Hydrology delivering Earth System Science to Society,
28 Feb. - 2 March 2007, Tsukuba, Japan

Experimental approaches to explore surface water / groundwater interactions at the hillslope and small catchment scale

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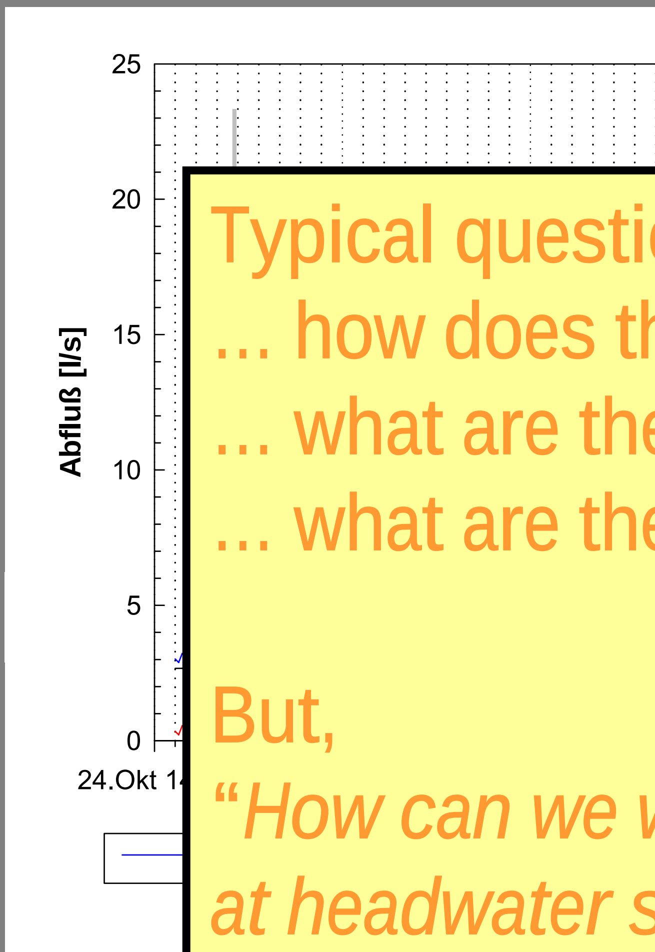
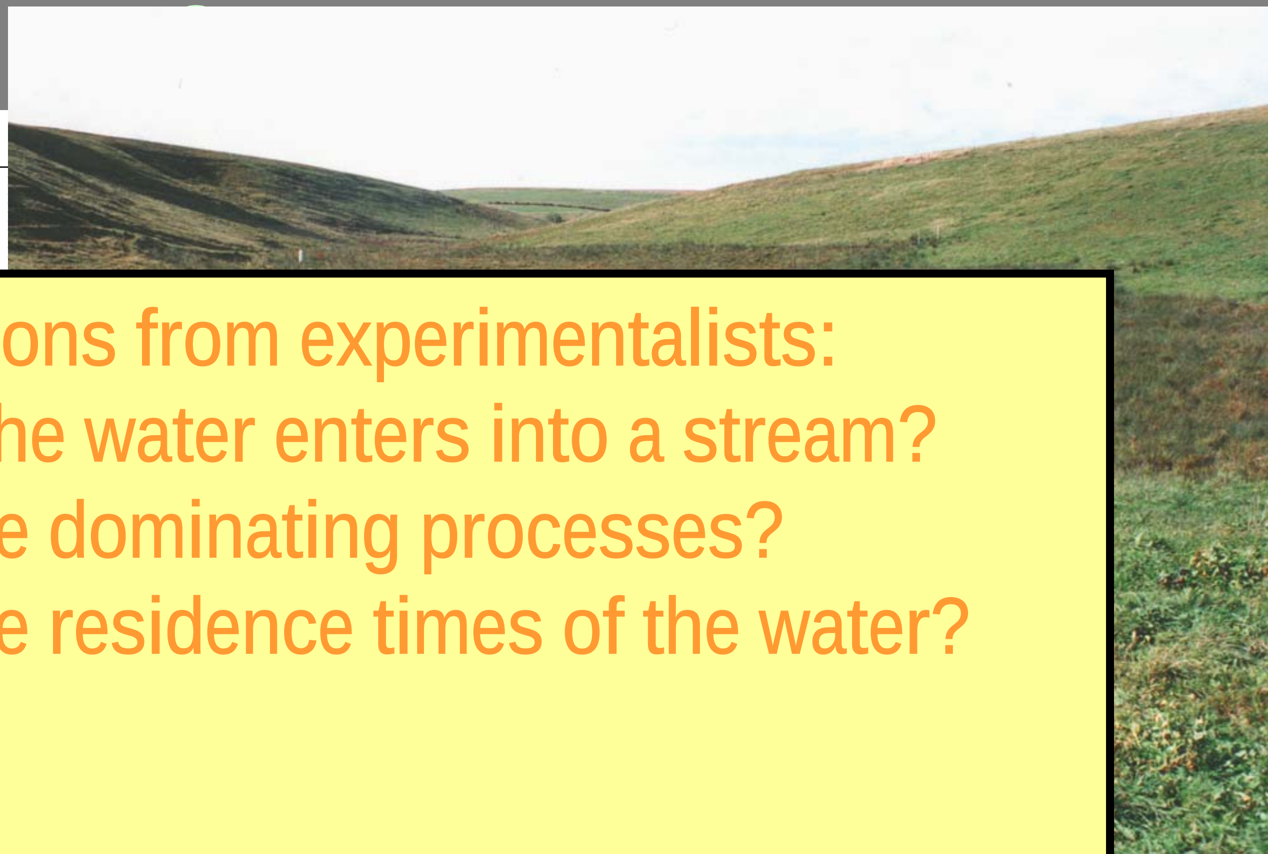
Institute for Water Education

Understanding Hydrological Processes

Flood events in the Haldenbächle, Black Forest Mountains,





Typical questions from experimentalists:

... how does the water enters into a stream?

... what are the dominating processes?

... what are the residence times of the water?

But,

“*How can we whittle down process complexity at headwater scale to process simplicity at catchment scale?*” (Sivapalan 2003, *HPToday*)

Structure of the Talk ➡ 3 Topics

(1) Multi-technical experiments at hillslope scale

(2) Scale influence on runoff generation and runoff components

Black Forest Mountains, Germany

(3) Surface water–groundwater interactions in a semi-arid environment

South Pare Mountains, Tanzania

Dreisam Catchment

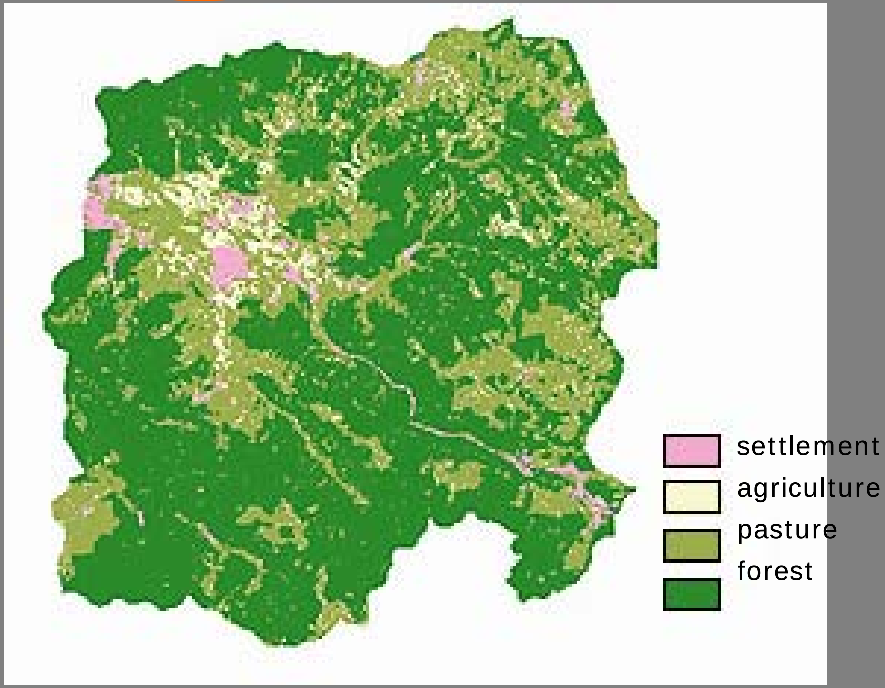
- south-west Germany (Southern Black Forest Mountains)
- 258 km² (Brugga: 40 km²)
- 308 – 1493 m a.s.l.
- P: 1500 mm / a
- R: 900 mm / a
- E: 600 mm / a

Geology

- metamorphic rocks
- drift cover (0 - 10 m)

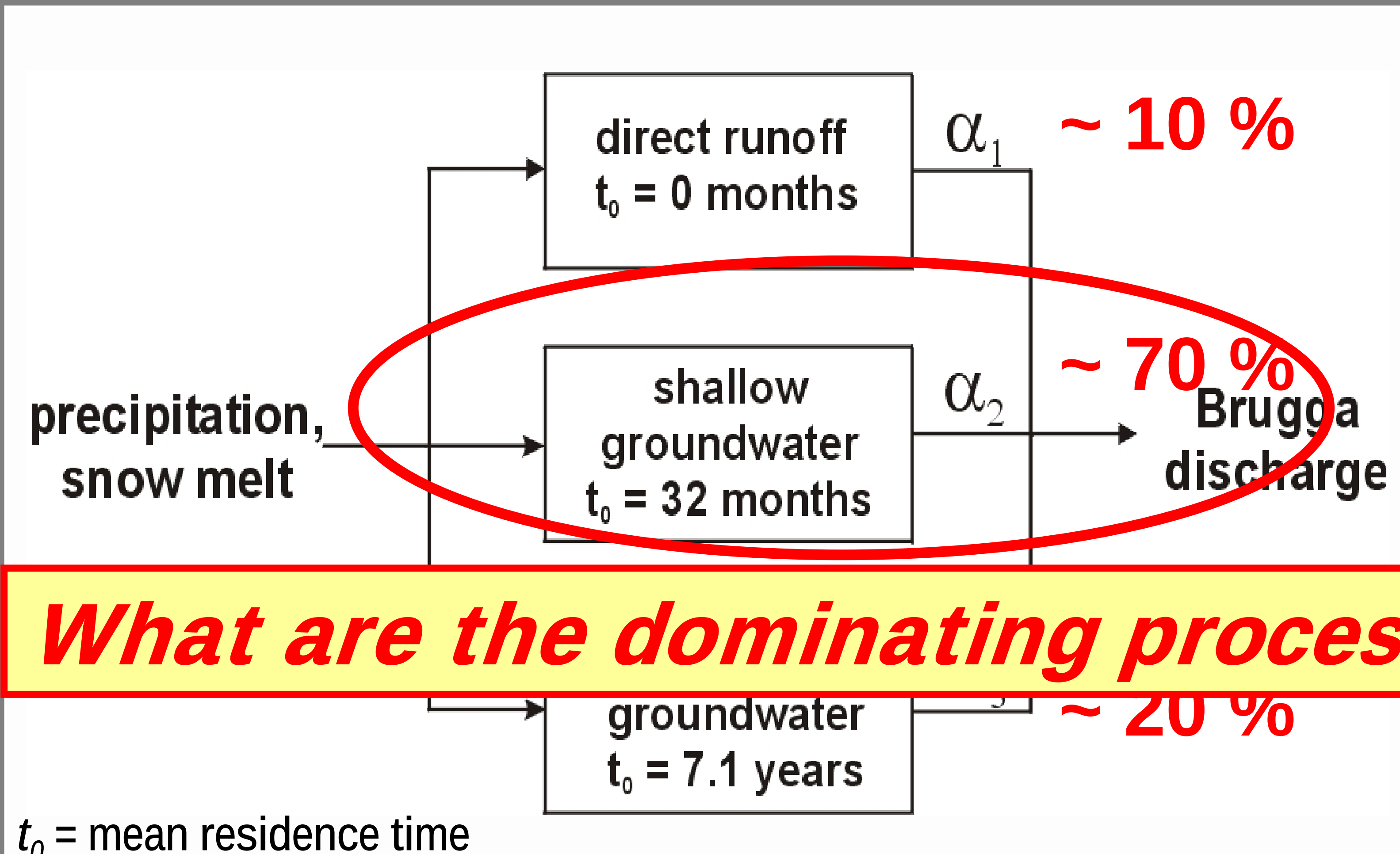
Land use

- settlement 3 %
- forest 61 %
- pasture 31 %
- agriculture 5 %



Sub-Catchment Brugga (40 km^2)

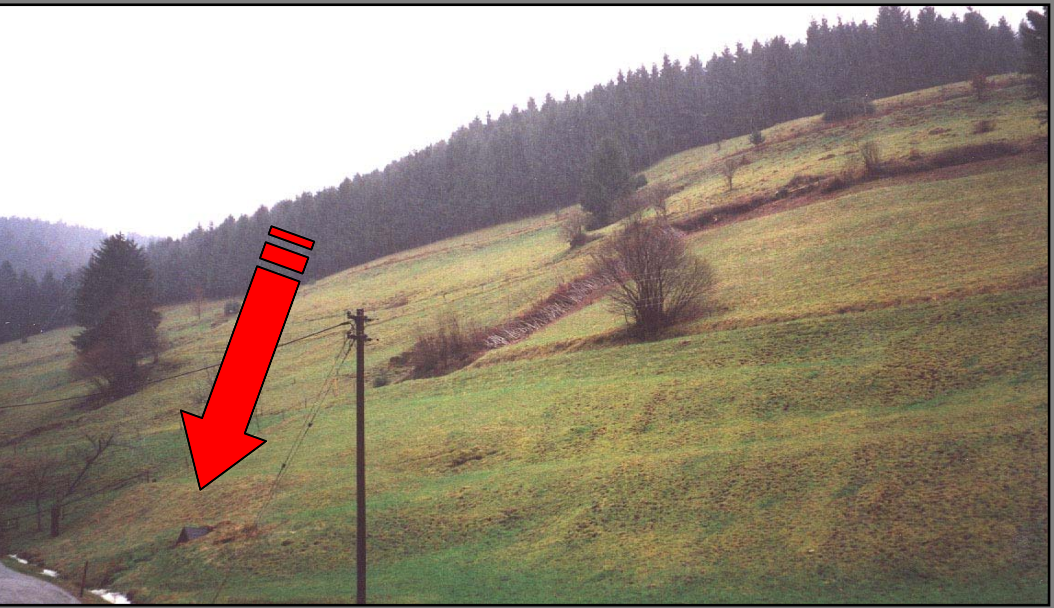
Three main flow systems with different residence times and contributions on a seasonal time scale



What are the dominating processes?

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

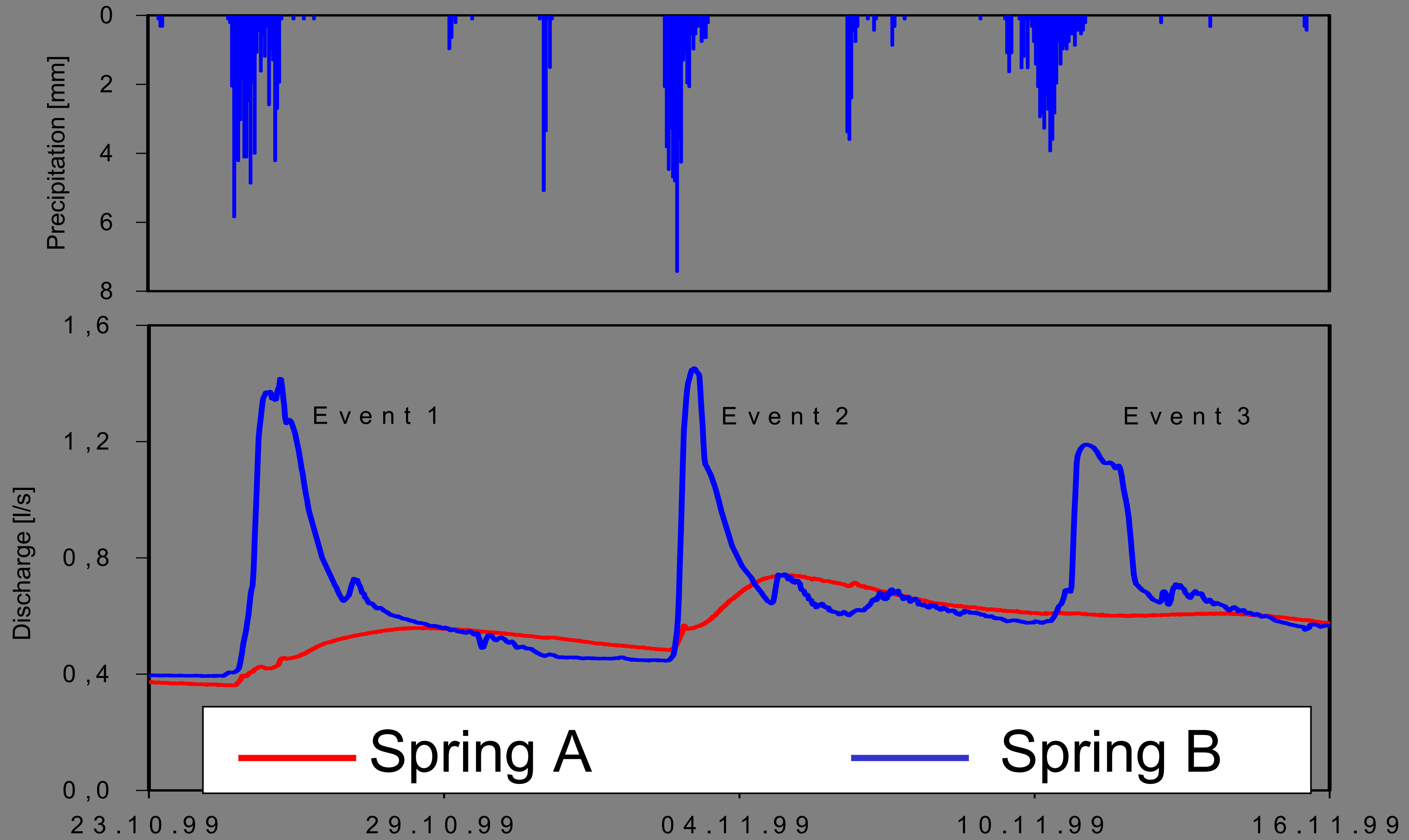
Test Sites



Spring A (Zipfeldobel)

Spring B (Zängerlehof II)

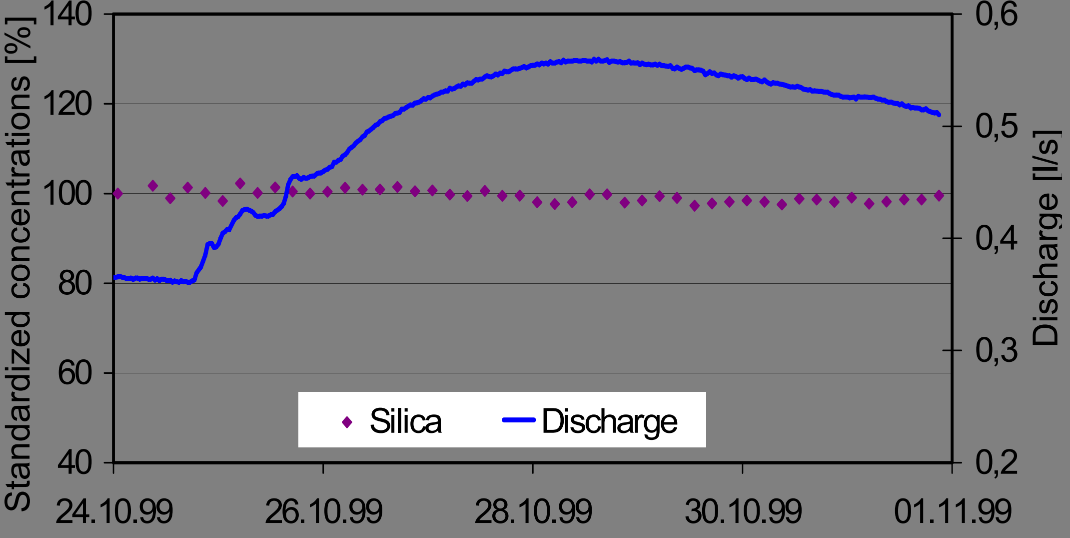
Investigation Period



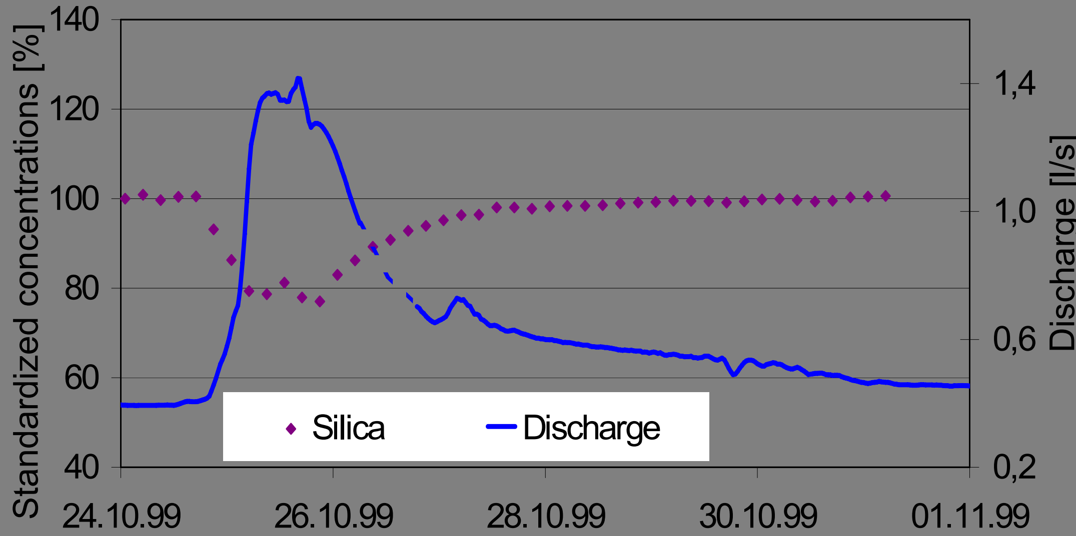
(Uhlenbrook et al., *HSJ*, in review)

Hydrochemical Dynamics: Dissolved Silica

Spring A



Spring B



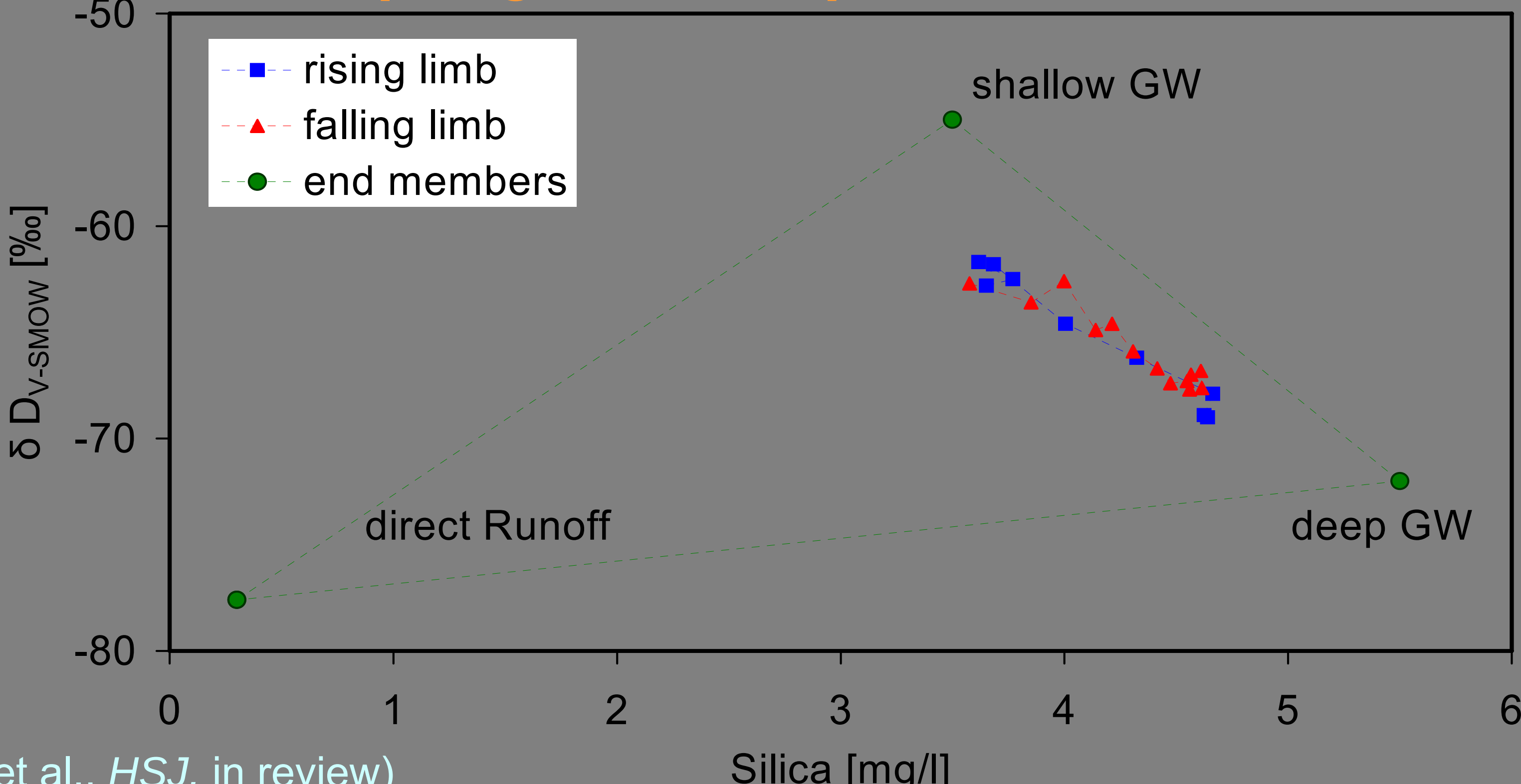
(Uhlenbrook et al., *HSJ*, in review)

End-Members for Hydrograph Separation

Spring A: 2 components

direct Runoff:	0.3 mg/l Silica
deep & shallow GW:	pre-event conc.

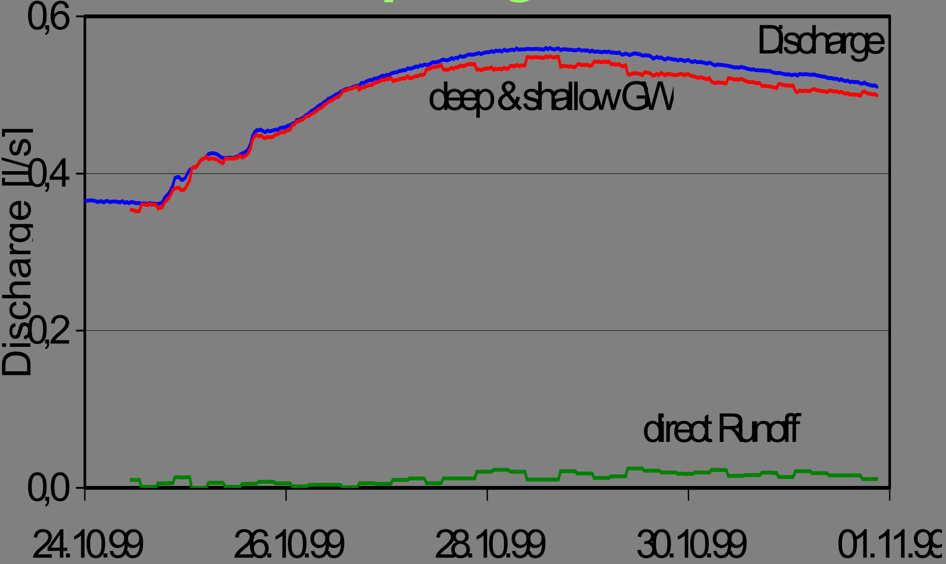
Spring B: 3 components



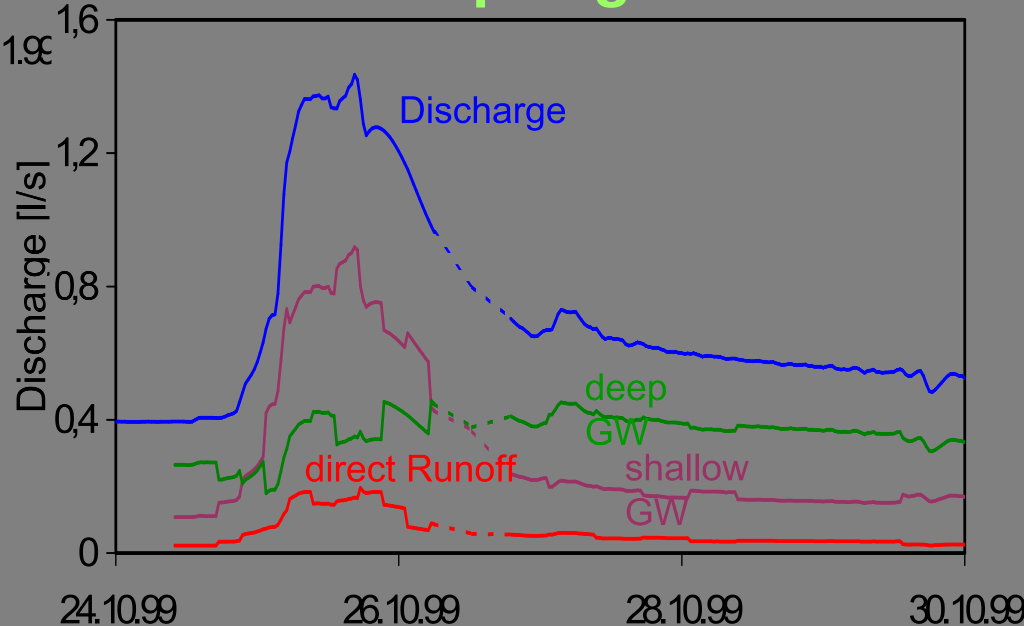
(Uhlenbrook et al., *HSJ*, in review)

Hydrograph Separation

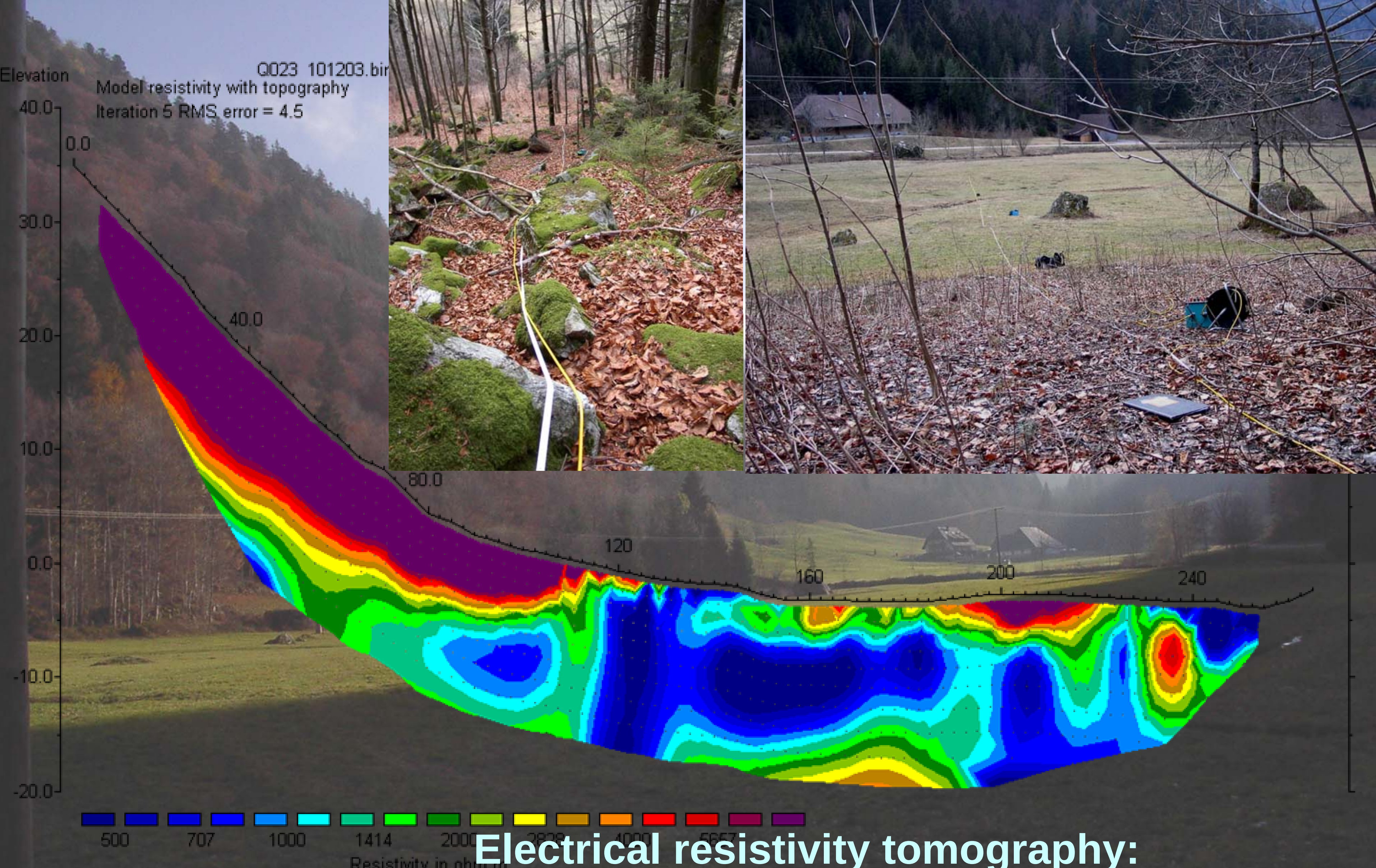
Spring A



Spring B



(Uhlenbrook et al., *HSJ*, in review)



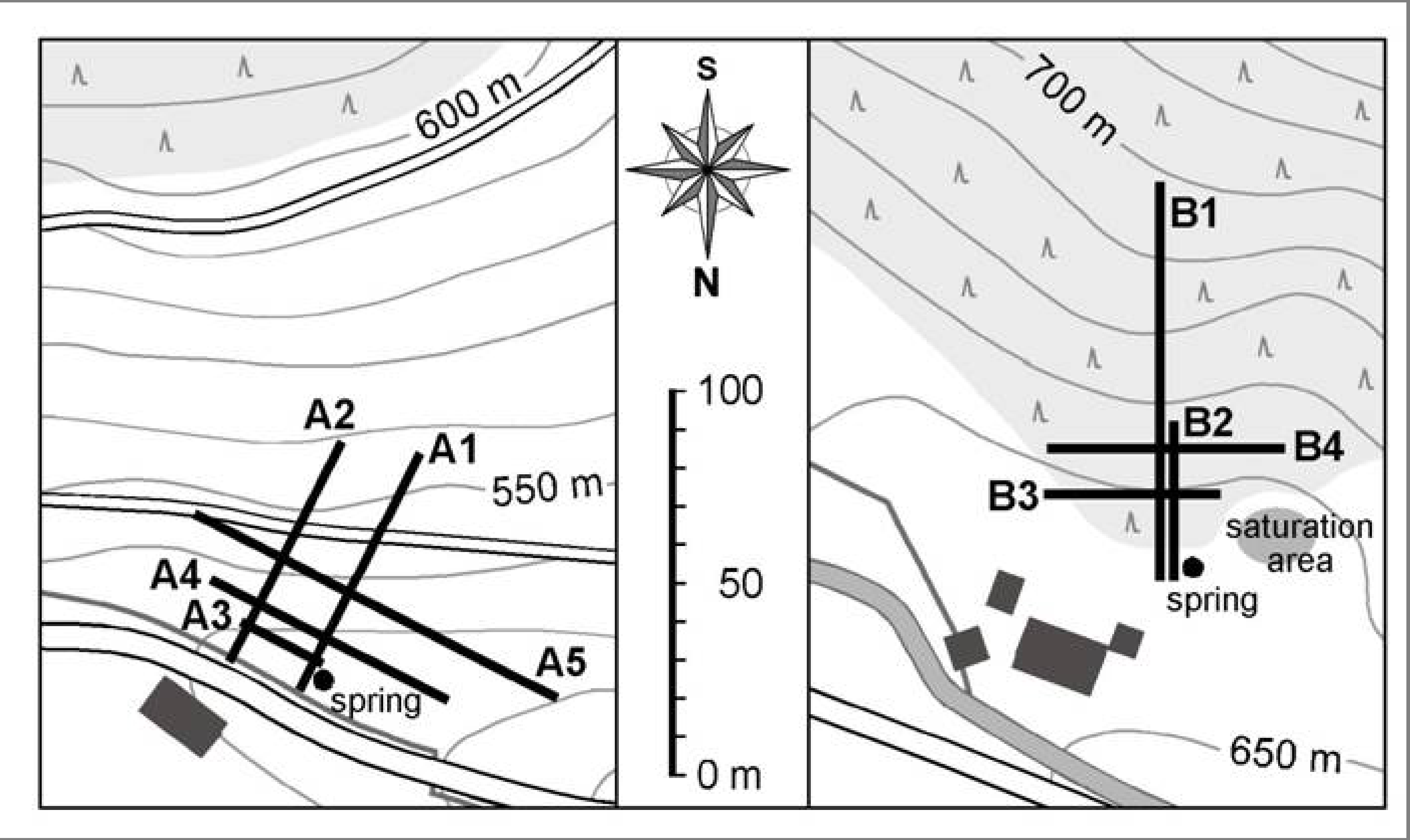
Electrical resistivity tomography:

- lithology (grain sizes, porosity and mineralogy)
- degree of water saturation
- fluid content (solutes)

(Kristoph Koch 2004)

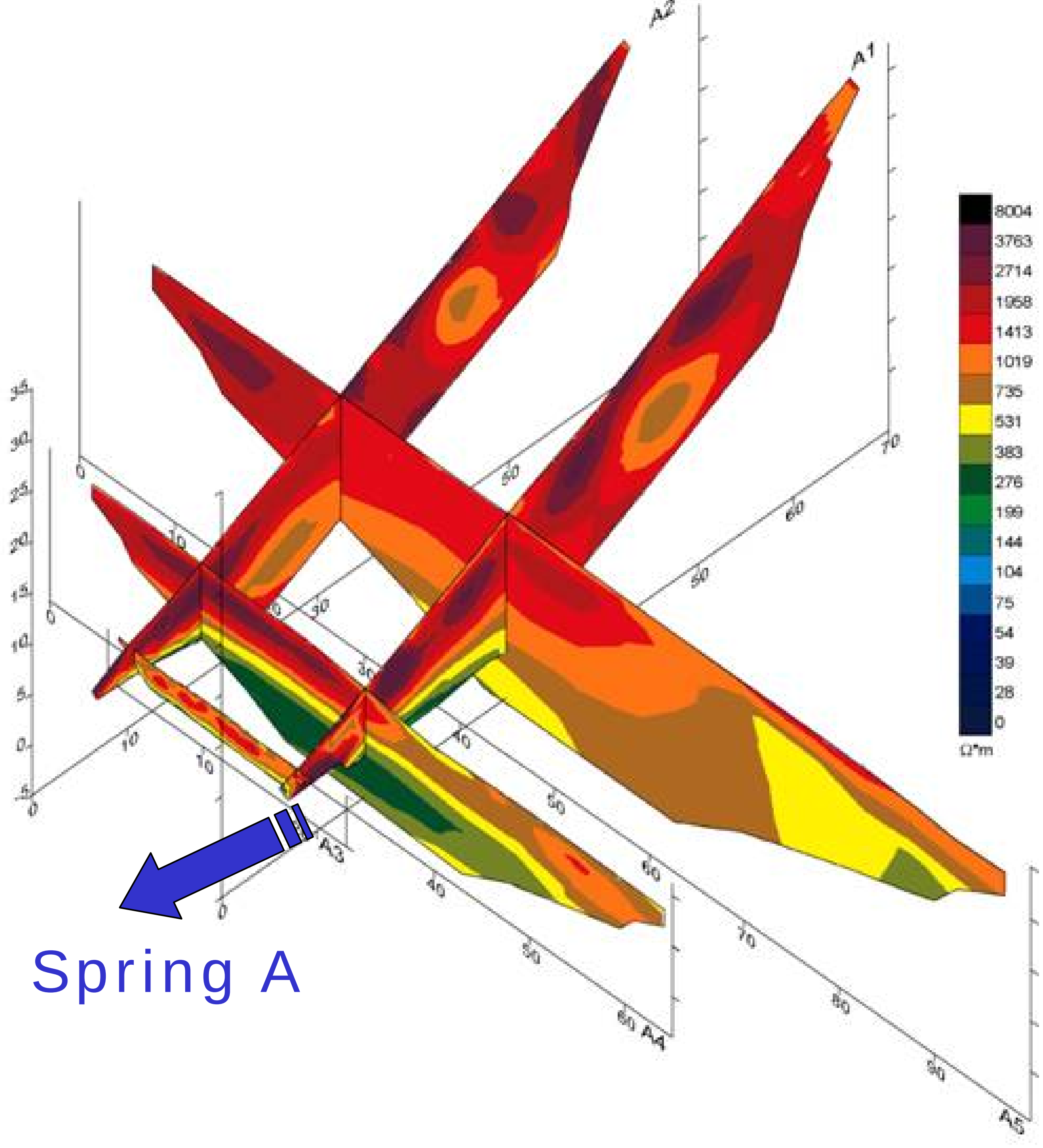
ERT Along Transects

Spring A
Spring B

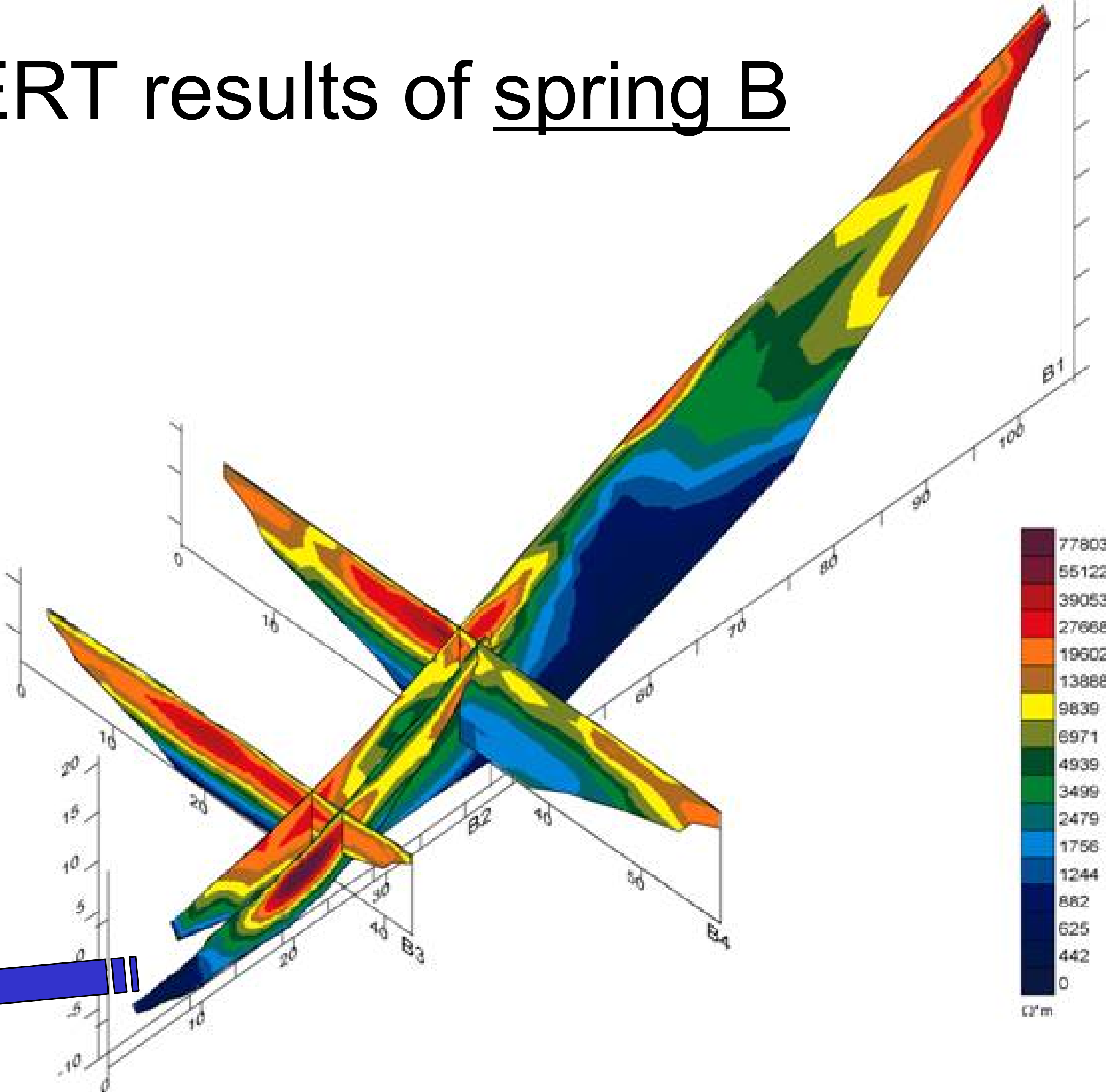


(Uhlenbrook et al., *HSJ*, in review)

ERT results of spring A

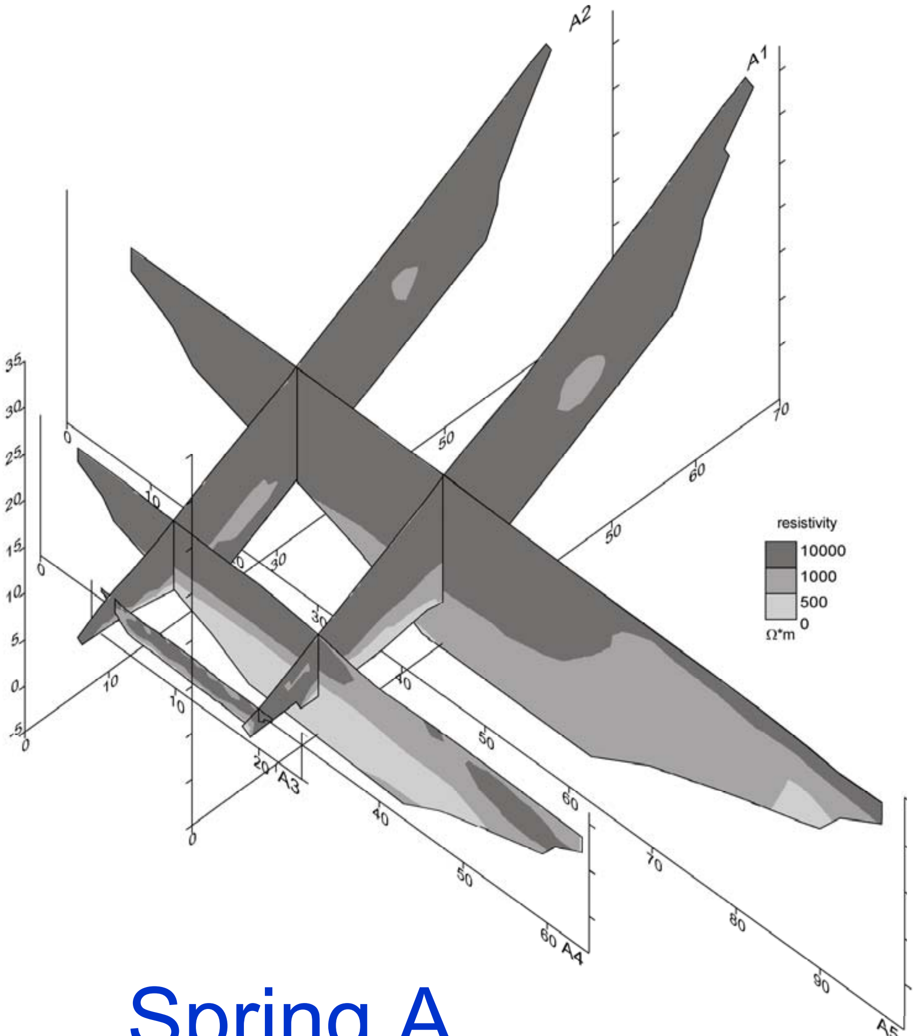


ERT results of spring B

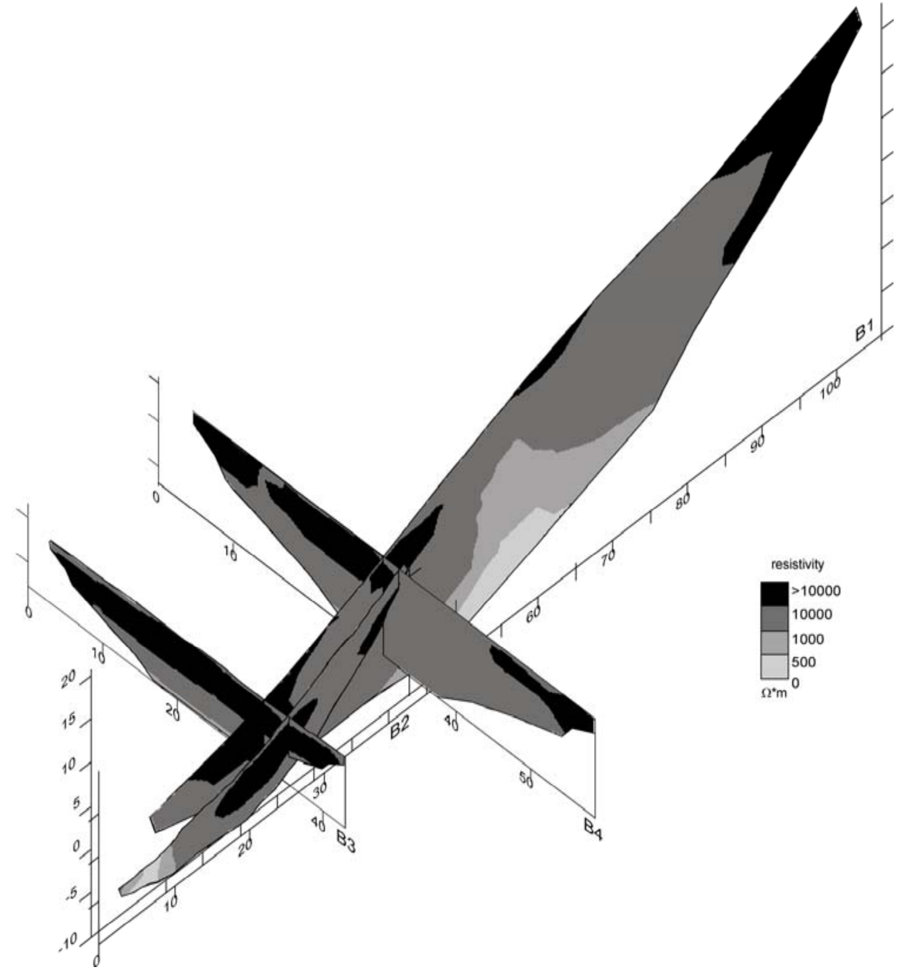


Spring B

Results of ERT Measurements



Spring A



Spring B

(Uhlenbrook et al., *HSJ,* in review)

Concluding Remarks (1)
Investigations of Hillslope Processes

(1) Classical hydrometric measurements in combination with tracers and ERT proofed useful to identify runoff components at the hillslope scale

- Spring A: damped (hydrology, hydrochemistry), 2 runoff components
- Spring B: very responsive, 3 runoff components, importance of shallow groundwater (further uphill!)

(2) Significant difference of hillslope processes appears to be controlled by variable soil and drift structure and less by land use (topography?)

alk → 3 Topics

xperiments at

Black Forest Mountains, Germany

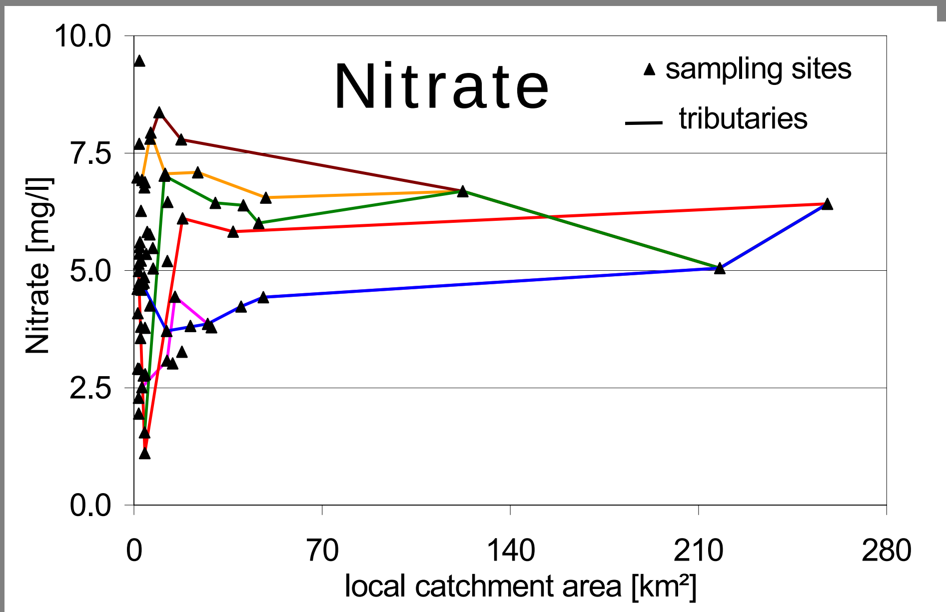
(2) Scale influence on runoff generation and runoff components

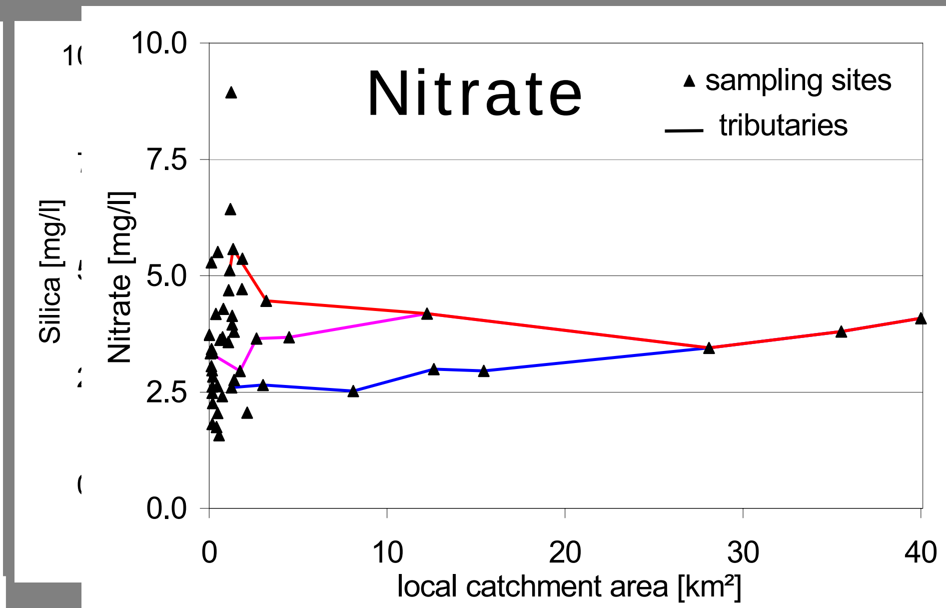
(3) Surface water–groundwater interactions in a semi-arid environment

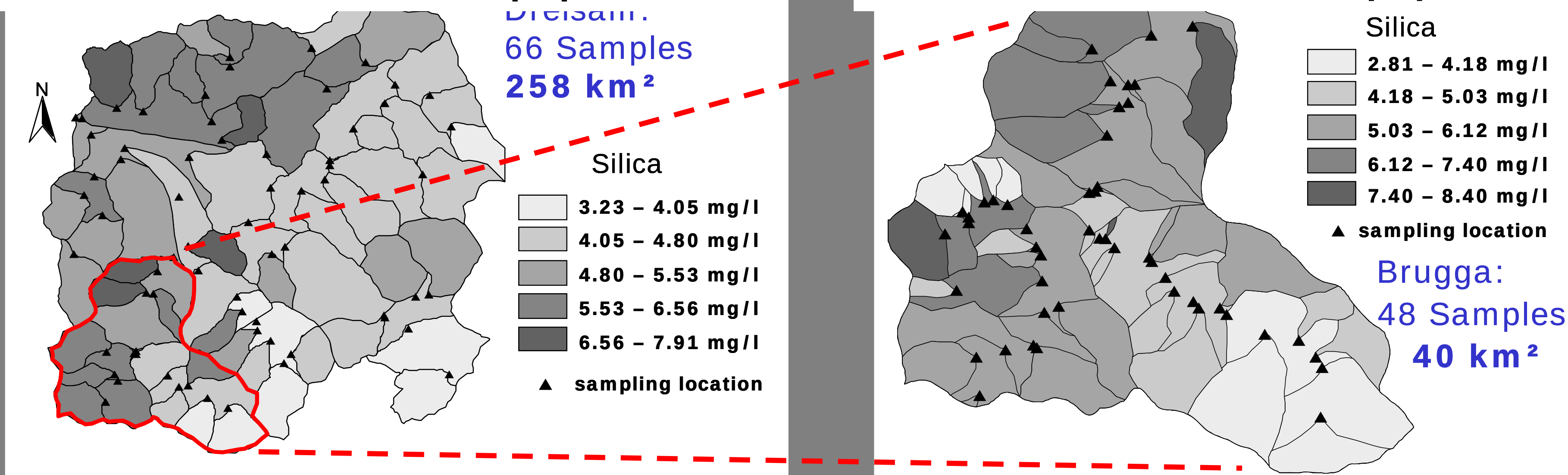
South Pare Mountains, Tanzania

Scale Influence on Runoff Components

1) Base Flow Investigations: Synoptic Sampling



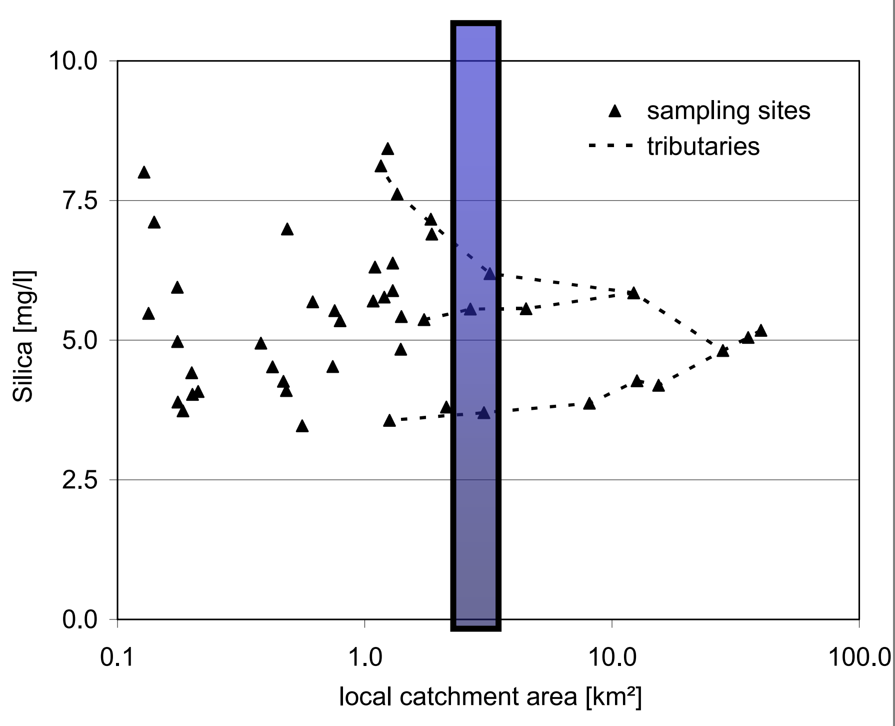




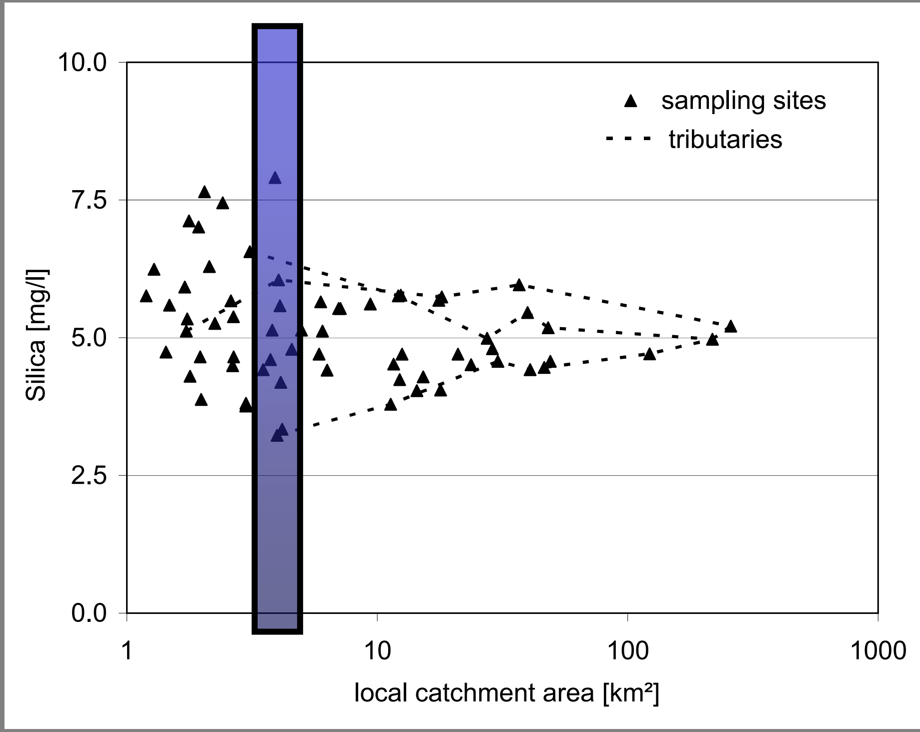
(Didszun and Uhlenbrook, *WRR*, in review)

Synoptic Sampling

1) only weak / moderate correlations (rank r: 0.04 – 0.7) between catchment properties (area, geology) and hydro-chemical parameters
2) moderate correlations between land use and hydro-chemical parameters (rank r: 0.5 – 0.7)



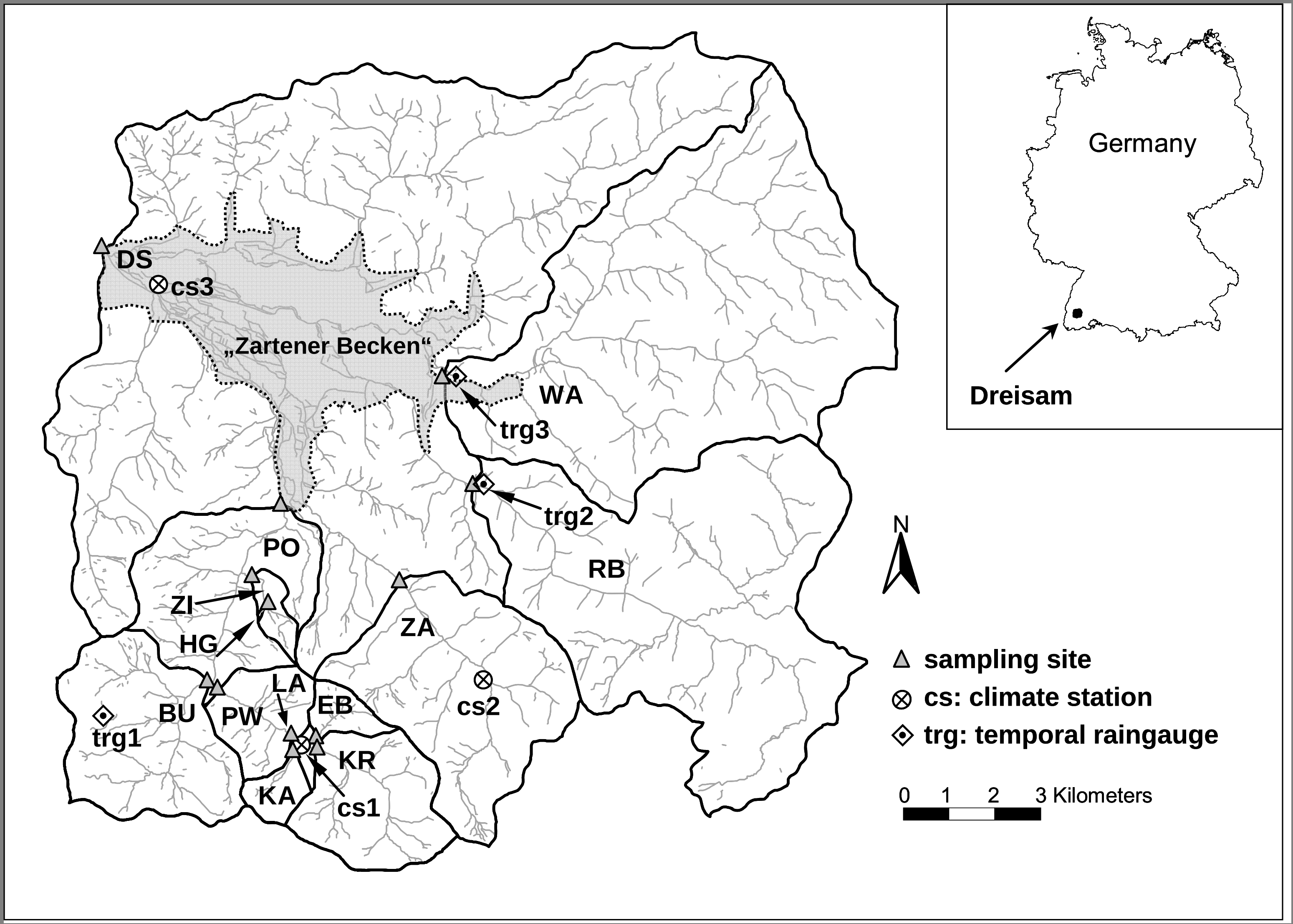
40 km²



258 km²

Scale Influence on Runoff Components

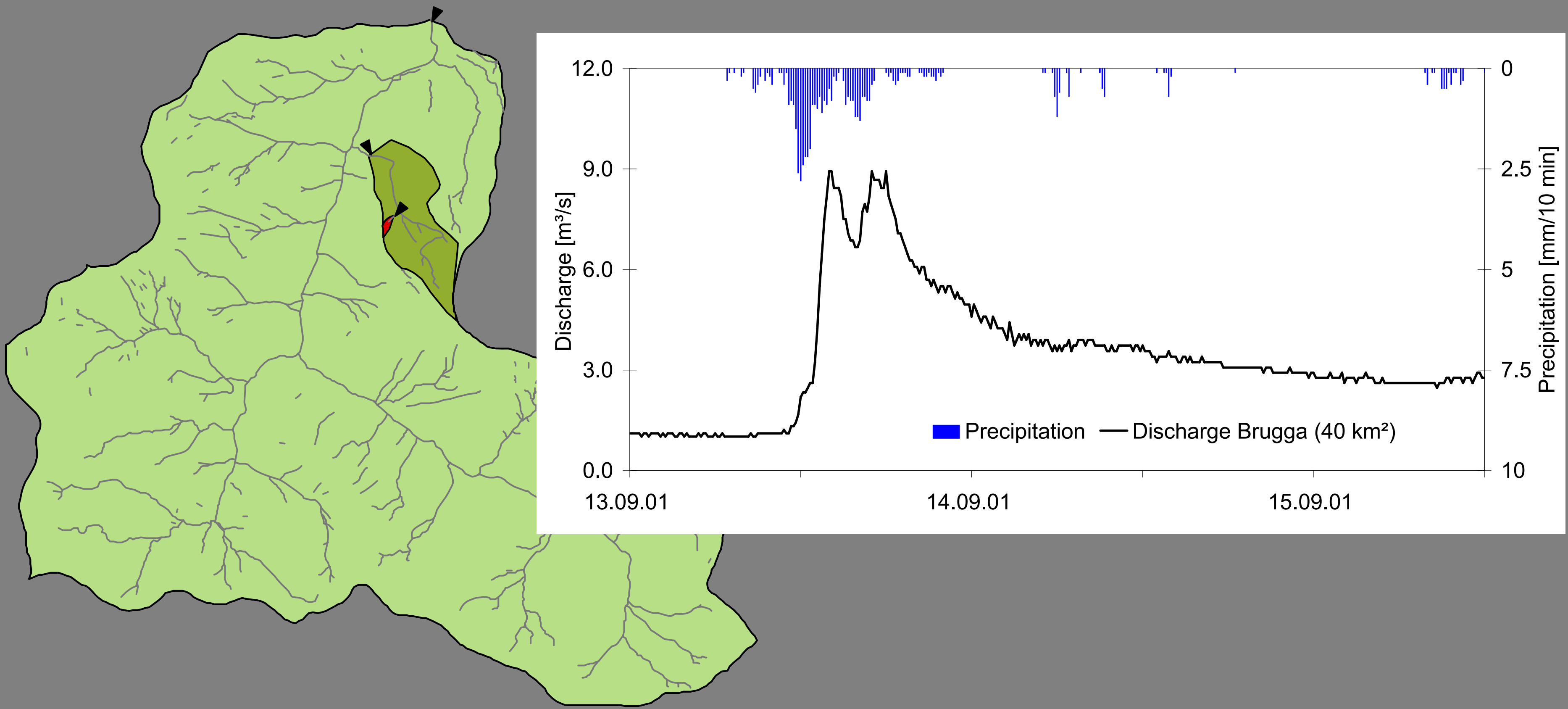
2) Event-based Investigations



(Didszun and Uhlenbrook, *WRR,* in review)

Scale dependence of runoff components during events?

- 3 catchments: 1.5 ha; 1.14 km²; 40 km²
- Event: September 2001



Scale dependence of runoff components?

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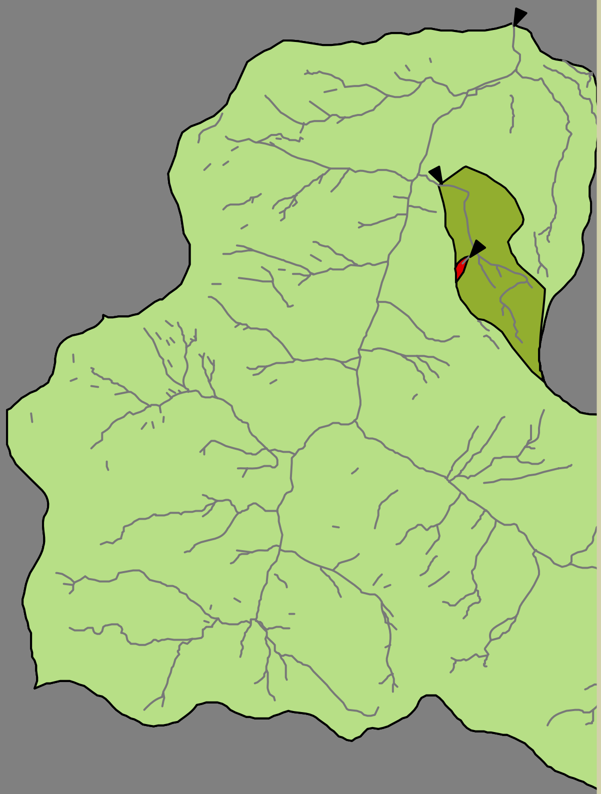
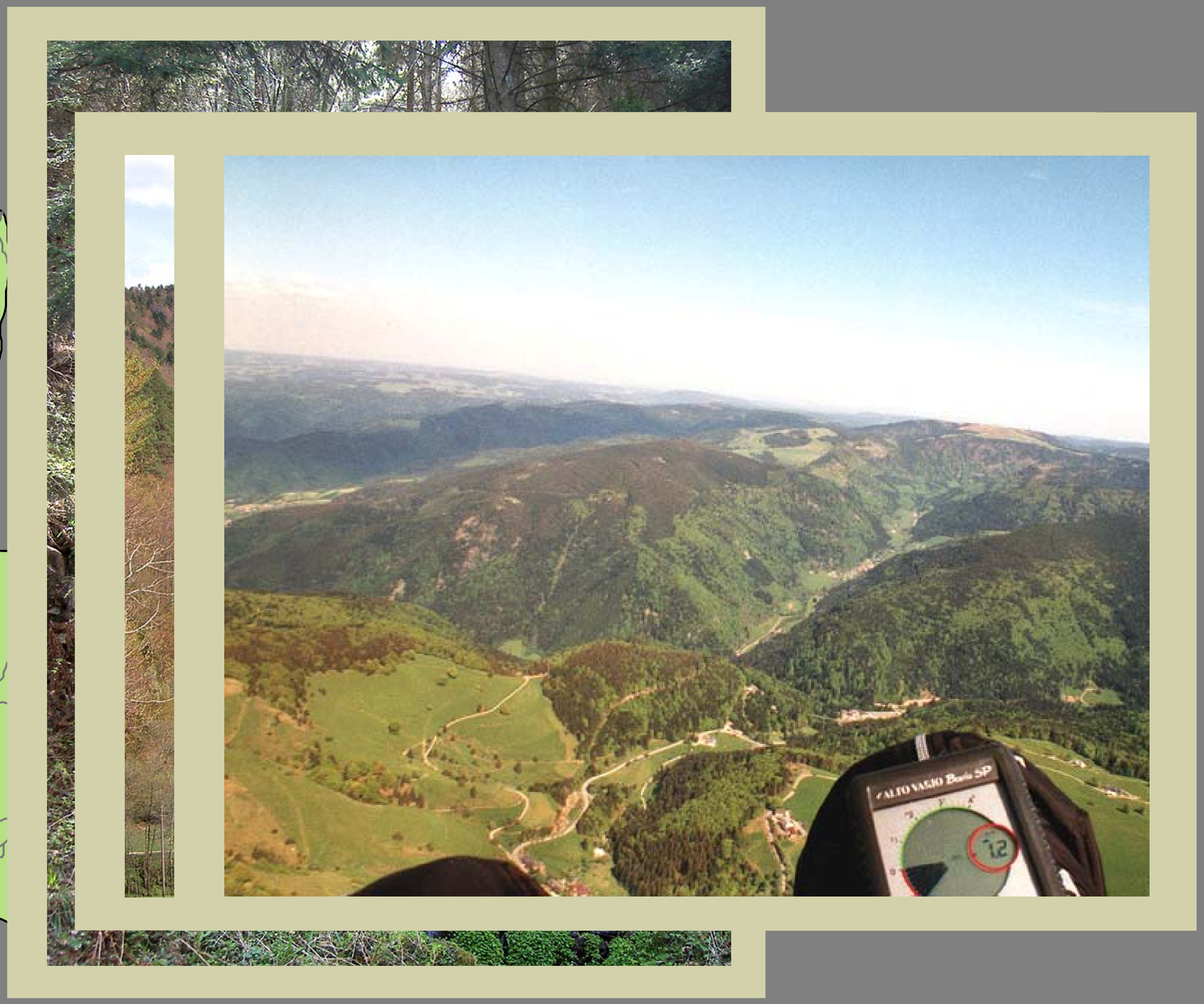
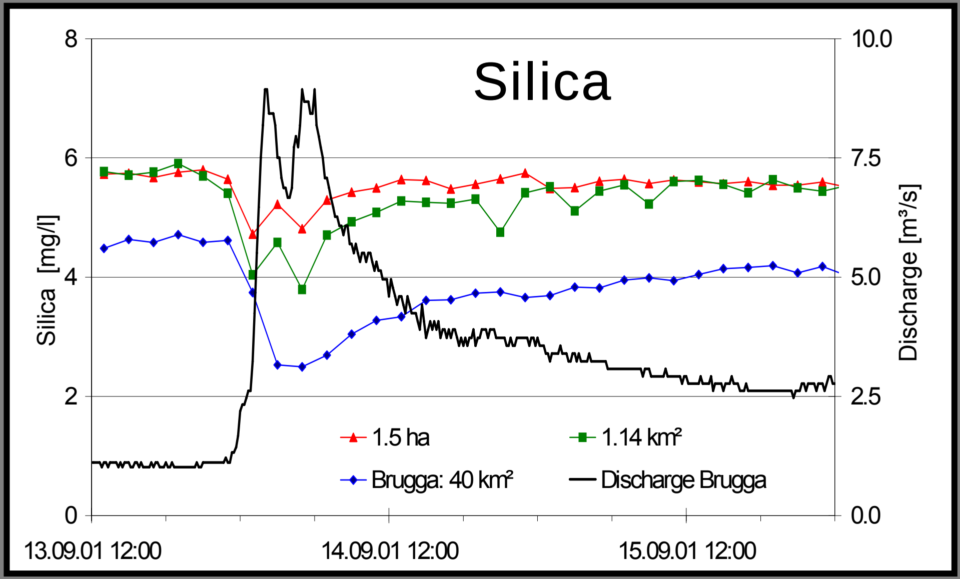
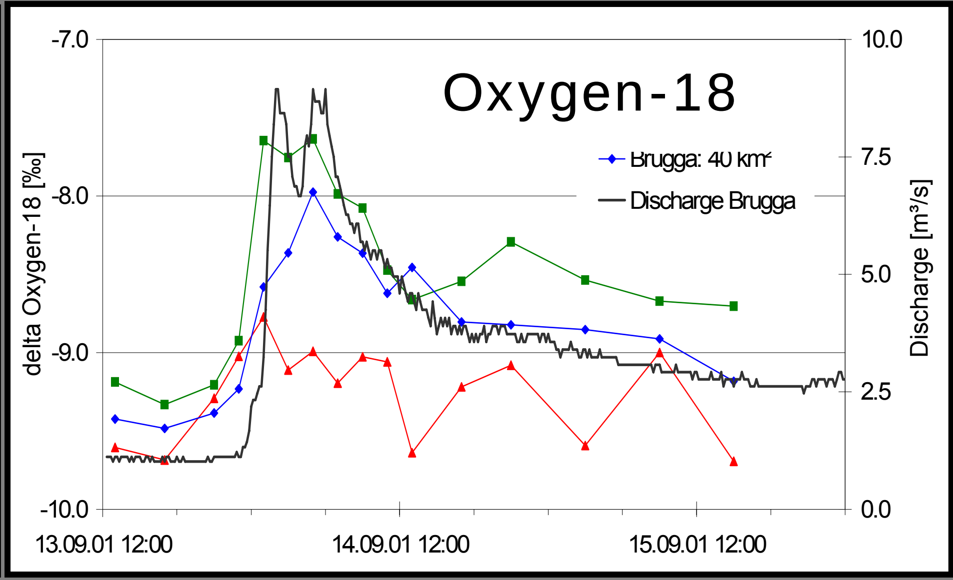
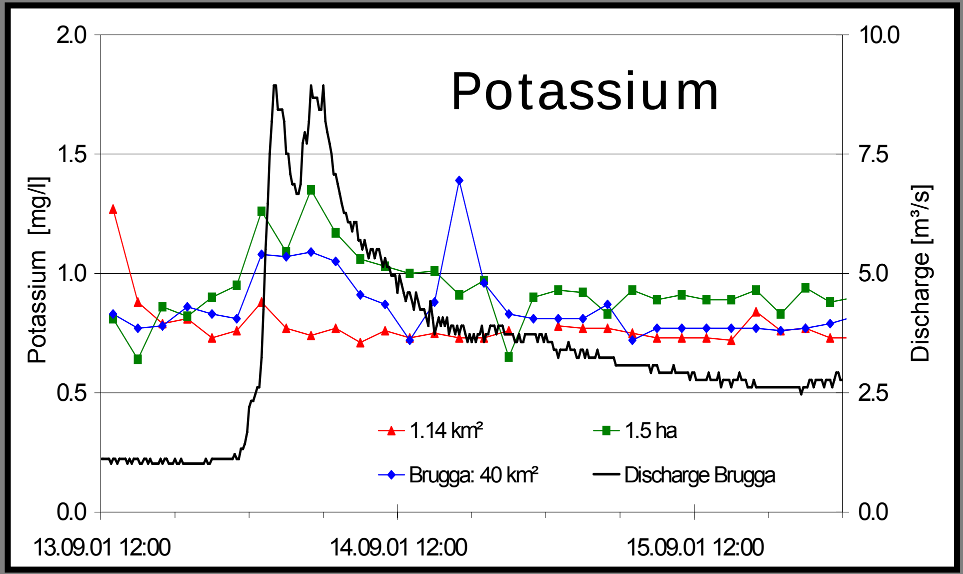




Hydro-chemical responses at different scales



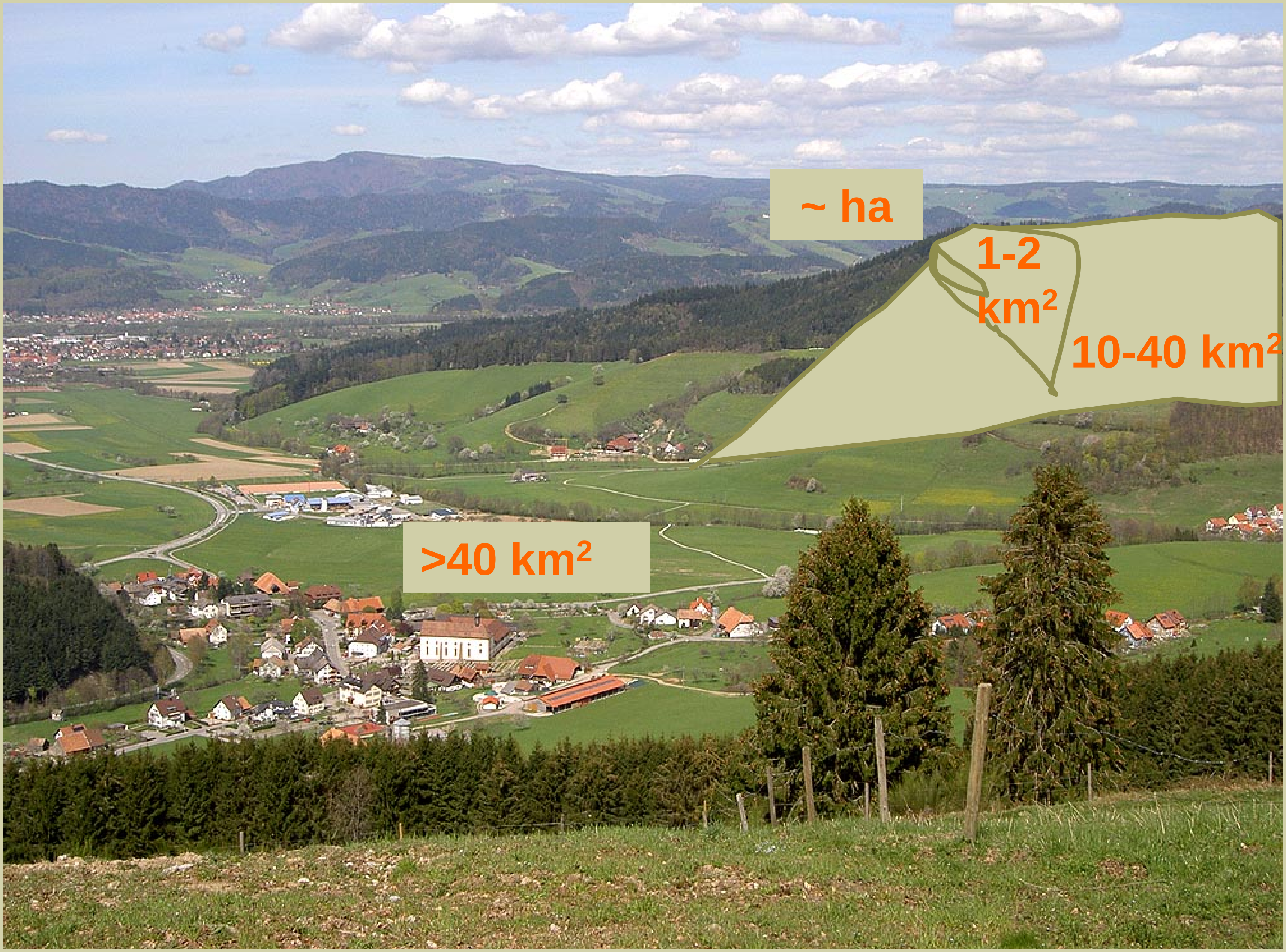




(Didszun and Uhlenbrook, 2006, *Wat. Res. Research*, in review)

Summary of Experimental Investigations

Scale Dependence of Runoff Components



Concluding Remarks (2)

Scale Dependence of Runoff Components

1) Large variability of chem. concentrations at hillslope and headwater scale – ‘converged’ at catchment scale

2) Only weak/moderate correlations between hydro-chemical concentrations and catchment properties

3) No classical scale-dependence, but the hydro-chemical response looks different as soon as the catchment is ‘complete’:

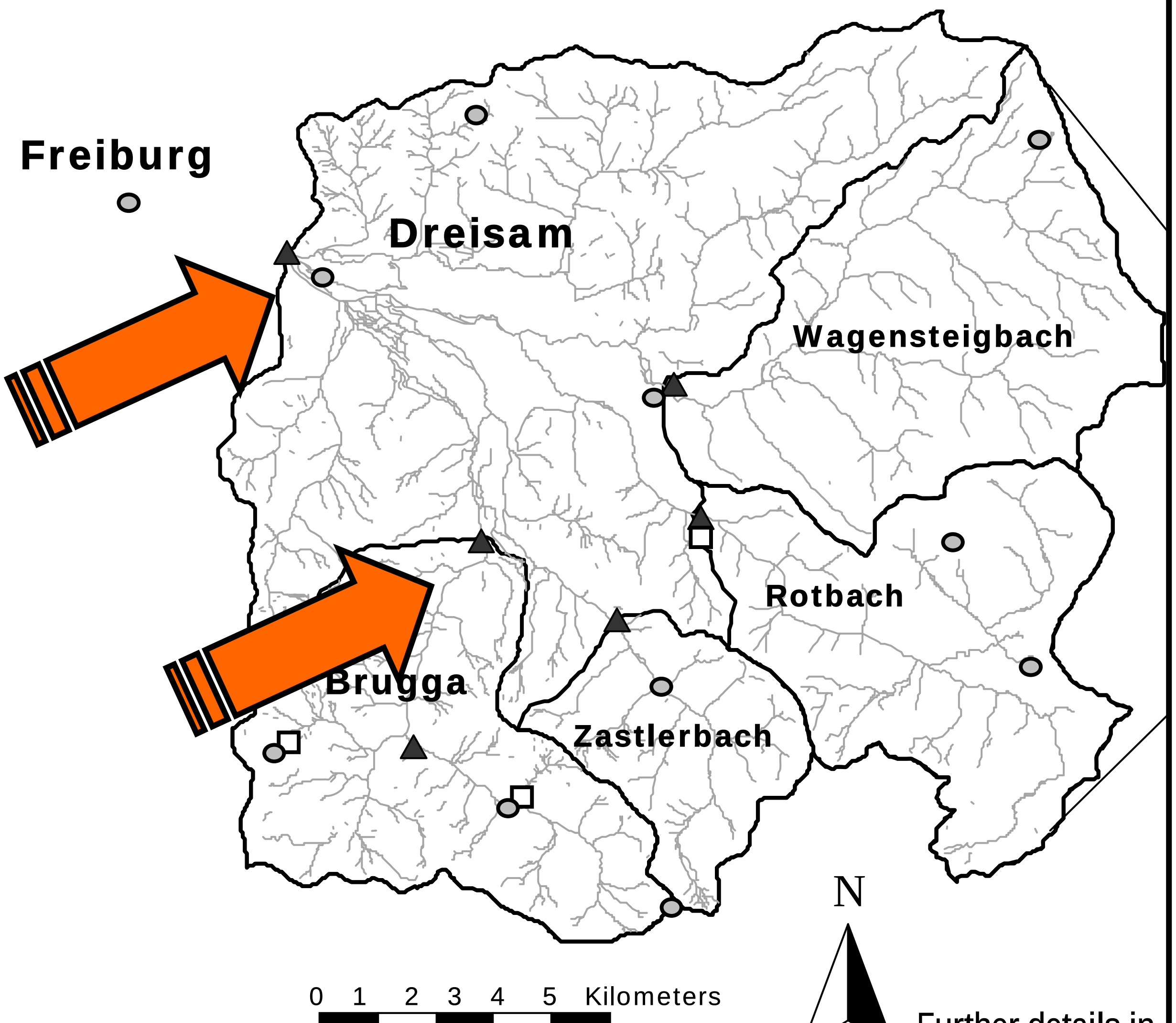
   ⇒ Headwater (< 1-2km^2) is typical dominated by the hillslope reaction

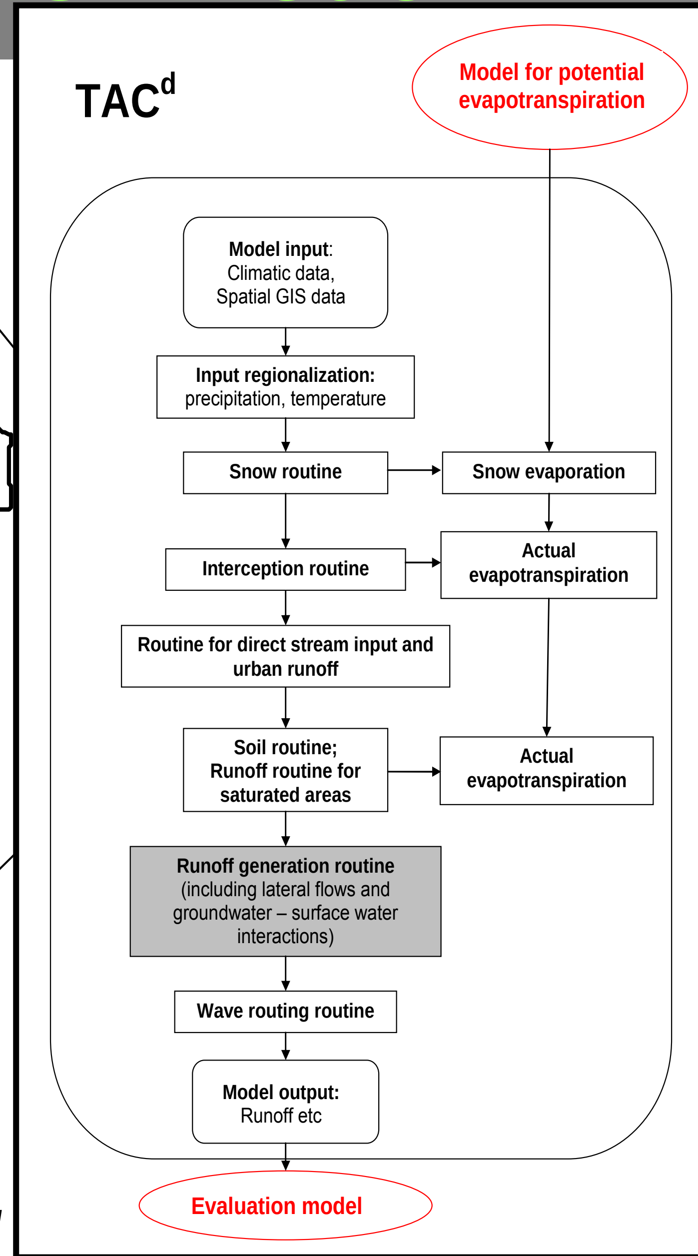
   ⇒ Catchments > 1-2 km^2 are different,
   influences of riparian zone / saturated areas are observable

   ⇒ Differences to catchments < 40 km^2 are relatively small

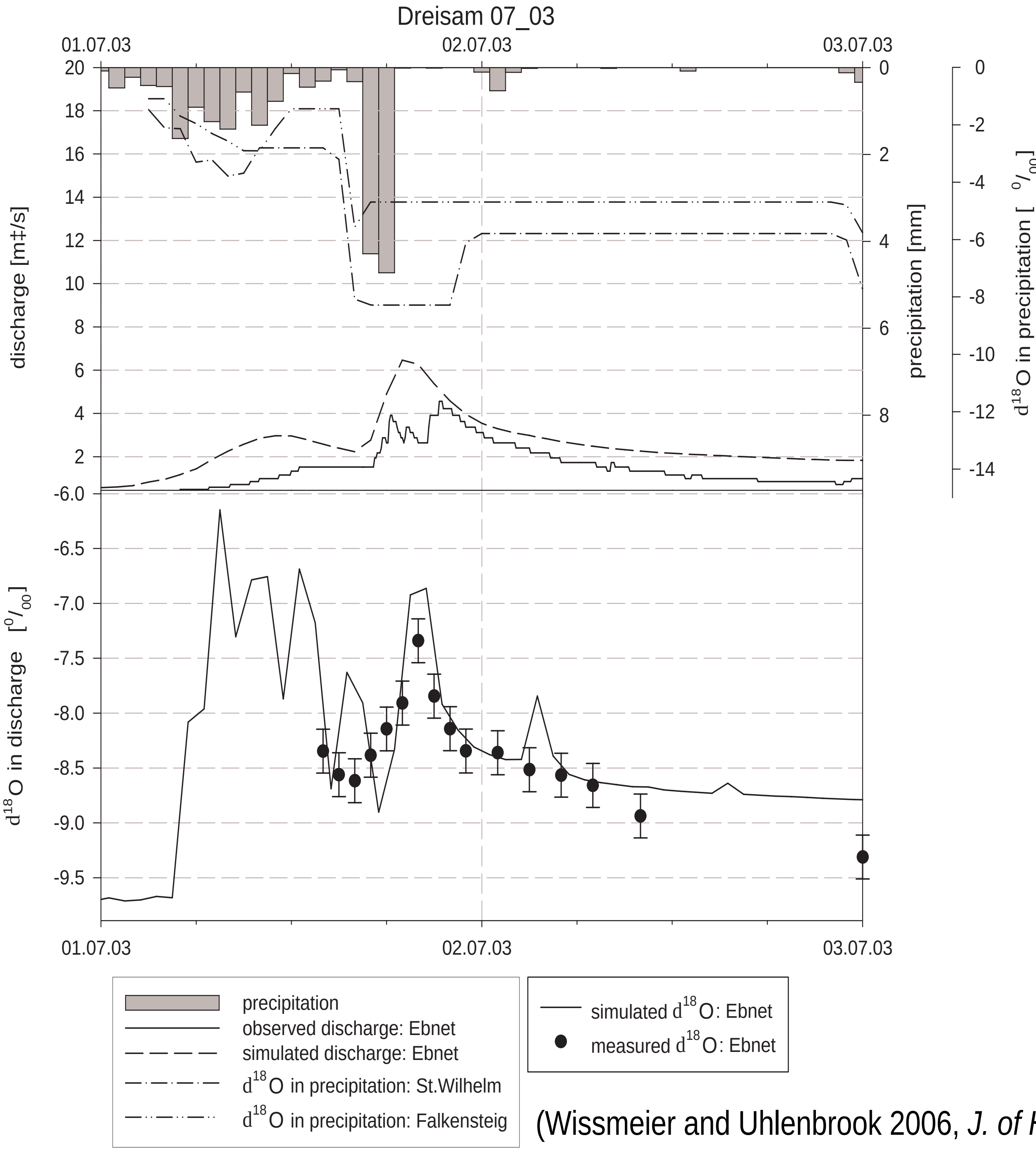
   ⇒ Larger catchments > 40 km^2 behave different (urban areas, groundwater etc.)

Application of the TAC^D model

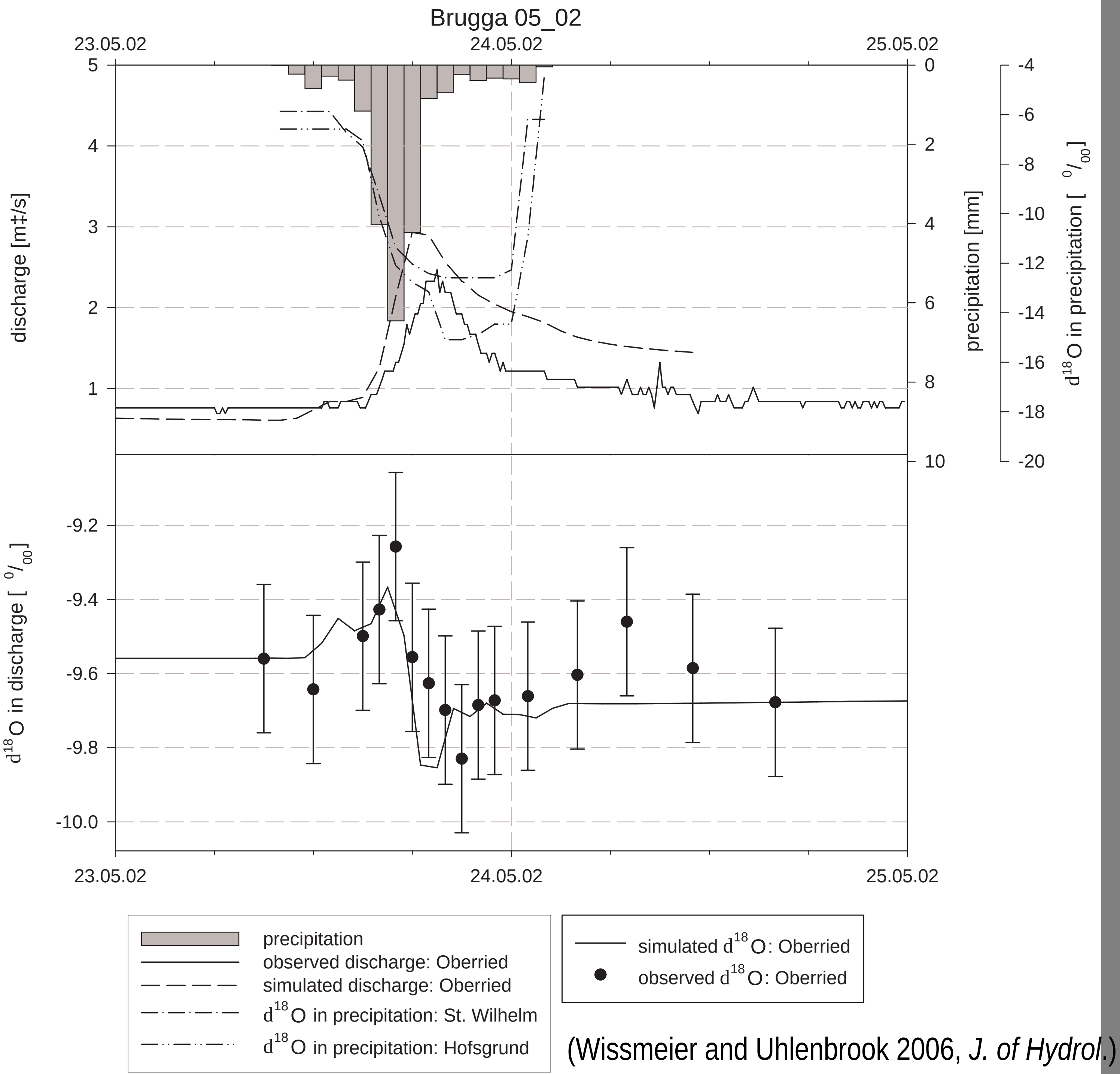




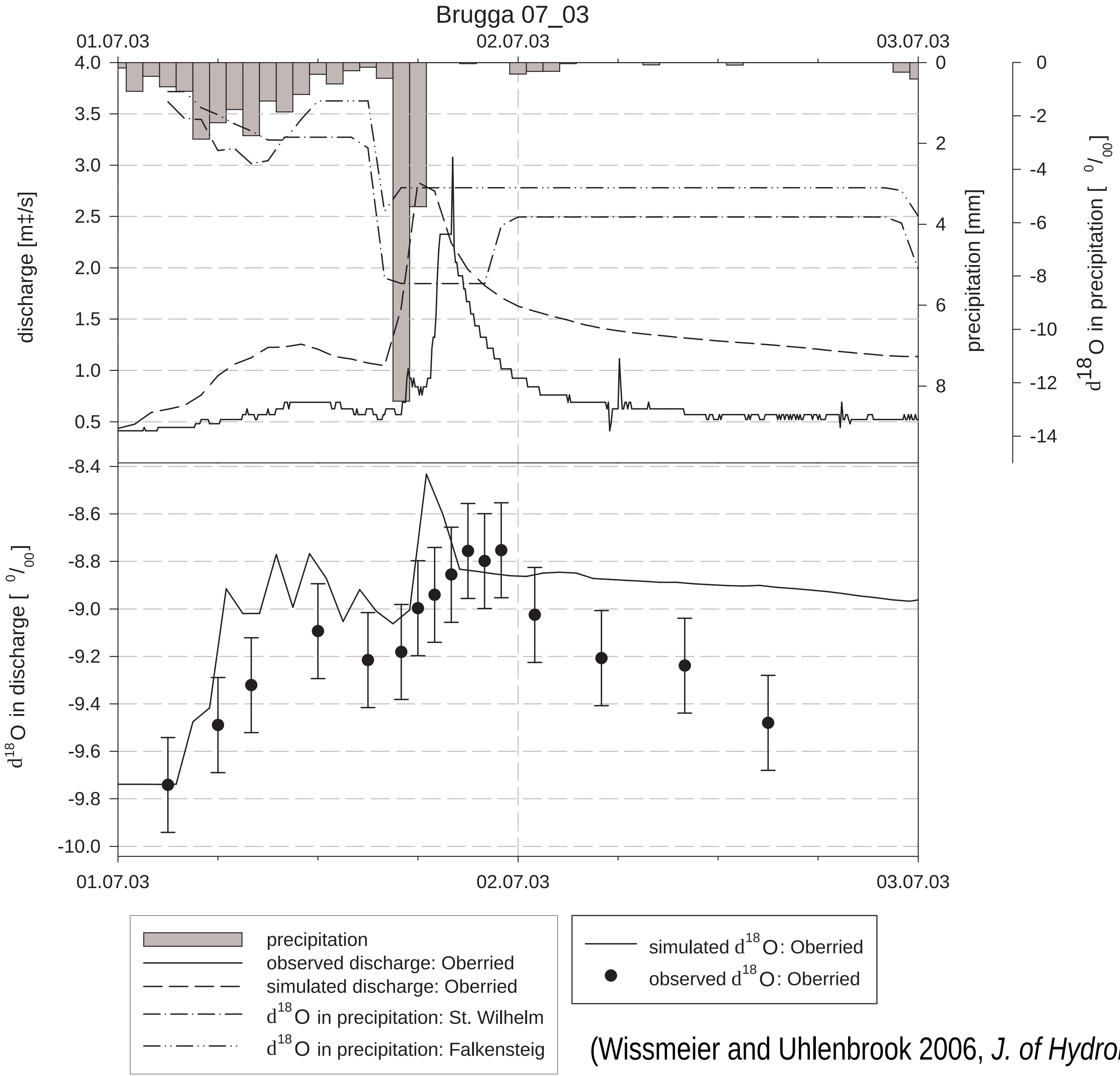
Further details in Uhlenbrook et al. 2004, *JoH*



(Wissmeier and Uhlenbrook 2006, *J. of Hydrol*.)



(Wissmeier and Uhlenbrook 2006, *J. of Hydrol*.)



(Wissmeier and Uhlenbrook 2006, *J. of Hydrol.*)

Concluding Remarks (3)
Use of tracer data to proof model concepts

1) Tracer simulation without additional calibration or additional model parameters (e.g. silica simulations)

   - ‘accounting’ model for ^{18}O directly coupled to the water balance model for every cell/layer (no further parameters introduced)

2) Independent data set (‘orthogonal data’)

3) Learned lessons about the source areas of surface runoff

3 Topics

ents at

ff generation

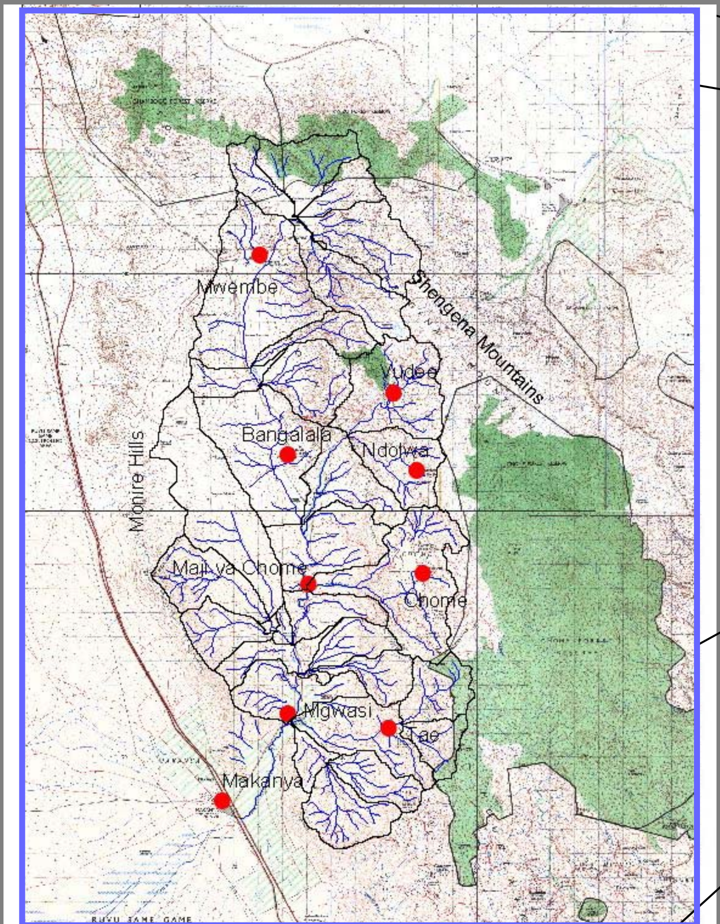
Black Forest Mountains, Germany

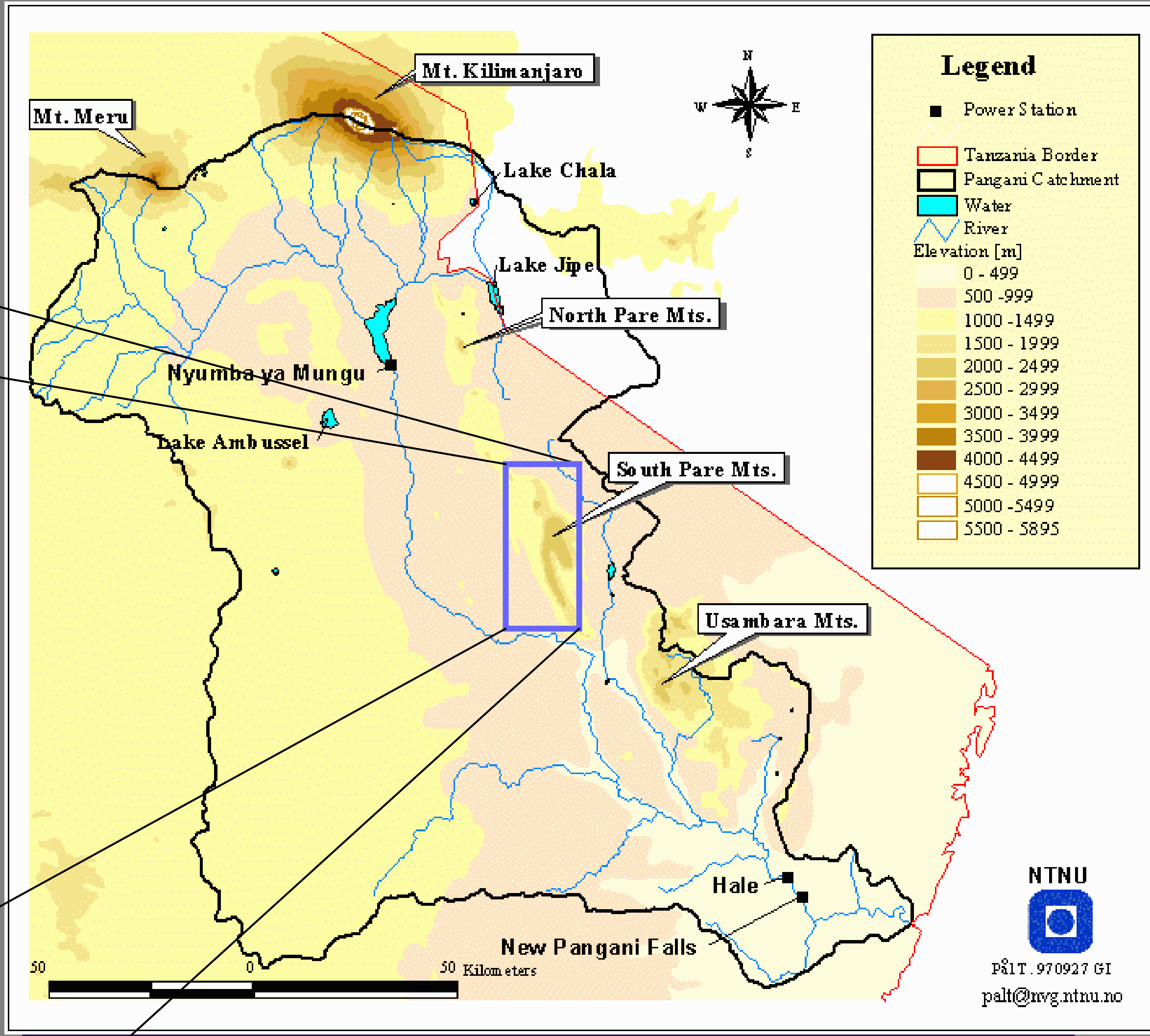
(3) Surface water–groundwater interactions in a semi-arid environment

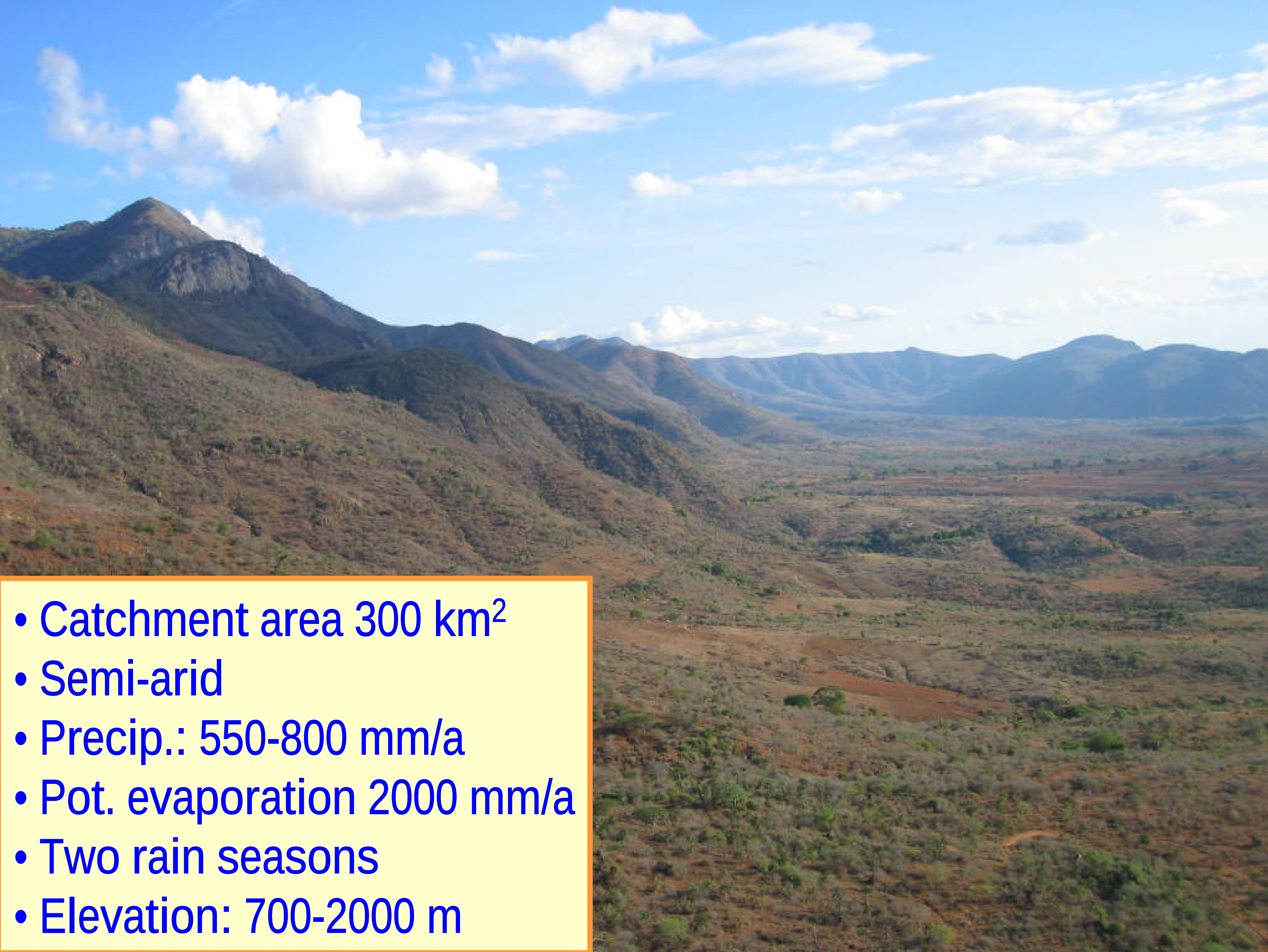
South Pare Mountains, Tanzania

Study area

- Pangani river basin
- Tanzania







- Catchment area 300 km^2
- Semi-arid
- Precip.: 550-800 mm/a
- Pot. evaporation 2000 mm/a
- Two rain seasons
- Elevation: 700-2000 m

(Pictures: H.H.G. Savenije;
M. Mul, March 2006)

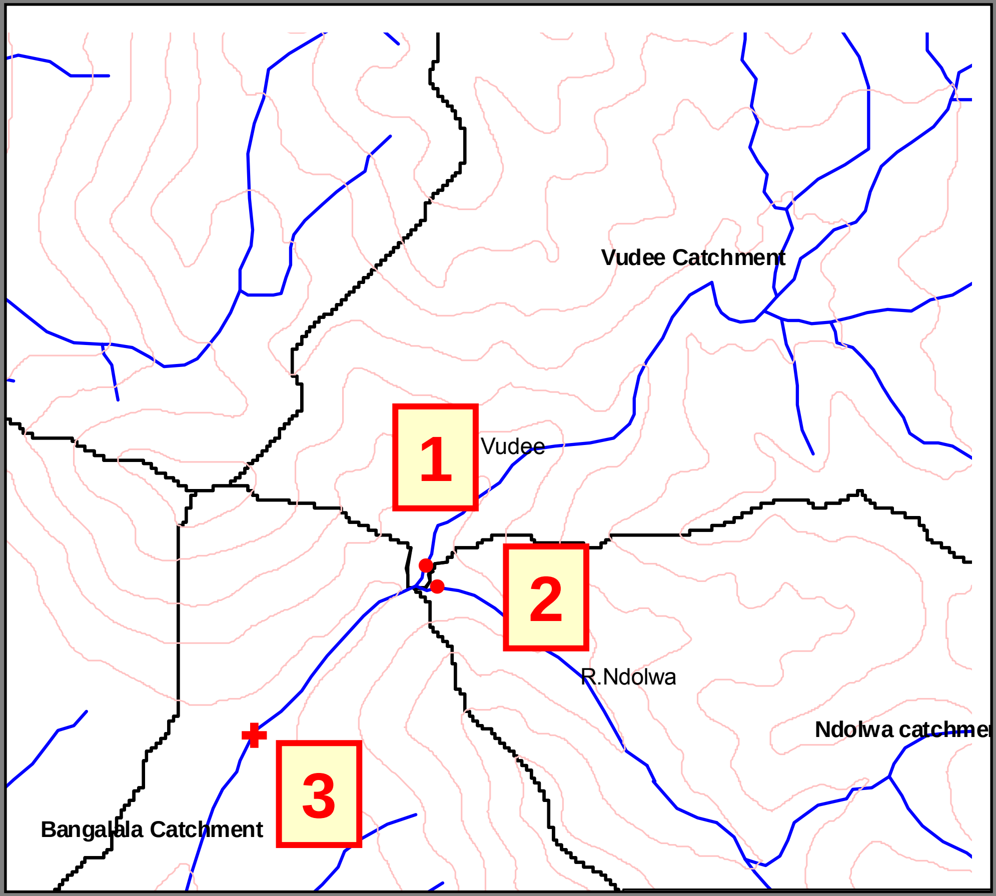
Investigation of flood events:
Chemical Hydrograph Separations

- Storm sampling at 3 locations
- Data collected
  - ⇒ EC, major anions and cations and dissolved silica
  - ⇒ Discharge measurements only at one weir
- Two storms investigated
- Hydrograph separation:

$$C_t Q_t = C_g Q_g + C_s Q_s$$

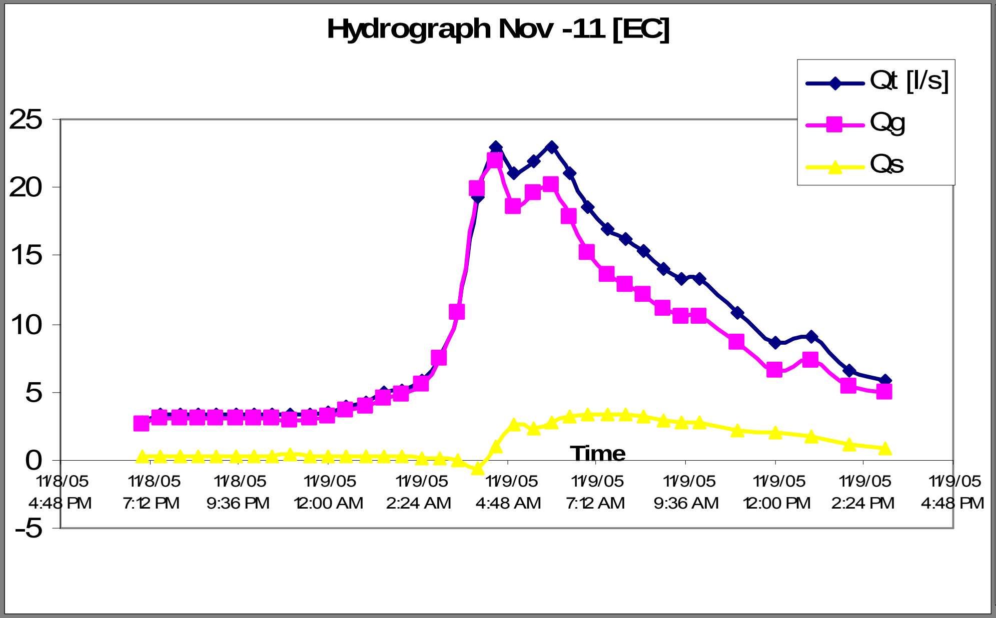
$$Q_t = Q_g + Q_s$$

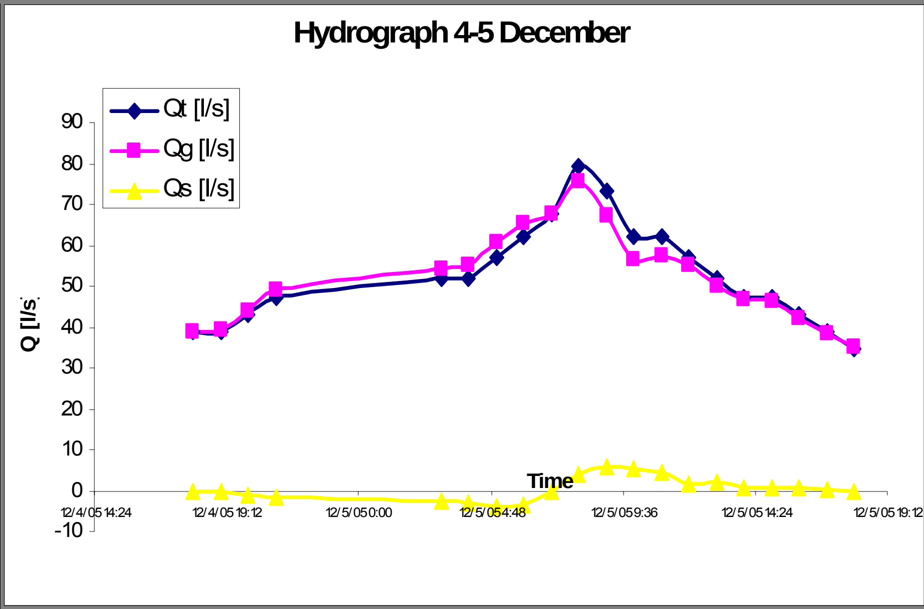
$$\frac{Q_s}{Q_g} = \frac{C_g - C_t}{C_t - C_s}$$



Rainfall-Runoff Investigations:
Separation in surface runoff / sub-surface runoff using EC

- First storm
  - ⇒ >80% baseflow
  - ⇒ Also negative baseflow
- Second storm
  - ⇒ >92% baseflow
  - ⇒ Also negative baseflow

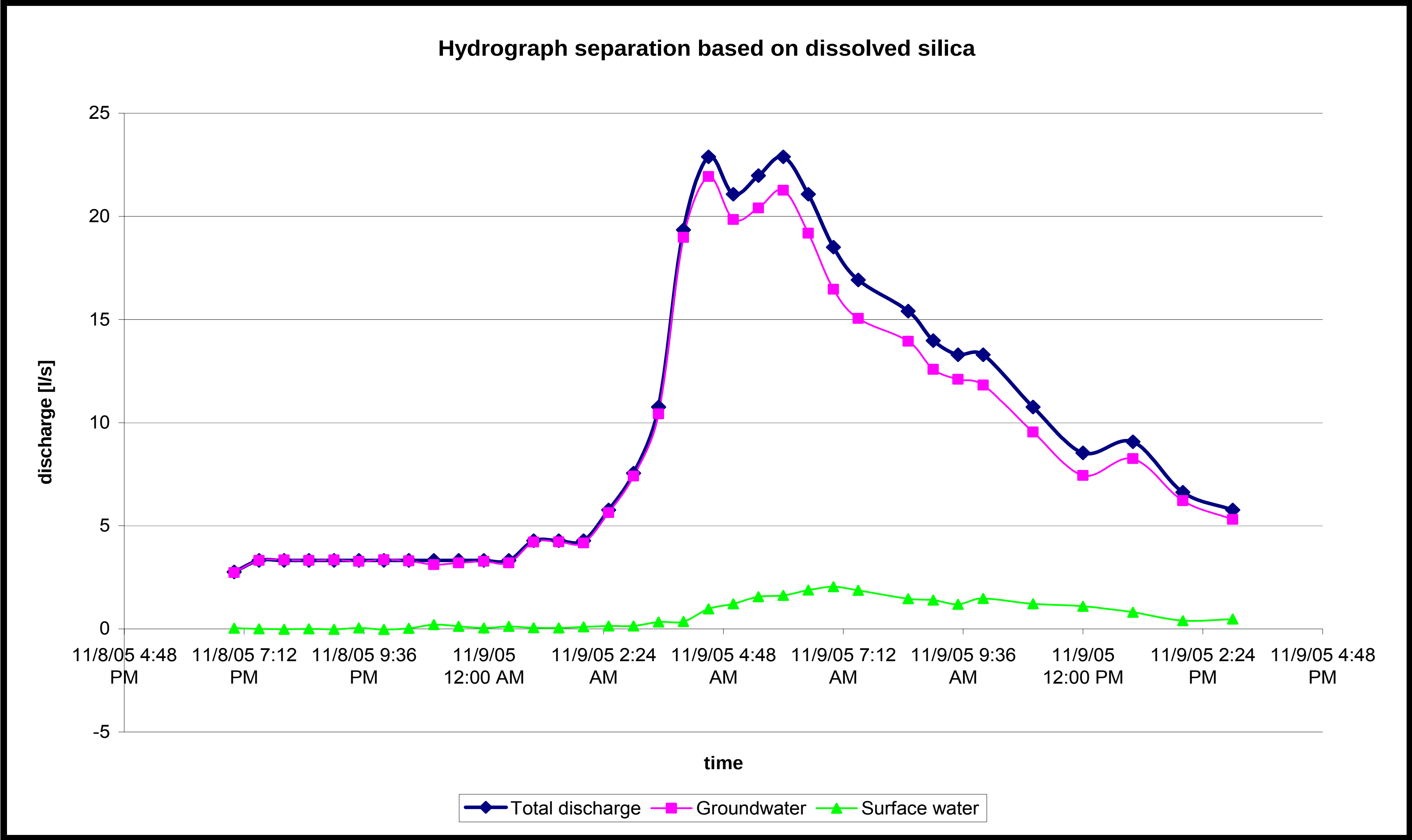




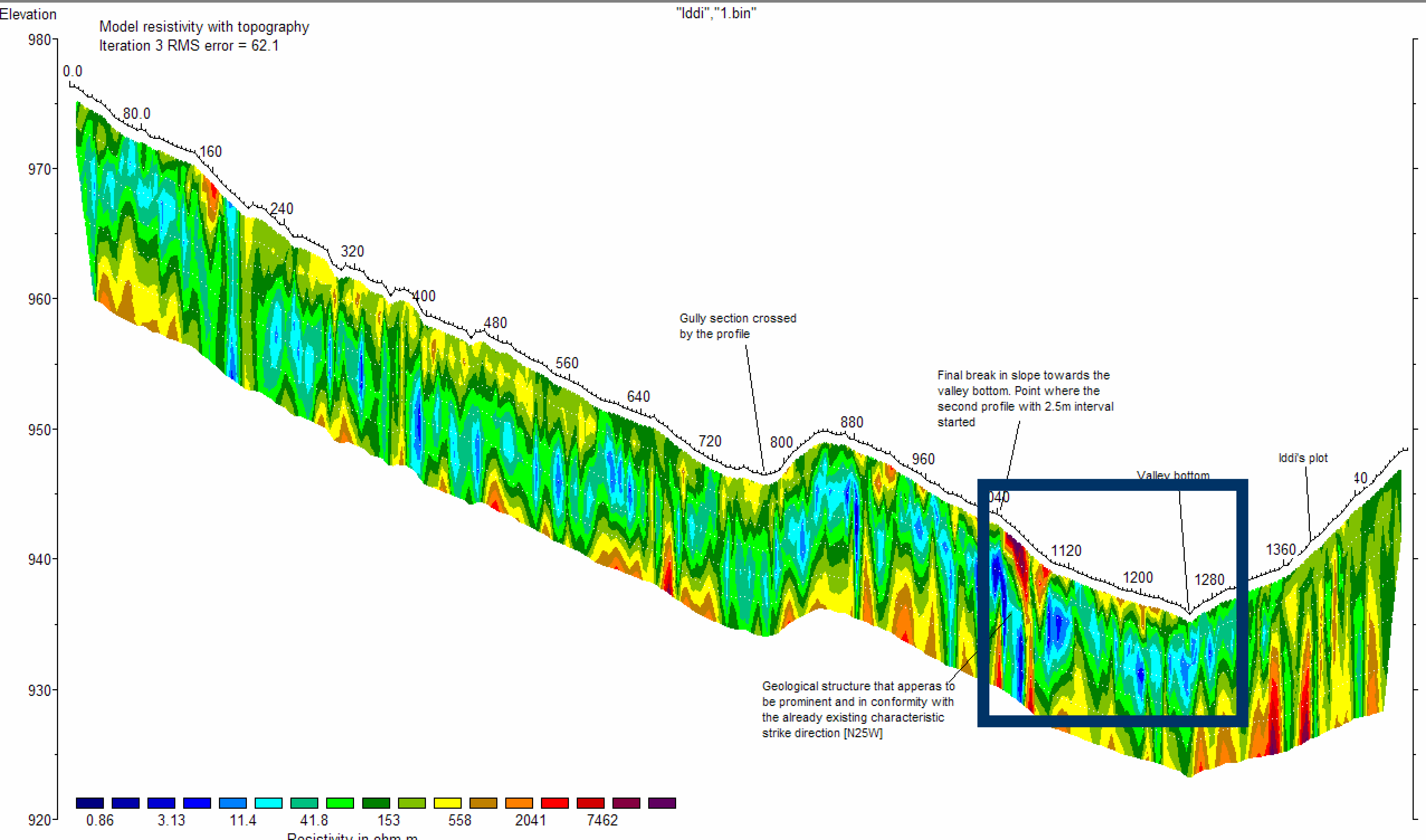
Uncertain, due to non-conservative behavior of EC!

Rainfall-Runoff Investigations

Separation in surface runoff / sub-surface runoff using dissolved silica (Si)



Electrical Resistivity Tomography (ERT) Investigations



Electrical Resistivity Tomography (ERT) Investigations

Geologic structure:

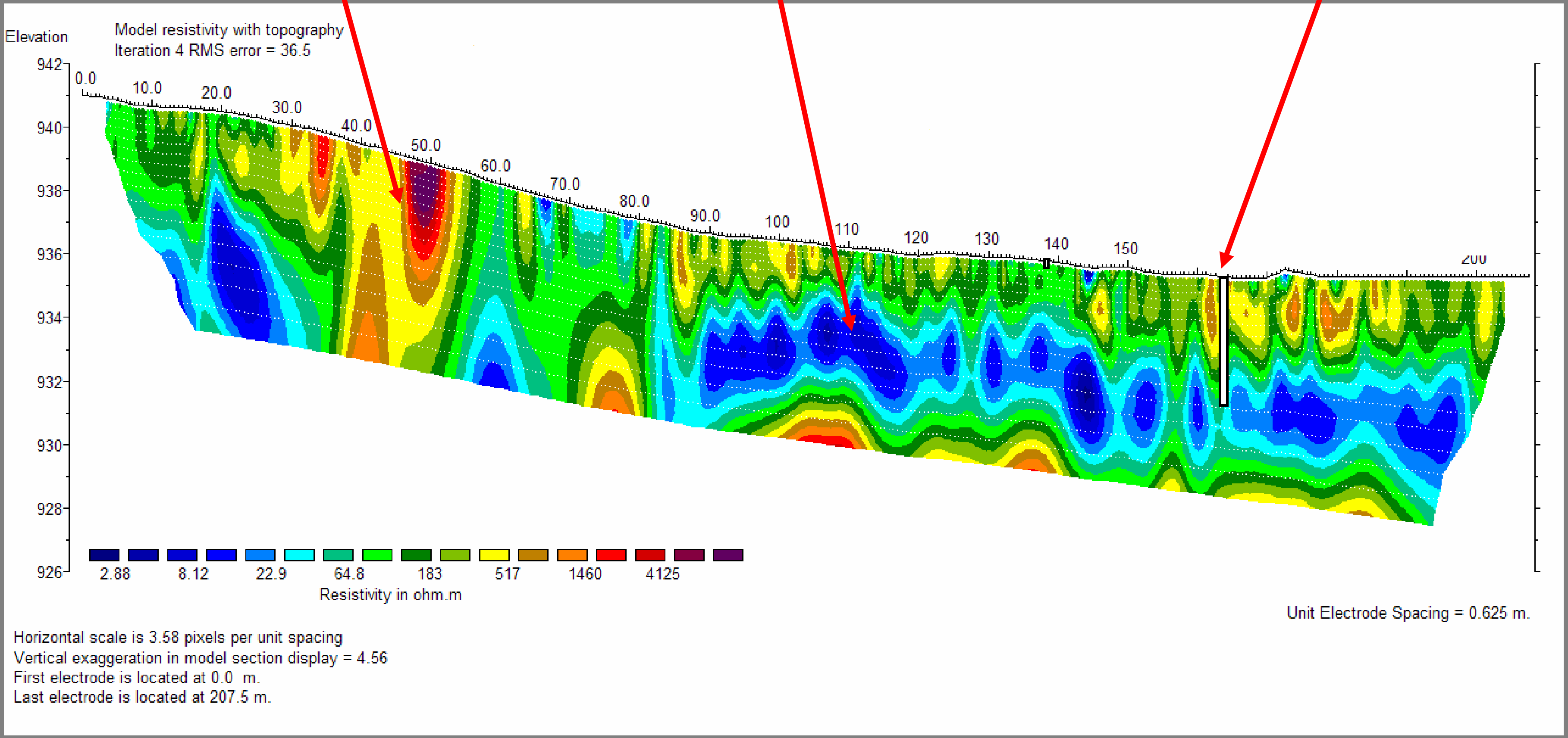
Fracture / fault

Low resistivity layer:

Clay

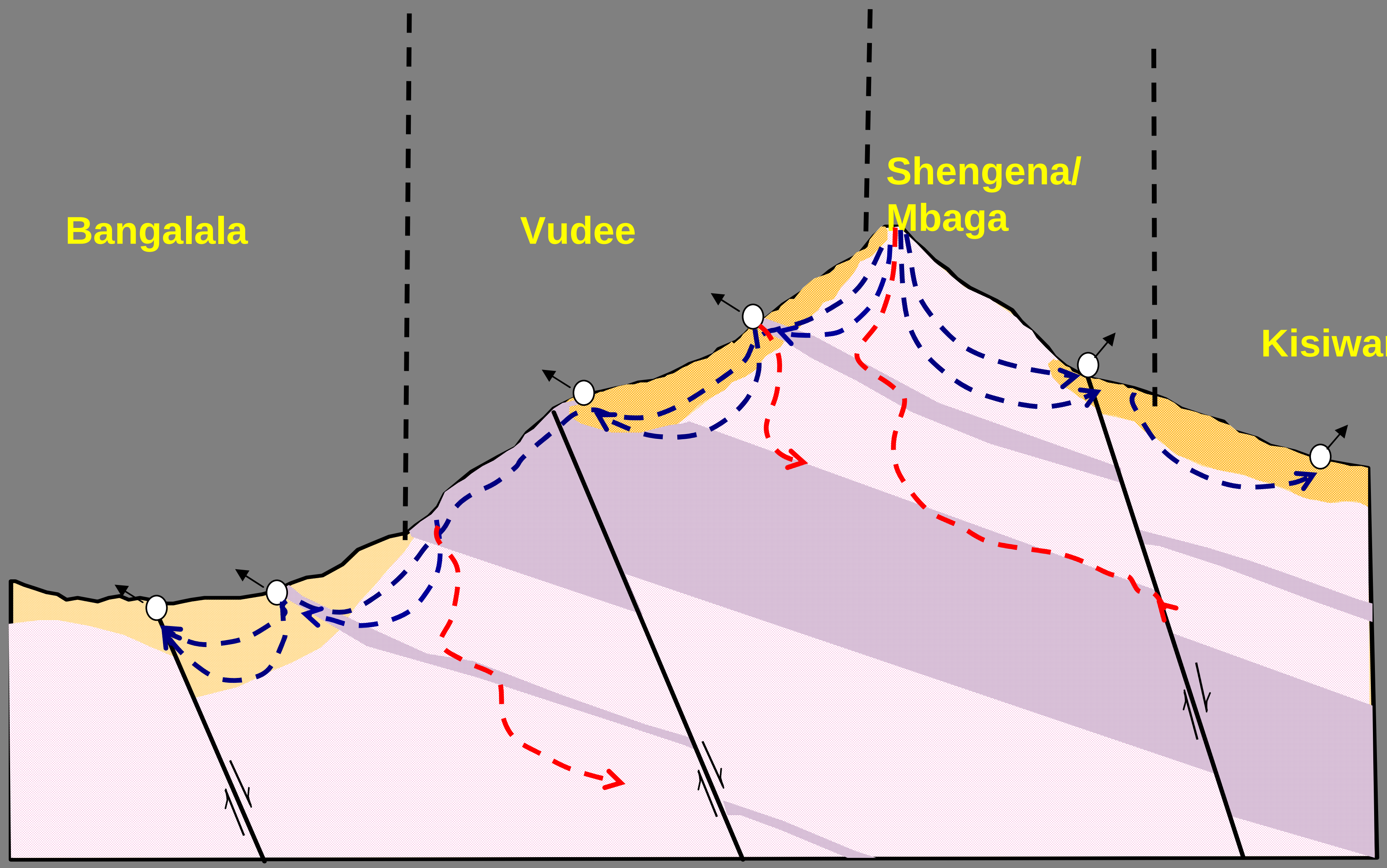
Auger well:

'ground truth' to calibrate the profile



Synthesis

Groundwater Flow Systems in the Makanya Catchment



Concluding Remarks (4)

Surface water-groundwater interactions in semi-arid environment

(1) Importance of subsurface water for formation of small floods

(2) Groundwater discharge into neighboring catchment (controlled by geology)

(3) Basis for
- ✓ development of conceptual catchment model
- ✓ design of next field studies

What did we learn?


(Keith J. Beven)

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


(Picture: Jan Hopmans, USA)

Zoom Out

nature Vol 445|1 February 2007|doi:10.1038/nature05508

LETTERS

Importa
convecti

John Worden[1], Da
contributors*

Atmospheric moistur
climate system, yet th
ity are poorly unders
rain contributes signi
clouds[5], but few obs
Similarly, the relative
land from local evapo
uncertain[3,7]. Lighter i
orate whereas heavier
isotopic composition
information combine
composition of tropo
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investigate aspects of
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spheric vapour conte
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ity, with typically 20%
convective clouds. O
nature of tropospheri
of precipitation[8,10,13],
both oceanic sources
moisture sources. Ou
intensity of the presen
future changes as the

HYDROLOGY

Tropical rain recycling

Thom Rahn

**The behaviour
hydrological cy
data provides a**

Water is arguably
It moves through
beginning with its
into the atmosph
and droplets coal
precipitation goes
while some enters
rain or snow. Ter
or is stored in glac
carried by rivers b
behind this delive

liquid phase, further depleting the remaining cloud water vapour (blue curves in Fig. 1) and removing the heavier isotopes from the atmosphere. When the remaining dry and depleted air is mixed with freshly evaporated

Challenge of further up-scaling isotope methods!

Out-scaling tracer techniques to tropical areas!

Responses to Taikan's Questions

1. "To review the state-of-the art modeling systems on large and global scale ..."

   - Not done.
     But, not only a question of computer power (Taikan: in 2020 we will model in high resolution, 0.01 km^2 and hourly).
     Different processes dominate at different scales

2. "To identify the gap between expectation from society and our ability to model ..."

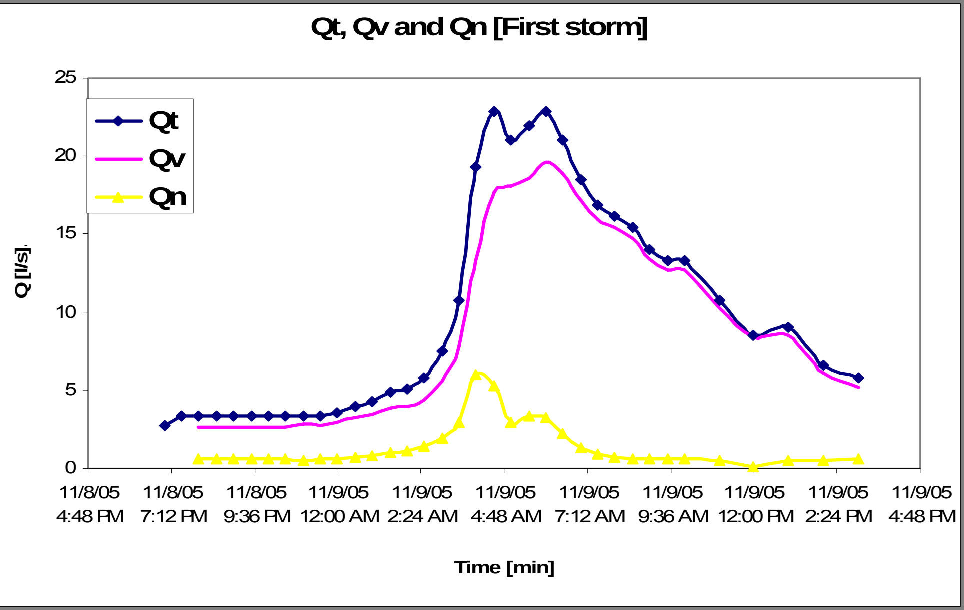
   - Reliable predictions under change circumstances
   - Beautiful (global) maps and nice fits of hydrographs do not guarantee sound process based predictions (focus on assumptions etc.)

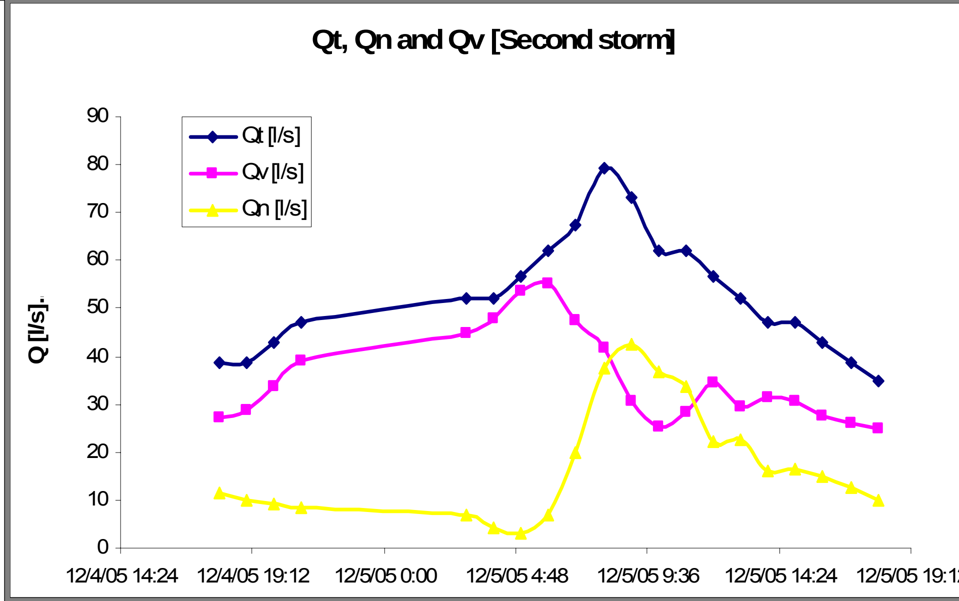
3. "To build a strategy for advancing current modeling systems"

   - Link of process researchers and global modelers

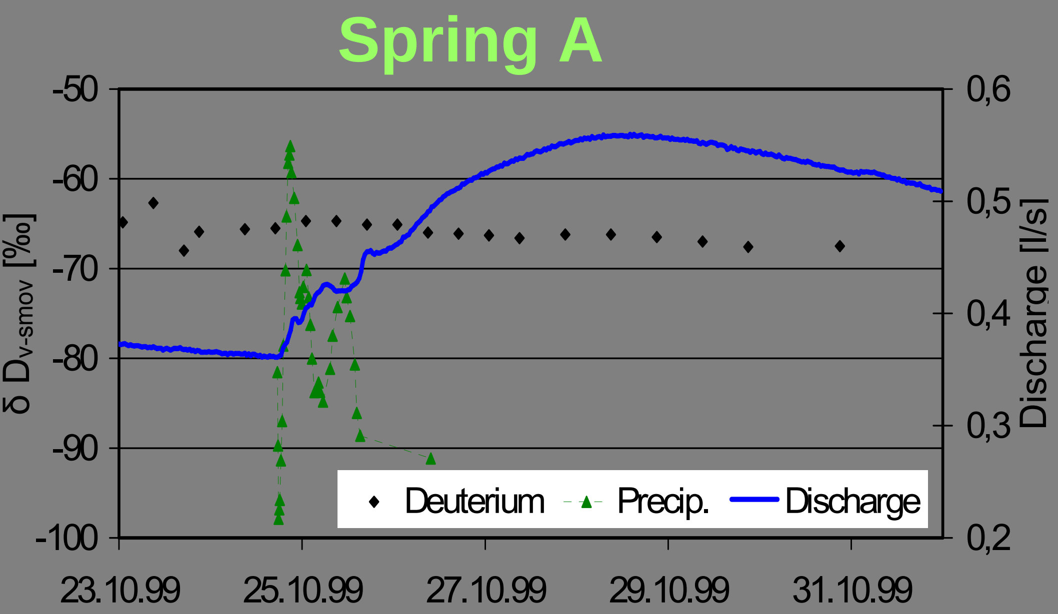
Rainfall-Runoff Investigations Contributions from 2 Sub-catchments using EC

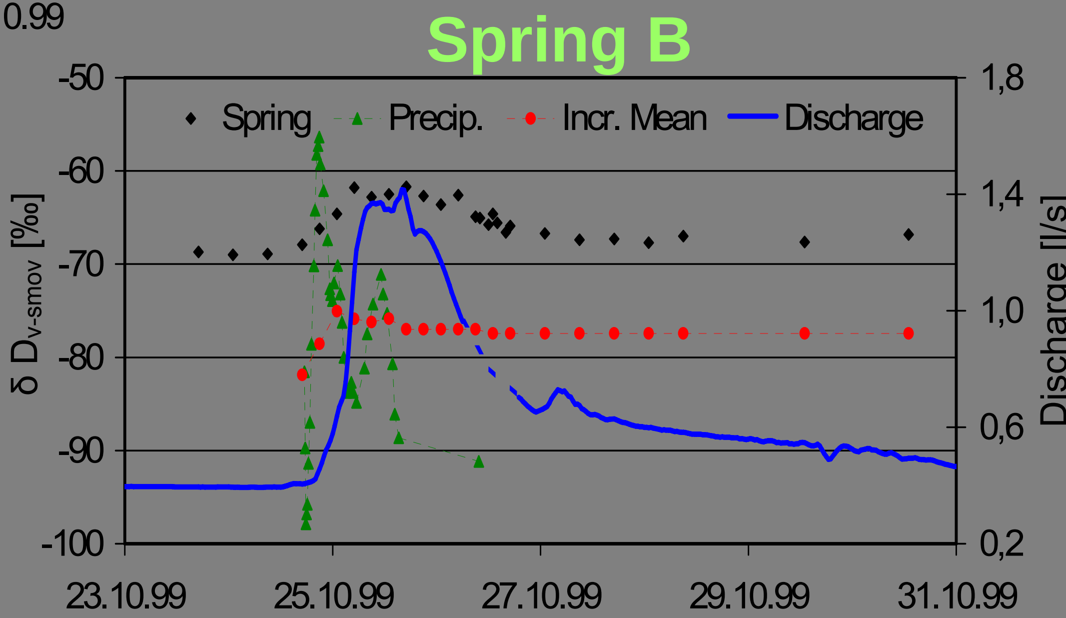
- First storm
  - ⇒Vudee 13.5mm
  - ⇒Ndolwa 7.9mm
- Second storm
  - ⇒Vudee 7mm
  - ⇒Ndolwa 17.6mm





Hydrochemical Dynamics: Deuterium

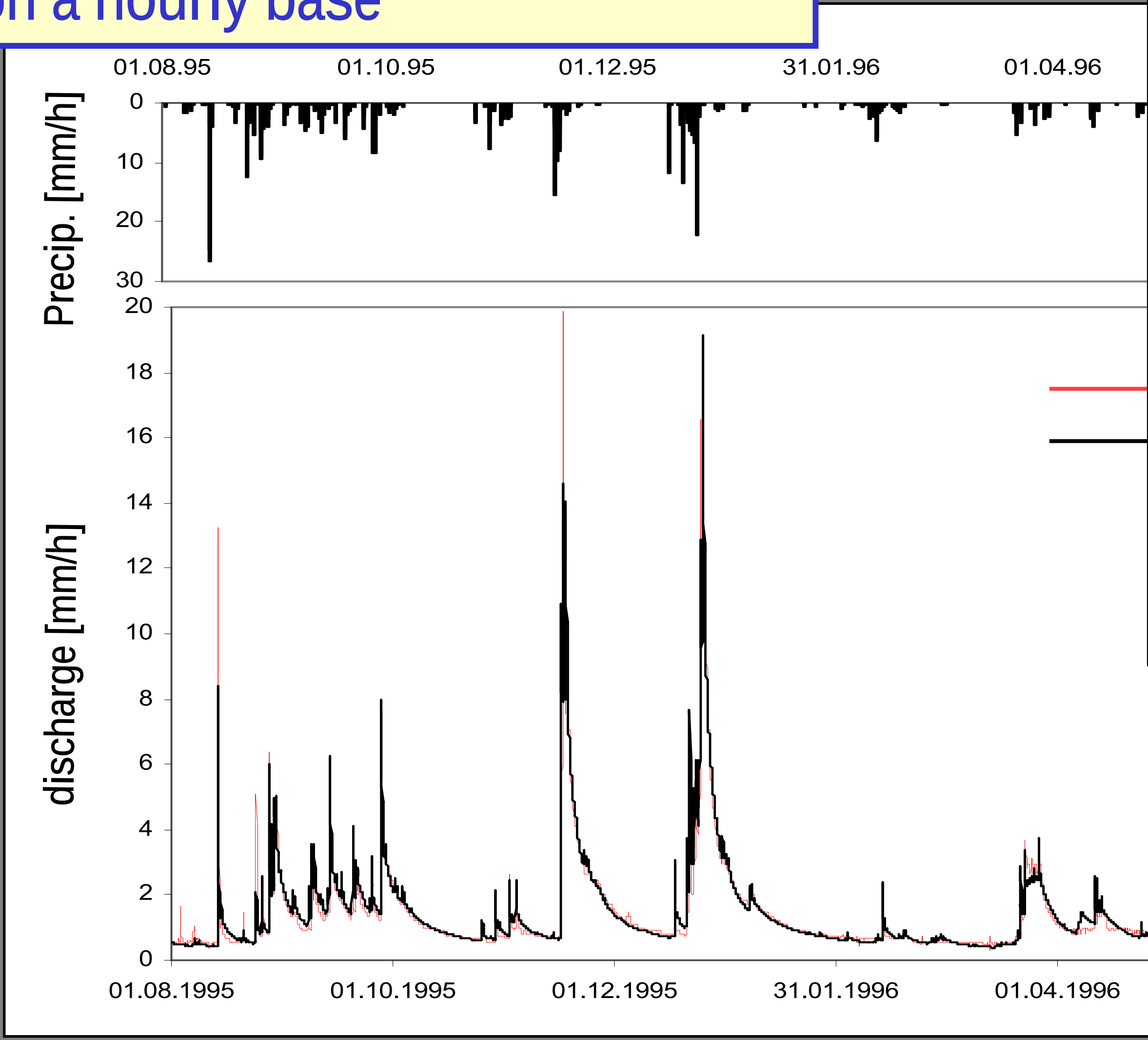




(Uhlenbrook, Didszun, Leibundgut, 2004)

Model simulation results using a calibrated model

Nash and Sutcliffe Efficieny > 0.8
on a hourly base

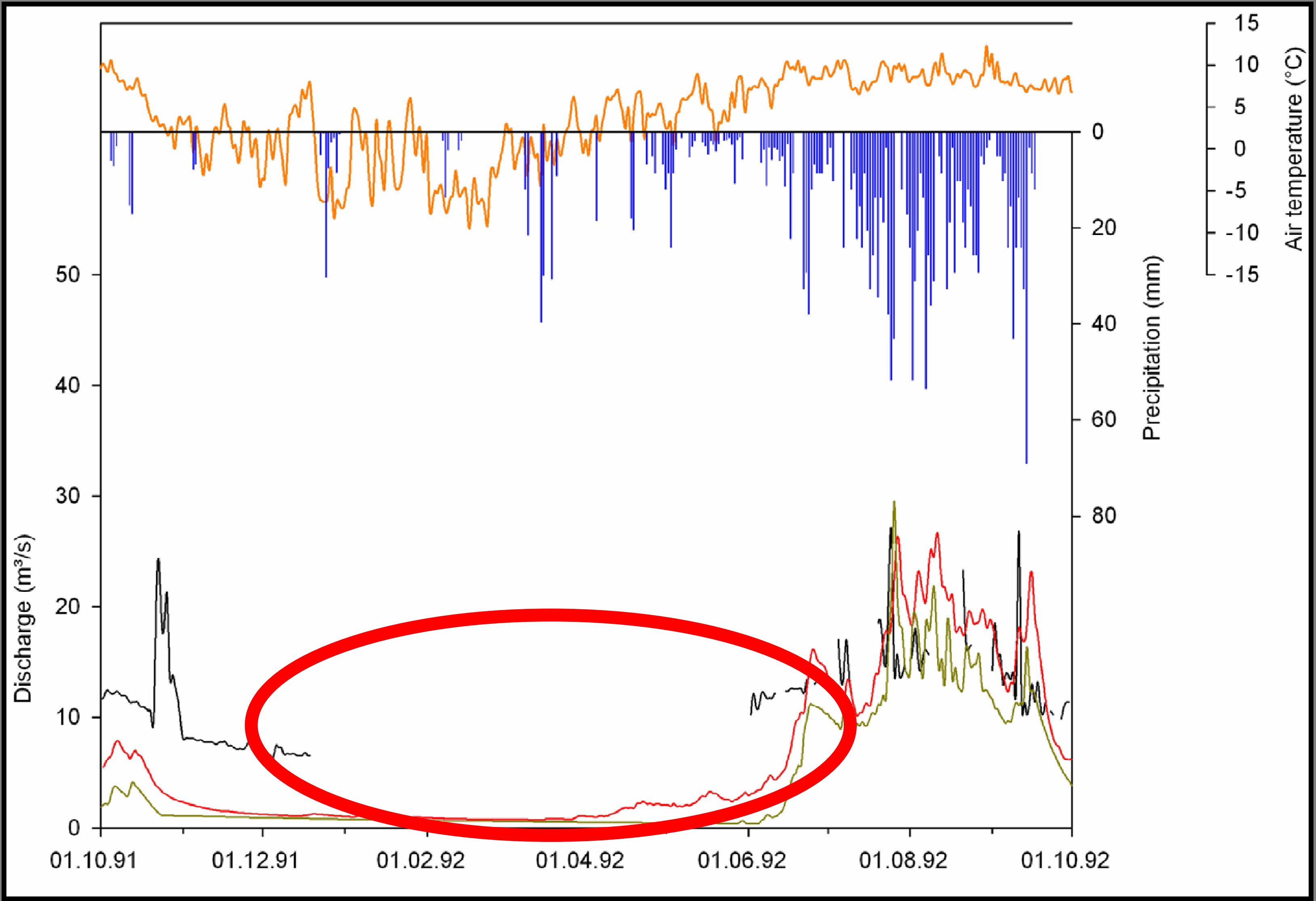


(Kirchner 2006, WRR)

(Uhlenbrook and Leibundgut 1999, IAHS Pub.)

But, most of the catchments world-wide are ungauged or poorly gauged!

(Example: Modi Khola catchment , Nepal)

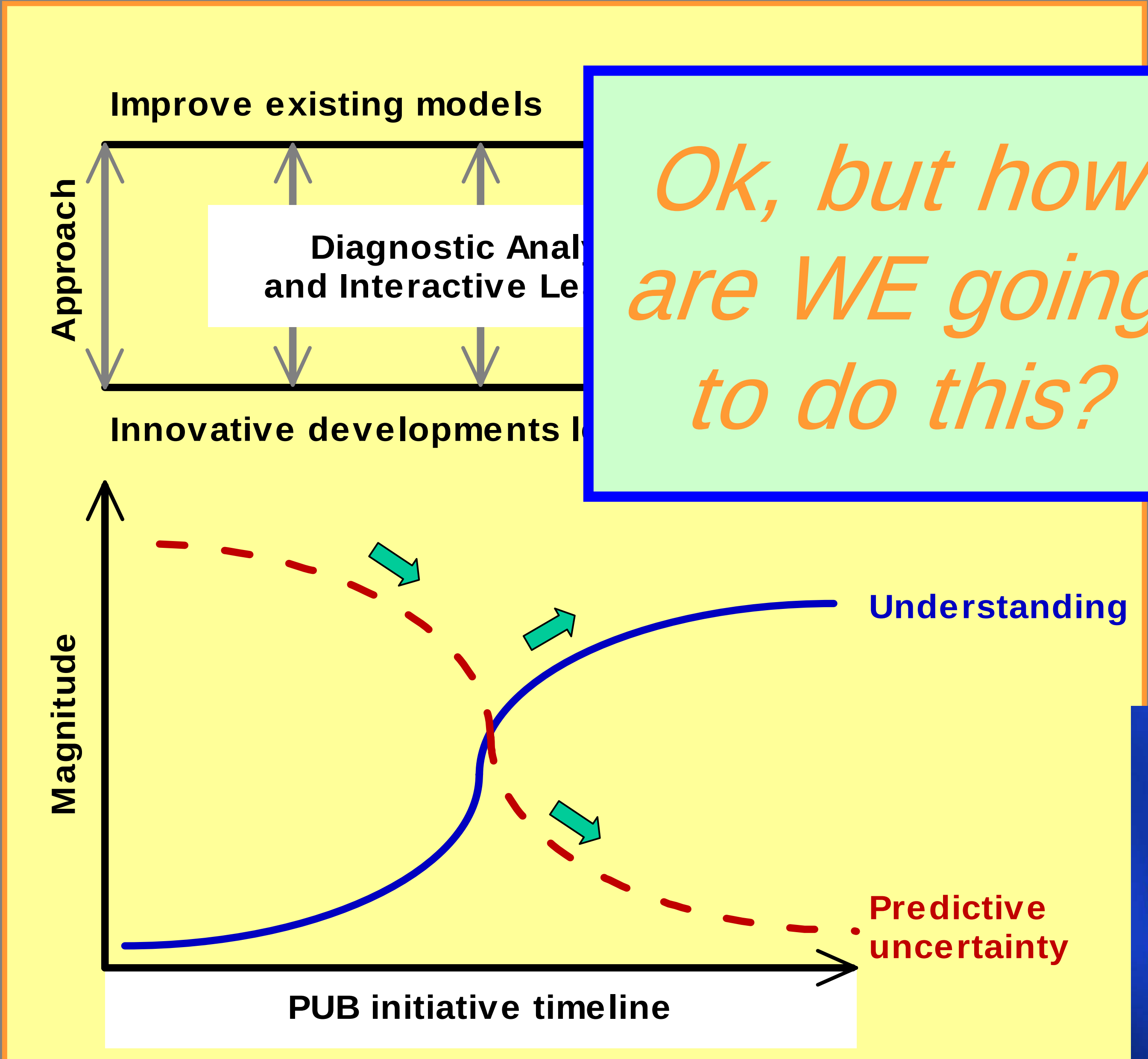


(Konz et al. 2006)

Searching for water level data in southern Zimbabwe

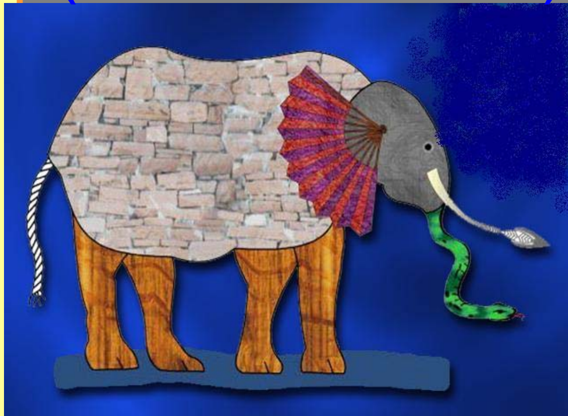
(Pictures: H.H.G. Savenije;
M. Mul, March 2006)

PUB Approach in a Nutshell
(Sivapalan et al. 2003, *HSJ*)

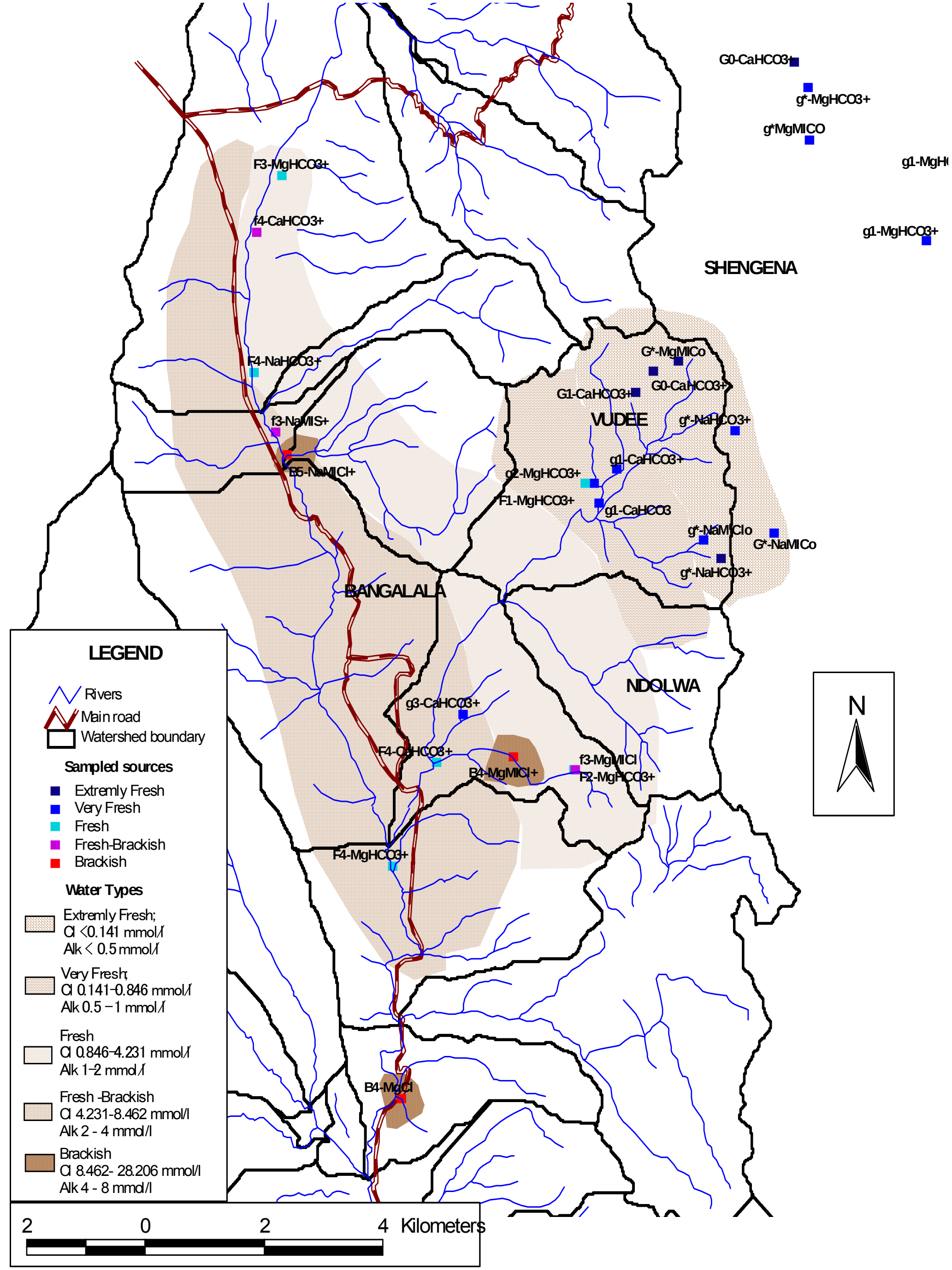


Ok, but how are WE going to do this?

PUB initiative from the IAHS (www.iahs.info)



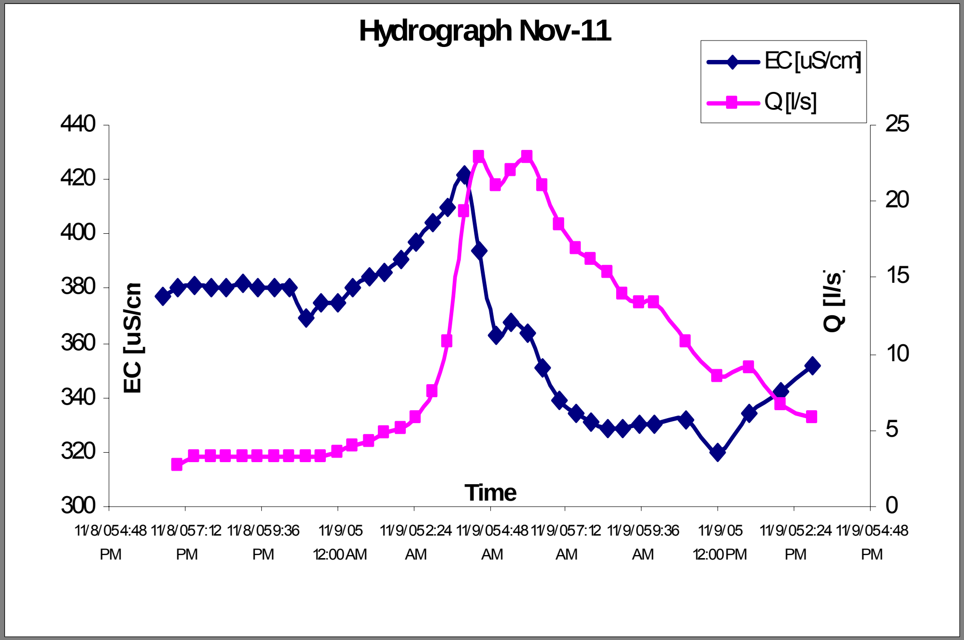
Variation of Water Quality of Springs During Base Flow Sampling

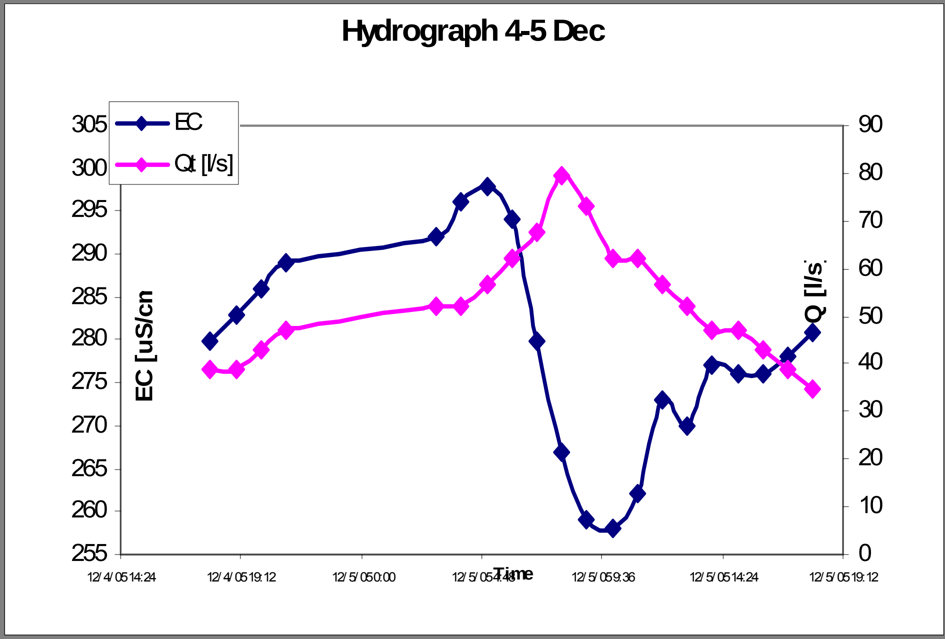


Rainfall-Runoff Investigations

- First storm
  - ⇒ 13.5mm and 7.9mm rainfall

- Second storm
  - ⇒ 7mm and 17.6mm rainfall





⇒ Two peaks

⇒ From different storages?

⇒ From different sub-catchments?

⇒ One peak

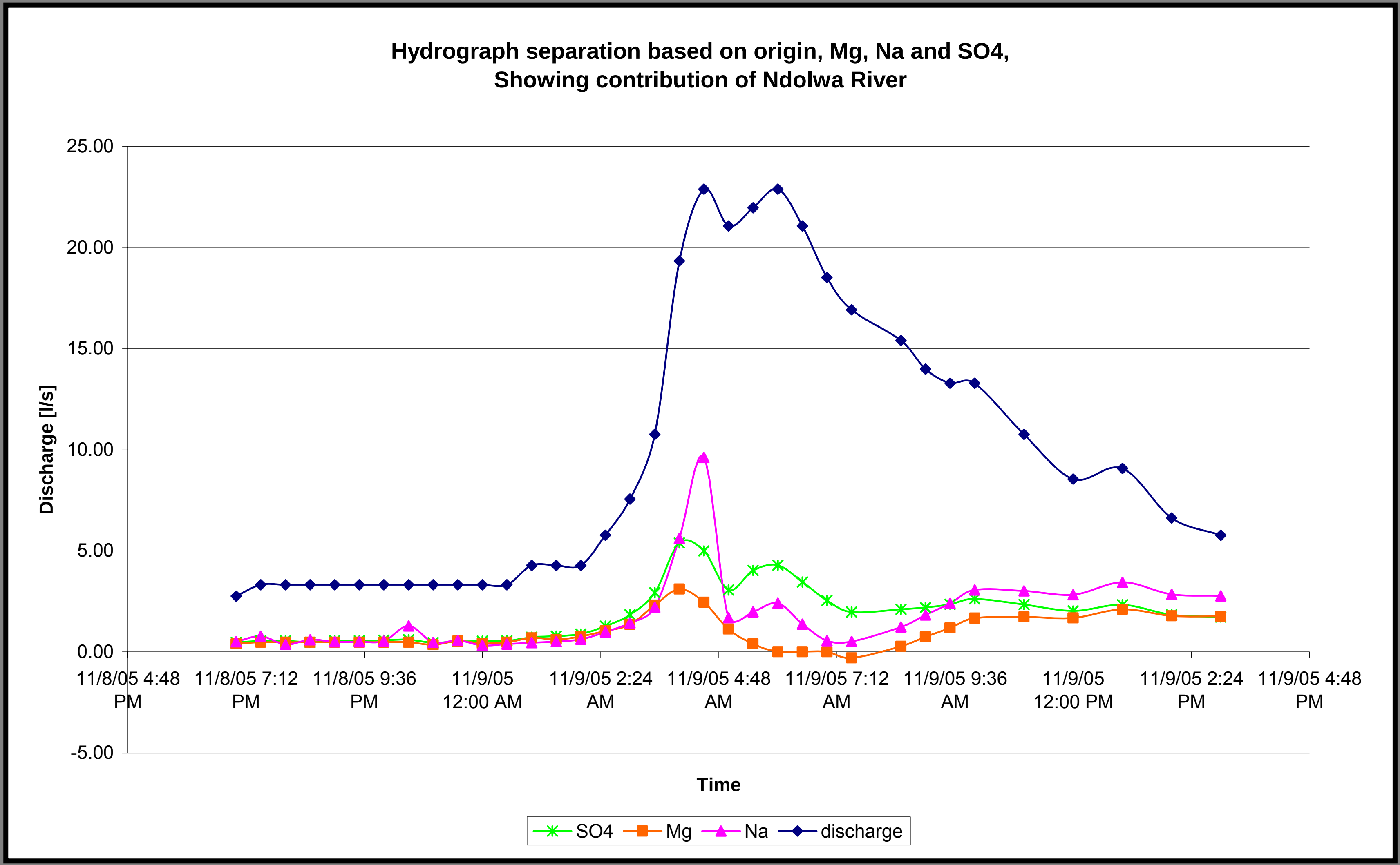
⇒ Also with a 'pre-peak' of EC

Hydrograph separation

Table 1 Background concentrations observed during base flow [mg/l]

	upper-Vudee	Ndolwa	Weir
EC [μS/cm]	315	659	380
Ca^{2+}	28	41	29
Mg^{2+}	16	44	20
Na^{+}	29	49	33
K^{+}	1.4	2.3	1.8
HCO_3^{-}	174	316	195
SO_4^{2-}	30.18	79.92	38.46
Dissolved silica	38	38	37.5
Cl^{-}	39.21	53.4	41.53
F^{-}	1.36	1.43	1.08

Hydrograph Separation Using Other Tracers: Mg^{2+}, Na^{+} and SO_4^{2-} Contribution of Sub-catchment Ndolwa



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