Using deuterium and tritium to estimate storage and mean transit times in watersheds, and applications to contamination problems

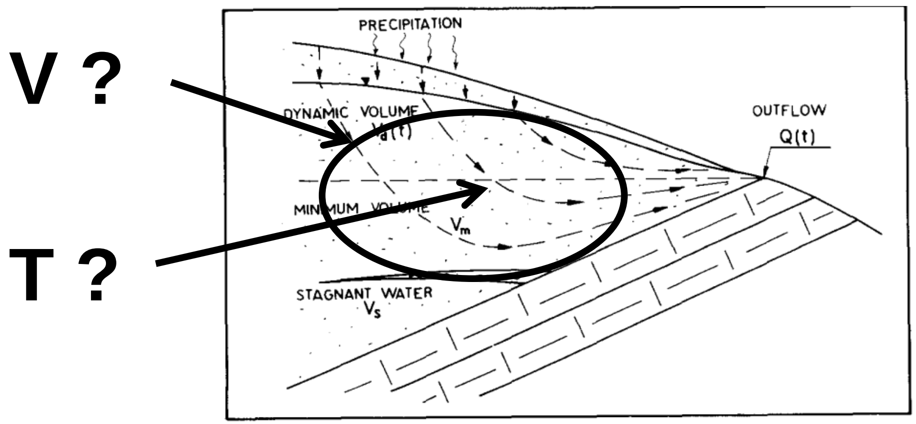
Copenhagen University
September 2023

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG
Ministère du Développement durable
et des Infrastructures

Administration de la gestion de l'eau

Two practical and related problems faced by hydrogeologists

- How much water (V) is stored in the aquifer or in the watershed ?
- In case of contamination by diffuse sources, what remediation times T are to be expected (i.e. how quickly contaminated water is replaced by uncontaminated water)?



Zuber (JoH 86, 1986)

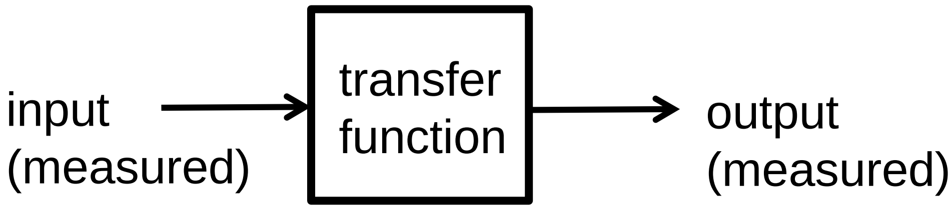
- Both quantities are related: T=V/Q

➔We can use a „tracer“ to learn about the storage volume and release behaviour of the aquifer/the watershed

Tracer: a measurable „substance“ applied naturally or artificially over the study area.

Principles of water dating using lumped-parameter models

- The problem is framed as an input-output situation

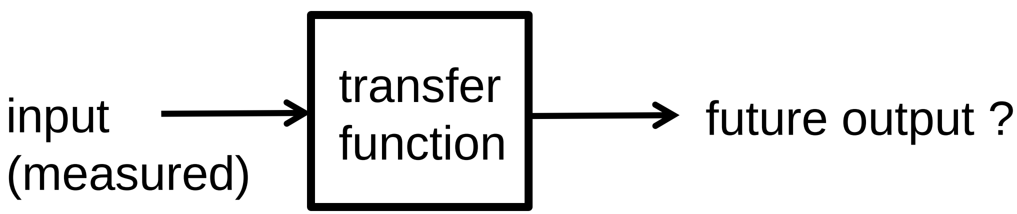


- Tracer input and output are <u>measured</u>
- The parameter(s) of the transfer function are <u>estimated</u>

➔ we obtain a mean transit time $\overline{T}$

➔ $V = \overline{T}.Q$ Or $V = \overline{T}.\mathrm{R}$ (Q=mean discharge, R=mean recharge)

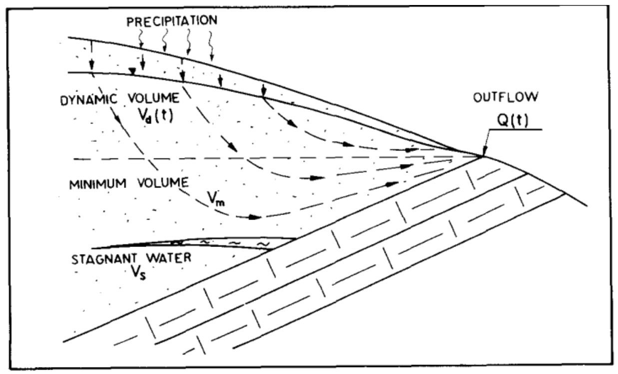
➔ We can then use the parameterized transfer function to estimate the future output



More about the “mean transit time”

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

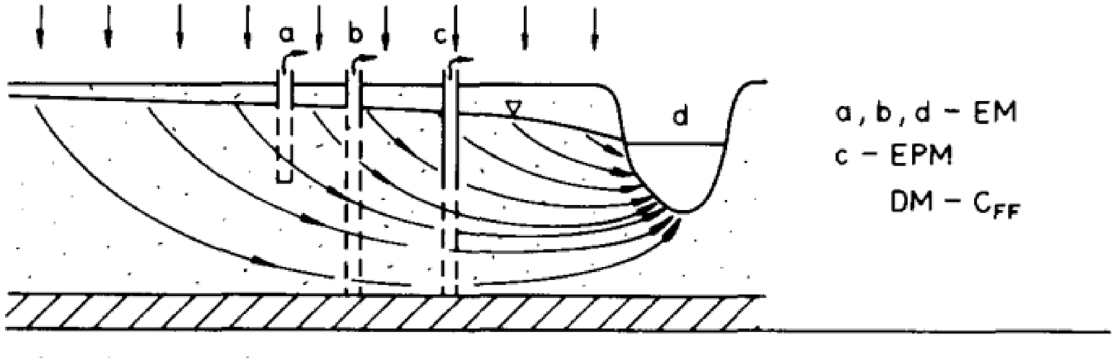
- The mean transit time $\overline{T}$ is estimated from modelling. But what does it mean physically ?
- The trajectory between the point of injection and the exit point is called a „flow line“.



- The transit time is the time taken for a particle to travel along an entire flow line from injection to exit point.
- Obviously, each flow line will be caracterized by a different transit time, depending on its length, which itself depends on the distance to the exit point and the groundwater gradient.
- $\overline{T}$ is the mean of all flow lines converging to the exit point.
- $\overline{T}$ is the mean transit time of tracer. If there are no microporous stagnant water zones, it is also the mean transit time of water.

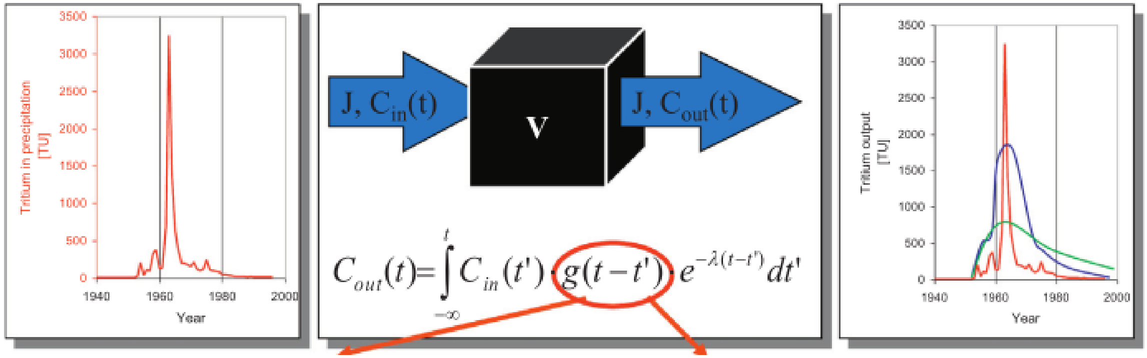
More about transfer functions

- The transfer function should represent the distribution of flow lines contributiing tracer to the exit point.
- The functions depends on the hydrogeological configuration, and on processes simulated or not.



Małoszewski and Zuber (JoH 57, 1982)

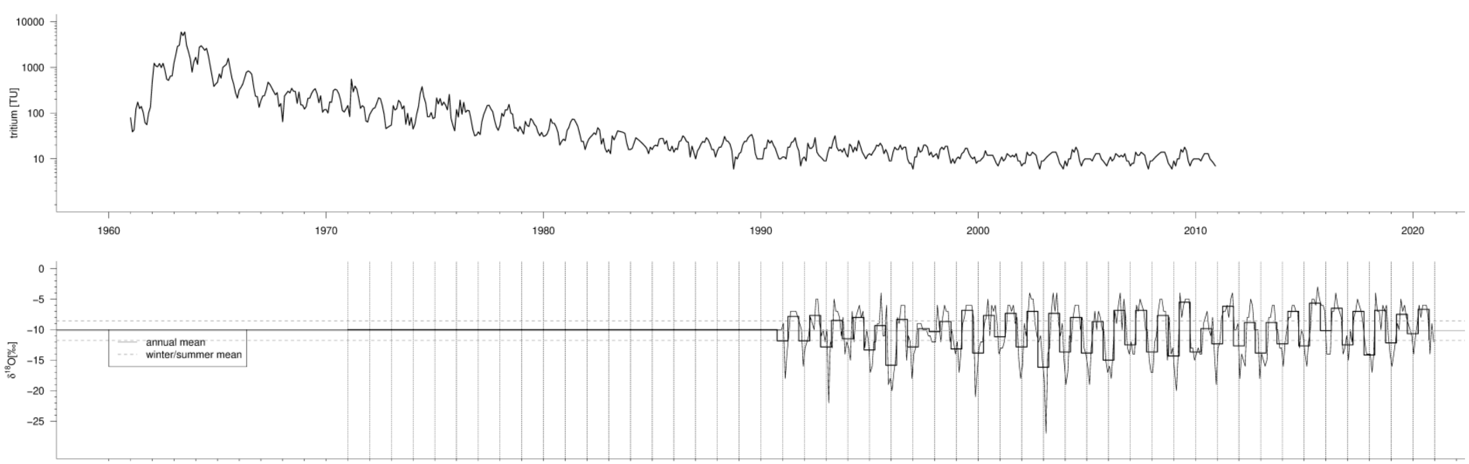
- Because the shape of the functions are different, the input-output relationship will change depending on the function chosen.



Suckow (appl. geochemistry 50, 2014)

Using environmental isotopes as tracers

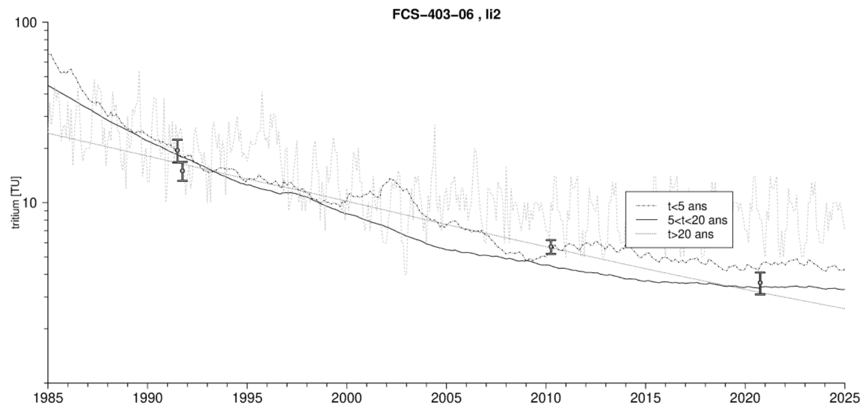
- Two isotopic tracers are particularly adapted to hydrogeology:
  - tritium
  - deuterium/oxygen 18
- As part of the water molecule, they are naturally „injected“ in watersheds by rainfall
- Their input is different
  - Tritium reached a peak in the 1960s and *decays*
  - Deuterium/oxygen 18 were not affected by atmospheric bomb testing and display a strong annual seasonality



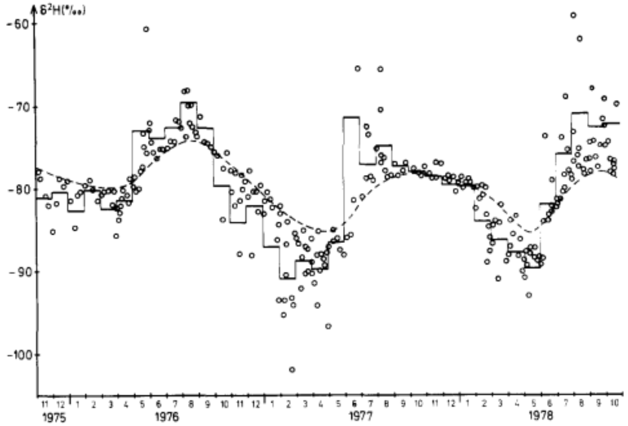
Examples of observed and fitted output

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

- tritium



- Deuterium



Małoszewski et al. (JoH 66, 1983)

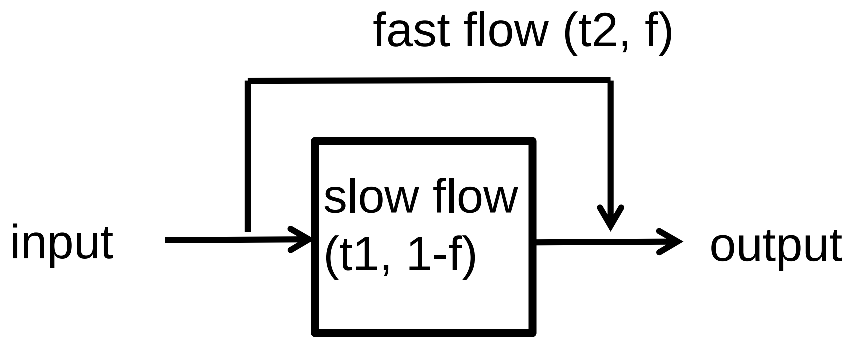
!!!! Often, different parameter combinations yield similarly good fits to the output data. Checking the plausibility of V is essential !!!

Also, different transfer functions are possible.

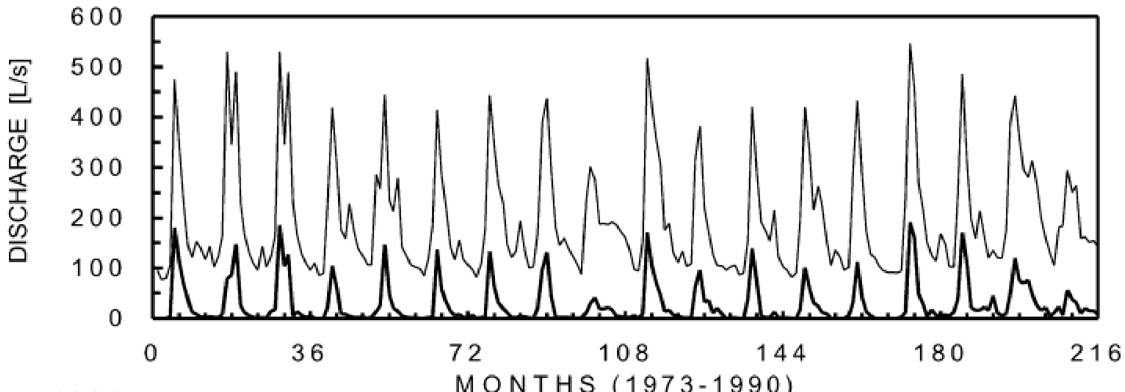
Combining both isotopes

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

- Tritium and deuterium can be combined to model a two-reservoir system



- Tritium is used to estimate t1 (mean transit time of the slow flow reservoir)
- Deuterium is used to estimate t2 (mean transit time of the fast flow reservoir) and f (fraction of discharge fed by fast flow)

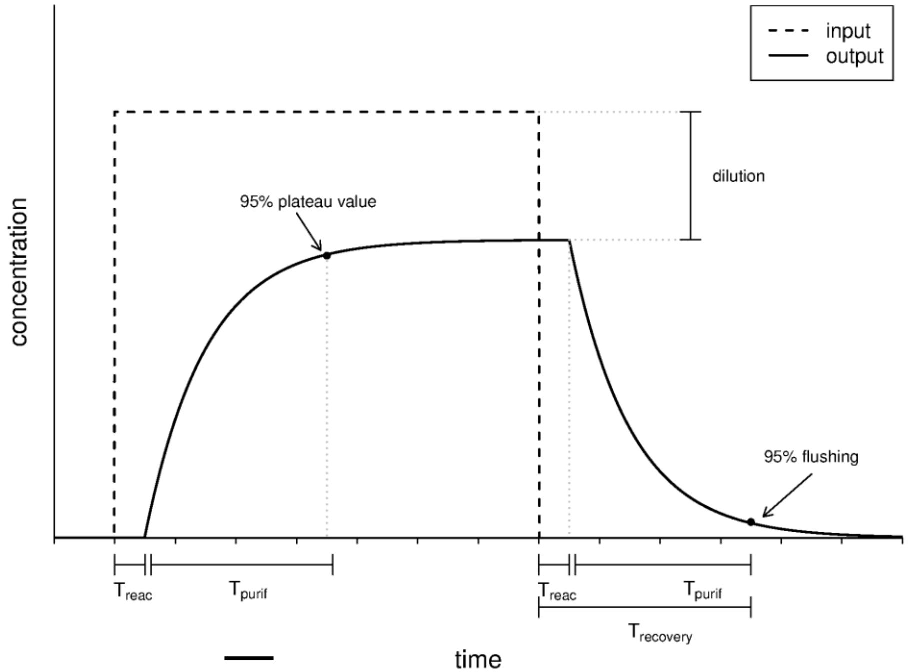


Małoszewski et al. (JoH 256, 2002)

Water quality problem: remediation times

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

- In case of a drinking water source contaminated by diffuse agrochemicals, water providers need to know the flushing time and the reaction time (lag between reduction of the source and begin of decrease in concentration).



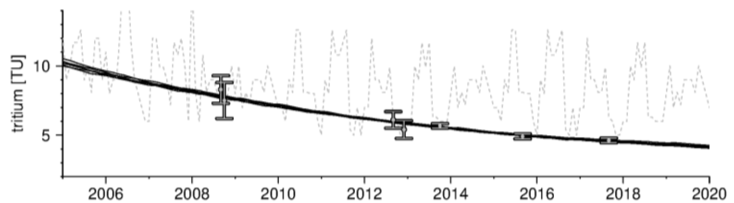
→ 95% flushing=3 $\overline{T}$

→ „reaction time“≠ $\overline{T}$

Remediation times: a case study

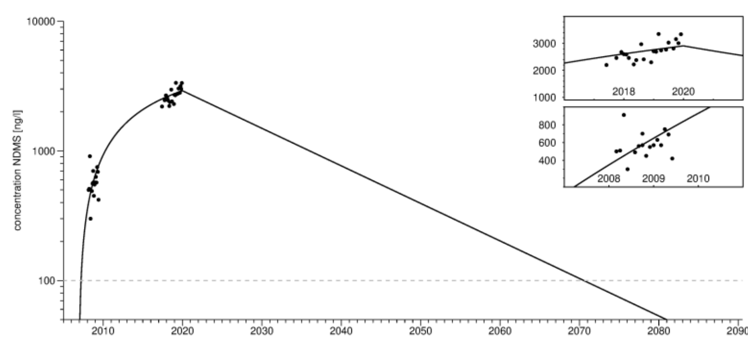
A series of springs are contaminated by n,n-dimethylsulfamide (NDMS) a fungicide metabolite used until 2008. How long until trend reversal ? How long until concentrations are back to the drinking water limit ?

- $\overline{T}$ obtained from tritium measurements



- Mean transit time:
  - saturated zone 11-13 years
  - unsaturated zone+distance 11 years (minimum)

  ➔ the water provider will built a treatment plant



Conclusions

- As they are naturally applied in watersheds, water isotopes are ideal tracers of water flow.
- If sampled at the exit of the watershed, they integrate its entire response, all storage compartments included.
- Using more than one tracer can allow the quantification of each compartment's contribution and volume.
- Lumped-parameter models are easy to implement and require few parameters, but long input time series.
- The choice of a transfer function can be guided by theoretical considerations, but is a matter of debate (and of taste !)

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

Thanks for listening. Are there any questions?