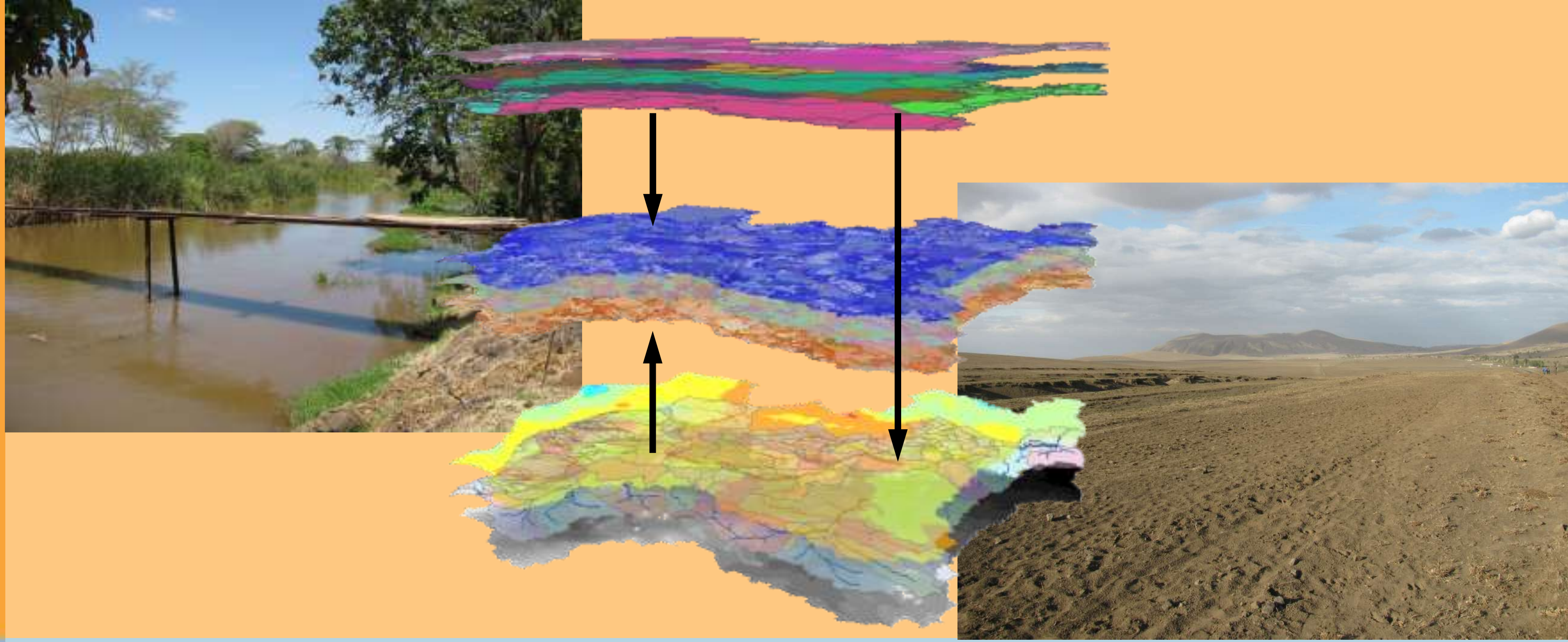

Dr. Benedikt Notter
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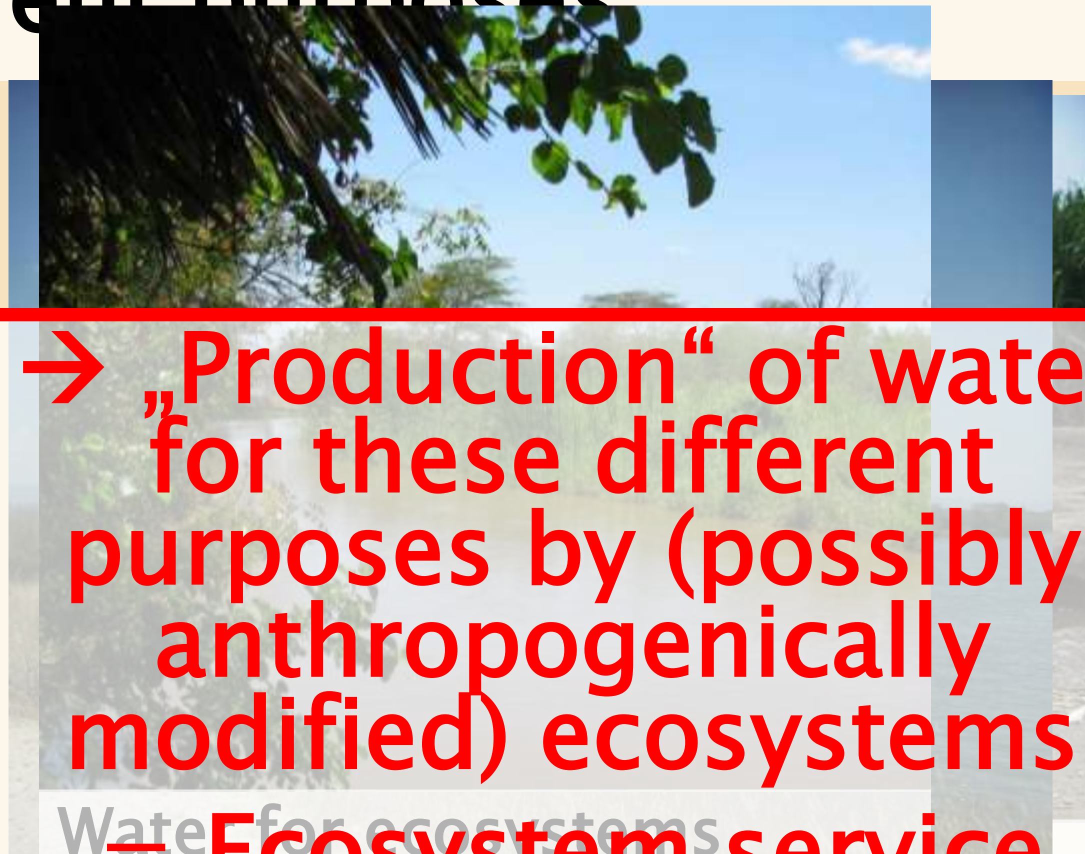
Water-related ecosystem services in the Pangani Basin, East Africa

2011 International SWAT conference
June 15, 2011, Toledo, Spain

Contents

Growing demand for water for different purposes



→ „Production“ of water for these different purposes by (possibly anthropogenically modified) ecosystems

= Ecosystem service

Water for ecosystems

→ Quantity and quality as natural as possible

→ Ethical duty to conserve, livelihoods of current and future generations

Objectives of the study

- At the practical level: To support decisions towards sustainable water management in the Pangani Basin, by quantitatively estimating the availability of water-related ecosystem services in the Basin

- At the conceptual/methodological level: To develop and apply a method to carry out such predictions

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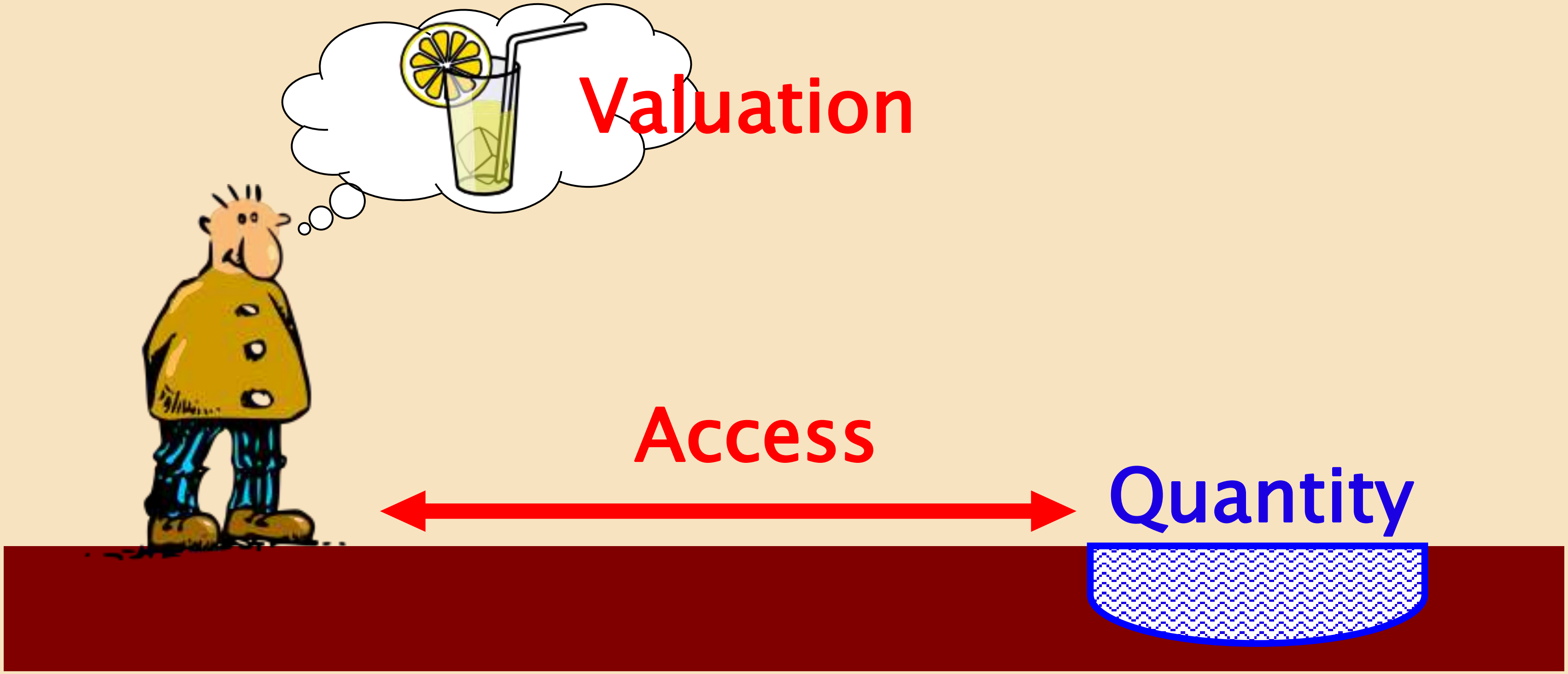
Definition of „ecosystem services“

„Ecosystem services are the **benefits** people **obtain** from ecosystems. These include products (such as food) and actual services (such as waste assimilation).“

(Millennium Ecosystem Assessment 2003)



Implications on research approach

- Explicit consideration of the valuation of ecosystems by stakeholders
- Sufficiently high spatial and temporal resolution to determine access of stakeholders to resources, and to produce outputs at the desired scale
- Use of a process model in order to simulate complex processes and make predictions into the future
- Quantification and minimisation of uncertainty in data and predictions

→ SWAT provides opportunity to incorporate all technical requirements

Ecosystem services, modeled proxies, and stakeholder requirements

Ecosystem service	Modelled proxy	Stakeholder Requirements			
		Quantity	Quality	Location	Timing
Water for drinking/ sanitation	Consumptive water use at 95% reliability	130 lcd in urban areas, 65 lcd in rural areas	WHO Guidelines for drinking water quality	Provided through water supply authority, or nearest source	95% reliability
Water for livestock	Consumptive water use at 95% reliability	50 lcd for cattle, 10 lcd for sheep & goats	Sediment load max. 30 kg/m³	nearest source	95% reliability
Water for irrigation	Consecutive months with [illegible] water stress per year (CMWAW)	Modelled crop demand	Sediment load max. 30 kg/m³	nearest upstream source	75% reliability
Hydropower production	Discharge at HP plant locations	Depending on turbine capacity	Sediment load max. 30 kg/m³	At power plant locations	95% reliability
Environmental flows	Discharge in rivers	Values from literature, Matthey formula	N/a	Perennial surface streams	95% reliability

→ **Main SWAT output variables of interest:**
- **Discharge (FLOW_OUT, .rch)**
- **Consumptive water use (WUS, .rch)**
- **Plant water stress (WSTRS, .hru)**

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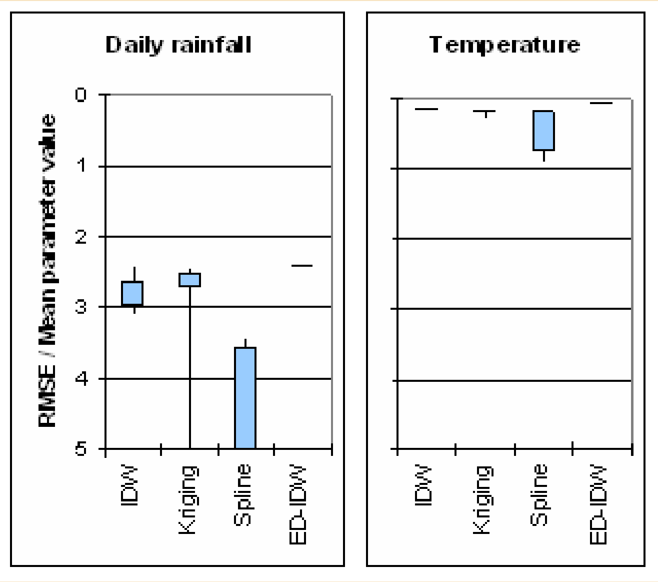
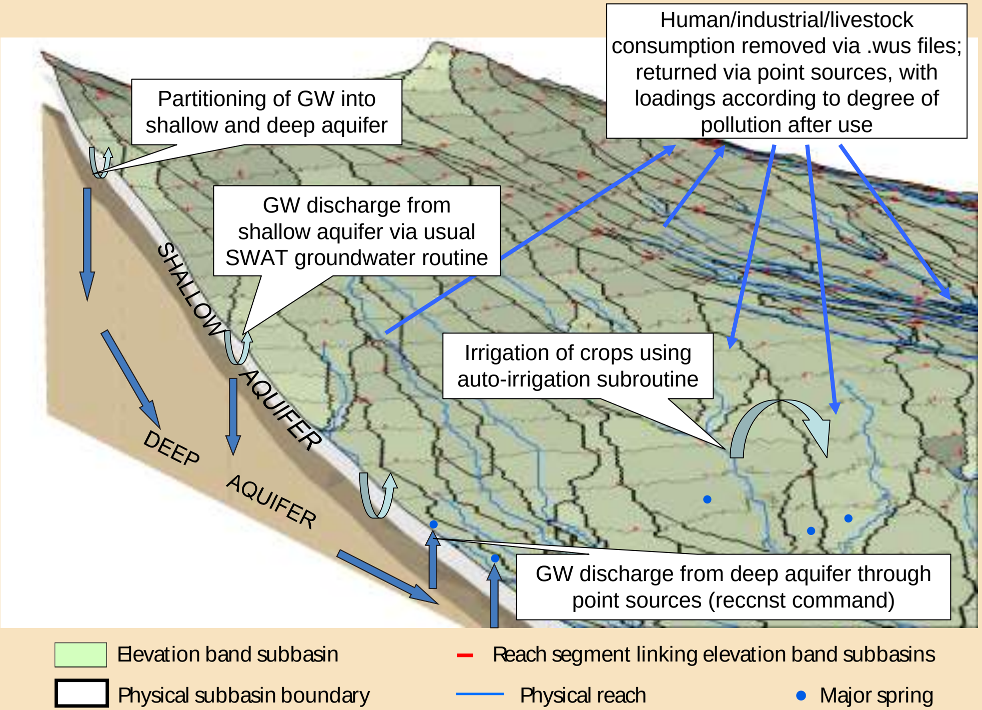
From SWAT2005 to SWAT-P

- Removed limitations on number of spatial units simulated (now >26‘000)
- Introduced correction factors for rainfall, temperature, point source inputs and maximum diversion amounts, in order to assess uncertainty with SUFI-2
- Changed order of removal of water for „consumptive“ use and irrigation → consumptive use is first in SWAT-P; effectively consumed amounts written to .rch output file
- New irrigation efficiency parameter

Input pre-processing

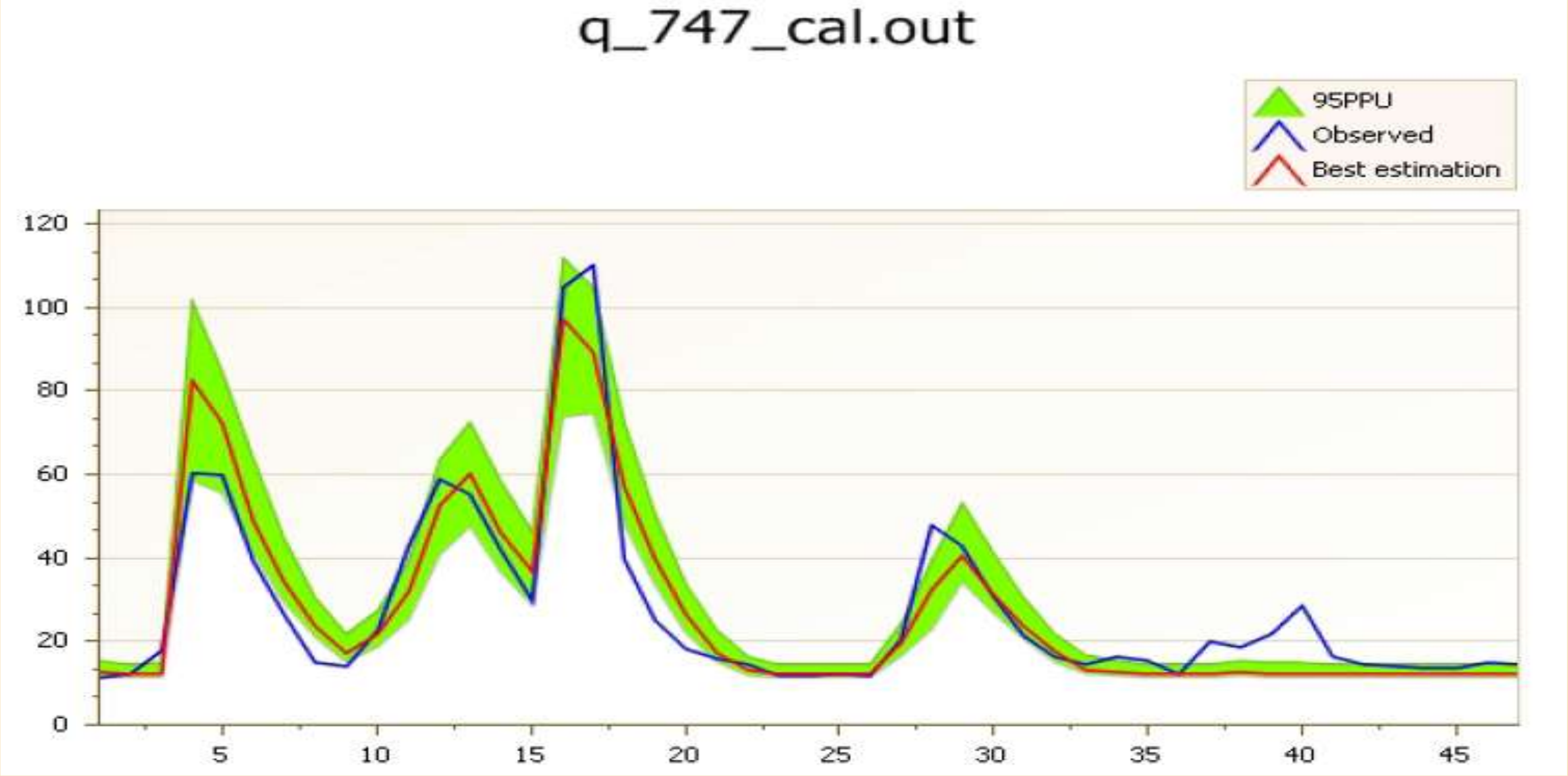
Elevation-dependent interpolation of met. inputs
→ Reduced RMSE in cross-validation by 10% for rainfall, 40% for temperature





Customized subbasin delineation based on topography and political units
→ 3800 Subbasins and ~25'000 HRUS

Uncertainty analysis with SUFI-2



- aims to maximize the „p-factor" (=percentage of data bracketed by 95% uncertainty interval) while minimizing the „r-factor" (=width of the interval)

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- →in this study: additional SWAT-P parameters describing uncertainty in measured inputs (rainfall, temperature, point sources, maximum diversions) calibrated with SUFI-2
- →initial sensitivity analysis yielded 16 parameters sensitive to Q to be calibrated:

Parameter name	Description
v__PCOR.sub	Correction factor for precipitation (introduced in SWAT-P)
v__TCOR.sub	Correction factor for temperature (introduced in SWAT-P)
v__ALPHA_BF.gw	Base flow alpha factor [days]
v__GW_DELAY.gw	Groundwater delay time [days]
v__GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur [mm]
v__CH_K2.rte	Effective hydraulic conductivity in the main channel [mm/h]
v__RCHRG_DP.gw	Deep aquifer percolation fraction
v__PSCOR.sub	Correction factor for point source inflow (introduced in SWAT-P)
v__DIVCOR.hru	Correction factor for maximum diversion for irrigation (introduced in SWAT-P)
r__CH_N2.rte	Manning's n value for main channel
r__CN2.hru	SCD runoff curve number for moisture condition II
r__SOL_K.sol	Soil conductivity [mm/h]
r__SOL_AWC.sol	Soil available water storage capacity [mm H_2O / mm soil]
r__SOL_BD.sol	Soil bulk density [g/cm^3]
r__ESCO.hru	Soil evaporation compensation factor
r__EPCO.hru	Plant evaporation compensation factor

Calibrated parameters varied in a regional approach by 11 parameter zones based on climate, topography, and geology

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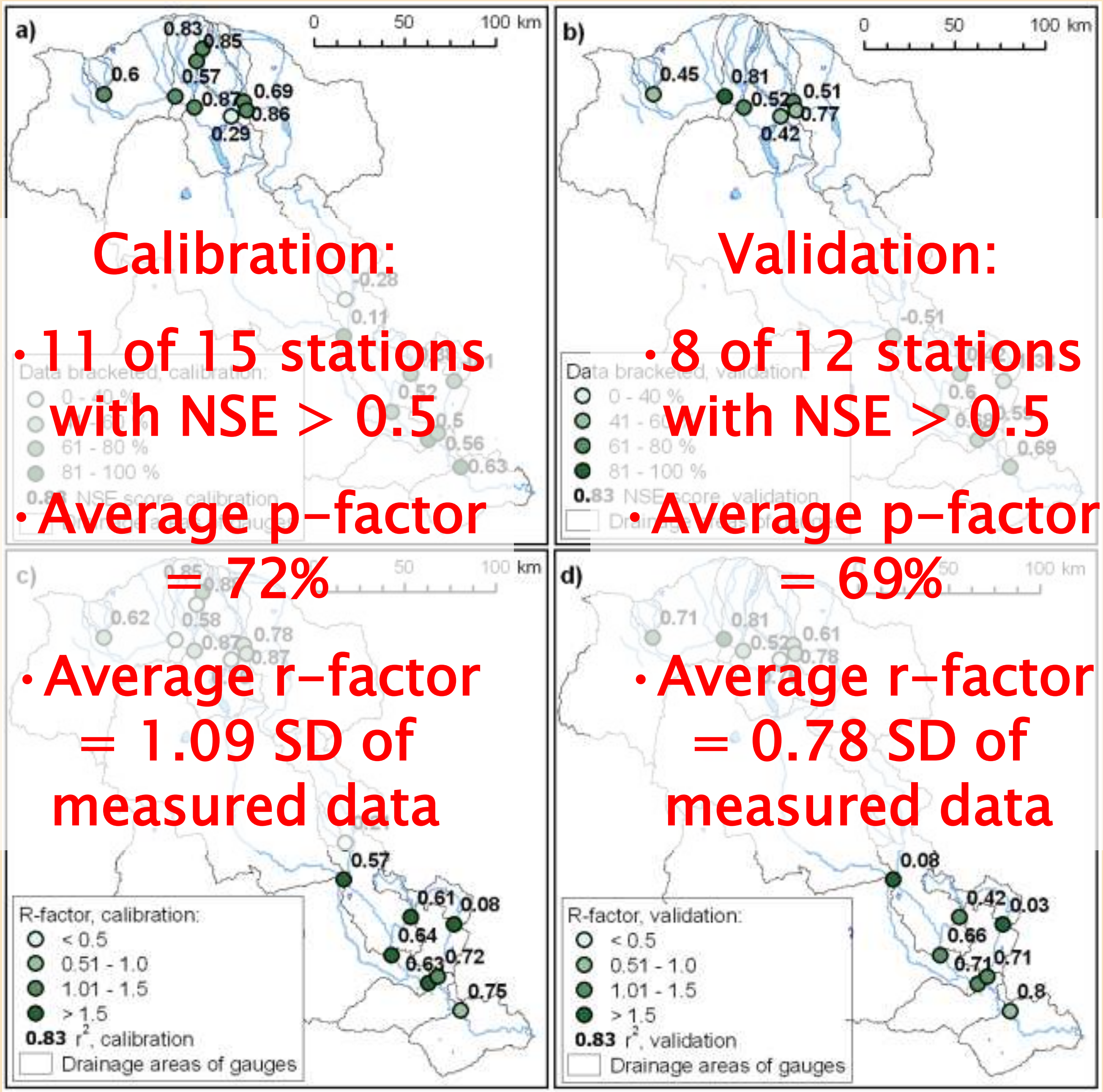
Calibration and validation results



Calibration:

- 11 of 15 stations with NSE > 0.5
- Average p-factor = 72%
- Average r-factor = 1.09 SD of measured data

Validation:

- 8 of 12 stations with NSE > 0.5
- Average p-factor = 69%
- Average r-factor = 0.78 SD of measured data

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Contents

„Year 2000“

Socio-economic situation around the year 2000 with 25 years of weather data to incorporate climatic variability

→ Weather data 1981-2005

→ Population & water use around 2000

95% prediction uncertainty (95PPU) derived from SUFI-2 iteration comprising 300 runs using parameter space established in calibration

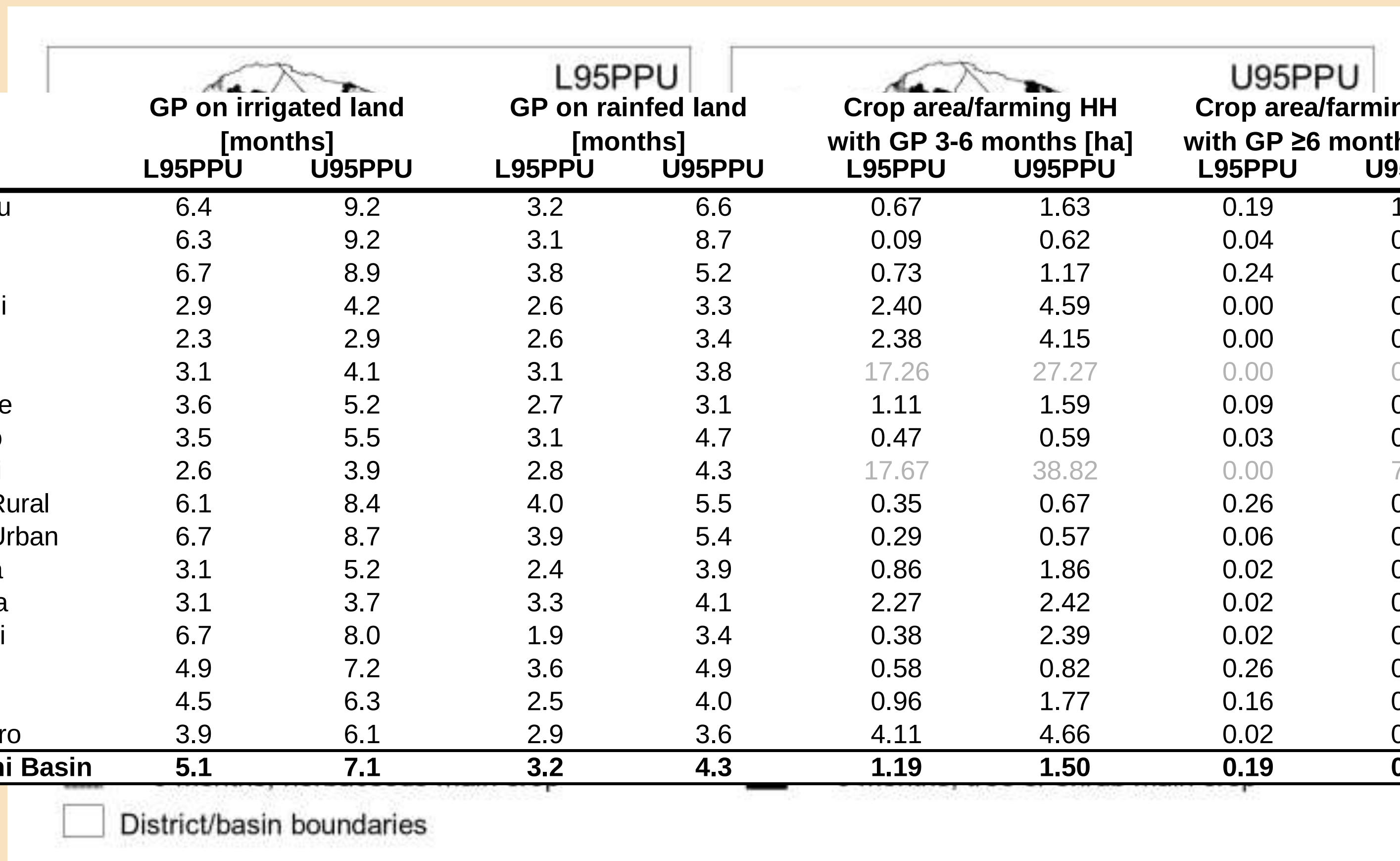
Year 2000 results and uncertainty

Water for households, livestock, industry
→ needed constantly → 95% reliability

District	2002 Population	Theoretical DLI demand [m3/s]	Actual use at 95% reliability [m3/s]		Available LCD at 95% reliability	
			L95PPU	**U95PPU**	**L95PPU**	**U95PPU**
Arumeru	435,600	0.59	0.44	0.48	87	95
Arusha	282,700	0.53	0.50	0.63	153	193
Hai	229,500	0.24	0.29	0.34	108	130
Handeni	87,100	0.08	0.02	0.02	24	24
Kilindi	20,200	0.03	0.01	0.01	51	53
Kiteto	10,100	0.01	0.003	0.003	27	27
Korogwe	247,200	0.38	0.20	0.22	71	78
Lushoto	294,500	0.38	0.13	0.17	37	51
Monduli	4,400	0.01	0.001	0.001	15	15
Moshi Rural	454,200	0.6	0.63	0.71	119	135
Moshi Urban	144,300	0.38	0.17	0.35	104	212
Muheza	36,400	0.04	0.01	0.02	33	43
Mwanga	115,600	0.13	0.09	0.11	71	79
Pangani	15,900	0.03	0.01	0.01	63	67
Rombo	121,800	0.11	0.08	0.12	56	85
Same	208,500	0.32	0.18	0.21	74	86
Simanjiro	98,600	0.15	0.05	0.05	43	46
Pangani Basin	**2,806,600**	**4.01**	**2.81**	**3.45**	**87**	**106**

„Year 2000“

Water for agriculture
→ Growing period duration (period with >50% plant water demand available) at 75% reliability



District	GP on irrigated land [months]		GP on rainfed land [months]		Crop area/farming HH with GP 3-6 months [ha]		Crop area/farming HH with GP ≥6 months [ha]	
	L95PPU	U95PPU	L95PPU	U95PPU	L95PPU	U95PPU	L95PPU	U95PPU
Arumeru	6.4	9.2	3.2	6.6	0.67	1.63	0.19	1.13
Arusha	6.3	9.2	3.1	8.7	0.09	0.62	0.04	0.59
Hai	6.7	8.9	3.8	5.2	0.73	1.17	0.24	0.62
Handeni	2.9	4.2	2.6	3.3	2.40	4.59	0.00	0.11
Kilindi	2.3	2.9	2.6	3.4	2.38	4.15	0.00	0.00
Kiteto	3.1	4.1	3.1	3.8	17.26	27.27	0.00	0.57
Korogwe	3.6	5.2	2.7	3.1	1.11	1.59	0.09	0.20
Lushoto	3.5	5.5	3.1	4.7	0.47	0.59	0.03	0.27
Monduli	2.6	3.9	2.8	4.3	17.67	38.82	0.00	7.55
Moshi Rural	6.1	8.4	4.0	5.5	0.35	0.67	0.26	0.60
Moshi Urban	6.7	8.7	3.9	5.4	0.29	0.57	0.06	0.36
Muheza	3.1	5.2	2.4	3.9	0.86	1.86	0.02	0.09
Mwanga	3.1	3.7	3.3	4.1	2.27	2.42	0.02	0.28
Pangani	6.7	8.0	1.9	3.4	0.38	2.39	0.02	0.05
Rombo	4.9	7.2	3.6	4.9	0.58	0.82	0.26	0.46
Same	4.5	6.3	2.5	4.0	0.96	1.77	0.16	0.48
Simanjiro	3.9	6.1	2.9	3.6	4.11	4.66	0.02	0.41
Pangani Basin	**5.1**	**7.1**	**3.2**	**4.3**	**1.19**	**1.50**	**0.19**	**0.51**

Year 2025 Scenarios

a) **3 management scenarios** (differ by priority given to each water use):

- „Maximise Agriculture"
- „Maximise Hydropower "
- „Sustainability"

b) **3 climate change scenarios** based on the 4th IPCC Assessment Report (wetter, drier, and today's climate, respectively) combined with management scenarios

Assumptions for 2025 scenarios

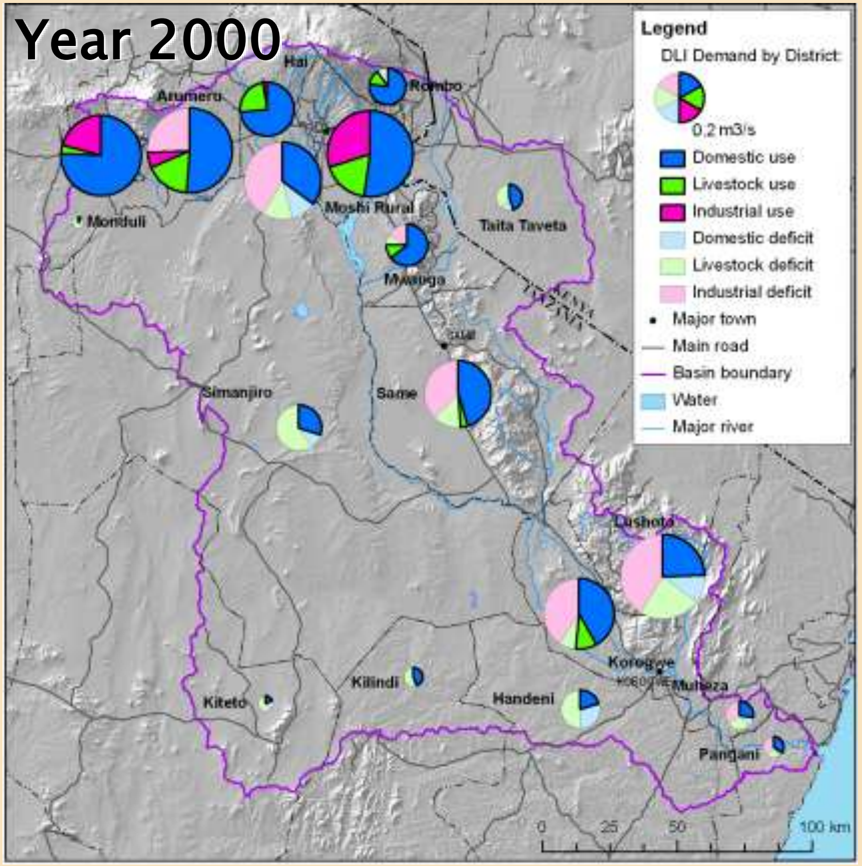
- Population and agricultural area increase according to official projections of the URT: 72.8% from 2000 to 2025
- Domestic water use given first priority, using same sources as in 2000 (except „Sustainability“ with development of additional sources)
- Irrigation efficiency rises from 25% to 32% (45% under „Sustainability“); irrigated area increase according to predictions by PBWO

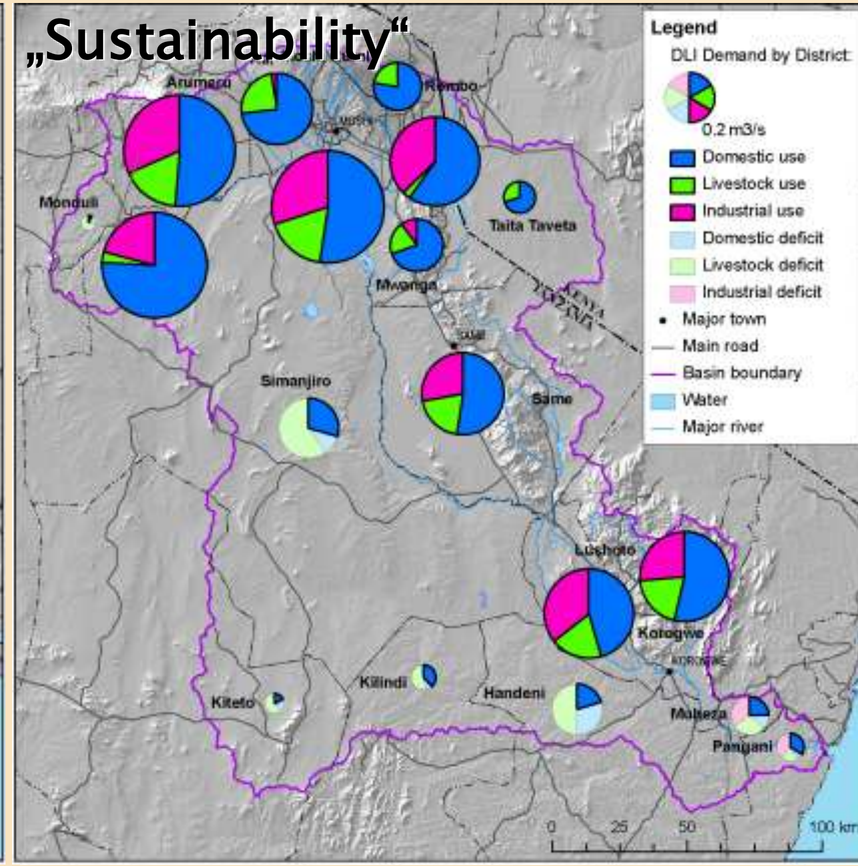
Results

→ Generally: **Access** and **distribution** of water are the greater limiting factors than natural water availability

→ Maintenance and even improvement of current provision levels of water-related ecosystem services is possible in spite of increasing demand; however, investments and regulations are necessary

Water provision for domestic, livestock, and industrial use





→„Sustainability“: Thanks to development of additional water sources, demand is met in most Districts

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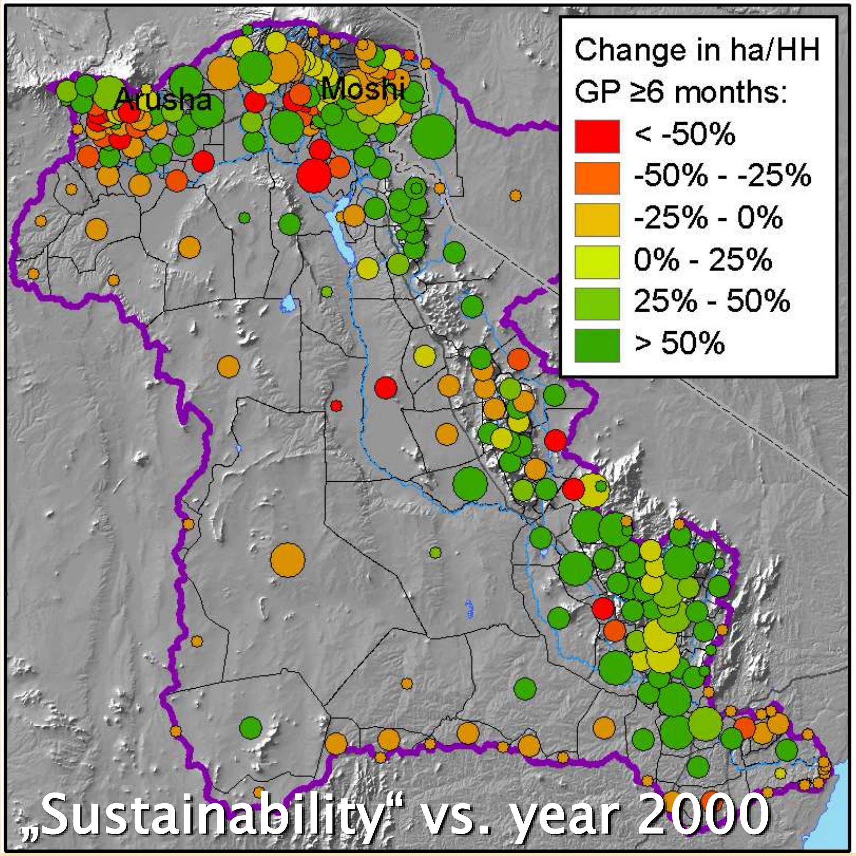
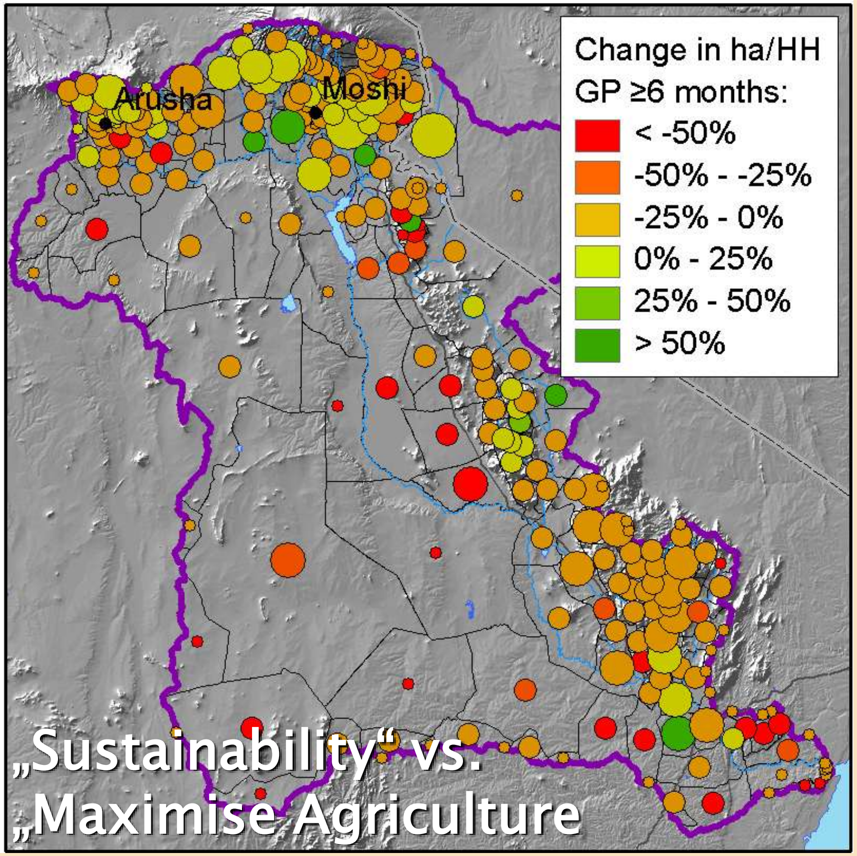
Water provision for agriculture





→„Sustainability" and „Maximise Agriculture" offer similar growing period durations for agriculture, but under „Sustainability", only 2/3 of the water is used due to better irrigation efficiency

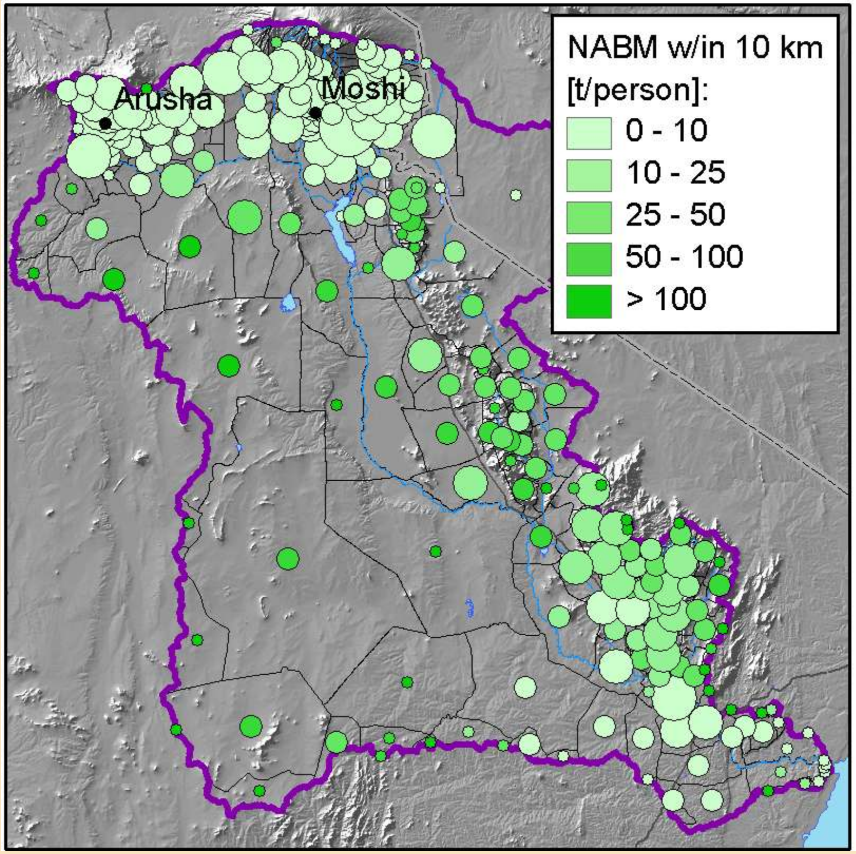
Results

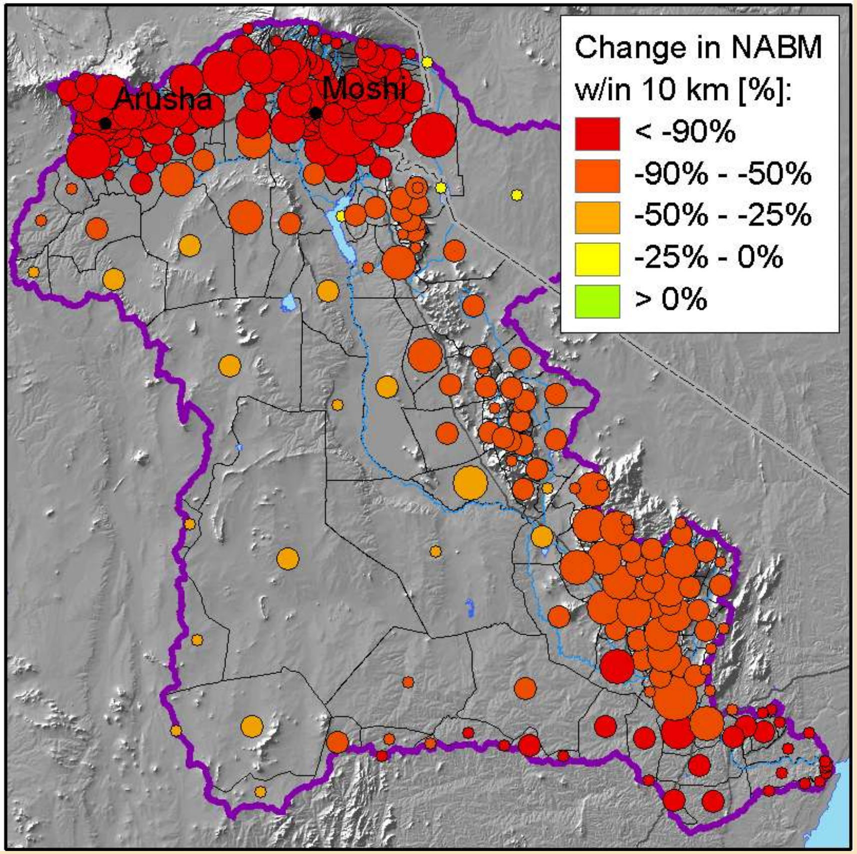
→ Generally: **Access** and **distribution** of water are the greater limiting factors than natural water availability

→ Maintenance and even improvement of current provision levels of water-related ecosystem services is possible in spite of increasing demand; however, investments and regulations are necessary

→ Decrease in ecosystem services from natural terrestrial ecosystems

Ecosystem services from natural terrestrial ecosystems (fuelwood, building materials, food, etc.)





→ Dramatic decrease compared to year 2000

→ Possible increase of risks of famines and degradation: Alternative resources during times of drought and land reserves are lacking

Results

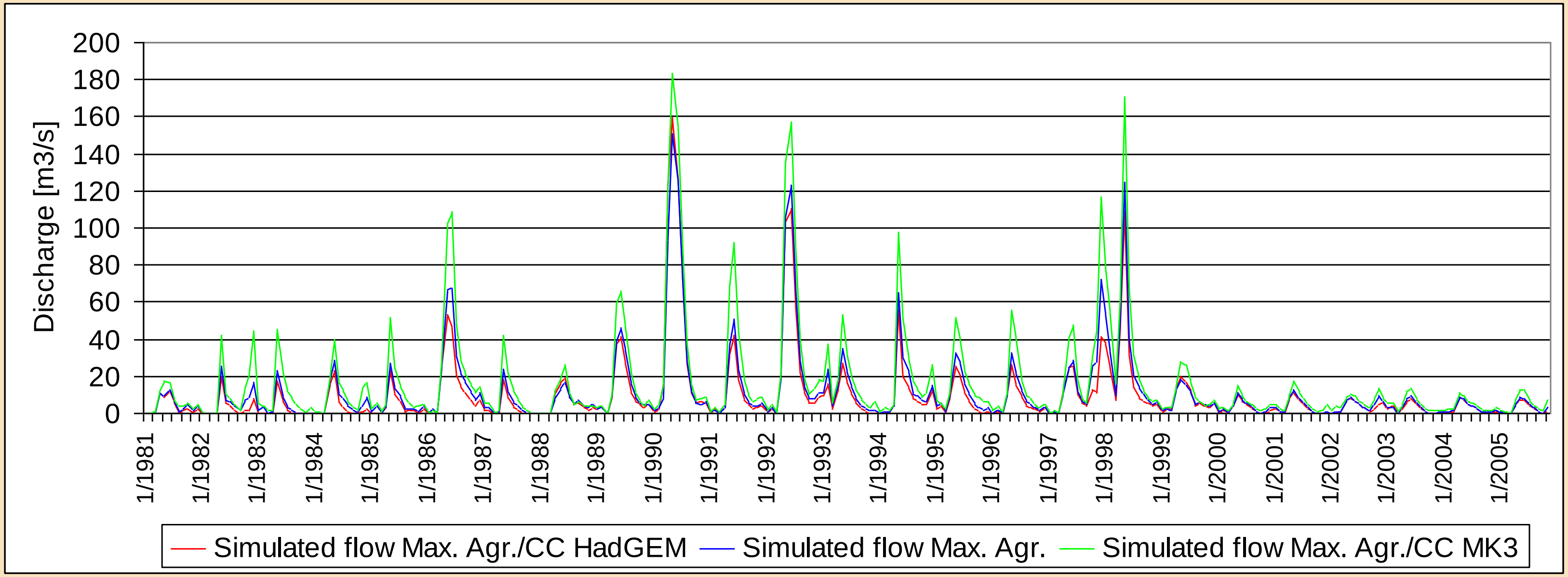
→ Generally: **Access** and **distribution** of water are the greater limiting factors than natural water availability

→ Maintenance and even improvement of current provision levels of water-related ecosystem services is possible in spite of increasing demand; however, investments and regulations are necessary

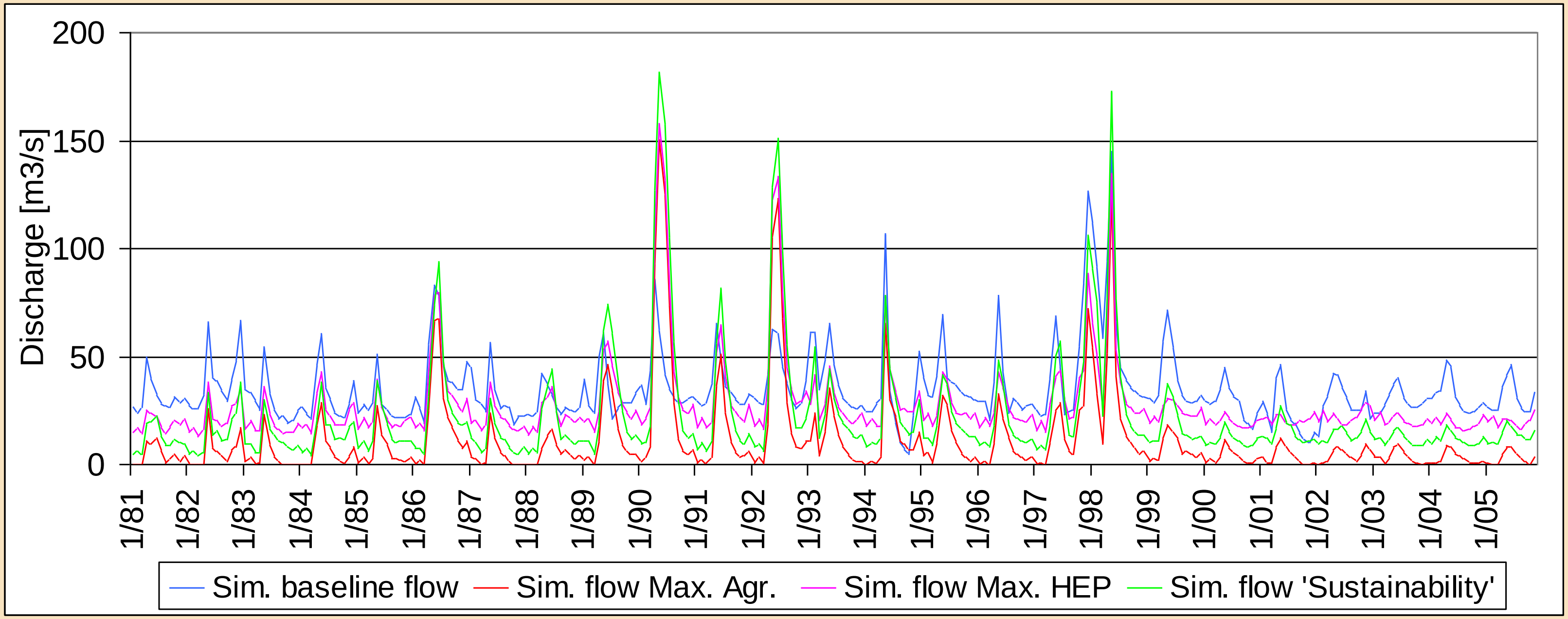
→ Decrease in ecosystem services from natural terrestrial ecosystems

→ Effects of climate change up to 2025 are rather marginal

a) Hale Power Station, climate change scenarios / Max. Agr.



b) Hale Power Station, management scenarios / present climate



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Contents

- Quantitative estimates of water-related ecosystem service provision could be made available for Pangani Basin for the years 2000/2025 at the required scales (Districts, subbasins, …)
  → however, important criterion of water quality could not be considered for lack of data to calibrate the model

- Spatio-temporal resolution and process simulation required could be realized using the SWAT model
  → but slight code modifications, as well as the development of pre- and post-processing tools, were necessary

- Computing time became limiting factor due to high resolution and number of runs necessary for uncertainty assessment
  → inputs of land use and political units inputs could be generalized to reduce number of HRUs without significant information loss in outputs
- Uncertainty could be reduced and quantified, but considerable uncertainty remains which can only be reduced with better measured data

Many thanks to…

… You (the audience)

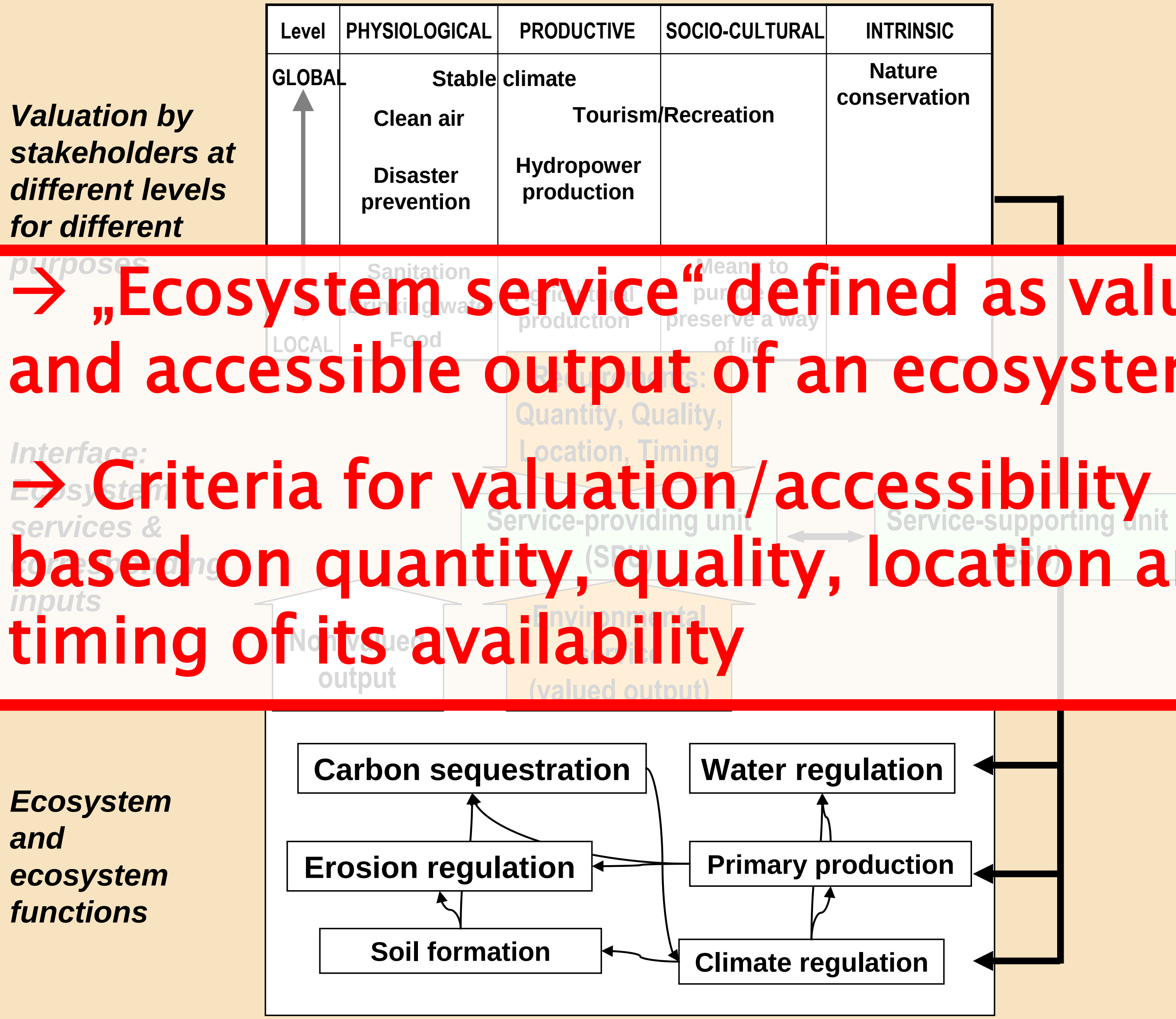
… the NCCR North-South research programme, and SDC (Swiss Agency for Development and Cooperation) for making possible and financing this study

… my supervisors at the Geographical Institute of the University of Bern, and the University of Dar es Salaam, for inputs, fruitful discussions and motivation

… the responsible offices and authorities in Tanzania and Kenya for making input data available

… Dr. Karim Abbaspour (SANDEC/EAWAG) for collaboration and support regarding SUFI-2

Conceptual framework for ecosystem service quantification



→ „Ecosystem service“ defined as valued and accessible output of an ecosystem

→ Criteria for valuation/accessibility based on quantity, quality, location and timing of its availability

Stakeholder requirements regarding water-related ecosystem services

r 2009

Recommendations

… for research:

- Access to, and valuation of components of ecosystems by stakeholders are central criteria for such components to represent a „benefit" (=definition of ES)
  → must be taken into account in any study targeting „ecosystem services"

- SWAT model:
  Simplify input file structure (100'000s of files slow down file systems!)

Recommendations

… for water management in Pangani Basin:

- Revise water rights
- Invest in distribution infrastructure
- Enforce minimum flow reserves
- Create incentives for saving water, e.g. by introducing temporally differentiated water rate for commercial use
- Increase general food and financial security by encouraging agro-processing industry, financial services

Physical complexity and variability

→ Not all ecosystem services in demand can be provided at the same time → this leads to trade-offs and target conflicts

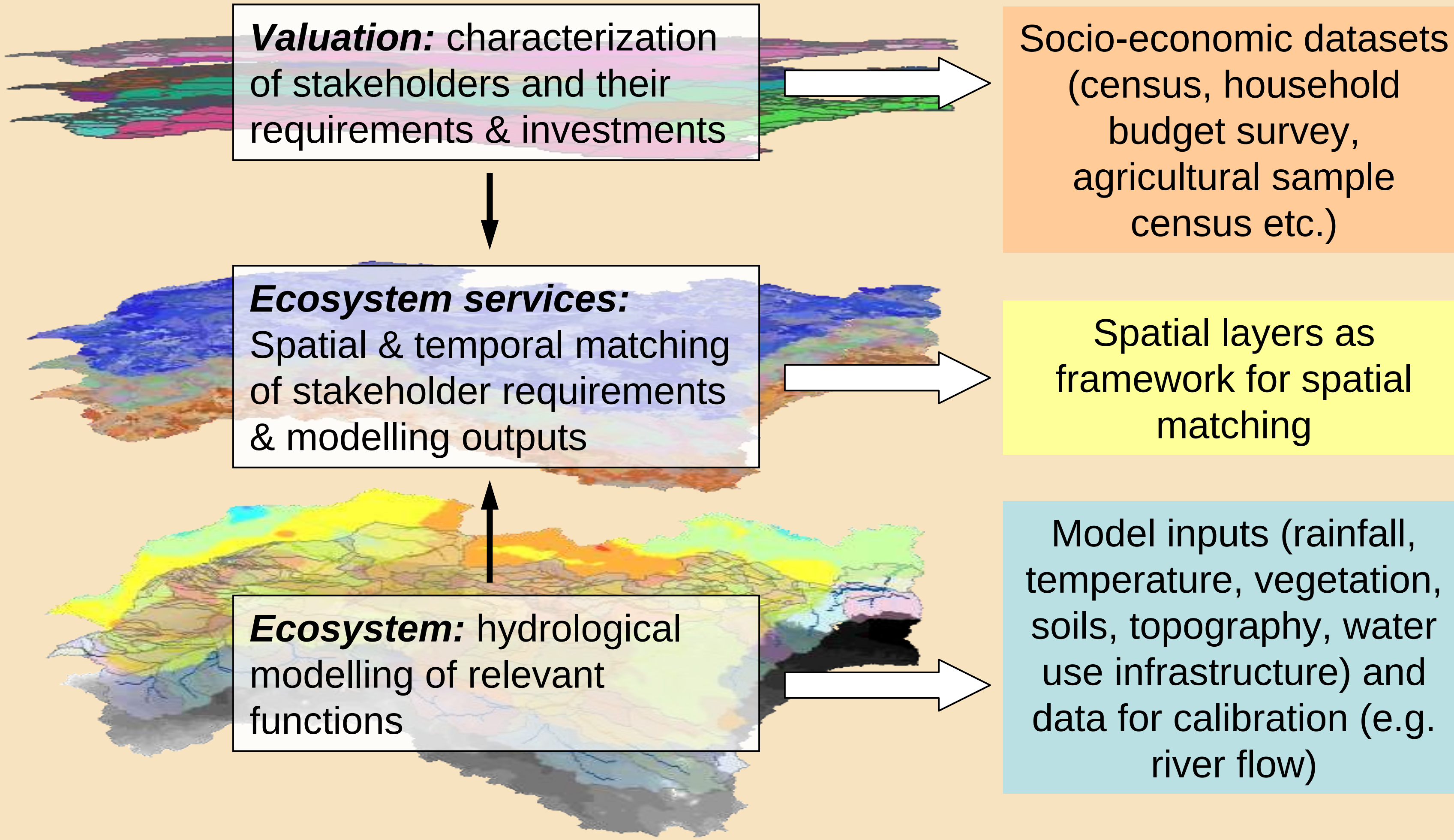
→ Targets of development must be negotiated by politics and society

→ Science can support such negotiation processes by predicting the quantity and combination of ecosystem services that can flow sustainably from a given environment under a given scenario

- Comparison to Pangani Basin Scenario Report by IUCN (2008) shows that increased resolution and modelling of hydrological processes leads to very different results and conclusions: Regarding domestic water, results from this study are more pessimistic since they show limited access to water; Regarding agriculture, they are more optimistic since they consider different runoff formation from different land use types, and return flows from irrigation

- SWAT model:
→ improvement of groundwater processes: movement of groundwater in deep aquifer should be explicitly modelled by e.g. providing for multiple deep aquifer stores
→ change from cumbersome file-per-unit to tabular input file structure would be beneficial, but entire SWAT community needs to agree due to dependencies of pre- and post-processing tools

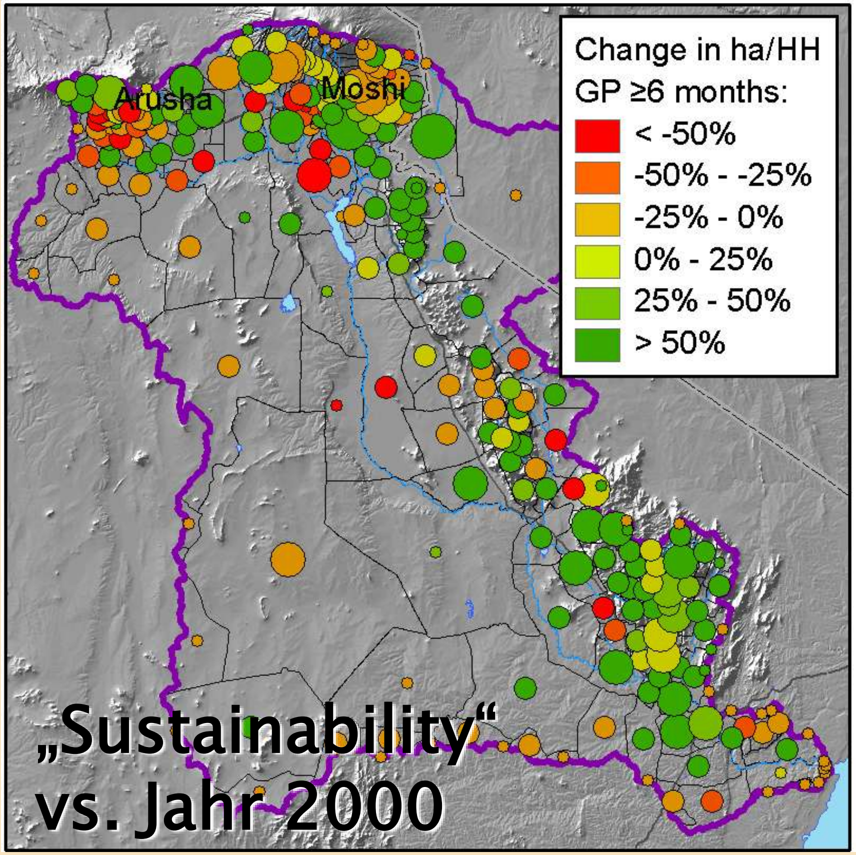
Data requirements

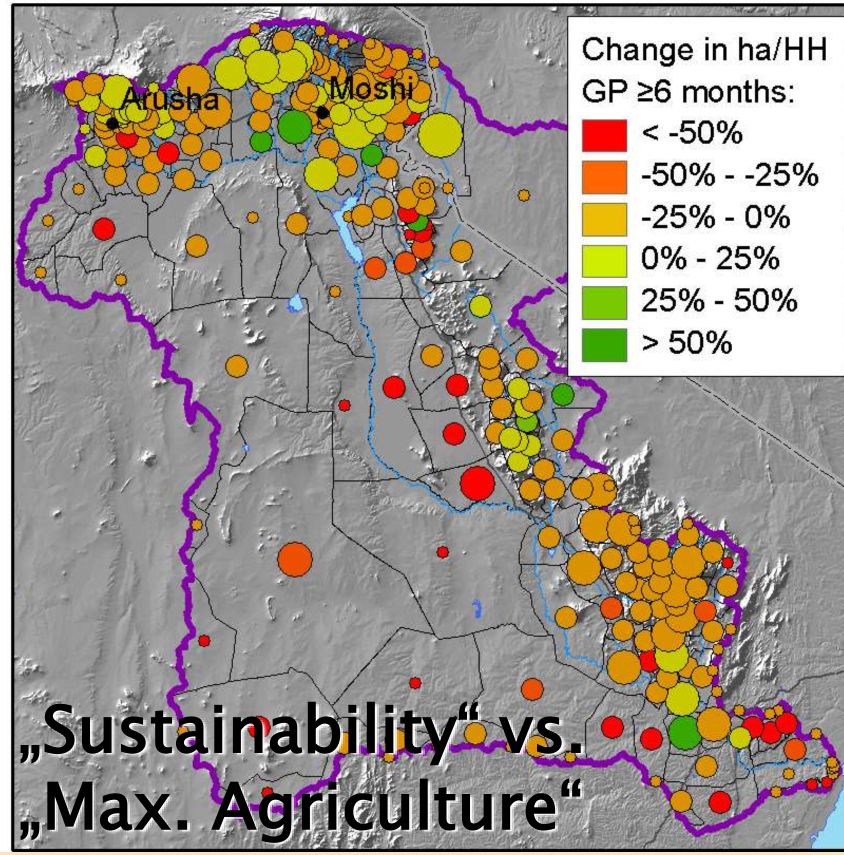


Output: Natural Resources Monitoring & GIS databases

→ Distributed to all contributing institutions; Introduction & training on use for PBWO staff carried out in workshop in November 2007

Verfügbarkeit von Agrarland mit Wachstumsperiode mind. 6 Monate

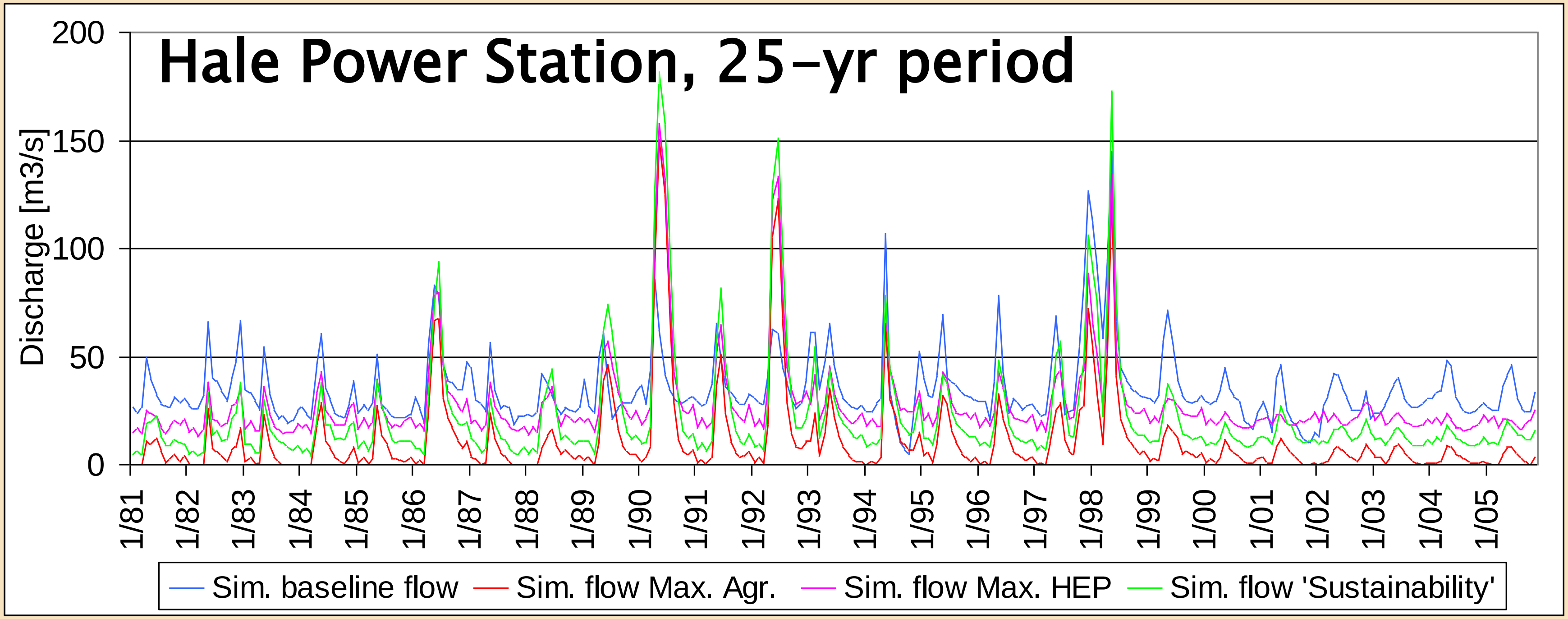




→ „Sustainability" gegenüber Jahr 2000: fast überall Verbesserung, z.T. dank höherer Bewäss.-Effizienz

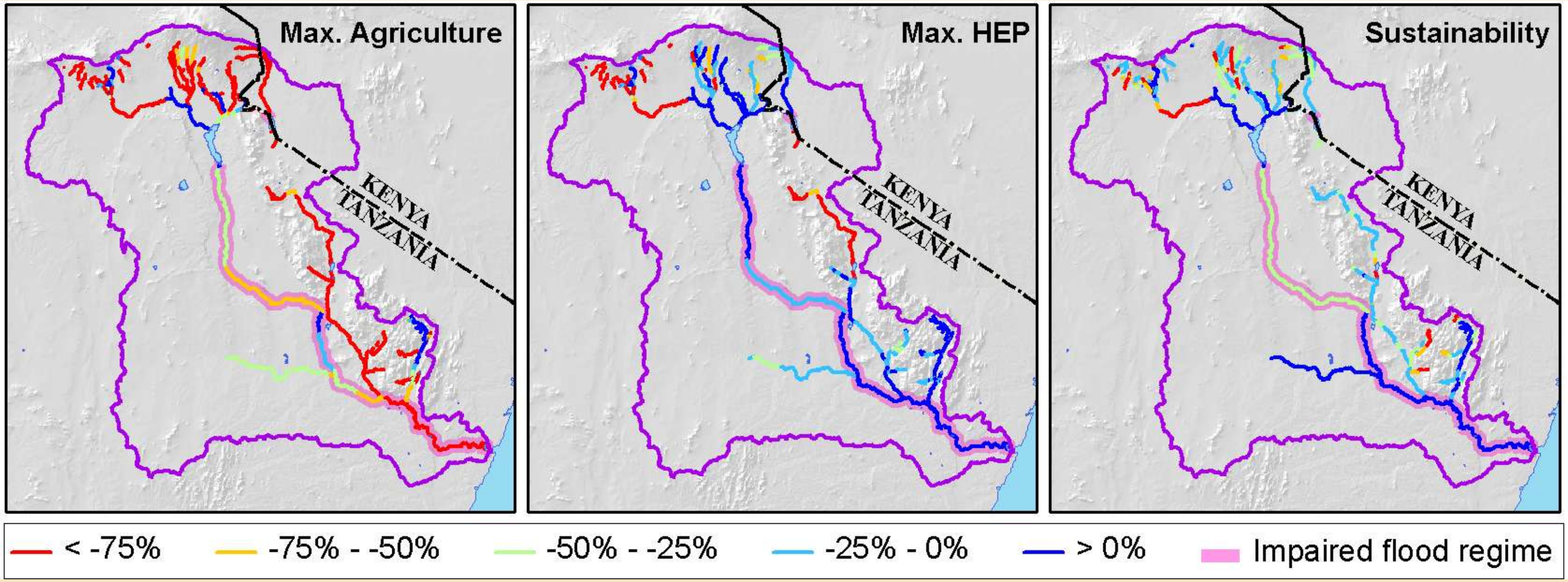
→ Gegenüber „Max. Agriculture": Leicht niedrigere Verfügbarkeit, aber nur 2/3 des Wasserverbrauchs

Energieproduktion aus Wasserkraft



→ Kaum Verbesserung gegenüber Jahr 2000 (blaue Linie) möglich, da Wasserkraft bereits heute priorisiert

Wasser für aquatische Ökosysteme

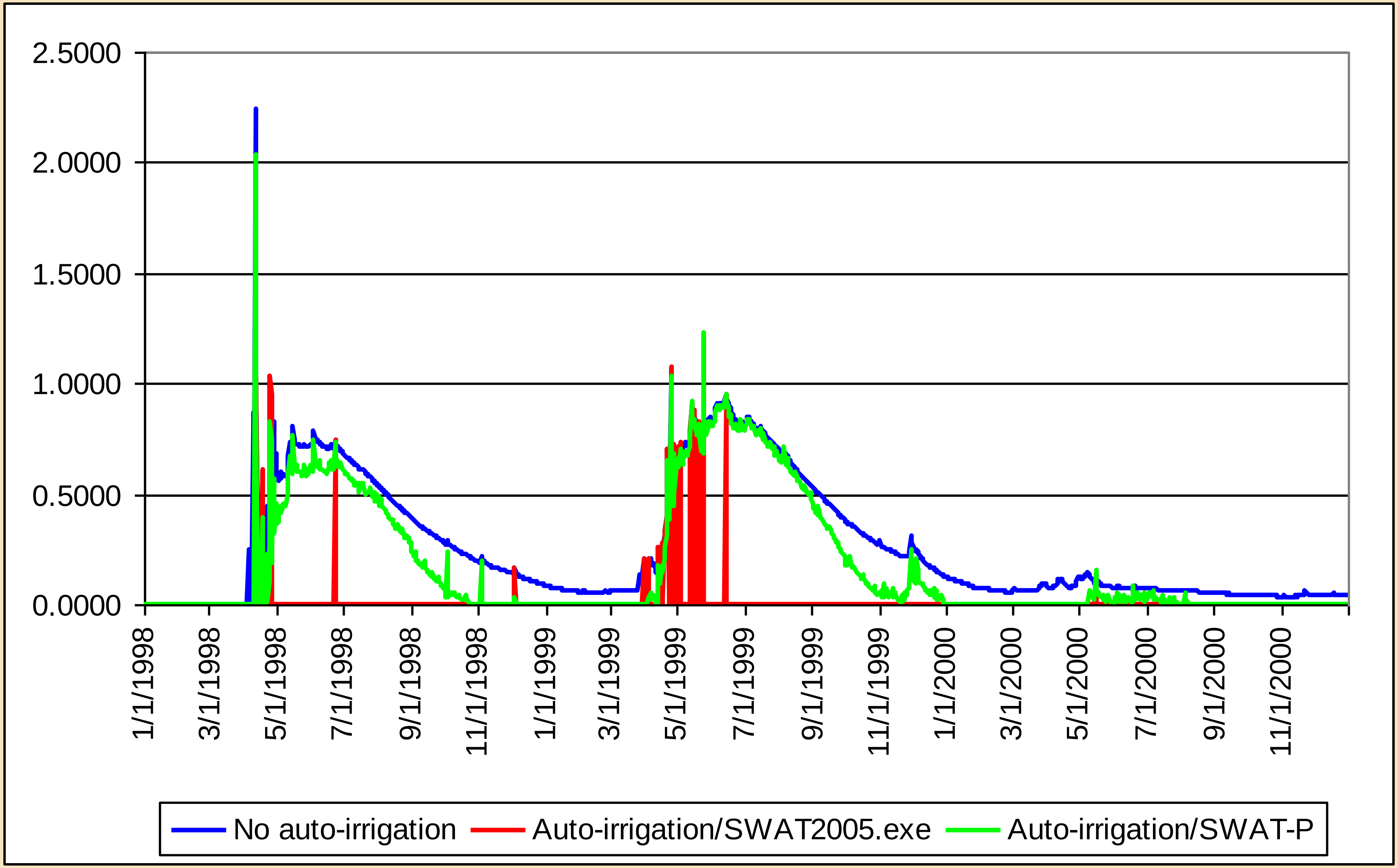


→ Generell: Überflutungsregime Pangani River durch Nyumba ya Mungu-Reservoir gestört

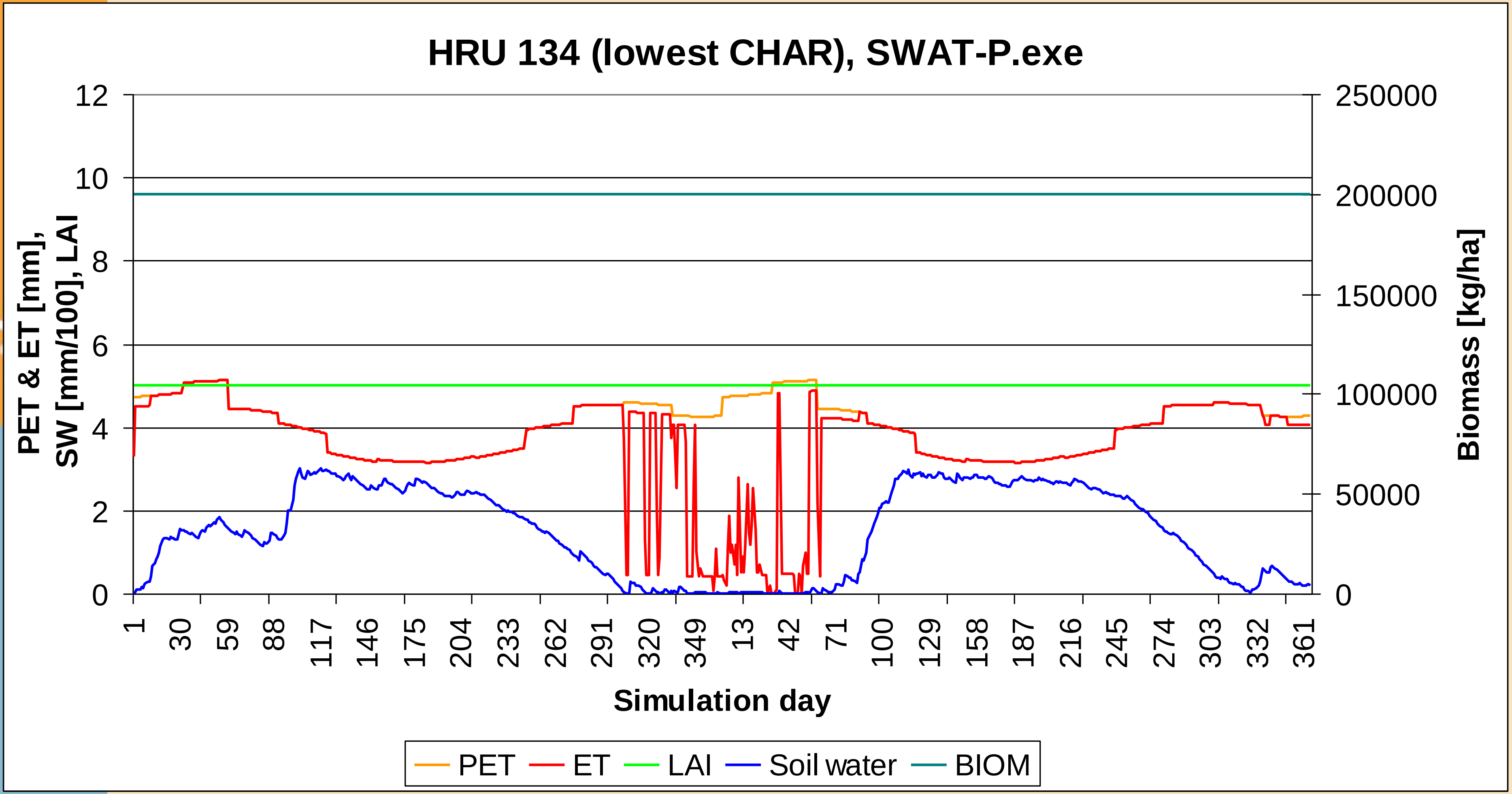
→ „Max. Agriculture": Über 75% des nötigen Minimal-Abflusses fehlen über weite Strecken

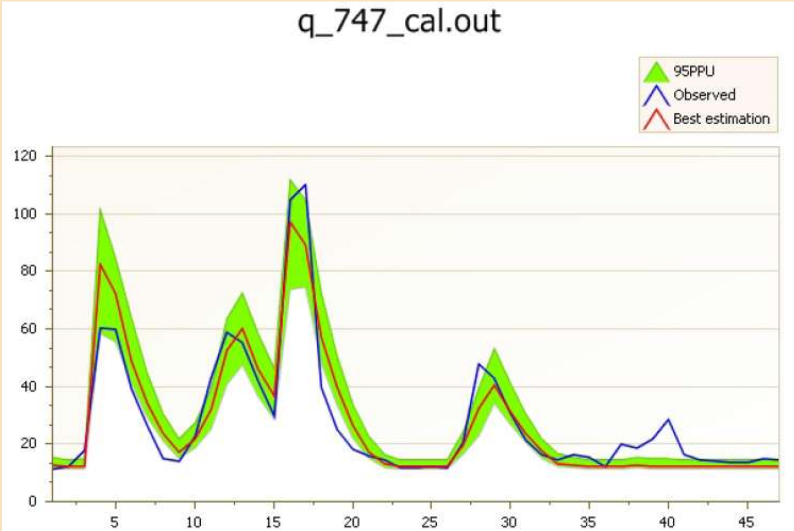
→ „Max. HEP": Erreichen des Minimalabflusses dort, wo keine anderen Nutzungen wegen Stromproduktion

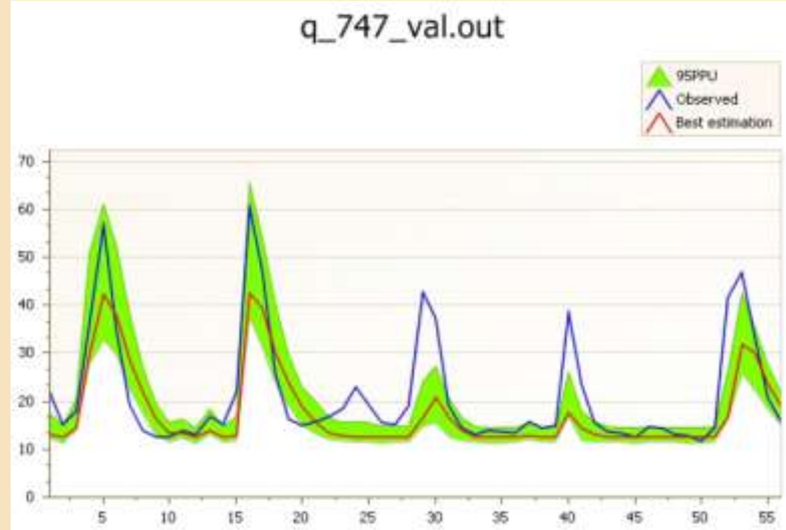
→ „Sustainability": Entlang meisten Strecken Minimal-Abfluss erreicht oder Defizit < 25%

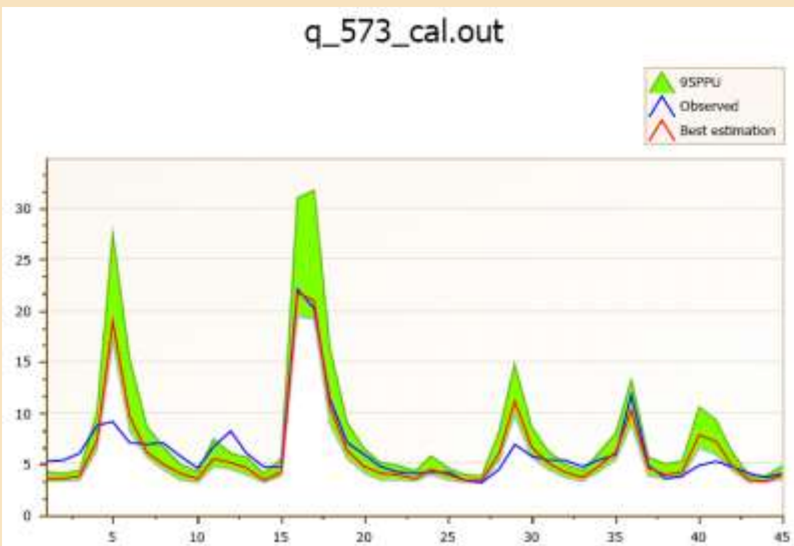


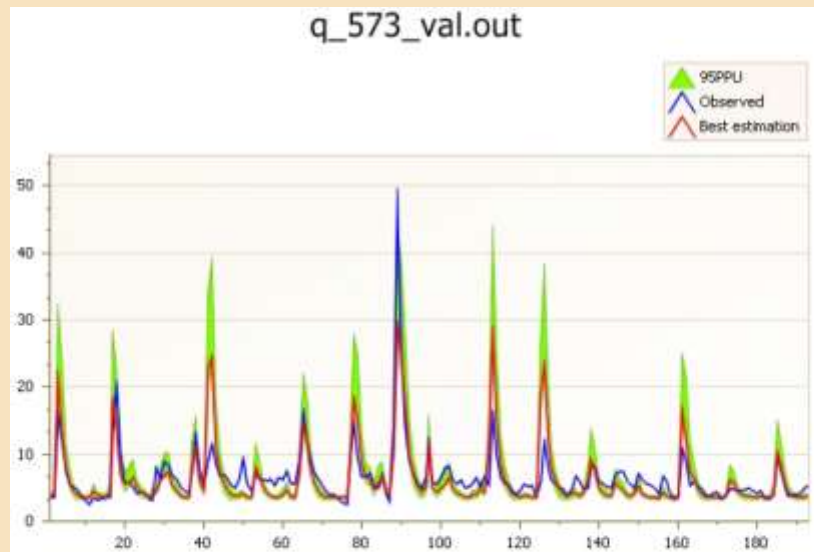
north south NCCR


HRU 134 (lowest CHAR), SWAT-P.exe
PET & ET [mm], SW [mm/100], LAI
Biomass [kg/ha]
0
2
4
6
8
10
12
0
50000
100000
150000
200000
250000
1
30
59
88
117
146
175
204
233
262
291
320
349
13
42
71
100
129
158
187
216
245
274
303
332
361
Simulation day
PET
ET
LAI
Soil water
BIOM









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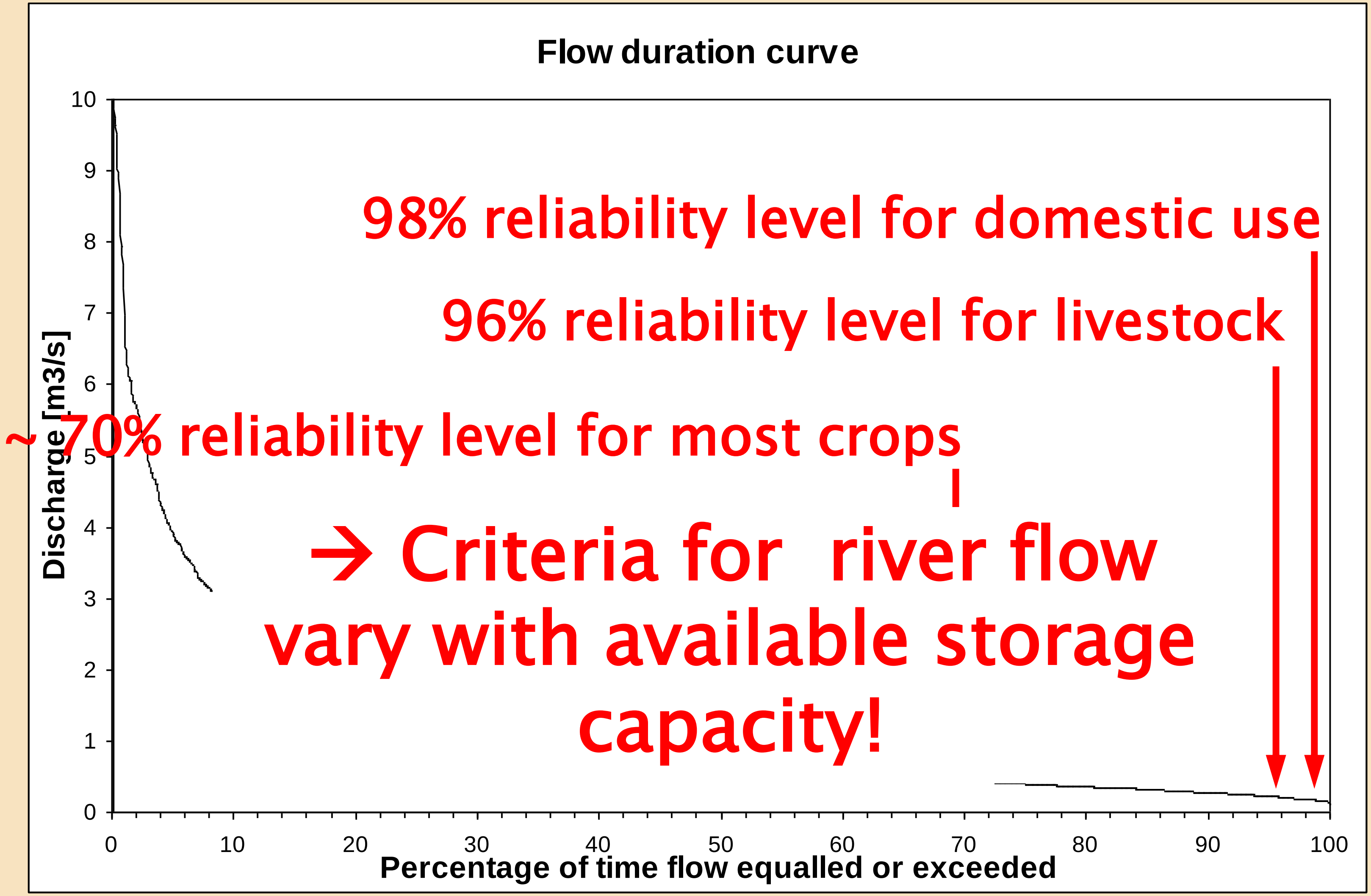
Requirements for delivery of benefits (1)

Quantity and timing:

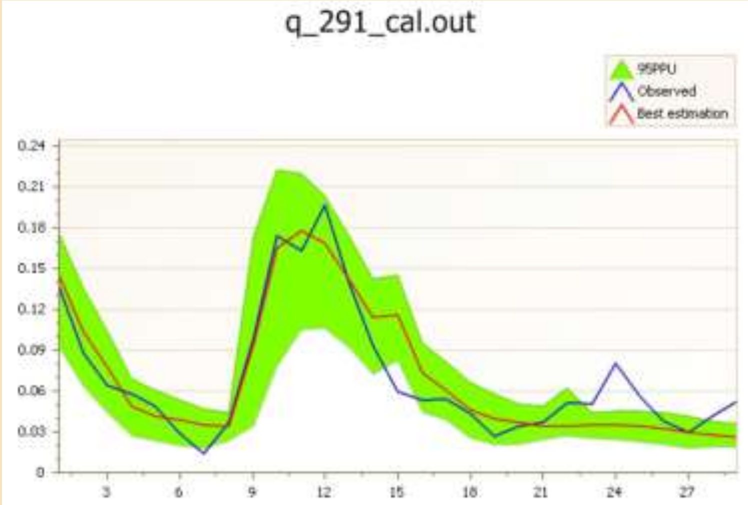


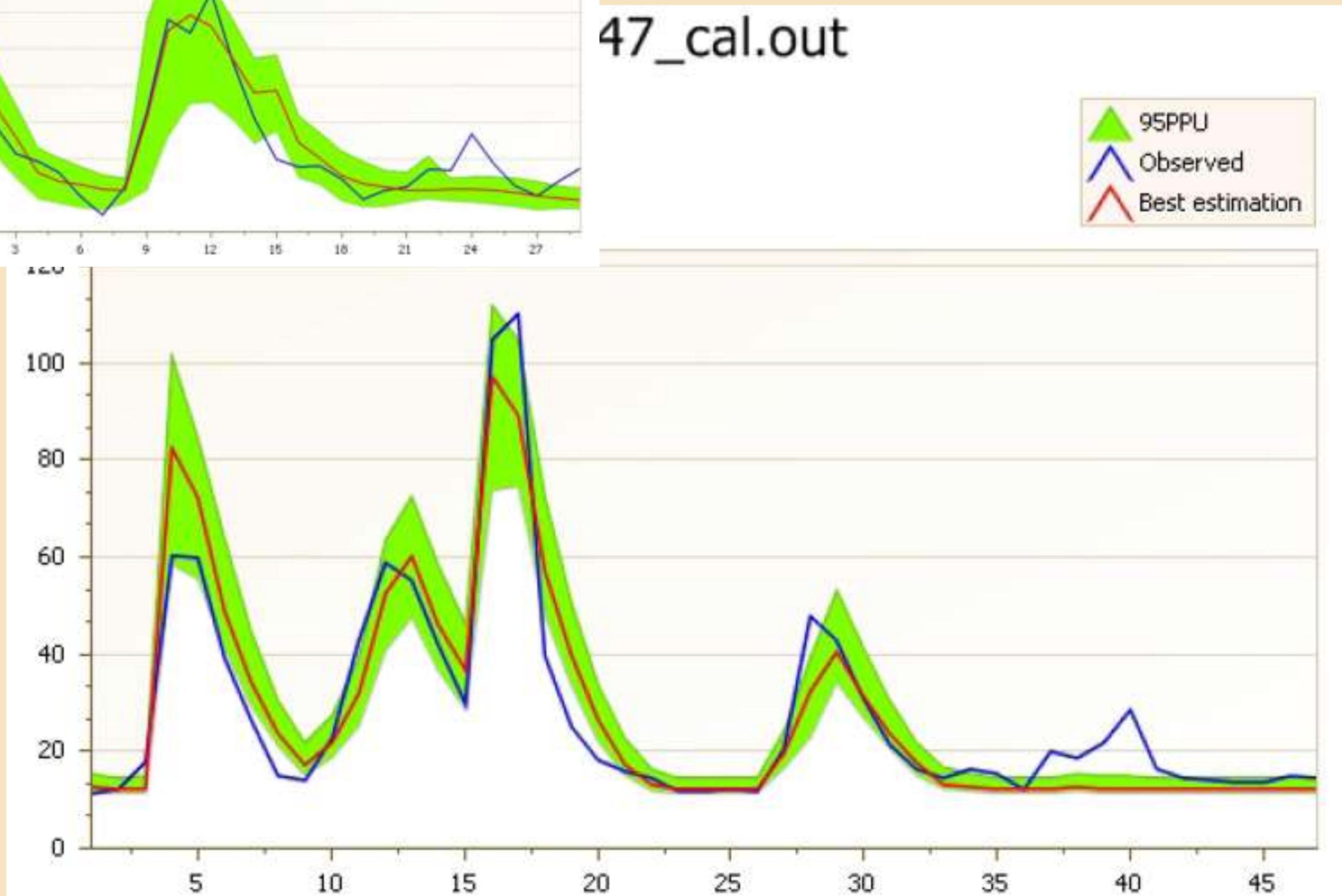
From SWAT2005 to SWAT-P

- Corrected error in auto-irrigation routine

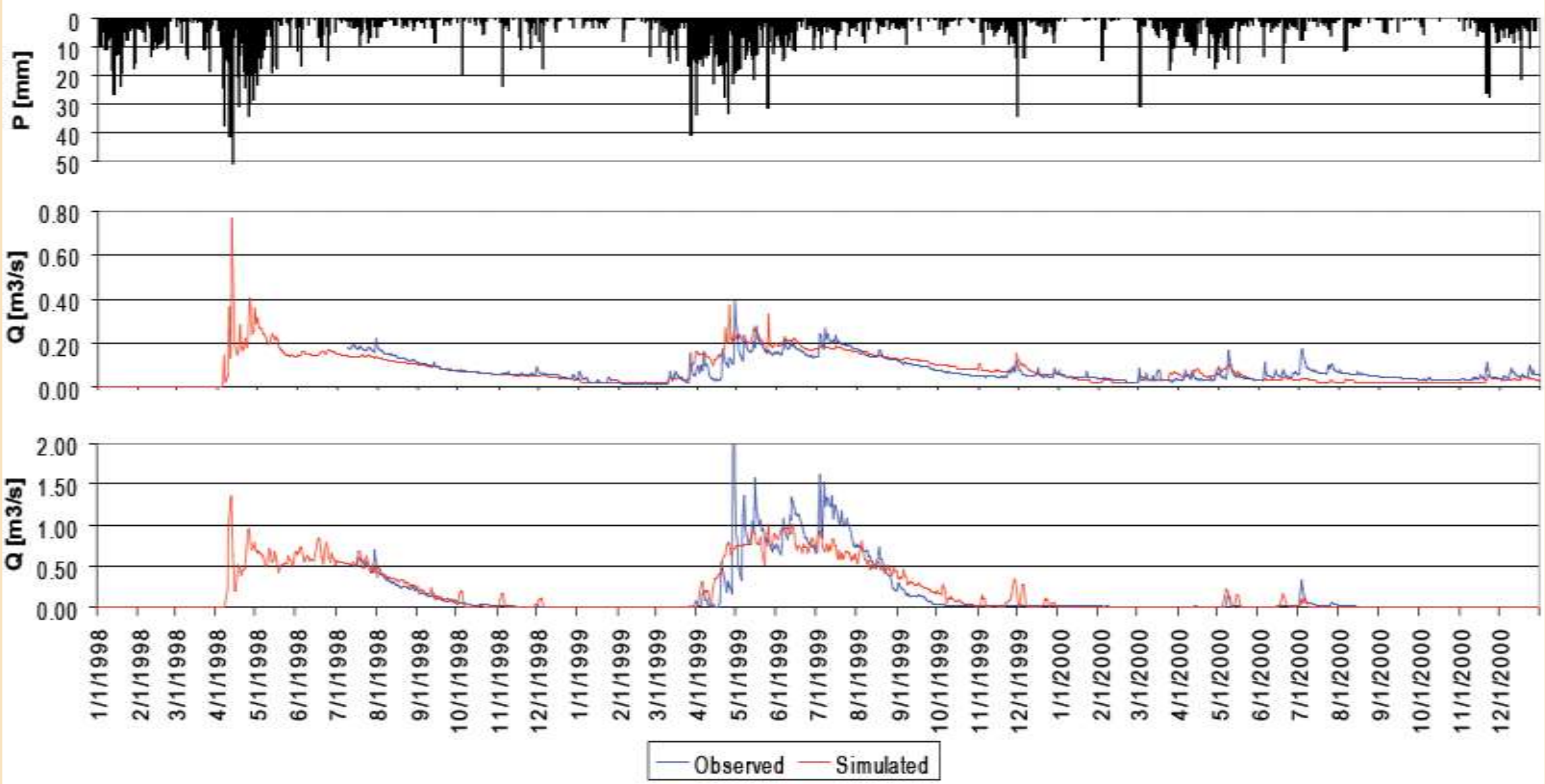
From SWAT2005 to SWAT-P

- Corrected error in auto-irrigation routine
- Changed dormancy threshold for tropical latitudes to avoid unintended dormancy


q_291_cal.out
95PPU
Observed
Best estimation
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
0
3
6
9
12
15
18
21
24
27

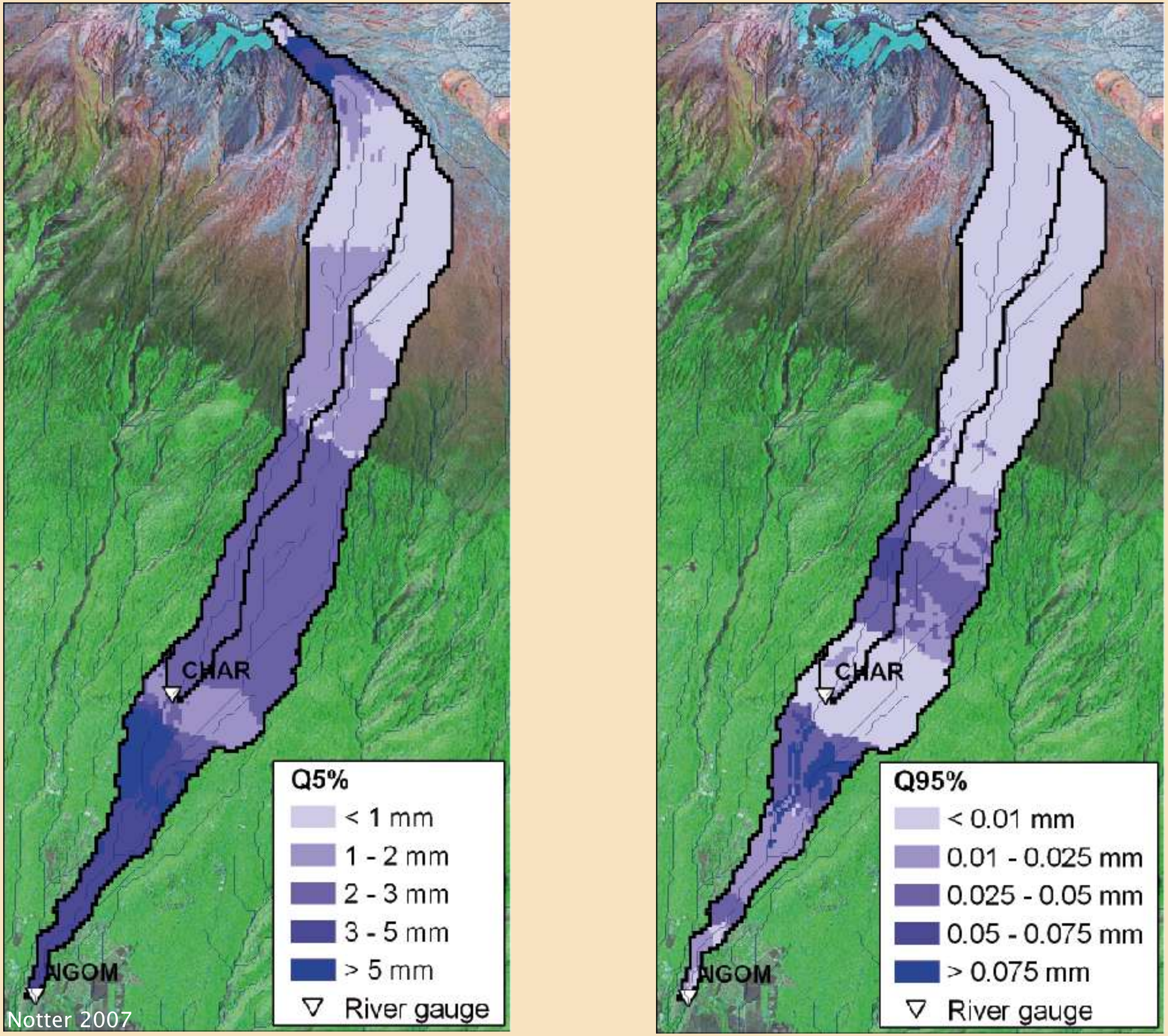

47_cal.out
95PPU
Observed
Best estimation
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45

1st SWAT modelling results

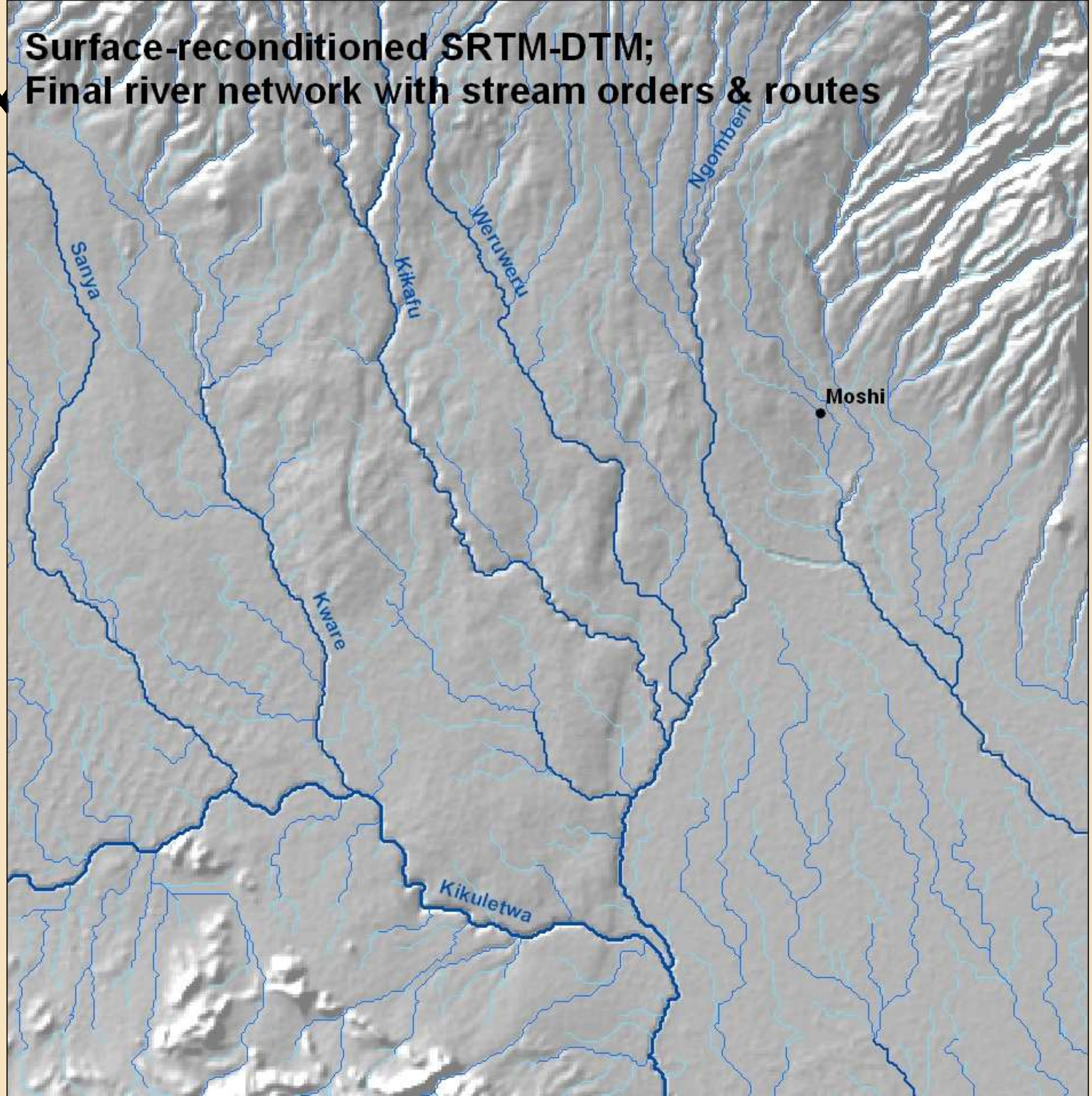


Performance measure	Charongo	Ngomberi
Daily r^2	0.72	0.82
Daily NSE	0.70	0.81
Monthly r^2	0.84	0.94
Monthly NSE	0.82	0.93
Total Q dev. (Sim – Obs) [%]	-0.40	-2.93

SWAT outputs: Areal contributions to river flow



Ex



NCCR north south