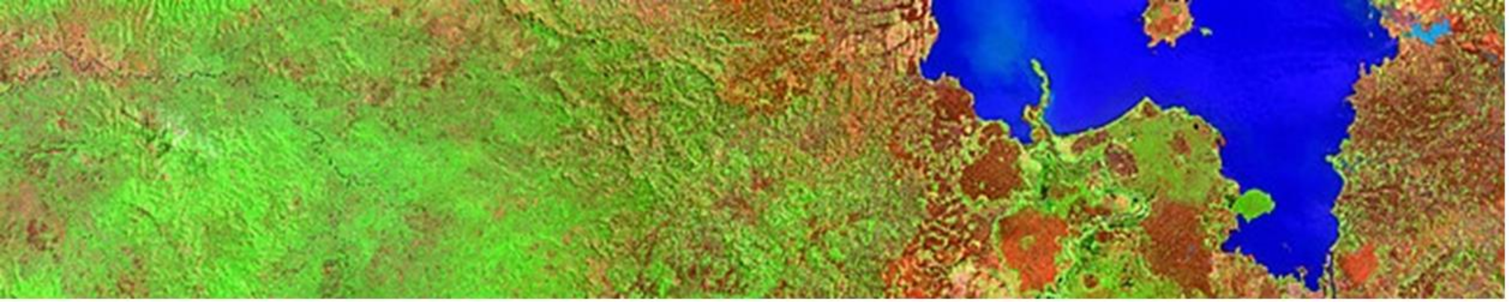


Water Consumption in the Karkheh River Basin, Iran
An approach using Remote Sensing and Multi-variable model calibration

Tom Rientjes & Lal Muthuwatta

1) Twente University; Faculty of Geo-information Science and Earth Observation, The Netherlands
2) International Water Management Institute (IWMI), Sri Lanka.

Outline

- Objectives
- Study area
- Estimating evapotranspiration
- Stream flow modelling
- Multi-variable calibration
- Some results

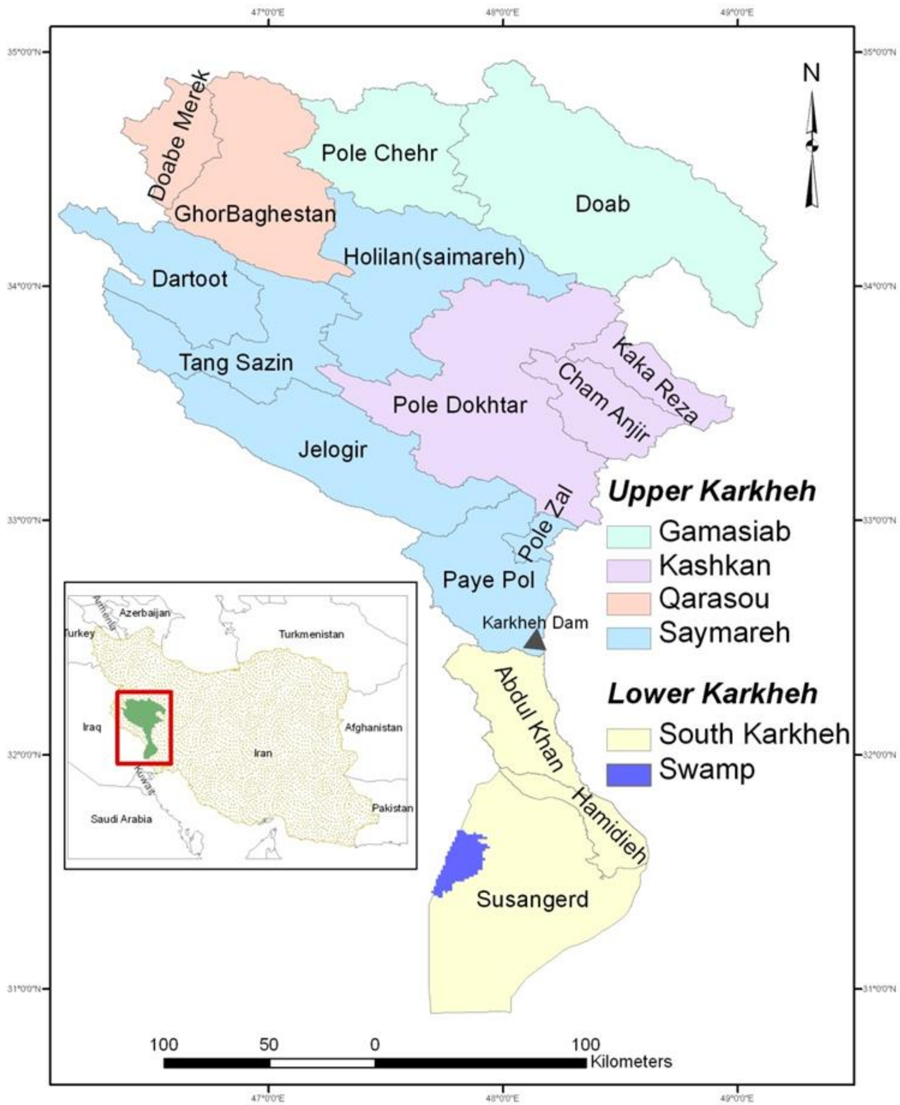
Objective

To assess reproduction of water balance of the Karkheh River basin by a Hydrological model using multi-variable model calibration and satellite based ETa… or …

'to test effectiveness of use of Satellite data (ETa) in a mass conservative, catchment scale hydrological model'

- **More specific:**
  - To assess use of Satellite based ETa in stream flow modelling
  - To assess reproduction of the catchment water balance
  - To test multi-variable model calibration for 2 outflow (sink) terms
  - To assess closure of the simulated water balance by Qs and ETa
  - To better understand closure error distributions
  - To assess parameter uncertainty
  - Etc.

The Karkheh river basin, Iran



Area:
- 50,764 km^2
- Northern part 4 subcatchments
- Southern part 2 subcatchments
- Hoor-Al-Azim swamp is Ramsar site

Population:
4 million but rapidly increasing

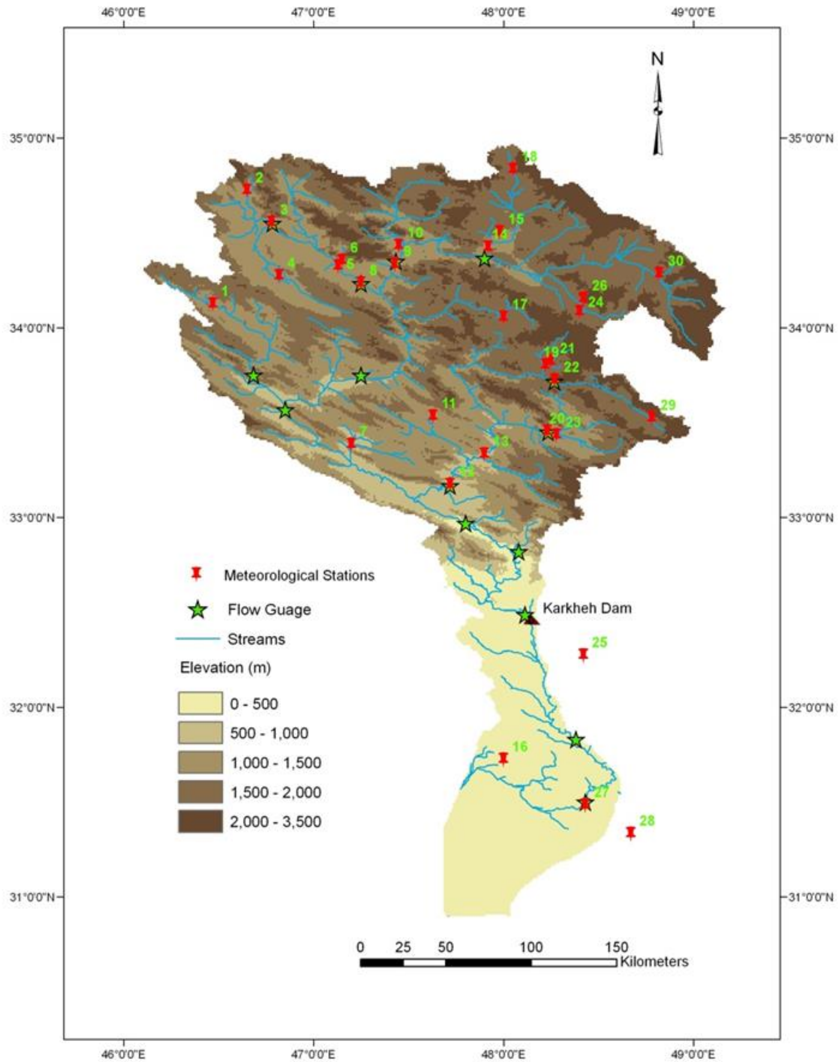
Precipitation:
150 mm in the south
750 mm in the north

Class A pan evaporation
2000 mm in the north
3600 mm in the south

Irrigated area:
1,100 km^2, with planned expansion to 3,400 km^2

Major crops
wheat and barley, 76%
pulses, 23%
orchards, vegetables, etc. 1%
10-11% of the countries wheat production

Meteorological stations + data



30 Meteorologic stations (rainfall, ETp)

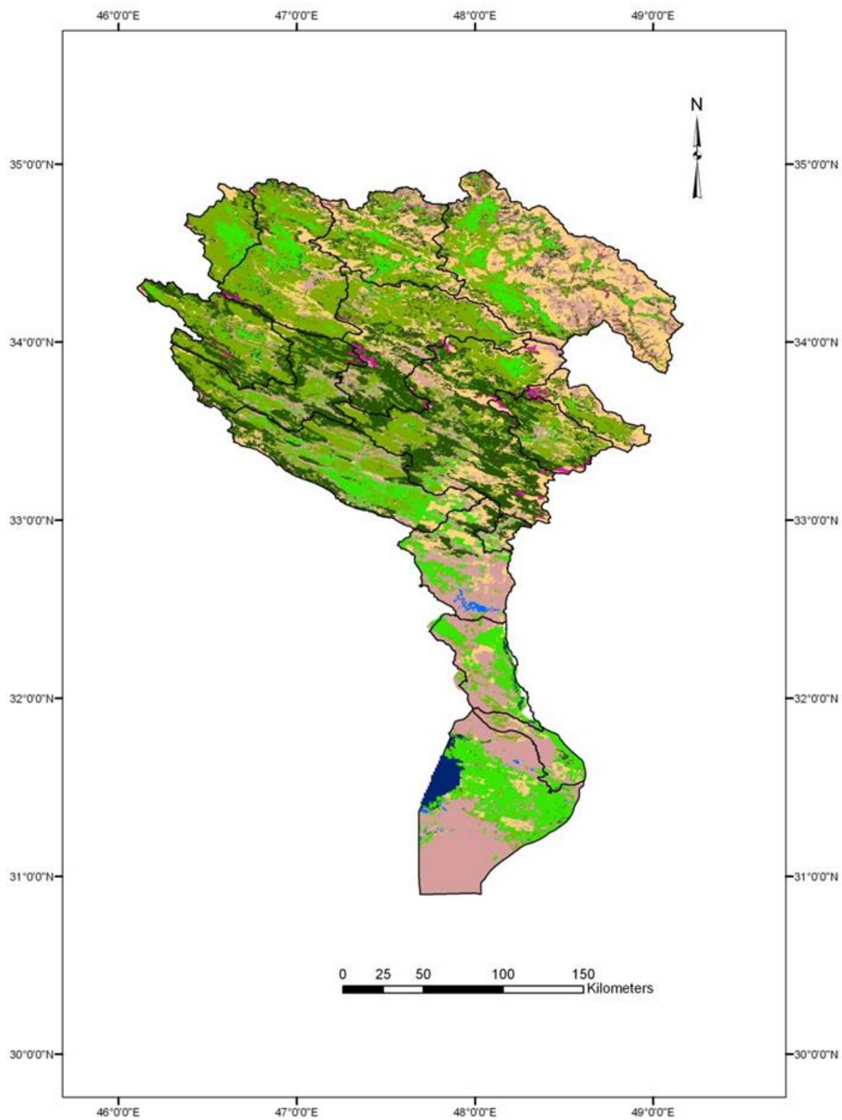
Daily stream flow 15 gauging stations

Inflow and outflow volumes of the Karkheh dam

Shuttle Radar Topography Mission (SRTM) digital

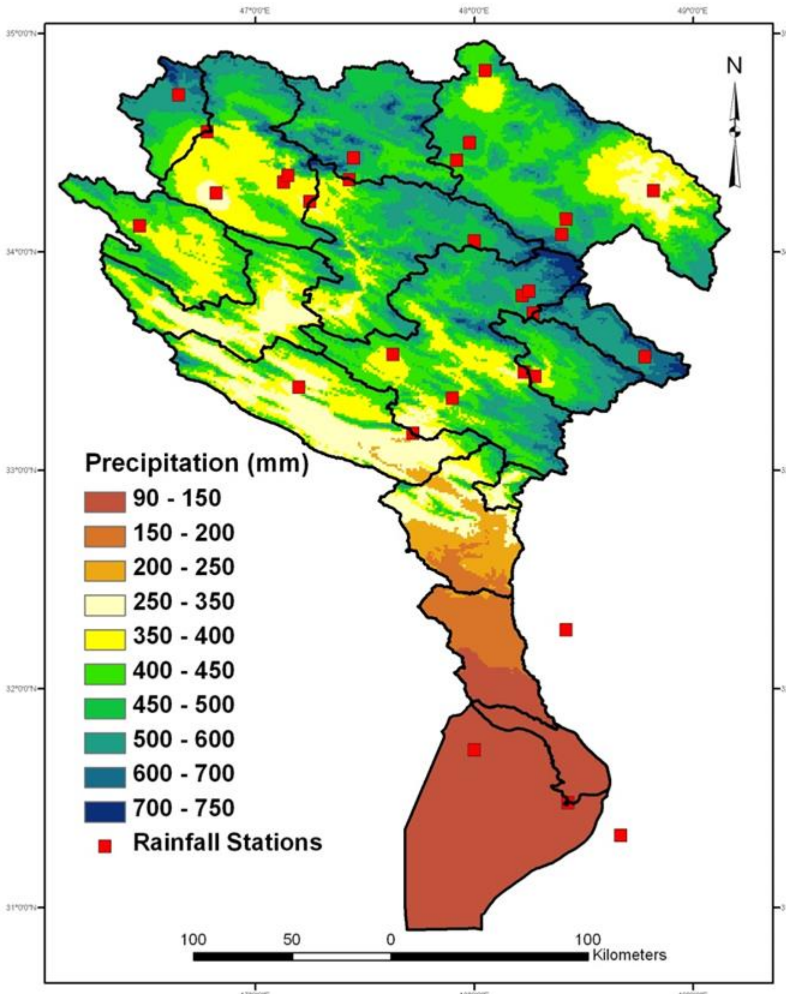
88 cloud free MODIS-TERRA images For estimation of SEBS ETa (April 2000 - December 2004)

Land use



Land use was classified using the time series of MODIS-TERRA (Islam *et al.* 2008) to identify irrigated and rainfed areas.

Precipitation (Rain and Snow)



Muthuwatta, L.P. ,et al., (2010) in *Water Resource Management*

750 mm (north) to 150 mm (south)

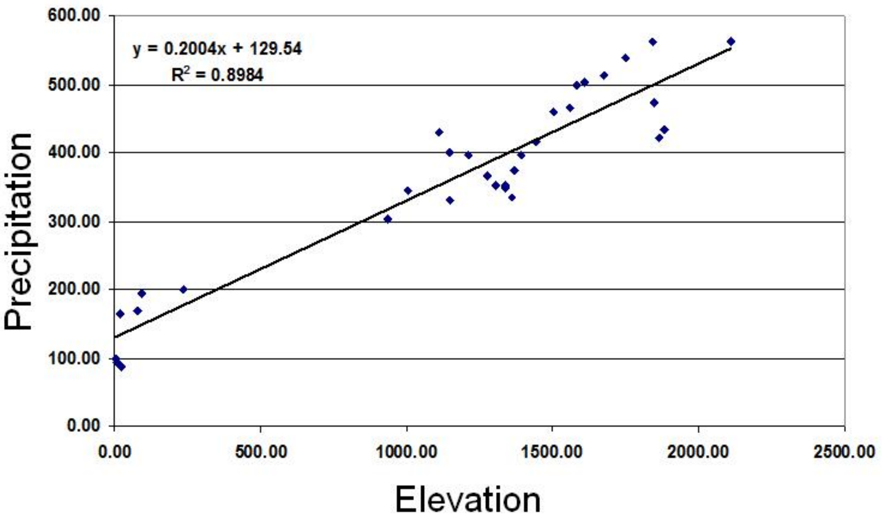
Large variation over space and time

Precipitation laps rate 200 mm/1000m

Records corrected for orographic effects

Data interpolated by Thiessen polygons and Simple Kriging (see left)

Wet season from December - July



ETa by the land surface energy balance (detailed lecture on Friday)

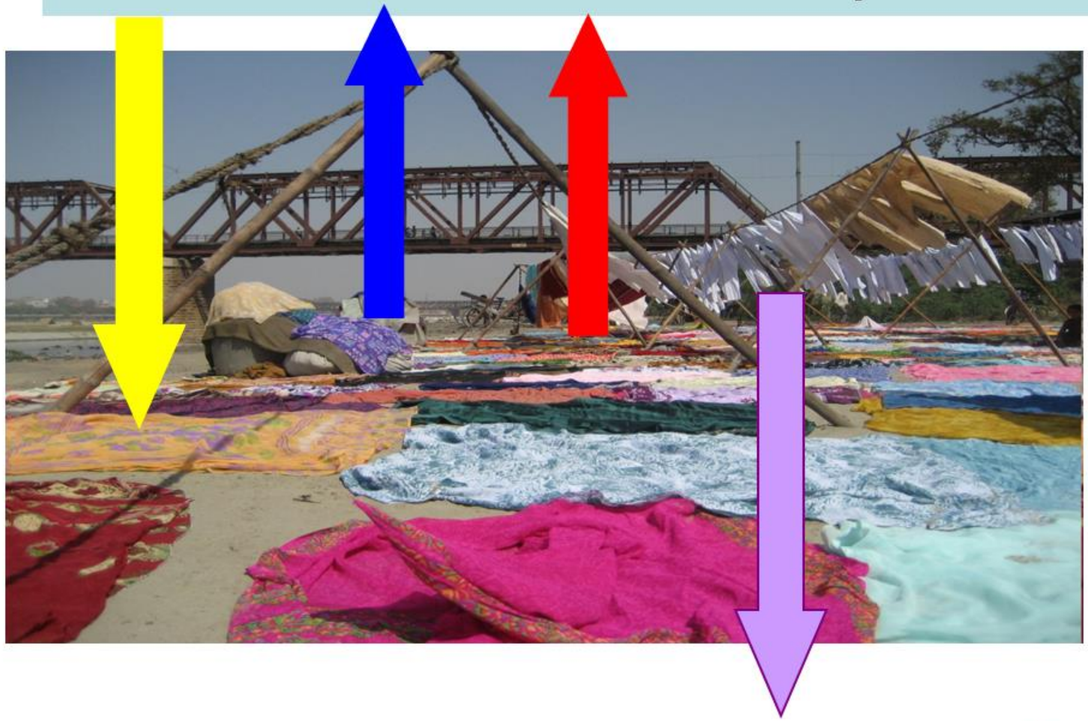
Latent heat flux

Net radiation

Sensible heat flux

Soil heat flux

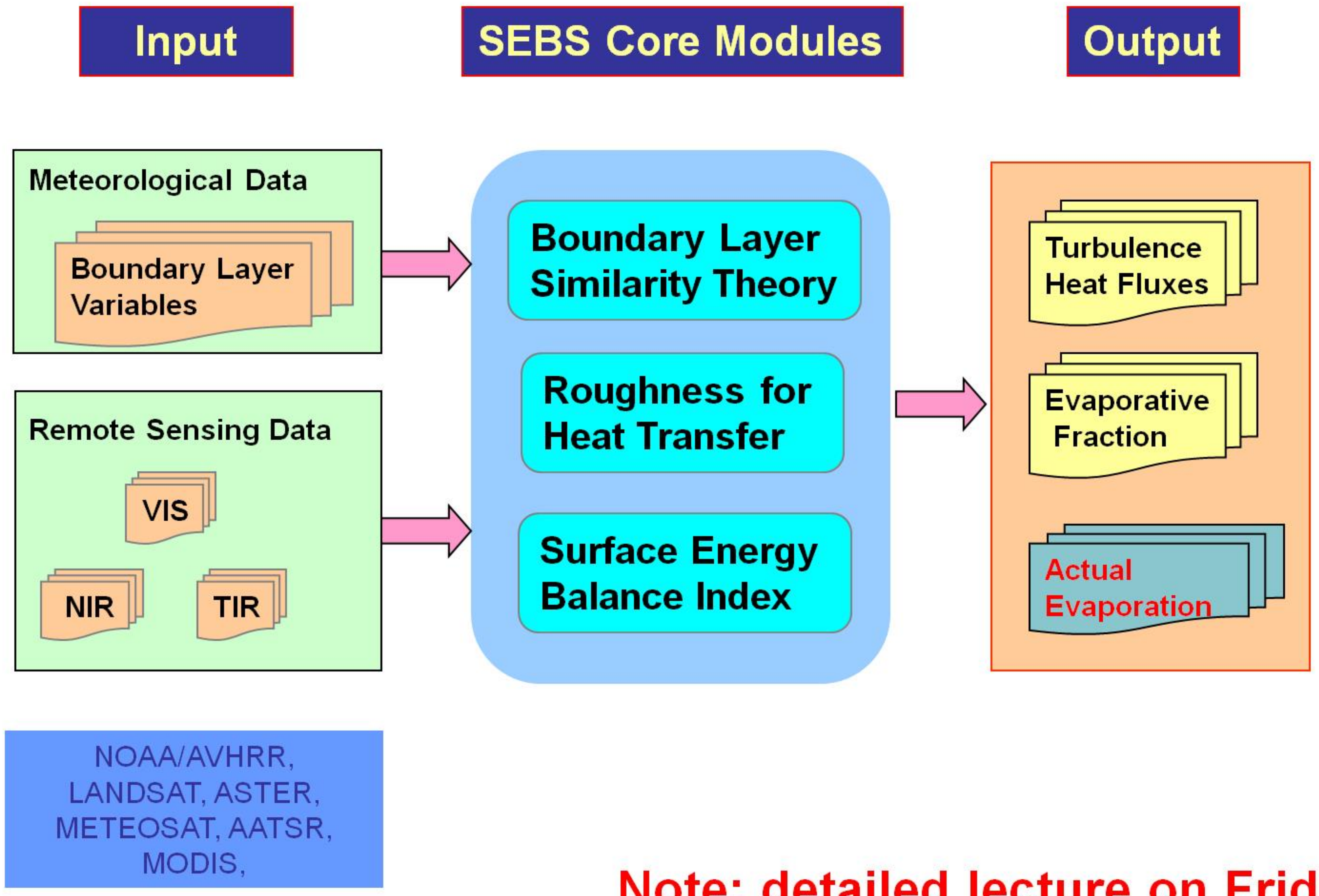
$$Rn = LE + H + G \quad (watt/m^2)$$



Notes a) Latent heat : "measure for evapotranspiration" (Eta)

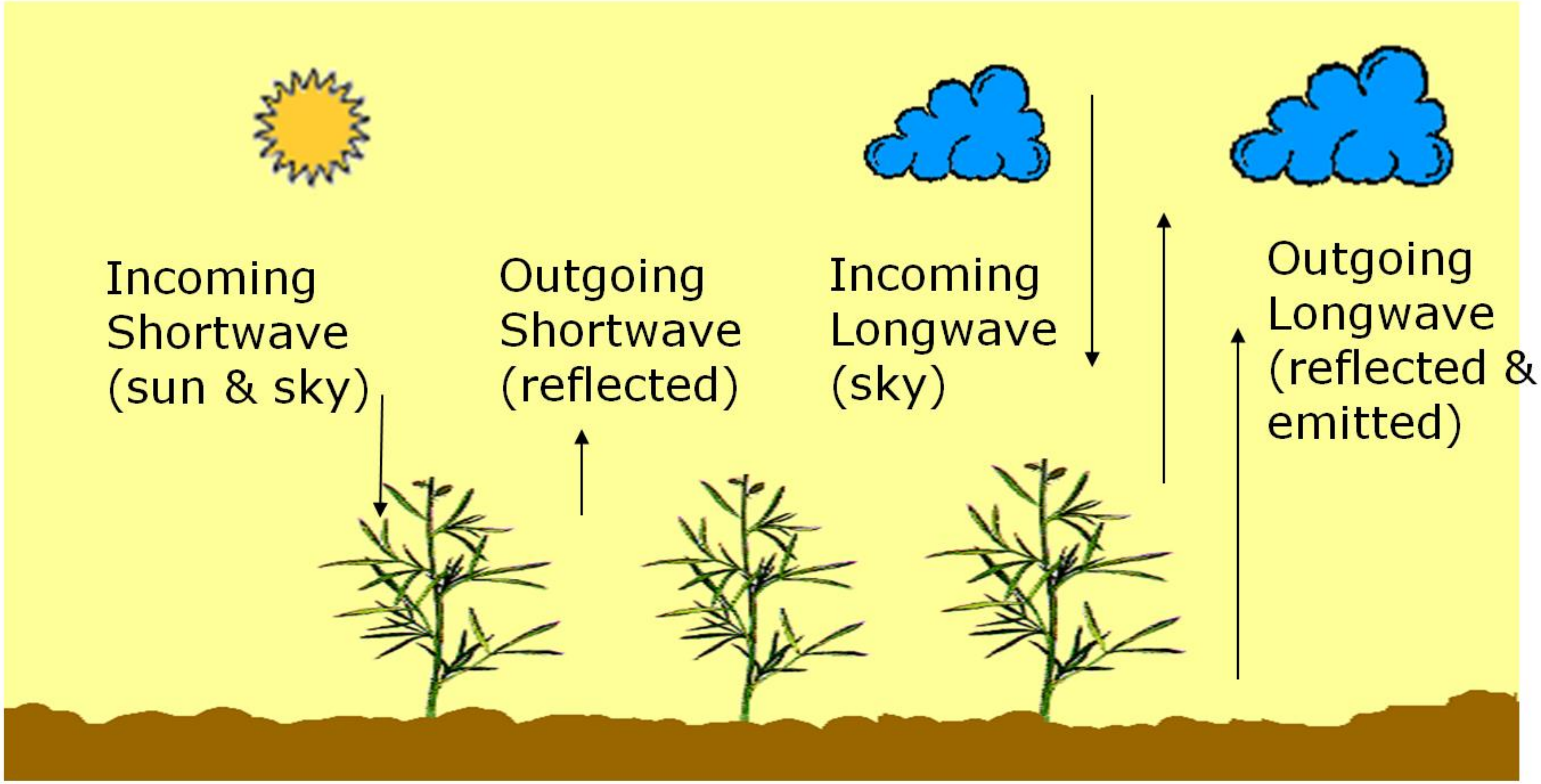
b) The RS approach is to evaluate Rn, G and H to estimate LE

SEBS "Surface Energy balance System"



Note: detailed lecture on Friday

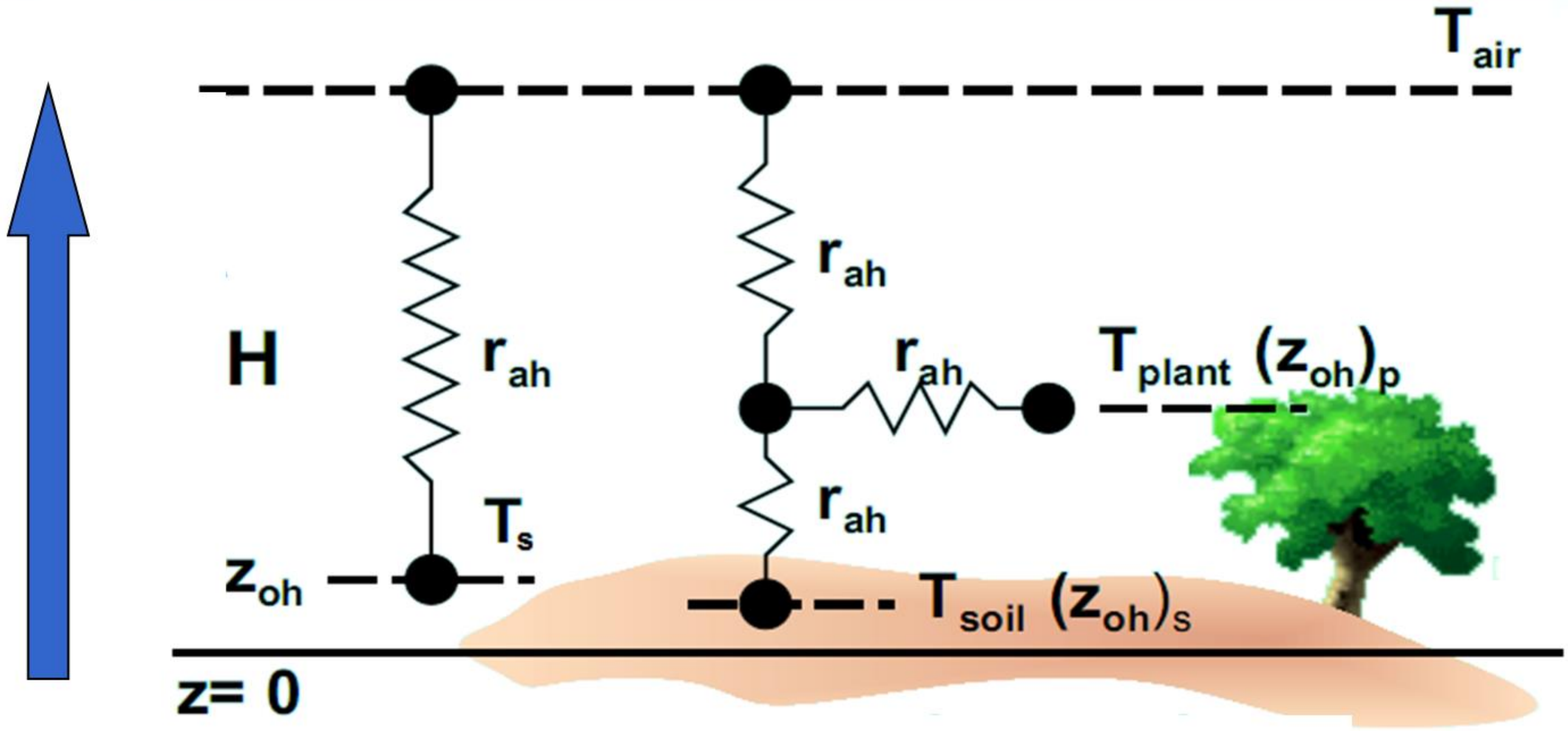
Net radiation at the land surface "R_n"



$$R_n = (1 - r_0)(R^{\downarrow}_{S,sun} + R^{\downarrow}_{S,sky}) + R^{\downarrow}_{L,sky} - R^{\uparrow}_{L}$$

Where r_0 = albedo

Sensible heat flux "H"



$$H = \rho_a C_p \frac{T_s - T_a}{r_{ah}}$$

ρ_a = moist air density

C_p = air specific heat

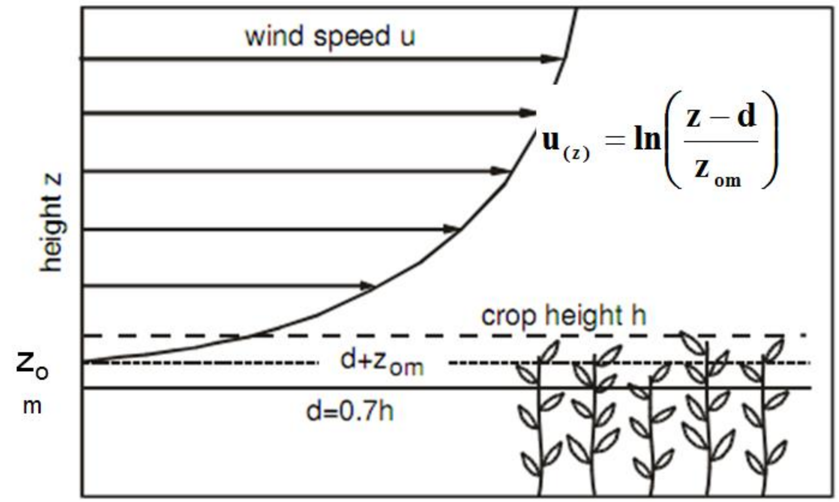
r_{ah} = aerodynamic resistance (iteration)

Heat flow by wind and free convection (ΔT)

Sensible heat flux "H"

Heat flow by wind and free convection (ΔT)

$$r_{ah} = \frac{1}{k^2 u}\left[\ln\left(\frac{z}{z_{om}}\right)\right]\ln\left[\left(\frac{z}{z_{oh}}\right)\right]$$



k = Von Karman's constant (0.41)

u = wind velocity

Z_{oh} = roughness length for heat transport

Z_{om} = height value for which u(z) = 0

TABLE 16.1 Roughness Lengths for Various Surfaces

Surface	z_0(m)
Very smooth (ice, mud flats)	10^{-5}
Snow	10^{-3}
Smooth sea	10^{-3}
Level desert	10^{-3}
Lawn	10^{-2}
Uncut grass	0.05
Fully grown root crops	0.1
Tree covered	1
Low-density residential	2
Central business district	5–10

Source: McRae et al. (1982).

Note a) use of Monin-Obukhov length $L = \frac{-\rho_a C_p u_*^3 T_a}{kgH}$

b) z_{oh} relates to z_{om} $\quad z_{oh} = z_{om} / \exp(kB^{-1})$

B^{-1} is the inverse of the Stanton number

Soil heat flux "G"

$$G_0 = R_n .\left[r_c + \left(1 - f_c\right).\left(r_s - r_c\right)\right]$$

r.. = ratio of soil heat flux to net radiation

r_c = 0.05 for full vegetation canopy (Monteith, 1973)

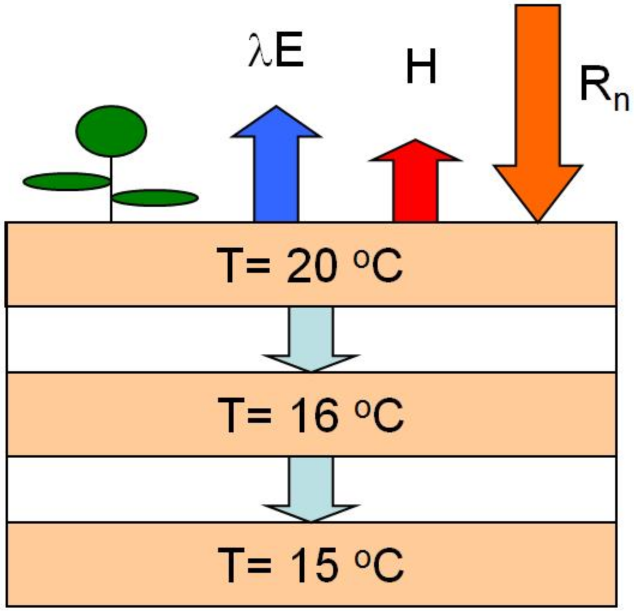
r_s = o.315 for bare soils (Kustas and Daughtry 1989)

f_c = fractional canopy coverage

or/and

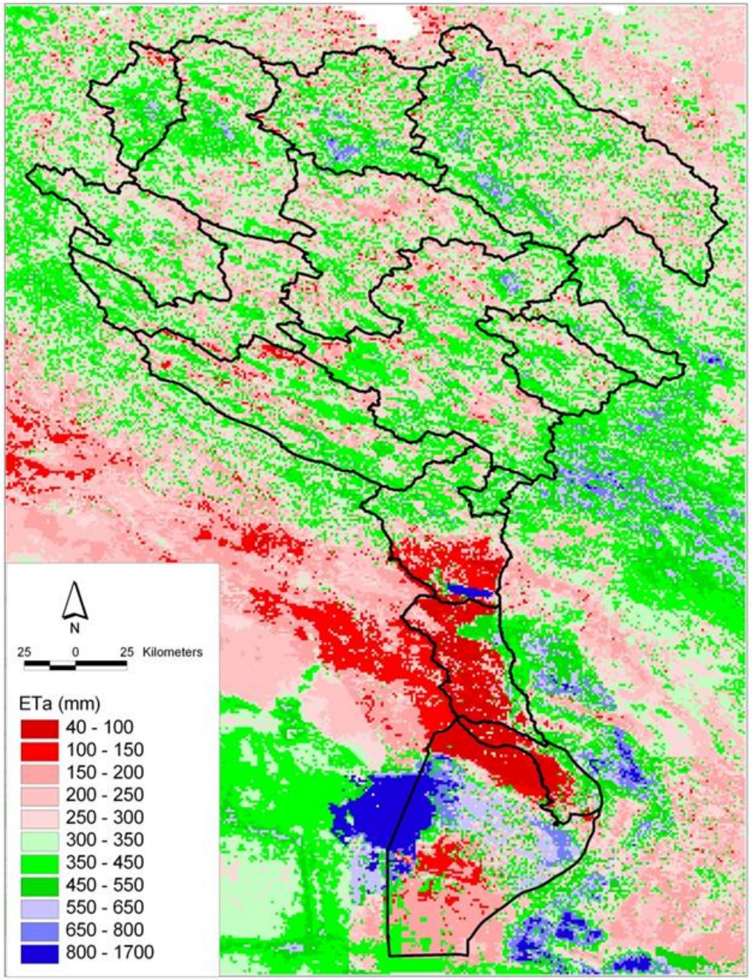
$$G_0 = -\kappa \frac{\partial T}{\partial z}$$

κ	Heat conductance	$W\ m^{-1}\ K^{-1}$
T	Soil temperature	K (or °C)
z	Soil depth	m



But at daily time step G_o is often taken at "0"

Annual Evapotranspiration estimates by SEBS



Muthuwatta, L.P. ,et al., (2010) in *Water Resource Management*

Image shows accumulated ETa for Nov. 2002 to Oct. 2003

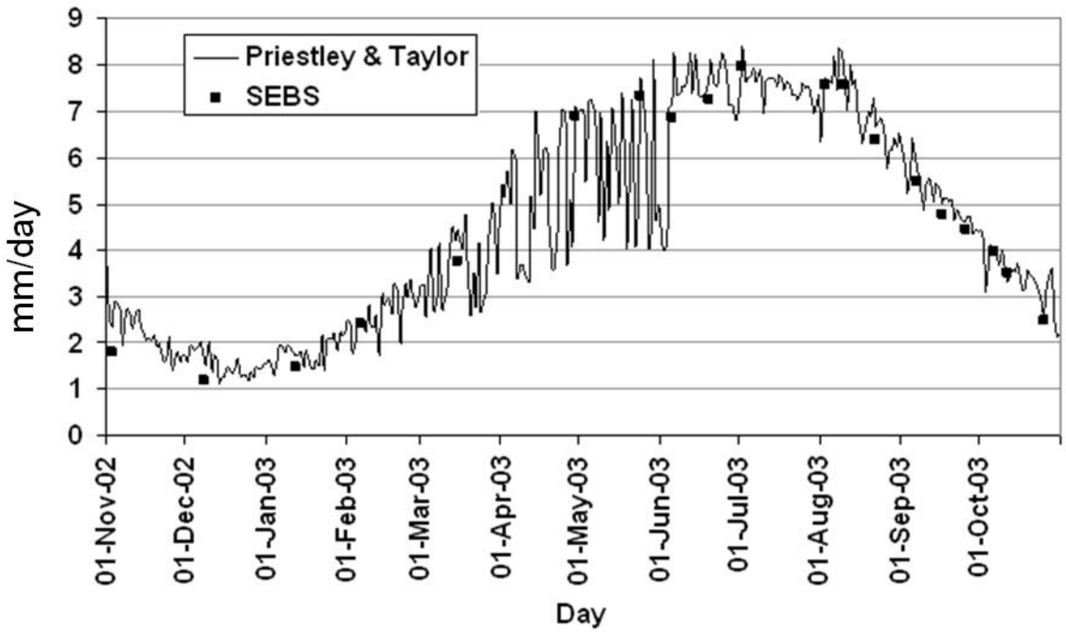
Highest value 1,681 mm in the Karkheh reservoir and swamp area

Lowest value 41 mm for bare land/desert areas downstream of the Karkheh dam.

Cropped areas show large spatial variations in the annual ETa

Irrigated areas in both Upper and Lower Karkheh are characterized by high ETa values

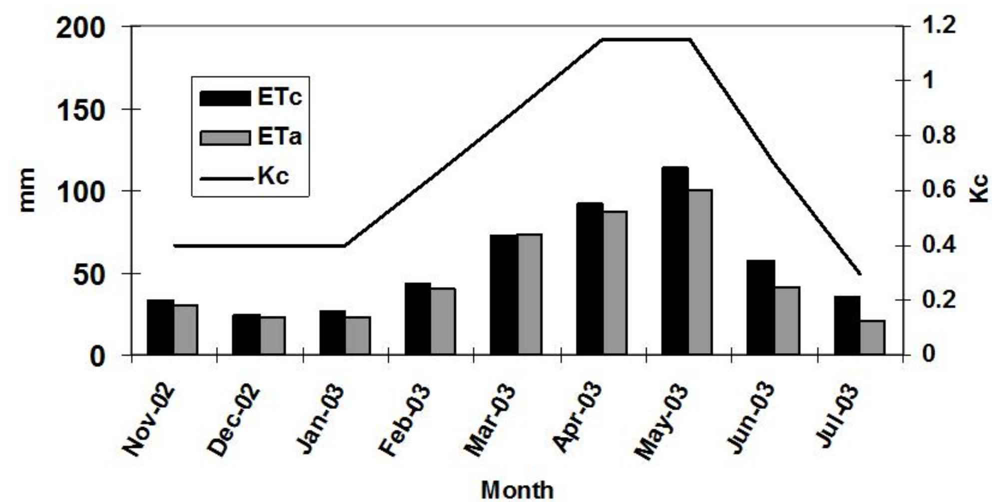
Evapotranspiration: validity of SEBS estimates



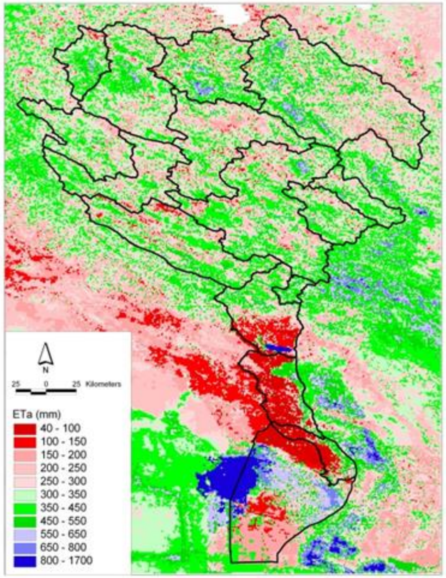
Comparing SEBS estimated ETa with the Priestley & Taylor ETo in the swamp of the Lower Karkheh Basin (19 images).

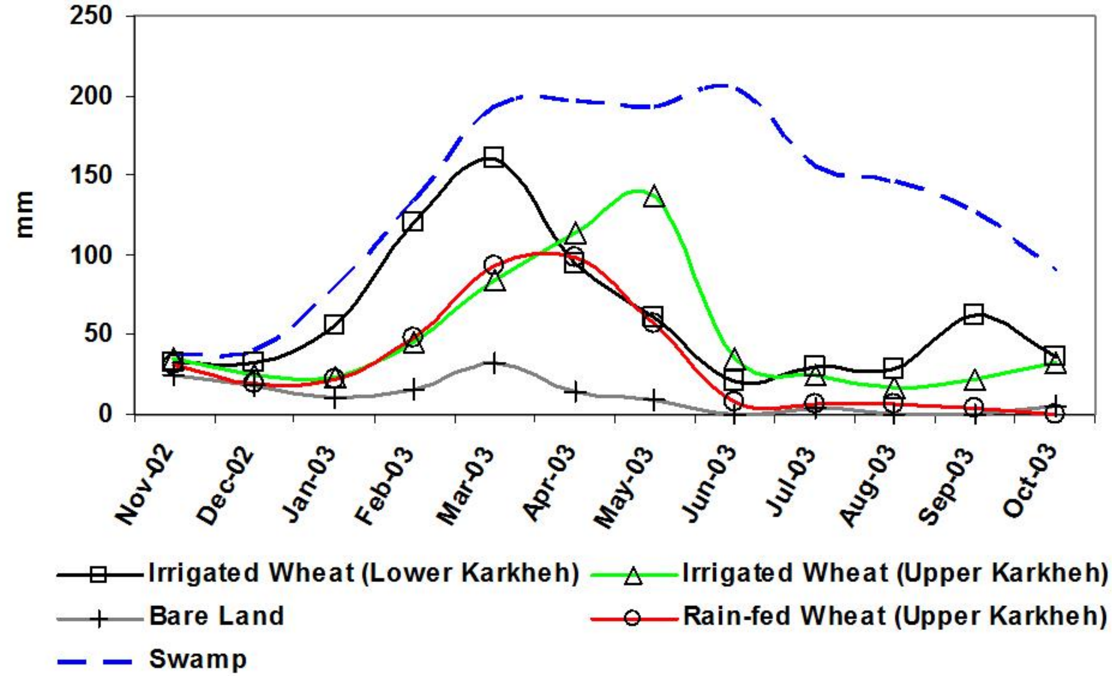
***ET*$_a$ at a wheat area compared to *ET*$_c$ for Kangavar meteorological station upper Karkheh Basin**

Crop coefficients (*Kc*) for wheat as obtained from FAO56 (Allen et al. 1998).



Crop water consumption (per subbasin per day)





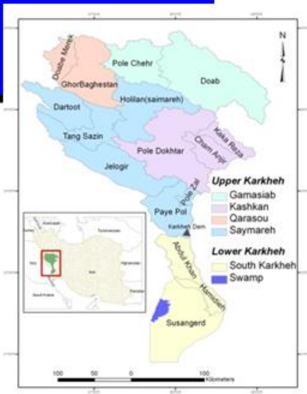
Difference in patterns due to different cropping periods and atmospheric forcing

- **Lower Karkheh has earlier crops**
- **Upper Karkheh has longer cropping season**
- **Nov – Dec has low atmospheric forcing**

Water Scarcity at major subbasins

Water balance in ($m^3 x 10^6$) from November 2002 to October 2003

Sub-basin	Precipi -tation (P)	Surface inflow (Q_{in})	SEBS Eta	Surface/ Reservoir change in storage (ΔS_S)	Surface outflow (Q_{out})	DR %
Gamasiab	4784	-	3697	-	742	7.2
Qarasou	2230	-	1764	-	399	3.0
Kashkan	4108	-	3143	-	939	0.6
Saymareh	6437	2079	5223	368	2851	1.1
Upper Karkheh	17559	-	13827	368	2851	2.9
Lower Karkheh	948	2880	2853	-	Not available	
Whole basin	18507	-	16680	368	1459*	



$$\text{Drainage ratio} = (P + Q_{in} - ET_a - \Delta S_S - Q_{out}) \times 100 / (P + Q_{in})$$

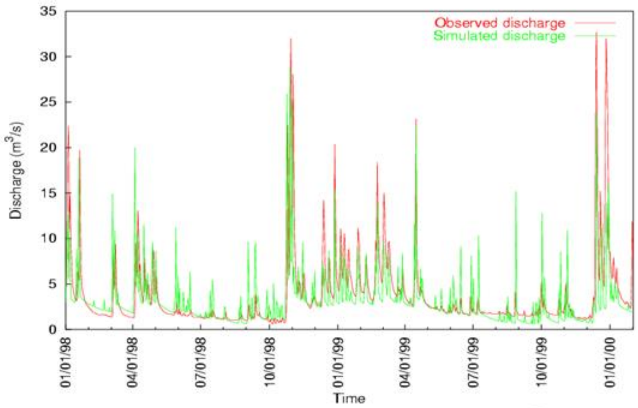
$$\text{Drainage ratio} : ((18507-16680) - 368) / 18507 = 7.8\%$$

The basin is "very water scarce"

Stream flow modeling: approaches to calibration

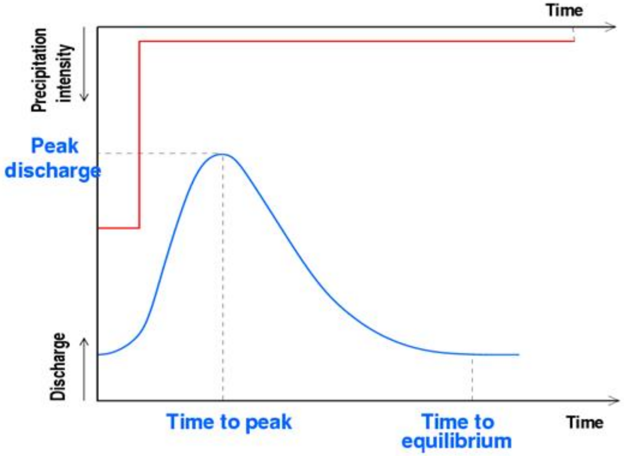
Single-objective calibration (1975-1990)

- Peak flows or Stream flow volumes
- Stream flow hydrographs for Rainfall-Runoff
- Assessments rely on a single objective (function) such as e.g. RMSE or NS



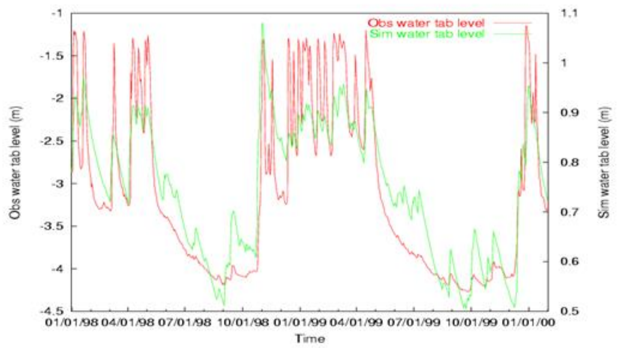
Multi-objective calibration (1990-2005)

- Common in stream flow modeling
- Multiple objectives defined for a single variable: Time to peak and Peak discharge
- Much effort on development of efficient optimization algorithms



Multi-variable calibration (2005 - present)

- Rely on 1 state variable + 1 flux term
- Piezometer heads + Stream flow
- Moisture + stream flow
- No assessment on reproduction of the WB
- No assessment on closure of the WB



Stream flow modeling: multi-variable calibration

Reproduction of the WB + closure assessment (3 Cases)

1) **Calibration on stream flow (how well is stream flow represented)**
   - model performance assessment on ETa

2) **Calibration on ETa (how well is ETa represented)**
   - model performance assessment on Stream flow

3) **Calibration on stream flow and ETa**

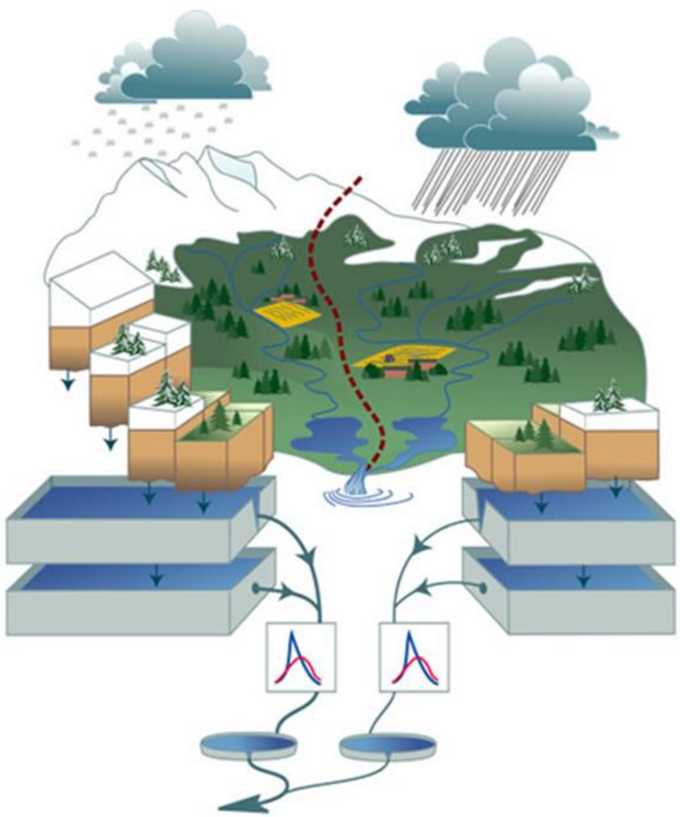
So how reliable are our models?

How robust is a model structure?

How uncertain are parameters?

How do we close the water balance

Stream flow modeling : The HBV-96 model (Lindström1997)



Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology 201, 272-288.

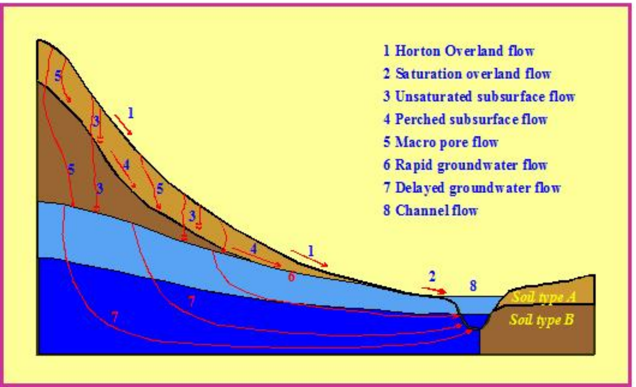
Seibert, J., 1999. Regionalisation of parameters for a conceptual rainfall-runoff model. Agricultural and Forest Meteorology 98-99, 279-293.

Merz, R., Blöschl, G., 2004. Regionalisation of catchment model parameters. Journal of Hydrology 287, 95-123.

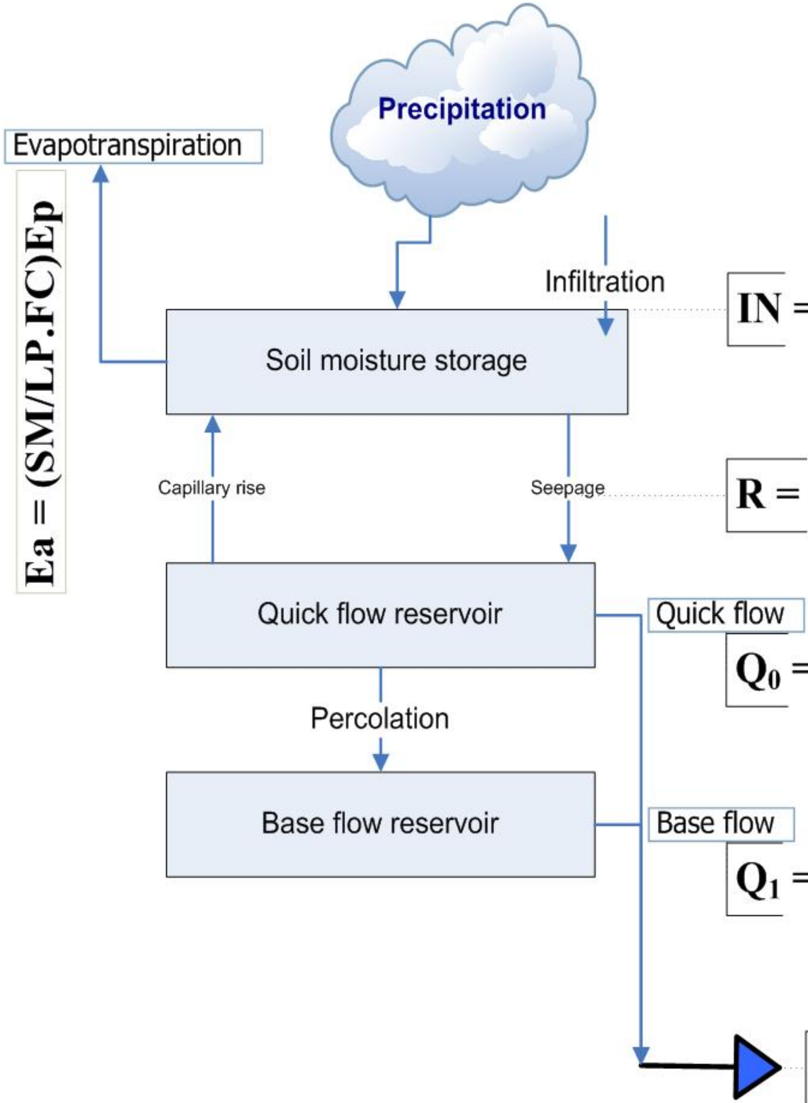
.....

....

Over 150 papers so a widely accepted model i) robust, ii) parsimonious iii) simple descriptions iv mass conservative iv etc.



The HBV approach (we used a lumped version)



$$IN = P - DR$$

$$R = IN \,.\, (SM/FC)^{(BETA)}$$

$$Q_0 = K_f \,.\, UZ^{(1+ALFA)}$$

$$Q_1 = K_s \,.\, LZ$$

$$Q = Q_0 + Q_1 + DR$$

Parameter ranges

Name	Prior range
FC	100 - 800
BETA	1 - 4
CFLUX	0 - 2
LP	0.1 - 1
ALFA	0.1 - 3
K_f	0.0005 - 0.15
K_s	0.0005 - 0.15
PERC	0.1 - 2.5

How to select optimal parameter values ?

MC-Model calibration for an aggregated function Y

Objective functions

$$RVE = \left(\frac{\sum_{i=1}^{n} \left(Q_{sim,i} - Q_{obs,i} \right)}{\sum_{i=1}^{n} Q_{obs,i}} \right) \times 100\%$$

Range: -∞ to + ∞

Best: 0%

Accept: between ±5%

$$NS = 1 - \frac{\sum_{i=1}^{n} (Q_{sim,i} - Q_{obs,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q_{obs}})^2}$$

Range: -∞ to 1

Best: 1

Accept: > 0.6

- Randomly selected par. values
- Robust sets (not the single best)
- Best set selected by Y
- Y combines Overall fit (NS) and volume error (RVE)
- Other functions possible though

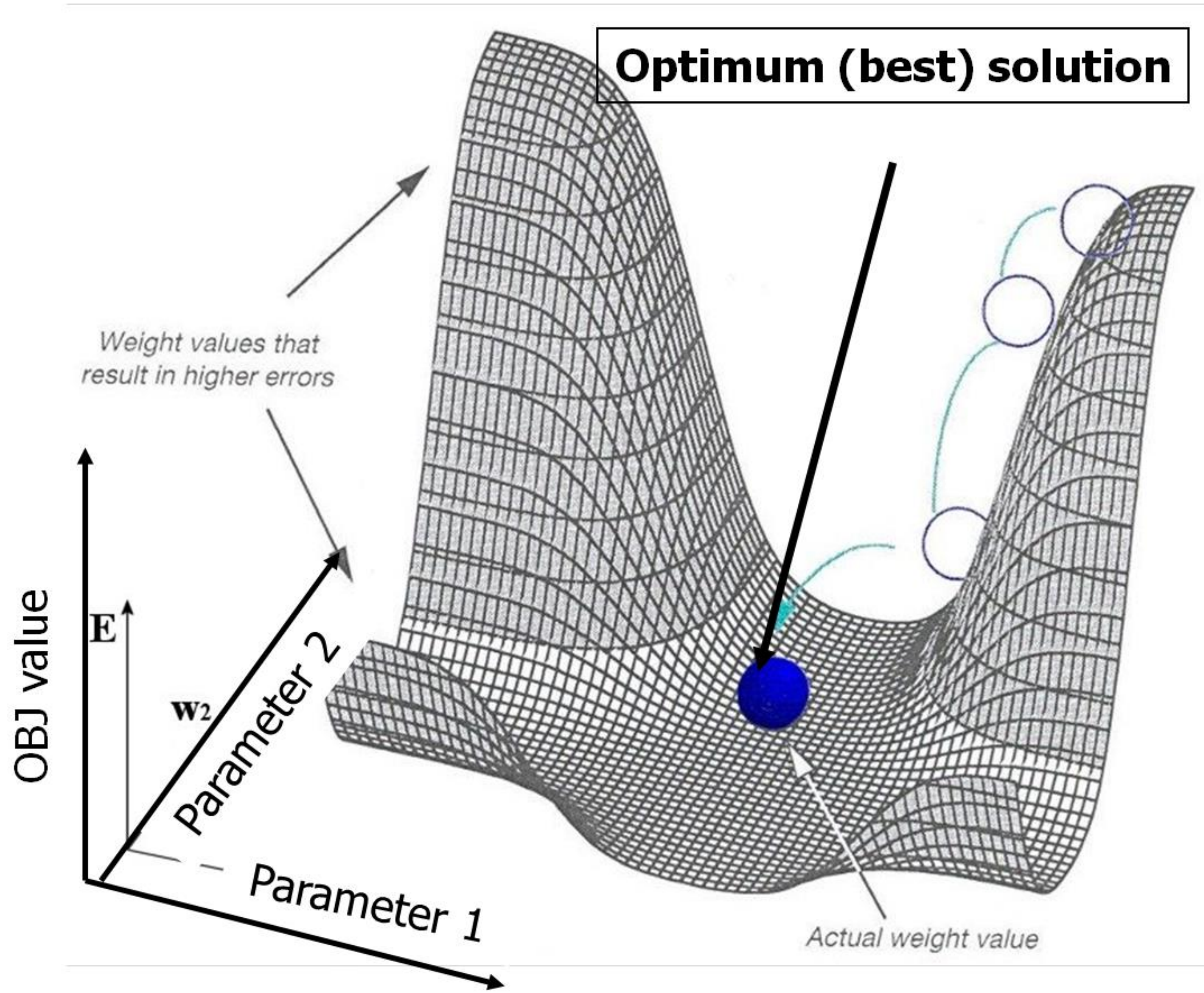
$$Y = \frac{NS}{1 + |RVE|}$$

Range: 0 to 1

Best: 1

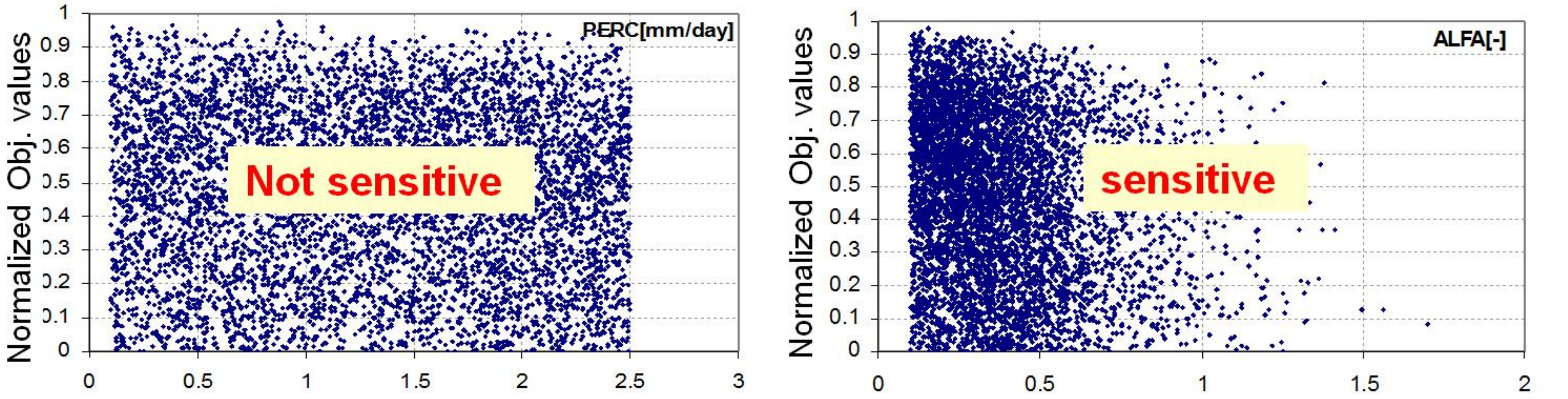
Accept: > 0.6

Calibration: Best Obj.Function value (e.g. NS or RVE)

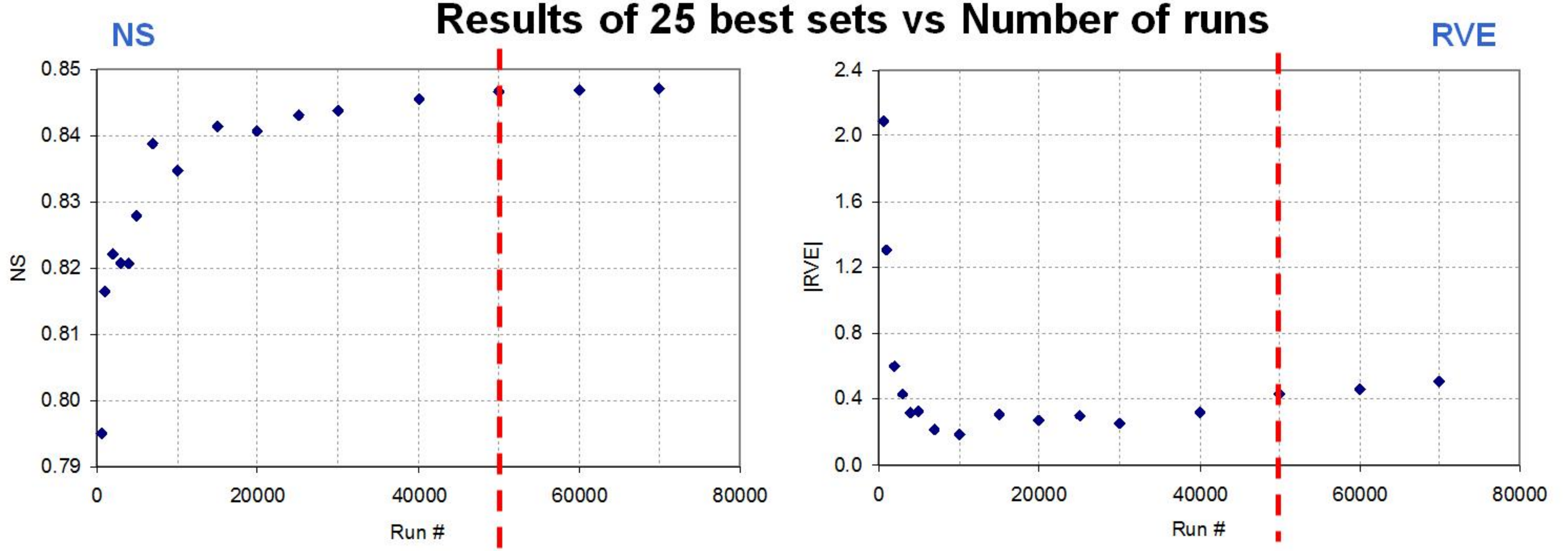


Monte Carlo simulation - Selecting run number

Parameter sensitivity

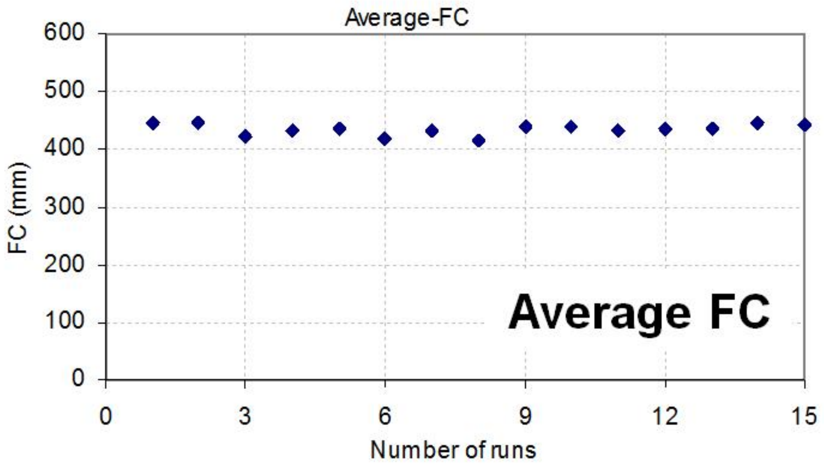


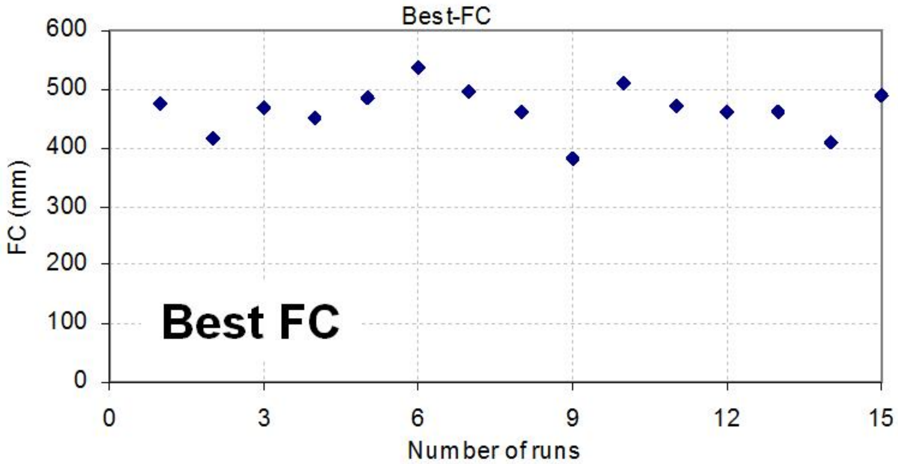
Results of 25 best sets vs Number of runs

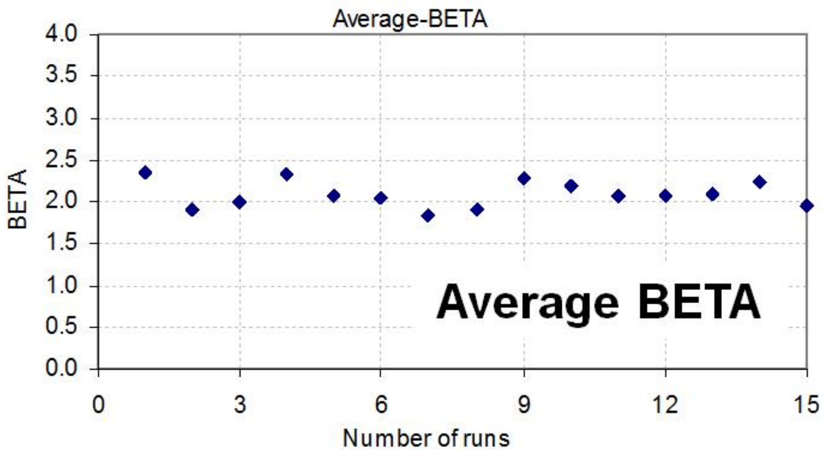


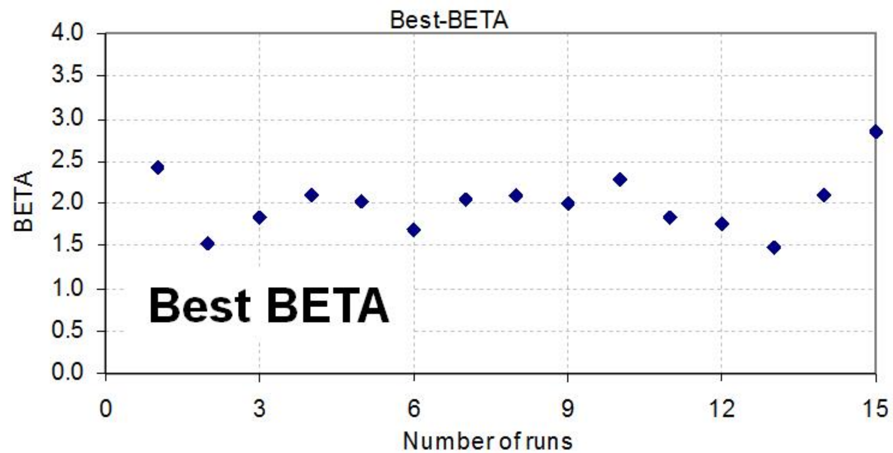
Model calibration - Selecting optimum parameter set

Each run number stands for 50.000 runs





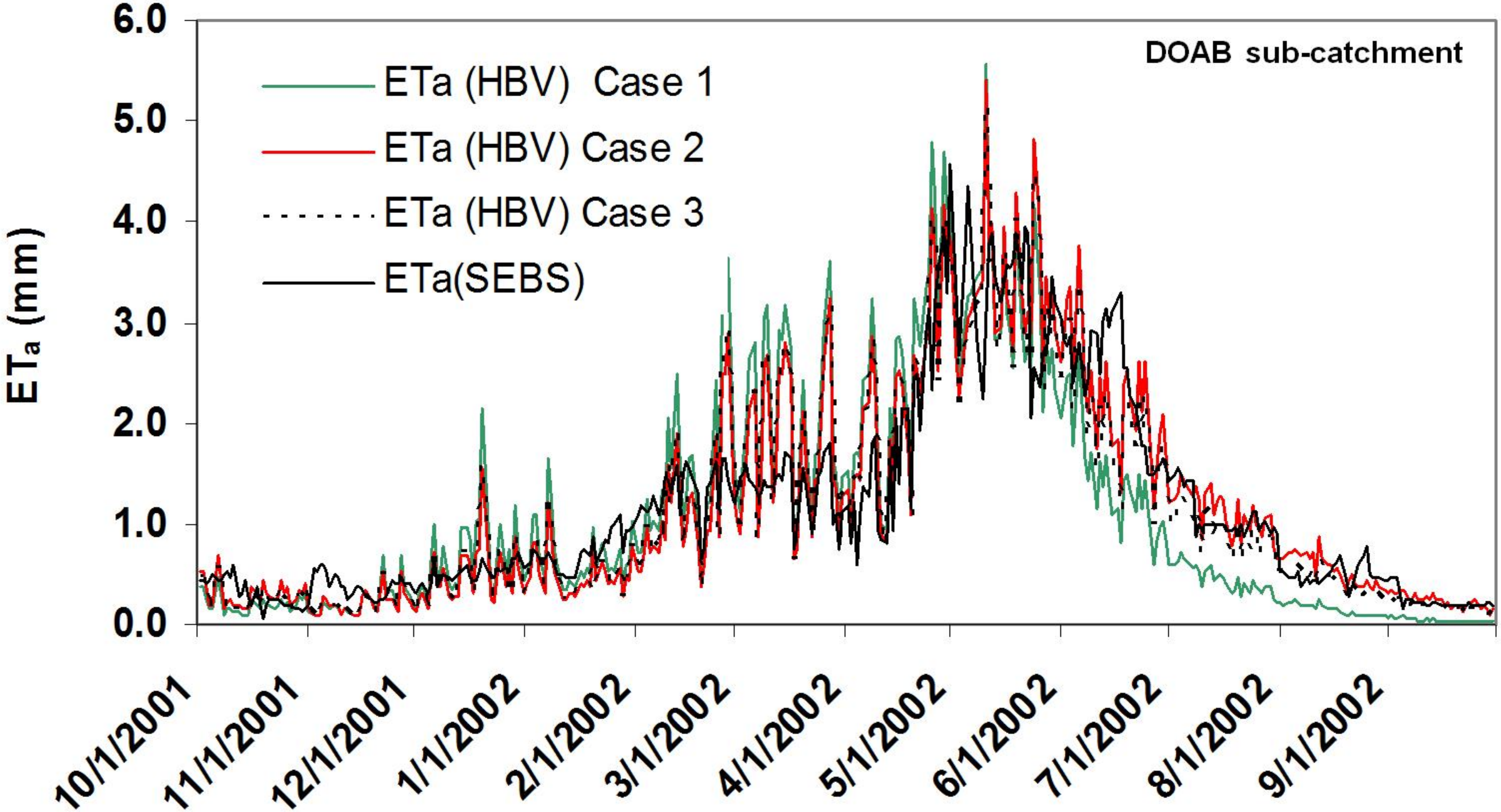




The average of the 25 runs is taken for further use

Best implies the single best value !

HBV-96 daily ETa vs SEBS based daily ETa

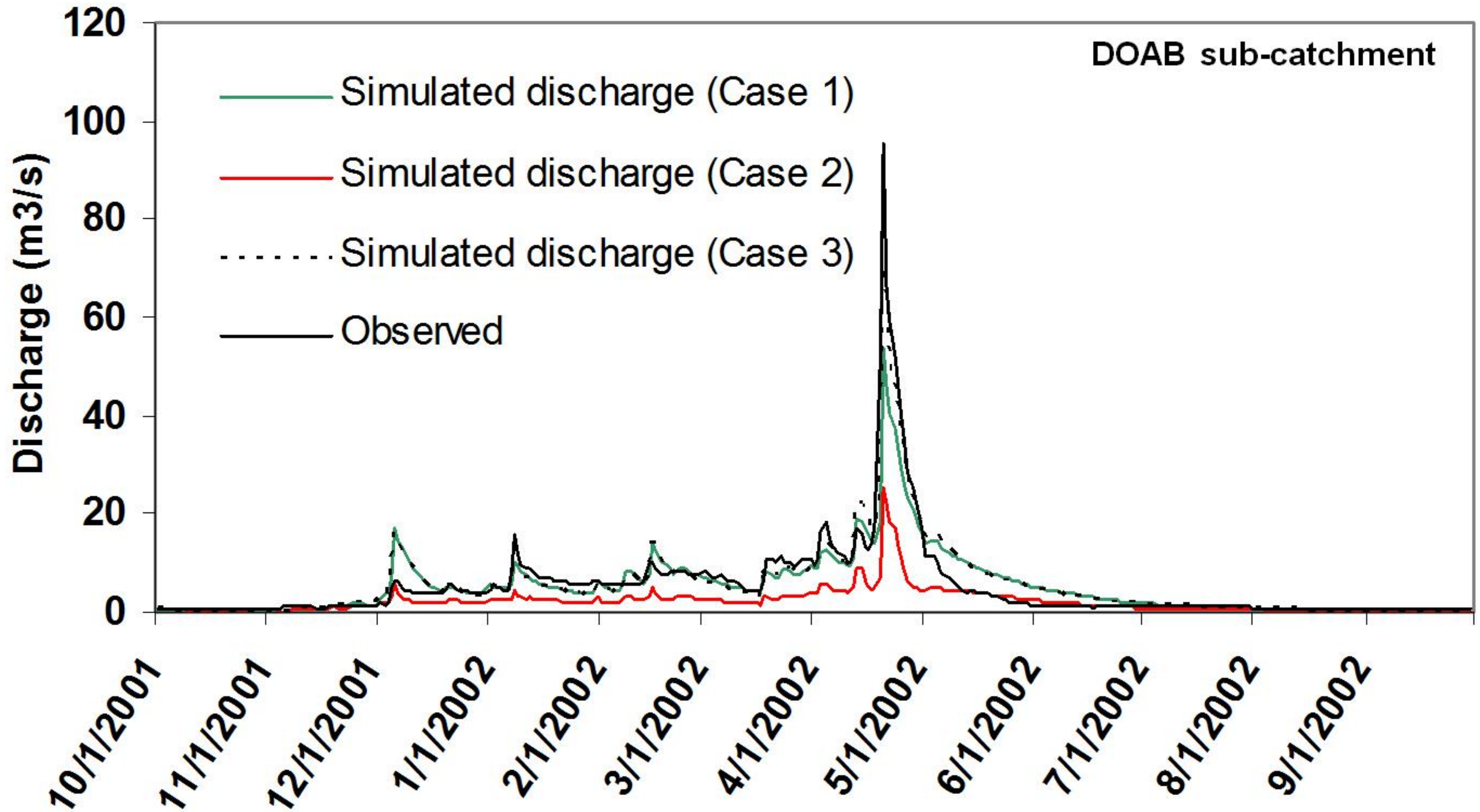


Case 1 Calibrate on Qs assessment on ETa

Case 2 Calibrat on ETa assessment on Qs

Case 3 Calibrate on Qs and ETa

Comparison of simulated daily stream flow

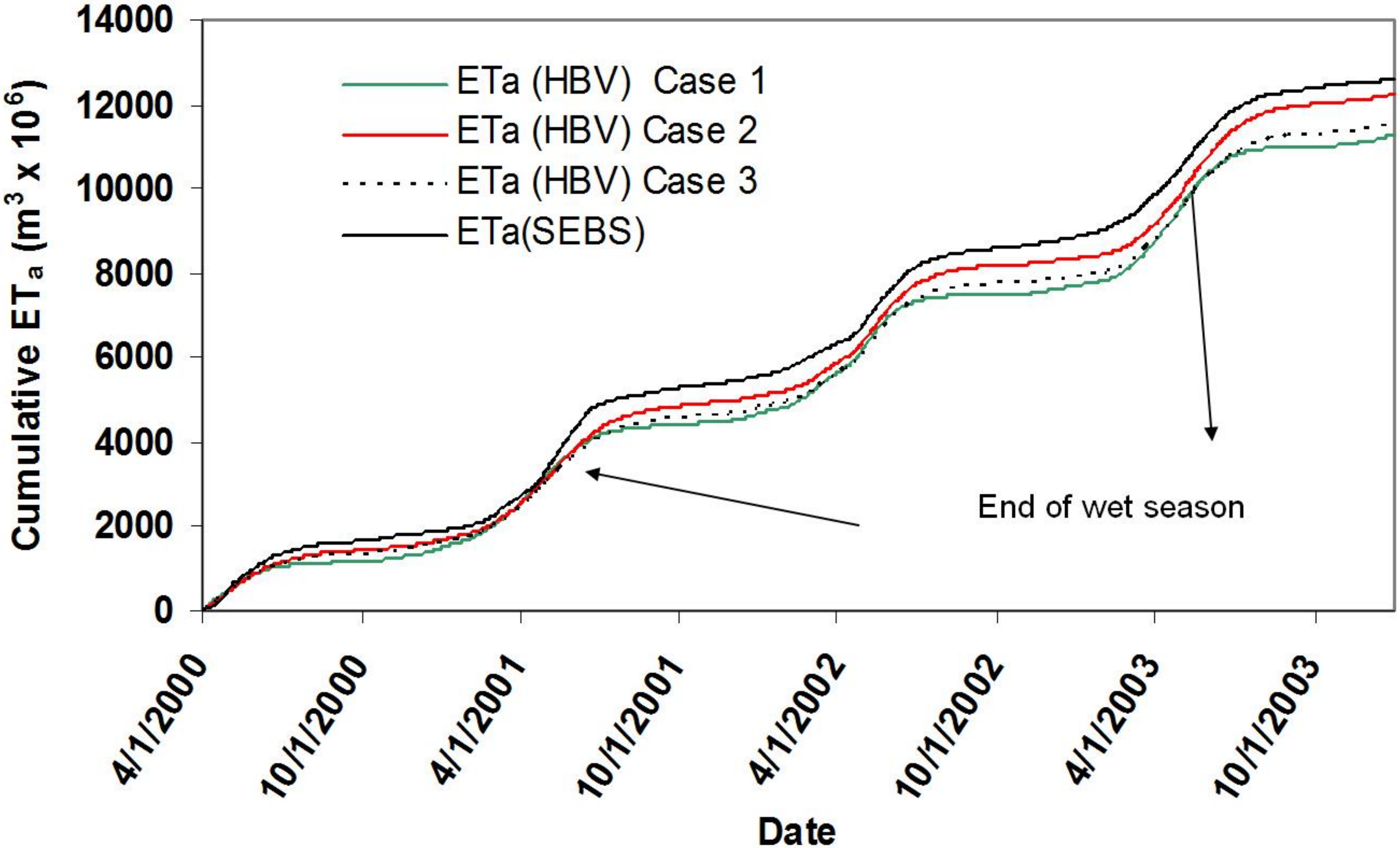


Case 1 Calibrate on Qs assessment on ETa

Case 2 Calibrat on ETa assessment on Qs

Case 3 Calibrate on Qs and ETa

Cumulative daily ETa from the HBV-96 approach and the SEBS approach

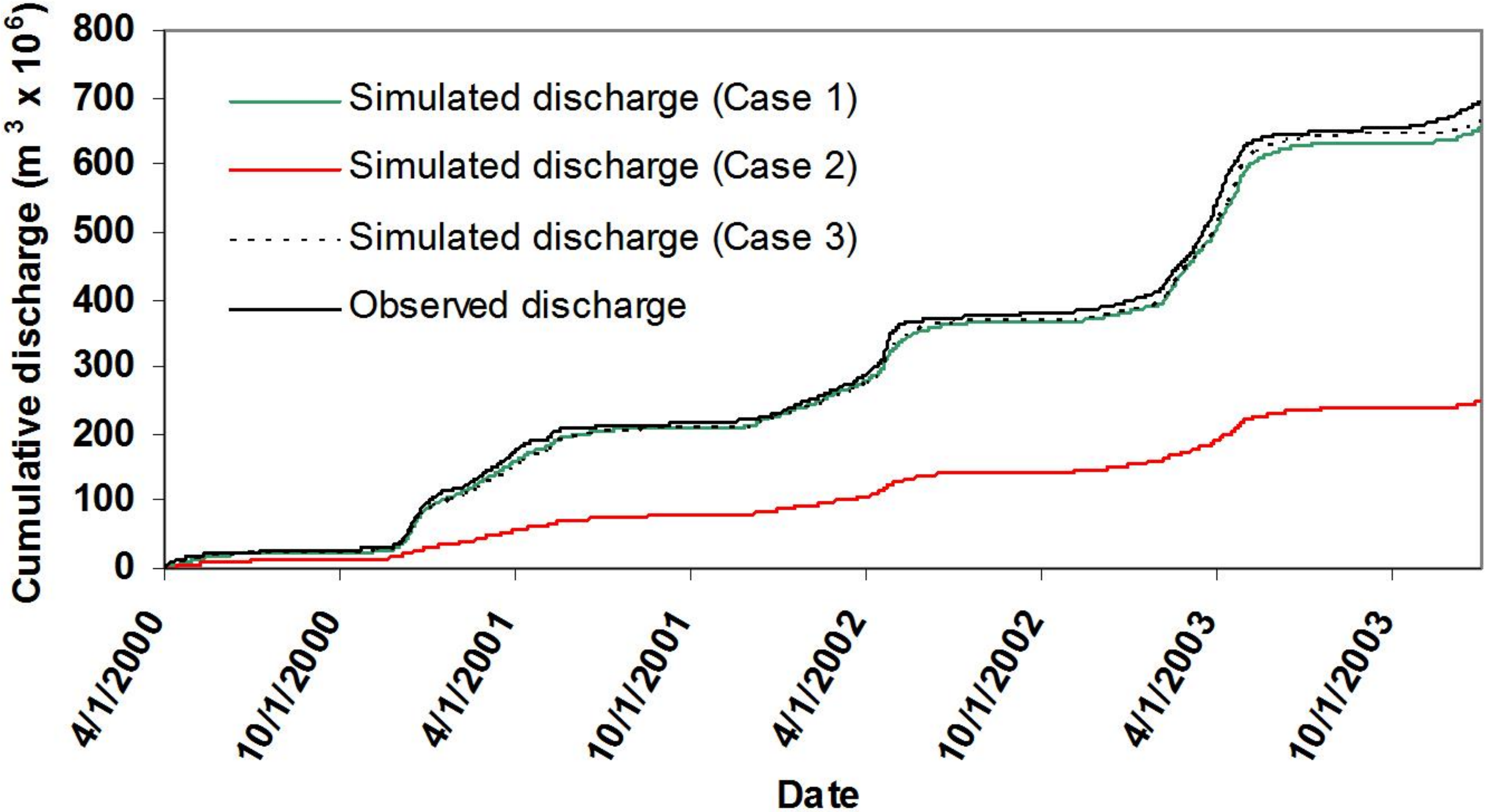


Case 1 Calibrate on Qs assessment on ETa

Case 2 Calibrat on ETa assessment on Qs

Case 3 Calibrate on Qs and ETa

Cumulative daily stream flow Qs



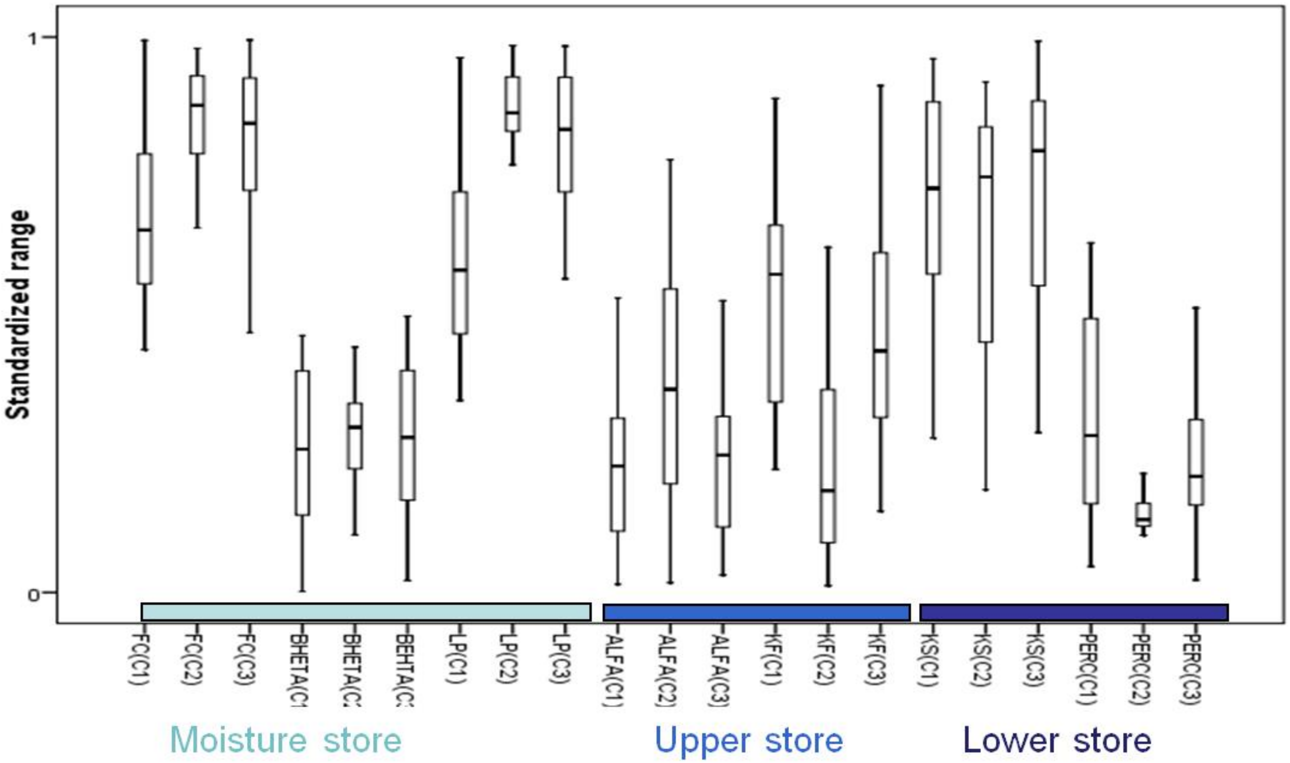
Case 1 Calibrate on Qs assessment on ETa

Case 2 Calibrat on ETa assessment on Qs

Case 3 Calibrate on Qs and ETa

Note : A large water balance error is observed for case 2 so the water balance is not well reproduced by the model

Results: Uncertainty of 25 best parameter sets



Box-whisker plots of parameters standardized by the prior range

- median
- Upper + lower quartiles
- 1.5 interquartile range

Optimized parameter values for stream flow calibration ≠ ETa calibration and cause poor simulation result for the variable that closes the water balance

'Soil moisture' store: parameters are most uncertain for stream flow calibration

'Upper store' reservoir: parameters are most uncertain for ETa calibration

'Lower store' reservoir: PERC is the least uncertain for ETa calibration

Results of (multi-variable) calibration

Sub- basin	Case	SV Calibration				MV Calibration		
		Y_Q	Y_{ETa}	Y_{TOT}		Y_Q	Y_{ETa}	Y_{TOT}
Doab	1	0.86	0.48	0.68		0.86	0.48	0.68
	2	0.32	0.66	0.48		0.32	0.66	0.48
	3	0.85	0.63	0.74		0.85	0.63	0.74
Pole Chehr	1	0.78	0.39	0.59		0.78	0.39	0.59
	2	0.41	0.72	0.56		0.41	0.72	0.56
	3	0.73	0.71	072		0.73	0.71	072
Doabe Merek	1	0.80	0.52	0.66		0.80	0.52	0.66
	2	0.52	0.74	0.63		0.52	0.74	0.63
	3	0.74	0.73	0.73		0.74	0.73	0.73
GhorBaghestan	1	0.65	0.43	0.54		0.65	0.43	0.54
	2	0.31	0.78	0.53		0.31	0.78	0.53
	3	0.62	0.72	0.66		0.62	0.72	0.66

$$Y_{TOT} = (cv_q \times Y_Q) + (cv_{ET_a} \times Y_{ET_a})$$

Conclusions

- Total drained water is 1457×10^6 m^3/year ; only 7.8% of precipitation
- The basin is very water scarce (drainge ratio < 0.1)
- RS based ET_a is effective to assess water productivity in a spatial distributed manner
- Single variable calibration results in poor representation of the basin water balance and may results in large water balance errors
- Multi-variable calibration is preferred with good performance for both variables
- Simulation results indicate deficiencies in the HBV'96 model structure
- Monte Carlo simulation was effective to assess parameter uncertainty
- Etc.

Questions....? Are wellcome but not by reviewers anymore..

Name	Date modified	Type
1st Resubmission JoH	24-9-2013 9:05	File folder
2nd Resubmisssion JoH	6-2-2013 12:39	File folder
3rd Resubmission JoH	20-8-2013 13:11	File folder
4th Resubmission JoH	19-7-2013 16:23	File folder
5th Submission JoH 23_07_2013	6-9-2013 11:02	File folder
6th Submission JoH	24-9-2013 8:58	File folder

Reviewer 1 : How about the hypothesis of spatially uniform ET_a (Line 408)? Do we really need a spatially ET_a, and what information is lost when calculating a lumped ET_a from a distributed one? The adequacy between lumped and spatial data needs to be discussed.

Reviewer 2 L538: Does the SEBS ET_a be considered the real world actual evapotranspiration? Please justify from the literature.

Reviewer 3 : the use of satellite based actual evapotranspiration (ET_a) in addition to observed stream flow is new and original, but the conclusions of the paper stated only that these techniques "for model calibration showed promising results“ => Highlight clearly the main results of this paper

Reviewer 4 : The SEBS model used for this study to retrieve ET was validated by Su (2002) using high-resolution data (18.5 m). The key assumption that SEBS results "represent the real world actual evapotranspiration" (L.415) is not sufficiently argued.

Reviewer 5 : Could the authors clarify if they also used naturalized streamflow data, and if not, how could it influence your results? Do you think that it would be consistent to calibrate a rainfall-runoff with naturalized streamflow if satellite-based ET data are used, as these data are supposed to represent the actual evapotranspiration over irrigated crops?

Questions....? Are wellcome but not by reviewers anymore..

Reviewer 6 : The authors assert that they accounted for the precipitation uncertainty but they only considered the in-situ measurement uncertainty, not the spatial uncertainty due to the dependence of precipitation with elevation. As a result the sensitivity analysis (uniform increase or decrease of the mean precipitation across the basin) is not really informative (the authors could refer here to Masih et al. 2011, JAWRA).

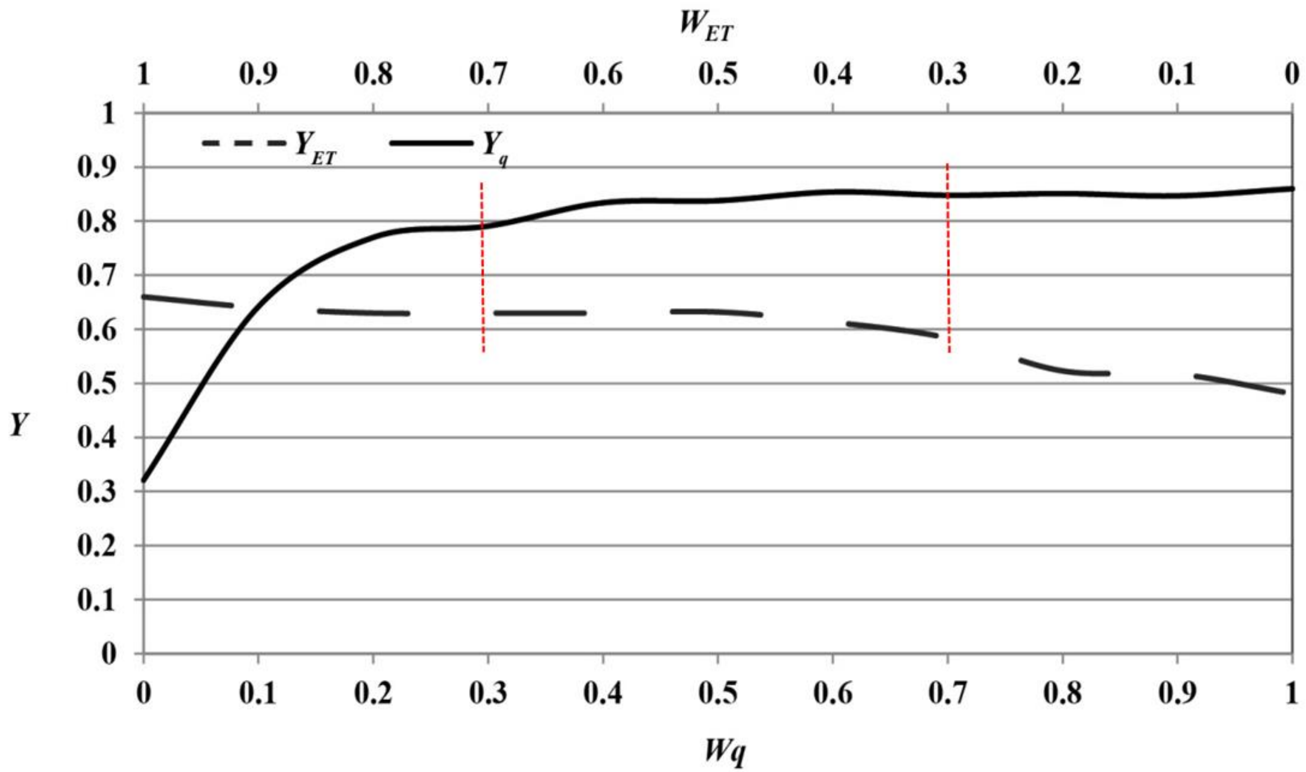
Reviewer 7 : The authors indicated that the SEBS results were validated at the annual timescale in Muthuwatta et al. (Water Resour. Manage. 24, 2010) using "ground observation" (L.414). This statement is somehow misleading as the SEBS estimates were not validated with in situ ET measurements (i.e. eddy correlation tower), but only by checking the water balance closure at the annual timescale. This is important to clarify as a key assumption of the study is that SEBS results "represent the real world actual evapotranspiration".

Reviewer 8 : To what extent is the subtraction of the inflow from the outflow for the modelling of the subcatchments reasonable. Why was the possible effect of routing neglected? How are the flow times from inflow to outflow locations?

The calibration of a daily model on actual evapotranspiration, described as case 2 (which in the case of remote sensing is smoothed because of missing values) is unrealistic. A reasonable calibration could only be obtained on a monthly time scale.

How would the models perform if one used the long term averages for ETa in the calibration? To what extent is remote sensing more skill-full?

Effects of weights on model performance



$$\mathbf{Y_{TOT} = (cv_q \times Y_Q) + (cv_{ET_a} \times Y_{ET_a})}$$

Weights are normalized and are inversely proportional to the CV (i.e, St.Dv/mean) to reflect on the relative magnitude of the observations so to rule out effects of large/small values

Effects of Precipitation uncertainty for Case 3

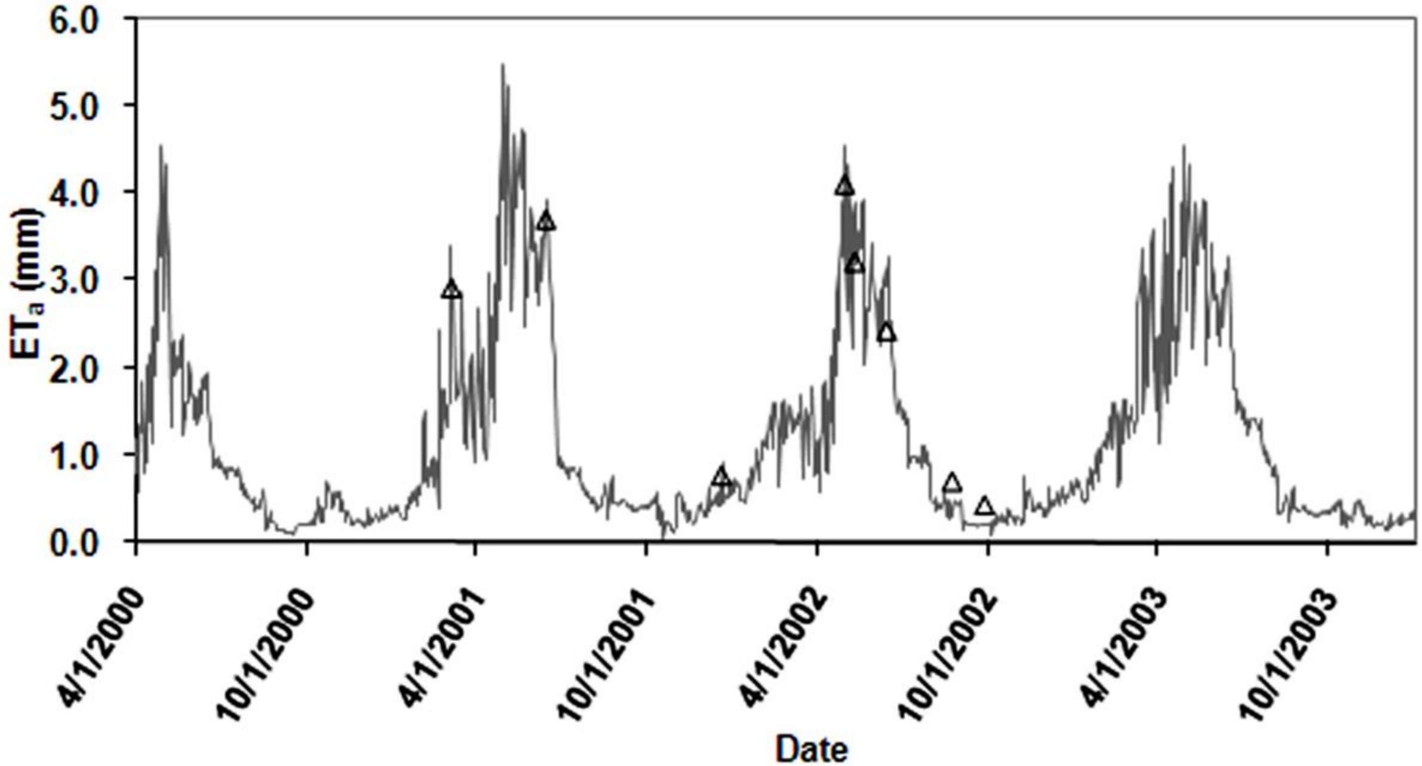
Changes in parameter values from optimized values in %

Result : Changes in model performance in % of Y_{TOT}

	Change in precipitation							
	-20%	-15%	-10%	-5%	5%	10%	15%	20%
PARAMETERS								
FC	-31.6	-24.3	-8.3	2.2	1.2	4.2	6.1	9.6
BETA	-8.3	-5.8	-3.1	-0.3	1.5	4.7	4.8	6.9
LP	9.4	7.4	5.2	3.9	1.7	2.3	2.8	3.1
ALFA	-6.2	-4.4	-3.7	-2.9	4.1	9.1	12.6	13.9
K_f	12.6	5.8	4.3	1.9	3.9	10.7	24.6	37.1
K_s	3.4	3.1	2.8	0.8	2.7	7.4	11.1	12.5
PERC	57.5	32.1	21.4	11.2	-4.9	-6.7	-14.6	-13.1
Y_{TOT}	-48.1	-37	-21.2	-9.3	-16.1	-21.7	-29.1	-36.3

Obvious : Each parameter has its own sensitivity…

Filling procedure (modified after Immerzeel and Droogers, 2008)



Validation of the filling procedure for 8 days that were not used for Development of the filling procedure

A summary presentation of few articles

Muthuwatta, L.P., Booij, M.J., Rientjes, T.H.M., Bos, M.G., Gieske, A.S.M. and Ahmad, M.D. (2009) Calibration of a semi - distributed hydrological model using discharge and remote sensing data. In: New approaches to hydrological prediction in data - sparse regions : proceedings of the symposium HS.2 at the joint IAHS & IAH convention, Hyderabad, India, September 2009. / ed. by K. Yilmaz ... [et al.] Wallingford ; IAHS, 2009. ISBN 978-1-907161-04-9 pp. 52-58.

Muthuwatta, L.P., Ahmad, M.D., Bos, M.G. and Rientjes, T.H.M. (2010) Assessment of water availability and consumption in the Karkheh River basin, Iran : using remote sensing and geo - statistics. In: Water resources management, 24 (2010)3 pp. 459-484.

Muthuwatta, L.P., Ahmad, M.D., Rientjes, T.H.M. and Bos, M.G. (2010) Estimating the spatial variability of water consumption in the Karkeh river basin, Iran : using MODIS data. In: AQUAmundi, 1(2010)2, pp. 115-122

Muthuwatta, L.P., Rientjes, T.H.M. and Bos, M.G. (2013) Strategies to increase wheat production in the water scarce Karkheh River Basin, Iran. In: Agricultural water management, 124 (2013) pp. 1-10

Rientjes, T.H.M., Muthuwatta, L.P., Bos, M.G., Booij, M.J. and Bhatti, H.A. (2013) Multi - variable calibration of a semi-distributed hydrological model using streamflow data and satellite - based evapotranspiration. In: Journal of hydrology, 505 (2013) pp. 276-290