20-23 September 2010, **HydroPredict' 2010**, 2nd Intern. Interdisciplinary Conference on Predictions for Hydrology, Ecology, and Water Resources Management: Changes and Hazards caused by Direct Human Interventions and Climate Change; Prague, Czech Republic

Predicting the Impact of Change – The need for a better hydrological process understanding through innovative experimental and modeling approaches

S. Uhlenbrook, J.W. Foppen, I. Masih, S. Maskey, C. Orup, A. Saraiva, V. Smakthin, J. Wenninger

International Water Management Institute

UNESCO-IHE Institute for Water Education

TU Delft Delft University of Technology

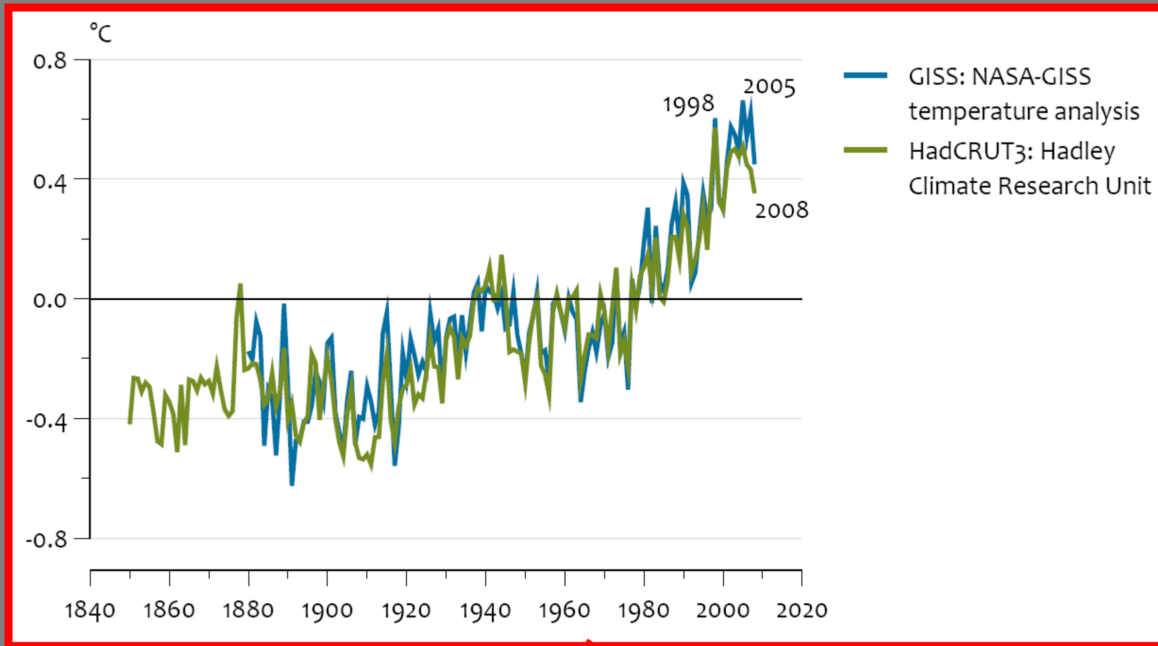
Outline

(1) Intro the world is changing ('stationary is dead')

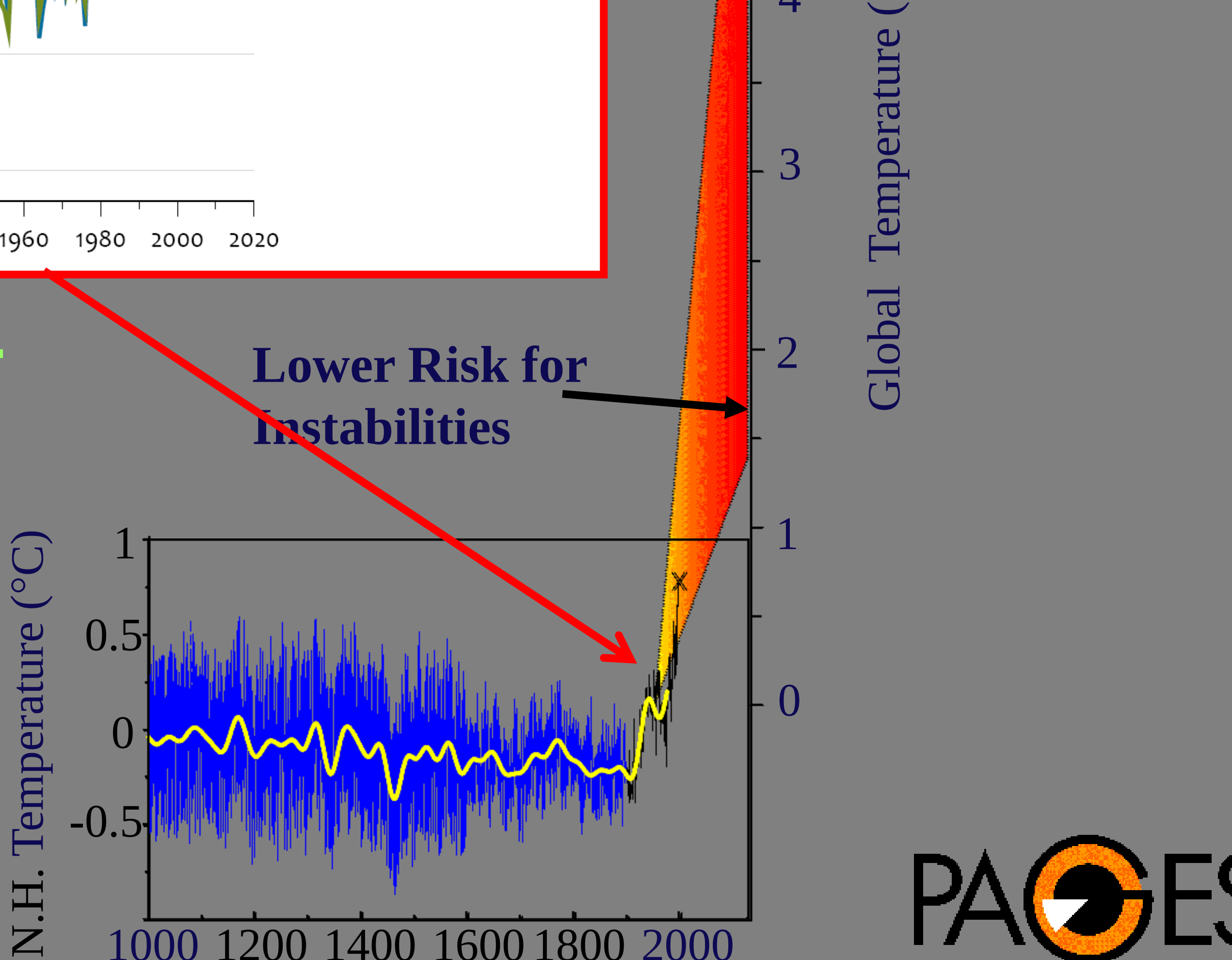
(2) Case study ONE:
Improving hydrological predictions in the semi-arid Karkheh basin, Iran

(3) Case study TWO:
DNA – New multi-tracing opportunities to study hydrological flow pathways

(4) Case study THREE:
The use of stable isotopes to improve our understanding of evaporation fluxes

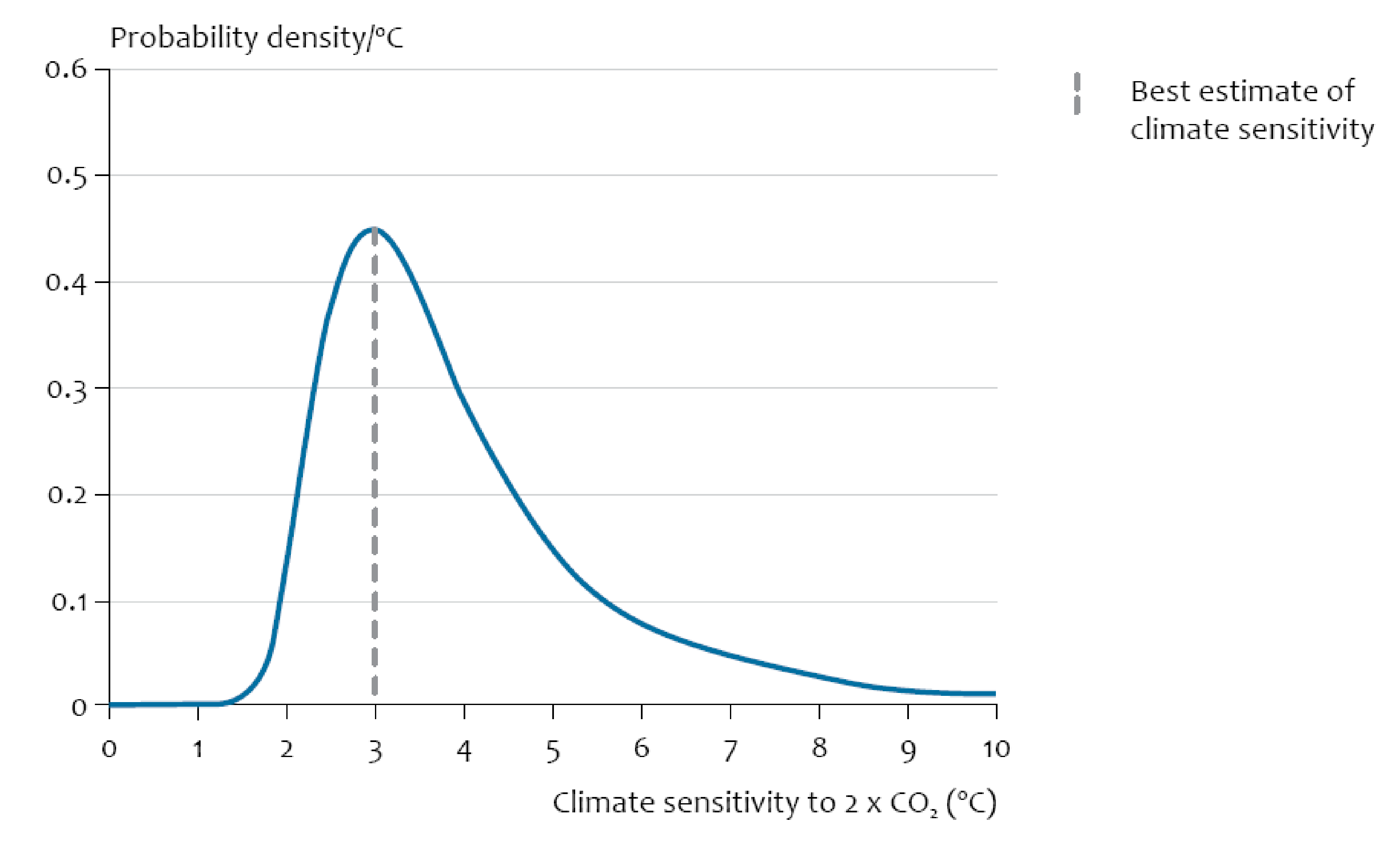


The context – ONE



(NEAA, 2009)

Climate Sensitivity – Best estimate +3C for 2x CO_2 pre-industrial, but it can be much higher …



(NEAA, 2009)

Change in annual runoff by 2041-60 (SRES A1B) – Ensemble of 12 climate models

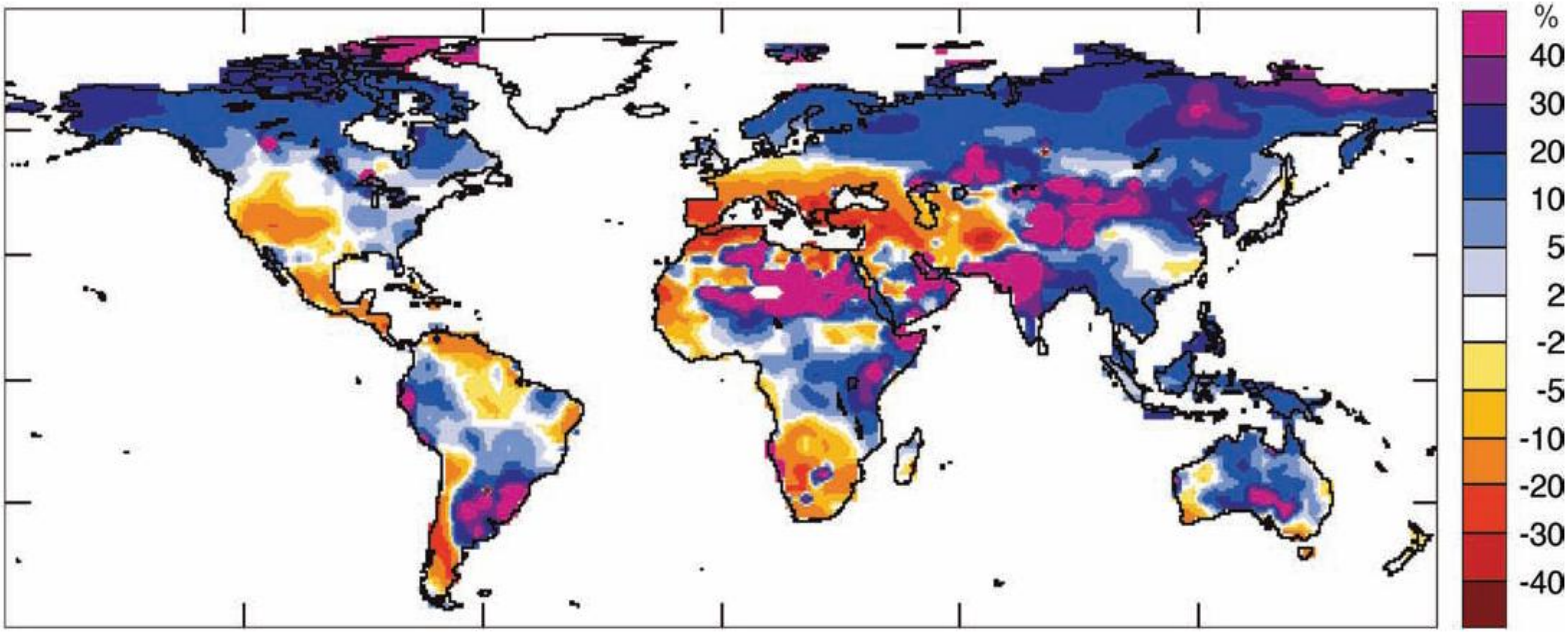


Figure 3.4. *Change in annual runoff by 2041-60 relative to 1900-70, in percent, under the SRES A1B emissions scenario and based on an ensemble of 12 climate models. Reprinted by permission from Macmillan Publishers Ltd. [Nature] (Milly et al., 2005), copyright 2005.*

Source: Kundzewicz et al. (2007); chapter in IPCC (2007)

The context – TWO

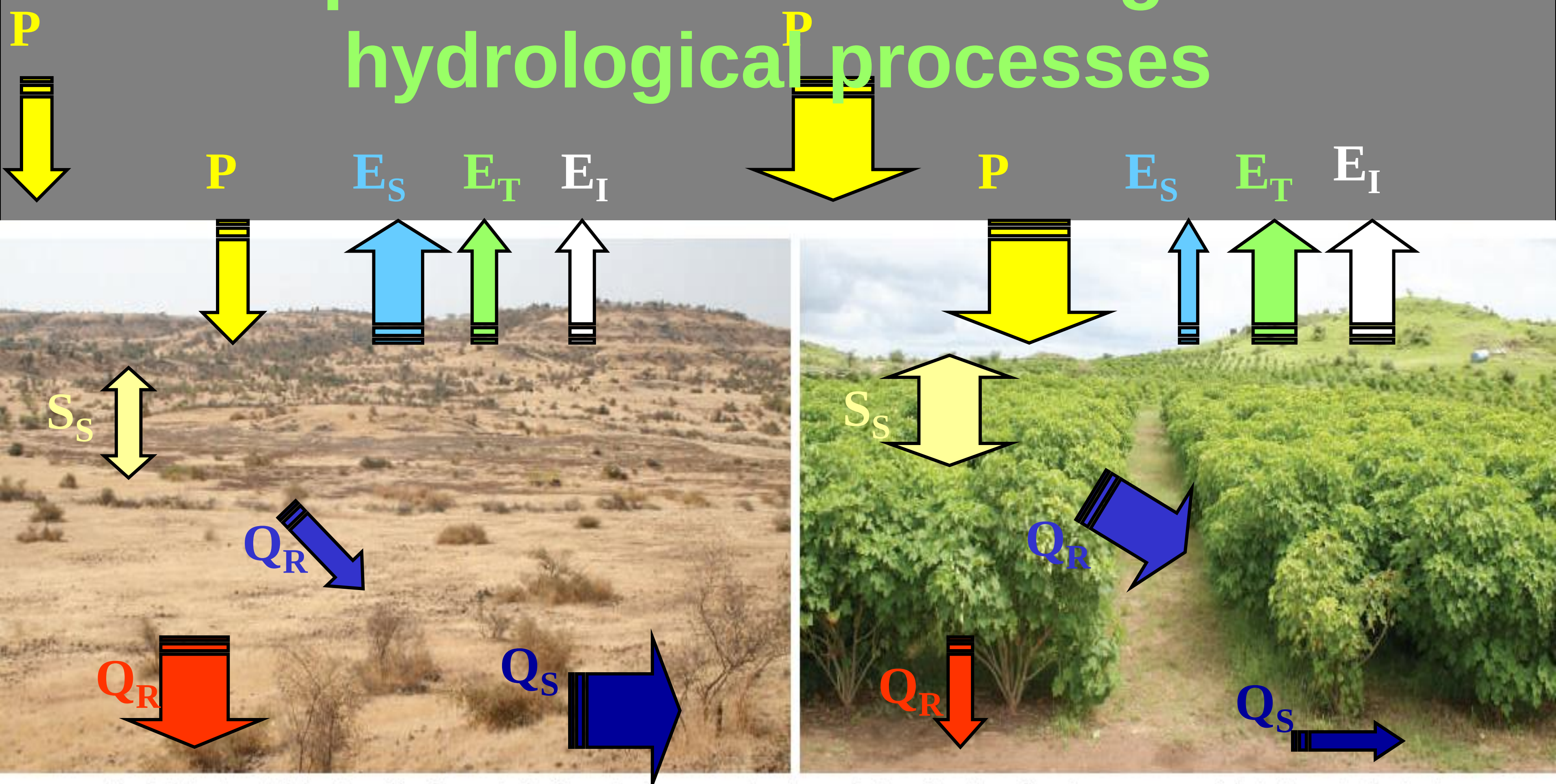
- *A massive land-grabbing scramble in Africa as foreign companies - some with foreign aid money support - rapidly establish enormous monoculture fields in tropical countries.*

  ⇒***Prof Seif Madoffe, SUA***

'climate colonialism'

Sugar Cane – Kilombera Basin, Tanzania

Impact of land use change on hydrological processes



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

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:

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

Where:

$$\left(\frac{dS_I}{dt}+E_I\right)$$ Interception processes

$$\left(\frac{dS_s}{dt}+E_s+Q_s\right)$$ Surface water processes

$$\left(\frac{dS_u}{dt}+E_T+E_u+Q_f\right)$$ Root zone moisture processes

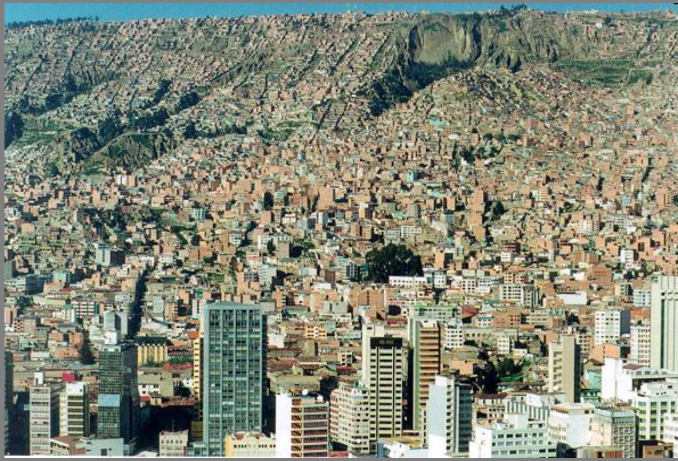
$$\left(\frac{dS_g}{dt}+Q_g\right)$$ Groundwater processes

Possible changes in all variables due to climate and/or land changes!!

Global Changes

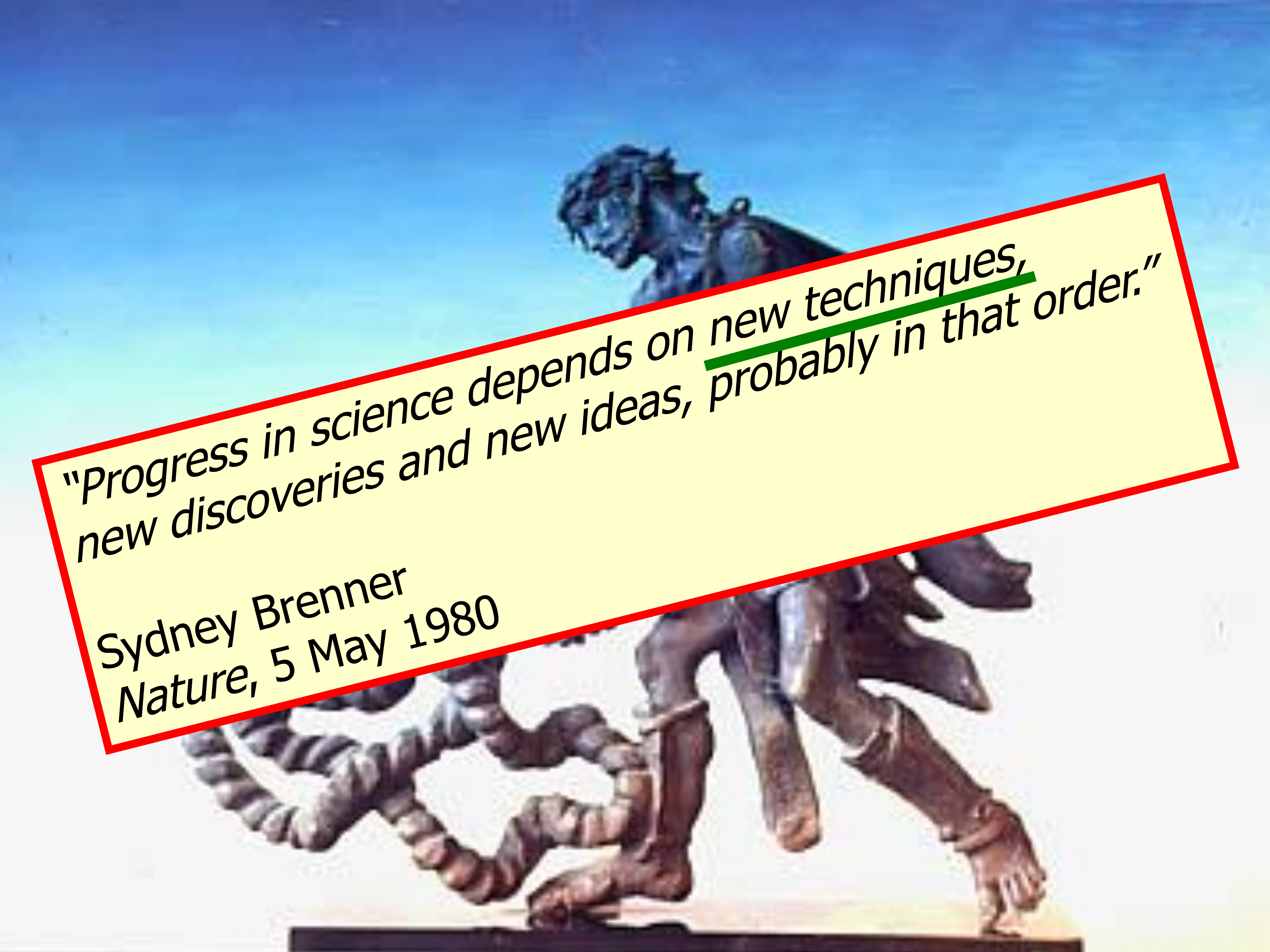
- Climate (temperature, precipitation, radiation …)
- Land use, land cover
  - ⇒ De-forestation / re-forestation
  - ⇒ Urbanisation
  - ⇒ Etc.
- Population (amount, density, structure, …)
- Hydraulic works
- Technological development
- Globalisation
- Water use in space and time
- Economic development
- 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!



Why is it so difficult to predict hydrological effects of change?

1. Many global changes occur simultaneously with positive or negative (unknow) feedbacks
2. Spatial and temporal scales for hydrological processes are different from scales dominant in other disciplines
3. Hydrological processes are often non-linear or depend on thresholds/tipping points
4. Hydrological extremes (e.g. floods and droughts) do not occur often and are difficult to measure, consequently, good data sets are usually not available
5. Boundary conditions during hydrological modelling are not clear (i.e. subsurface flows)
6. Hydrological observation methods are insufficient to study hydrological process dynamics (e.g. subsurface flow processes, extreme events etc.)


"Progress in science depends on new techniques,
new discoveries and new ideas, probably in that order."
Sydney Brenner
Nature, 5 May 1980

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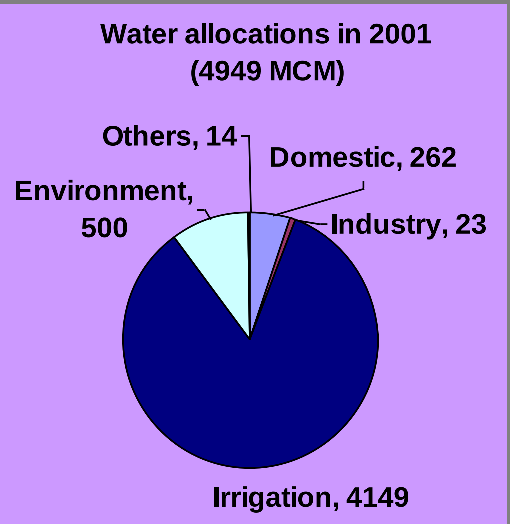
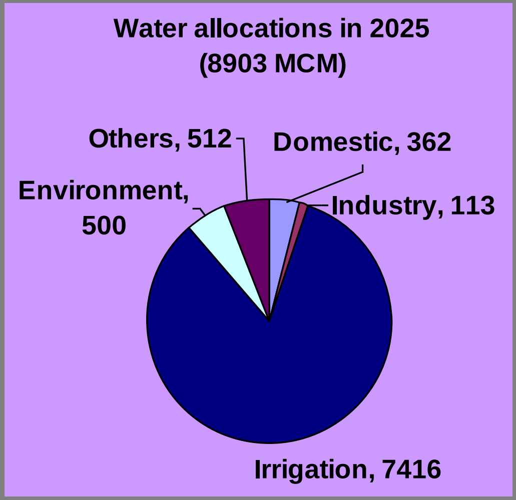
The Karkheh basin, Iran

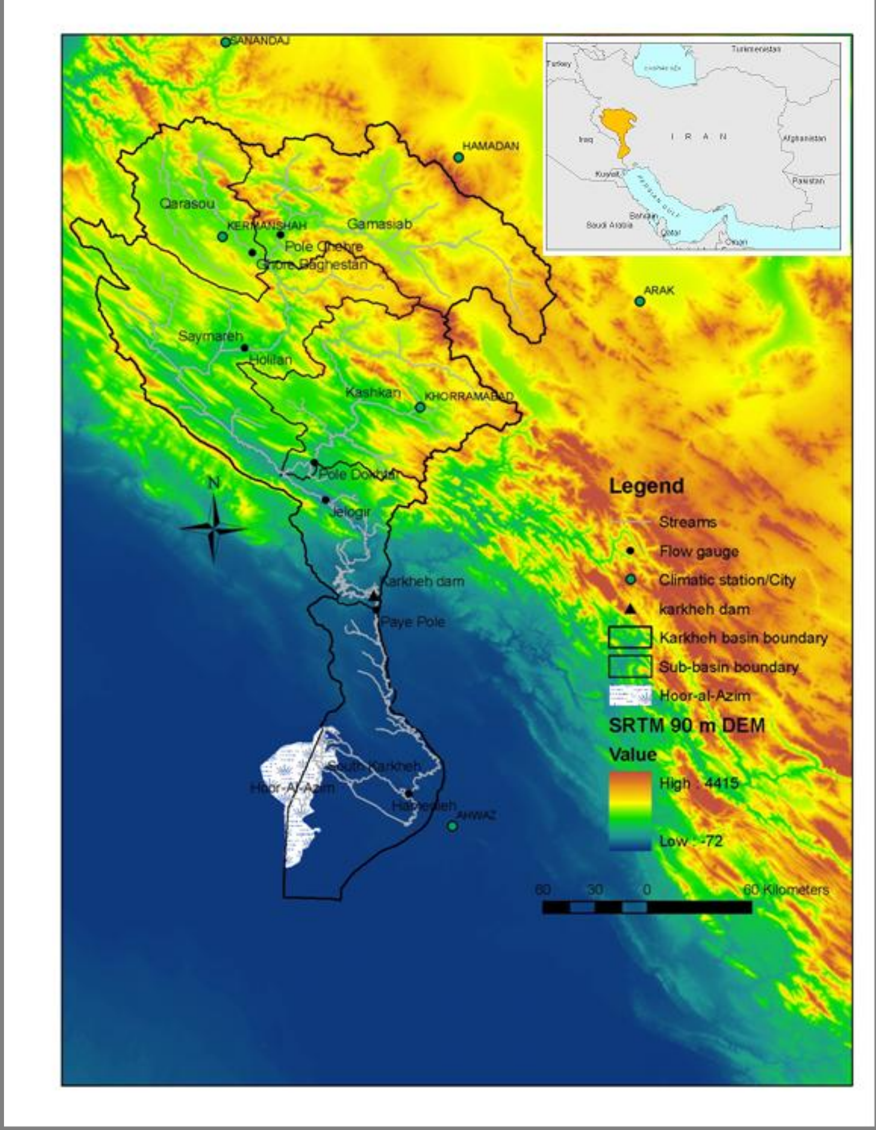
Some basic facts and figures

- **Drainage area: 50,764 km^2**
  - **More than 80 % is mountainous**
  - **Divided into five sub-basins**

- **Mediterranean climate: Cool and wet winter; dry and hot summers**
  - **Precipitation 450 mm/year, range: 150 mm to 750 mm**







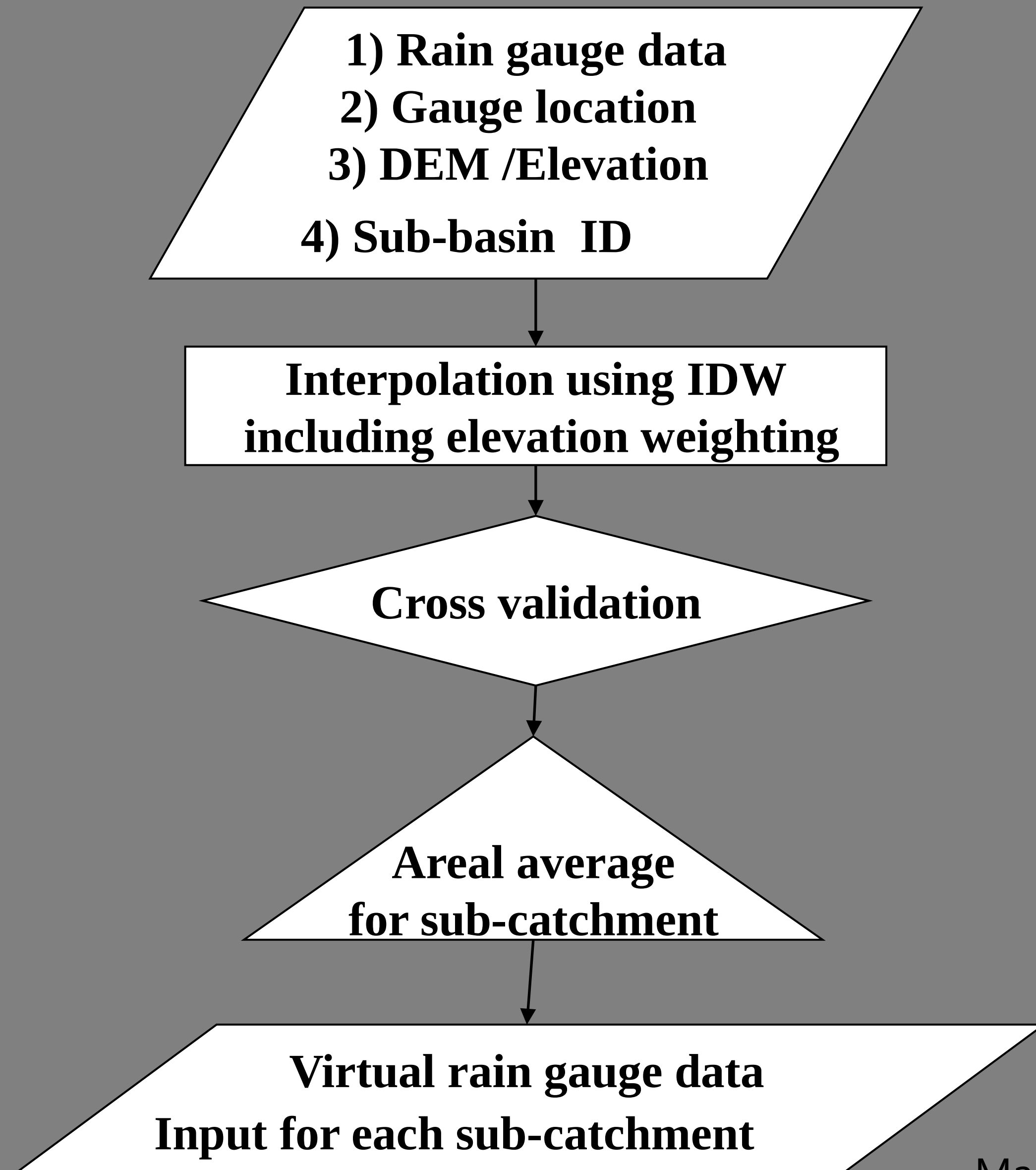
Source: JAMAB 2006

Improving precipitation input in rainfall-runoff modeling using SWAT

- The current way of climatic data input in SWAT is rather simple
  - ⇒ One station nearest to the centroid of a catchment
    - ❖ Gauge nearest to the centroid may not be the best representative
    - ❖ This can undermine the full use of available data (e.g. if two stations in a sub-catchment, only one will be used)

- Quality of the climatic data input will has serious implications for the model parameterization and quality of (spatial and temporal) the results

Preparation of areal precipitation input



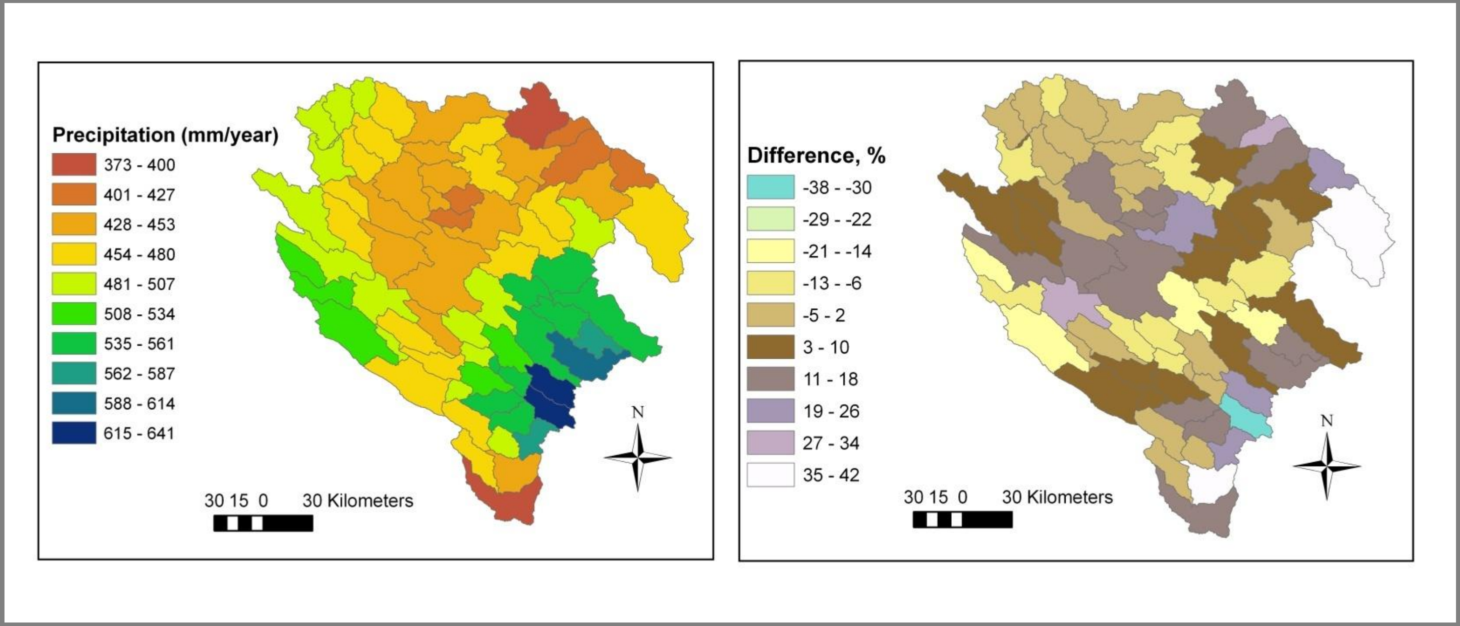
Masih et al., JAWRA; in review

Comparison of the input precipitation:

Case II (areal precipitation) vs. Case I (station data): Spatial view

Sub-catchment precipitation (Case II)

Precipitation difference (Case II vs. Case 1)



High spatial variability, mainly influenced by topography (left)

The precipitation difference in Case II compared to Case I ranged from -40 to 40 % (right)

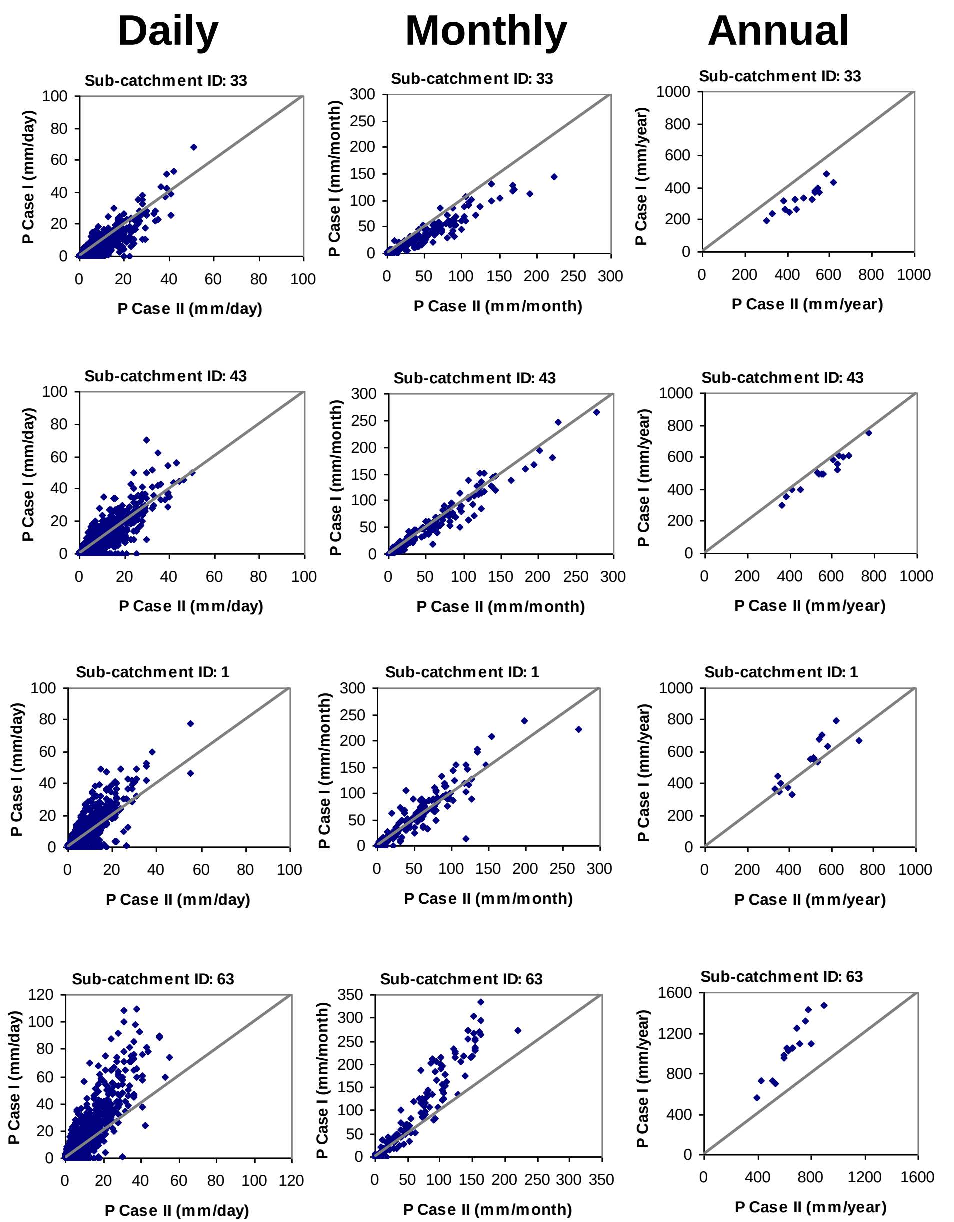
Comparison Case II vs. Case I: Temporal view

Divergent variations by sub-catchment, illustrated by four selected cases.

Precipitation dynamics in Case II could be different in many respects.

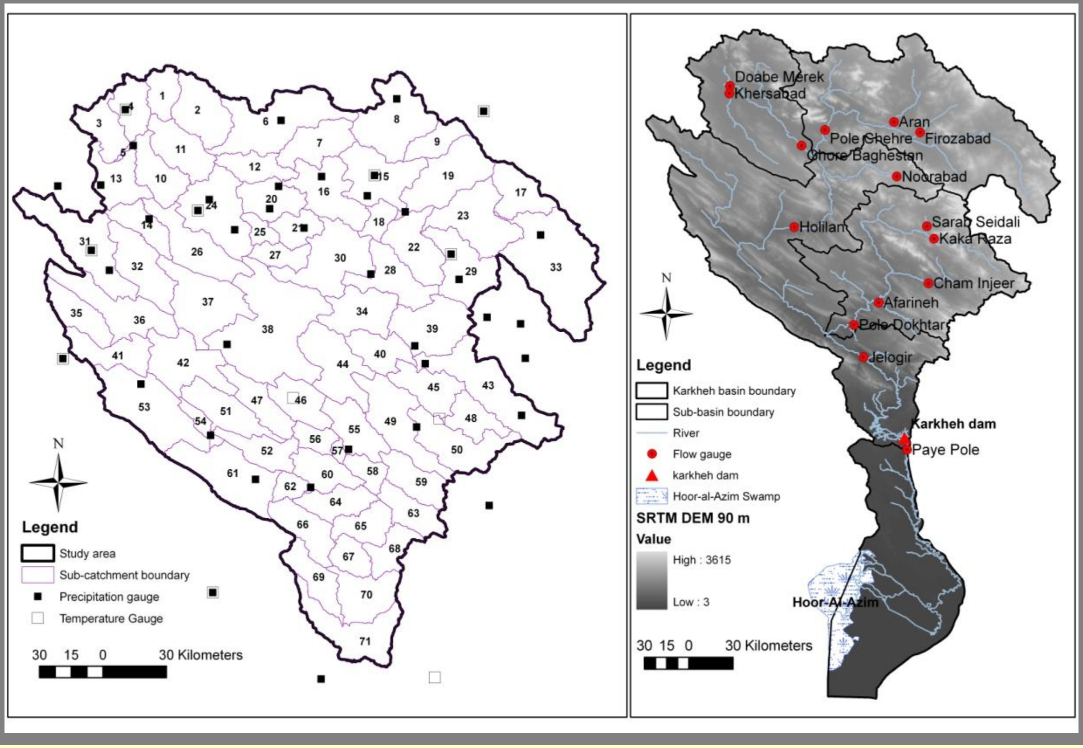
Daily values can be higher/lower. They also show clear pattern in extreme values:

1) lower P events can be totally missed out be a single rain gauge;
2) extremes in Case II are comparatively small in most cases, though could be other way around for some sub-catchments and P events.



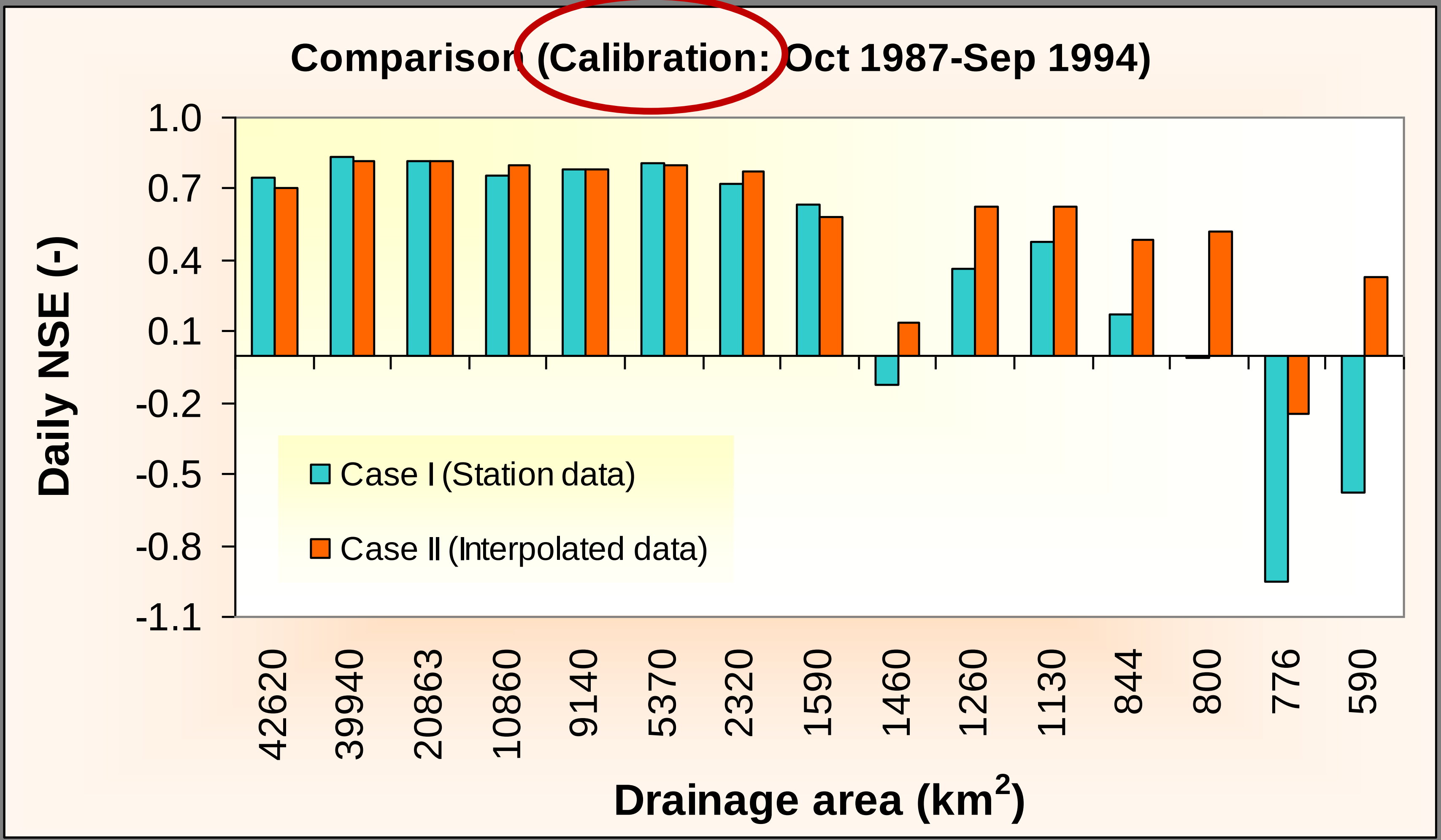
Masih et al., JAWRA; in review

SWAT calibration and performance evaluation



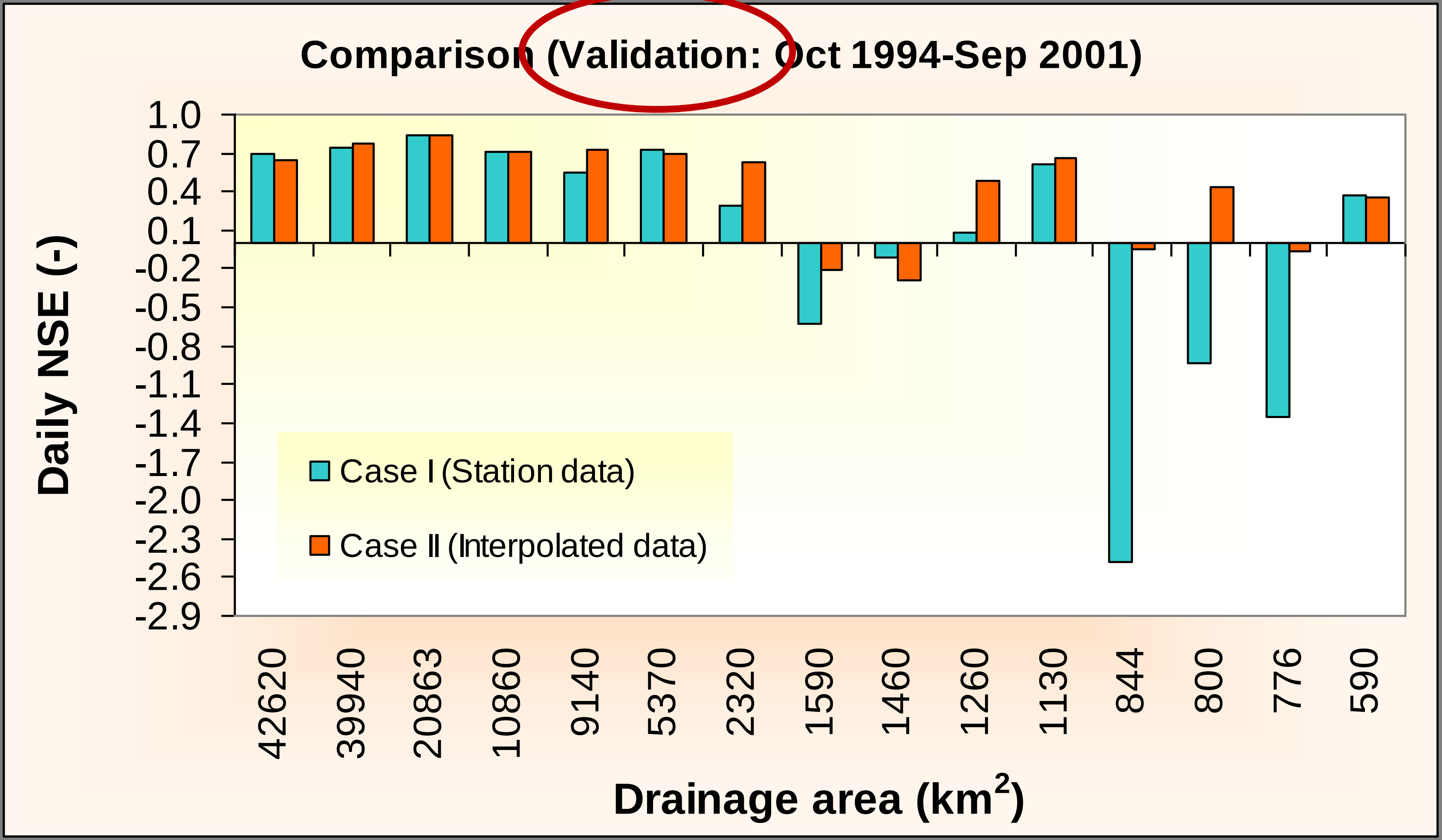
- **Rigorous calibration approach using both manual and automatic procedure (SUFI-2, Abbaspour et al., 2007)**
- **Daily climatic data of 1987-2001 (Precipitation: 41 stations; Temperature: 11 stations)**
- **Performance evaluation: NSE, R^2 and annual volume balance**
  - **15 stream flow gauges across the Karkheh River System**
  - **Temporally at daily, monthly and annual time scales, over period of 1987-2001 (Calibration: Oct 1987-Sep1994; Validation: Oct 1994-Sep 2001)**

Comparison of stream flow simulations under Case I & II



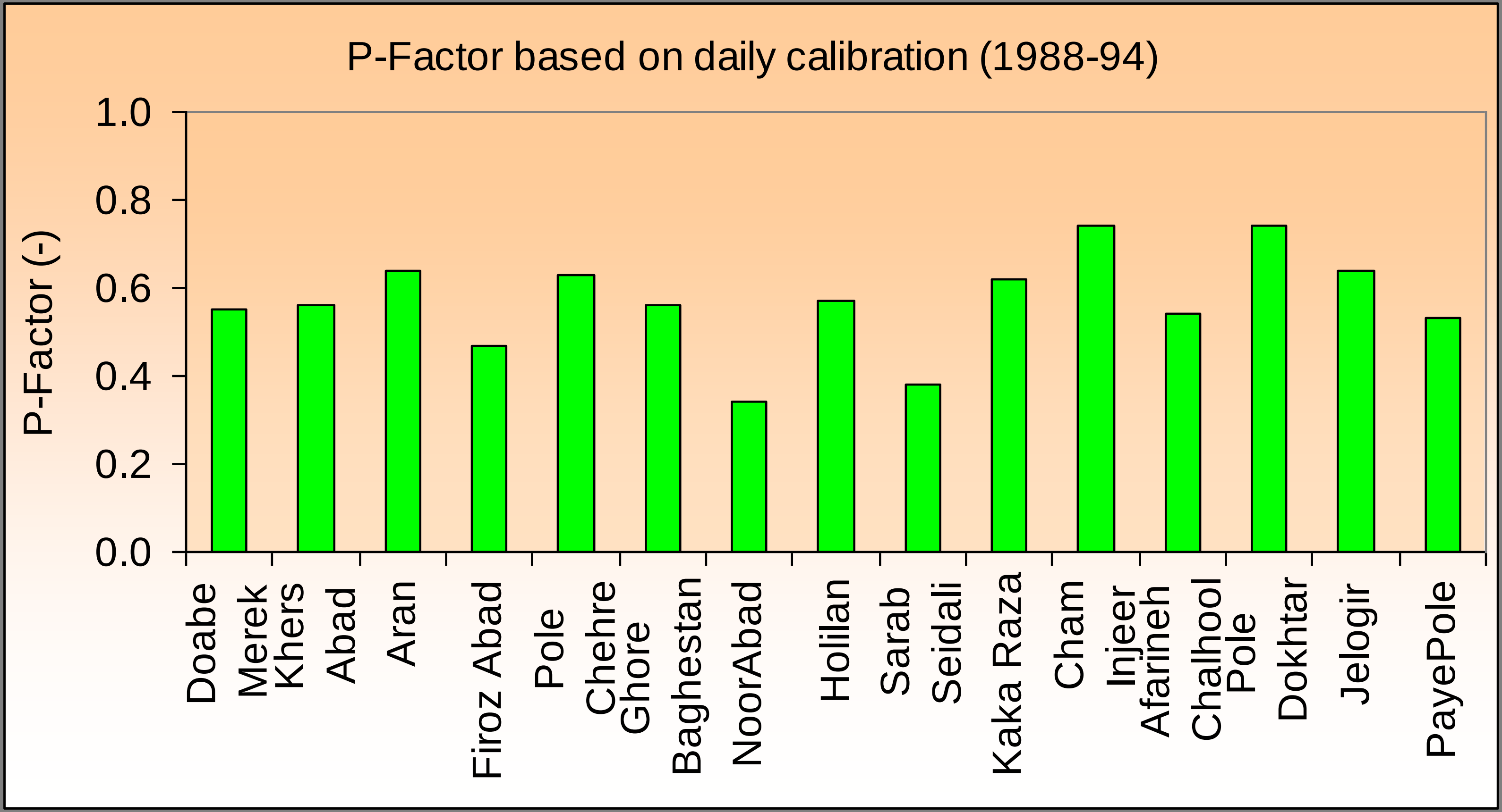
Masih et al., JAWRA; in review

Comparison of streamflow simulations under Case I & II



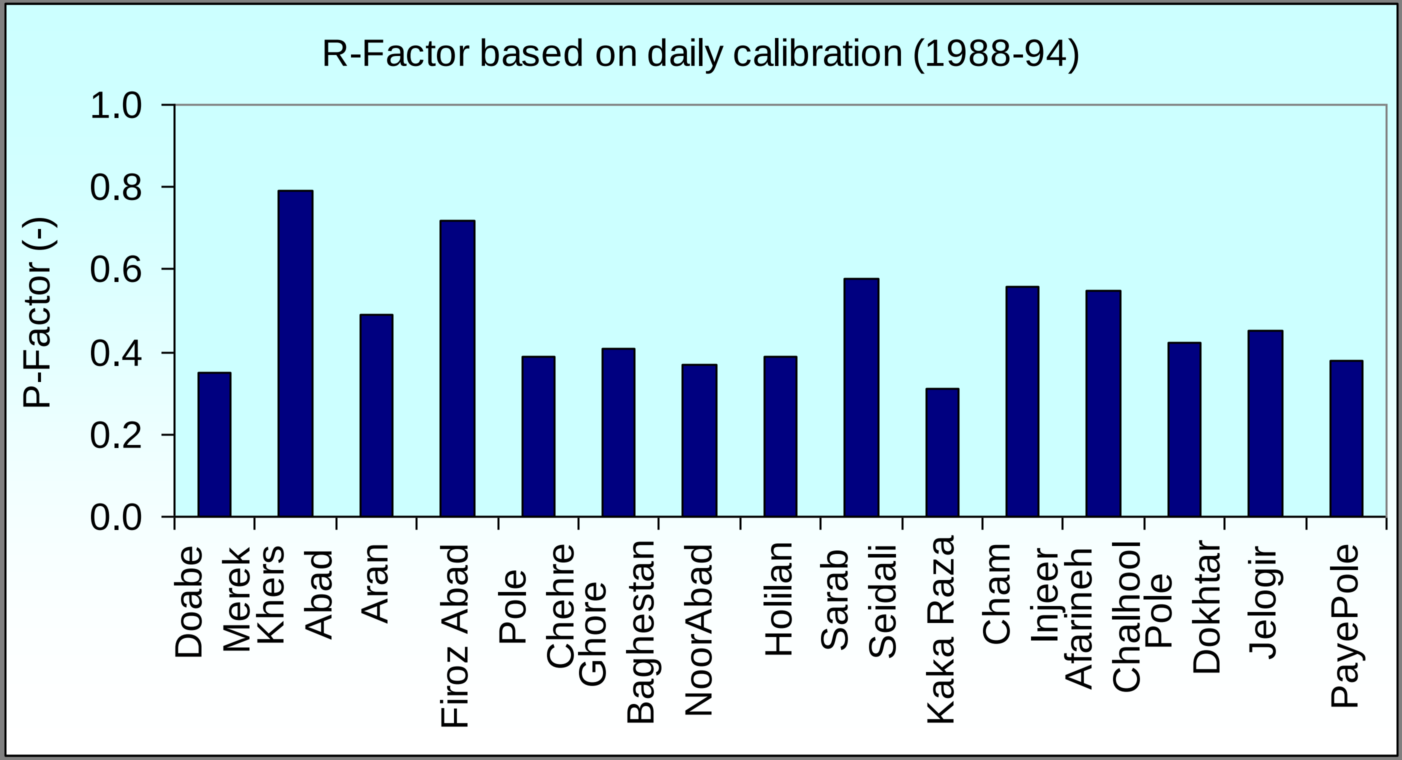
Masih et al., JAWRA; in review

Uncertainty analysis using SWAT-CUP: Summary of results



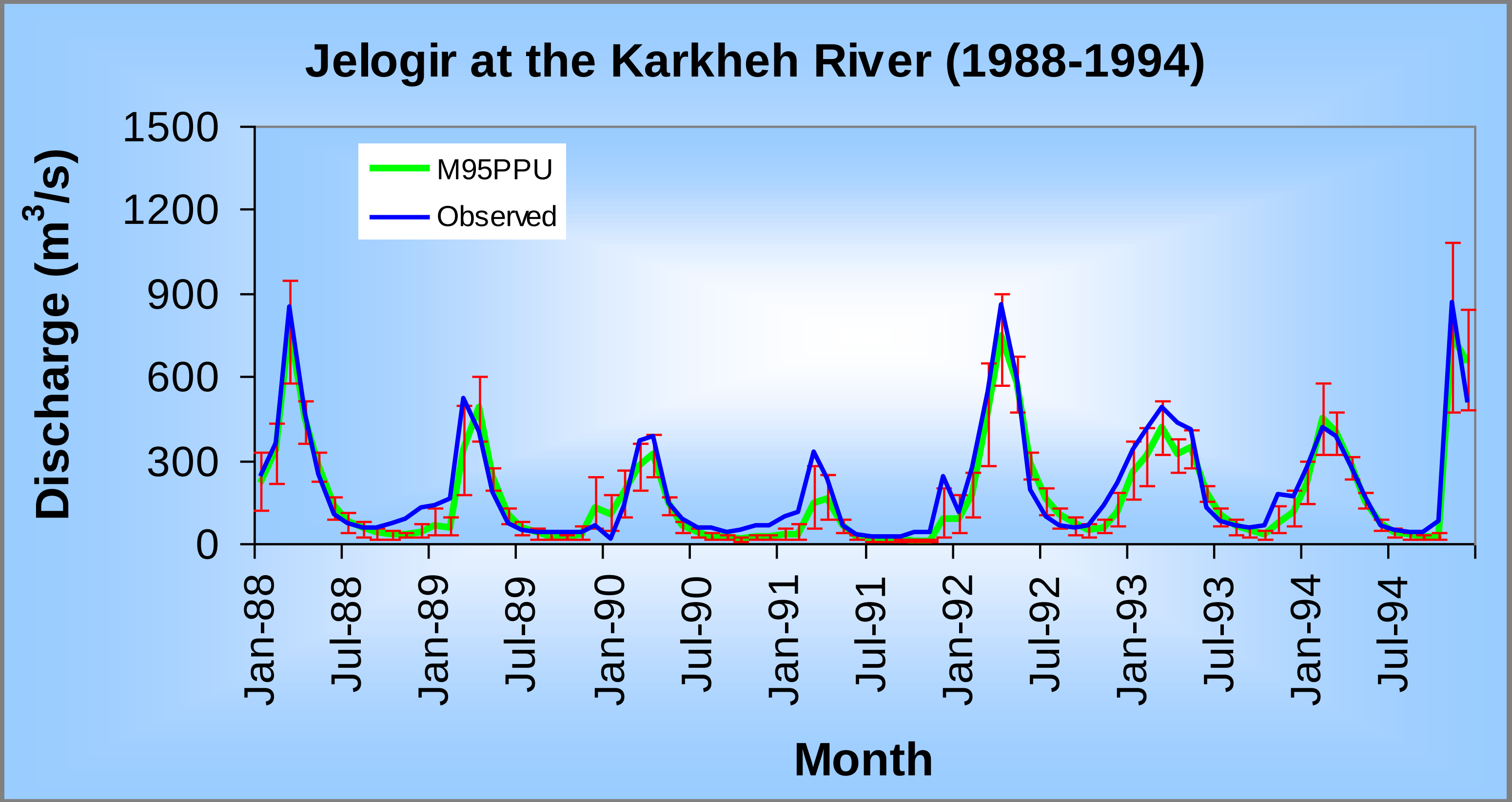
P-Factor indicates the percentage of observed data bracketed by 95PPU band. The achieved values are in reasonably good range (e.g. >0.5 in most cases)

Uncertainty analysis using SWAT-CUP: Summary of results



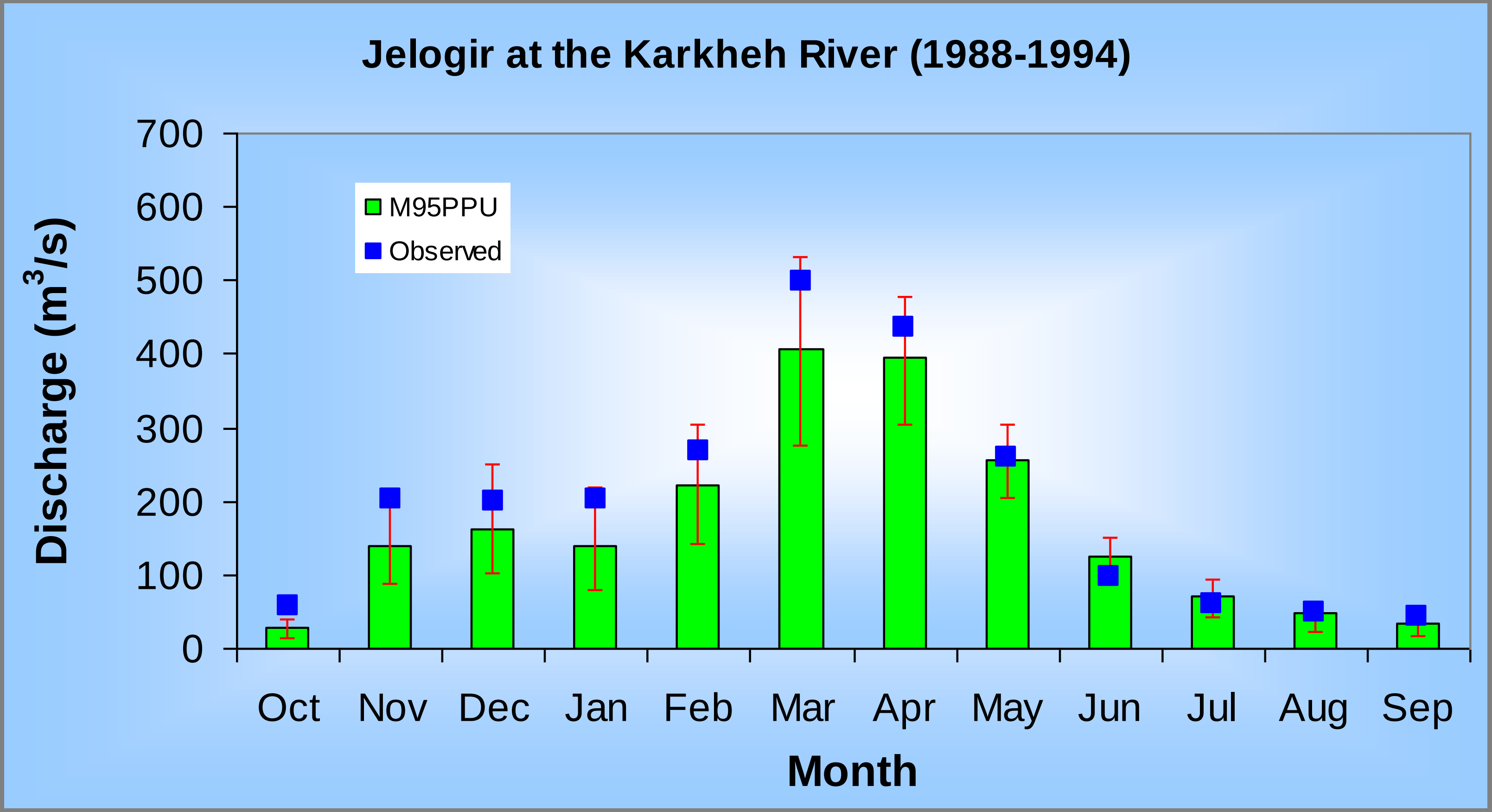
R-Factor indicates the width of the 95PPU band. The achieved values are in reasonably good range (<0.5 in most cases)

Uncertainty analysis using SWAT-CUP: Example results



Most of the observed data fall well within 95PPU band.

Uncertainty analysis using SWAT-CUP: Example results



Most of the observed data fall well within 95PPU band.

Main findings from this case study

- Areal precipitation, based on interpolation of the available station data, improved SWAT model
- Results were strongly influenced by the spatial extent and the station density/spatial distribution of the rain gauges
  - ⇒ Smaller catchments (600-1600 km^2) showed noteworthy improvements
  - ⇒ Larger catchments (>5000 km^2) showed comparable performance
- Uncertainty analysis applying SUFI-2 algorithm was used (Abbaspour et al., 2007)
- Next steps:
  - ⇒ Testing of other (semi-)distributed models
  - ⇒ Use of other input data, e.g. interpolation methods, radar data and satellite observations
  - ⇒ More attention to model parameterization and uncertainty analysis
  - ⇒ Evaluating the downstream impacts of increasing water consumption in the upstream rain-fed area

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Background

Synthetic DNA in multi-tracing hydrological processes

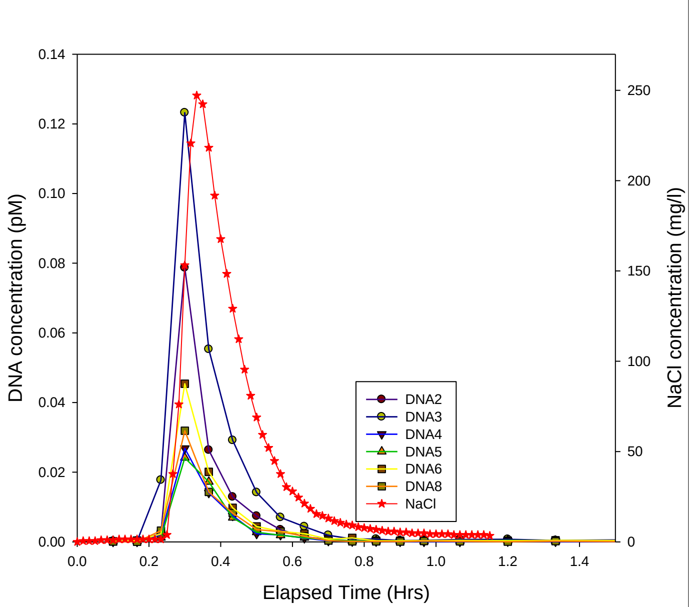
- DNA is a nucleic acid → contains genetic instructions
- DNA has got unique inherent coding abilities
- Multiple DNA can be designed and produced in the laboratory
- Each DNA can be determined specifically in solution using quantitative polymerase chain reaction (qPCR)
- First experiments in groundwater studies (Sabir et al., 1999) – were only qualitative and showed how DNA can be used as a marker
- Two case studies were carried out in surface water and laboratory column experiment between May and July 2010

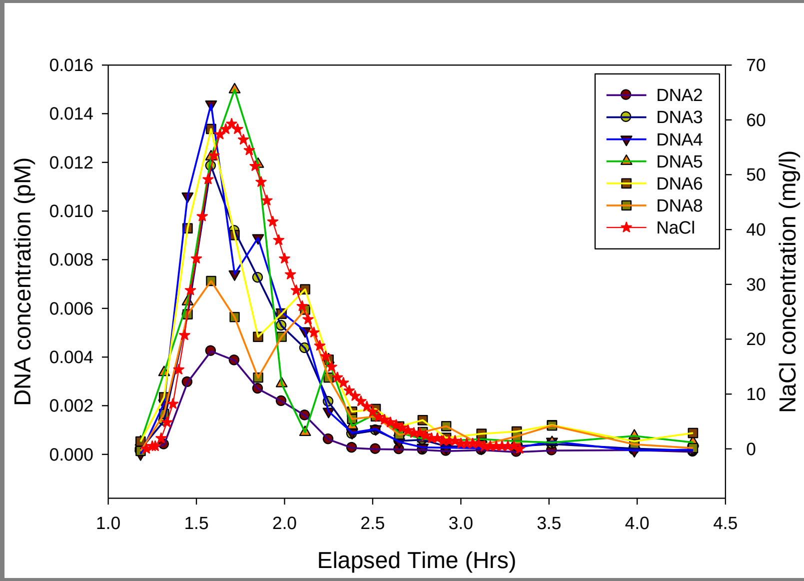
Results – Surface water

1) Merkske stream, The Netherlands

600 m downstream

100 m downstream





- Discharge of 50 l/s
- 6 kg of NaCl injected
- 6 DNA (each 1ml of 1.67 μ M) injected
- All DNA traced downstream
- Similar BTC as that of NaCl

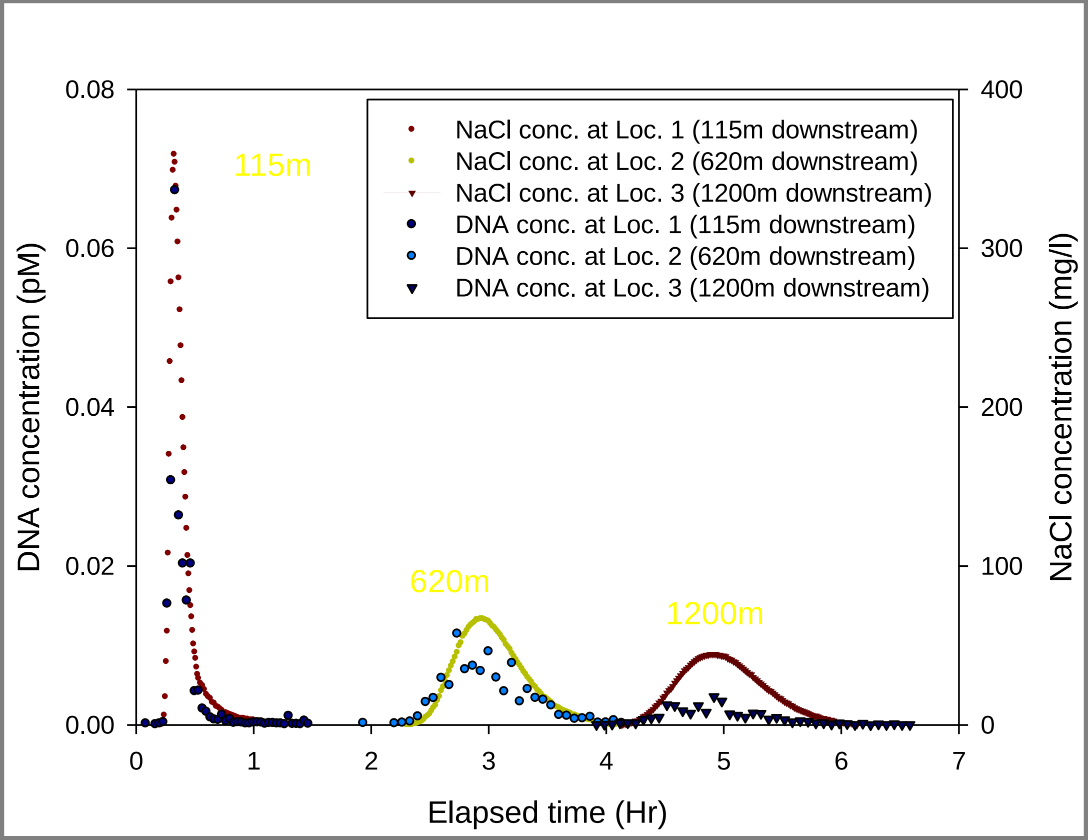
PERCENTAGE RECOVERY AT LOCATION 2 – 600m					
DNA2	DNA3	DNA4	DNA5	DNA6	DNA8
25%	64%	73%	82%	85%	59%

Foppen et al., in prep.

Results – Surface water

2) Strijsbeekse beek stream, The Netherlands

- Discharge of 40 l/s
- 6 kg of NaCl injected
- 6 DNA (each 1ml of 1.67 μ M)
- All DNA traced downstream
- Similar BTC as that of NaCl

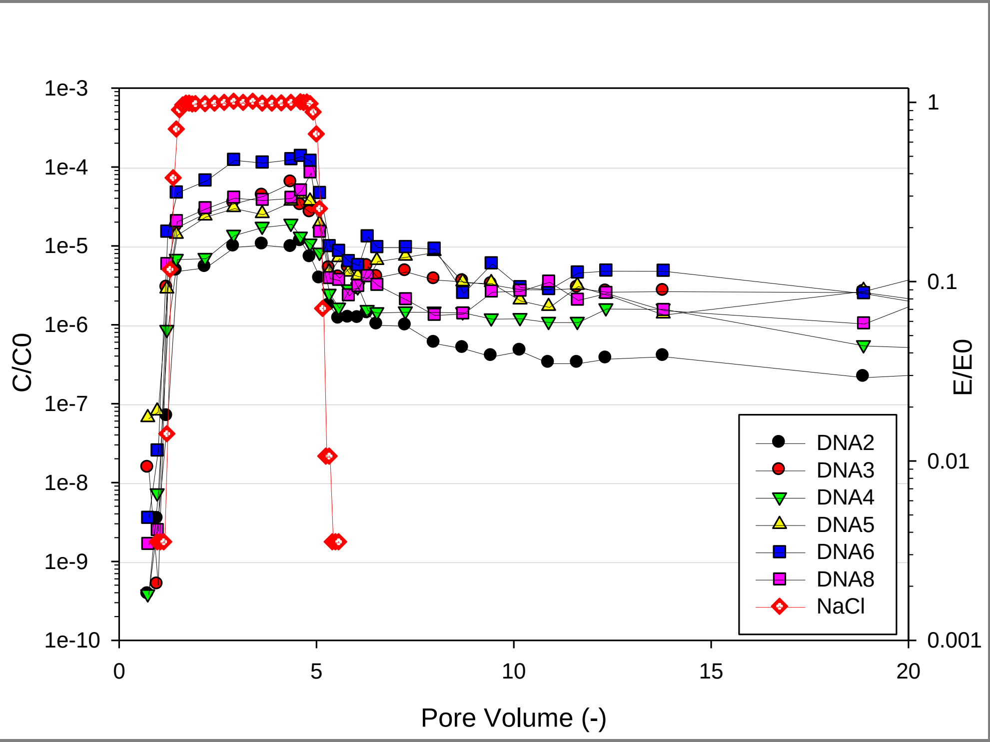


Foppen et al., in prep.

Results – Transport in porous media

BTC of NaCl and DNA , laboratory column – pure quartz sand

- NaCl influent concentration - 0.5 g/l
- DNA influent concentration - 0.01 μ M
- 4 PV of NaCl and DNA injected at pore water velocity of 0.4 cm/min
- Similar BTC as that of NaCl → DNA travels with water
- Kinetic attachment, and not retarded – reduced peak concentration
- Slow detachment – seen in recession limb



Foppen et al., in prep.

Main findings - DNA as Tracer

- DNA travels with water and can be detected at very low concentrations consisting of multiple DNAs

- Very small quantities were required as input

- Suitable as tracers for multi-tracing experiments

- More experiments (lab and field) needed to further understand its transport properties

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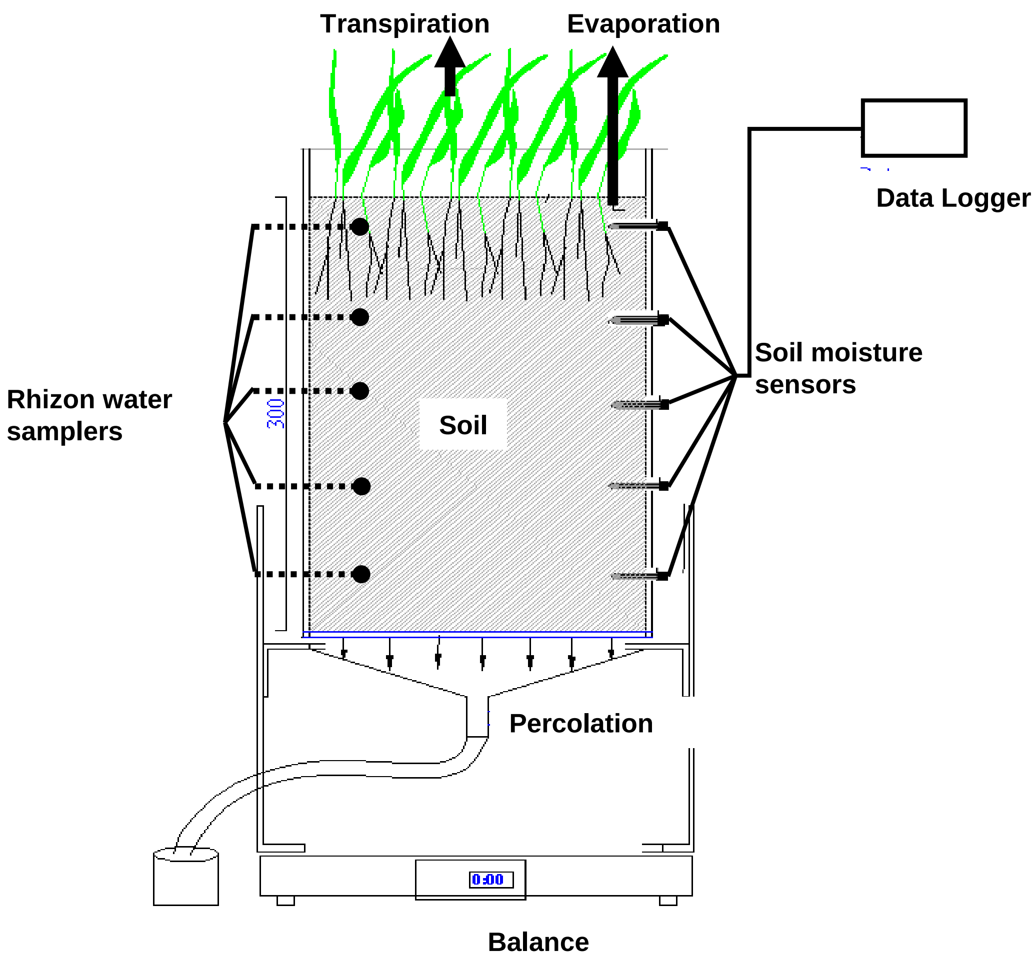
Better Understanding of *Evaporation Fluxes* using Environmental Isotopes



Wenninger et al., 2010; PCE

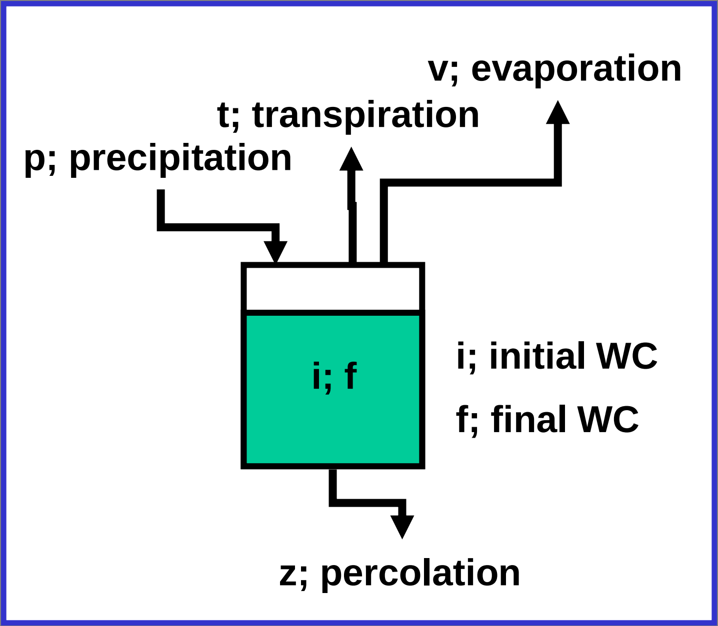
Isotope Mass Balance

- 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

$$m_f - m_i = m_p - m_v - m_t - m_z$$

$$\delta_f x_f + \delta_v x_v + \delta_t x_t + \delta_z x_z = \delta_i x_i + \delta_p x_p$$

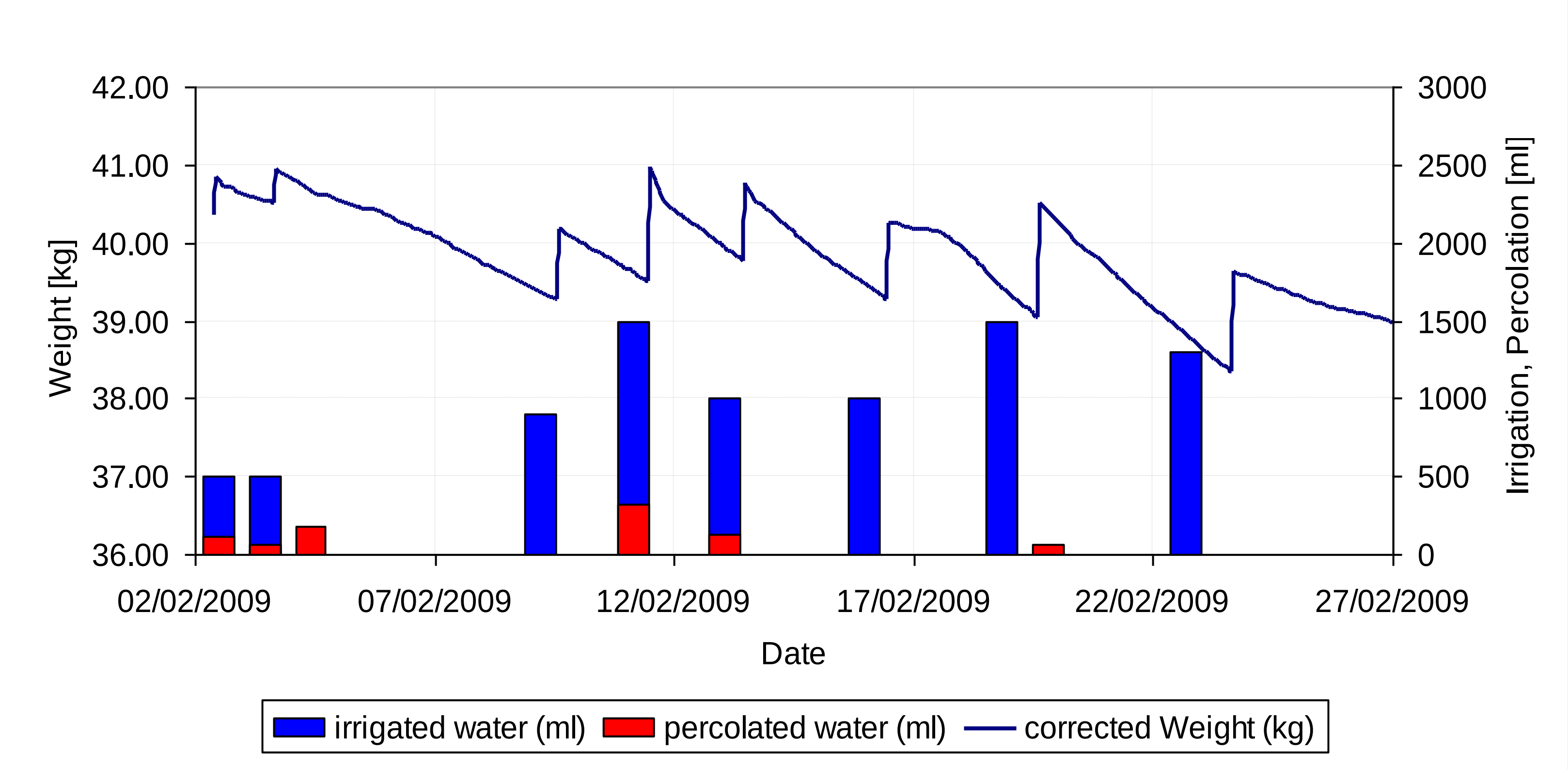
with: $x_j = {m_j}/{m_{Total}}$ $\quad m_{Total} = m_i + m_p$



(e.g. Robertson et al. 2006, J. of Hydrol.)

Results Lysimeter Experiments

Measured water fluxes: Lysimeter A (+vegetation cover)

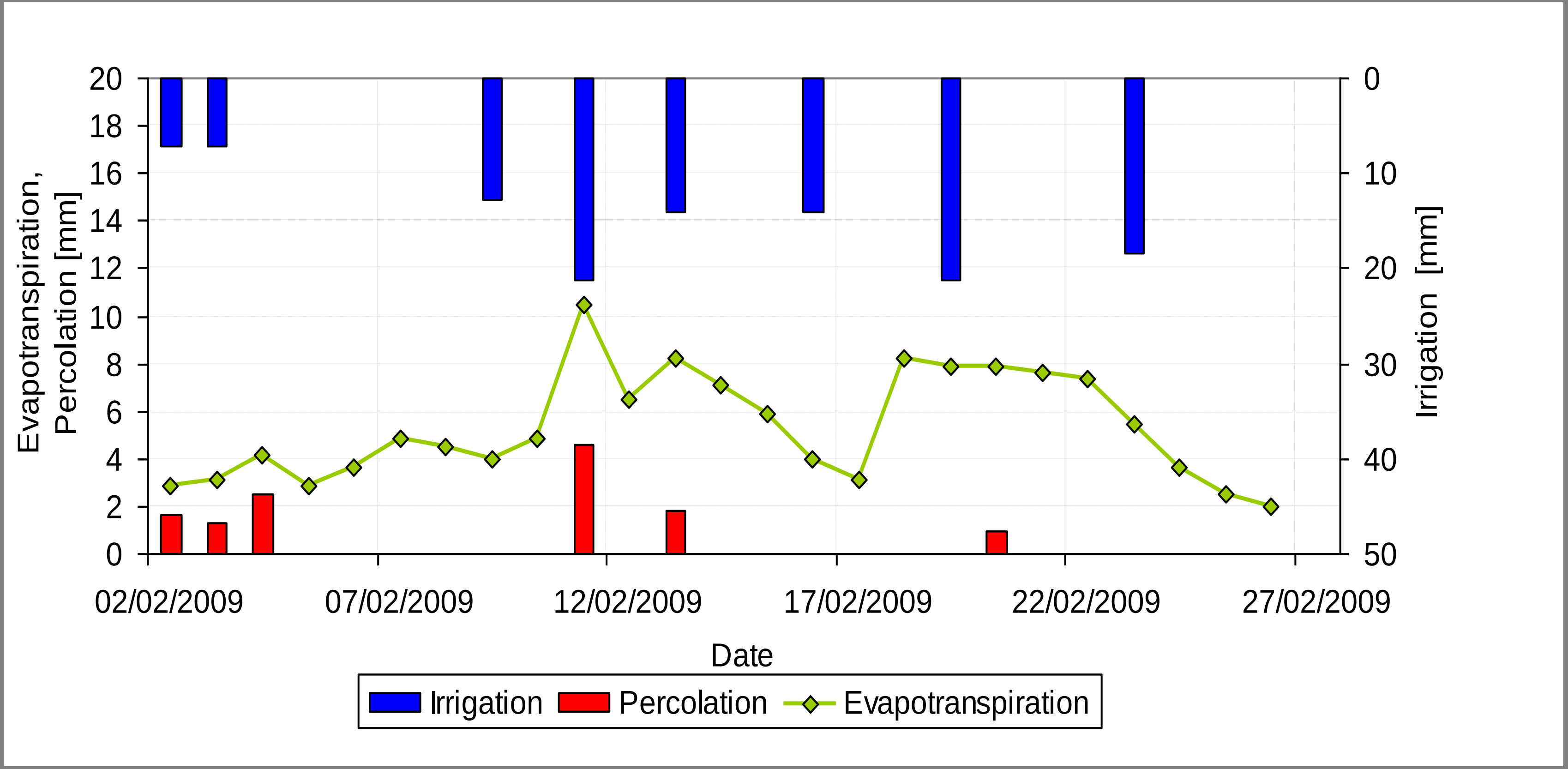


Irrigation (mm)	Percolation (mm)
116	13

Wenninger et al., 2010; PCE

Results Lysimeter Experiments

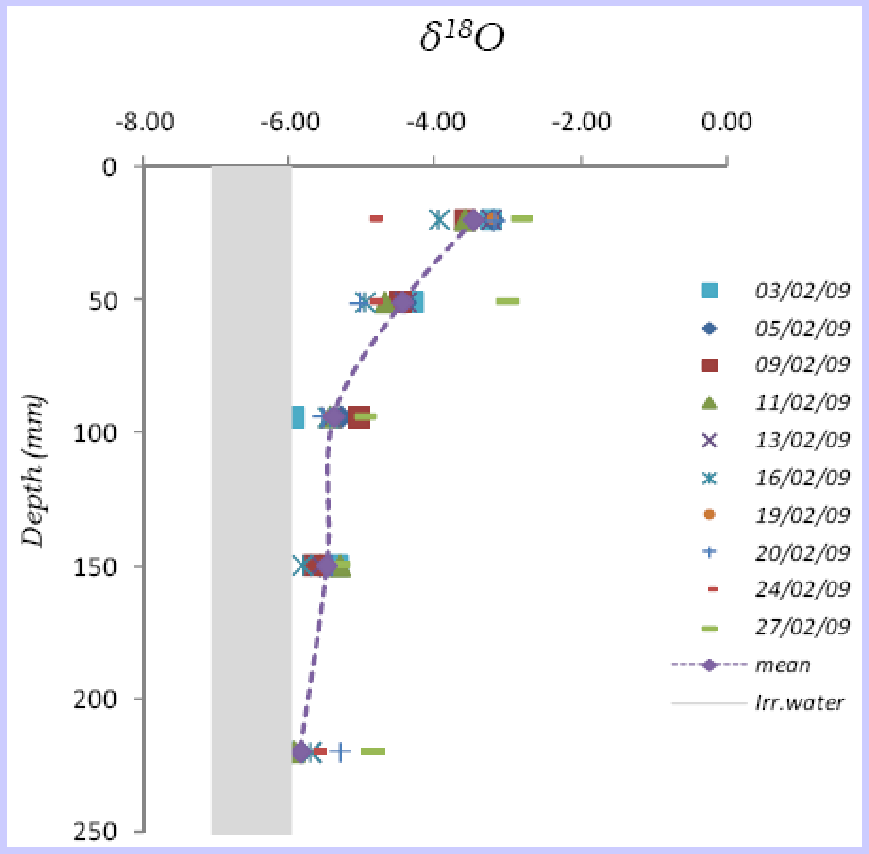
Measured water fluxes: Lysimeter A (+vegetation cover)

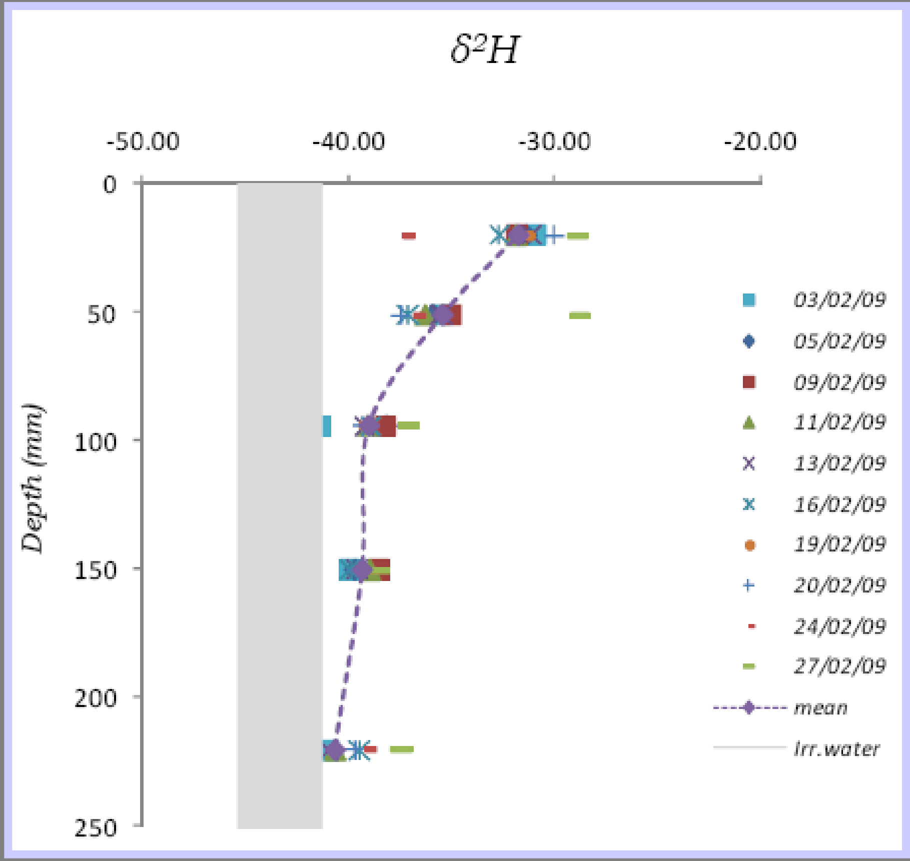


Irrigation (mm)	Percolation (mm)	Evapotranspiration (mm)
116	13	134

Wenninger et al., 2010; PCE

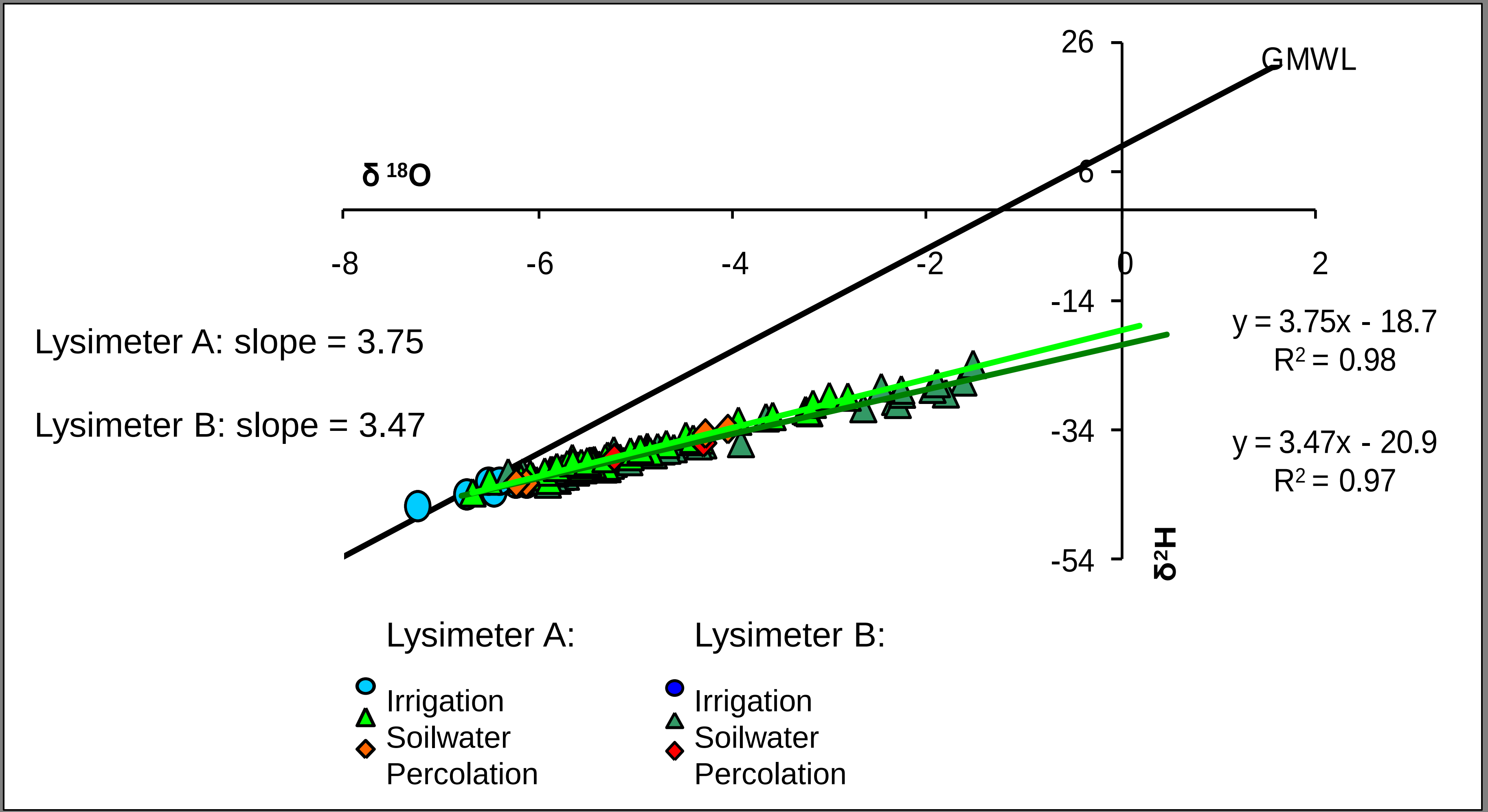
Isotope Depths Profiles and Evaporation Line





Wenninger et al., 2010; PCE

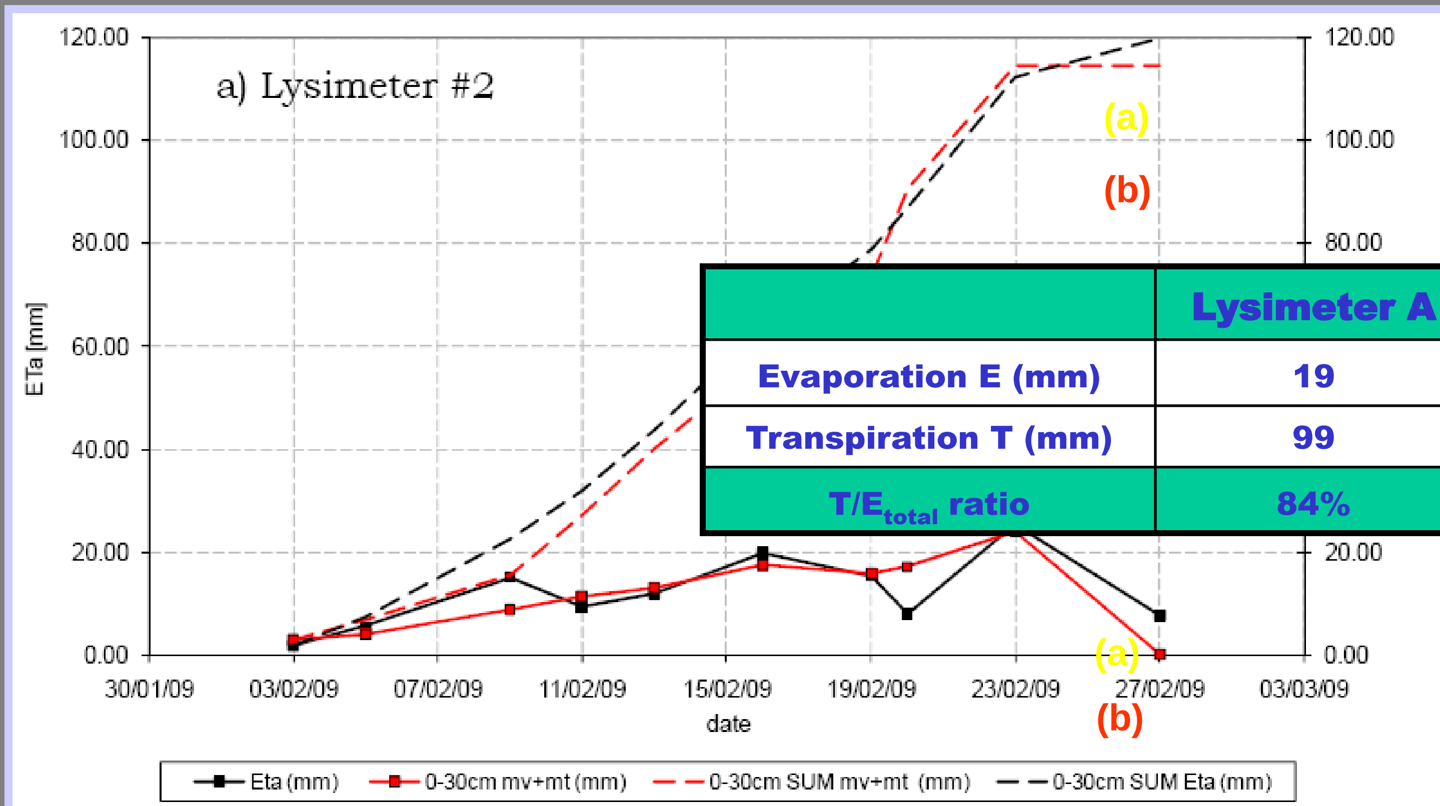
Meteoric Water Line and Evaporation Line



- The irrigation water is in the range of the GMWL
- Soil water samples are isotopically heavier and move along the evaporation lines

Wenninger et al., 2010; PCE

New way to estimate evaporation fluxes?!



	Lysimeter A	Lysimeter B
Evaporation E (mm)	19	77
Transpiration T (mm)	99	0
T/E_{total} ratio	84%	0

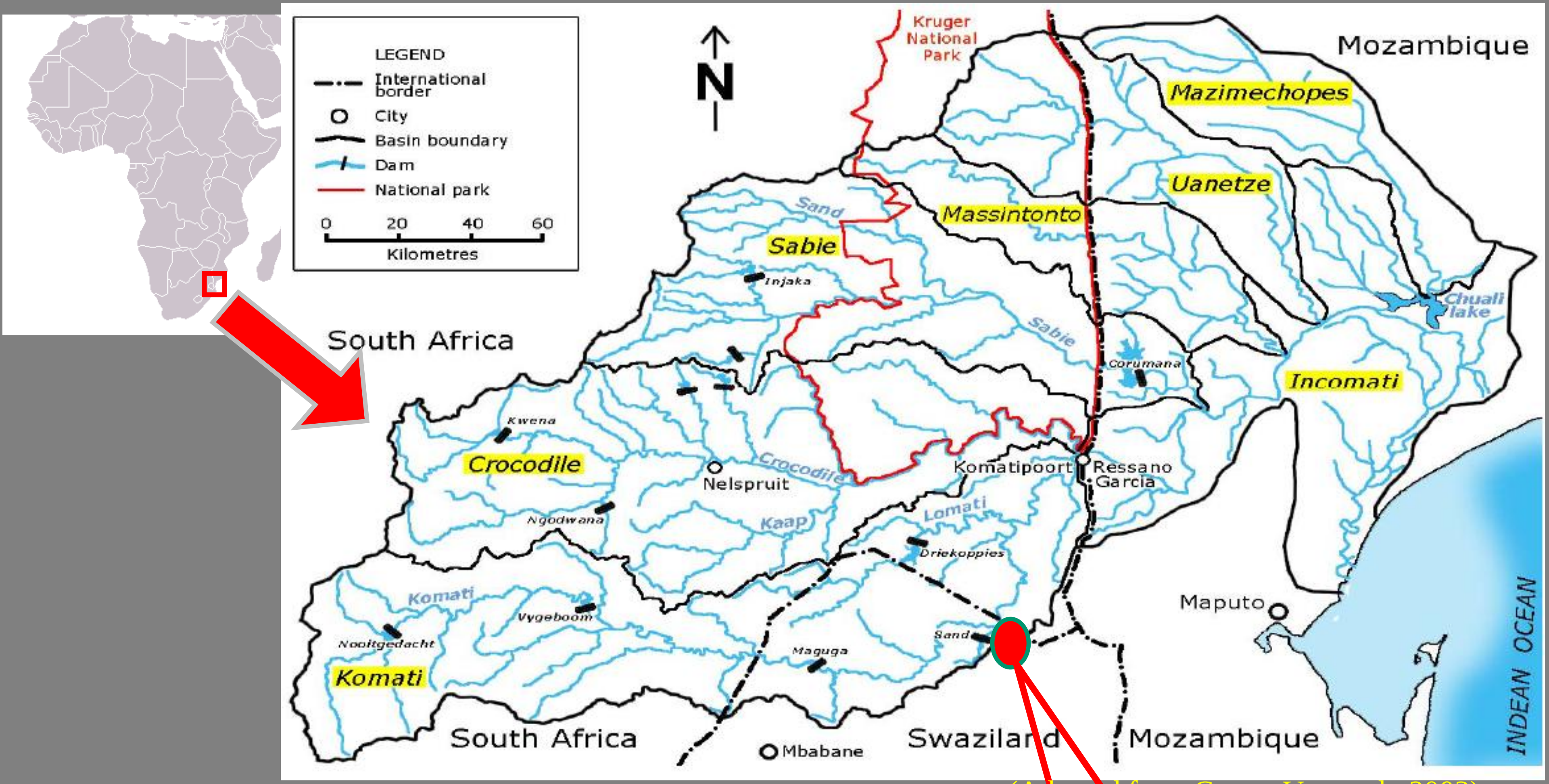
Comparison between different evaporation estimations:

(a) measured using hydrometric data and HYDRUS 1D, and

(b) calculated using isotope mass balance.

First field results from sugar cane in Swaziland

INTRODUCTION – STUDY AREA



(Adapted from Carmo Vaz et al., 2003)

- Area: 46,800 km^2
- Semi-arid climate
  - Rainfall ~ 740 mm/a
  - Epot ~ 1900 mm/a

Water scarcity

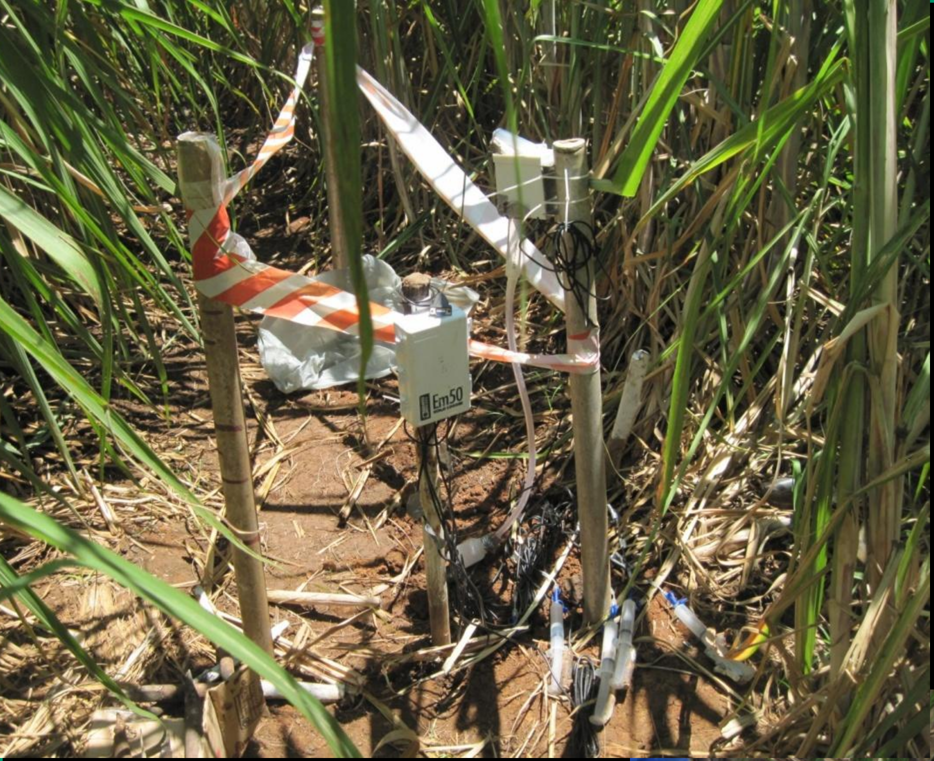
Mhlume Estates

- Irrigated sugar cane

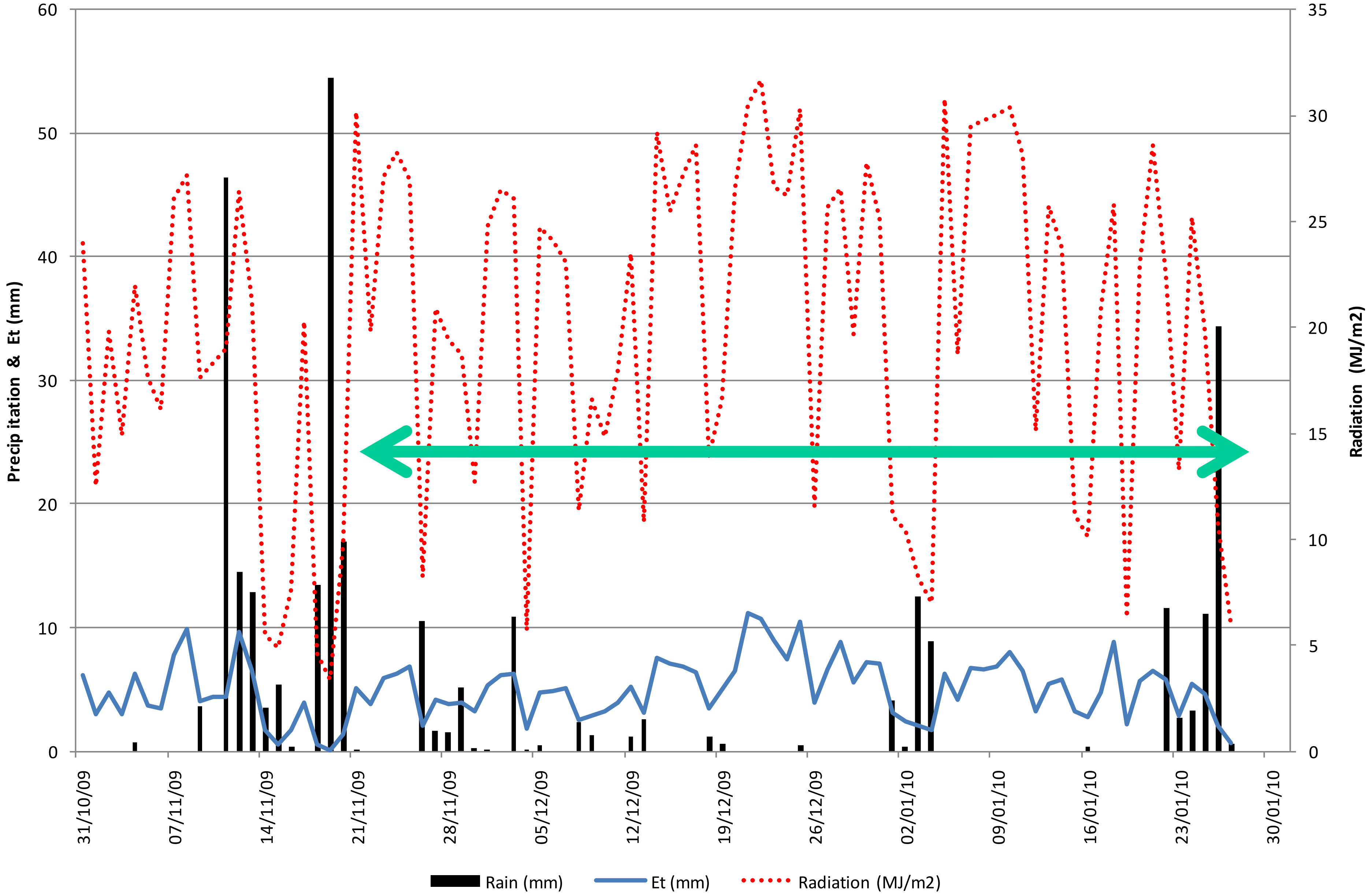

31/10/200


31/10/2009 10:50

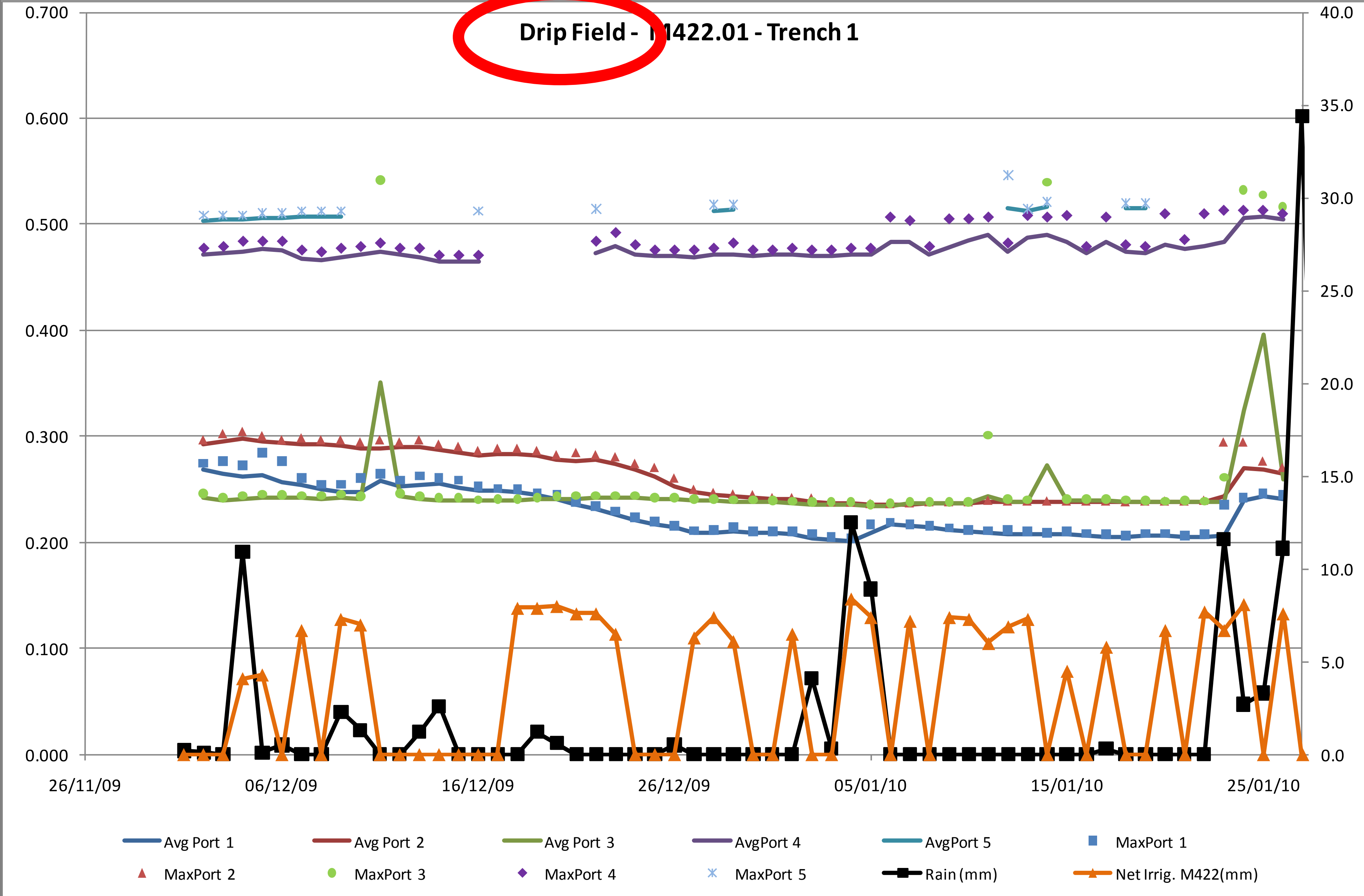

Flow4™
Sap Flow Logger
DYNAMAX INC.


Em50

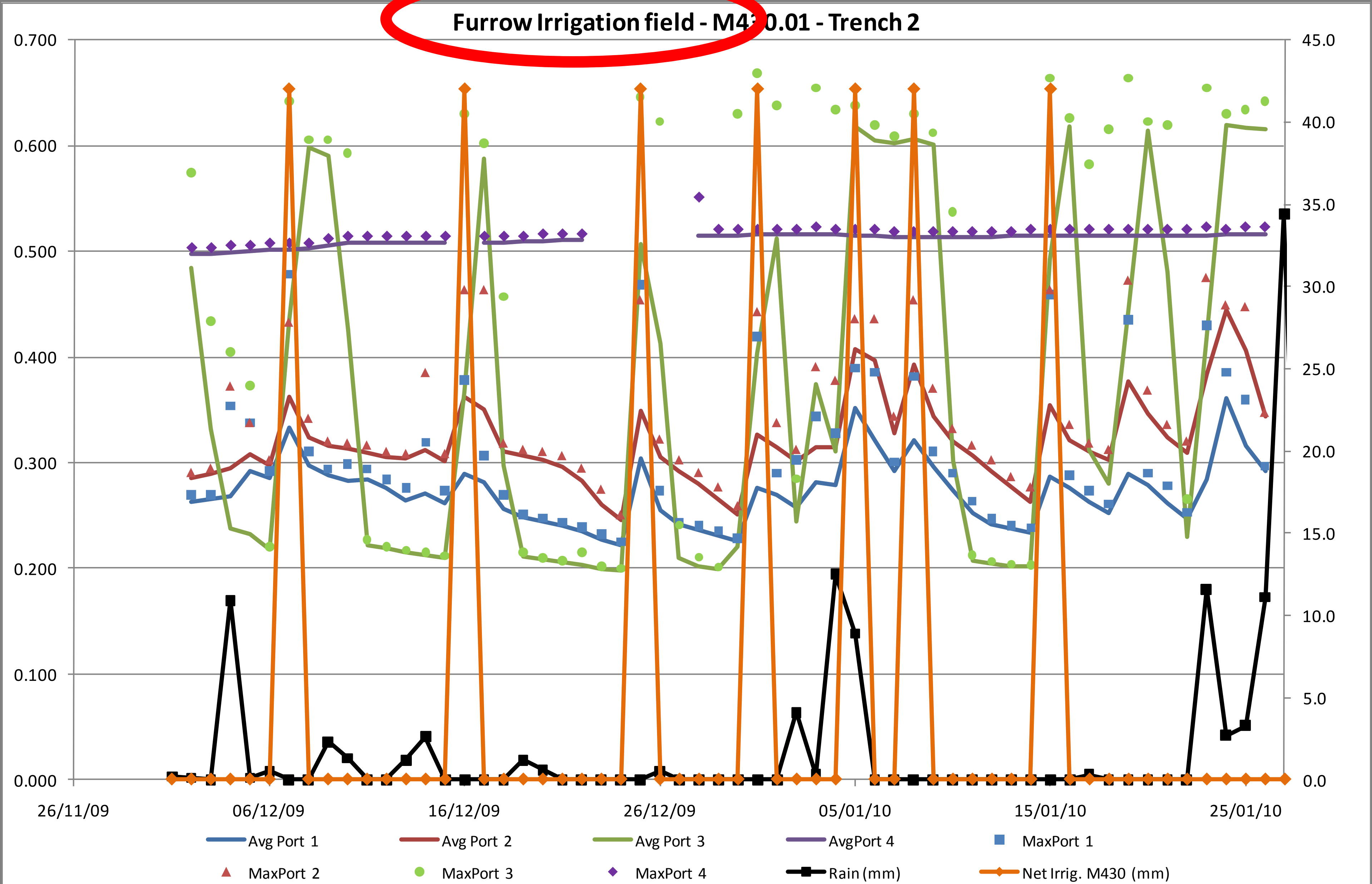
Results - Climate data



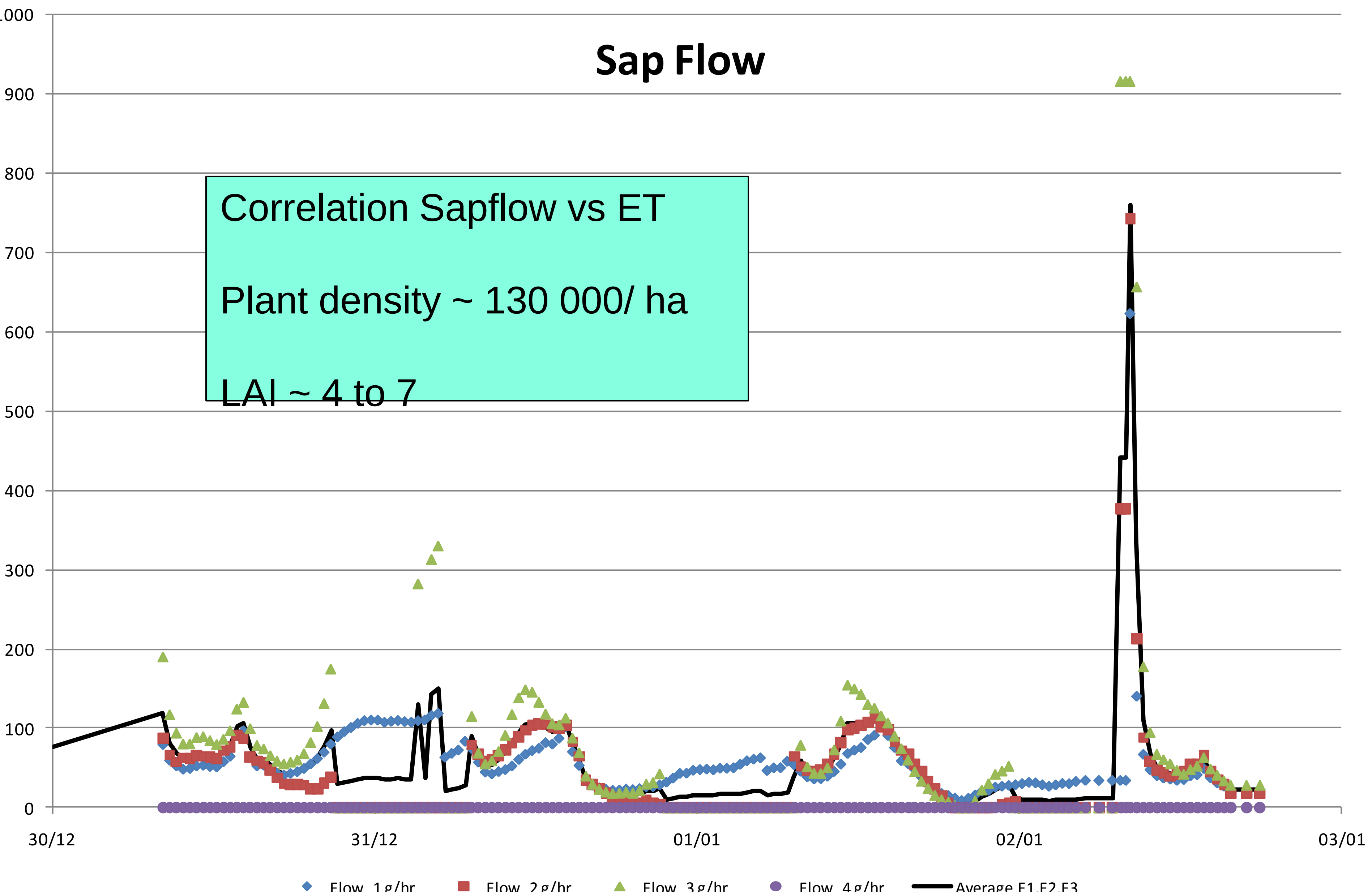
Results - Soil Moisture



Results - Soil Moisture



Results - Sap Flow / Transpiration



Correlation Sapflow vs ET

Plant density ~ 130 000/ ha

LAI ~ 4 to 7

Concluding Remarks

- The world is changing – Hydrology too (‘stationary is dead’)
- Global changes (incl. CC) are impacting the hydrological cycle; i.e. often ‘acceleration of the water cycle’, but not consistent world-wide
- SWAT application in Karkheh basin: Need for new model? Innovate existing ones?
- New experimental methods are needed!
  - DNA offers new possibilities to trace flow pathways
  - Potential of environmental isotopes to measure evaporation fluxes demonstrated through lab experiments
  - First interesting field results from Swaziland – *more to come …*

Progress in science depends on new techniques, new discoveries and new ideas, probably in that order (S. Brenner, 1980)