation Solution of mass balance expression

If,  $Q_s = \text{stream flow (m^3/s)}$   $\delta_s = \text{isotopic comp. stream flow (‰)}$   $Q_o = \text{old water (m^3/s)}$   $\delta_o = \text{isotopic comp. old water (‰)}$  $Q_n = \text{new water (m^3/s)}$   $\delta_n = \text{isotopic comp. new water (‰)}$ 

$$\begin{aligned} Q_{s} \cdot \delta_{s} &= Q_{o} \cdot \delta_{o} + Q_{n} \cdot \delta_{n} \\ Q_{s} &= Q_{o} + Q_{n} \\ \end{aligned}$$
Then, 
$$\begin{aligned} Q_{n} &= Q_{s} \cdot (\delta_{s} - \delta_{o}) / (\delta_{n} - \delta_{o}) \end{aligned}$$

 Can calculate the proportion of stream flow that consists of new and old water at any point during a storm for which isotope samples have been collected

# Example from New Zealand



(Anderson and Burt, 1990) .

## Data needed to perform a two-component separation

- Continuous measurement of stream discharge
- Bulk sample of the rainfall or snowmelt (better: incremental sample -> intra-storm variability)
- Sample of stream water collected at base flow before the event or sample of 'representative' groundwater (but also soil water and other old water components ...)
- Series of samples of the stream collected throughout the event

## Isotope hydrograph separation vs. graphical hydrograph separation



### Example: Woods Lake, Adirondack Mtns., New York

- Snowmelt, March, 1990 Base flow, March 12,  $\delta^{18}O = -13.40$ Melting Snow  $\delta^{18}O = -17.98$ Peak flow, March 16,  $\delta^{18}O = -14.85$
- What is the percentage of "new" water in the stream at peak flow?

• 
$$Q_n/Q_s = (\delta_s - \delta_o)/(\delta_n - \delta_o)$$

$$= [-14.85 - (-13.40)]/[-17.98 - (-13.40)] = 0.317$$

31.7% of stream flow was snowmelt at peak flow

Effect of small difference in isotopic composition on separation result (*uncertainty!*)

Example from Woods Lake: Assume that the stream base flow was only 0.2 ‰ (2 x analytical precision of +/- 0.1 ‰) different than the snowmelt

If  $\delta^{18}$ O of snowmelt = - 13.60 ‰  $\delta^{18}$ O of base flow = - 13.40 ‰  $\delta^{18}$ O of peak flow = -13.50 +/- 0.1 ‰

Then % of new water in stream at peak flow: 50% if  $\delta^{18}$ O of peak flow was -13.50 ‰ 0% if  $\delta^{18}$ O of peak flow was -13.40 ‰ 100% if  $\delta^{18}$ O of peak flow was -13.60 ‰

# Assumptions of isotope hydrograph separations

- 1. Significant difference in the isotopic composition of the new and old water
- 2. Rainfall or snowmelt (event water) has isotopic composition constant in space and time or variations can be accounted for
- 3. Old water (pre-event water) has isotopic composition that is constant in space and time or variations can be accounted for
- 4. Contributions from any other component (e.g. soil water) are negligible or are similar to groundwater (old water)
- 5. Contributions from surface water storage are negligible

# Key conclusions from 2-component isotope hydrograph separations

- Most of the quick flow consists of water stored in the catchment prior to the event (old water, preevent water); at least in humid temperate zone
- Contrary to the results of graphical hydrograph separation
- "Robert E. Horton was wrong (with some exceptions)?!?" (or, used to simple assumptions?)
- Limitation: Isotope hydrograph separations alone cannot tell us the hydrologic flow paths by which runoff reaches the stream

Are contributions from a 3<sup>rd</sup> component (e.g. soil water) always negligible?

• NO, of course not!

Two-component hydrograph models often yield impossible results when the isotopic composition of a third component (often soil water) is not included in the model

 Need to incorporate soil water in humid temperate region has led to the development of three-component models

Example: DeWalle et al. (1988) found old water that exceeded 100% of stream flow before soil water was incorporated into the model

# Three-component hydrograph separation

- This approach arose largely because many two-component model approaches yielded impossible results because soil water of a different isotopic composition than groundwater was contributing to streamflow during storms (Kennedy et al. 1986; DeWalle et al. 1988); in particular in North-America and Europe
- To perform a three-component separation, you need to use two tracers (commonly an isotope and a solute such as chloride or silica), and you often need to sample soil water prior to the storm (usually with tension or zero-tension lysimeters)
- Two approaches to three-component modeling have been used:
   1. DeWalle et al. (1988) method measures throughfall intensity and incorporates into the model

2. Ogunkoya and Jenkins (1993) solved three equations with two unknowns

Better look to my set of equations on the black board!

### Mixing triangle



Burns et al., 2001



## Example: three-component separation

# Hydrochemical tracers can be used similarly to isotope tracers

- Often easier to obtain/analyze than isotope data because of cost and ease of analysis (there are still not so many labs that analyze  $\delta^{18}$ O and  $\delta$ D)
- Biggest hurdle is assumption of conservative mixing, solute tracers are altered by biogeochemical processes
- Probably most common solute used as tracer is chloride, Cl<sup>-</sup>, and then alkalinity (or acid-neutralizing capacity, ANC) and dissolved silica, Si, but studies have used DOC, SO<sub>4</sub><sup>2-</sup>, Na<sup>+</sup>, and many others
- Just because solute tracer participates in biogeochemical reactions in watershed (e.g. Si is released by chemical weathering, but sometimes taken up by diatoms) doesn't necessarily mean that it doesn't behave conservatively over a short period of time during runoff from a rainstorm

## Hydrochemical vs. isotope tracers (2 component separations)



Richey et al., 1998



### Take home messages

- Hydrograph separations can provide further insights into the water origin, flow paths and residence time
- Hydrograph separations using graphical method or tracer method (isotopes of hydrochemistry) result in different results (different approaches!)
- Classical 2-component separation using isotopes quantifies the contributions of new (event) water and old (pre-event) water
- 3-component separation needs an additional tracer (usually hydrochemical tracer)
- Runoff generation process identification requires more hydrometric data (groundwater levels, soil moisture, etc.)