Groundwater hydraulics 9
Natural tracers in hydrology

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Dept. Landscape Water Conservation

Contents

- Tracers in hydrology
- Stable water isotopes in hydrosphere
- Laser spectroscopy as analytical tool
- Use of stable isotopes

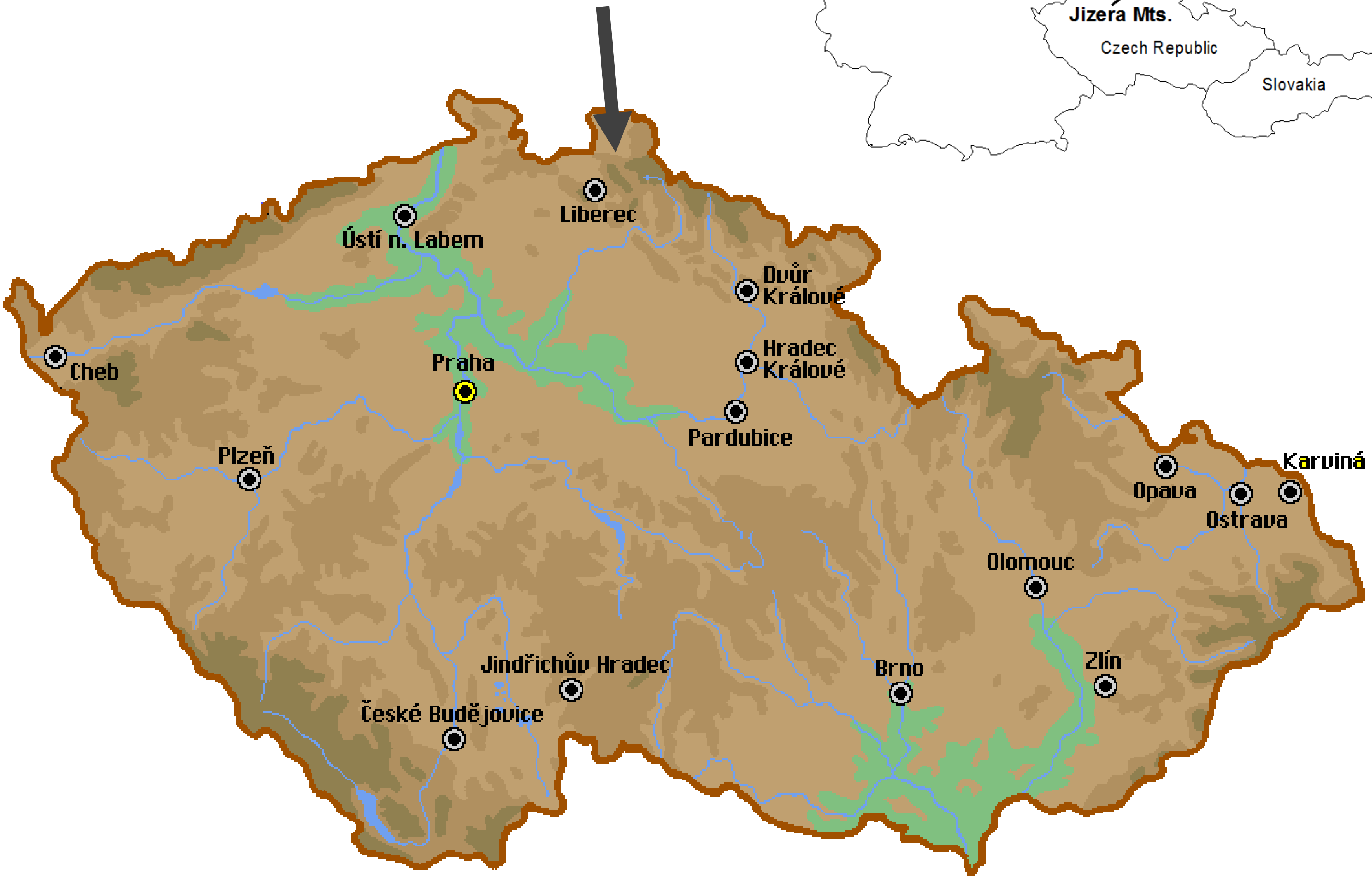
Hydrology – water in the environment

Monitoring of hydrological variables
mostly precipitation, runoff, groundwater, soil moisture

Site description
Topography, soil science, geology, geophysics

Tracking water flow
Mostly "natural" compounds in water

Location of Jizera Mountains



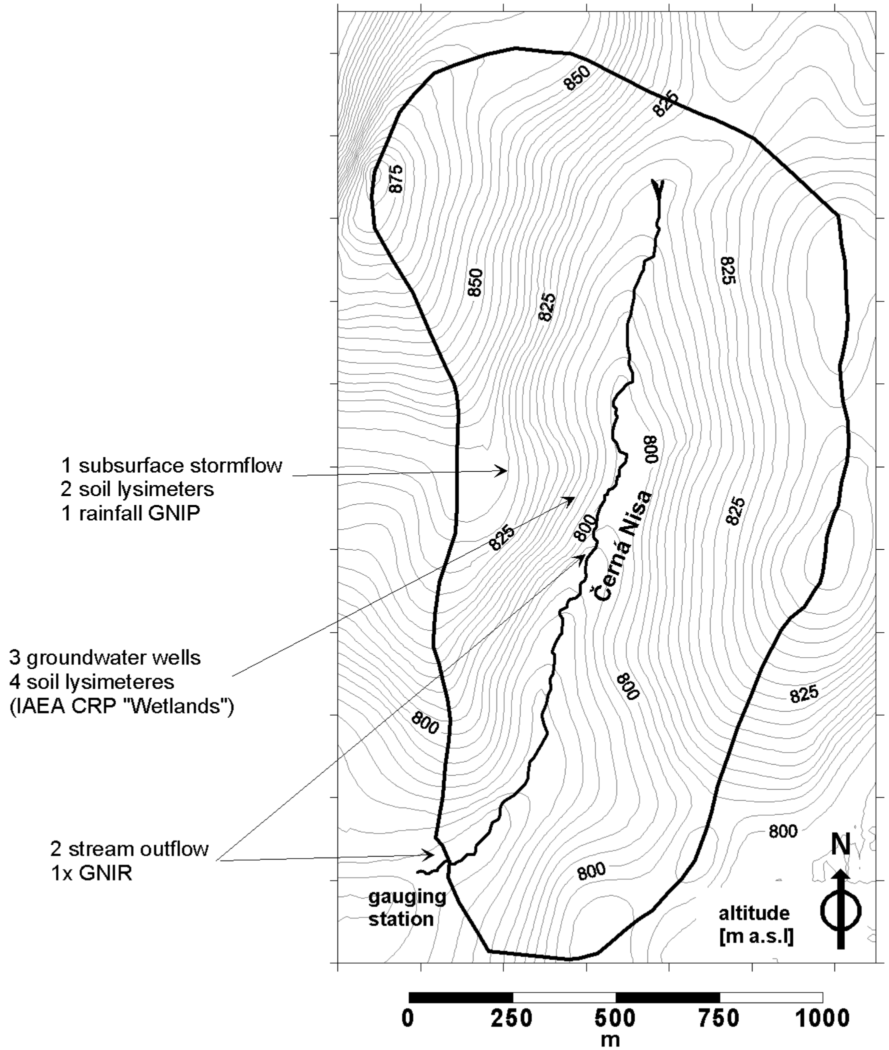
Small experimental catchment Uhlířská, Jizera mountains

Uhlířská (1.78 km^2)
(700-900 m altitude)

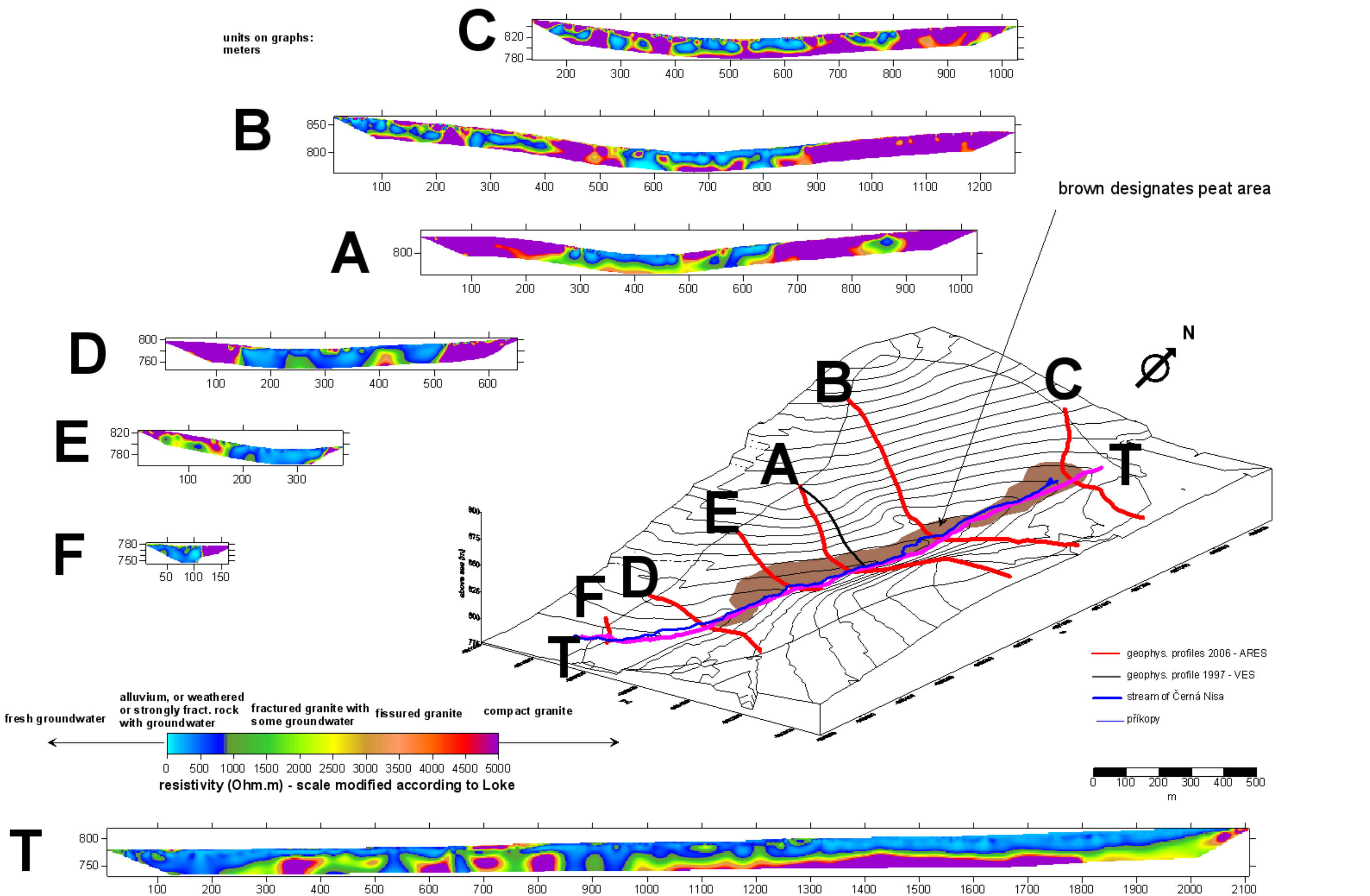
- humid (1200 mm/yr) and cold (5°C)

- 10-60 m deep deluviofluvial aquifer

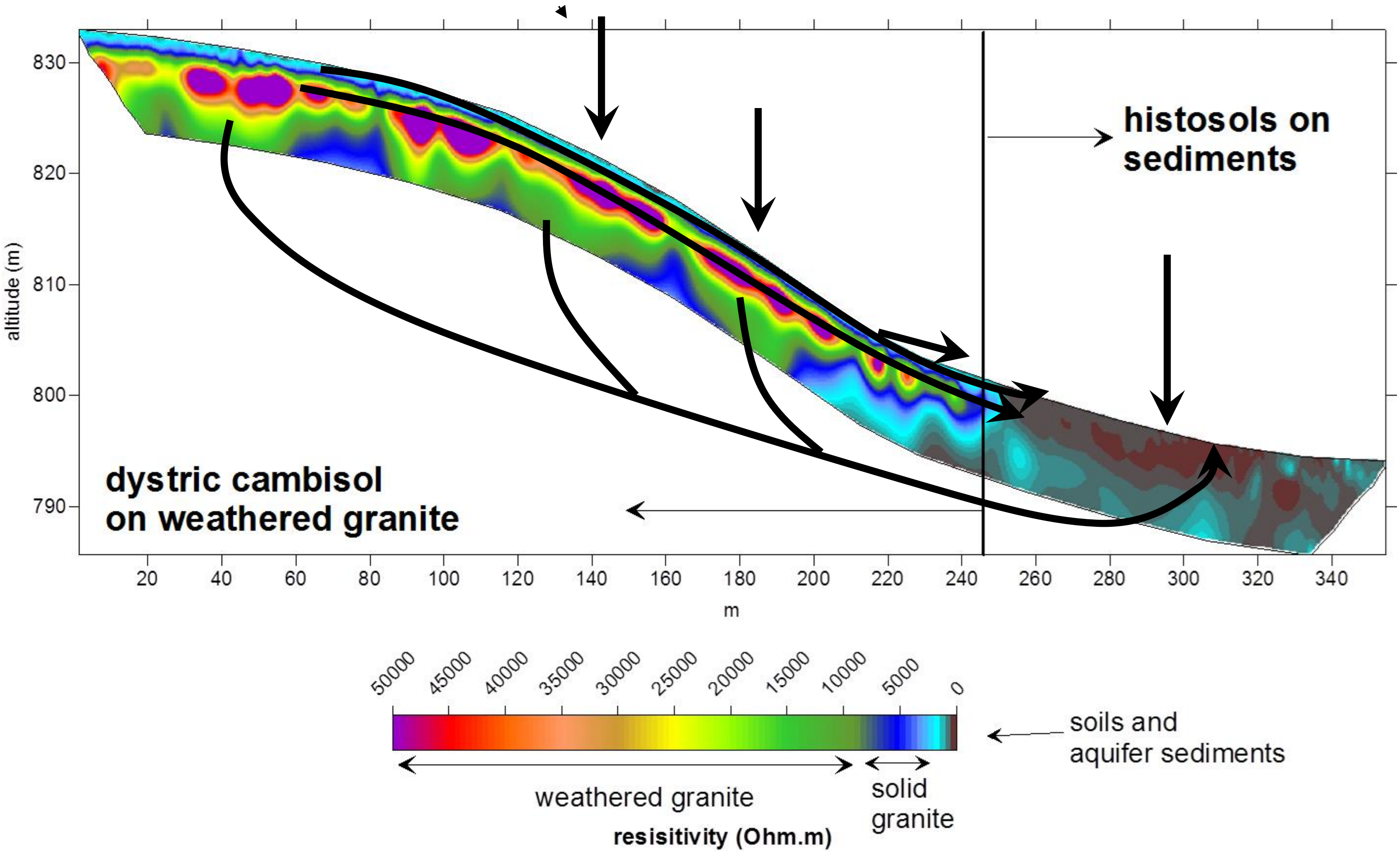
- fractured and fissured granitic bedrock



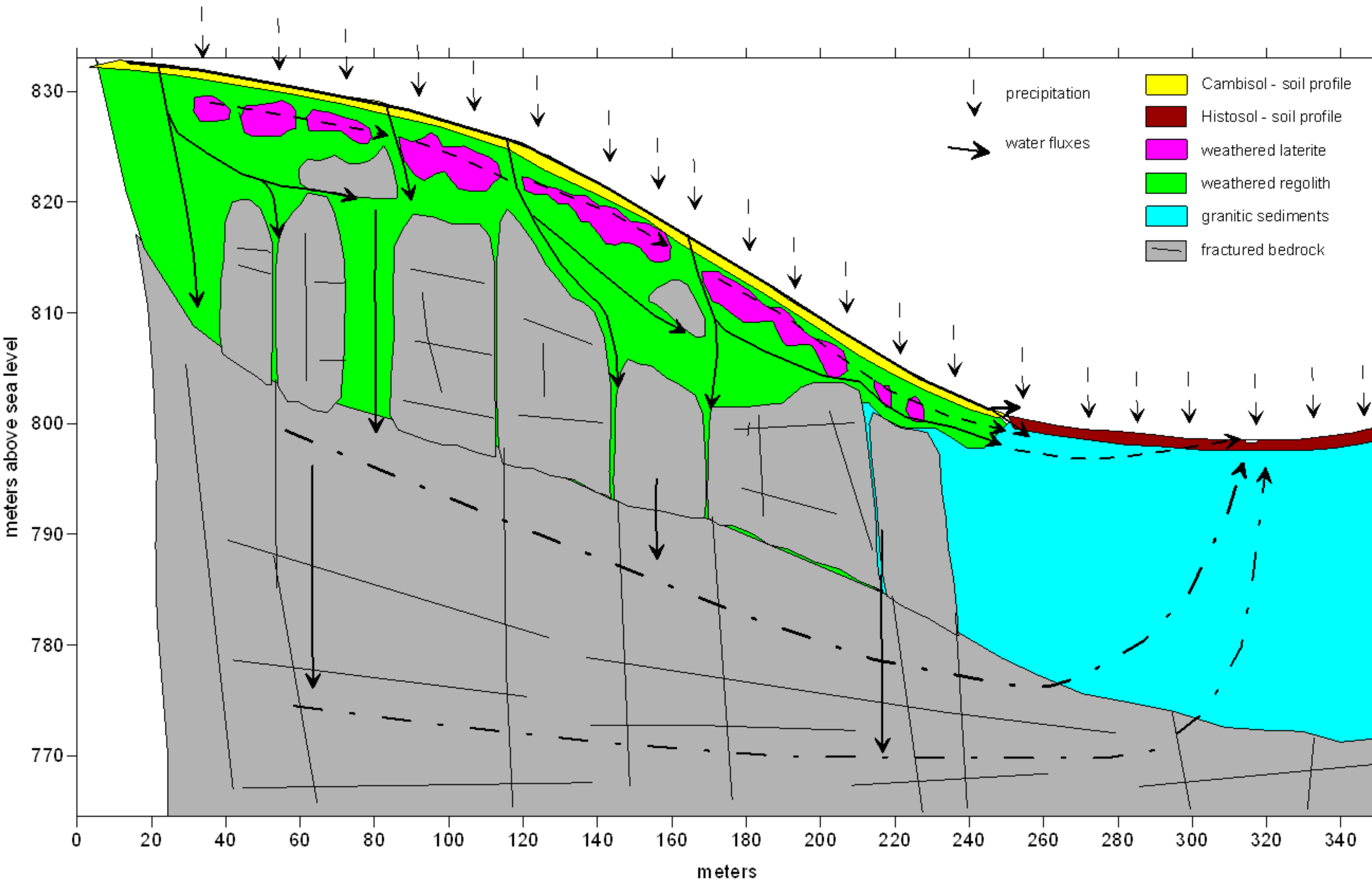
Electrical resistivity tomography for the detection of large scale formations



Possible travel paths of water



Possible travel paths of water



Soil profile upslope

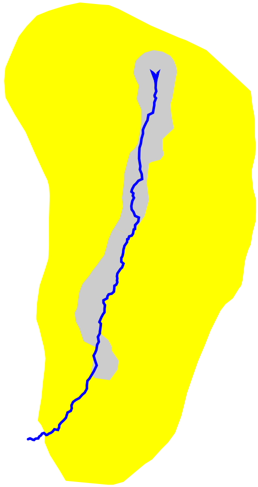
Cambisols and Podzols

based on the decayed granite bedrock

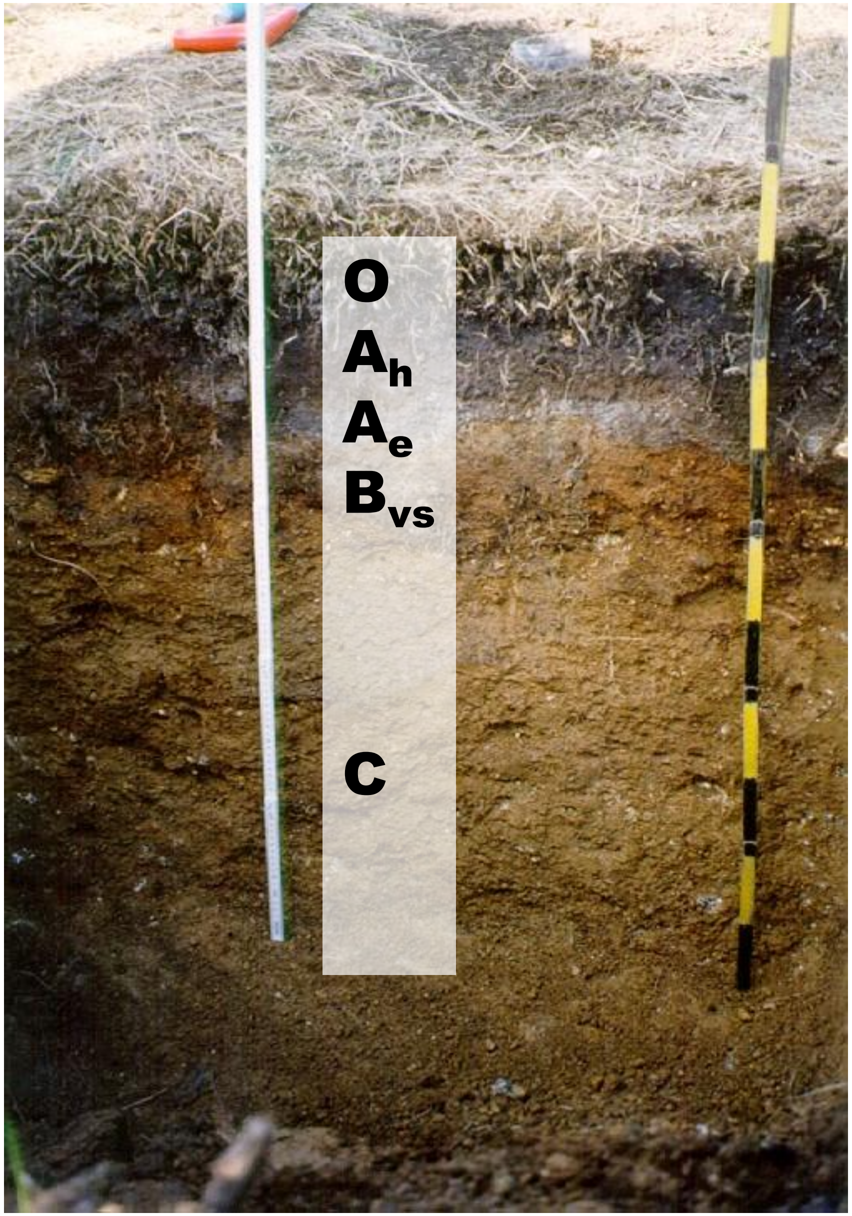
<ins>shallow (app. 80 cm)</ins>

<ins>very heterogeneous</ins>

<ins>layered</ins> due to hydrological, and geopedological factors (peaty topsoil, stony decaying bedrock layer)



90% area



Soil profile downslope

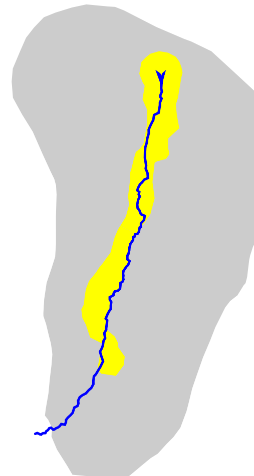
Histosols

based on the alluvial sediments

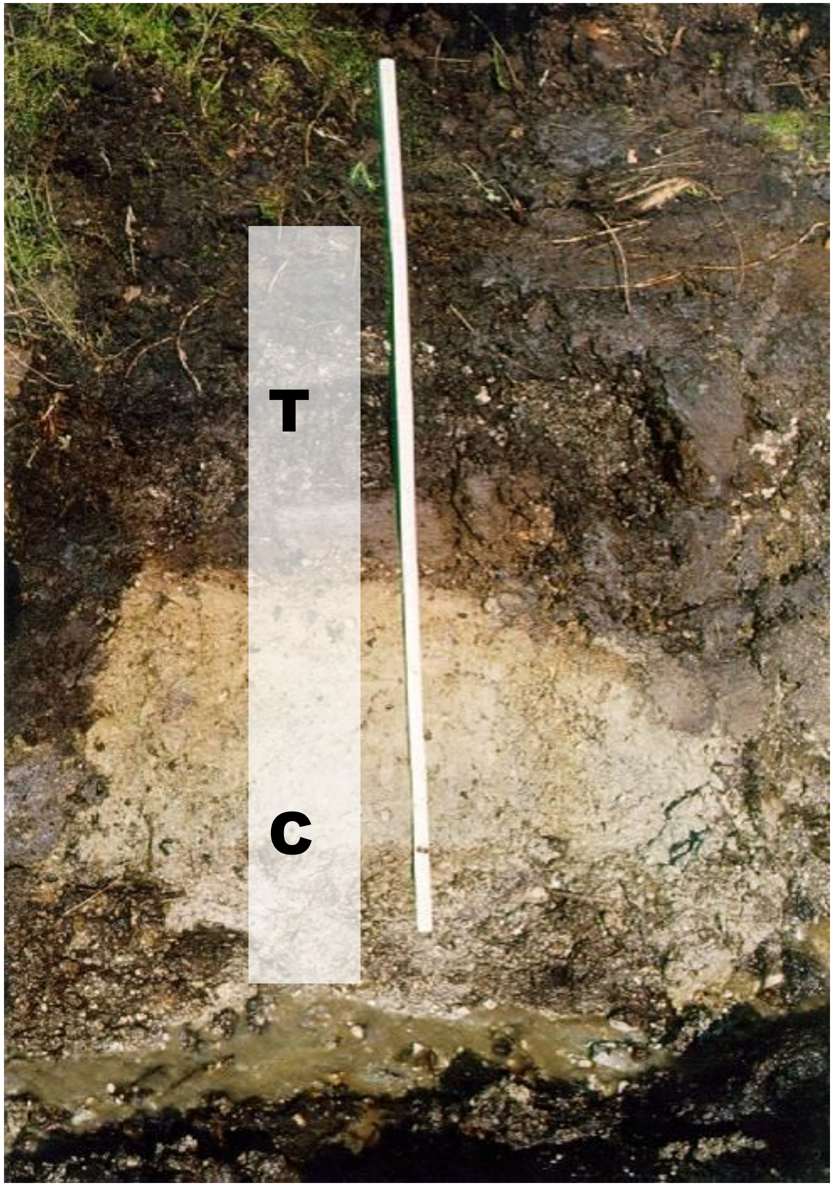
<u>1-3 m in depth of peat uneven thickness</u>

<u>thicker (est. 10-60 m) of alluvial deposits</u>

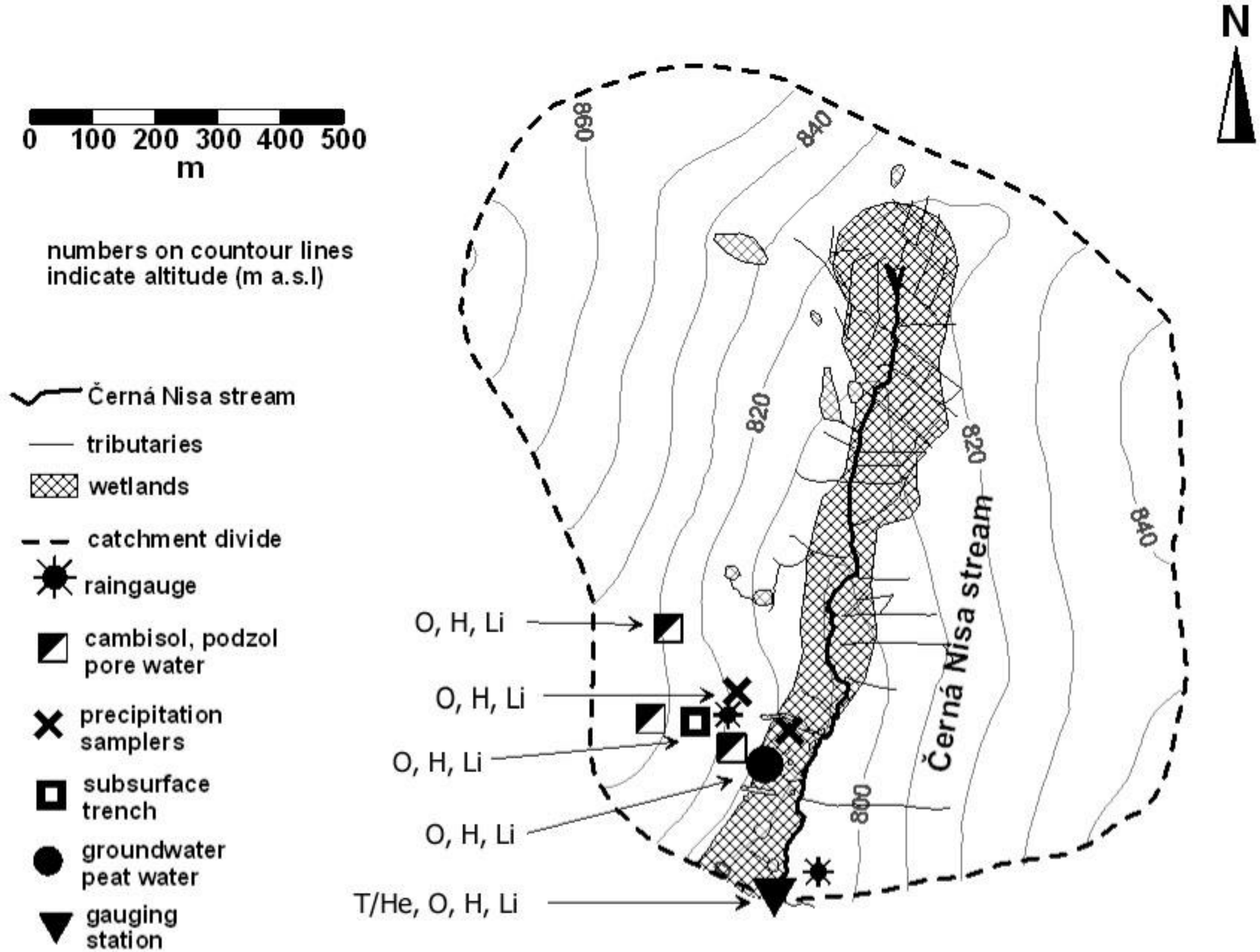
drainage ditches by forestry management (spruce production)



10% area

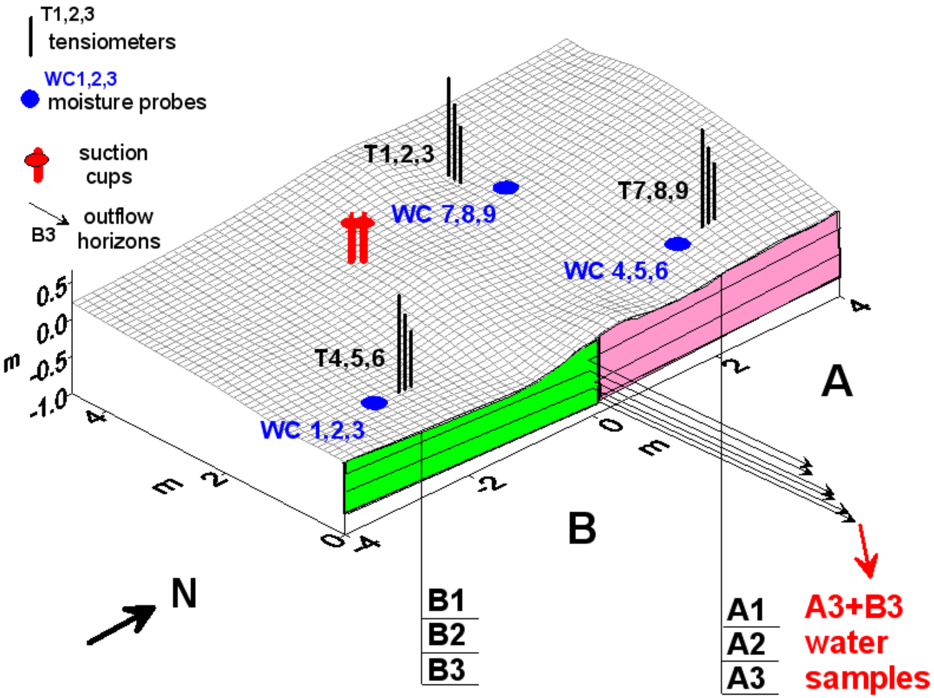


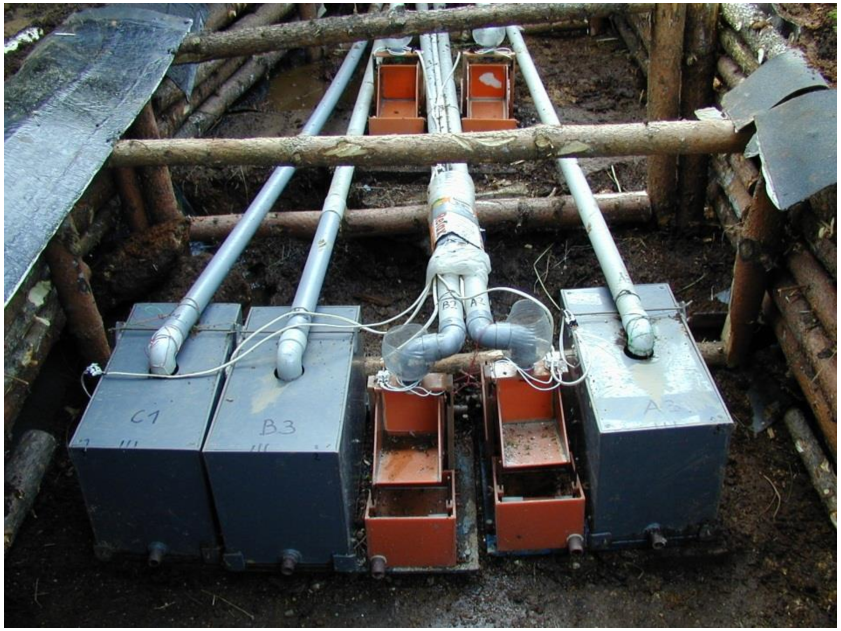
Subcatchment Porsche (1.18 km^2) in Uhlířská



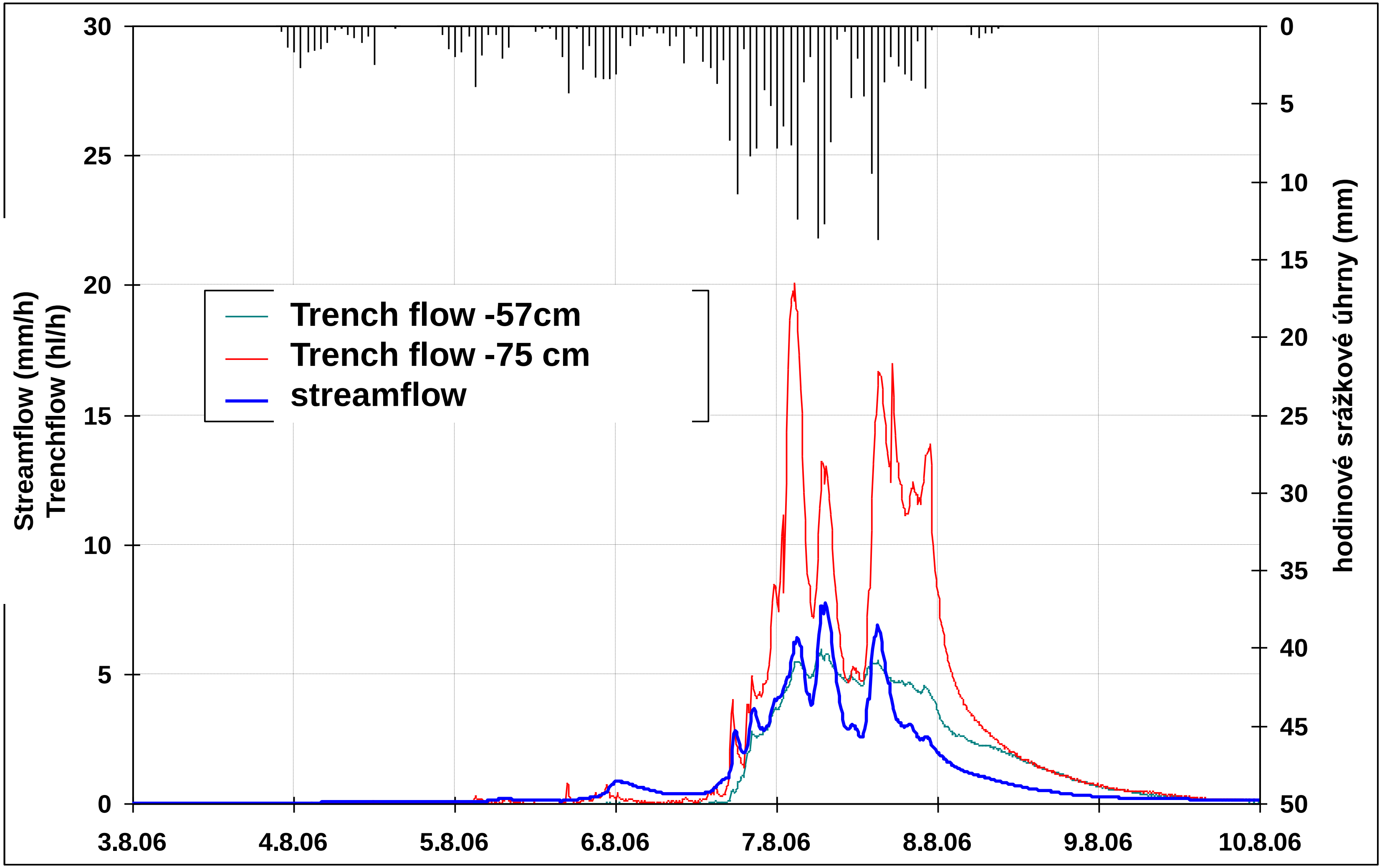
Subsurface processes on the hillslope

Subsurface trench with the monitoring system





Subsuface outflow and streamflow
Similar dynamics thanks to preferential paths



Why tracers?

- tool for the evaluation
  of runoff formation mechanisms

- identification of water motion mostly under
  surface

- mathematical modelling of water cycle

Natural tracers in hydrology

Available ions and compounds, e.g. Ca^{2+}, SiO_2

Concentration change in water after contact with soil-rock environment – good for water origin

Isotopes: mostly stable ^{18}O, ^{2}H

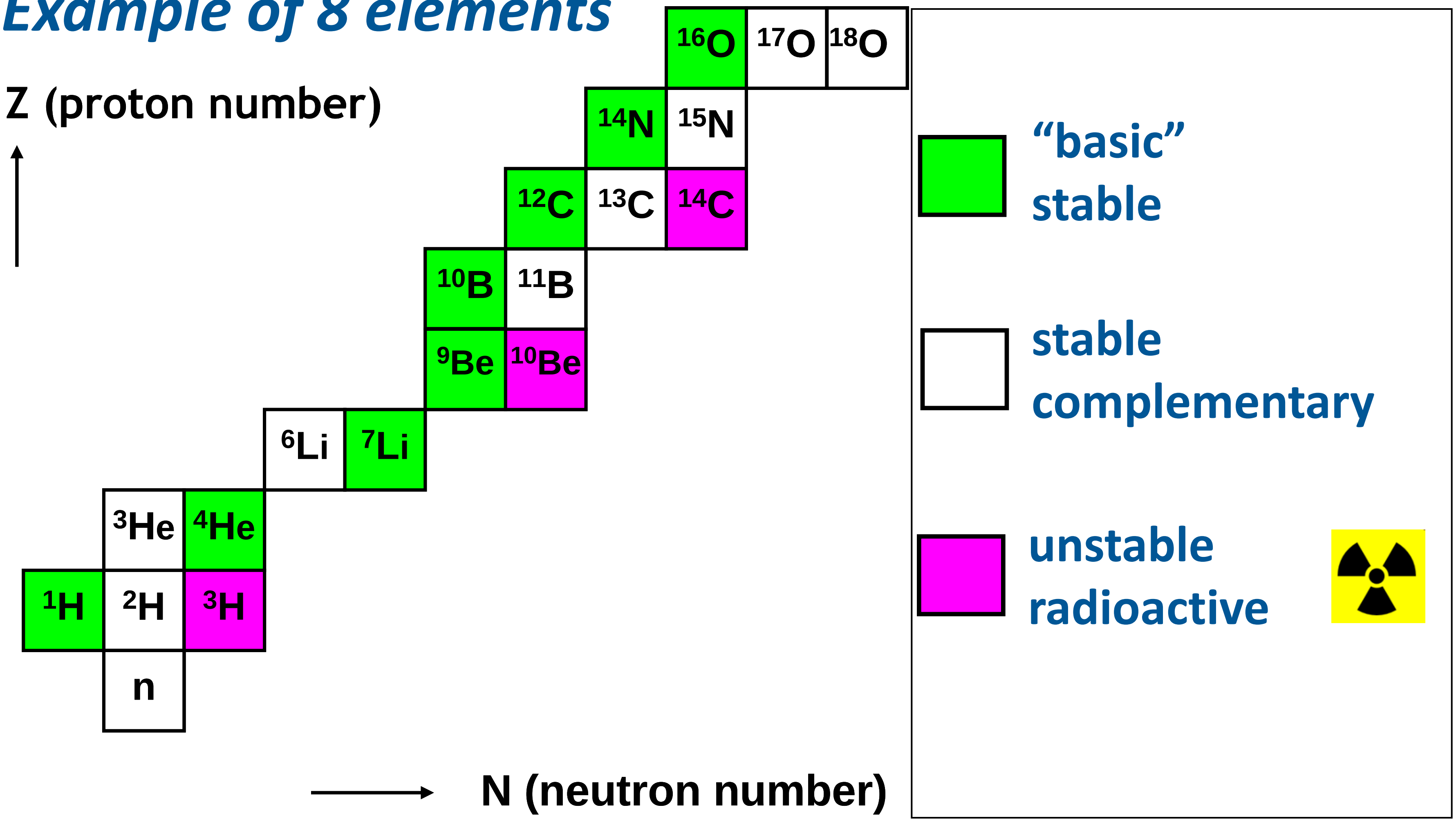
Variable concentration in precipitation – good for water dynamics

Globally spread compounds (anthropogenic) e.g. ^{3}H-^{3}He, freons (CFC)

Changing concentration source in the atmosphere - good for age dating

Isotopes in natural environment

Example of 8 elements



IAEA

IAEA-Int. Atomic Energy Agency

Stable isotopes in water molecule

^{1}H, ^{2}H, ^{16}O, ^{17}O, ^{18}O,

- **present in hydrological cycle**
- **variable concentration in precipitation**
- **molecules themselves are tracers**
- **easy to handle and analyse**

Heaviear stable isotopes in water molecule

^{2}H (Deuterium)

$^{2}H/^{1}H = 1.5576*10^{-4}$ (V-SMOW), approx 1:6400

$$\delta^{2}H_{sample} = \left(\frac{\left({}^{2}H/{}^{1}H\right)_{sample}}{\left({}^{2}H/{}^{1}H\right)_{V-SMOW}} - 1 \right) * 1000[‰]$$

^{18}O

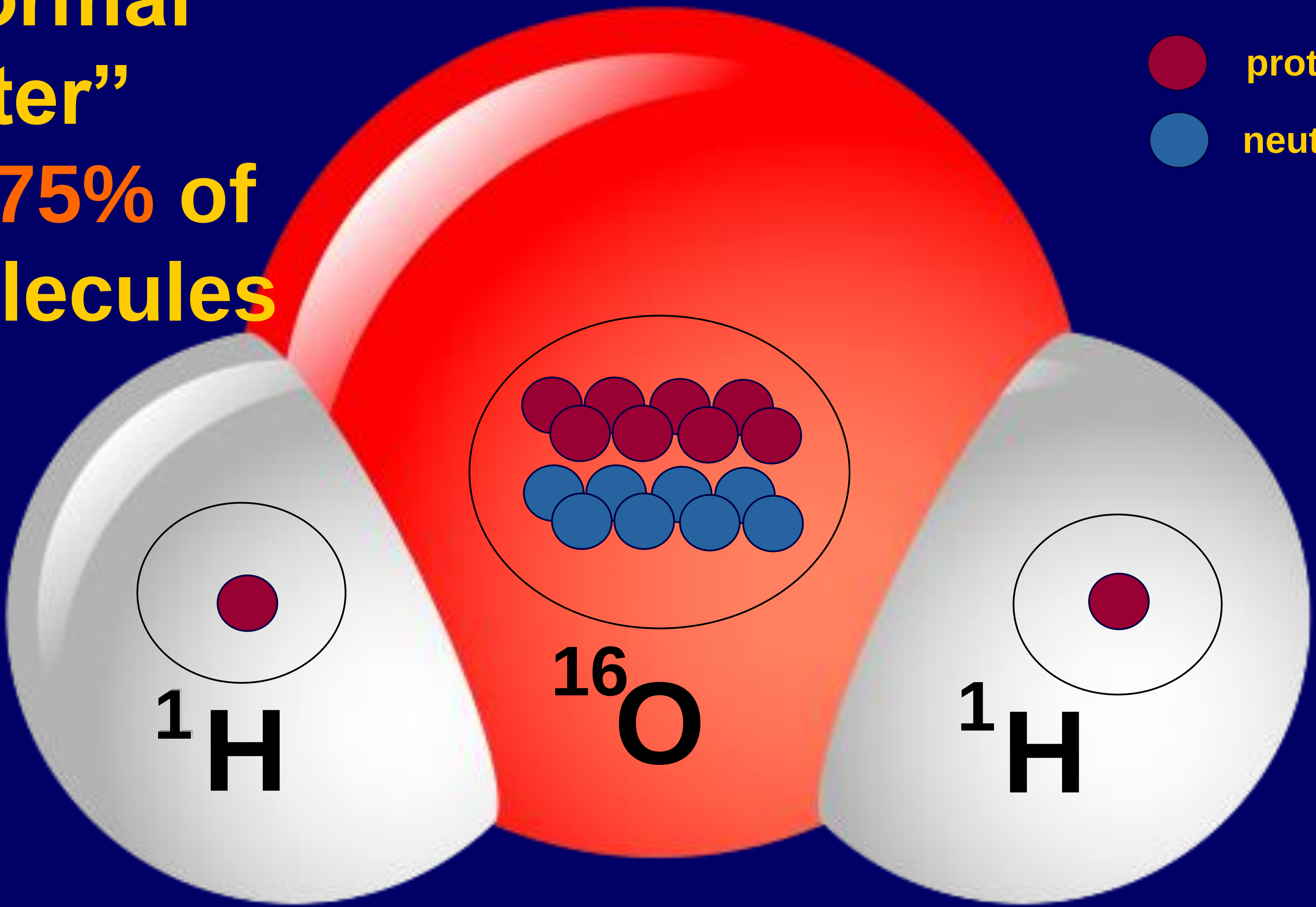
$^{18}O/^{16}O = 2.0052*10^{-3}$ (V-SMOW), approx 1:500

$$\delta^{18}O_{sample} = \left(\frac{\left({}^{18}O/{}^{16}O\right)_{sample}}{\left({}^{18}O/{}^{16}O\right)_{V-SMOW}} - 1 \right) * 1000[‰]$$

Concentration relative to V-SMOW
(Vienna Standard Mean Ocean Water $\delta^{2}H=0‰$, $\delta^{18}O=0‰$)

Stable isotopes of water molecule

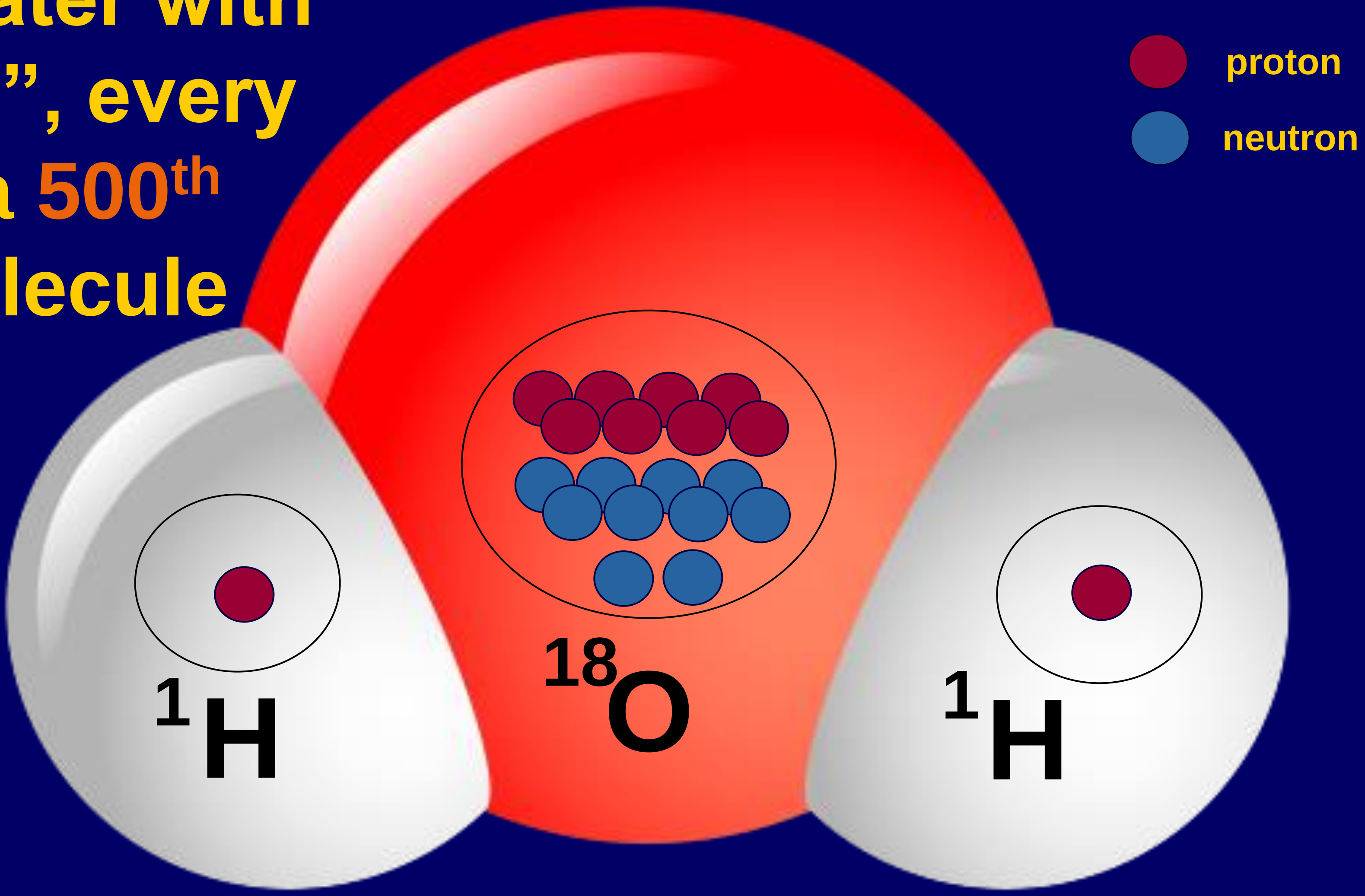
"normal water"
99.75% of molecules



Total molecular weight = 18

Stable isotopes of water molecule

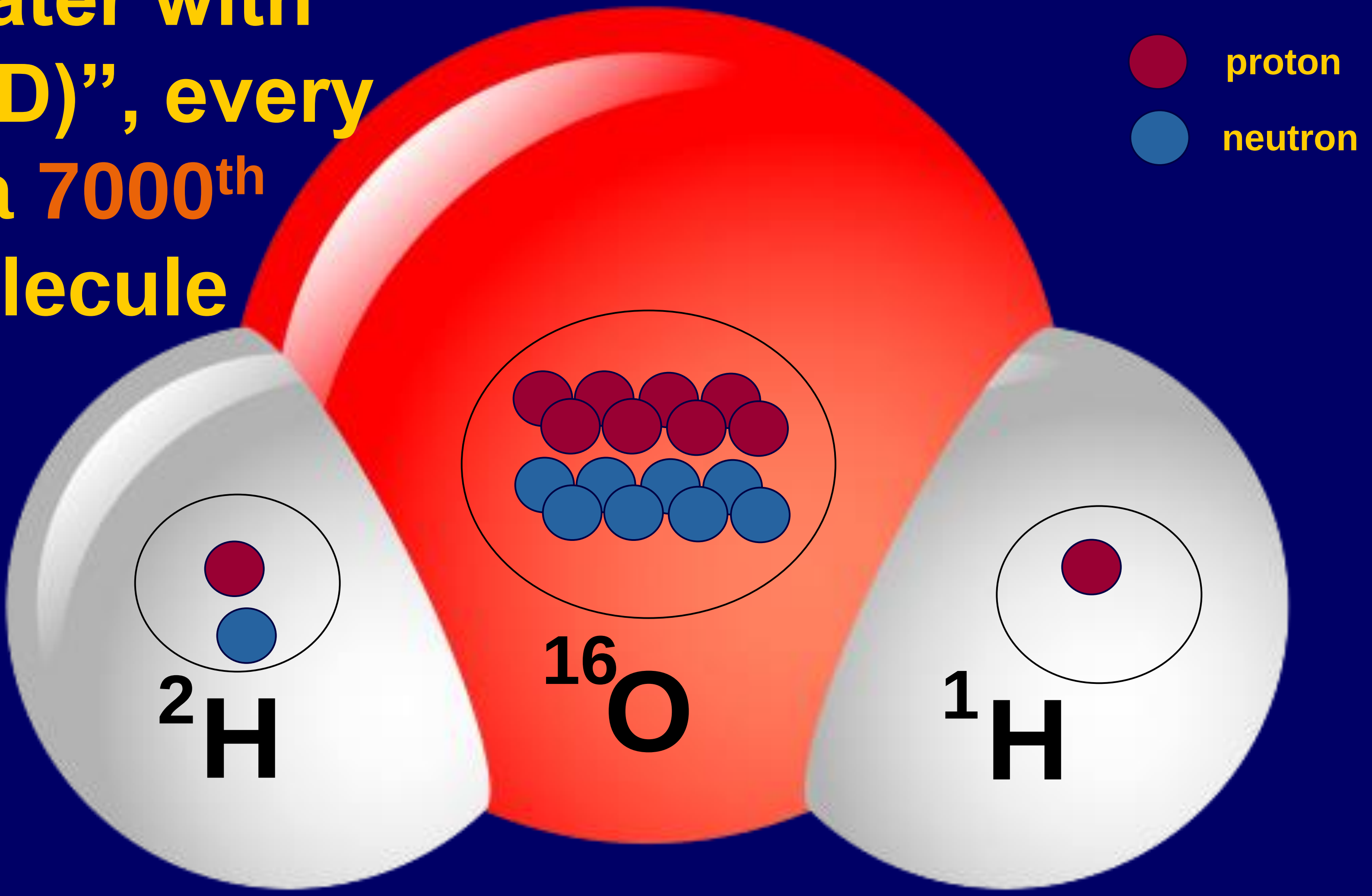
"water with ^{18}O", every cca 500th molecule



Total molecular weight = 20

Stable isotopes of water molecule

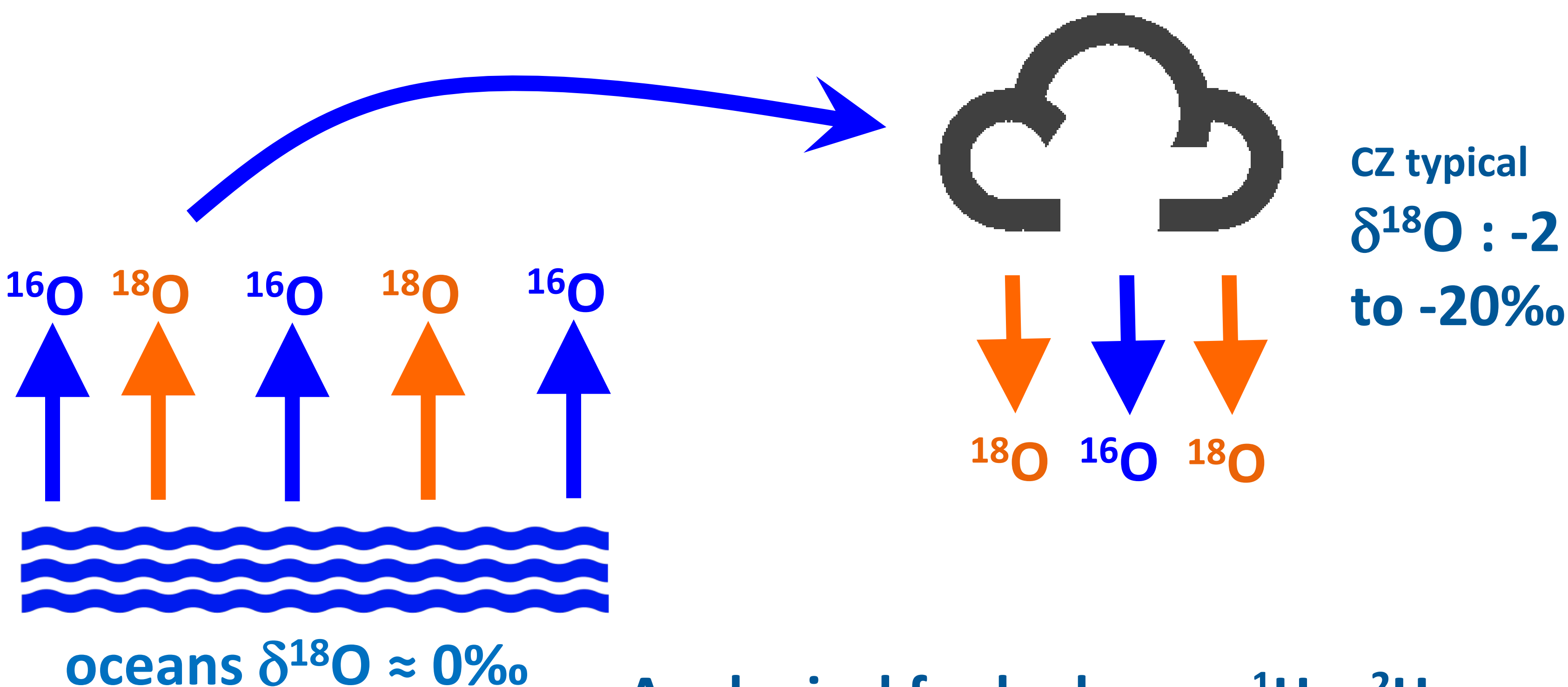
“water with ^{2}H(D)”, every cca 7000th molecule



Total molecular weight = 19

Stable isotopes of water in hydrocycle

- Difficult evaporation of molecule with heavier atoms
- Easier condensation of heavier molecules
  - ie. Depletion of water masses in terms of heavier isotopes



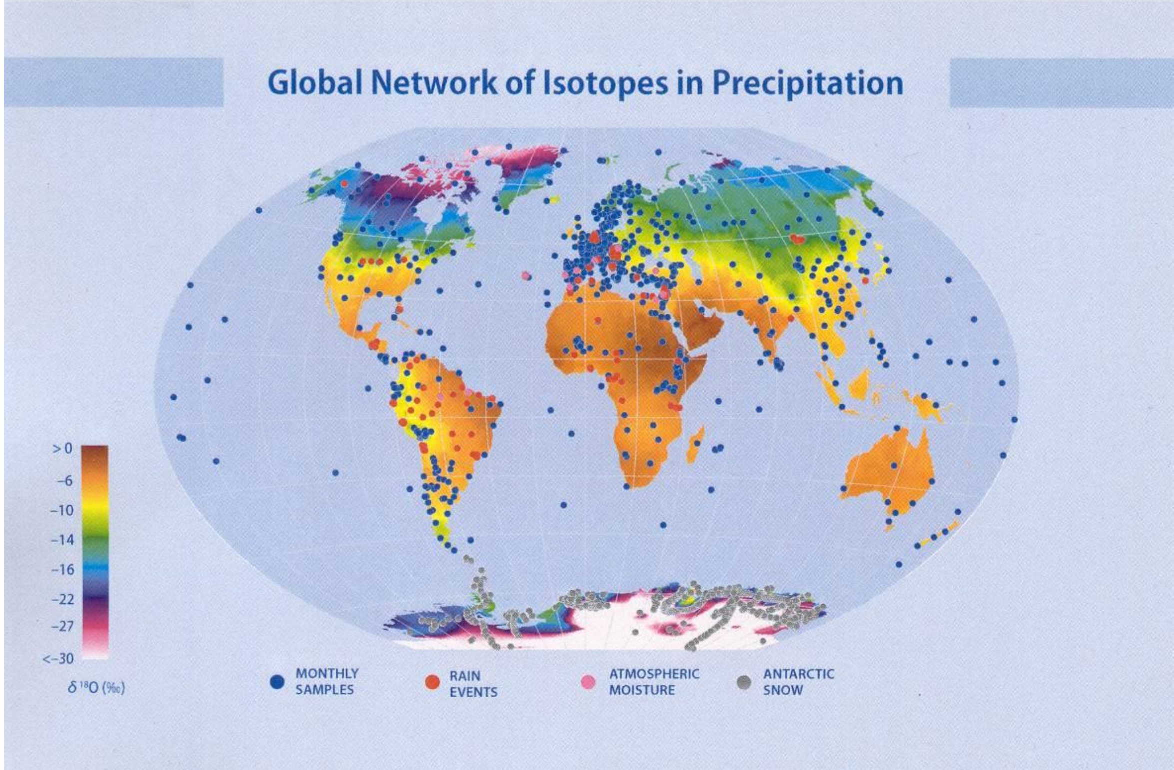
Analogical for hydrogen ^{1}H a ^{2}H

Occurs for O and H inside water mol.

Concentration of stable isotopes depends on:

- distance from the ocean
- altitude and geographical latitude
- temperature of the atmosphere forming precipitation (frontal rain, local storm)

GNIP – Global network of isotopes in precipitation
(IAEA, Vienna)



Determination of isotopic concentrations

Isotope ratio mass spectrometry (IRMS)

Very precise, for all isotopes, separate O and H measurements, financially demanding, sample preparation is tedious, active since 1950

Laser spectroscopy (ICOS/CRDS)

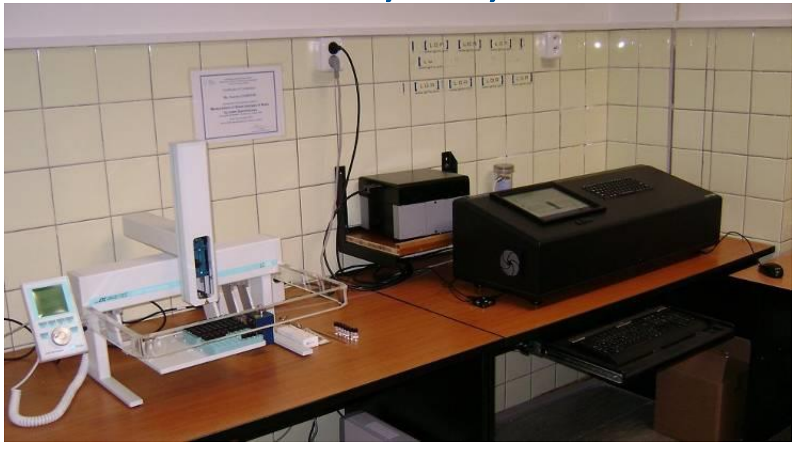
Quite precise, for some isotopes/molecules only, quick and simultaneous measurement of O aand H, 10x cheaper than IRMS,

Easy sample preparation

Easy operation

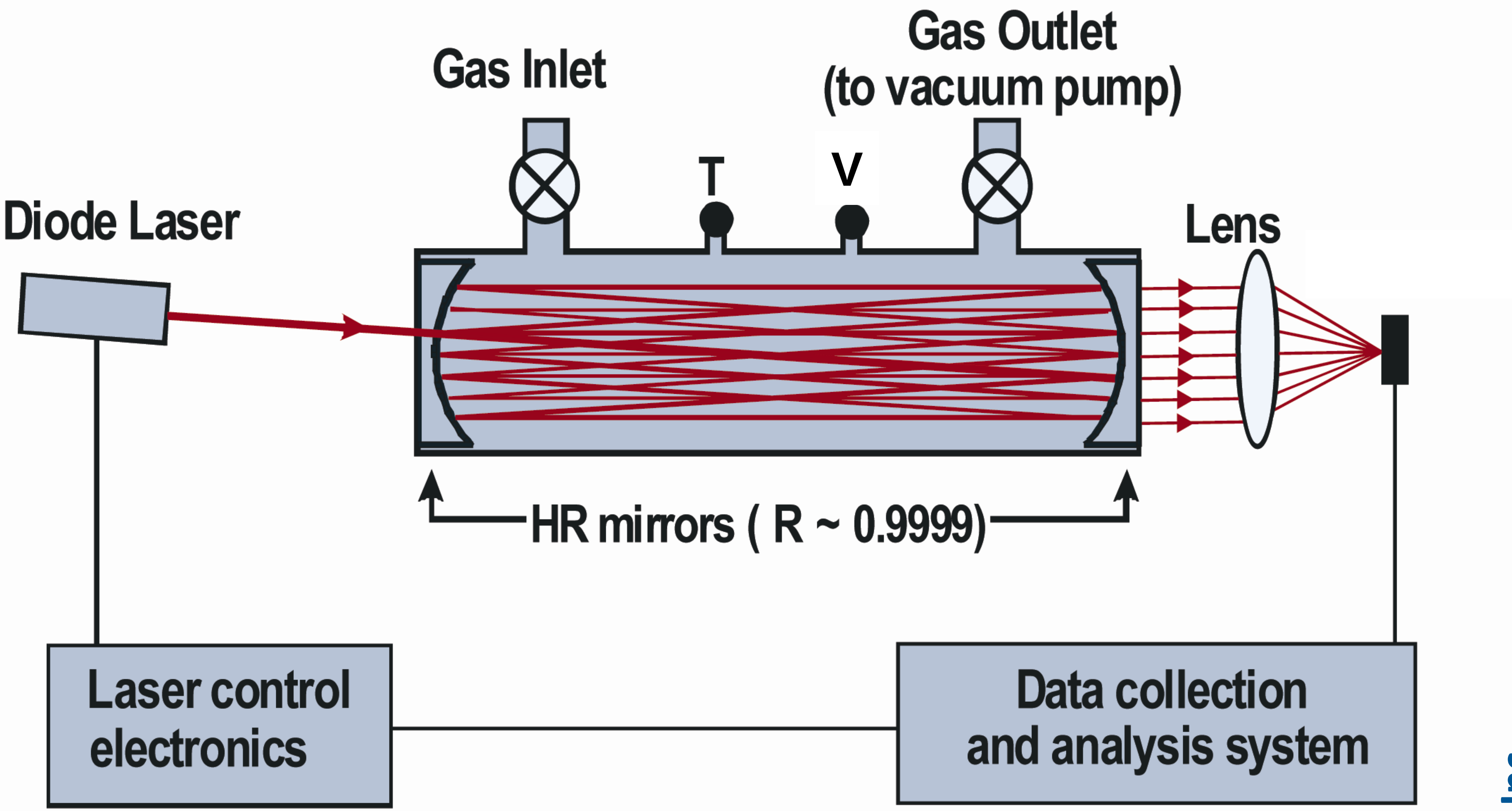
Commercially available since about 2007

Lab CTU, FCE, K143



Scheme of off-axis spectroscope

Integrated Cavity Output Spectroscopy (ICOS)
Cavity Ring Down Spectroscopy (CRDS)



vzorek vody – cca 500 nl je vypařen a převeden do komory laseru
vodní pára $3x10^{16}$ molekul/ml, absolutní tlak max. 5 mBar (0.5 kPa)

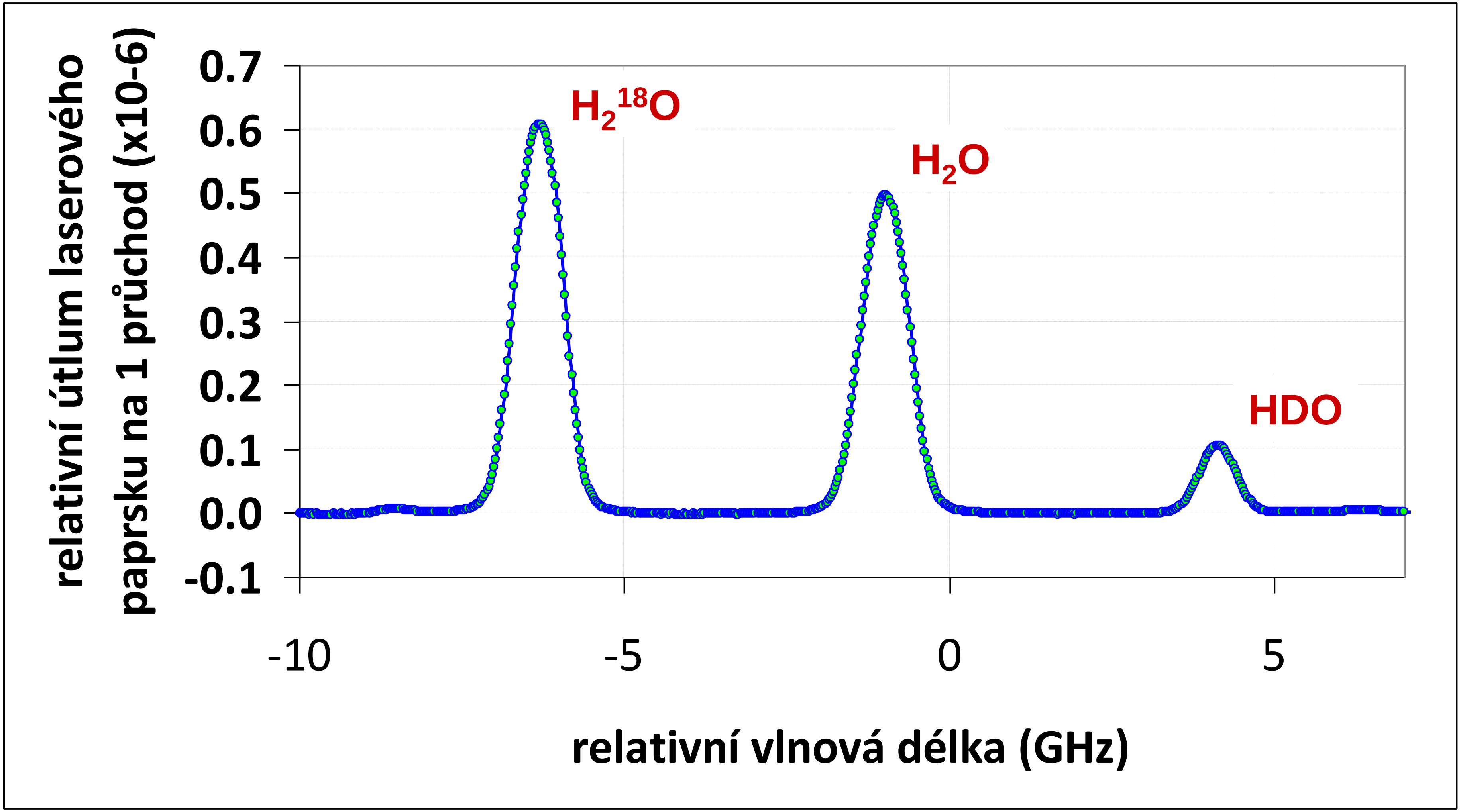
LGR, Inc.

Beer law of absorption

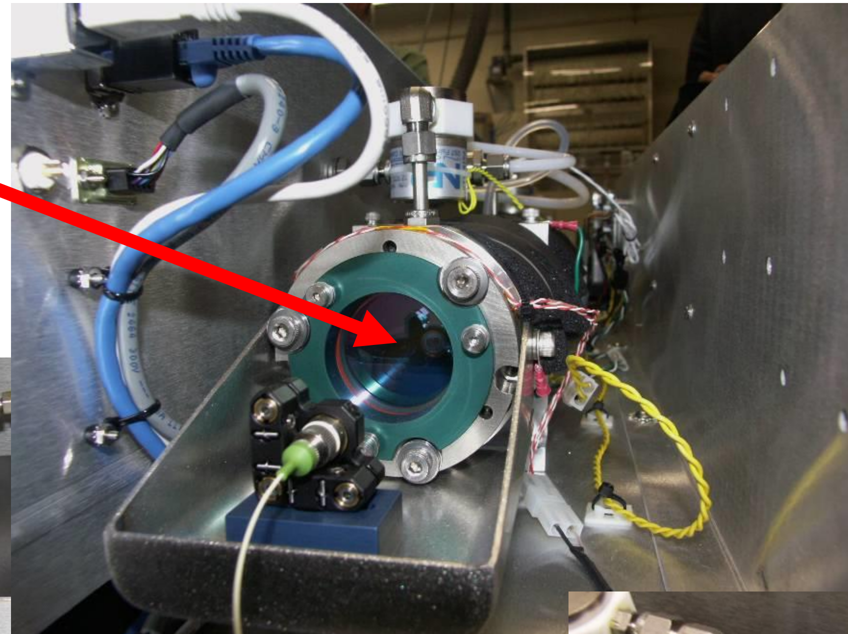
$$I = I_0 e^{-\mu d}$$

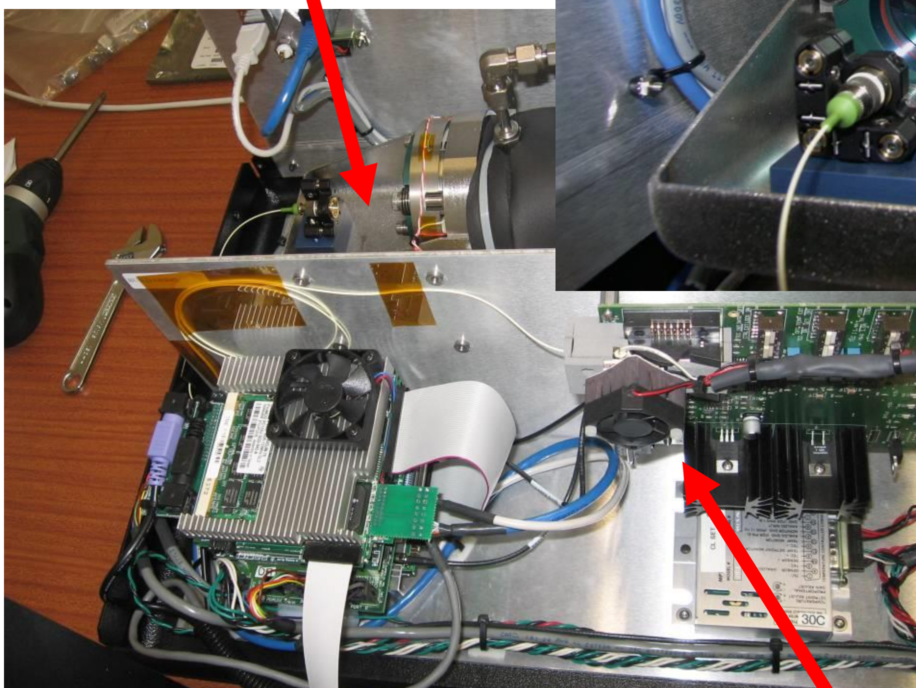
I- output intensity, Io – input intensity, μ – coef. attenuation – acc. to pressure and isotopic concentration
d- length of laser beam travel

spectrogram example

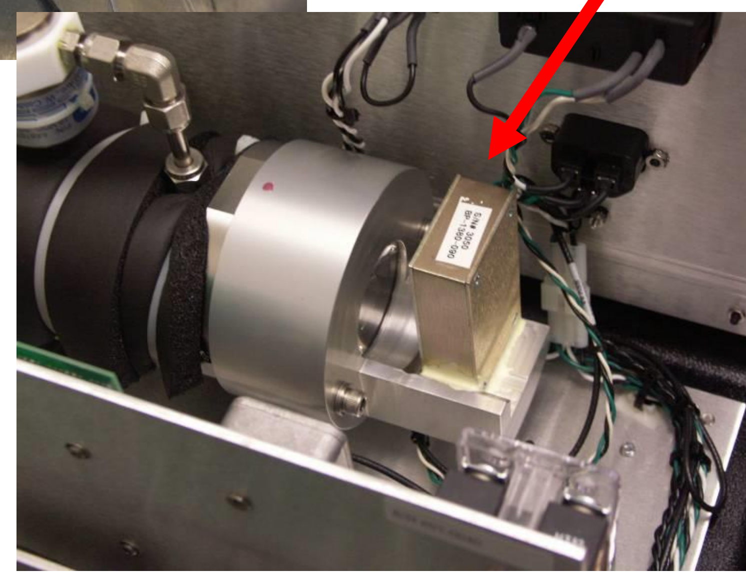


Laser diode entry



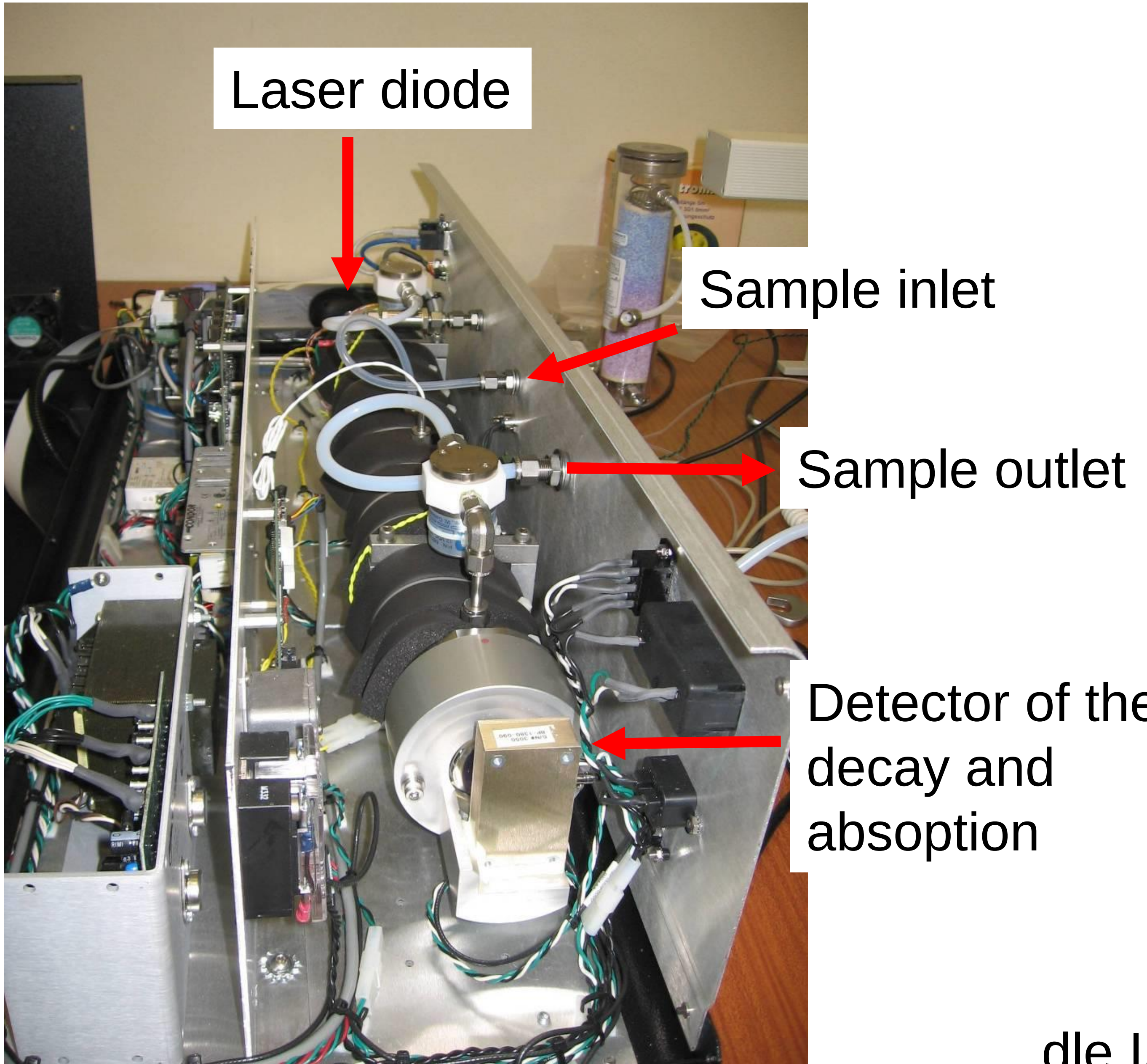


detector



computer

IAEA



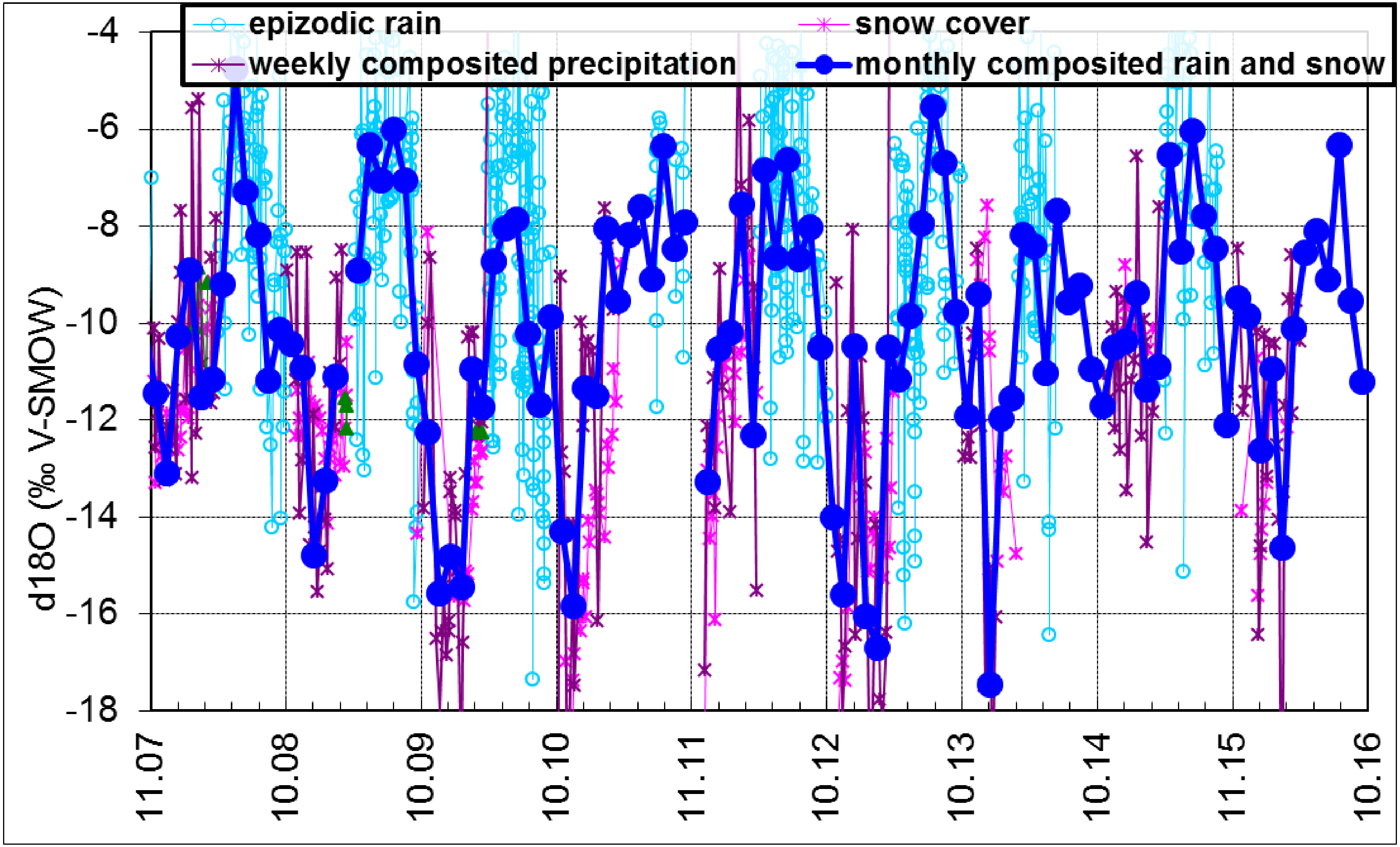
Laser diode
Sample inlet
Sample outlet
Detector of the decay and absoption

dle IAEA

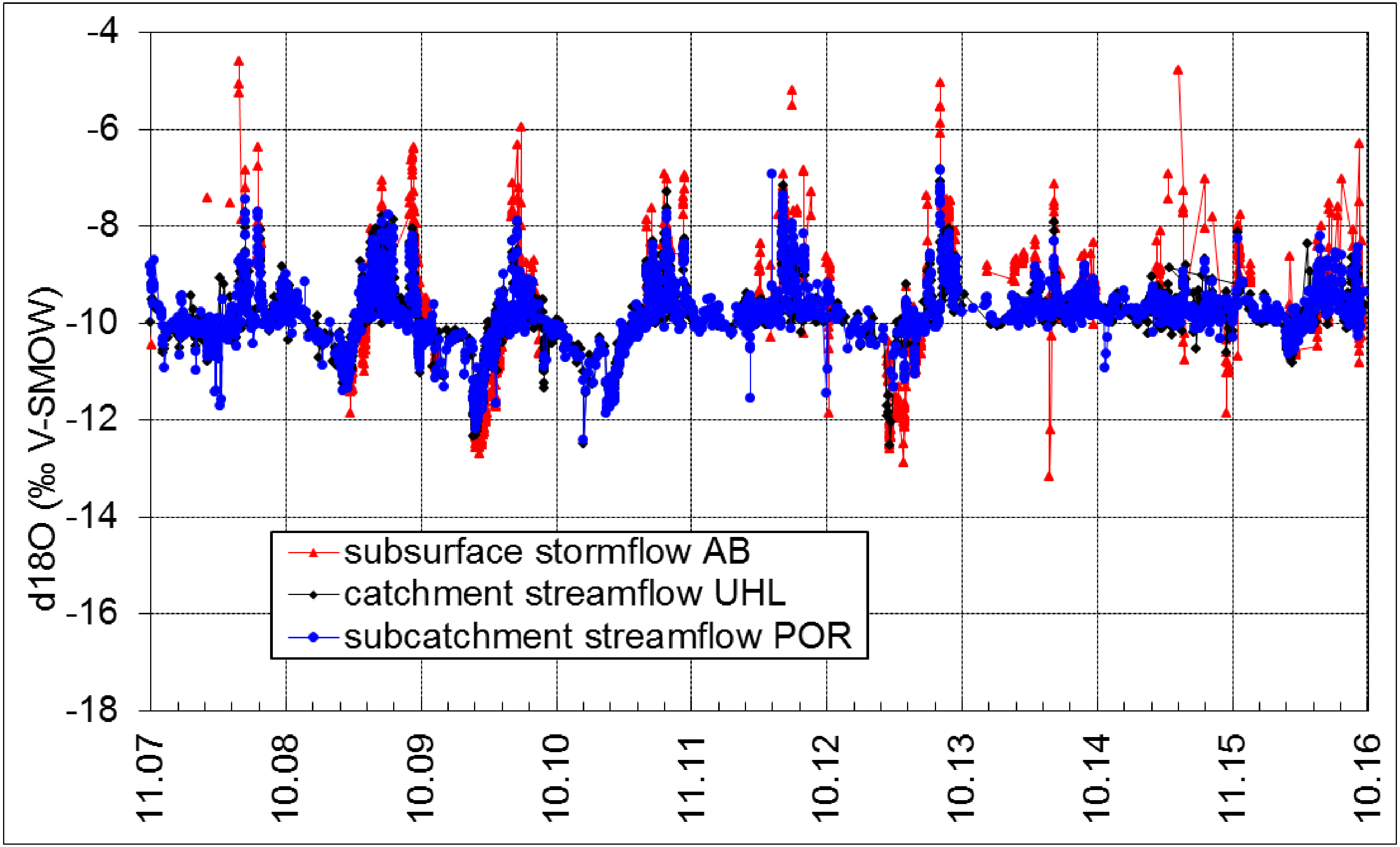
Stable isotopes use in hydrology

- mean residence time of water in system
- isotopic separation> how much of even and pre-event water is in the stormflow
- flow in soil profile, in groundwater
- detection of sources (dam seepage vs. groundwater; sewage vs. groundwater)
- snowmelt
- evaporation evaluation
- paleohydrology (recent and old water)
- climate change (ice core isotope hydrology)
- total balance

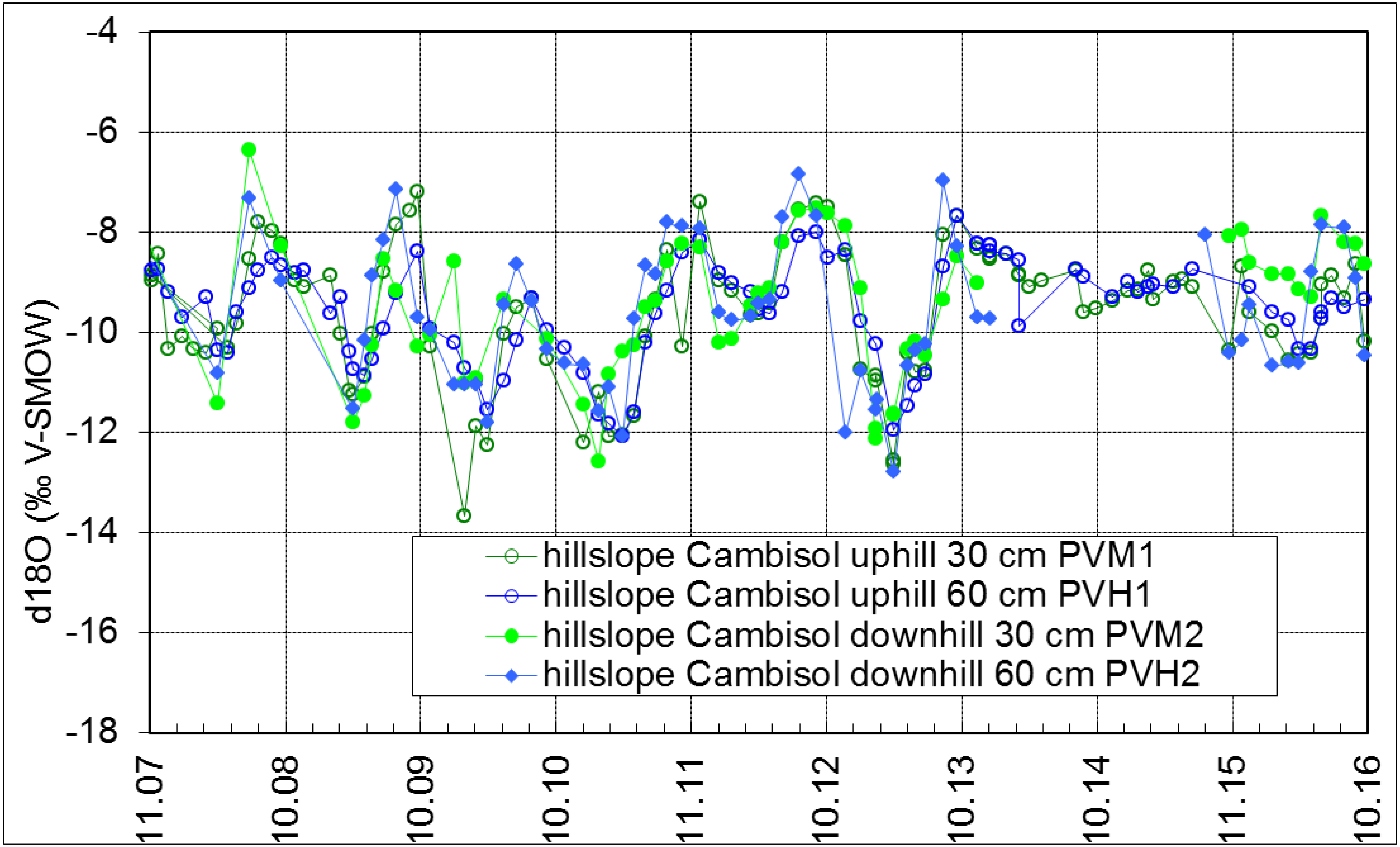
^{18}O in precipitation



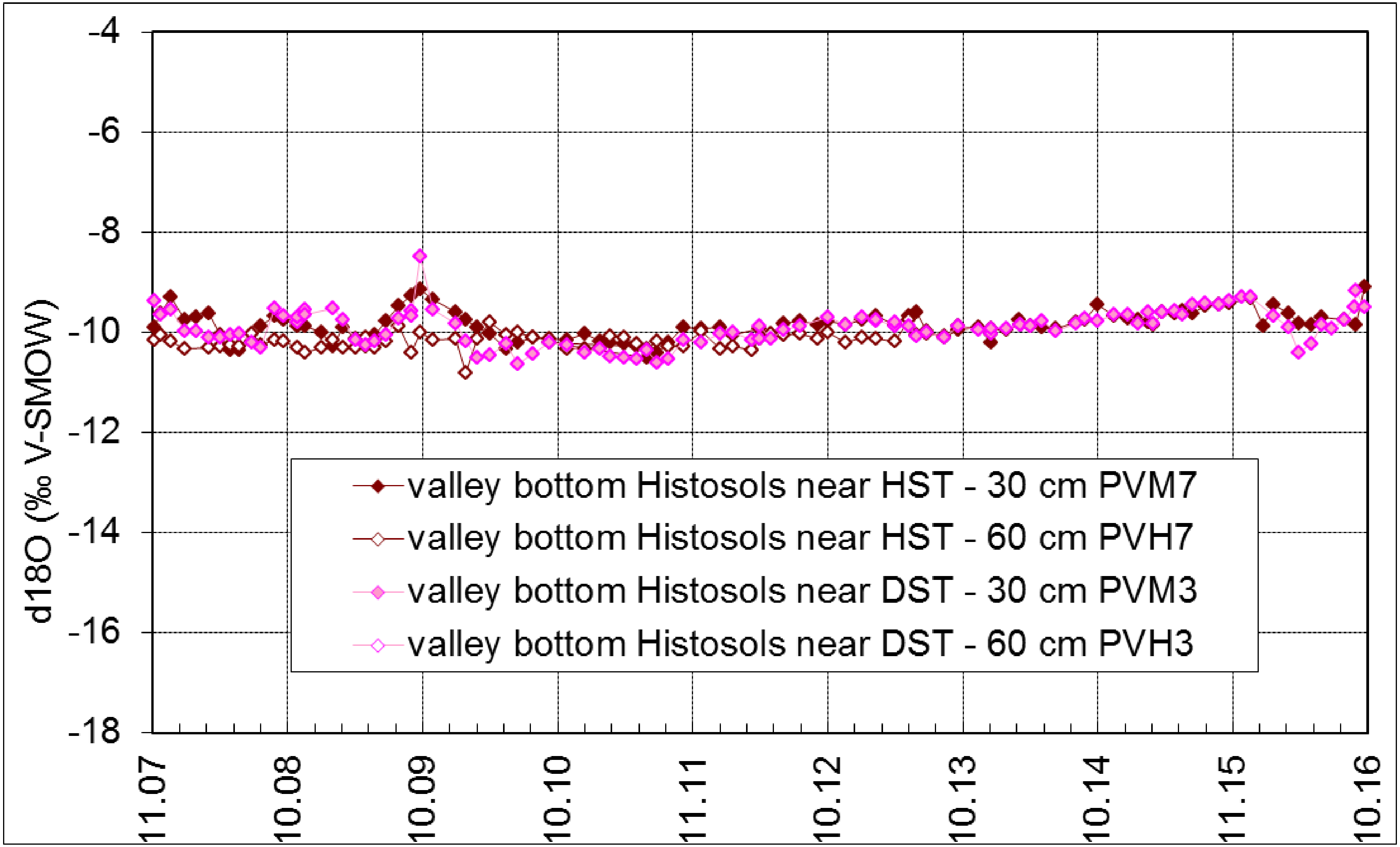
^{18}O in soil runoff and streamflow



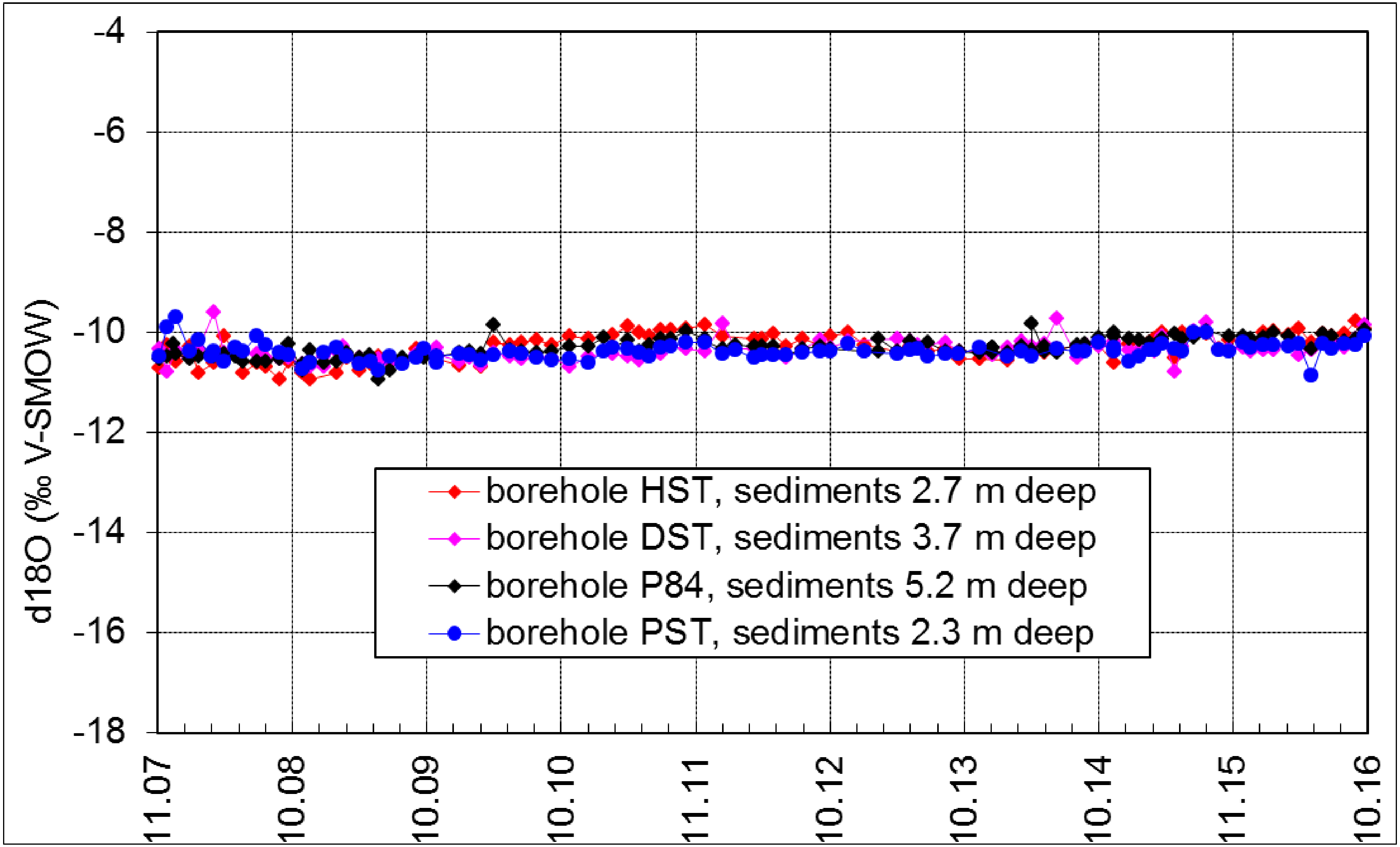
^{18}O in Cambisol and Podzols pore water



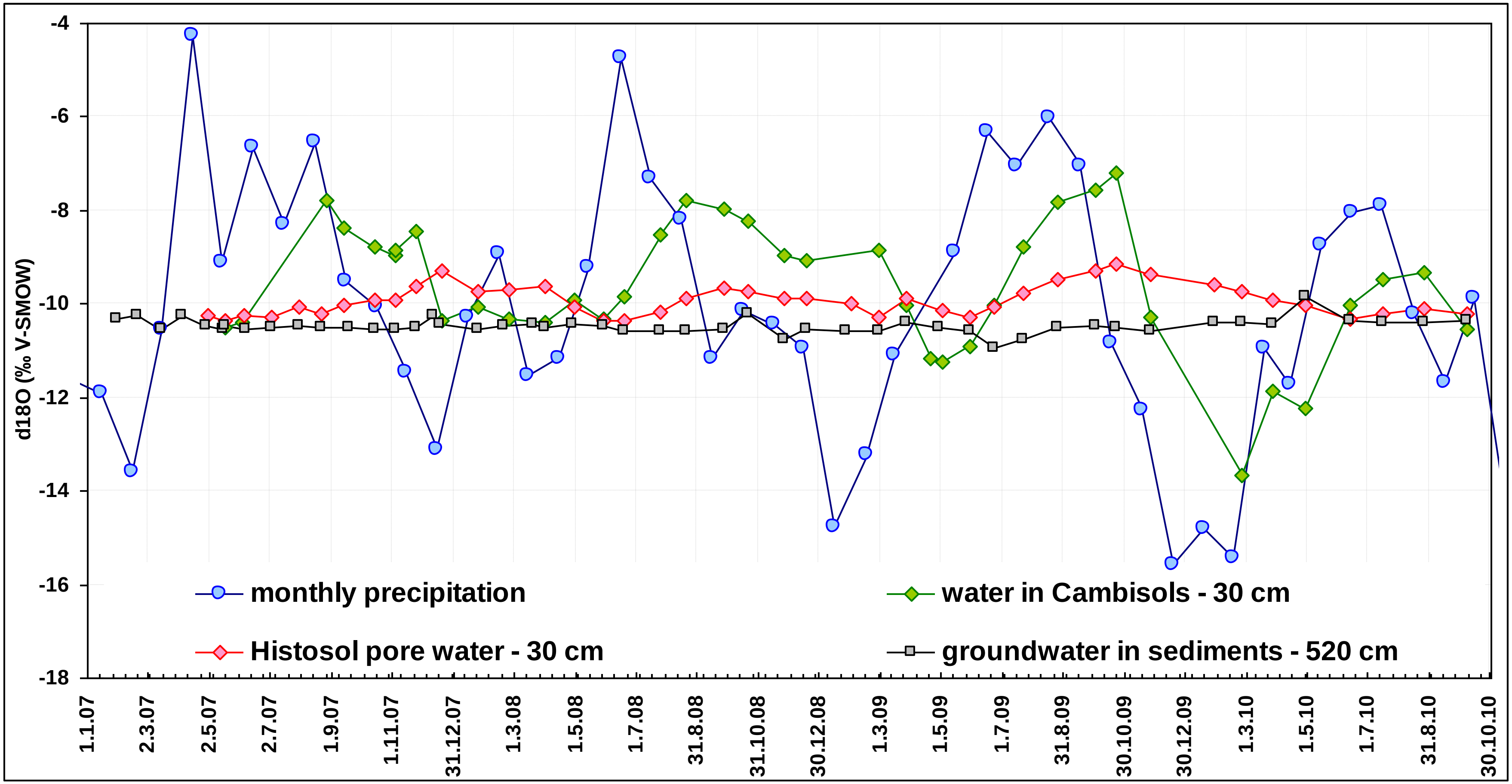
^{18}O in Histosol pore water



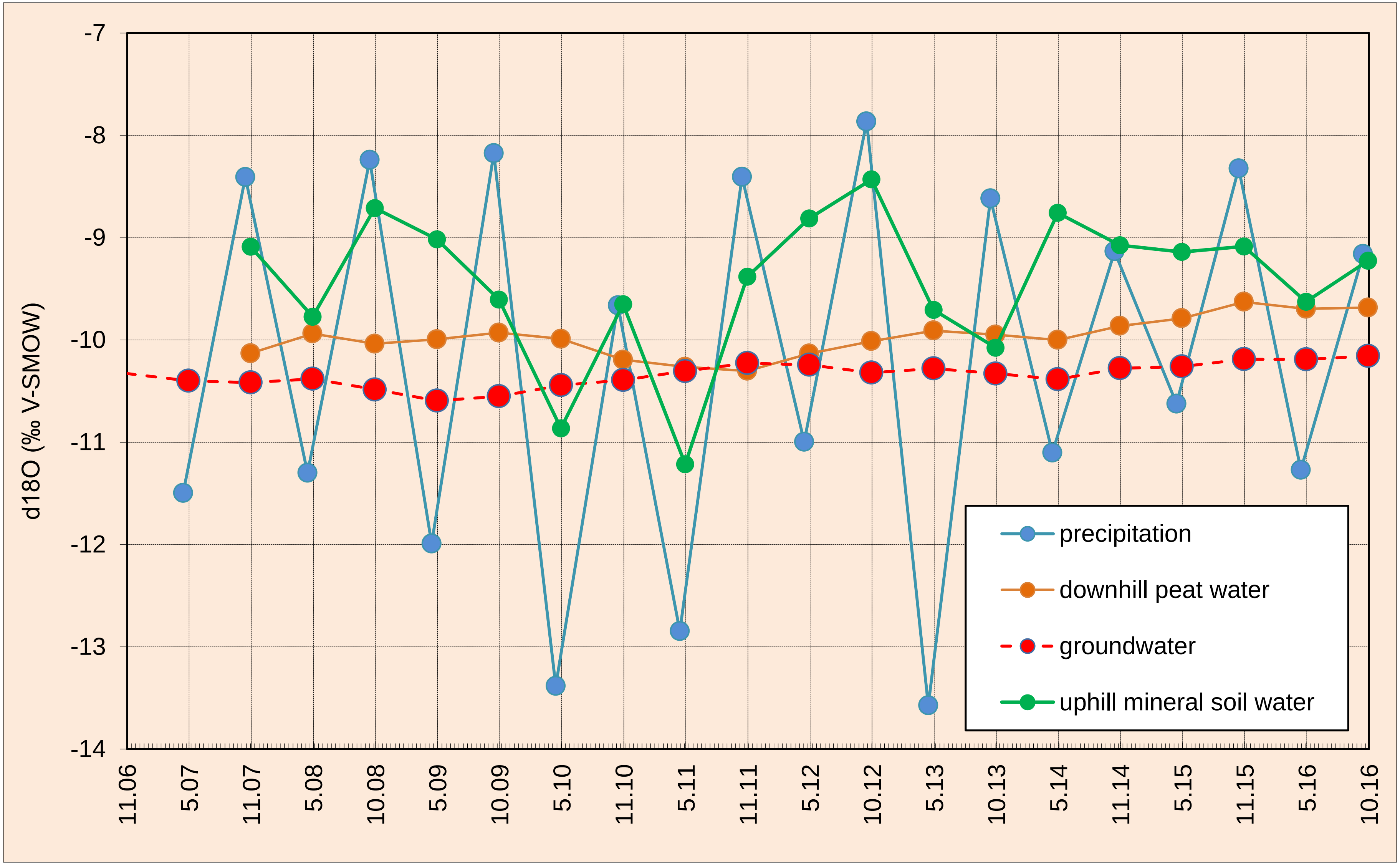
^{18}O in groundwater



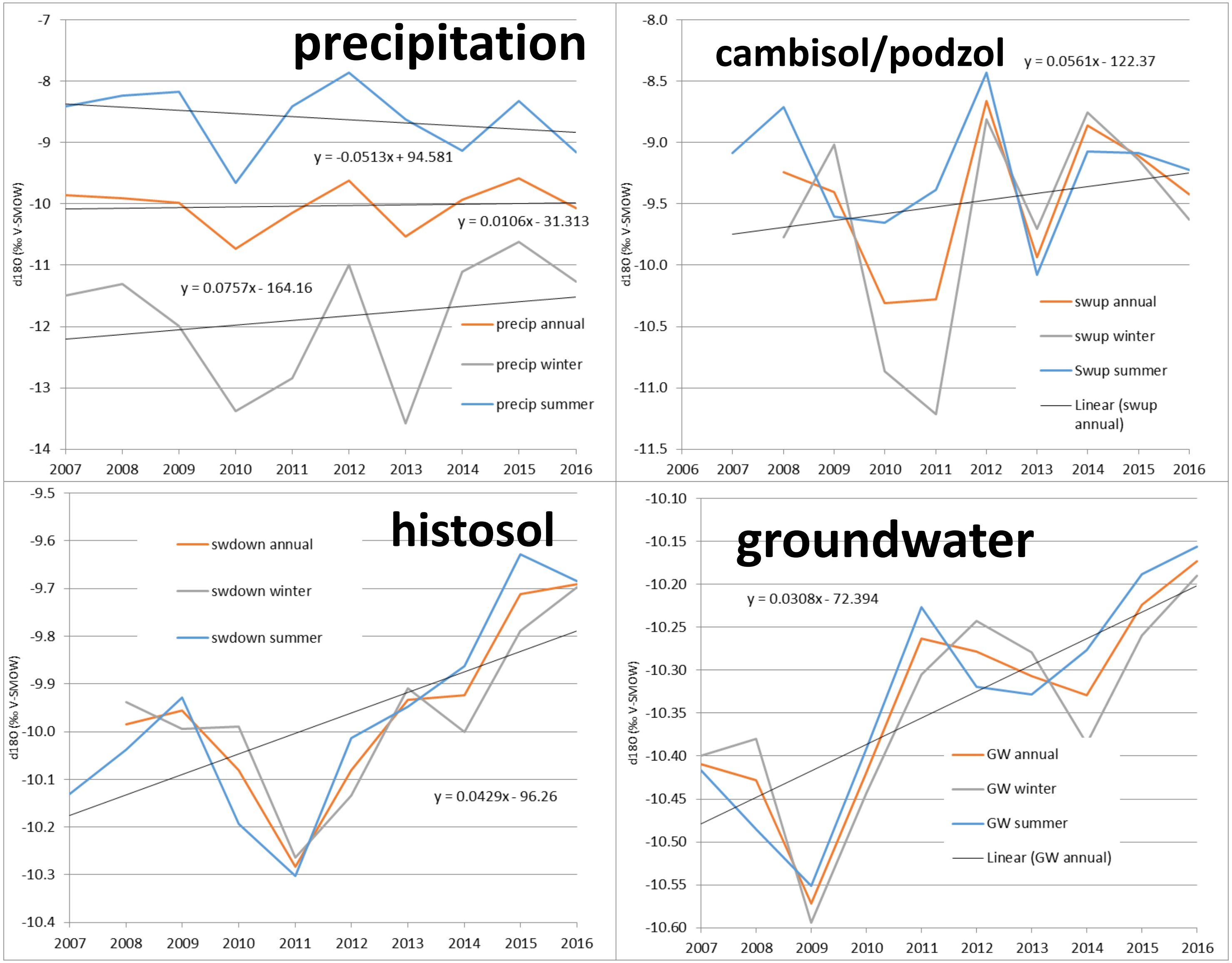
Seasonal mixing of waters in the soils and groundwater



Isotope decade 2007-2016



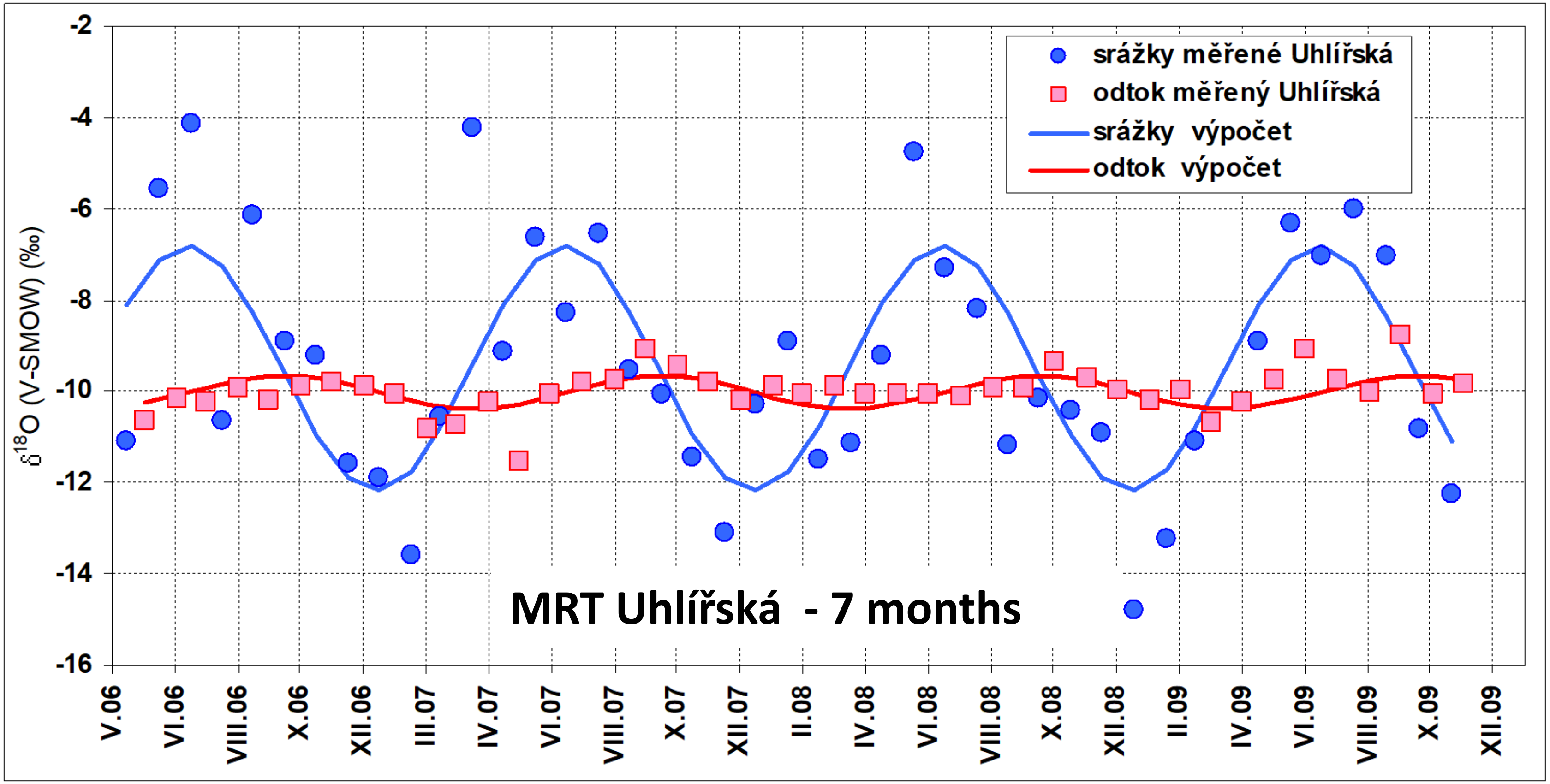
Isotope decade 2007-2016



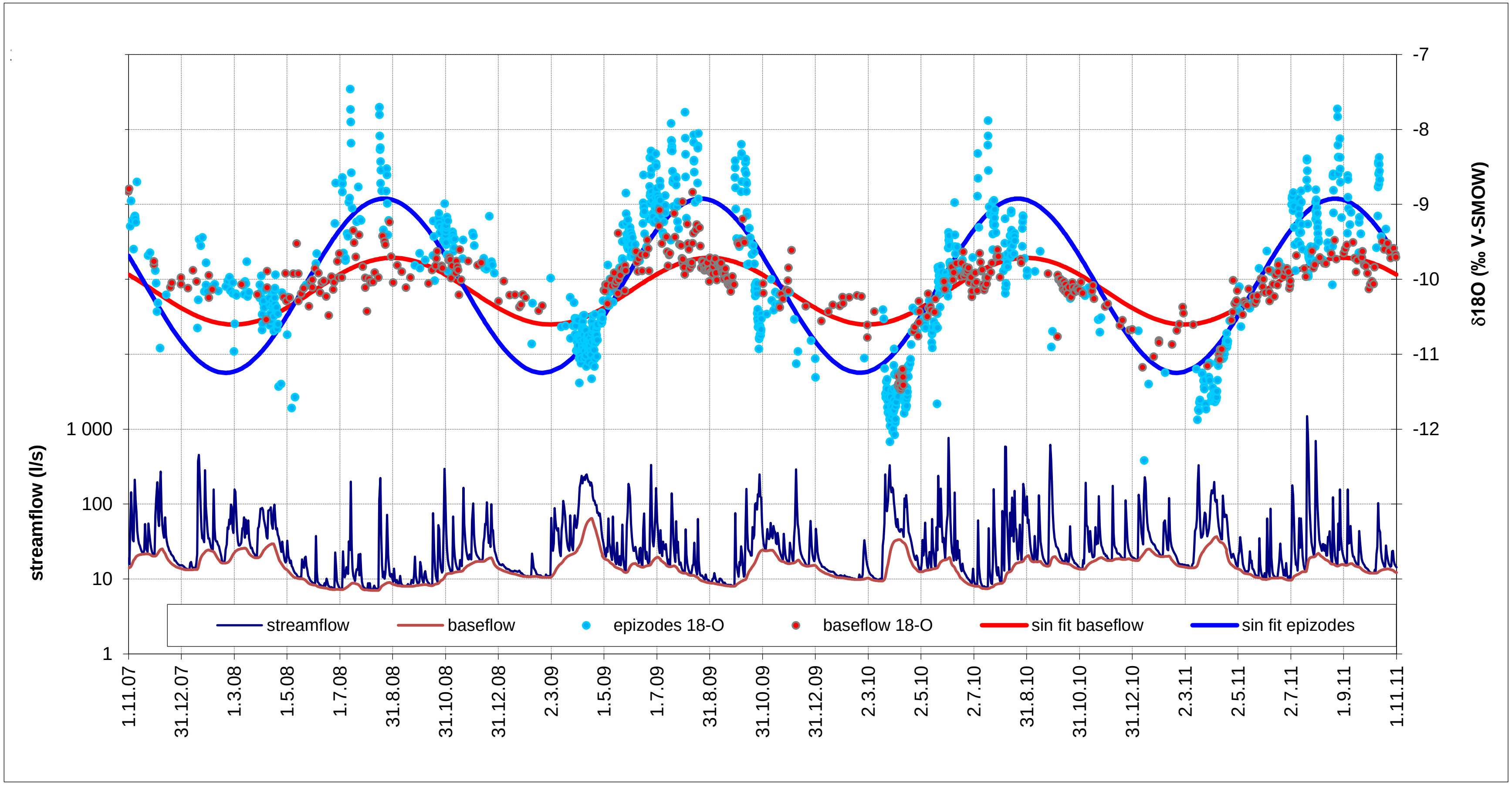
Use of isotopic data for Mean residence time (MRT) of water in system – linear reservoir model

$$MRT = \left(\frac{1}{b'}\right)\left[\left(\frac{A_p}{A}\right)^2 - 1\right]^{0.5}$$

Attenuation of precipitation on runoff
Input – (rain A_p) a output (runoff A)
conversion ((1/b´) = 6/π (for months)



Mean residence time of baseflow and events



BFLOW average index of baseflow is 0,673

Mean residence time is 12.3 for baseflow, 4.4 months for event flow

Groundwater is main component in summer storm flow and snowmelt

Gradual attenuation of ^{18}O signal in catchment waters

Summer precipitation

Winter precipitation

Quick soil outflow

Pore water in Cambisol

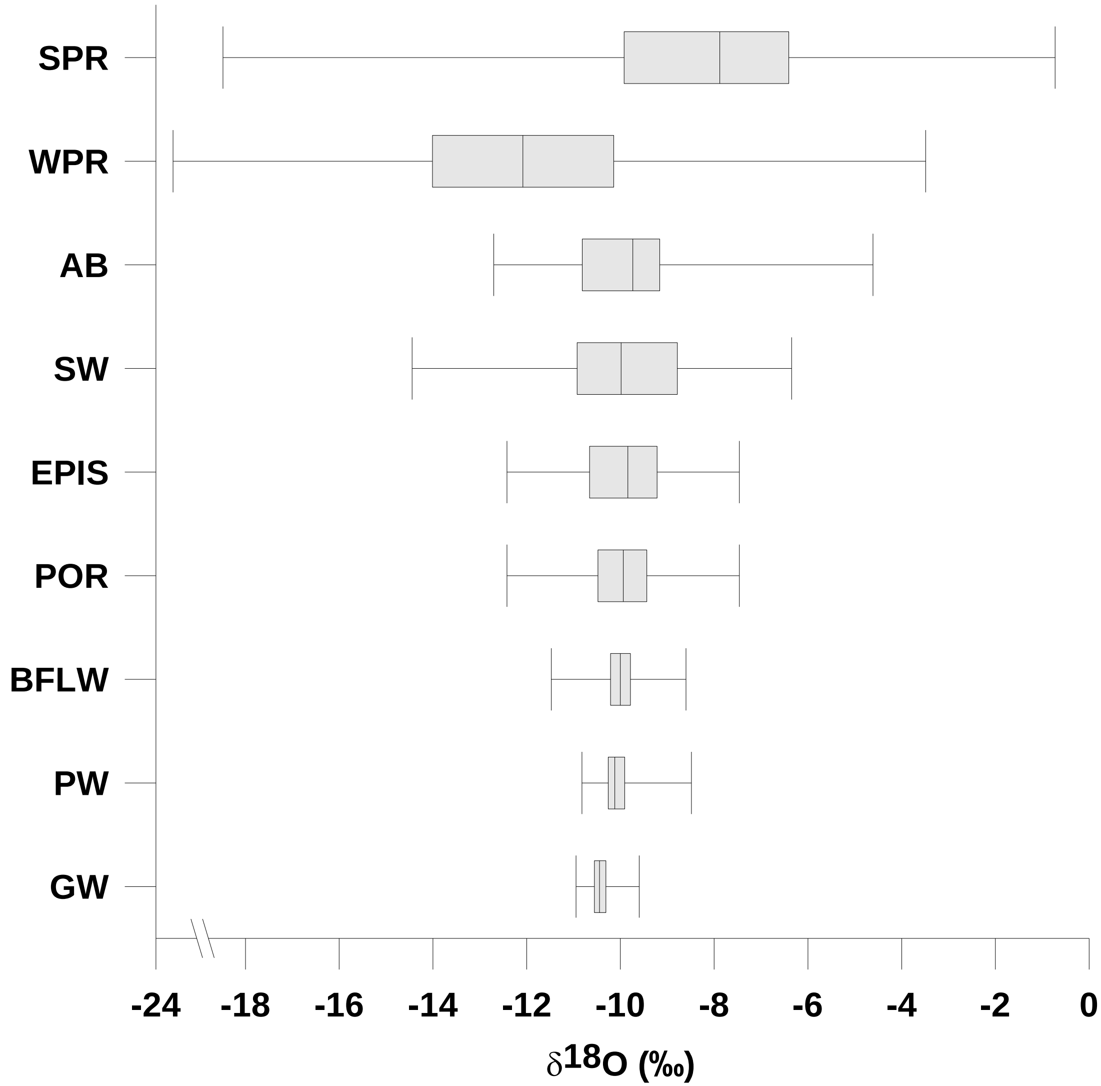
Episode outflow in stream

Total outflow in stream

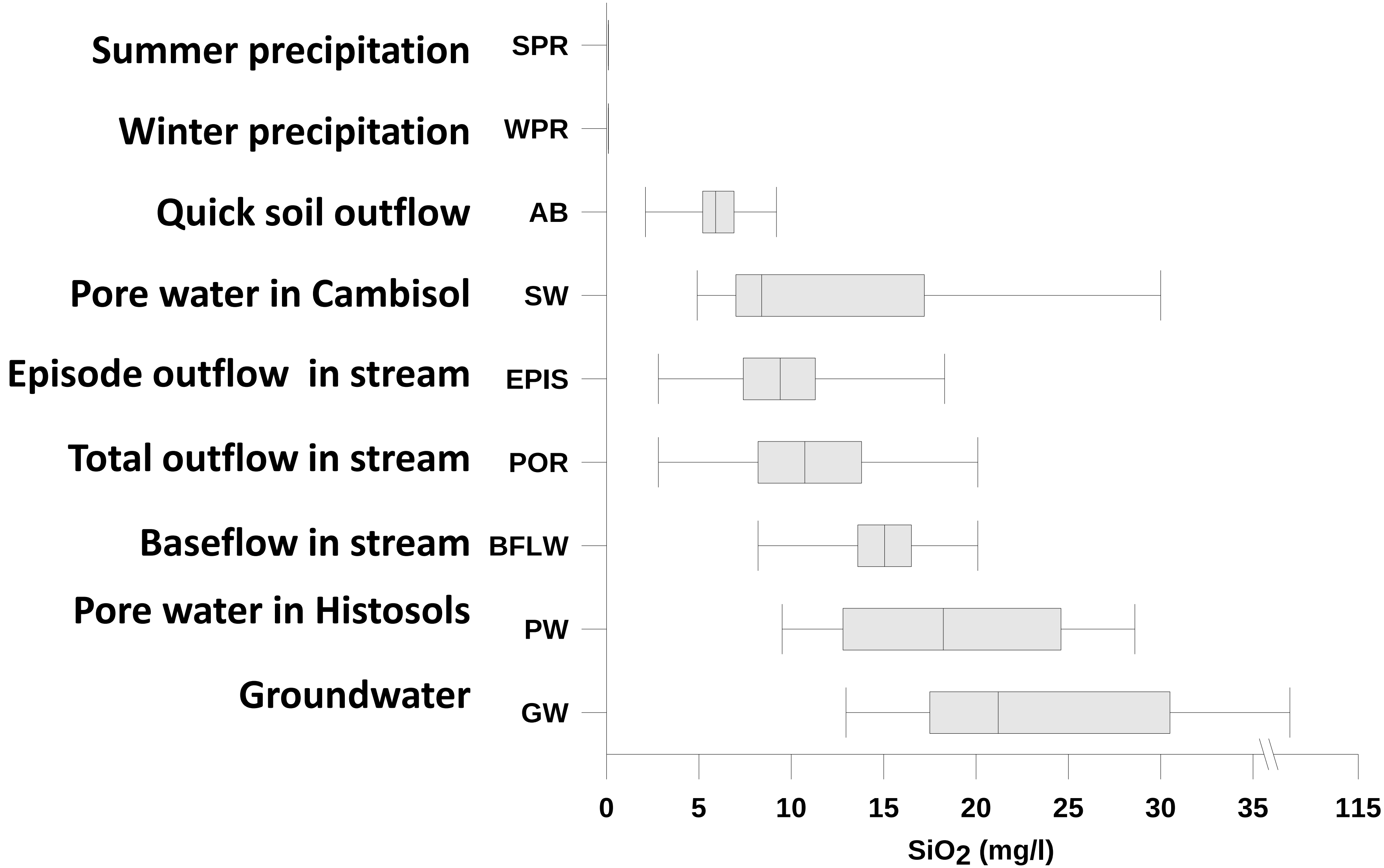
Baseflow in stream

Pore water in Histosols

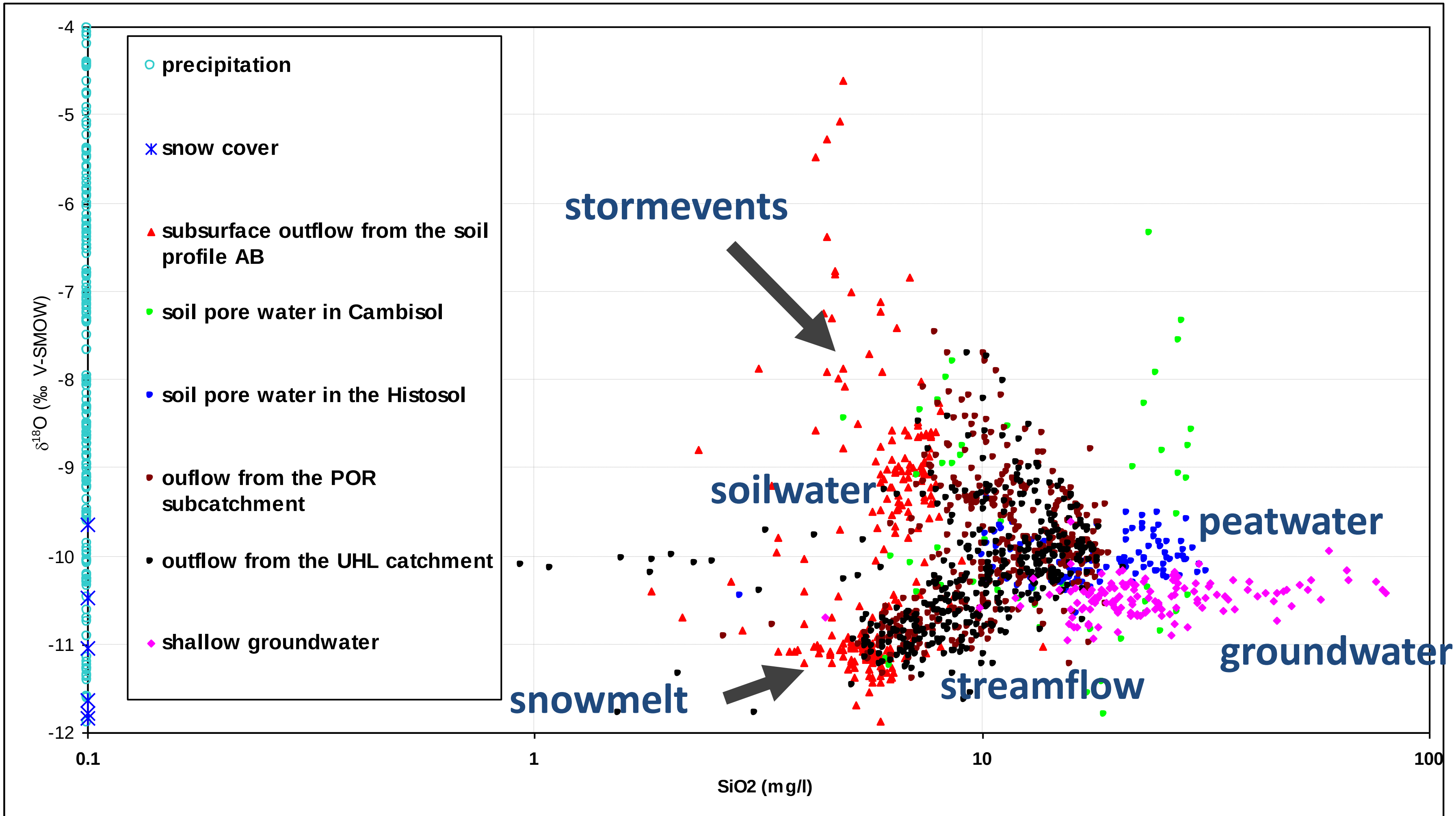
Groundwater



Gradual increase of SiO_2 in catchment waters

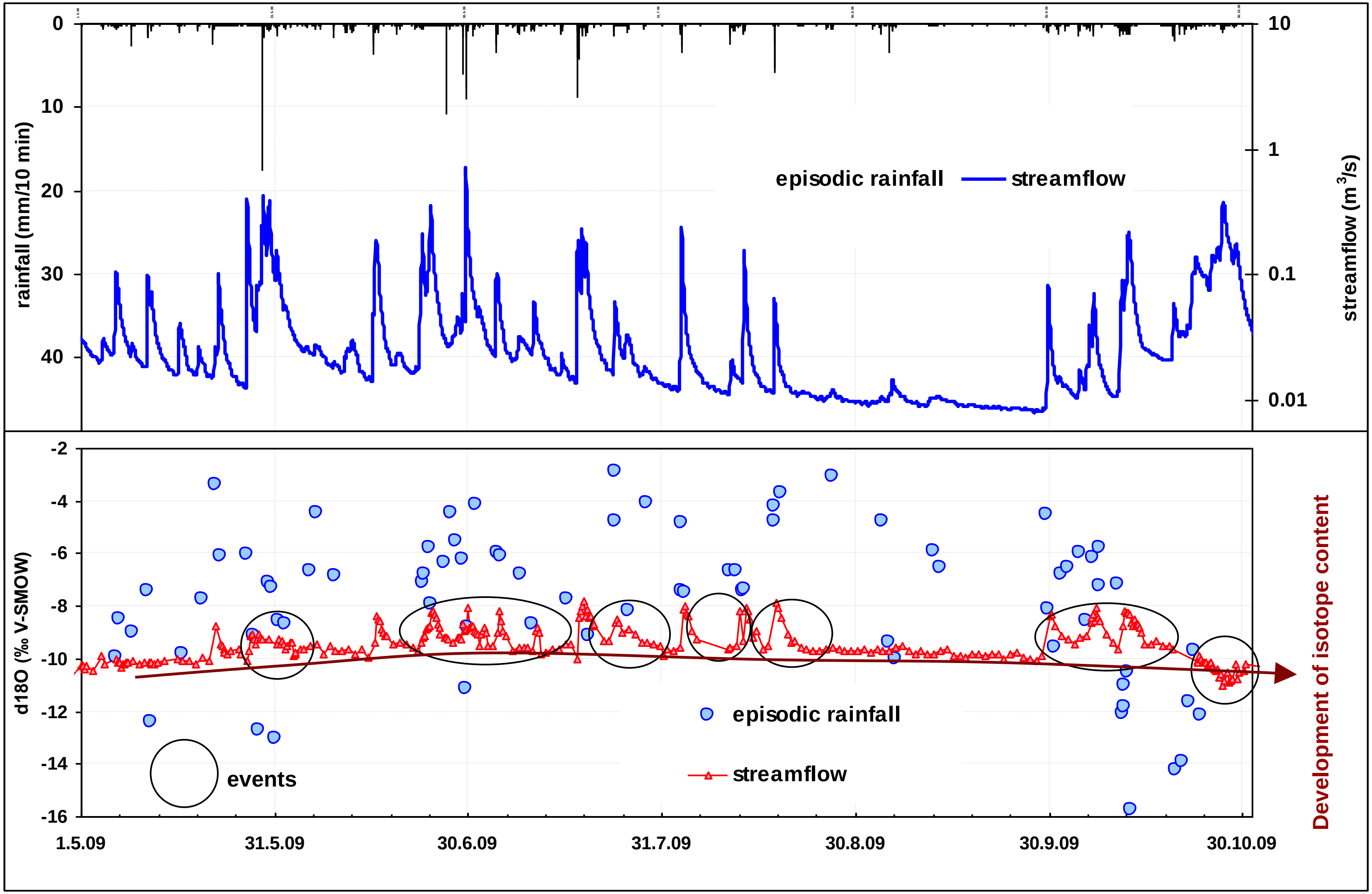


End members by ^{18}O and SiO_2 in catchment waters

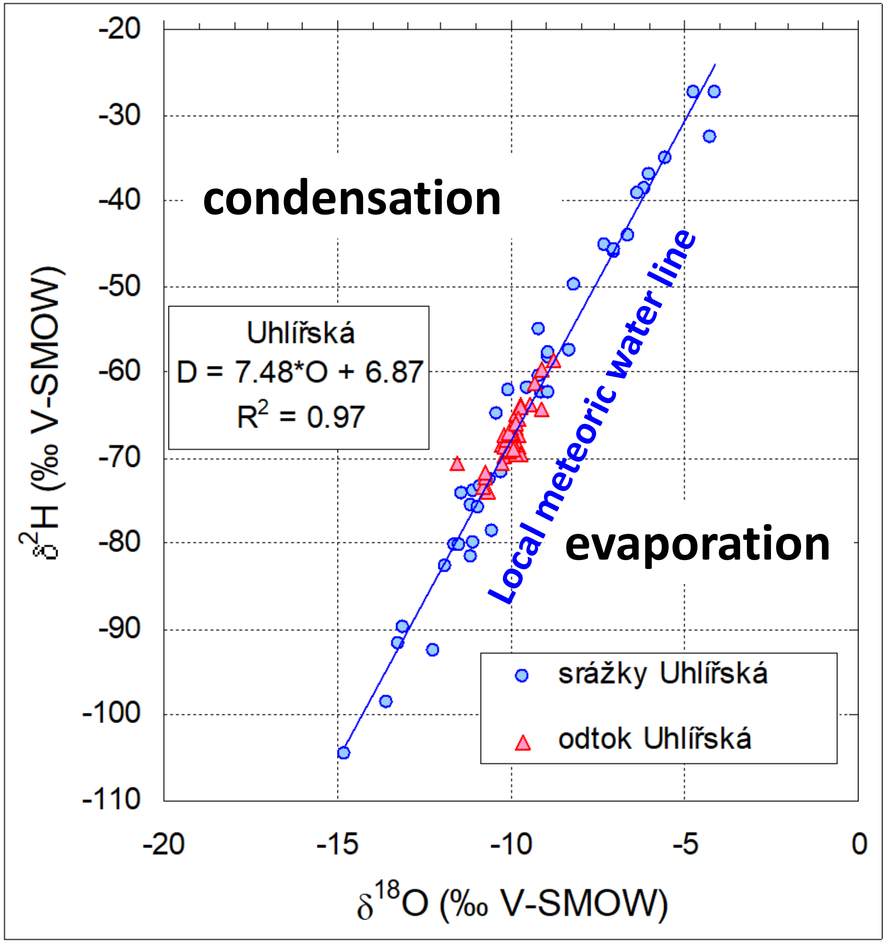


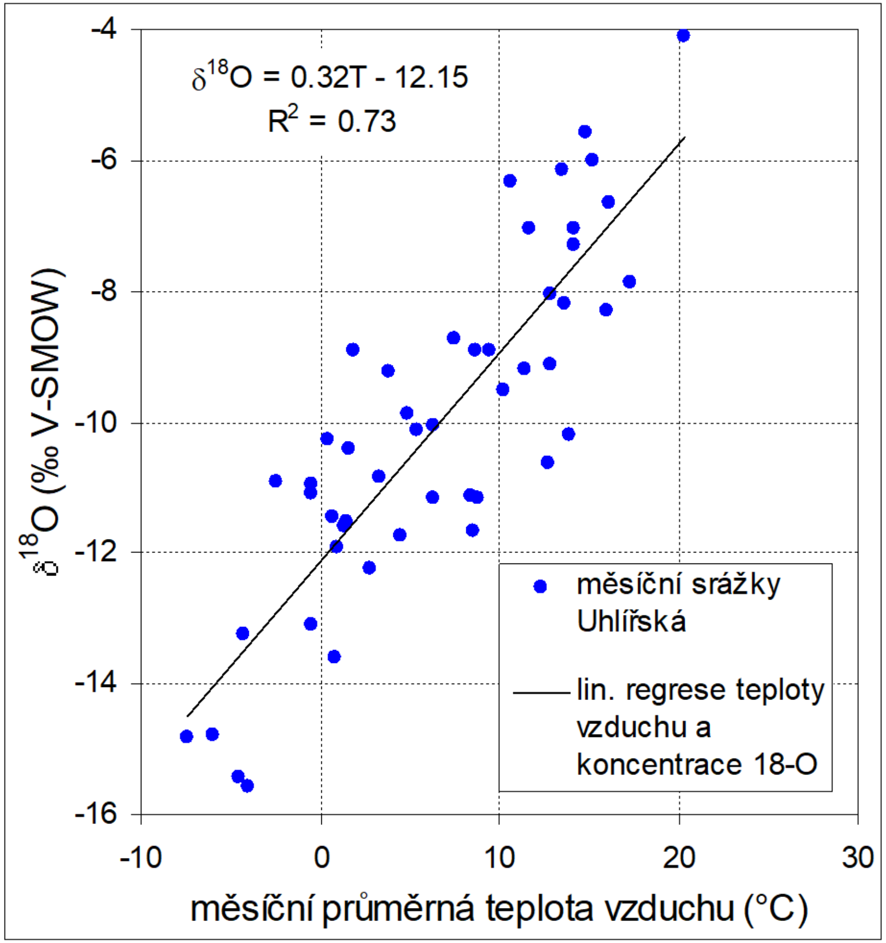
Response of streamflow to rainfall

Dominant effect of pressure drained groundwater mixed with soil and rain water



Vztah δ²H a δ¹⁸O ve srážkové vodě a odtoku a vztah k teplotě prostředí

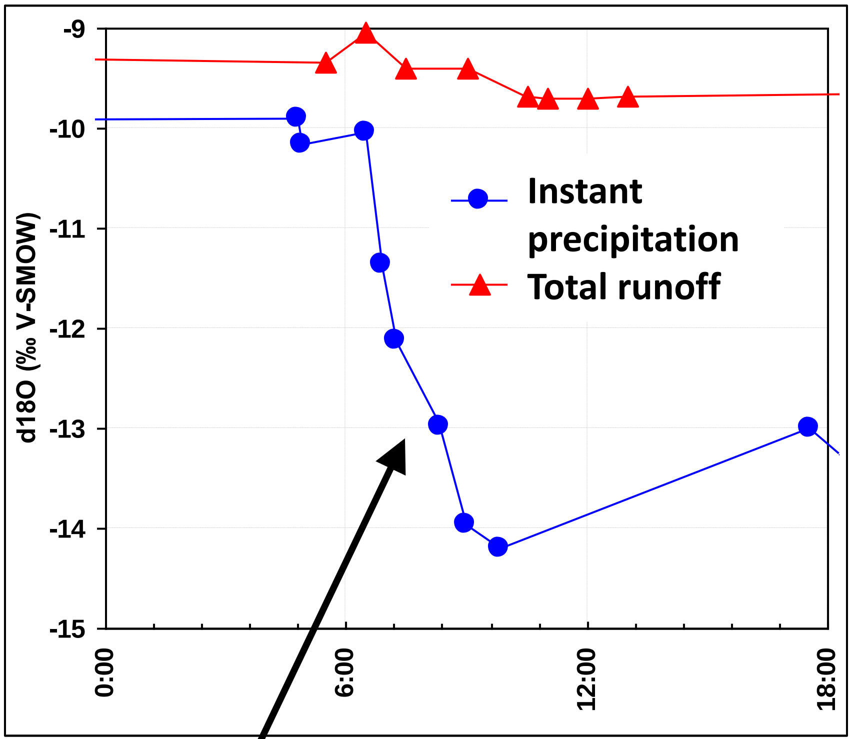


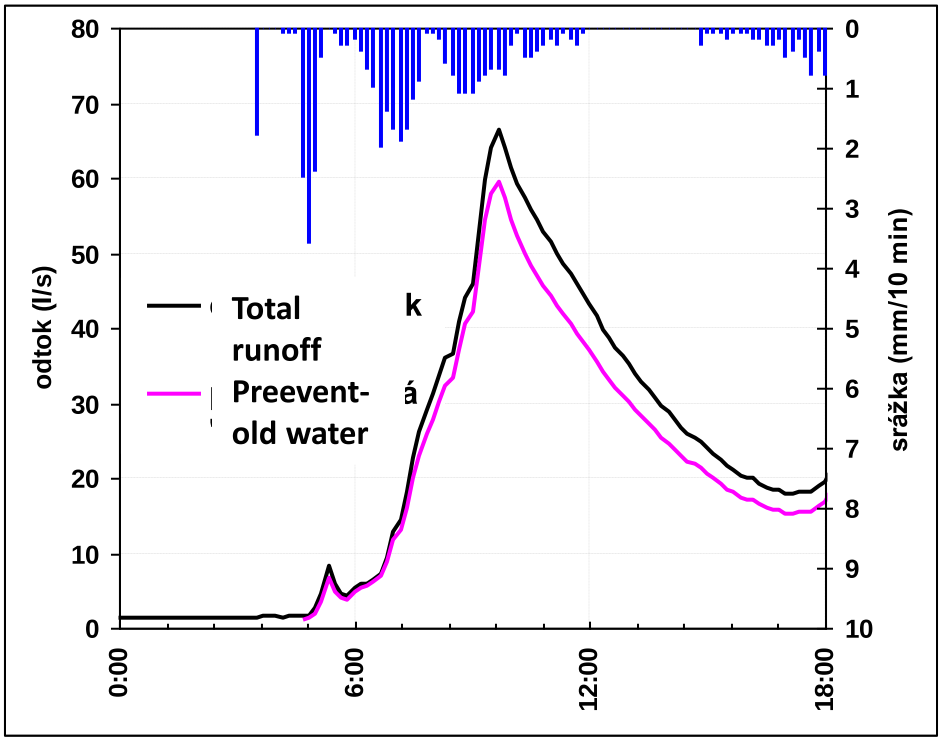


Isotopic separation

$$R_s = \frac{Q_s}{Q_t} = \frac{c_t - c_n}{c_s - c_n}$$

Q_t total runoff, Q_s runoff of "old" water, Q_n runoff of "new" water
c_t concentration of isotopes in total runoff
c_s concentration of isotopes in old water – groundwater or baseflow
c_n concentration of isotopes in precipitation
R_s instant ration of old-preevent water in runoff





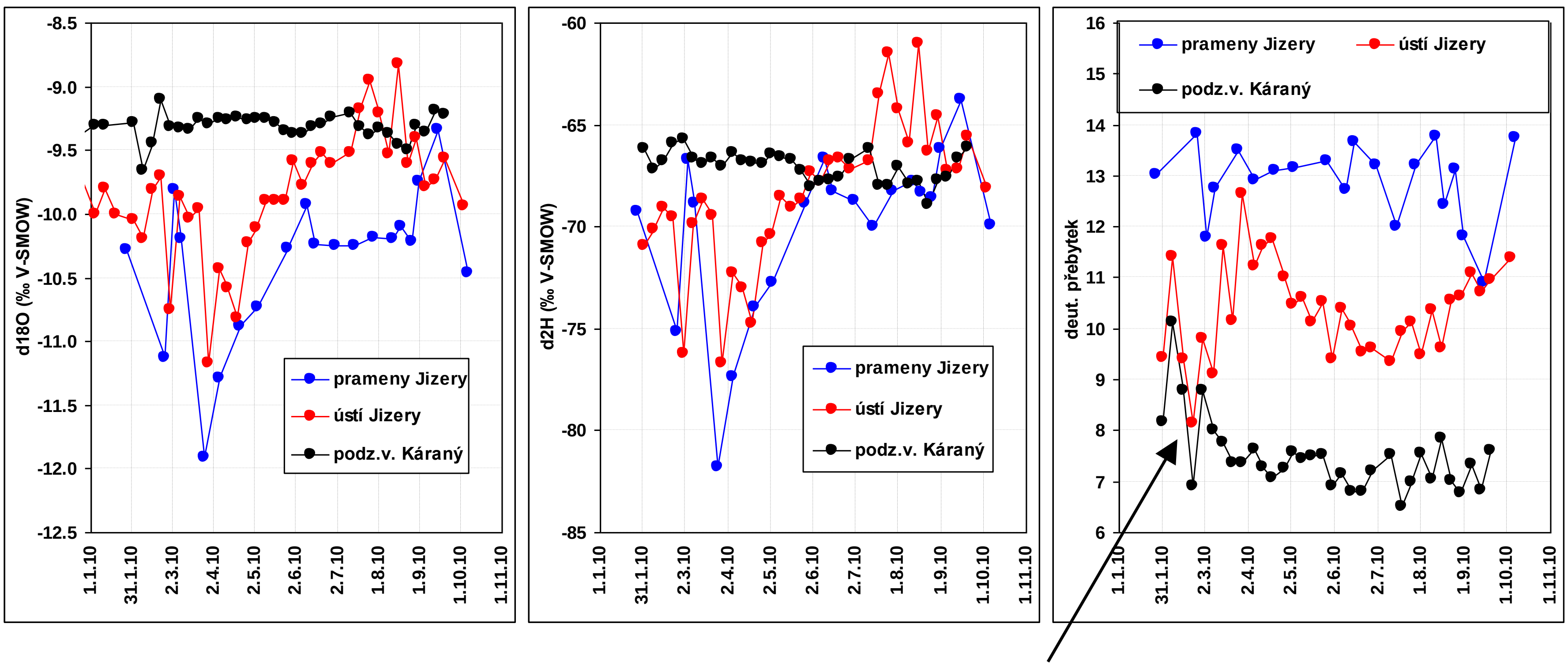
rainfall-runoff even in drained agricultural catchment, 7.8.2010

Rainout effect – decrease of concentration of heavier isotopes of O (and H) during frontal rain.

Deuterium excess in decoding sources of water in the catchment

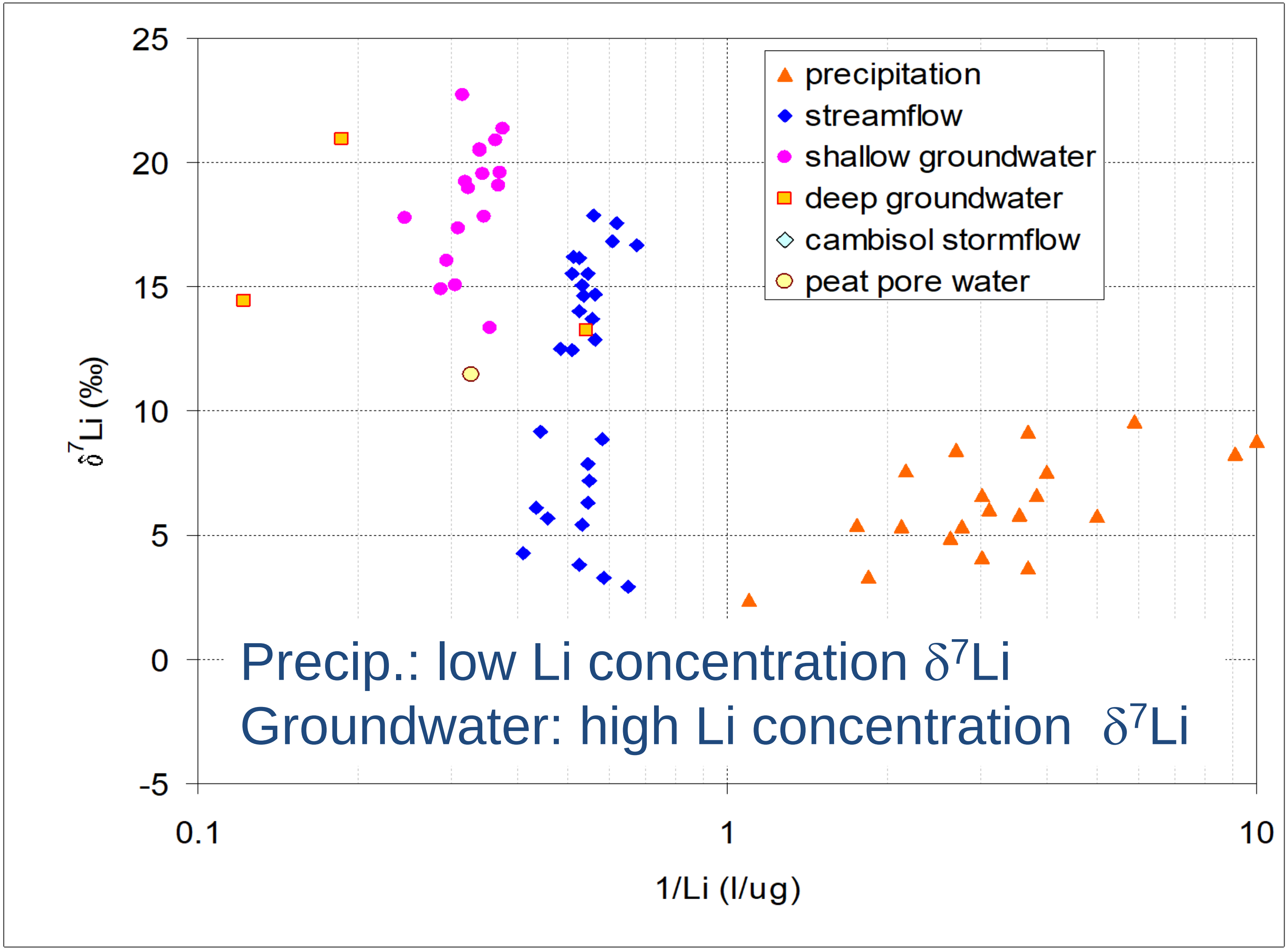
d=$\delta^2H-8*\delta^{18}O$ **d .. Deut. excess (-)**

$\delta^{18}O$ **δ^2H** **deut. excess**

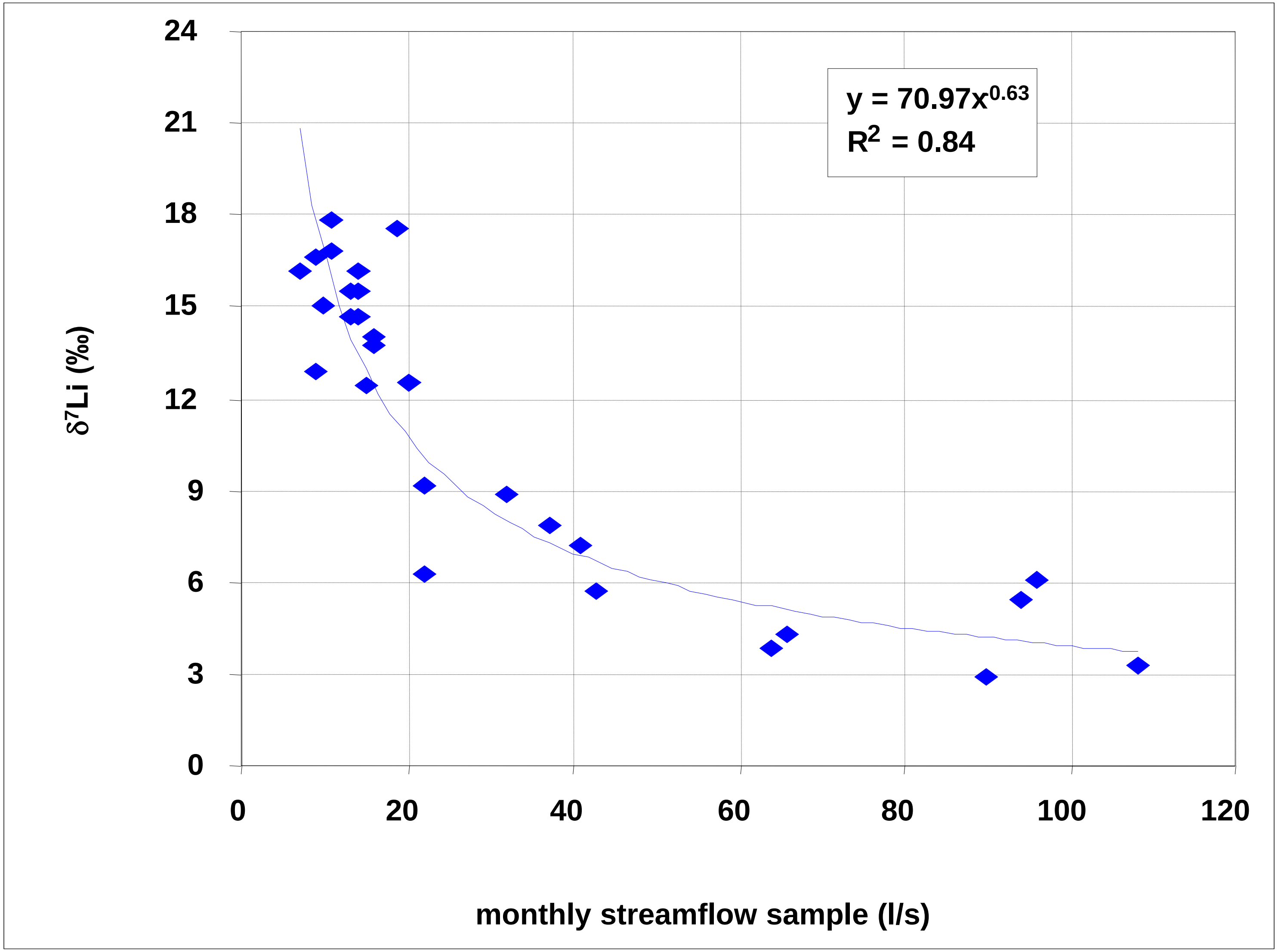


Mixed Jizera river water and local groundwater while pumped

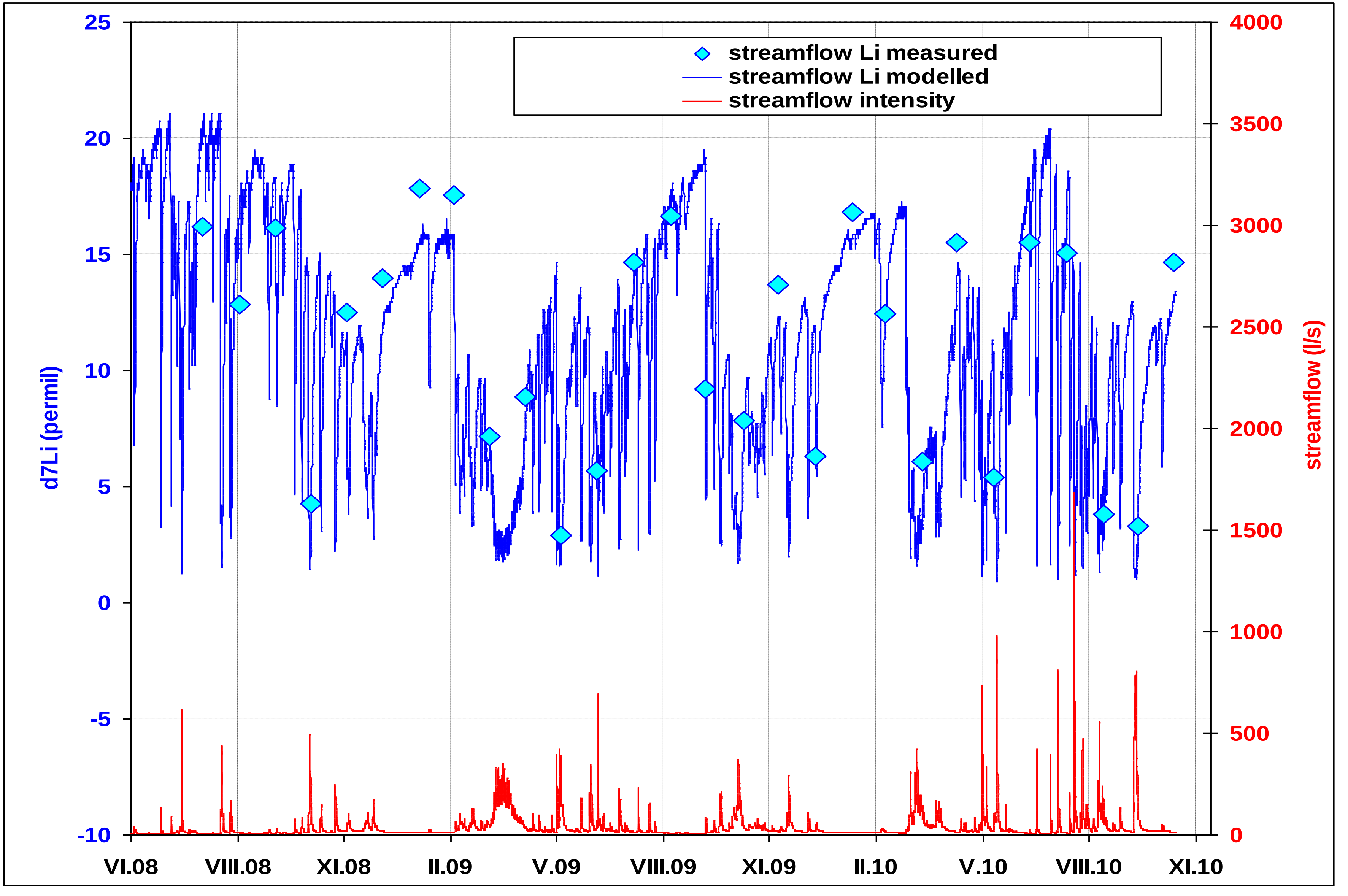
Li isotopes– causalities – end members



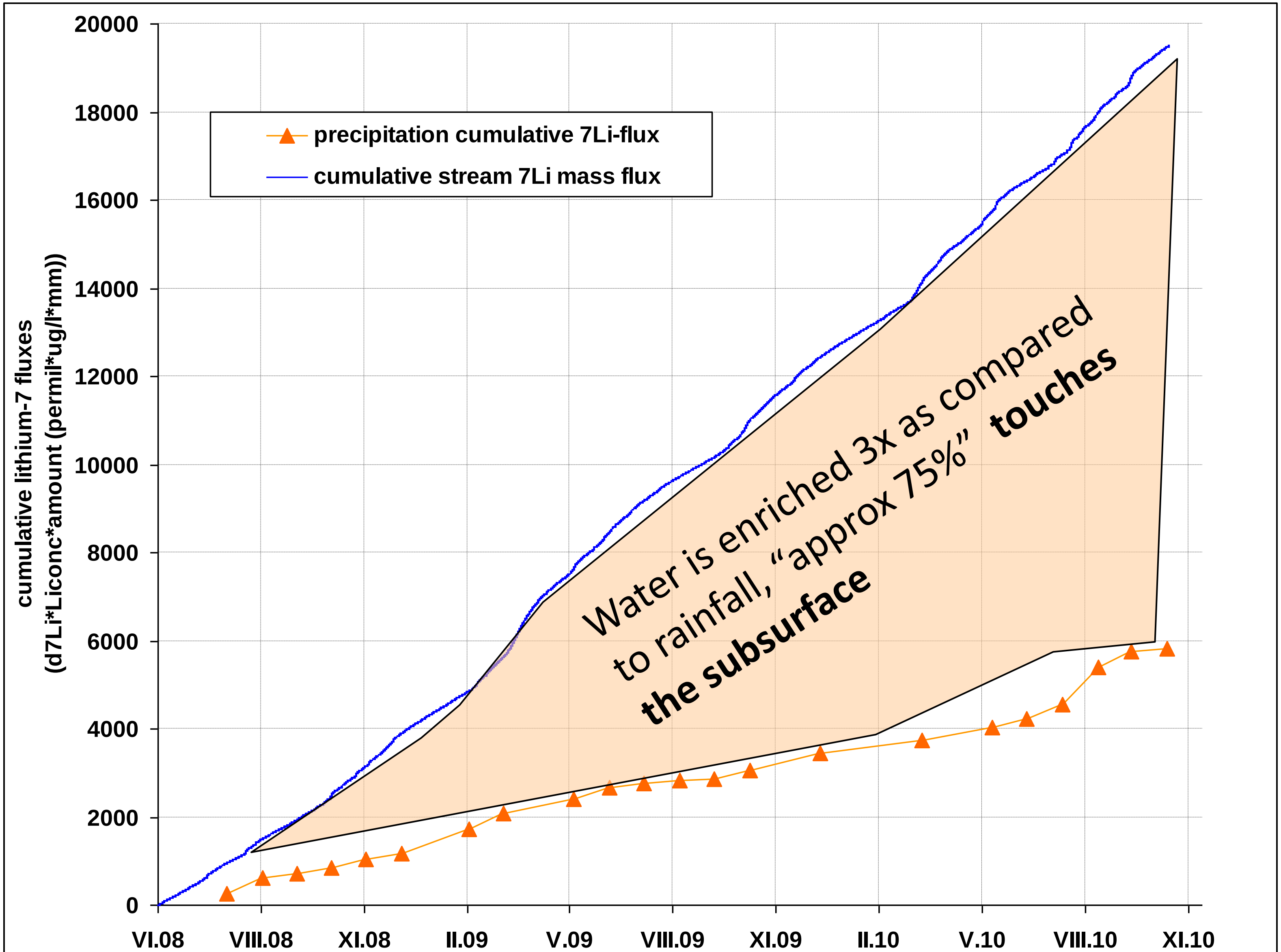
“Rock” δ⁷Li is present in baseflow
Less present in event flow



Outflow and δ^7Li content

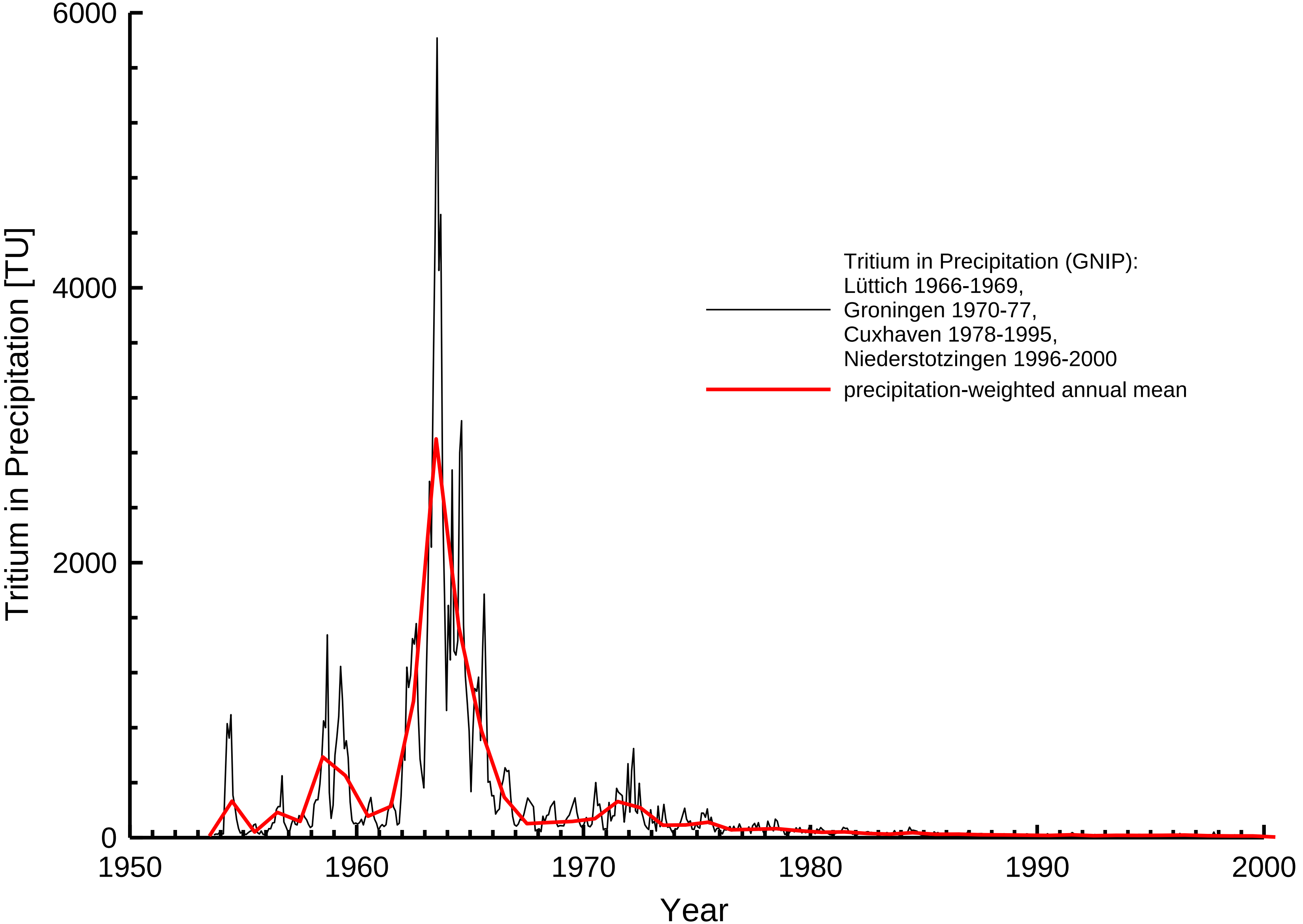


cumulative mass flux of δ^7Li



Tritium / Helium

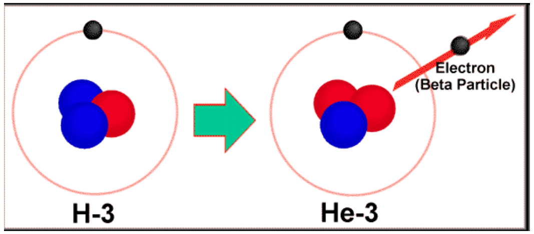
Tritium input function



Groundwater dating by T/He in multiscreen well

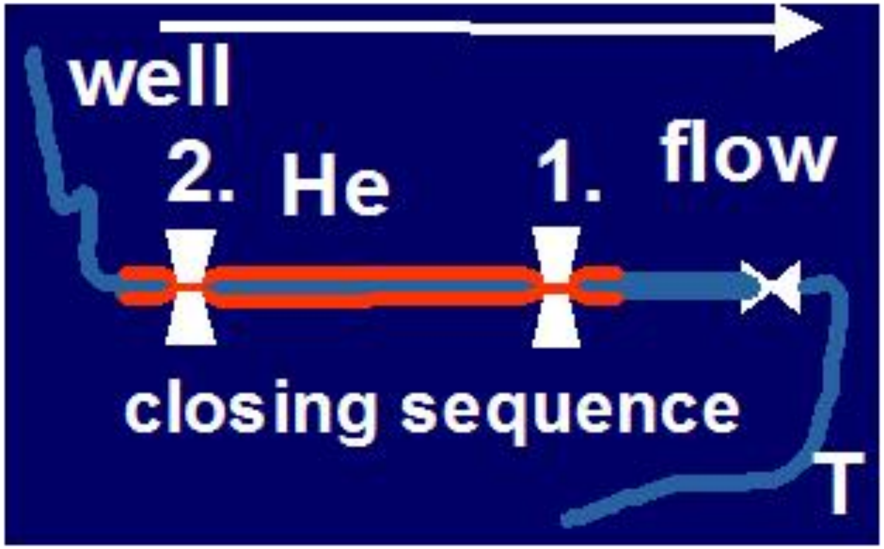
3 adjacent wells at the gauging station 10,20,30 m deep

Tritiu to helium

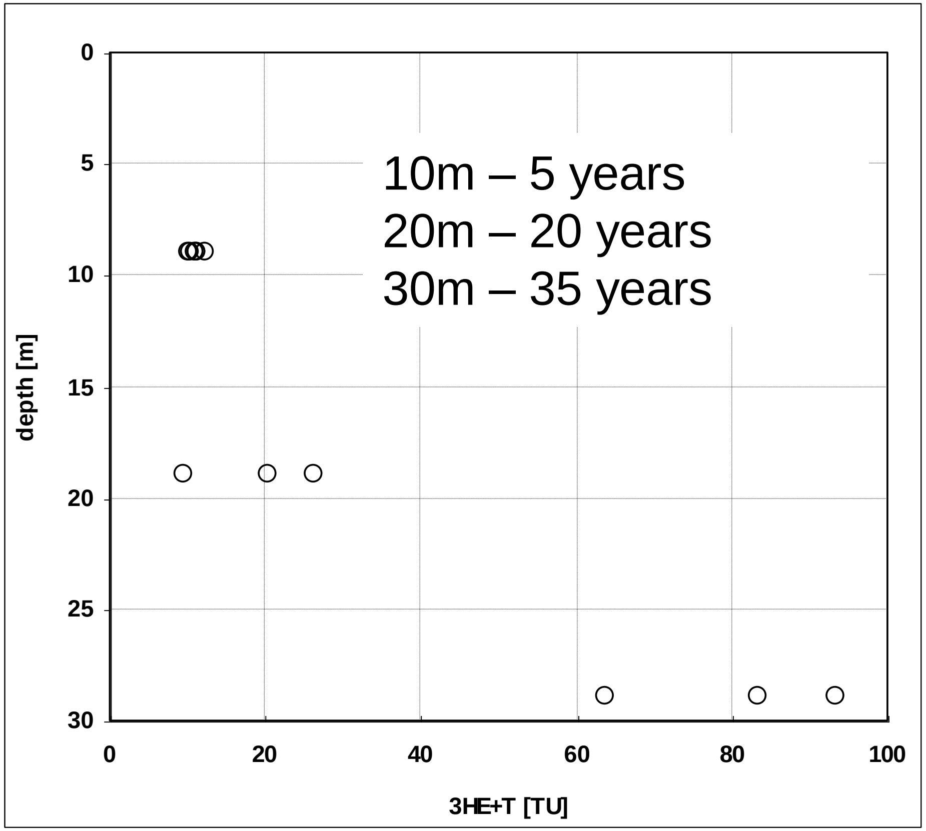


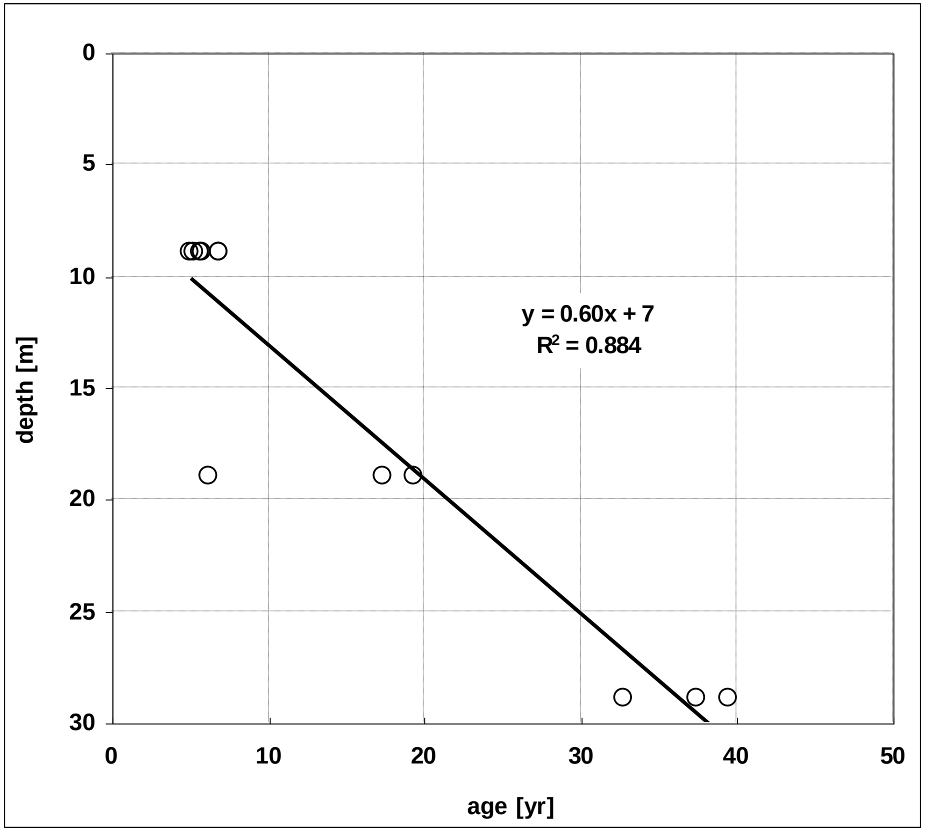
$t_{1/2}$=12.33 years

Isotope sampling – copper tubes



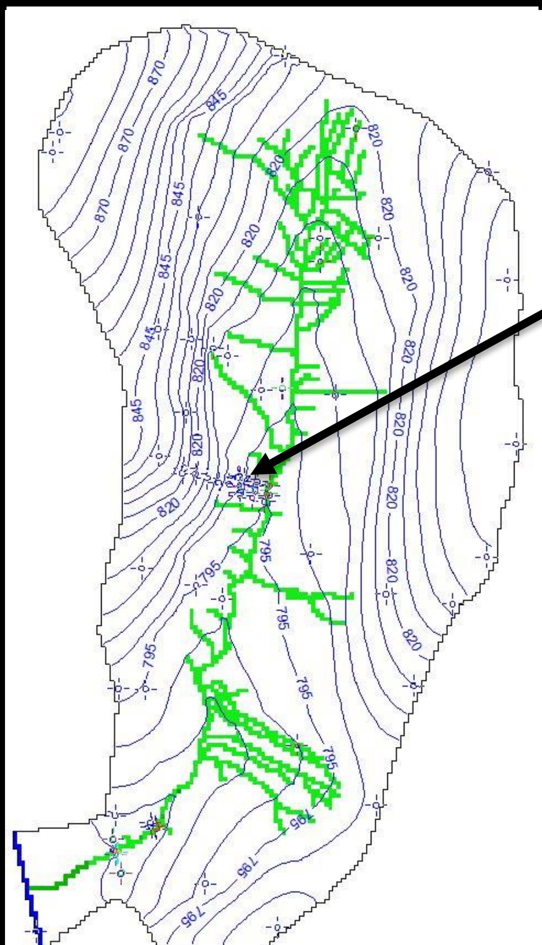
T/He dating - 3 campaigns of sampling of multiscreen well by std. Cu tubes



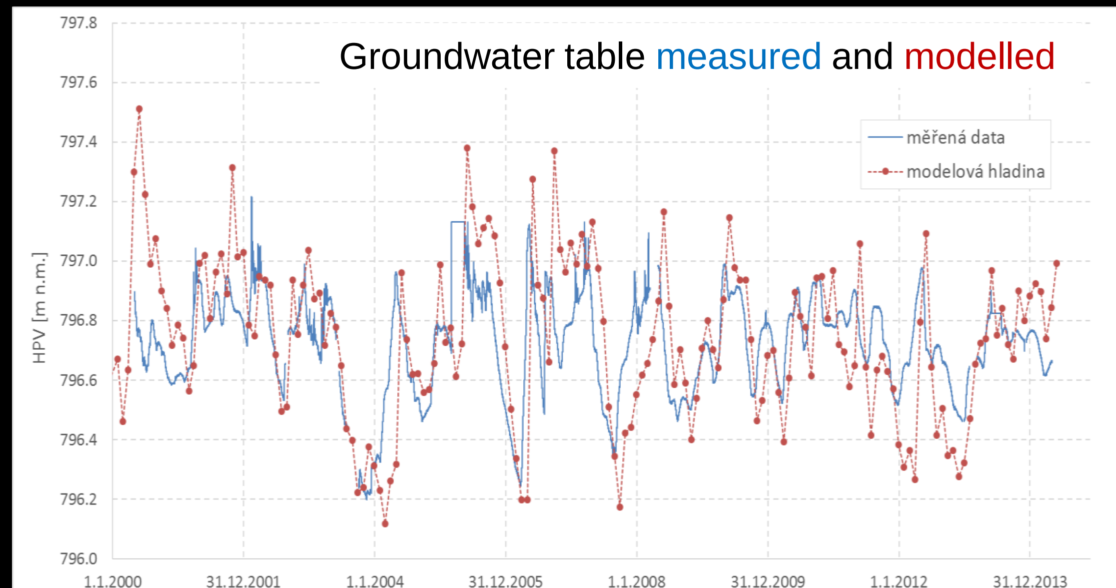


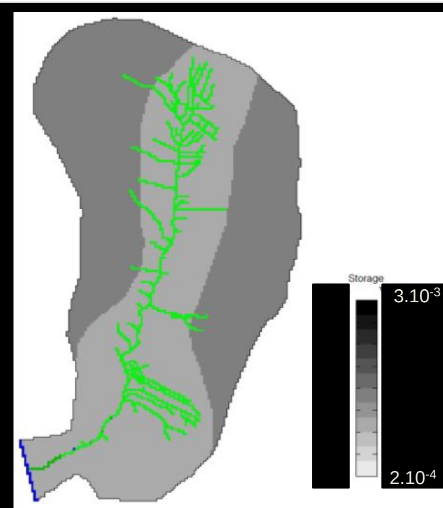
deep percolation of 0.6 m/year, i.e. assuming 20% porosity – 120 mm (10% of precipitation)

Groundwater modelling using isotopes



Groundwater in calibrated model

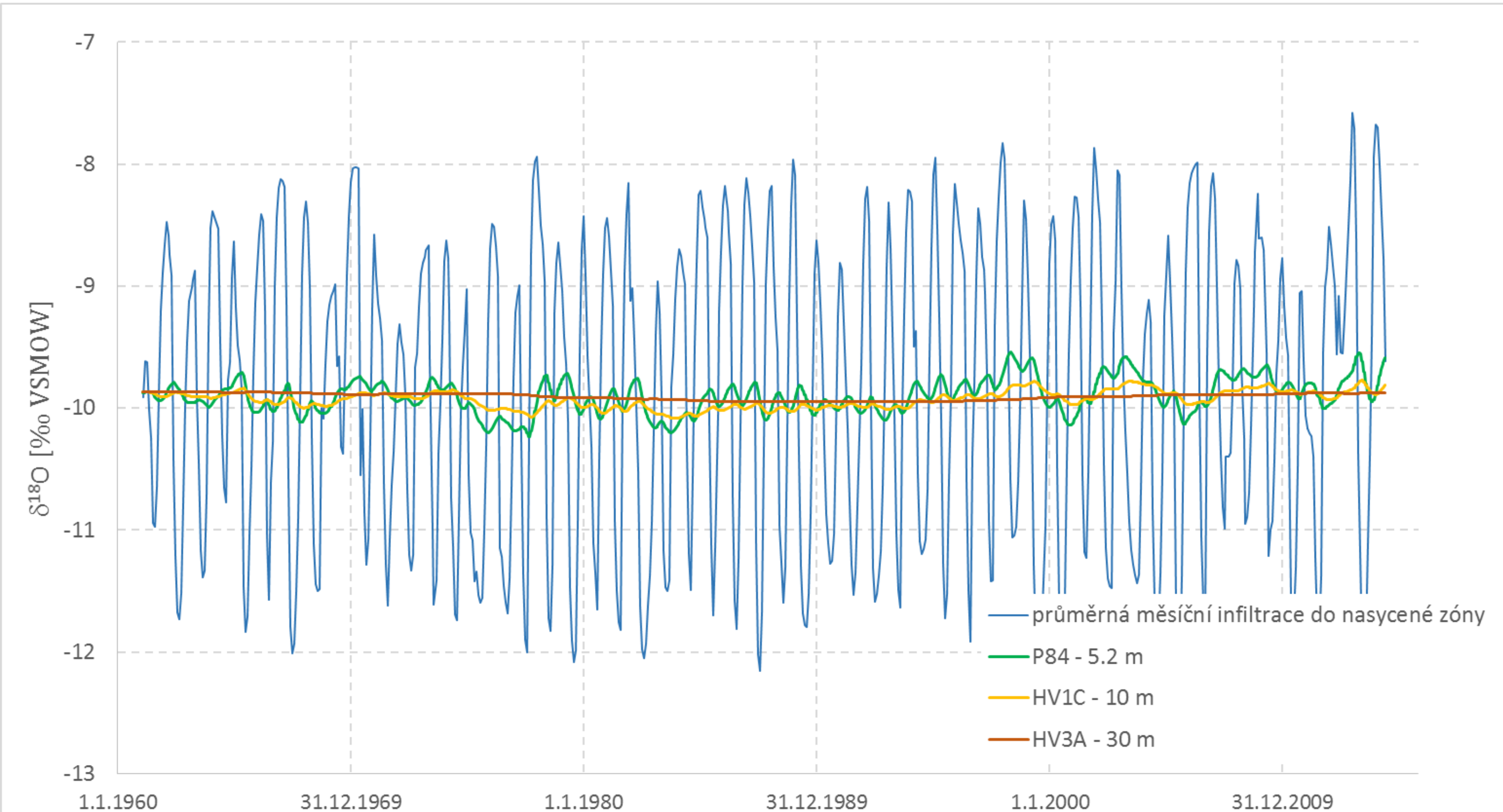




Storativiy in first model layer

Modelling of flow of groundwater and transport of ^{18}O

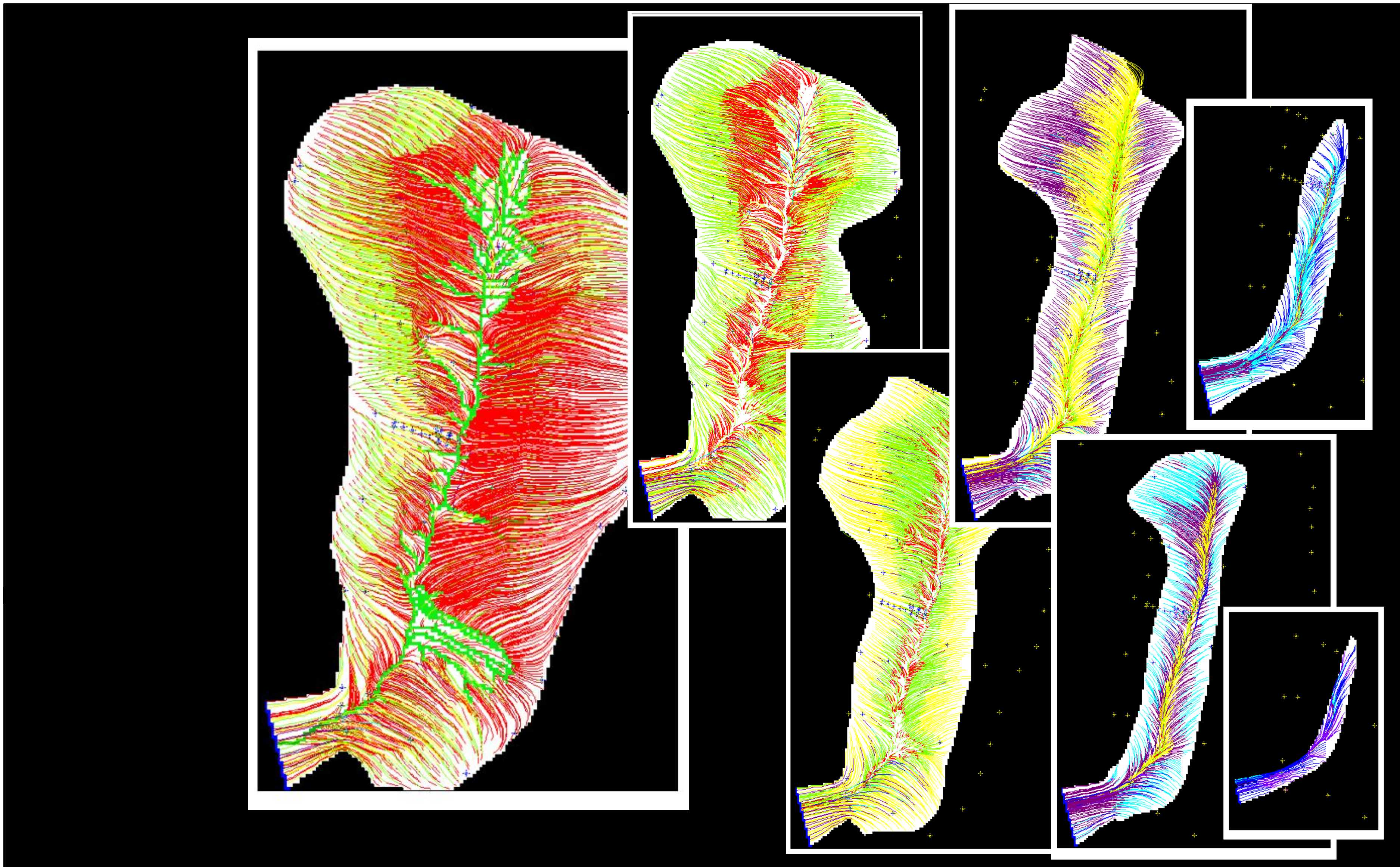
MODFLOW, MT3D



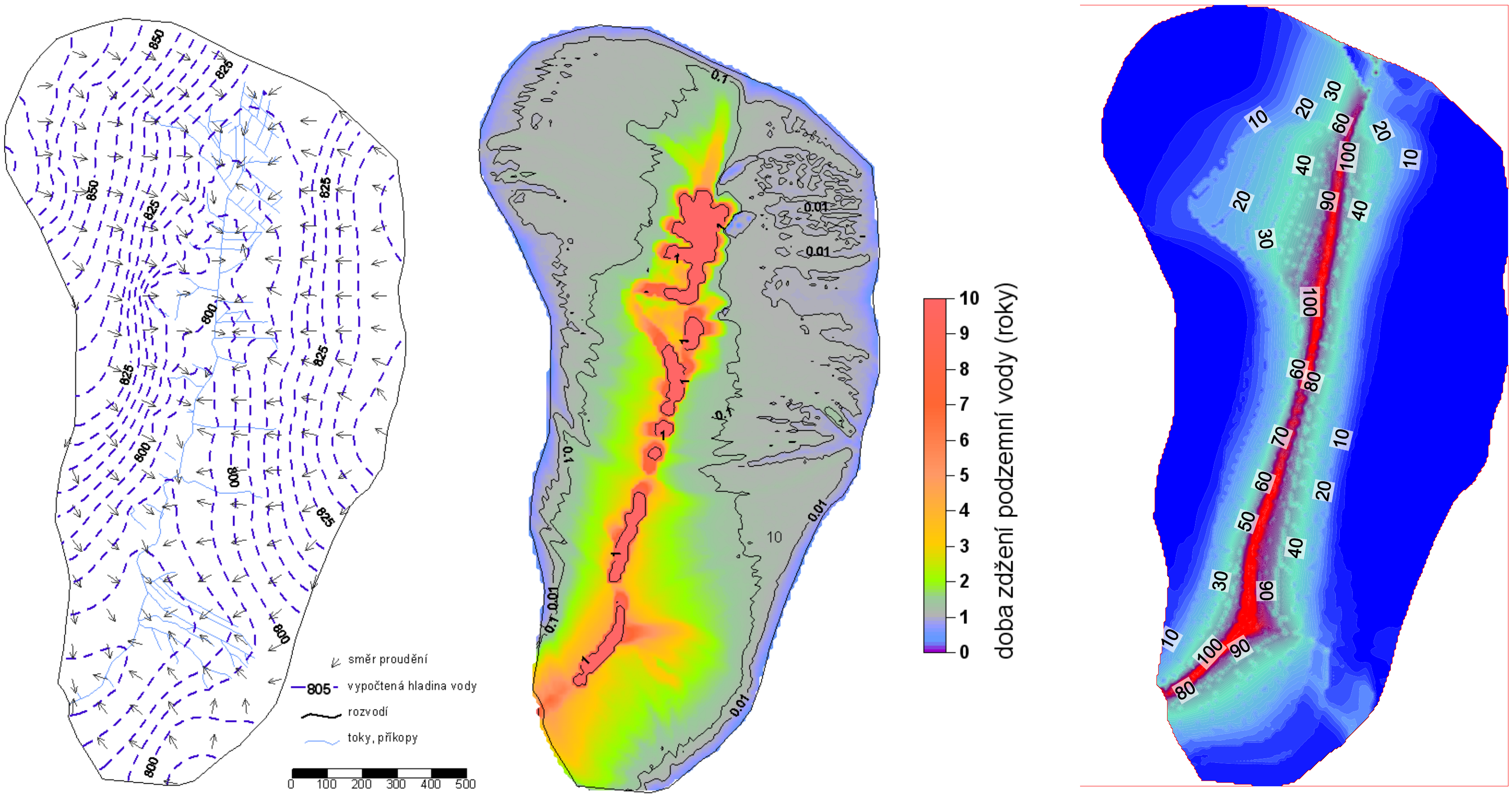
Confirmation of major mixing effect in the aquifer

Groundwater recharge isotopic concentration in blue series

Particle tracking in MODPATH in all 7 layers

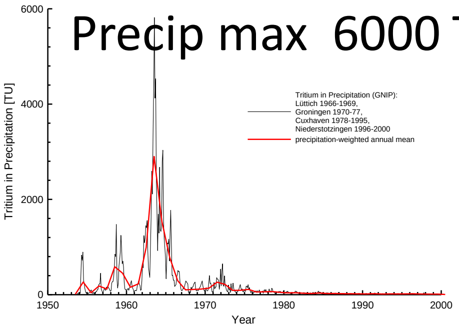


Simplified version of 1 layear model with variable depth of the aquifer. Steady state (MODFLOW, MODPATH)



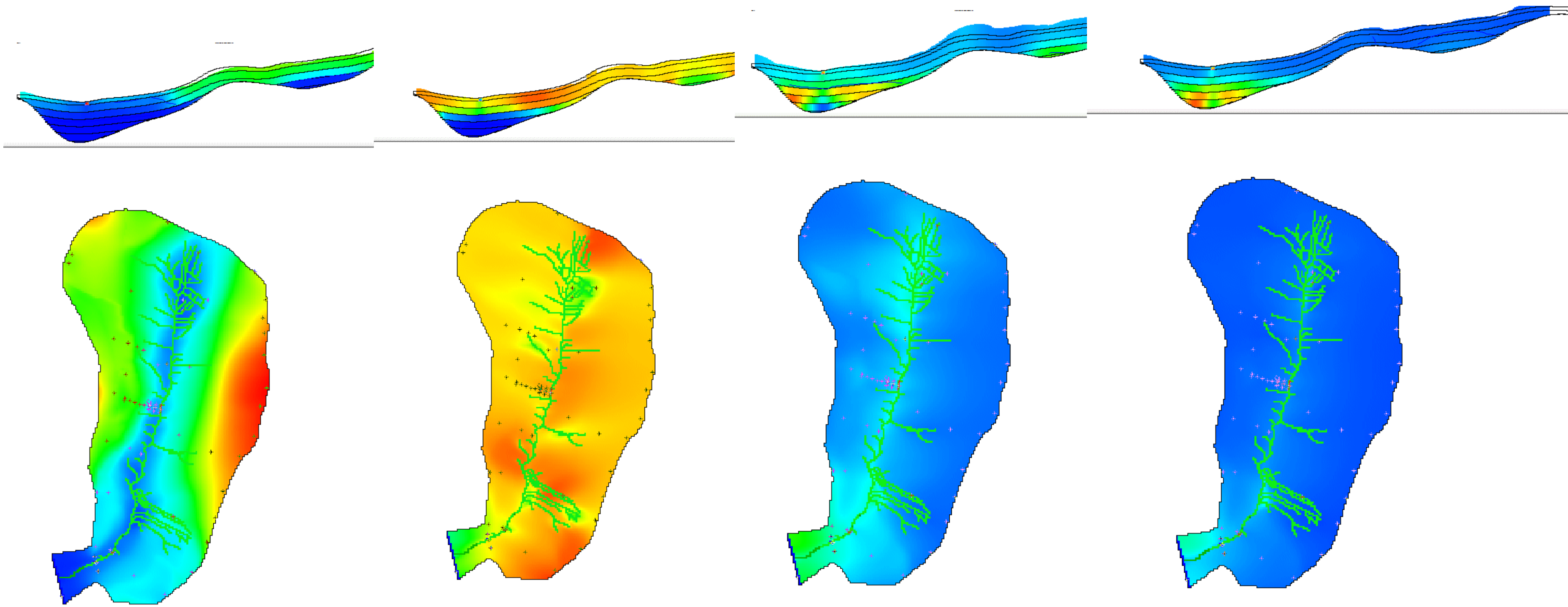
Groundwater table, isochrones (scale in years)

Flow and tritium+helium transport



Precip max 6000 TU

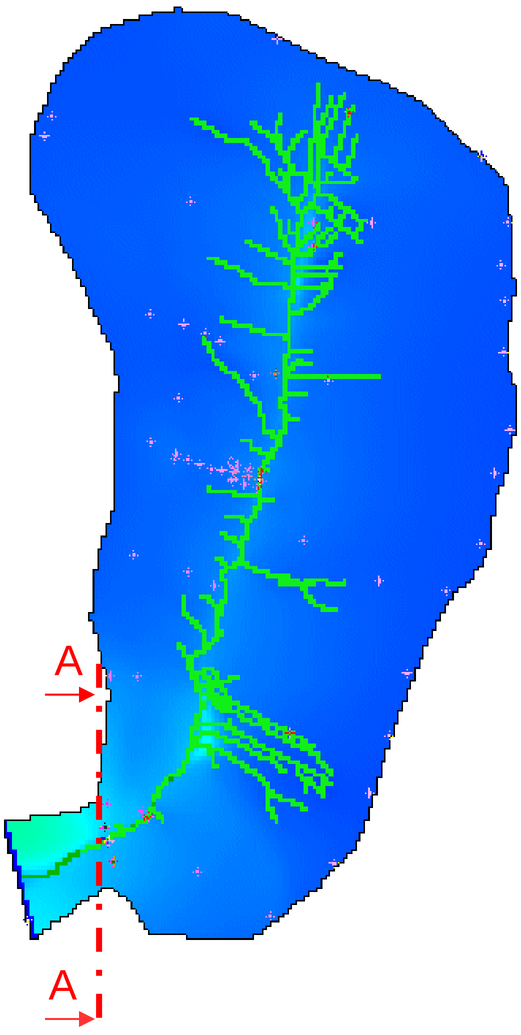
1961 | 1966 | 1986 | 2014

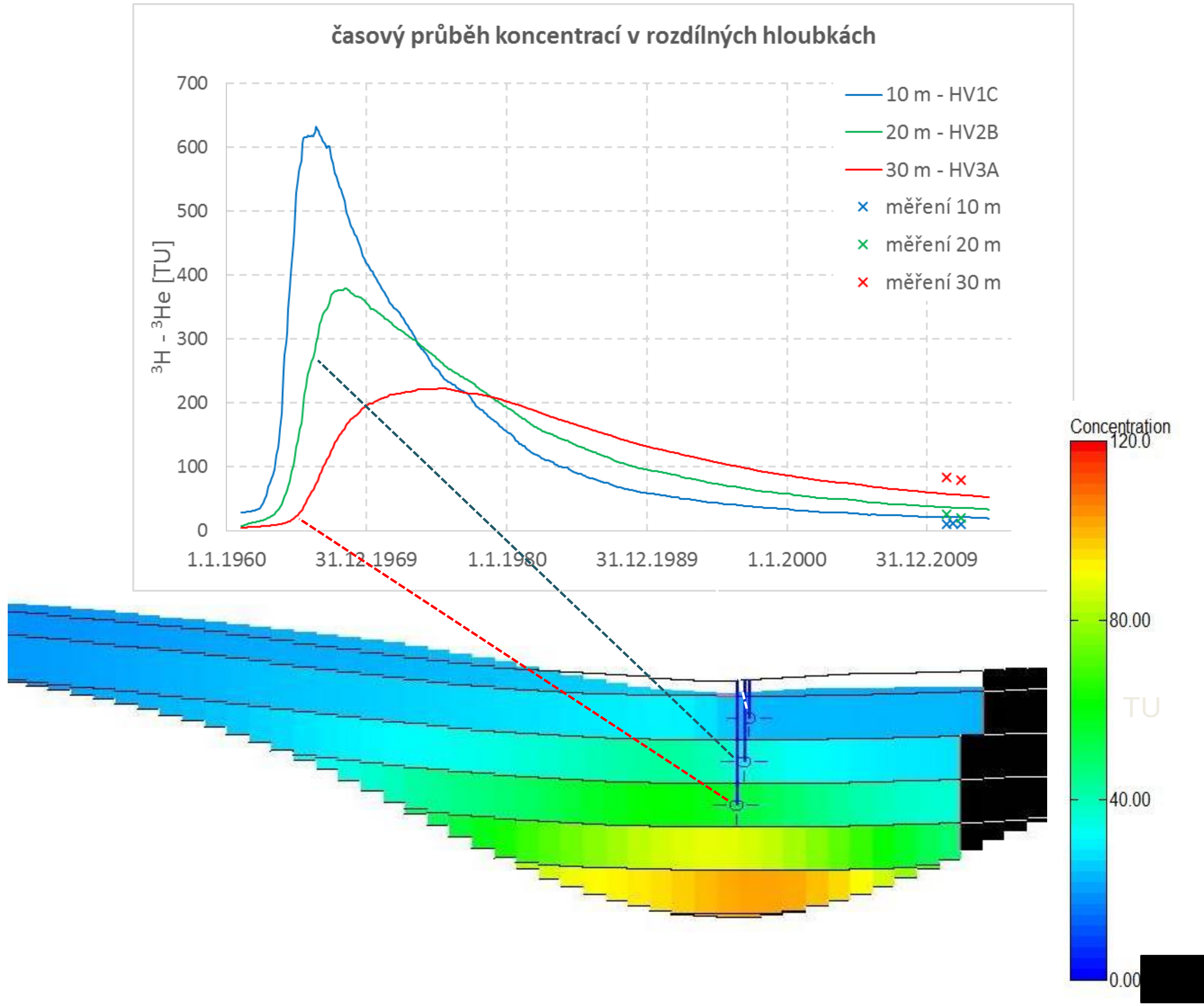


5- 660 TU | 5-856 TU | 17-750 TU | 5-100 TU

Flow and tritium+helium transport

Breakthrough in different depths





Thanks to your attention