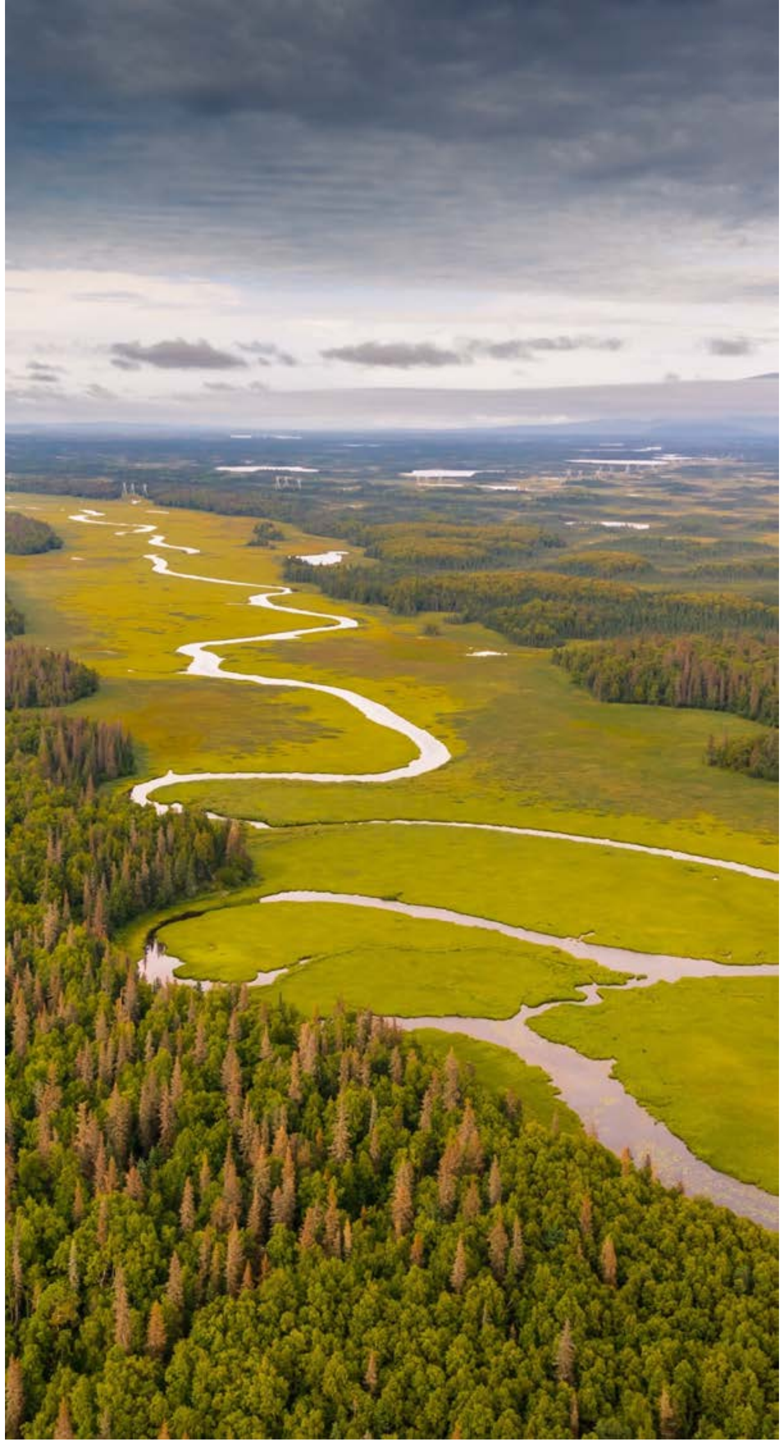

Hydrologic Modeling

Part I

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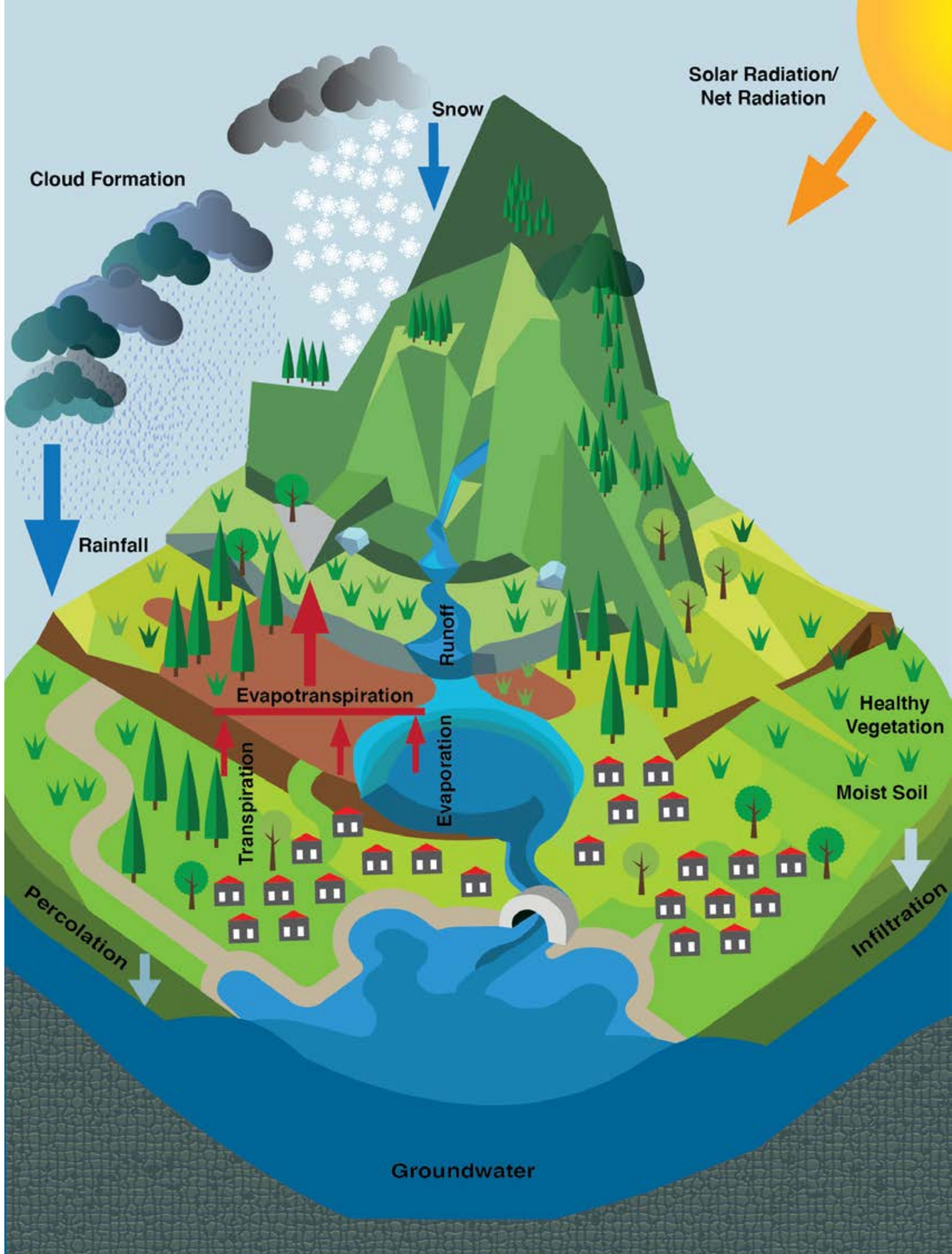
: @AmirAghaKouchak

Who is this Course for?

-In this introductory course, you will learn about fundamentals of hydrologic modeling.

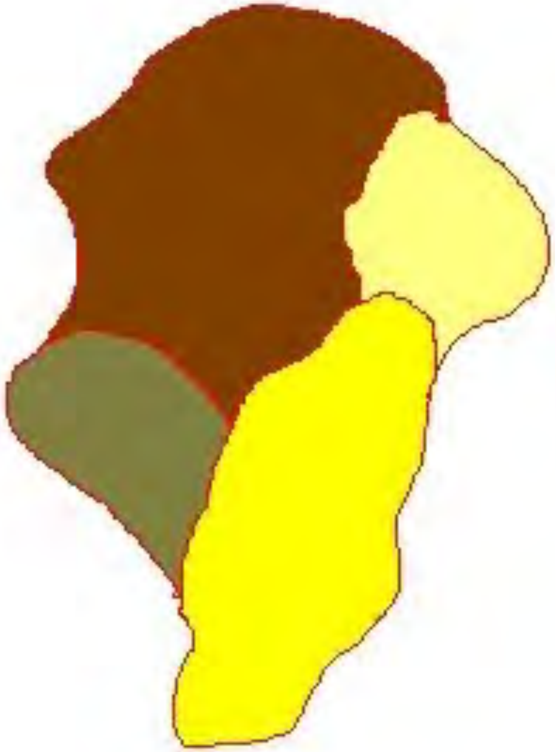
-You should have some background in hydrology and relevant processes (e.g., evapotranspiration, runoff, infiltration).

-We build a hydrologic model from scratch to show how different components of the hydrologic cycle interact with each other.

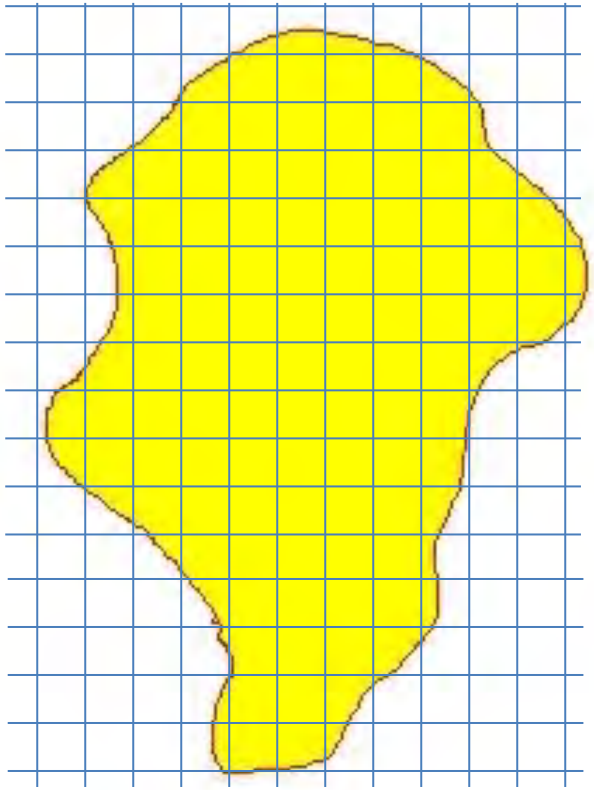


Types of Models

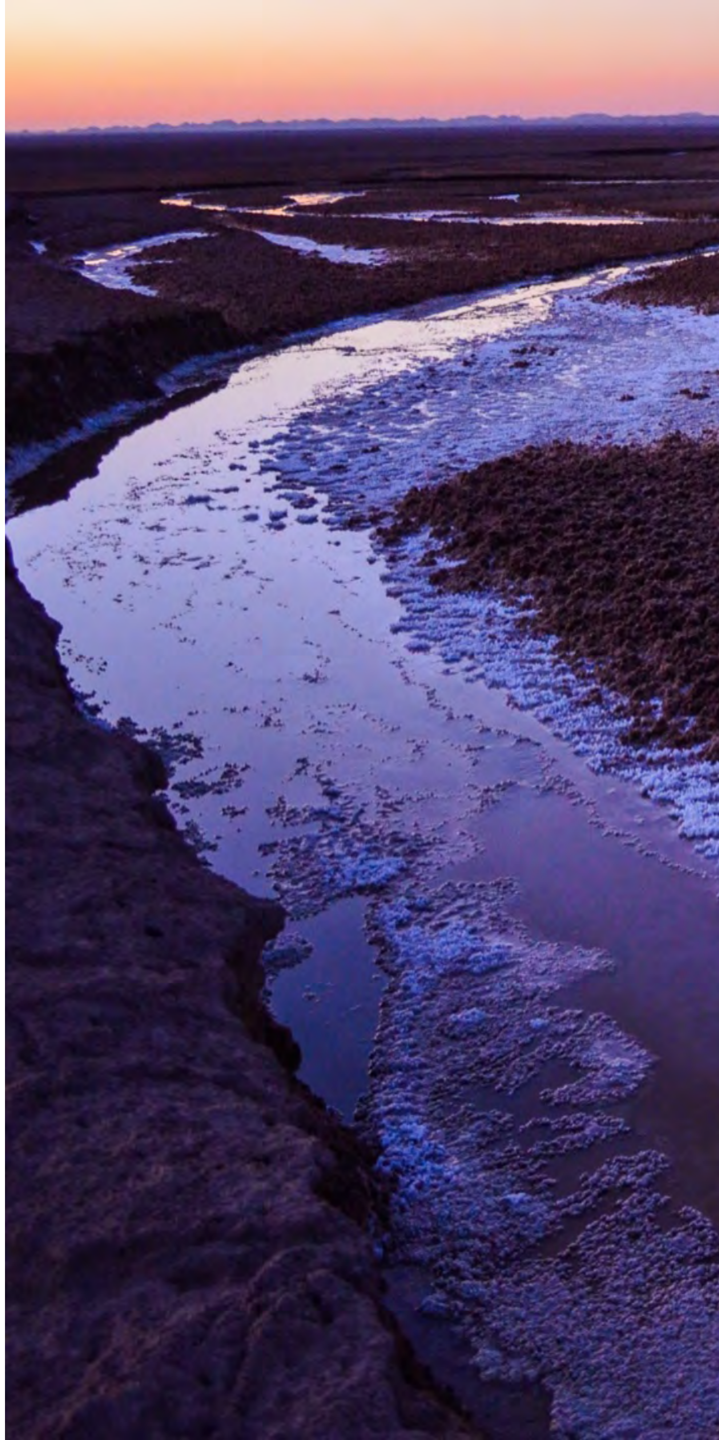
Lumped



Semi-Distributed



Distributed



Types of Models

Physically-Based Models

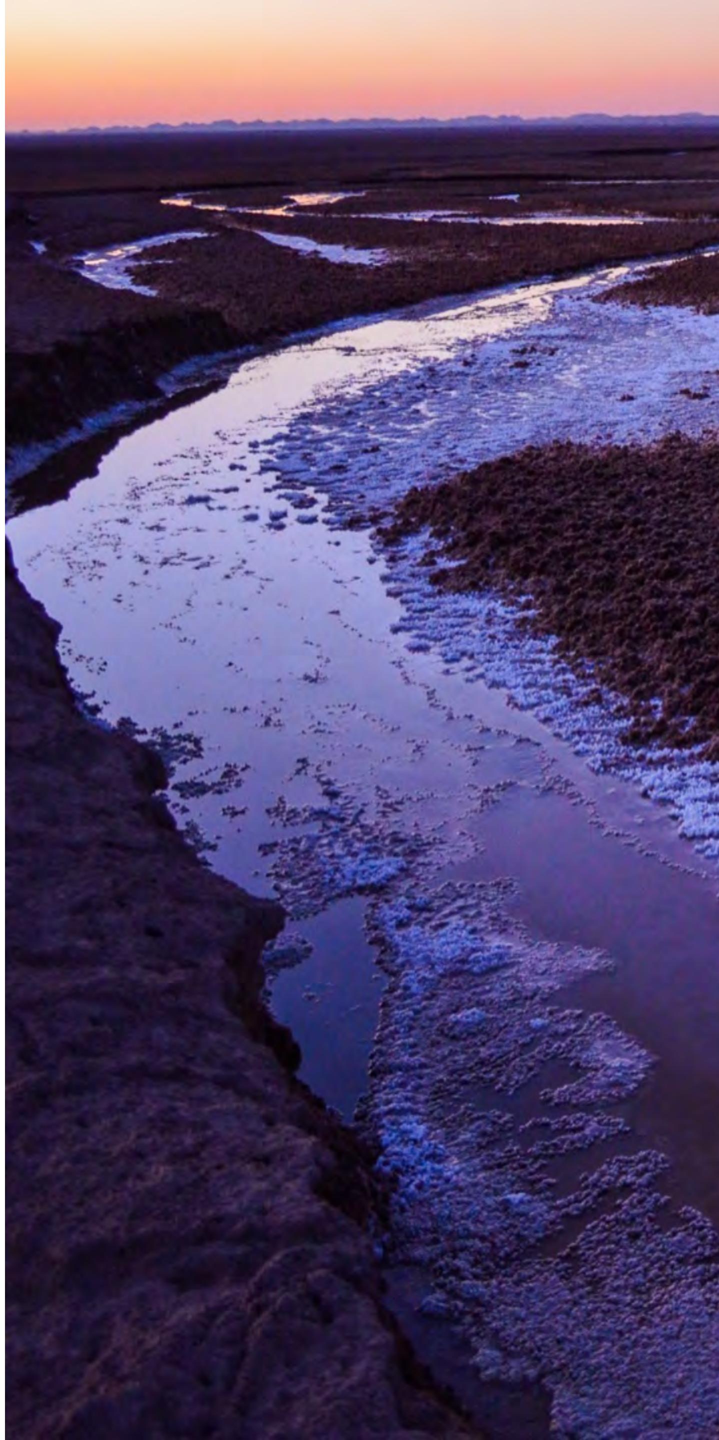
These models are based on governing equations such as conservation of mass, the momentum equation, etc. The disadvantage of physically based models is that they require complicated numerical solving techniques and large amount of input data.

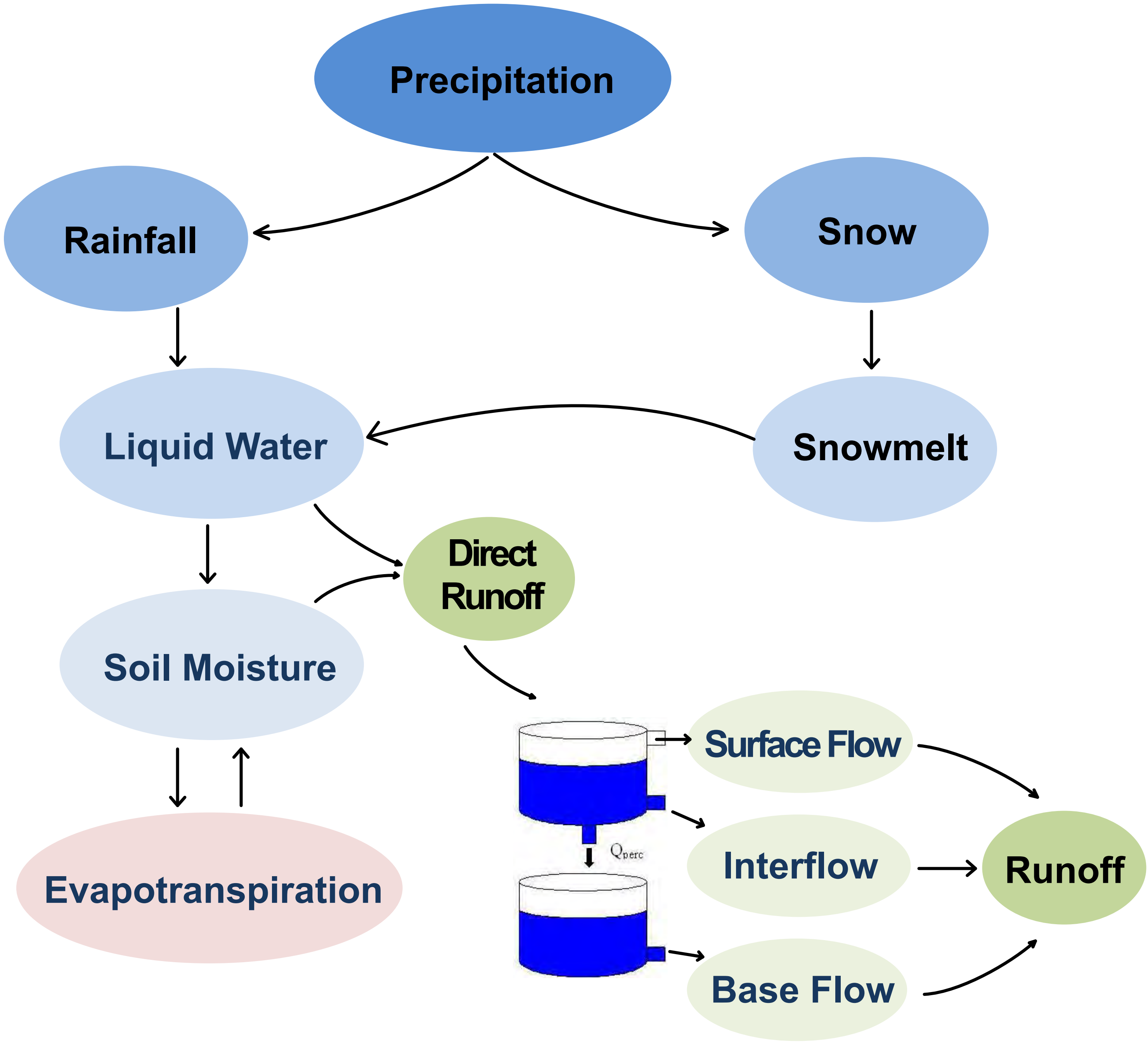
Conceptual Models

Conceptual models describe the processes with simple (typically linear) mathematical equations. Conceptual models are much simpler than physically-based models from a mathematical viewpoint.

Empirical Models

Empirical models are based on empirical analysis of observed input (e.g., rainfall) and output (discharge) data. Disadvantages: often not transferable to other locations; understanding of the relevant physical processes can be difficult to ascertain; and the model may not valid if the study area experiences land use or climate change.





Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

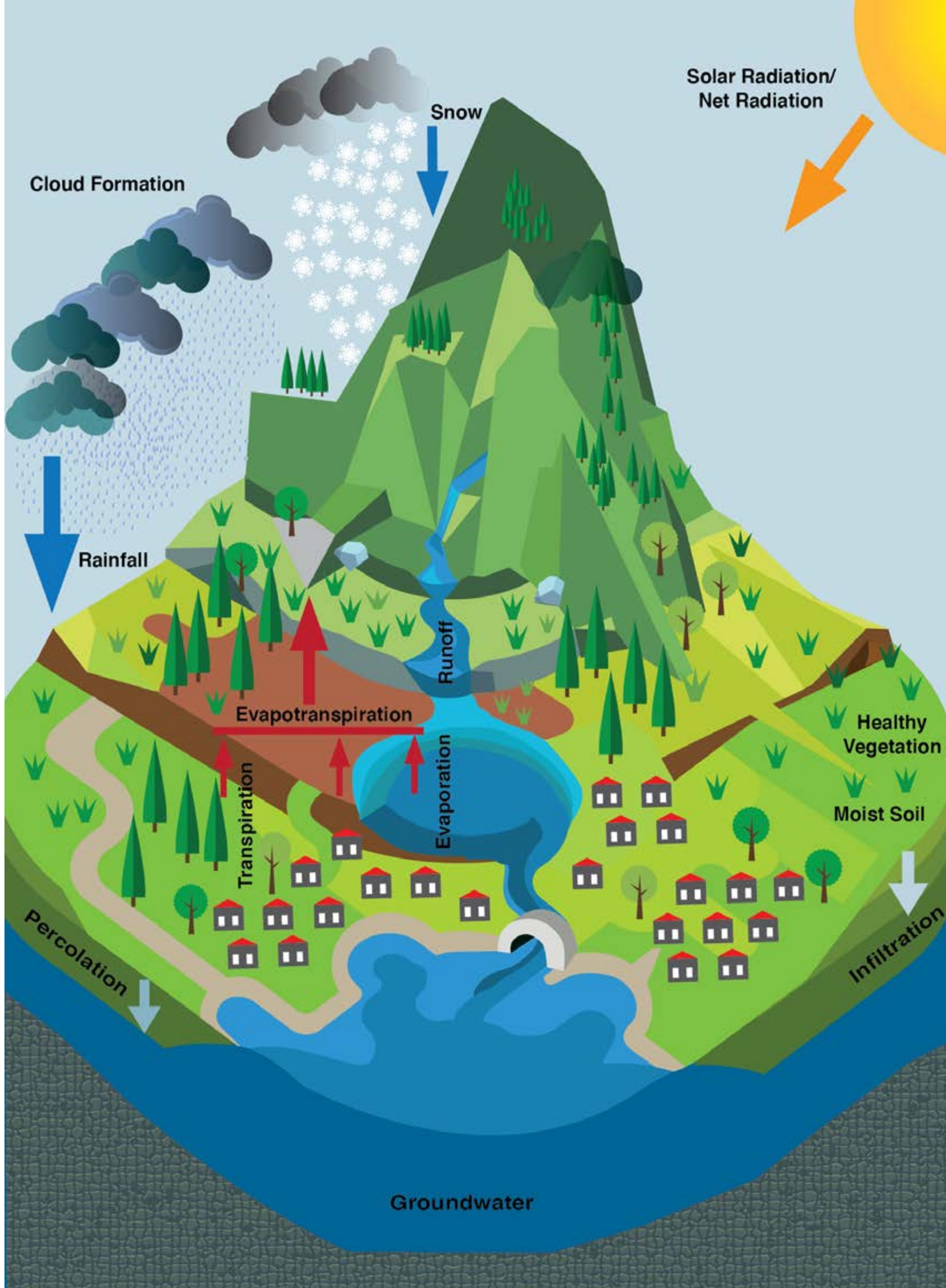
Evapotranspiration

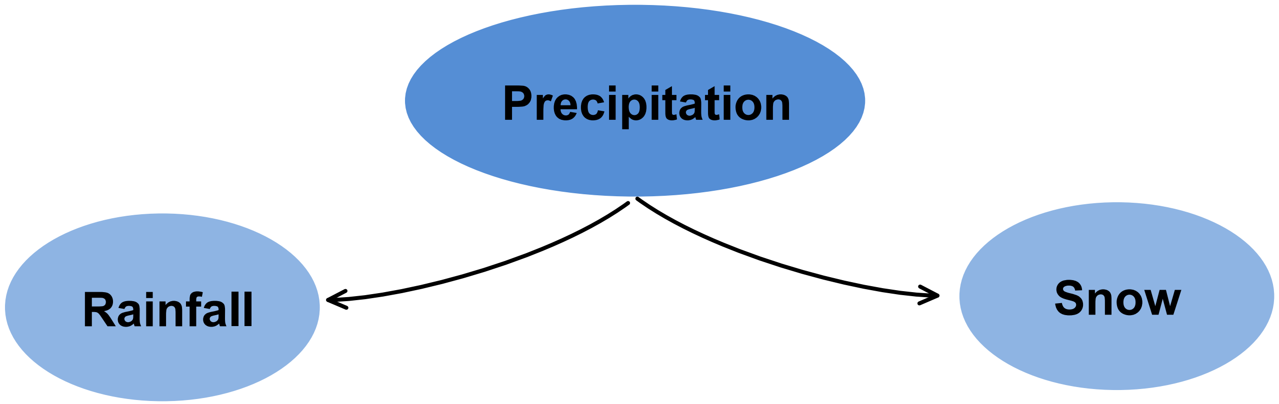
Surface Flow

Interflow

Base Flow

Runoff





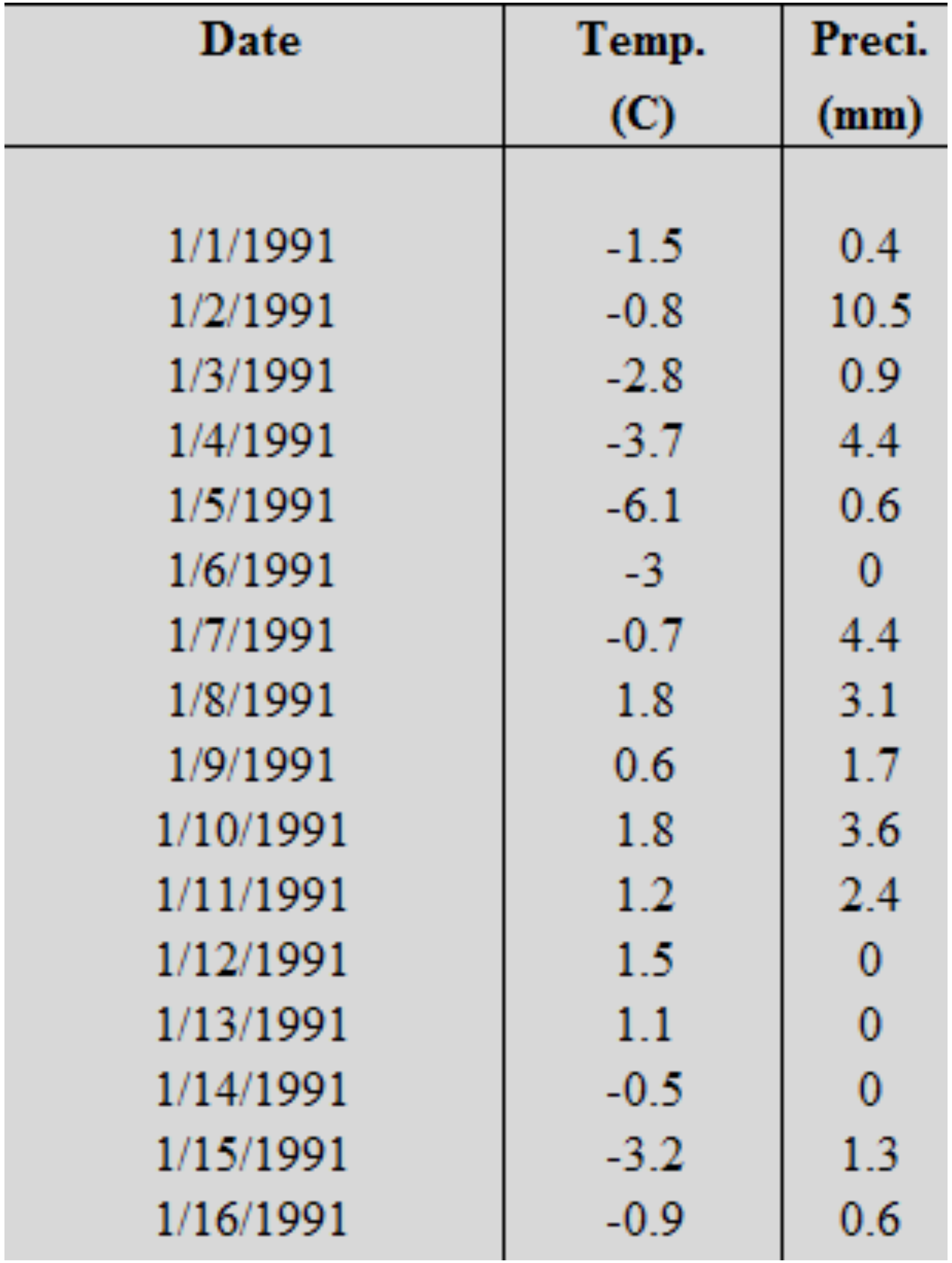
Precipitation

Rainfall

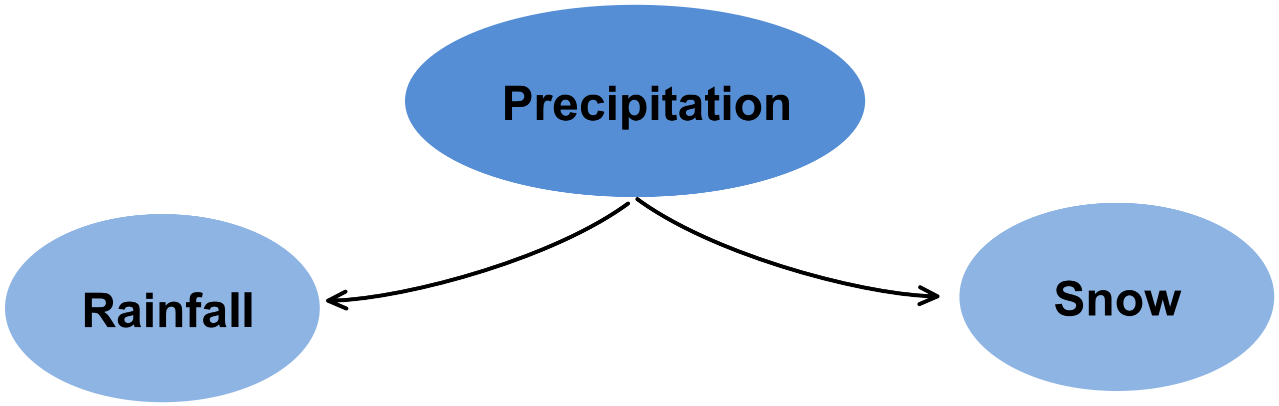
- Infiltration
- Direct Runoff

Snow

- Snowmelt
- Snow Accumulation



Date	Temp. (C)	Preci. (mm)
1/1/1991	-1.5	0.4
1/2/1991	-0.8	10.5
1/3/1991	-2.8	0.9
1/4/1991	-3.7	4.4
1/5/1991	-6.1	0.6
1/6/1991	-3	0
1/7/1991	-0.7	4.4
1/8/1991	1.8	3.1
1/9/1991	0.6	1.7
1/10/1991	1.8	3.6
1/11/1991	1.2	2.4
1/12/1991	1.5	0
1/13/1991	1.1	0
1/14/1991	-0.5	0
1/15/1991	-3.2	1.3
1/16/1991	-0.9	0.6



Precipitation

Rainfall

Snow

- Infiltration
- Direct Runoff

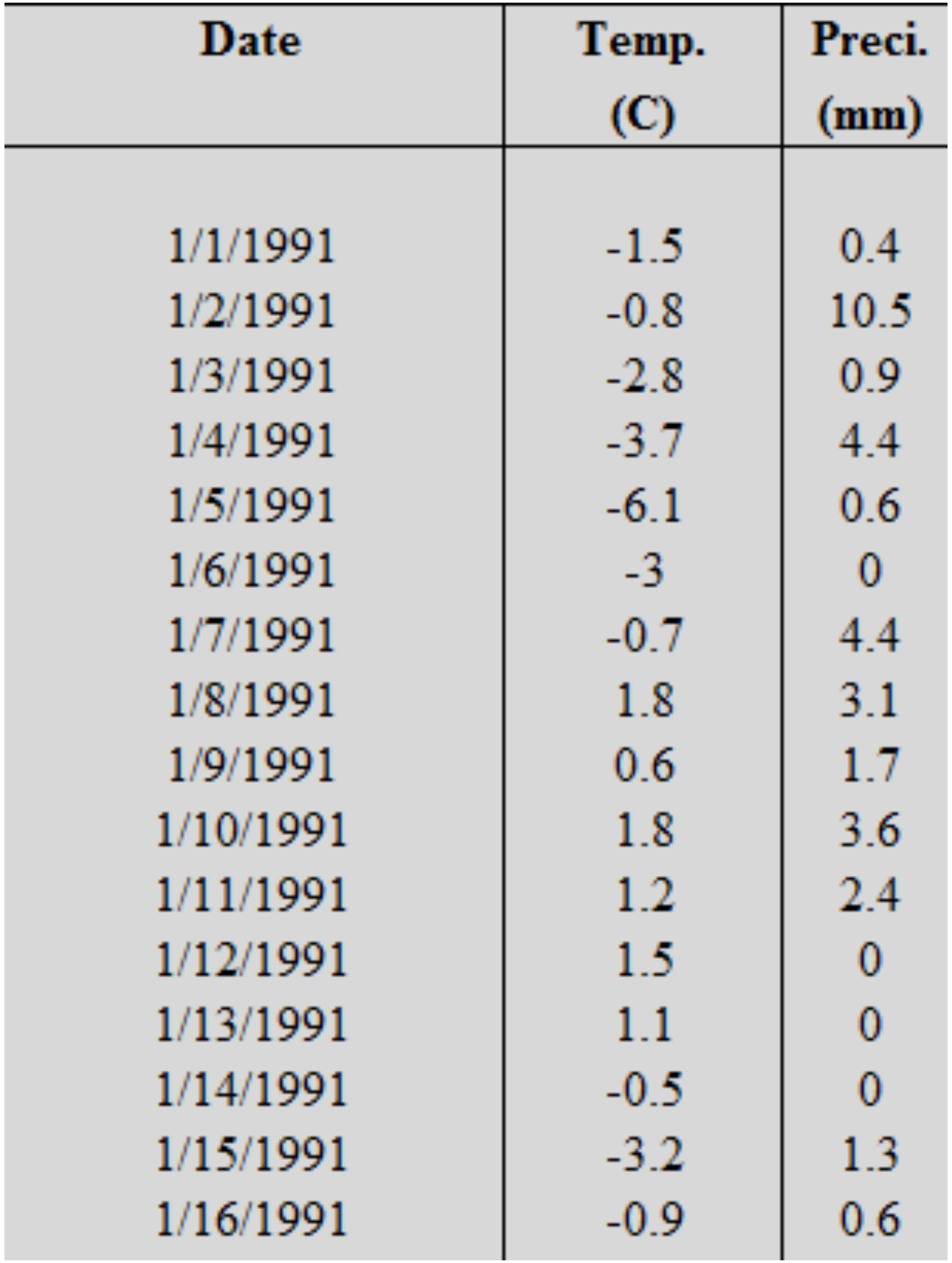
- Snowmelt
- Snow Accumulation

Precipitation separation into rainfall and snow based on temperature:

If $T > T_t$: Rainfall

If $T \leq T_t$: Snow

$T_{t.}$: Threshold temperature (0 ^{o}C / 32 ^{o}F)



Date	Temp. (C)	Preci. (mm)
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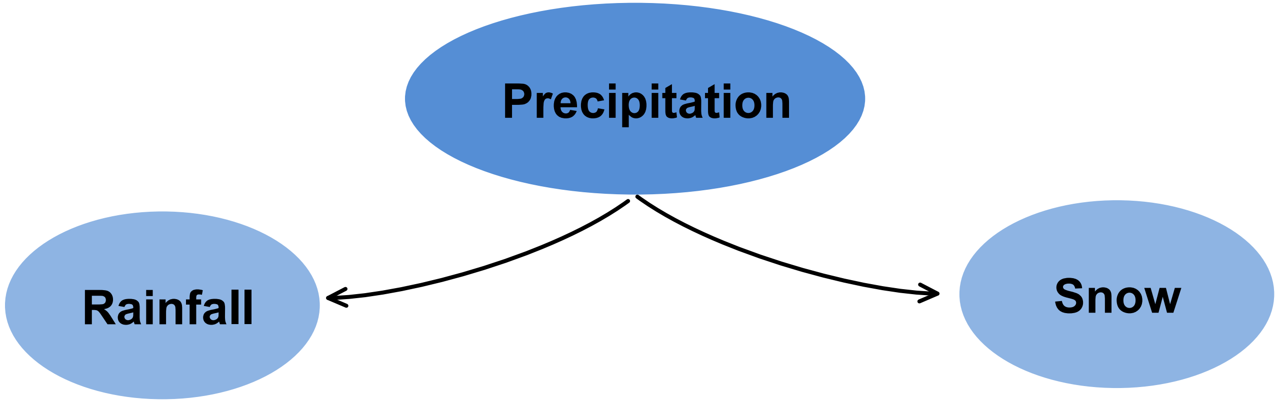
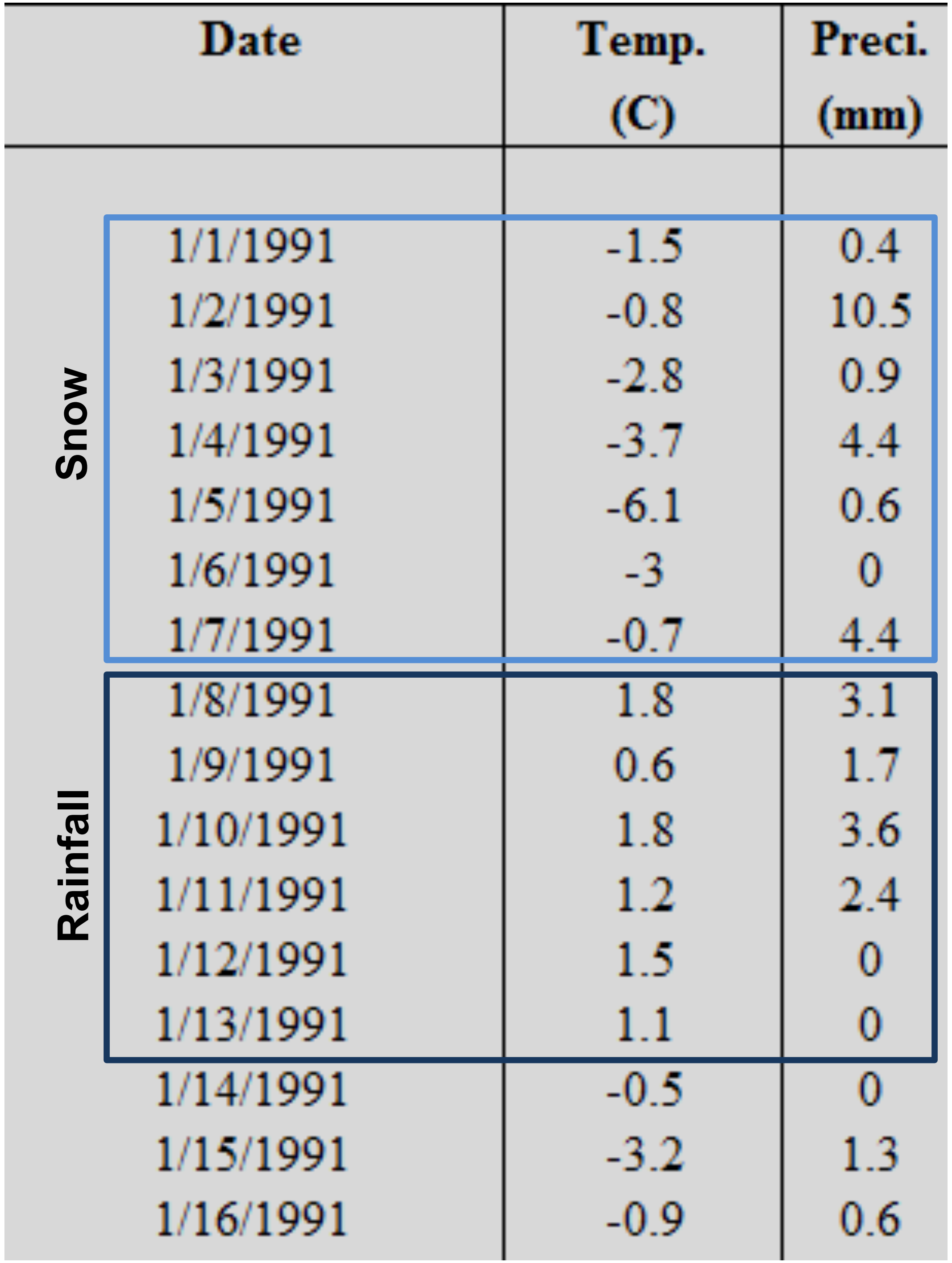
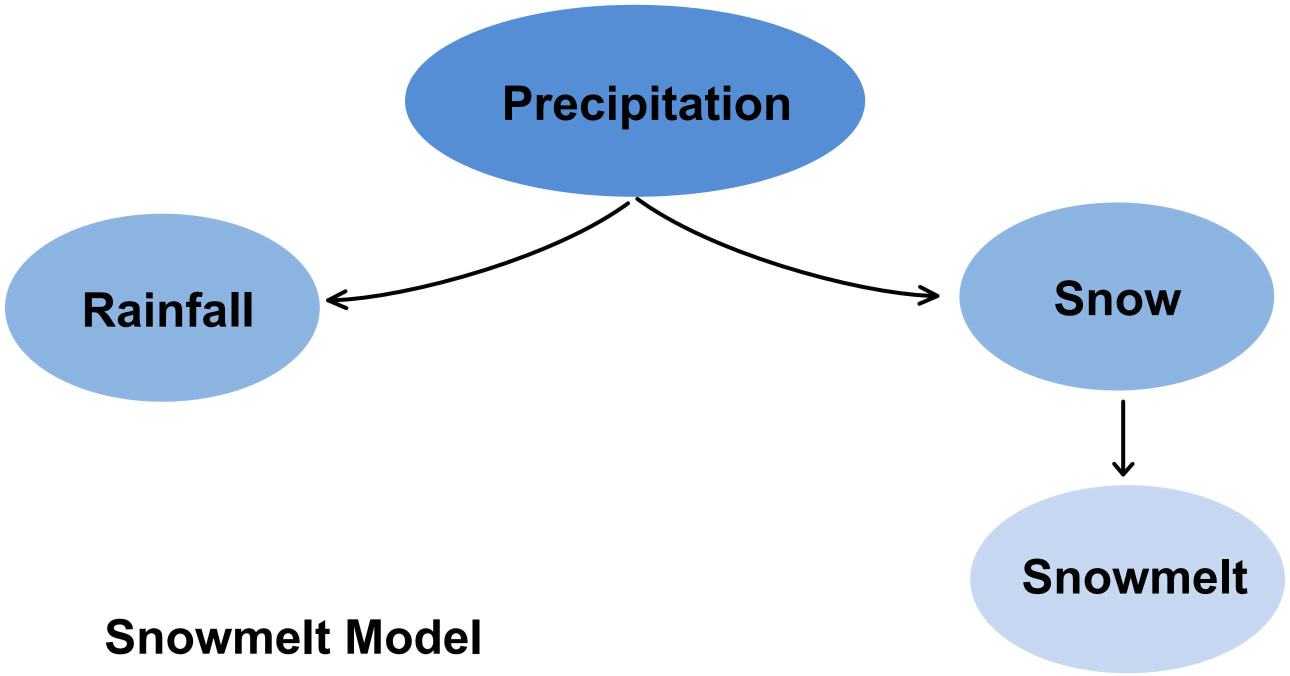
1/5/1991	-6.1	0.6
1/6/1991	-3	0
1/7/1991	-0.7	4.4
1/8/1991	1.8	3.1
1/9/1991	0.6	1.7
1/10/1991	1.8	3.6
1/11/1991	1.2	2.4
1/12/1991	1.5	0
1/13/1991	1.1	0
1/14/1991	-0.5	0
1/15/1991	-3.2	1.3
1/16/1991	-0.9	0.6





	Date	Temp. (C)	Preci. (mm)
Snow	1/1/1991	-1.5	0.4
	1/2/1991	-0.8	10.5
	1/3/1991	-2.8	0.9
	1/4/1991	-3.7	4.4
	1/5/1991	-6.1	0.6
	1/6/1991	-3	0
	1/7/1991	-0.7	4.4
Rainfall	1/8/1991	1.8	3.1
	1/9/1991	0.6	1.7
	1/10/1991	1.8	3.6
	1/11/1991	1.2	2.4
	1/12/1991	1.5	0
	1/13/1991	1.1	0
	1/14/1991	-0.5	0
	1/15/1991	-3.2	1.3
	1/16/1991	-0.9	0.6


Precipitation

Rainfall

Snow

Snowmelt

Snowmelt Model

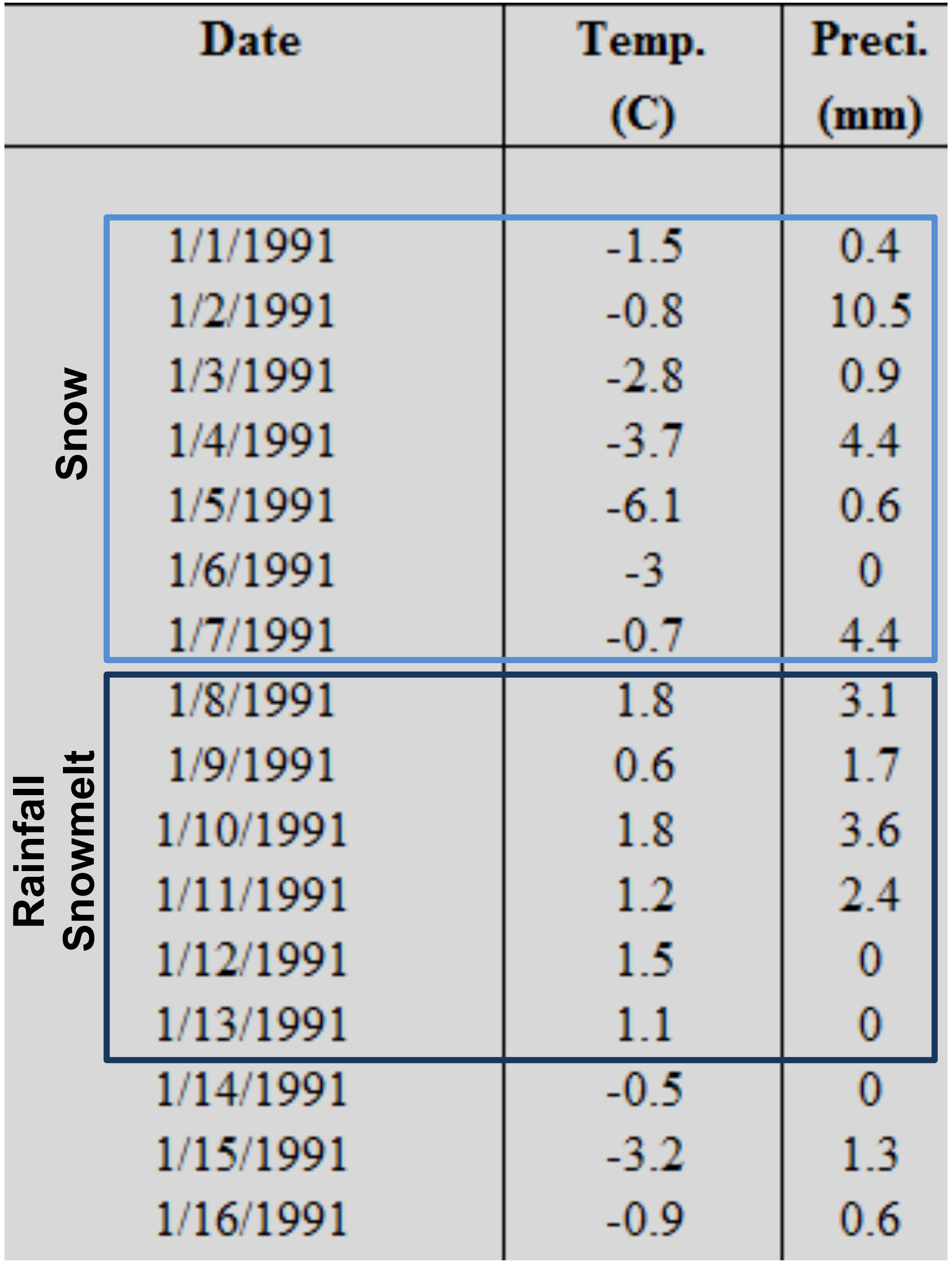
$$snowmelt = DD.(T - T_t)$$

Snowmelt ($[LT^{-1}]$): snowmelt rate as water equivalent

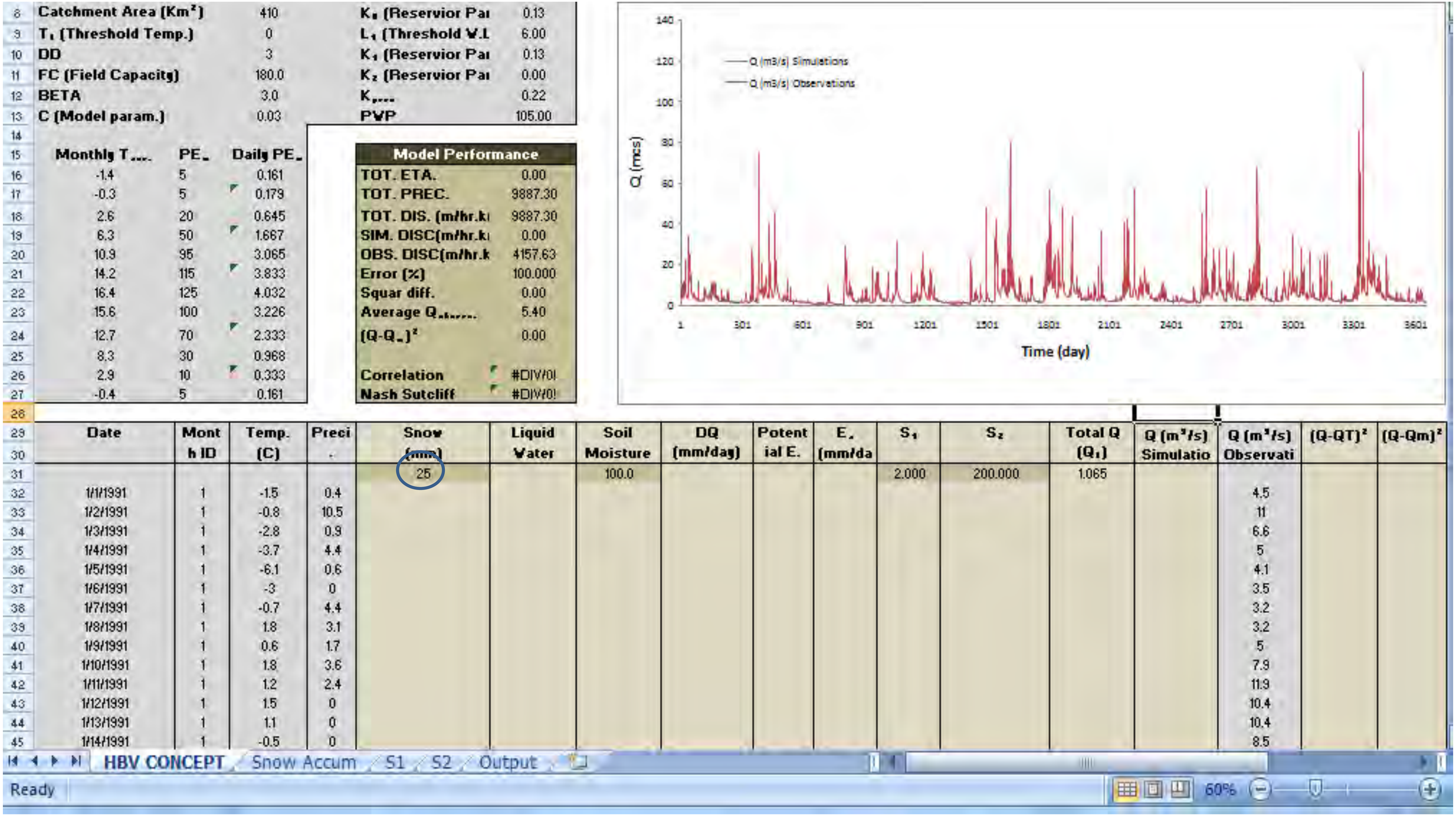
DD ($[L\theta^{-1}T^{-1}]$) : degree-day factor

T ($[\theta]$): mean daily air temperature

T_t ($[\theta]$): threshold temperature



	Date	Temp. (C)	Preci. (mm)
Snow	1/1/1991	-1.5	0.4
	1/2/1991	-0.8	10.5
	1/3/1991	-2.8	0.9
	1/4/1991	-3.7	4.4
	1/5/1991	-6.1	0.6
	1/6/1991	-3	0
	1/7/1991	-0.7	4.4
Rainfall Snowmelt	1/8/1991	1.8	3.1
	1/9/1991	0.6	1.7
	1/10/1991	1.8	3.6
	1/11/1991	1.2	2.4
	1/12/1991	1.5	0
	1/13/1991	1.1	0
	1/14/1991	-0.5	0
	1/15/1991	-3.2	1.3
	1/16/1991	-0.9	0.6



8	Catchment Area (Km²)	410	K₀ (Reservior Pa	0.13
9	T₁ (Threshold Temp.)	0	L₁ (Threshold V.L	6.00
10	DD	3	K₁ (Reservior Pa	0.13
11	FC (Field Capacity)	180.0	K₂ (Reservior Pa	0.00
12	BETA	3.0	K....	0.22
13	C (Model param.)	0.03	PWP	105.00
14				

	Monthly T....	PE..	Daily PE..
15			
16	-1.4	5	0.161
17	-0.3	5	0.179
18	2.6	20	0.645
19	6.3	50	1.667
20	10.9	95	3.065
21	14.2	115	3.833
22	16.4	125	4.032
23	15.6	100	3.226
24	12.7	70	2.333
25	8.3	30	0.968
26	2.9	10	0.333
27	-0.4	5	0.161

Model Performance	
TOT. ETA.	0.00
TOT. PREC.	9887.30
TOT. DIS. (m/hr.k	9887.30
SIM. DISC(m/hr.k	0.00
OBS. DISC(m/hr.k	4157.63
Error (%)	100.000
Squar diff.	0.00
Average Q......	5.40
(Q-Q..)²	0.00
Correlation	#DIV/0!
Nash Sutcliff	#DIV/0!

	Date	Month ID	Temp. (C)	Preci.	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day)	Potential E.	E. (mm/da	S₁	S₂	Total Q (Q₁)	Q (m³/s) Simulatio	Q (m³/s) Observati	(Q-QT)²	(Q-Qm)²
28																	
29–30																	
31					25		100.0				2.000	200.000	1.065				
32	1/1/1991	1	-1.5	0.4											4.5		
33	1/2/1991	1	-0.8	10.5											11		
34	1/3/1991	1	-2.8	0.9											6.6		
35	1/4/1991	1	-3.7	4.4											5		
36	1/5/1991	1	-6.1	0.6											4.1		
37	1/6/1991	1	-3	0											3.5		
38	1/7/1991	1	-0.7	4.4											3.2		
39	1/8/1991	1	1.8	3.1											3.2		
40	1/9/1991	1	0.6	1.7											5		
41	1/10/1991	1	1.8	3.6											7.9		
42	1/11/1991	1	1.2	2.4											11.9		
43	1/12/1991	1	1.5	0											10.4		
44	1/13/1991	1	1.1	0											10.4		
45	1/14/1991	1	-0.5	0											8.5		

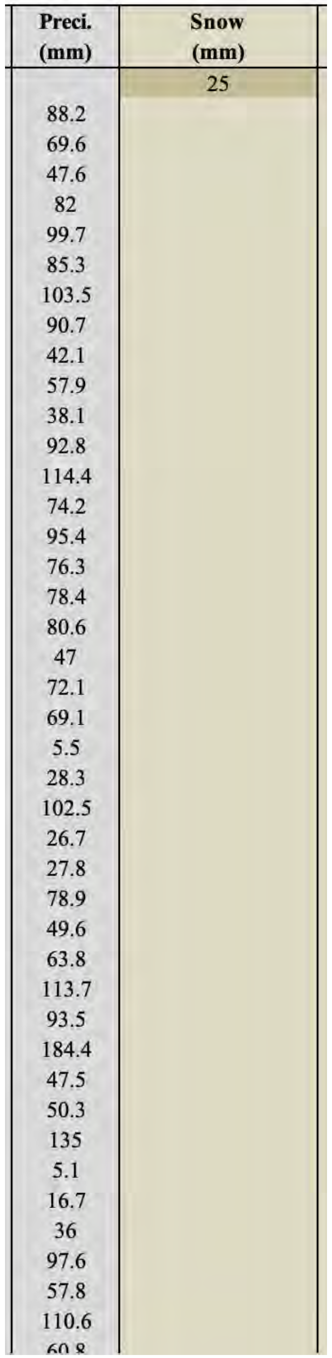
If $T \le T_t$: $\text{Snow}_{t-1} + \text{Snow}_t$

If $T > T_t$: $\text{Snow}_{t-1} - \text{DD.}(\text{T}-\text{T}_t)$

$T_{t.}$: Threshold temperature (0 ^{o}C / 32 ^{o}F)

$$=\text{IF}(\underbrace{\text{C32>\$C\$9}}_{T > T_t}\text{,MAX(E31-\$C\$10*(C32-\$C\$9),0),}\underbrace{\text{E31+D32}}_{T \le T_t})$$

NOTE: The MAX function in the above statement is used to prevent negative values of snow height!

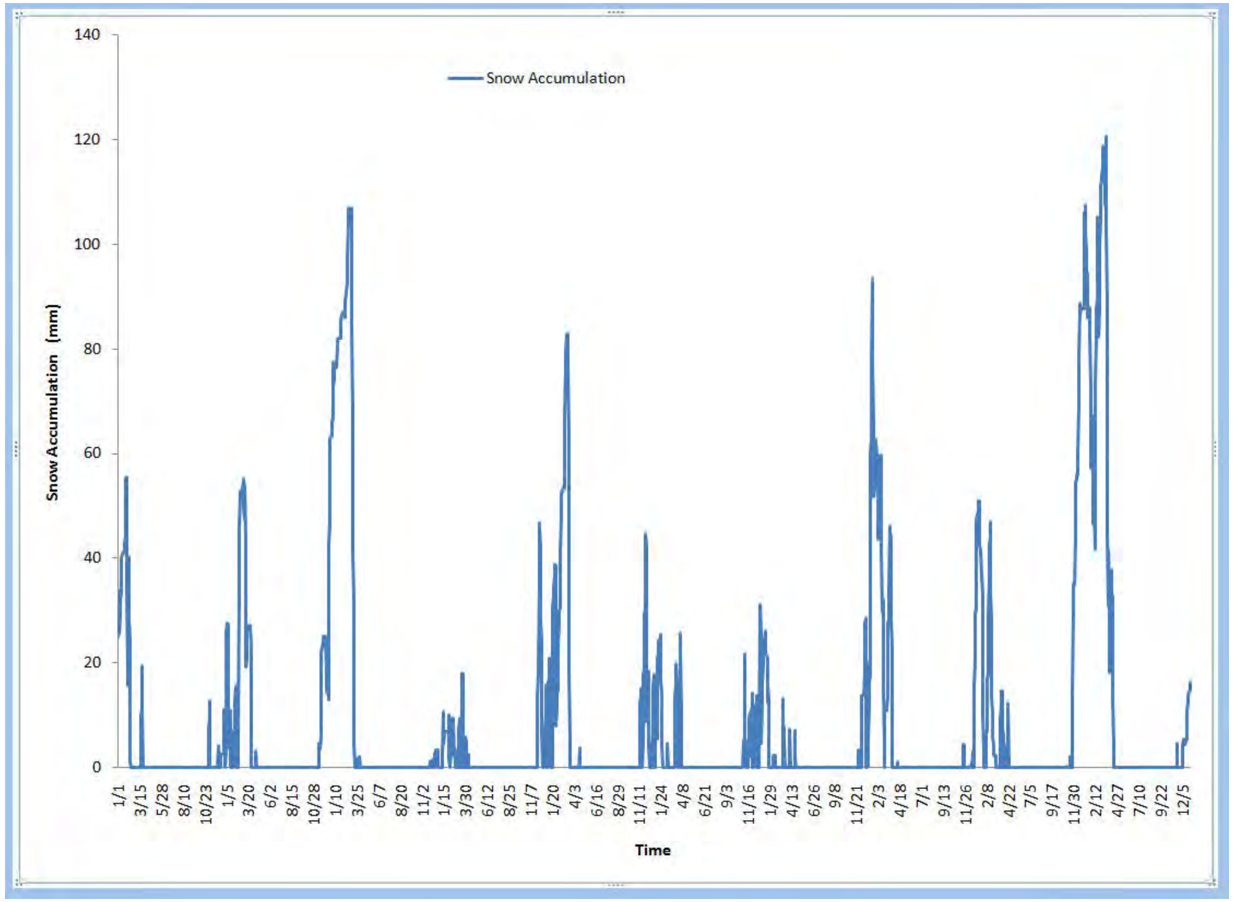


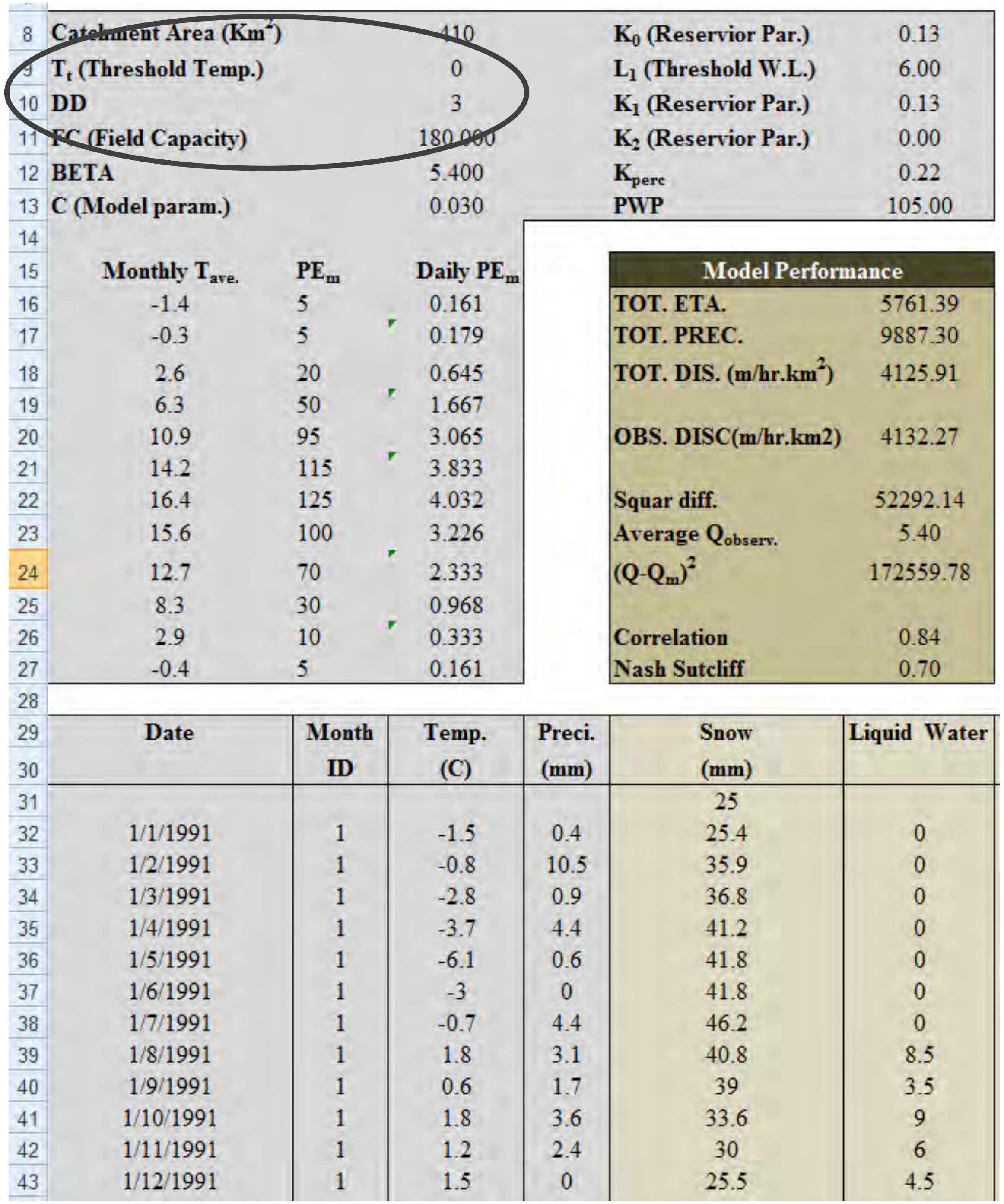
Preci. (mm)	Snow (mm)
	25
88.2	
69.6	
47.6	
82	
99.7	
85.3	
103.5	
90.7	
42.1	
57.9	
38.1	
92.8	
114.4	
74.2	
95.4	
76.3	
78.4	
80.6	
47	
72.1	
69.1	
5.5	
28.3	
102.5	
26.7	
27.8	
78.9	
49.6	
63.8	
113.7	
93.5	
184.4	
47.5	
50.3	
135	
5.1	
16.7	
36	
97.6	
57.8	
110.6	
60.8	

$snowmelt = DD.(T-T_t)$

=IF(C32>$C$9,MAX(E31-$C$10*(C32-$C$9),0),E31+D32)

NOTE: The MAX function in the above statement is used to prevent negative values of snow height!

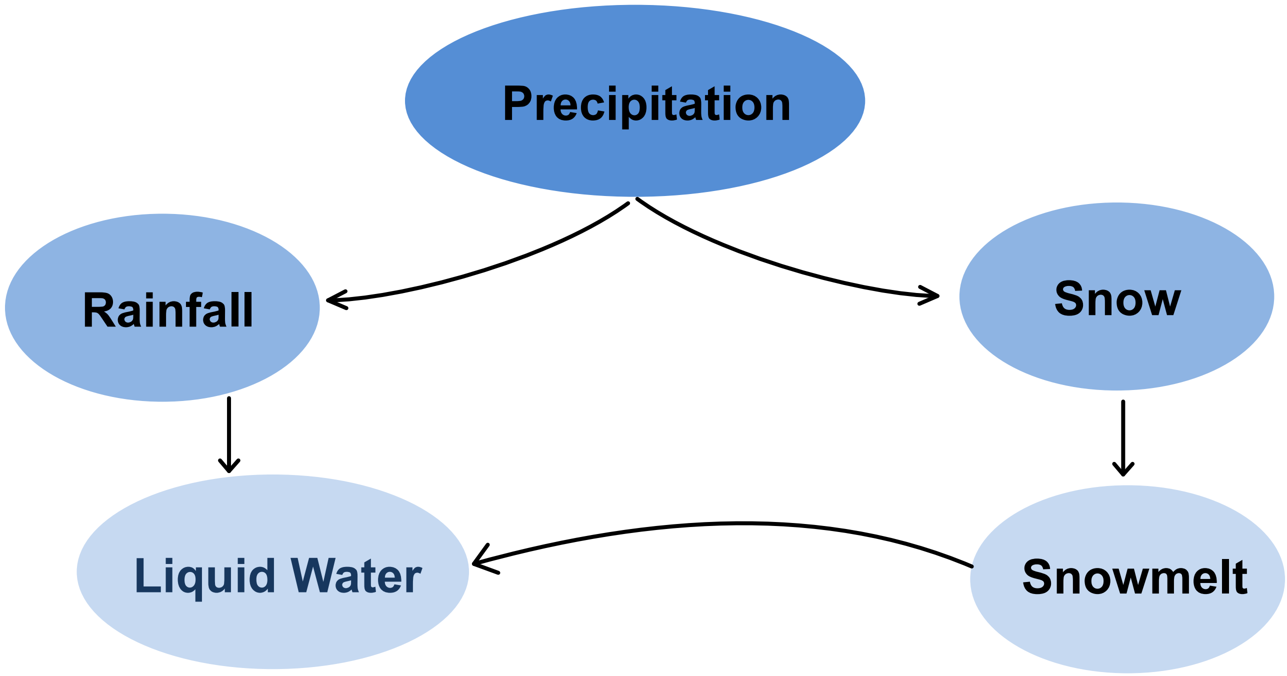




8	Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.13
9	T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
10	DD	3	K_1 (Reservior Par.)	0.13
11	FC (Field Capacity)	180.000	K_2 (Reservior Par.)	0.00
12	BETA	5.400	K_{perc}	0.22
13	C (Model param.)	0.030	PWP	105.00
14				

15	Monthly $T_{ave.}$	PE_m	Daily PE_m	**Model Performance**	
16	-1.4	5	0.161	TOT. ETA.	5761.39
17	-0.3	5	0.179	TOT. PREC.	9887.30
18	2.6	20	0.645	TOT. DIS. (m/hr.km^2)	4125.91
19	6.3	50	1.667		
20	10.9	95	3.065	OBS. DISC(m/hr.km2)	4132.27
21	14.2	115	3.833		
22	16.4	125	4.032	Squar diff.	52292.14
23	15.6	100	3.226	Average $Q_{observ.}$	5.40
24	12.7	70	2.333	$(Q-Q_m)^2$	172559.78
25	8.3	30	0.968		
26	2.9	10	0.333	Correlation	0.84
27	-0.4	5	0.161	Nash Sutcliff	0.70
28					

29	Date	Month	Temp.	Preci.	Snow	Liquid Water
30		ID	(C)	(mm)	(mm)	
31					25	
32	1/1/1991	1	-1.5	0.4	25.4	0
33	1/2/1991	1	-0.8	10.5	35.9	0
34	1/3/1991	1	-2.8	0.9	36.8	0
35	1/4/1991	1	-3.7	4.4	41.2	0
36	1/5/1991	1	-6.1	0.6	41.8	0
37	1/6/1991	1	-3	0	41.8	0
38	1/7/1991	1	-0.7	4.4	46.2	0
39	1/8/1991	1	1.8	3.1	40.8	8.5
40	1/9/1991	1	0.6	1.7	39	3.5
41	1/10/1991	1	1.8	3.6	33.6	9
42	1/11/1991	1	1.2	2.4	30	6
43	1/12/1991	1	1.5	0	25.5	4.5



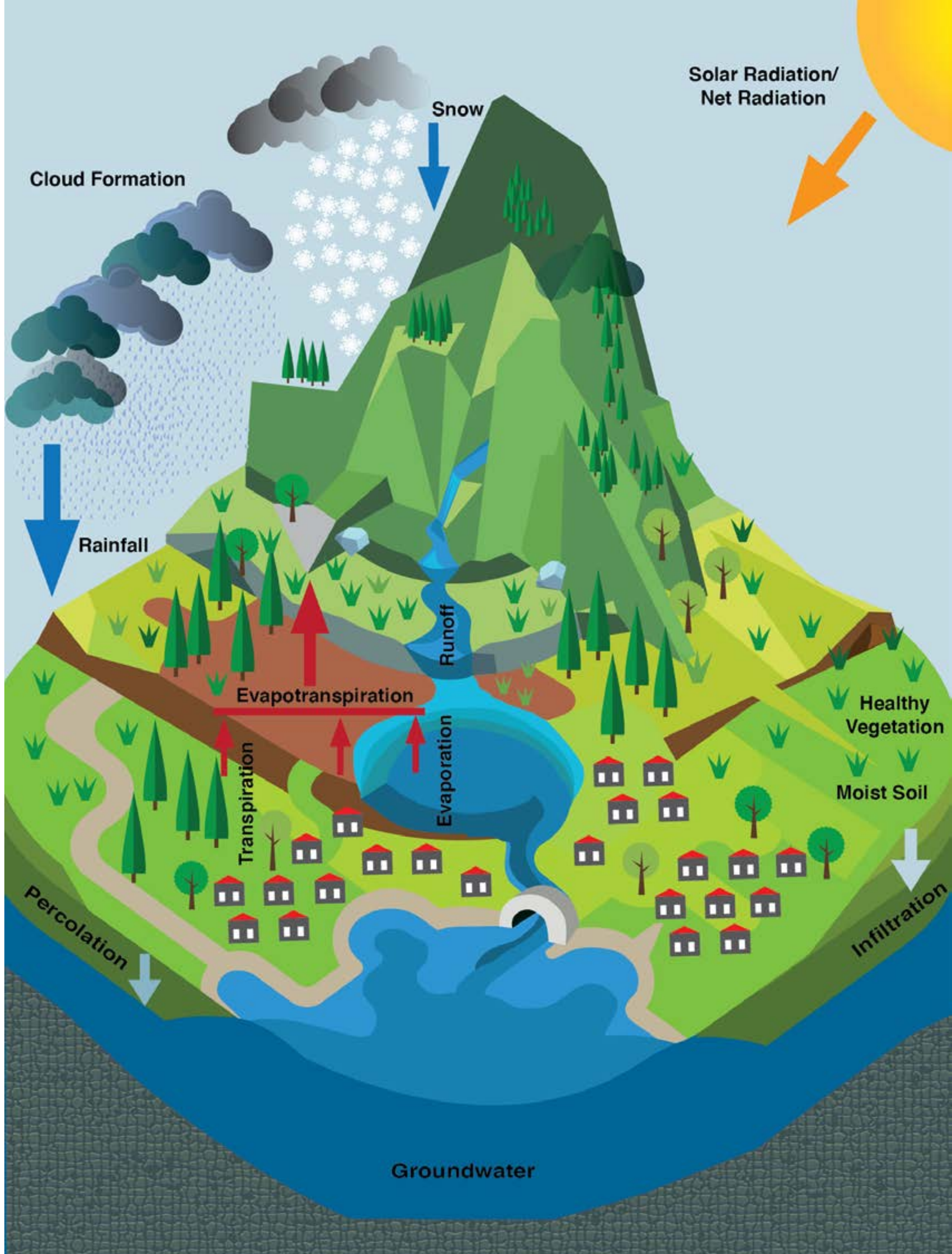
Precipitation

Rainfall

Snow

Liquid Water

Snowmelt



Liquid Water = P + S_m

P= Rainfall (Precipitation in Liquid Form)
S_m= Snowmelt

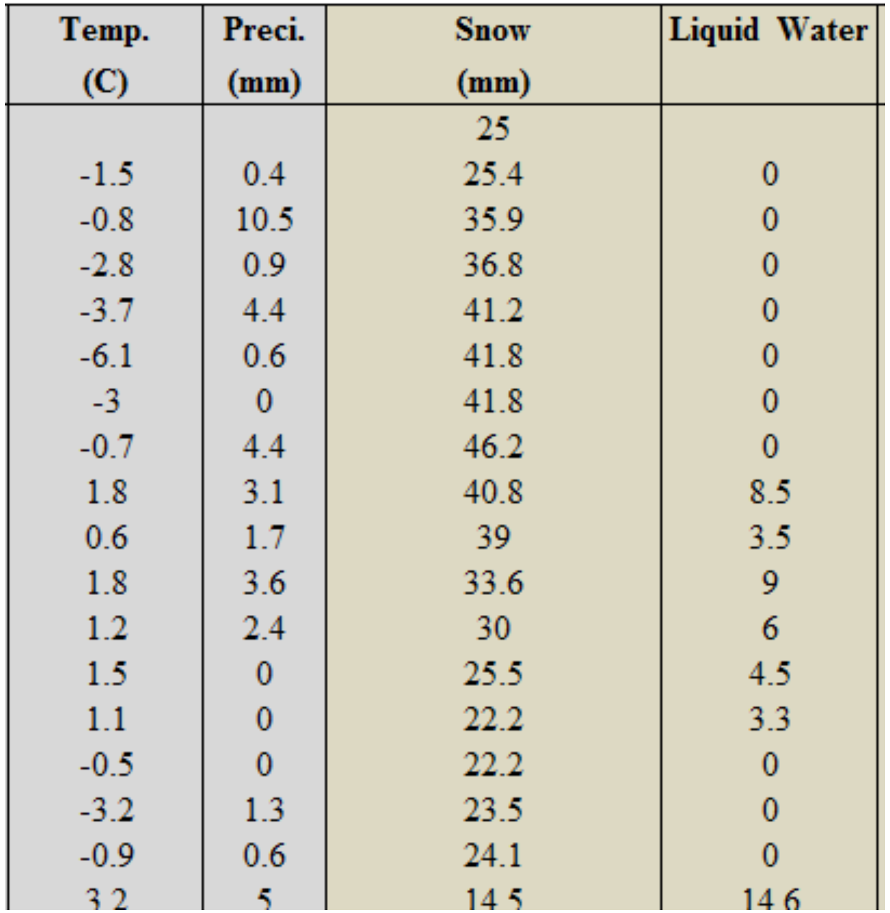
If $T < T_t$: Liquid Water = 0

If $T > T_t$: Liquid Water = P+S_m

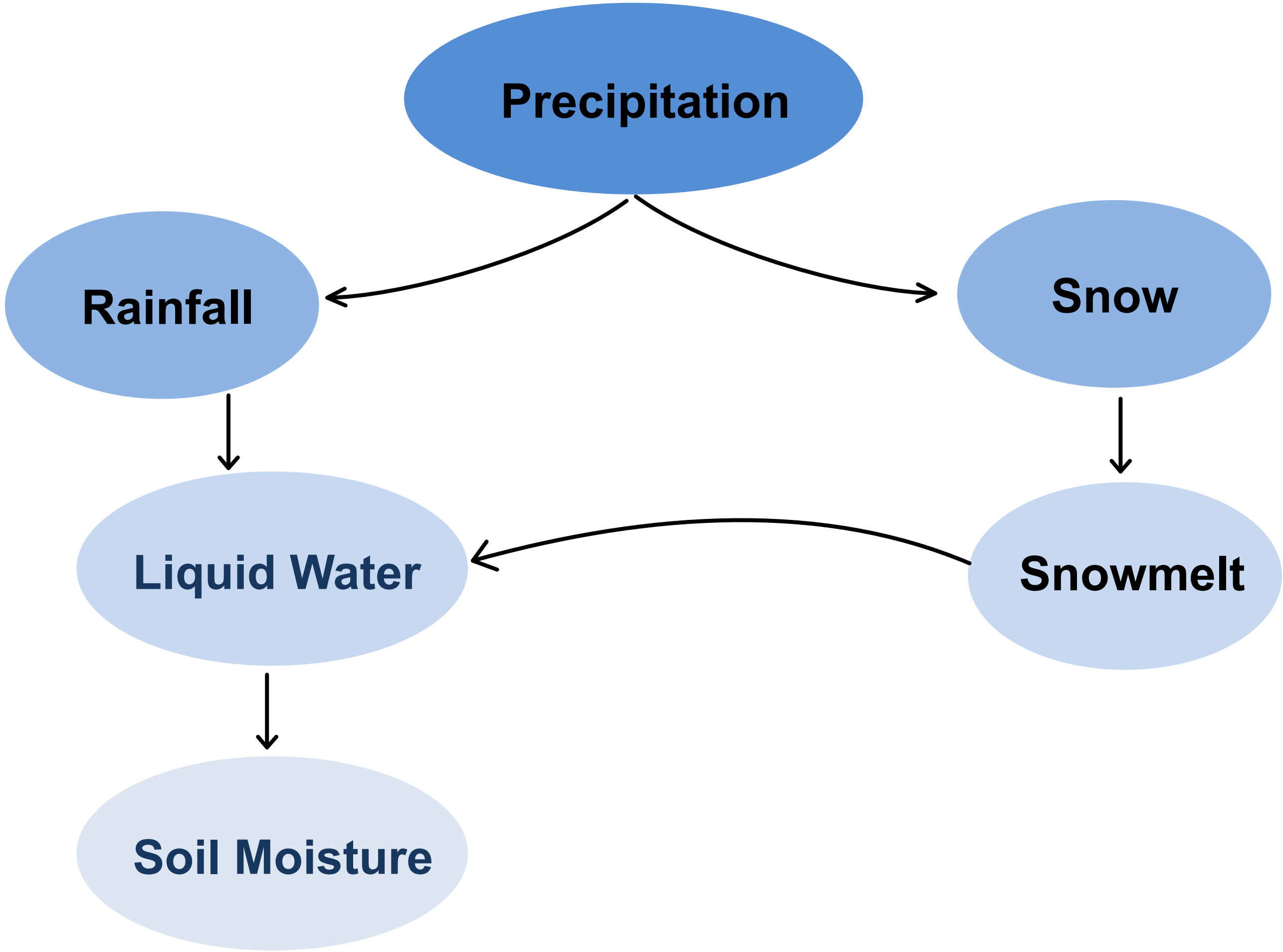
$T_{t.}$: Threshold temperature (0 ^{o}C / 32 ^{o}F)

$$\textbf{IF(}\underbrace{\textbf{C32>\$C\$9}}_{T > T_t}\textbf{,D32+MIN(E31,\$C\$10*(C32-\$C\$9)),}\underbrace{\textbf{0}}_{T \le T_t}\textbf{)}$$

NOTE: The MIN function in the above statement is used to prevent negative values



Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water
		25	
-1.5	0.4	25.4	0
-0.8	10.5	35.9	0
-2.8	0.9	36.8	0
-3.7	4.4	41.2	0
-6.1	0.6	41.8	0
-3	0	41.8	0
-0.7	4.4	46.2	0
1.8	3.1	40.8	8.5
0.6	1.7	39	3.5
1.8	3.6	33.6	9
1.2	2.4	30	6
1.5	0	25.5	4.5
1.1	0	22.2	3.3
-0.5	0	22.2	0
-3.2	1.3	23.5	0
-0.9	0.6	24.1	0
3.2	5	14.5	14.6



Precipitation

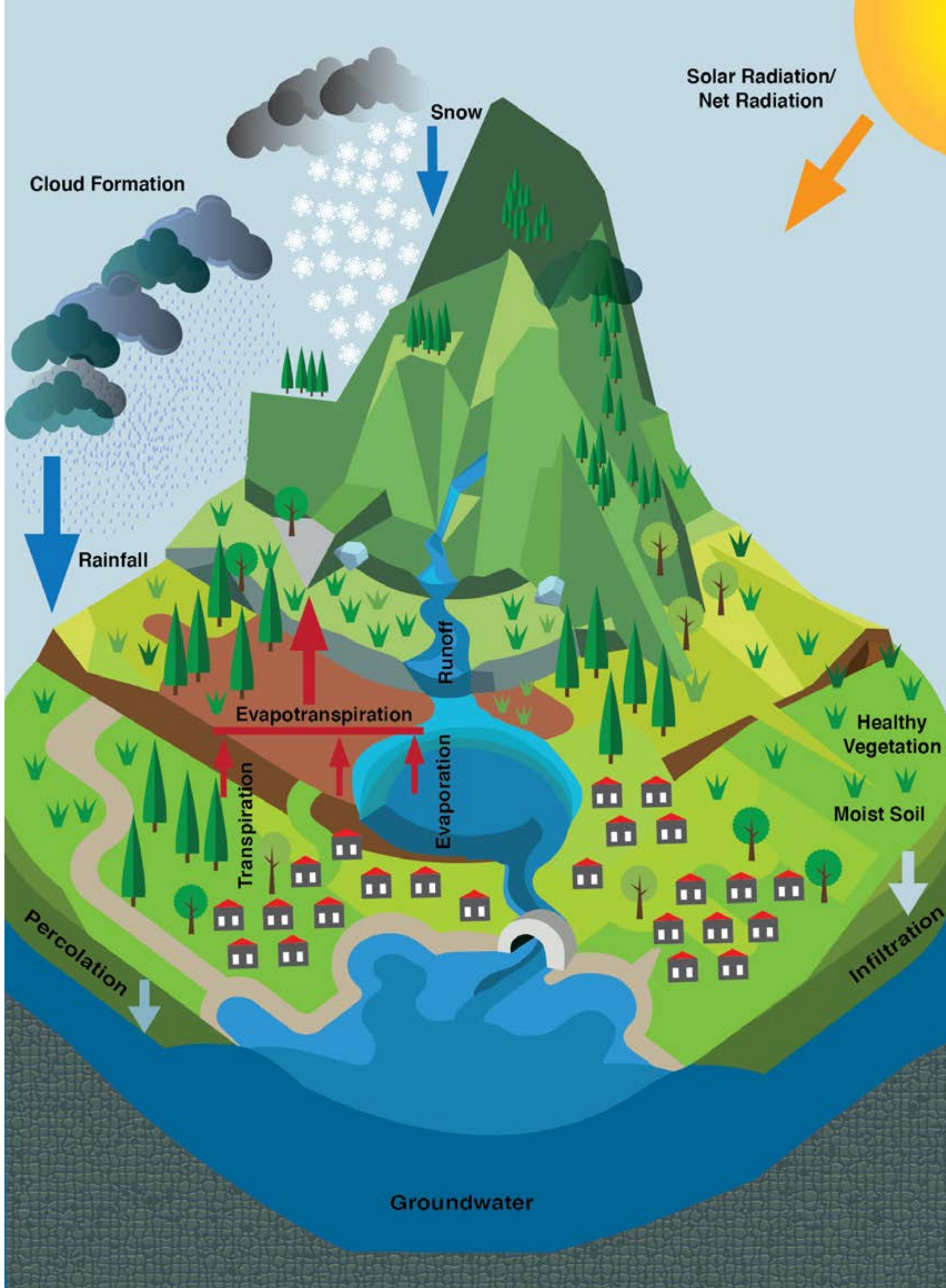
Rainfall

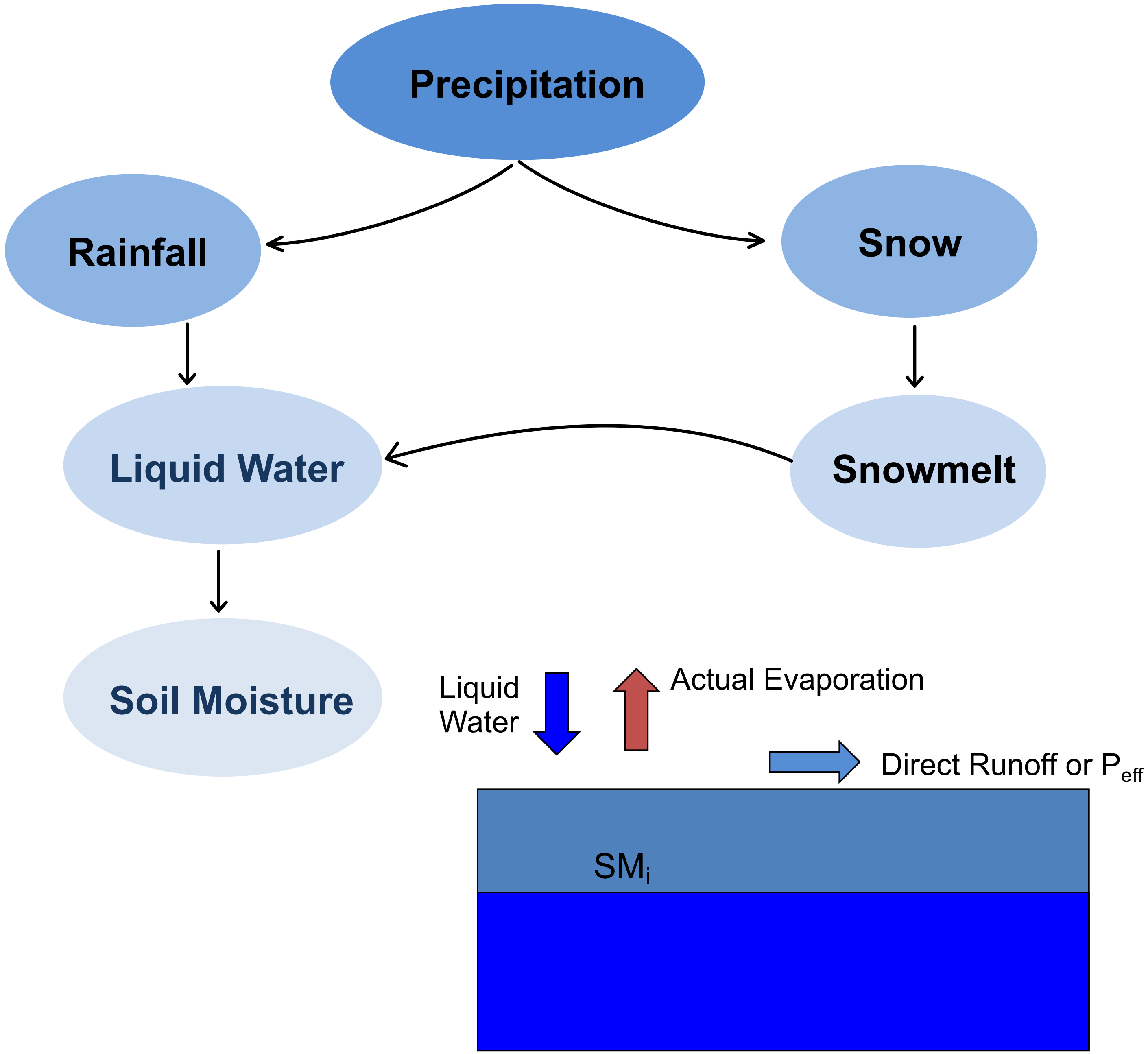
Snow

Liquid Water

Snowmelt

Soil Moisture





Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

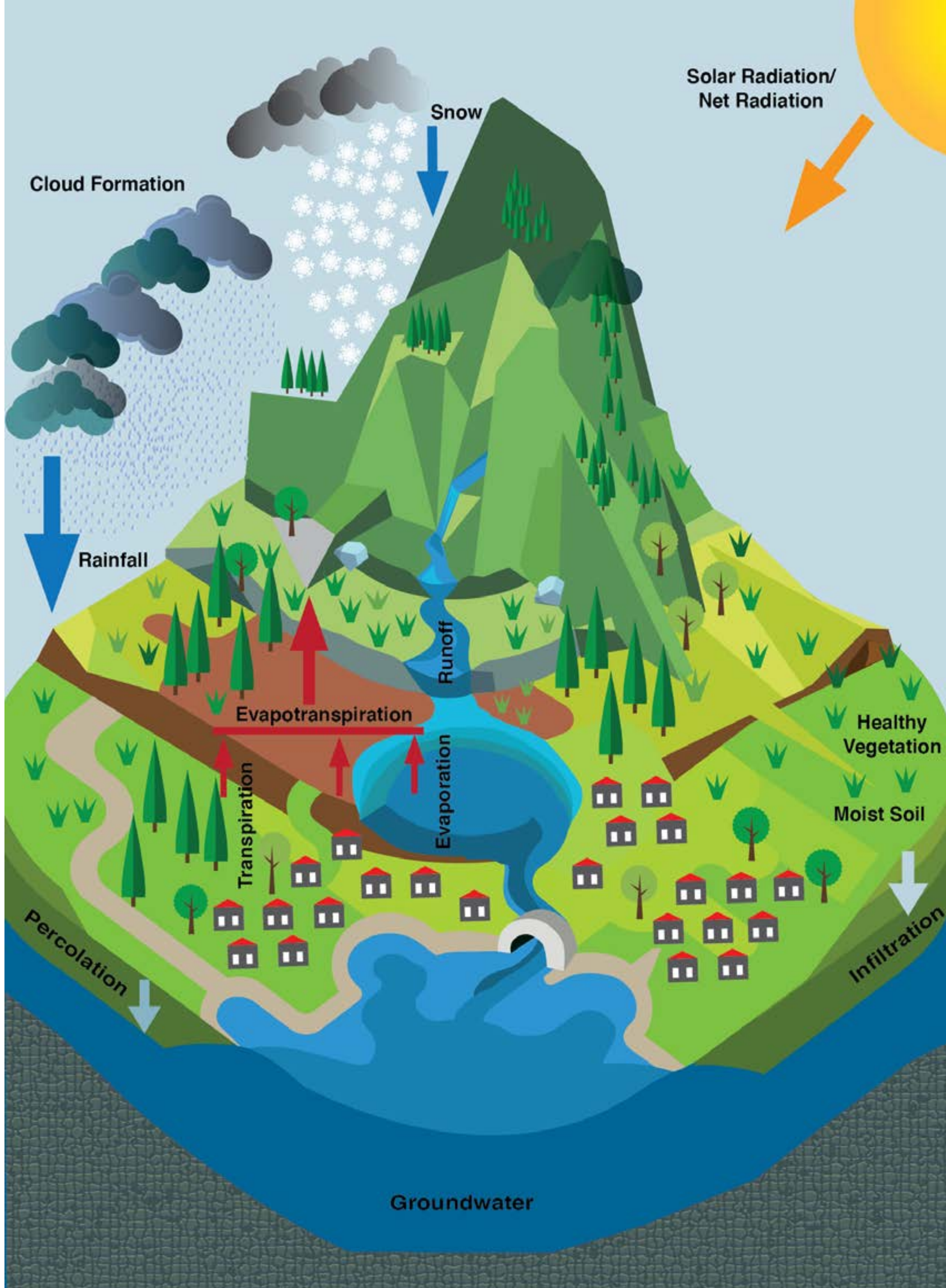
Soil Moisture

Liquid Water

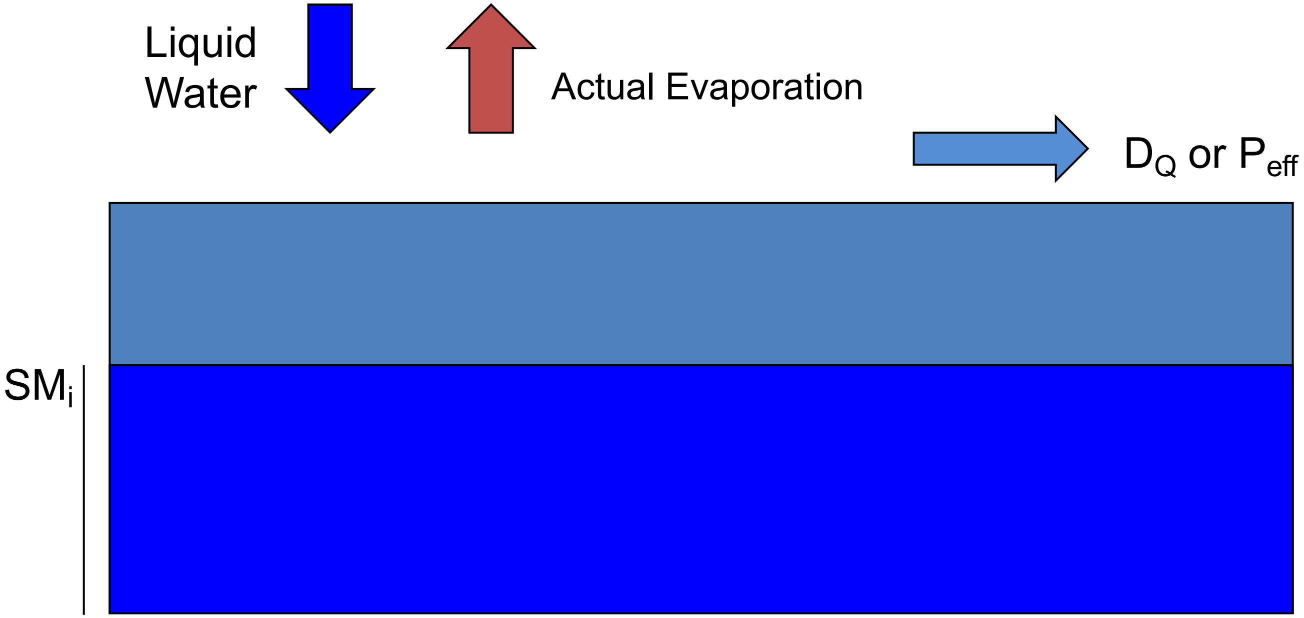
Actual Evaporation

Direct Runoff or P_{eff}

SM_i



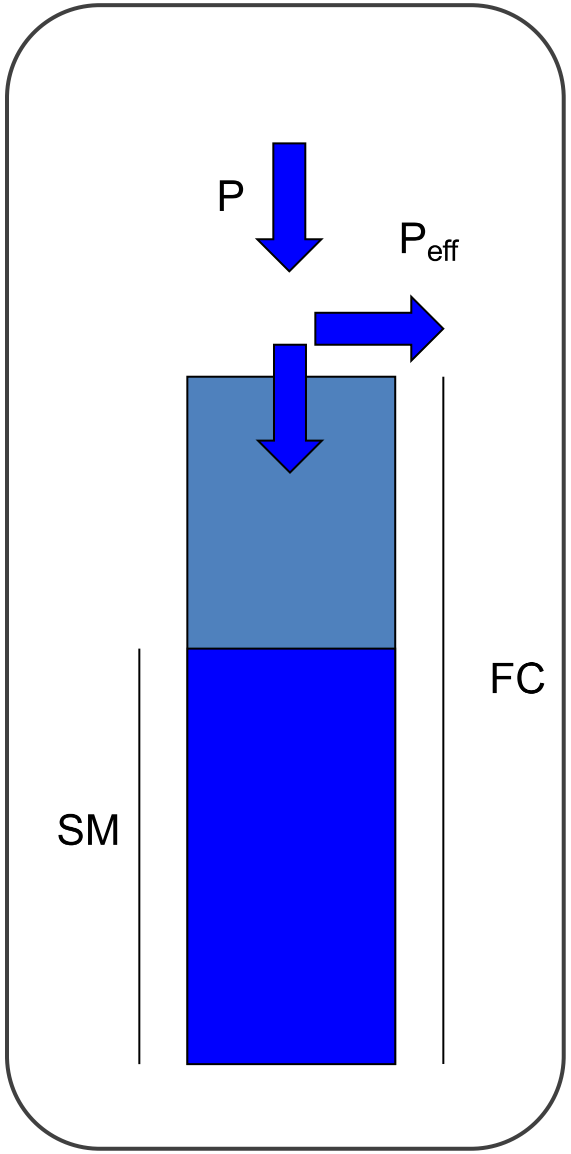
Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration



$$P_{eff} = \left[\frac{SM}{FC}\right]^{\beta} \left(P + SNOWMELT\right)$$

Peff ([L])	effective precipitation or direct runoff
SM [L]	actual soil-moisture
FC ([L])	maximum soil storage capacity
β ([-])	model parameter
P ([L])	depth of daily precipitation

Field capacity (*FC*) : describes maximum soil moisture storage in the catchment. The higher the amount of soil moisture; the more precipitation contributes to runoff production.



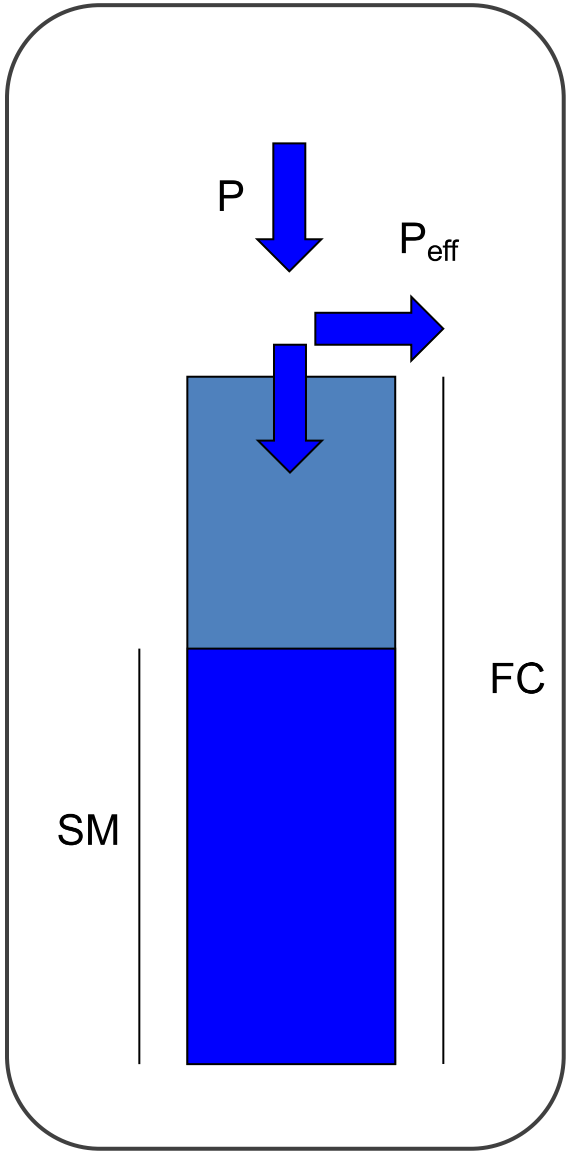
$$P_{eff} = \boxed{\left[\frac{SM}{FC}\right]^{\beta}}\boxed{\left(P + SNOWMELT\right)}$$

Runoff Coefficient

Liquid Water

Peff	([L])	effective precipitation or direct runoff
SM	[L]	actual soil-moisture
FC	([L])	maximum soil storage capacity
β	([-])	model parameter
P	([L])	depth of daily precipitation

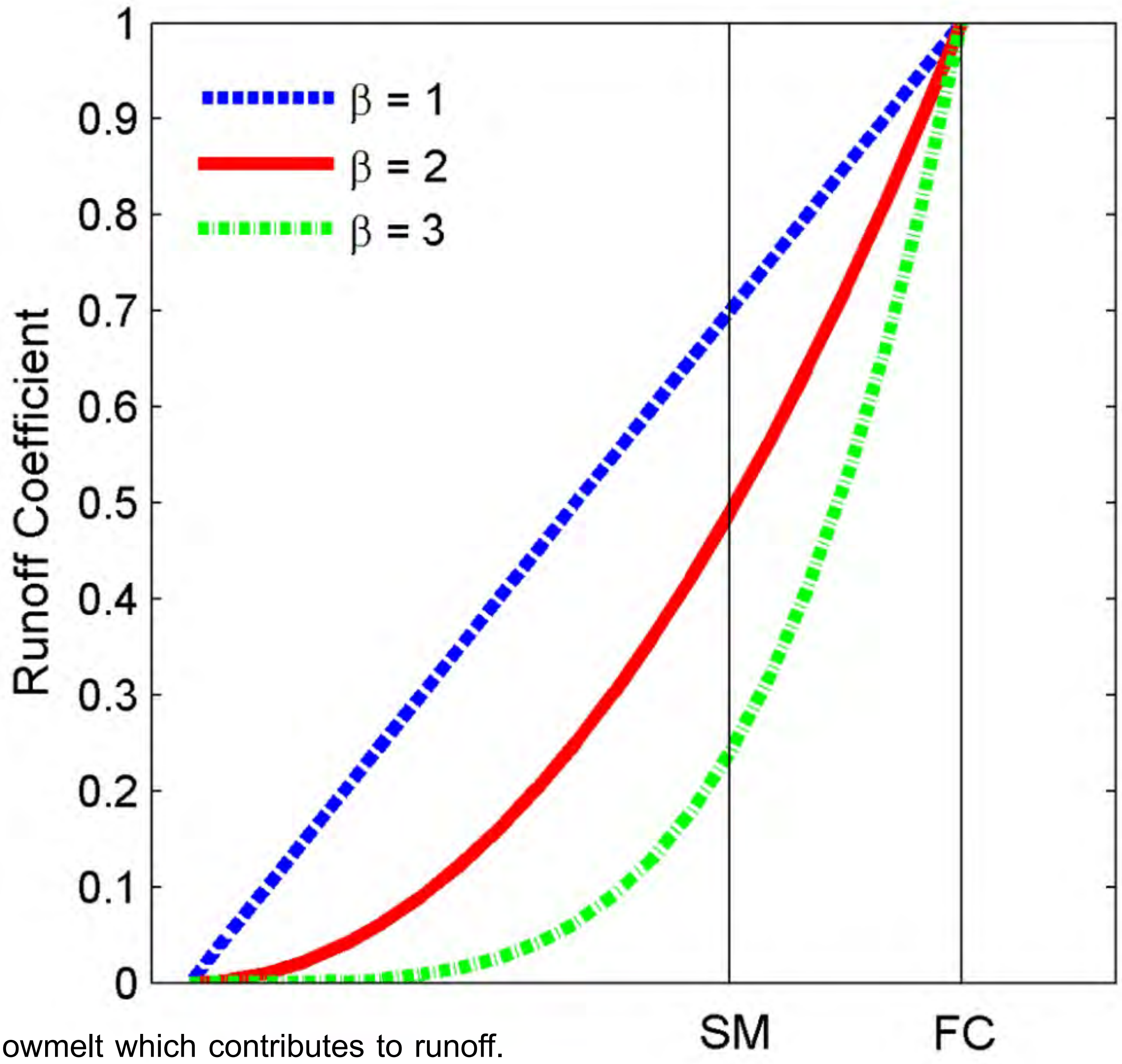
Field capacity (*FC*) : describes maximum soil moisture storage in the catchment. The higher the amount of soil moisture; the more precipitation contributes to runoff production.



$$P_{eff} = \underbrace{\left[\frac{SM}{FC}\right]^{\beta}}_{\text{Runoff Coefficient}} \underbrace{\left(P + SNOWMELT\right)}_{\text{Liquid Water}}$$

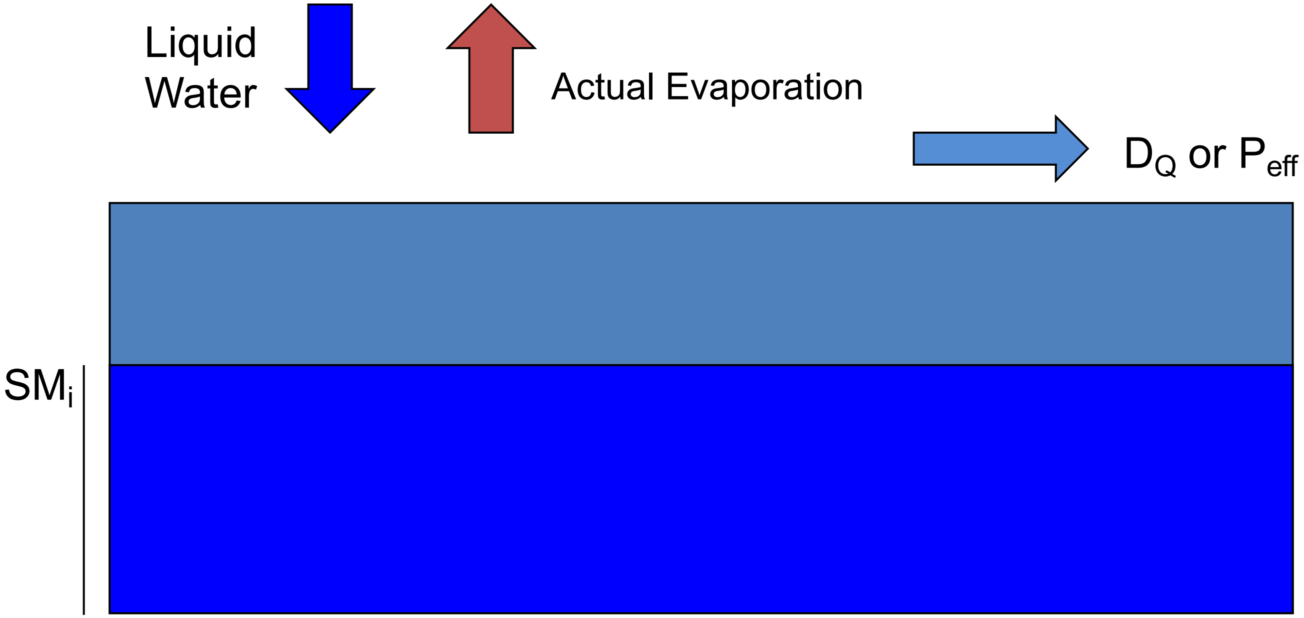
Peff	([L])	effective precipitation or direct runoff
SM	[L]	actual soil-moisture
FC	([L])	maximum soil storage capacity
β	([-])	model parameter
P	([L])	depth of daily precipitation

Field capacity (*FC*) : describes maximum soil moisture storage in the catchment. The higher the amount of soil moisture; the more precipitation contributes to runoff production.



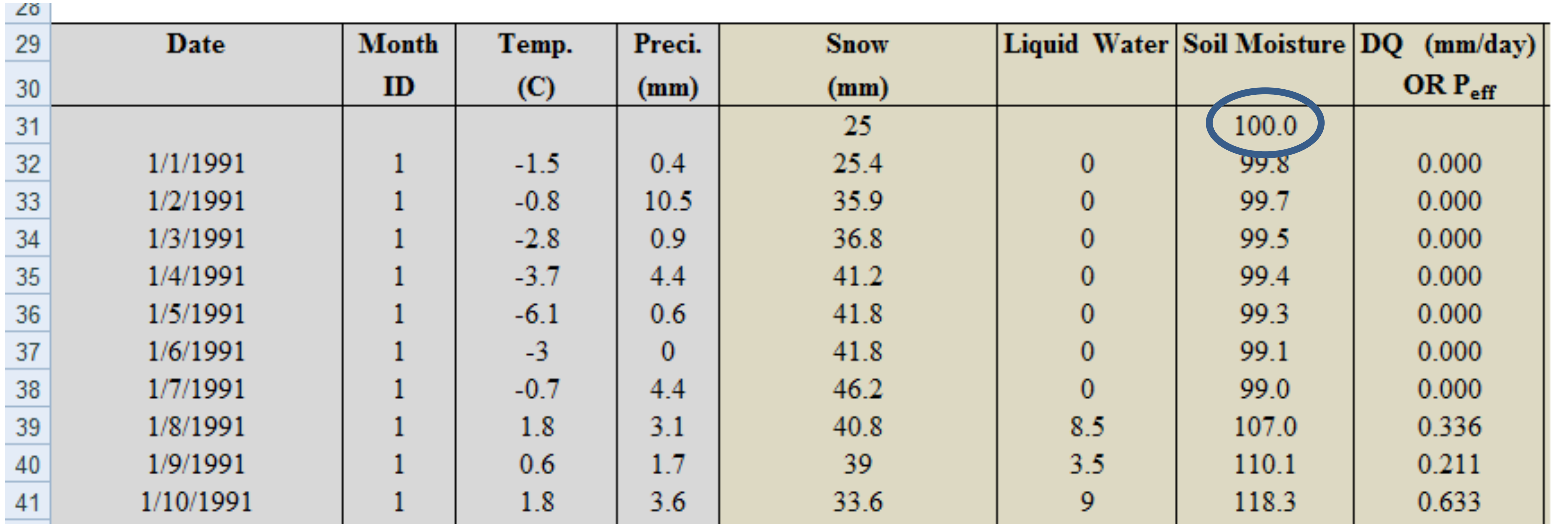
For a given soil-moisture deficit, β determines the amount of rain or snowmelt which contributes to runoff. The graph shows that for a specific soil moisture, the higher the β, the lower the runoff coefficient. Further, as the soil moisture (*SM*) approaches the field capacity (*FC*); the runoff coefficient increases.

Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration



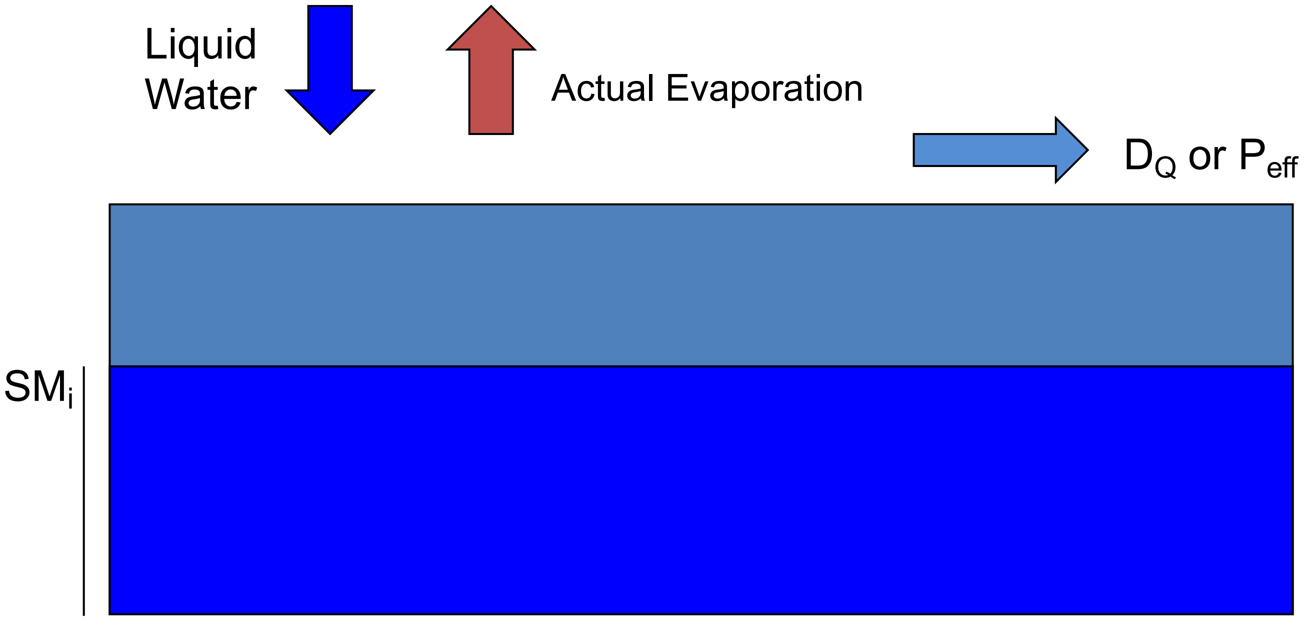
$$P_{eff} = \left[\frac{SM}{FC}\right]^{\beta}\left(P + SNOWMELT\right)$$

`=(F32*(G31/$C$11)^$C$12)`



29 30	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}
31					25		100.0	
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000
39	1/8/1991	1	1.8	3.1	40.8	8.5	107.0	0.336
40	1/9/1991	1	0.6	1.7	39	3.5	110.1	0.211
41	1/10/1991	1	1.8	3.6	33.6	9	118.3	0.633

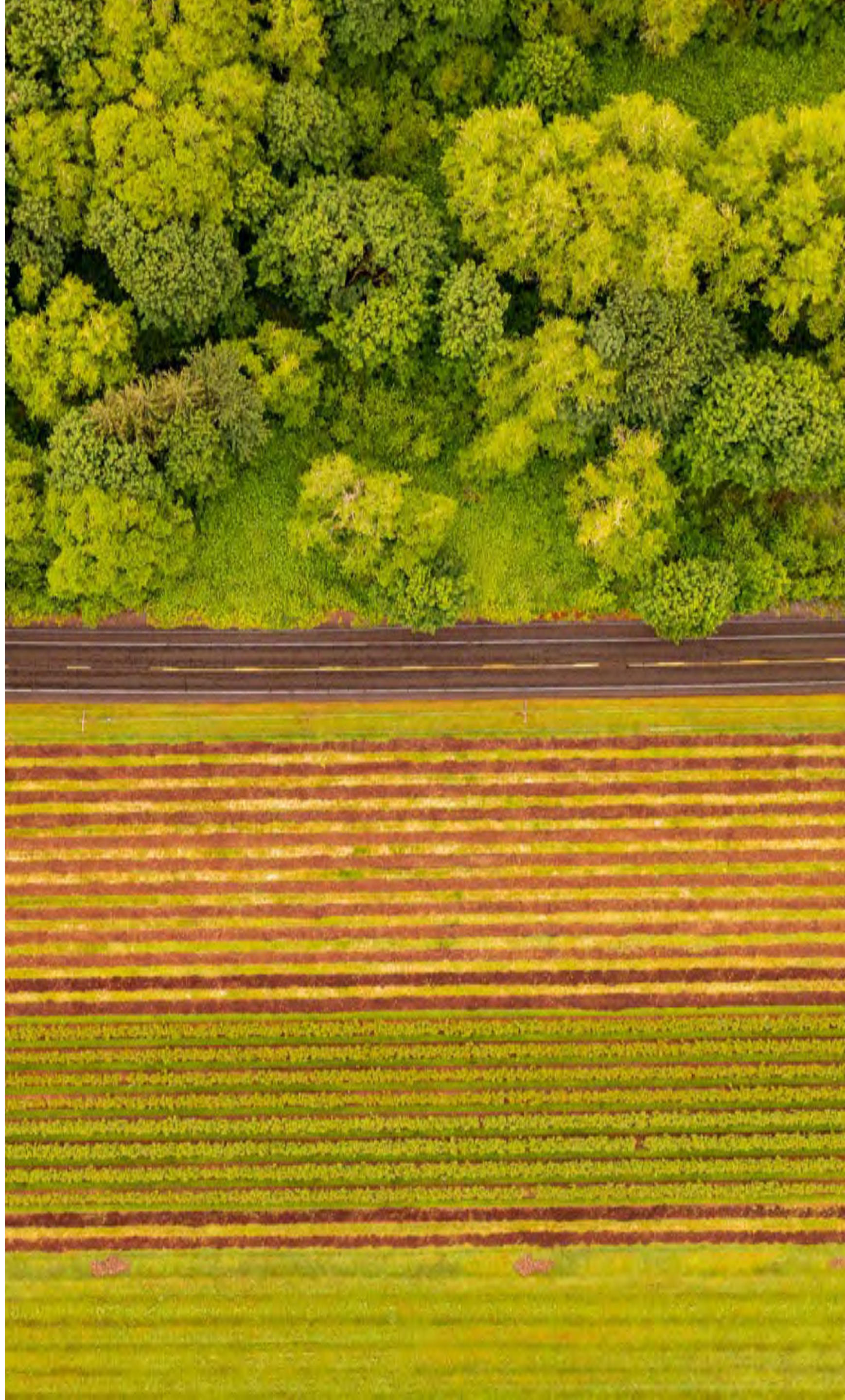
Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration



$$PE_a = (1 + C \cdot (T - T_m)) \cdot PE_m$$

PE_a ([L]) : adjusted potential evapotranspiration (none negative)
C ([θ^{-1}]) : model parameter
T ([θ]) : mean daily air temperature
T_m ([θ]) : long term mean monthly air temperature
PE_m ([L]) : long term mean monthly potential evapotranspiration

The model parameter *C* is used to improve model performance when the mean daily temperature deviates considerably from its long-term mean. The soil moisture and the actual evapotranspiration are coupled through the use of the soil moisture limit, Soil Permanent Wilting Point (PWP).

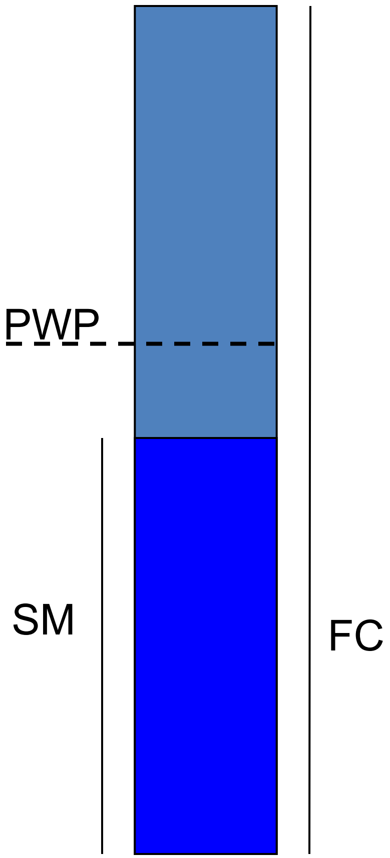


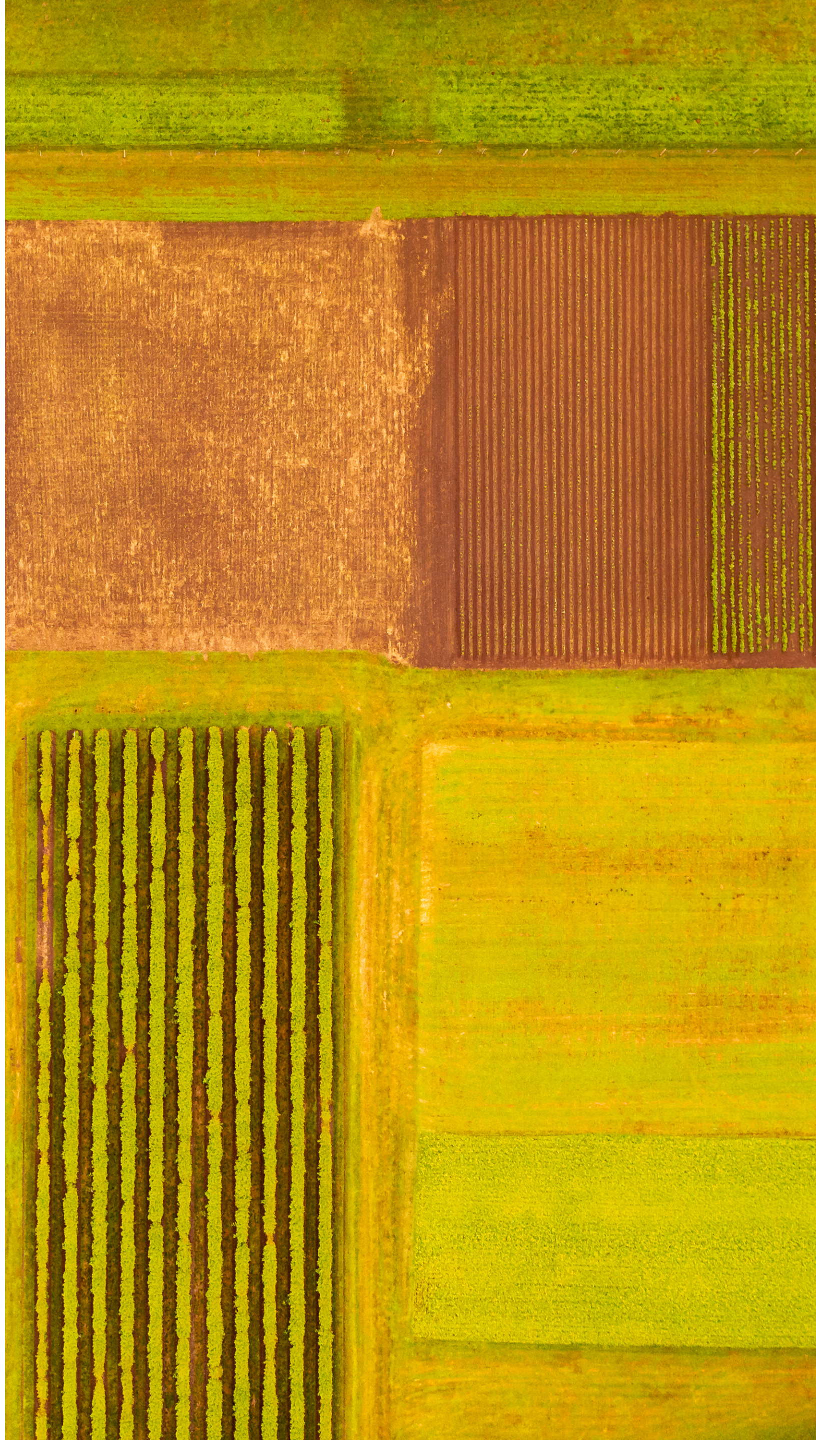
$$E_a = PE_a \cdot \frac{SM}{PWP} \quad \text{for} \quad SM < PWP$$

$$E_a = PE_a \quad \text{for} \quad SM \geq PWP$$

E_a ([L])	Actual evapotranspiration
PWP ([L])	Soil Permanent Wilting Point

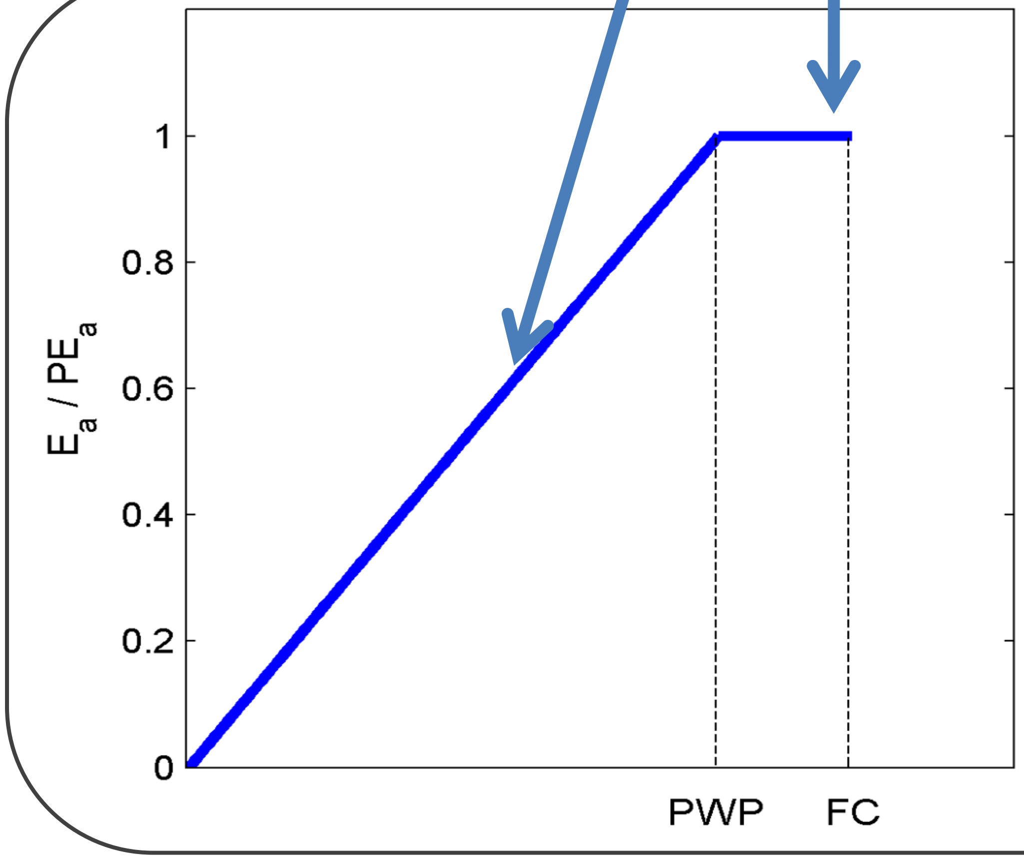
When the soil moisture is above the PWP, actual evapotranspiration occurs at the same rate as potential evapotranspiration. PWP is the soil-moisture limit for evapotranspiration (when the soil moisture is less than PWP, the actual evapotranspiration is less then the adjusted evapotranspiration).

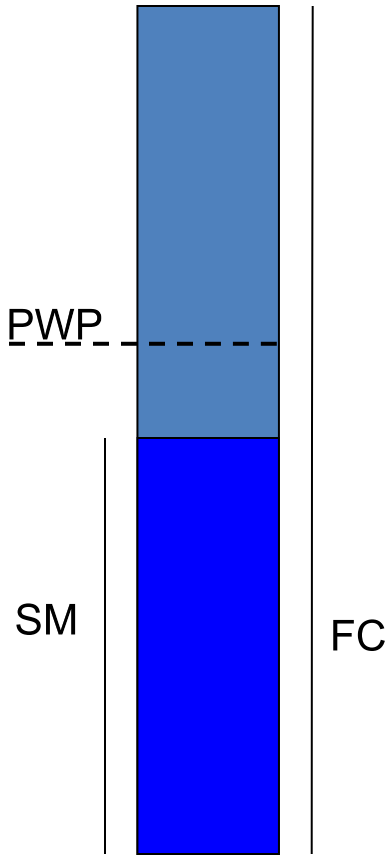




$$E_a = PE_a \cdot \frac{SM}{PWP} \quad \text{for } SM < PWP$$

$$E_a = PE_a \quad \text{for } SM \geq PWP$$

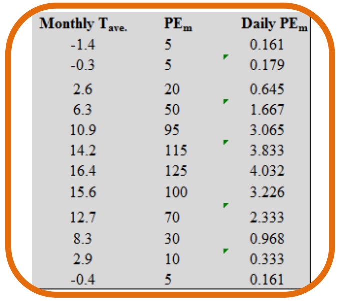




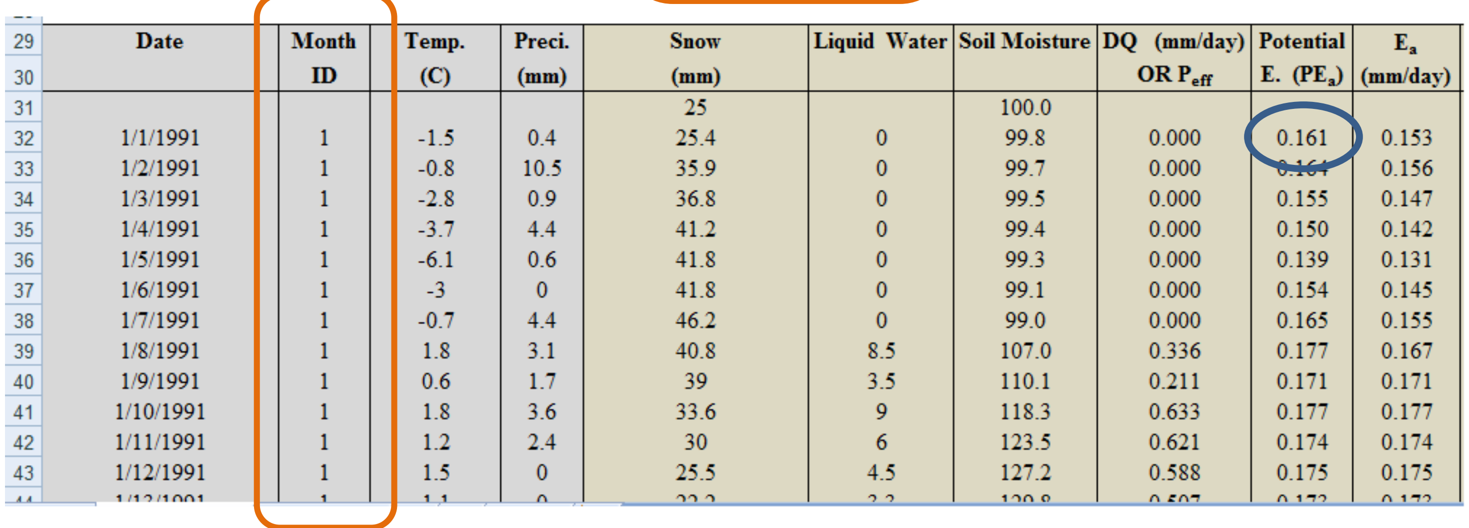
PE_a ([L]) : adjusted potential evapotranspiration
E_a ([L]) : actual evapotranspiration

$$PE_a = (1 + C \cdot (T - T_m)) \cdot PE_m$$

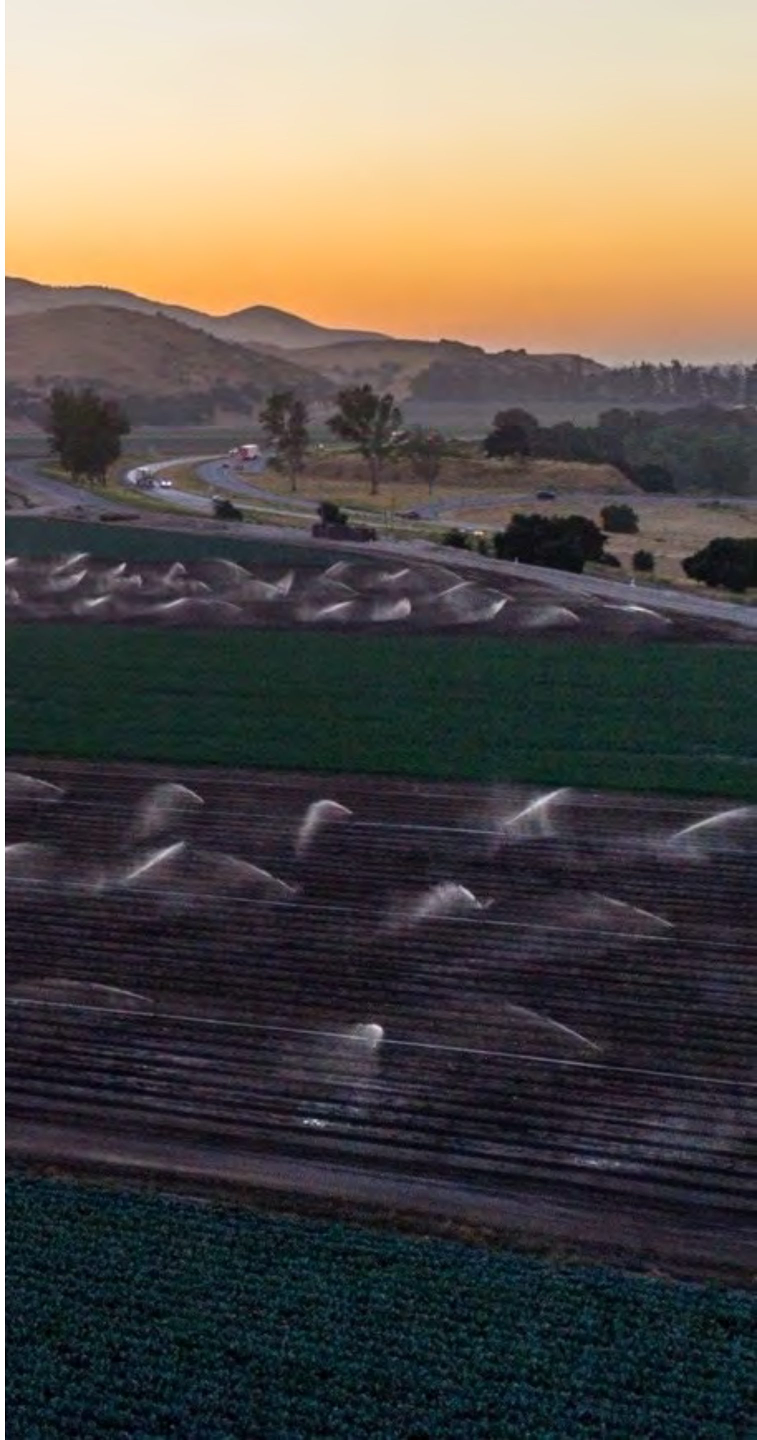
=(1+$C$13*(C32-INDEX($A$16:$A$27,B32)))*INDEX($C$16:$C$27,B32)



Monthly $T_{ave.}$	PE_m	Daily PE_m
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161



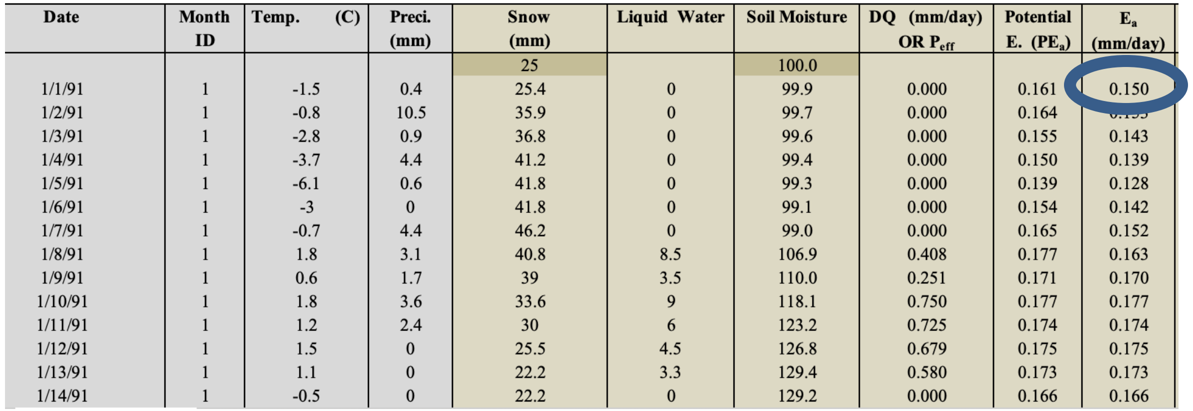
29 30	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)
31					25		100.0			
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155
39	1/8/1991	1	1.8	3.1	40.8	8.5	107.0	0.336	0.177	0.167
40	1/9/1991	1	0.6	1.7	39	3.5	110.1	0.211	0.171	0.171
41	1/10/1991	1	1.8	3.6	33.6	9	118.3	0.633	0.177	0.177
42	1/11/1991	1	1.2	2.4	30	6	123.5	0.621	0.174	0.174
43	1/12/1991	1	1.5	0	25.5	4.5	127.2	0.588	0.175	0.175



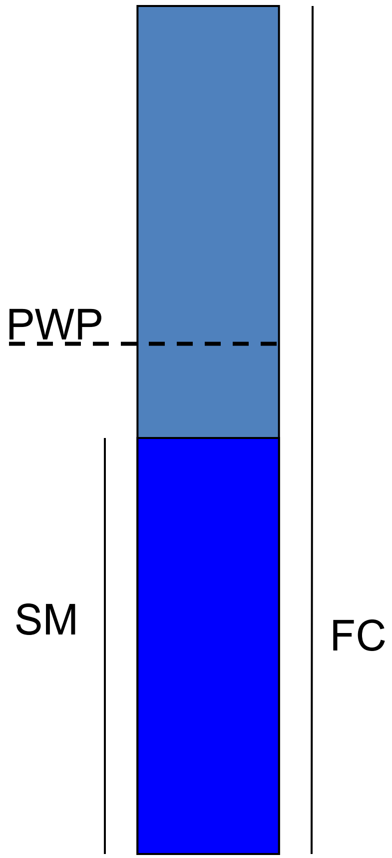
$$E_a = PE_a \cdot \frac{SM}{PWP} \quad \text{for} \quad SM < PWP$$

$$E_a = PE_a \quad \text{for} \quad SM \geq PWP$$

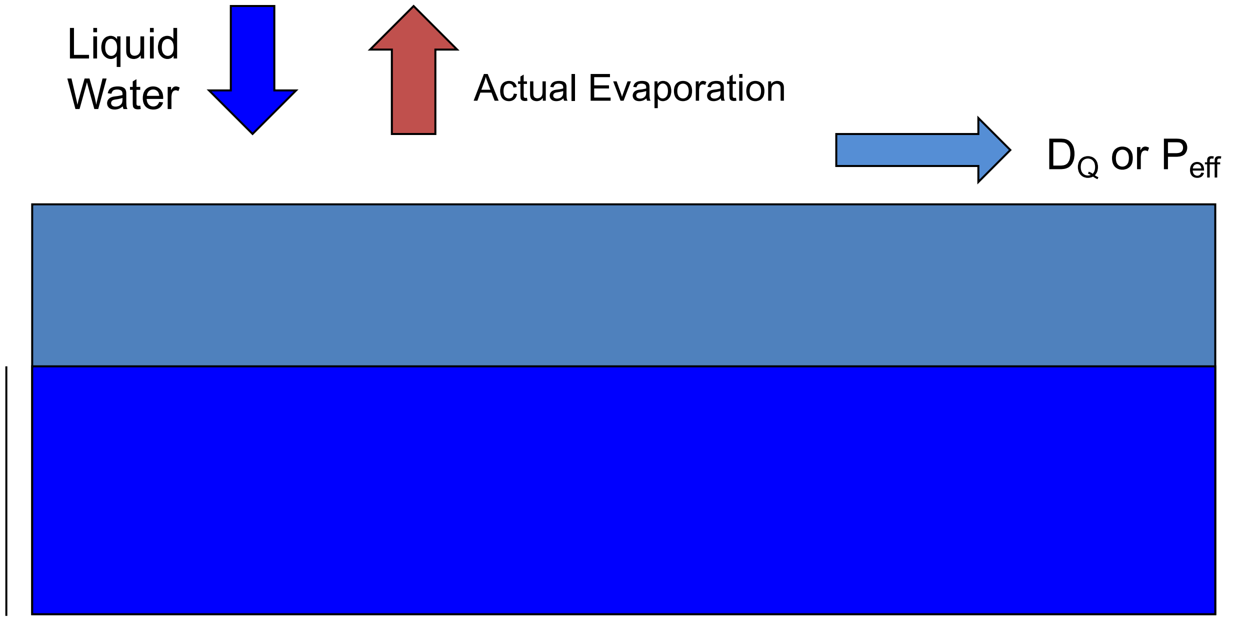
=IF(G31>=$F$13,I32,I32*(G31/$F$13))



Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)
				25		100.0			
1/1/91	1	-1.5	0.4	25.4	0	99.9	0.000	0.161	0.150
1/2/91	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	[illegible]
1/3/91	1	-2.8	0.9	36.8	0	99.6	0.000	0.155	0.143
1/4/91	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.139
1/5/91	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.128
1/6/91	1	-3	0	41.8	0	99.1	0.000	0.154	0.142
1/7/91	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.152
1/8/91	1	1.8	3.1	40.8	8.5	106.9	0.408	0.177	0.163
1/9/91	1	0.6	1.7	39	3.5	110.0	0.251	0.171	0.170
1/10/91	1	1.8	3.6	33.6	9	118.1	0.750	0.177	0.177
1/11/91	1	1.2	2.4	30	6	123.2	0.725	0.174	0.174
1/12/91	1	1.5	0	25.5	4.5	126.8	0.679	0.175	0.175
1/13/91	1	1.1	0	22.2	3.3	129.4	0.580	0.173	0.173
1/14/91	1	-0.5	0	22.2	0	129.2	0.000	0.166	0.166

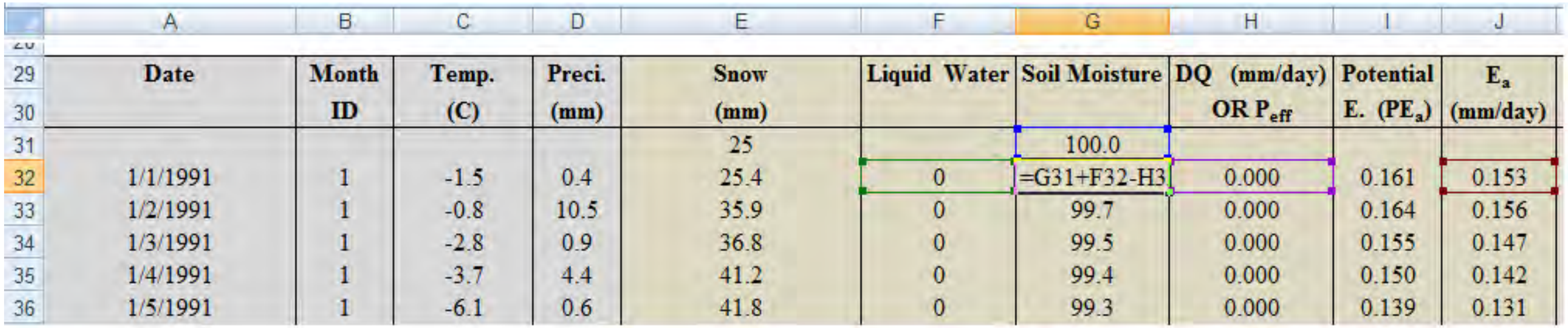


Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration

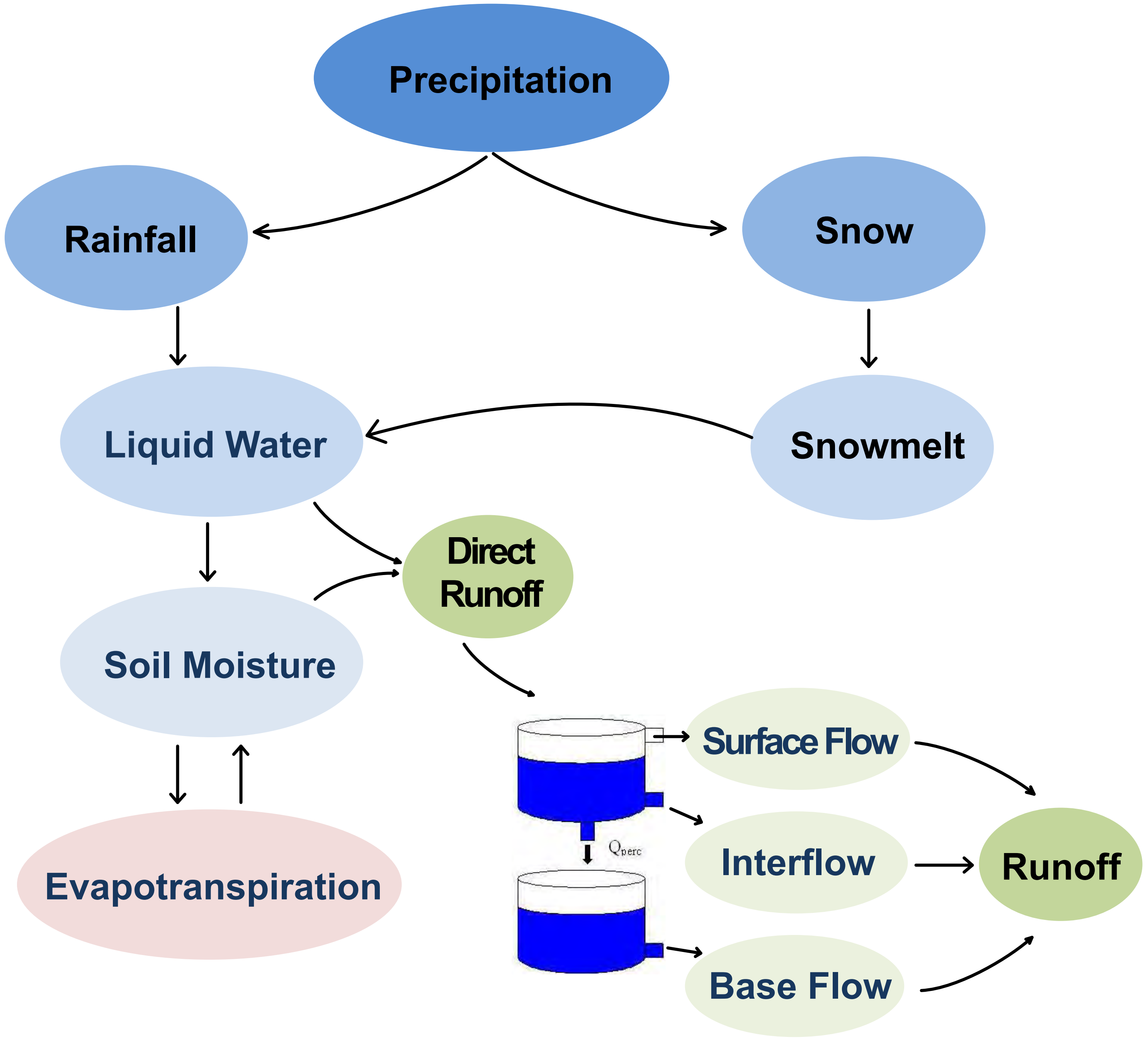


Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration

=G31+F32-H32-J32



	A	B	C	D	E	F	G	H	I	J
29 30	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)
31					25		100.0			
32	1/1/1991	1	-1.5	0.4	25.4	0	=G31+F32-H3	0.000	0.161	0.153
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131



Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

Evapotranspiration

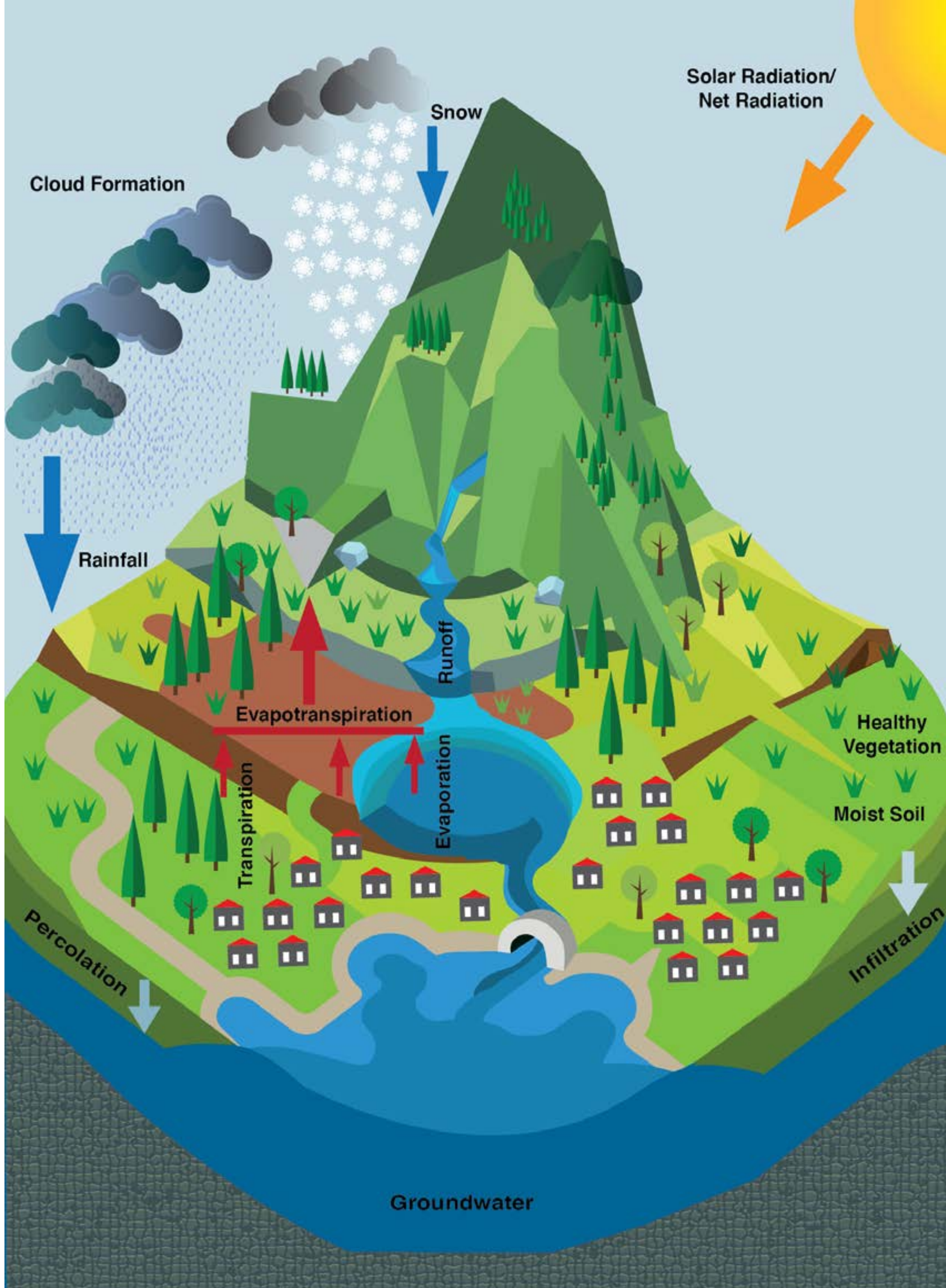
Q_{perc}

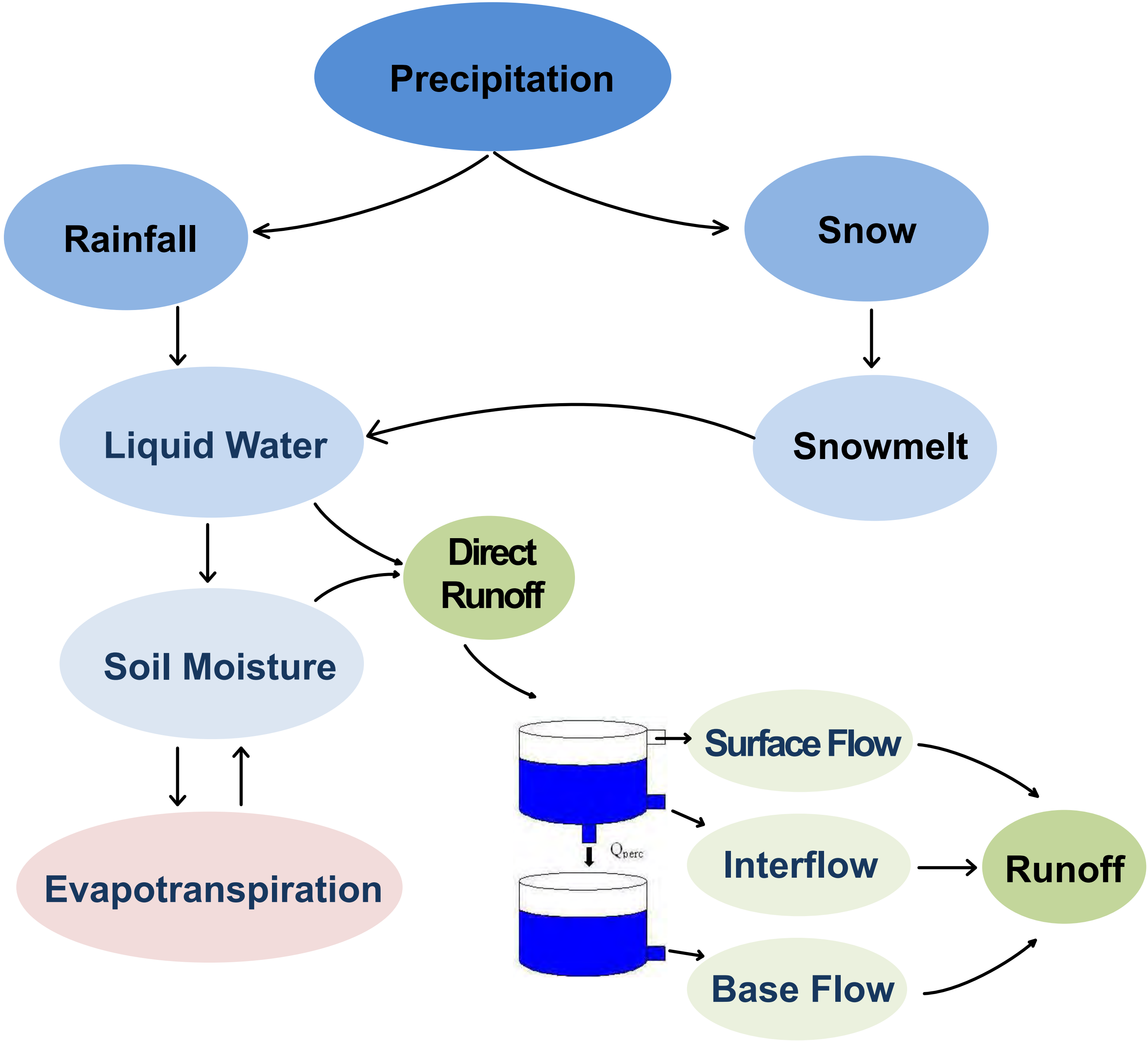
Surface Flow

Interflow

Base Flow

Runoff





Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

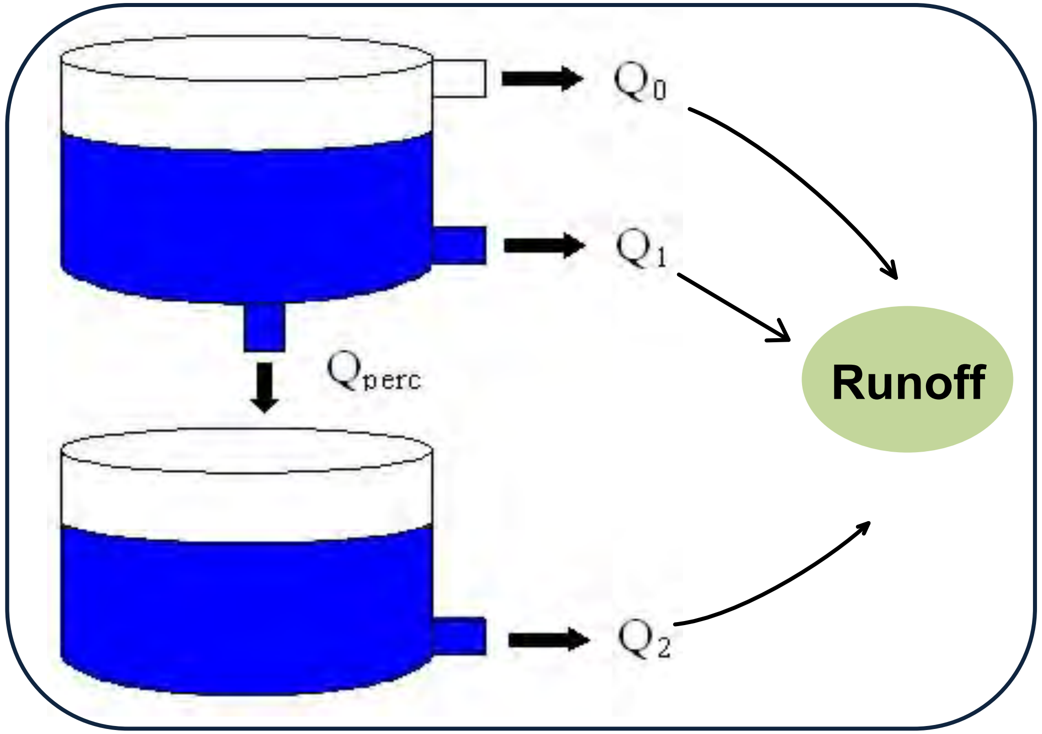
Evapotranspiration

Surface Flow

Interflow

Base Flow

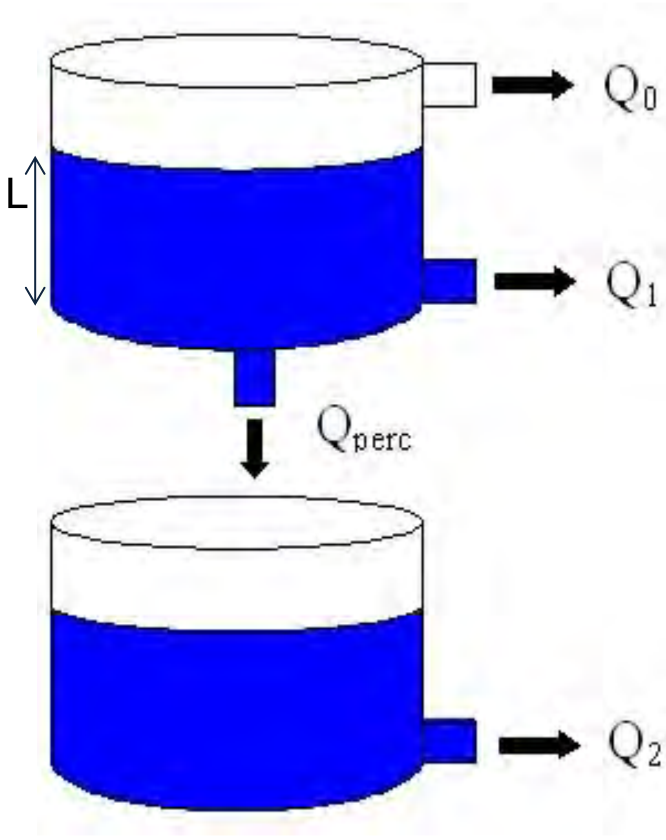
Runoff



This module estimates the runoff at the catchment outlet based on the bucket model (reservoir) concept. Here, the system consists of two conceptual reservoirs one above the other.

The first reservoir is used to model the near surface flow, and the second reservoir is used to simulate the base flow. The reservoirs are directly connected to each other through the use of a constant percolation rate (Q_{perc}).

Bucket Model Concept



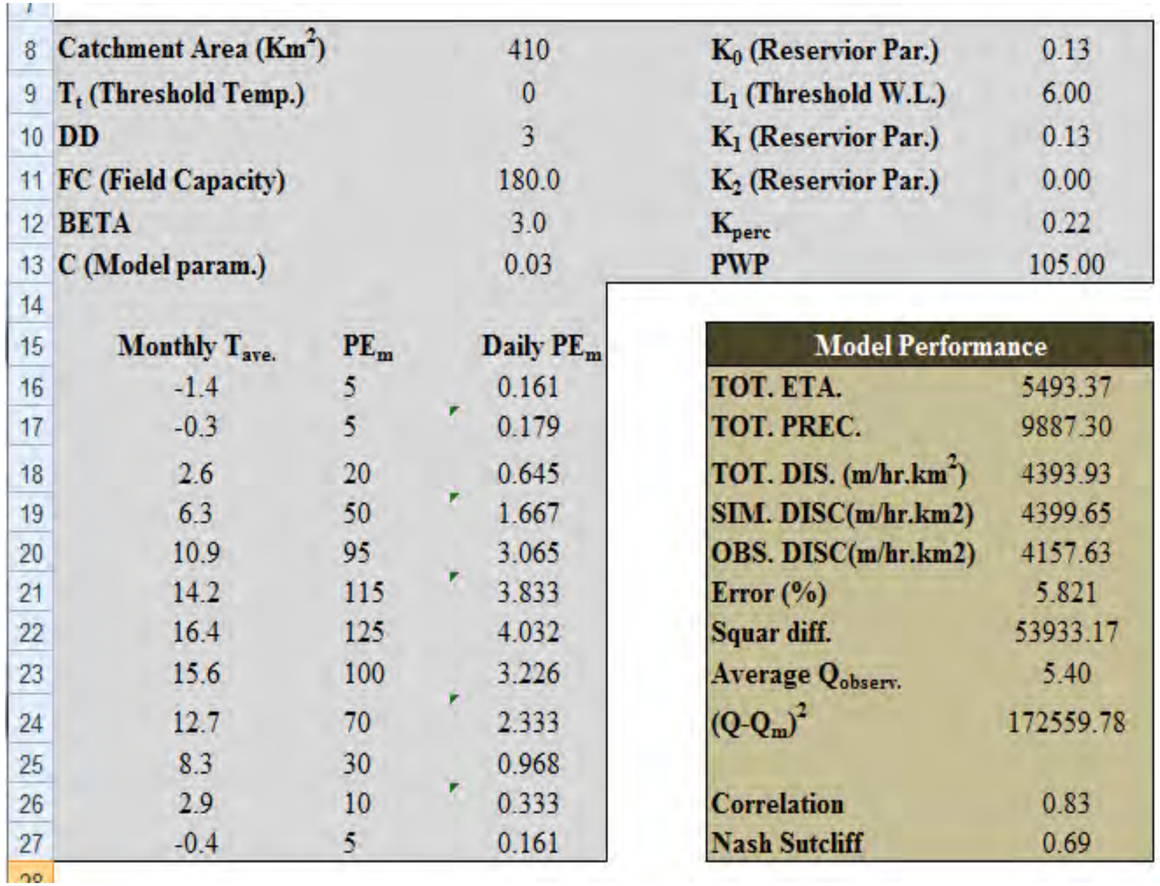
$$Q_0 = \begin{cases} K_0 \cdot (S_i - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \leq L \end{cases}$$

$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

$$Q_{perc} = K_{perc} \cdot (S_i) \cdot A_{sc}$$

$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$

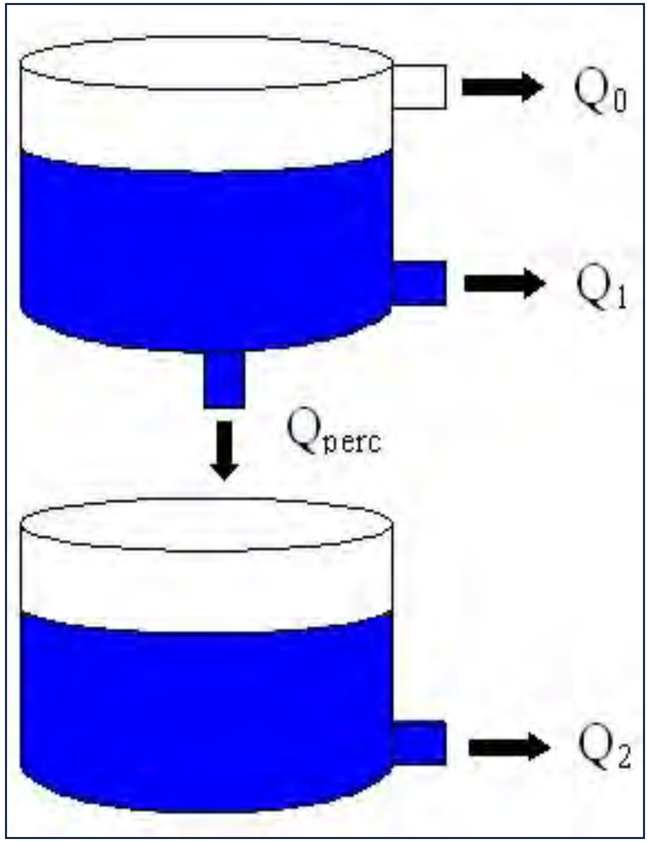
Q_0 ($[L^3T^{-1}]$) near surface flow
Q_1 ($[L^3T^{-1}]$) Interflow
Q_{perc} ($[L^3T^{-1}]$) Percolation
Q_2 ($[L^3T^{-1}]$) base flow
K_0 ($[T^{-1}]$) subsurface storage constant
K_1 ($[T^{-1}]$) interflow storage constant
K_{perc} ($[T^{-1}]$) percolation storage constant
K_2 ($[T^{-1}]$) base flow storage constant
S_i ([L]) upper reservoir water level (WL)
S_b ([L]) lower reservoir WL
L ([L]) threshold for subsurface flow
Asc [L2] Sub-catchment area

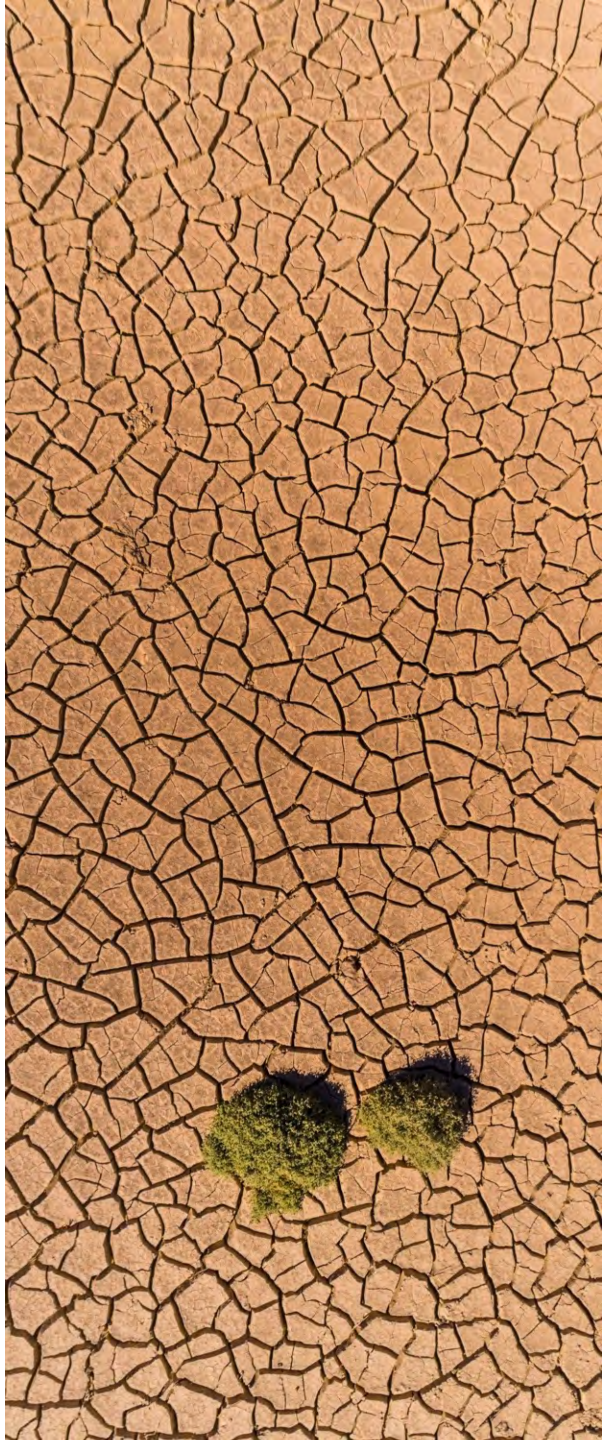


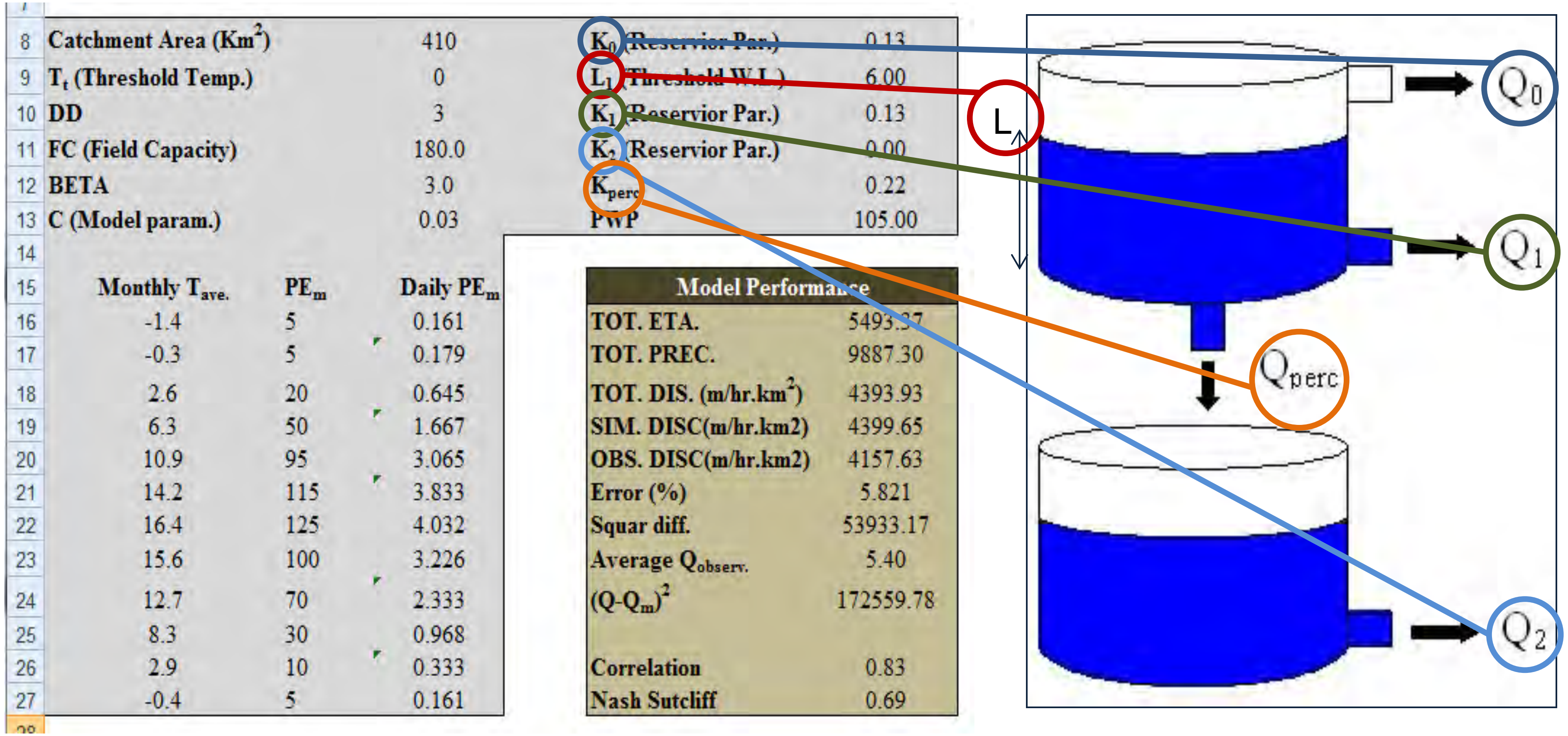
Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.13
T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
DD	3	K_1 (Reservior Par.)	0.13
FC (Field Capacity)	180.0	K_2 (Reservior Par.)	0.00
BETA	3.0	K_{perc}	0.22
C (Model param.)	0.03	PWP	105.00

Monthly $T_{ave.}$	PE_m	Daily PE_m
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

Model Performance	
TOT. ETA.	5493.37
TOT. PREC.	9887.30
TOT. DIS. ($m/hr.km^2$)	4393.93
SIM. DISC(m/hr.km2)	4399.65
OBS. DISC(m/hr.km2)	4157.63
Error (%)	5.821
Squar diff.	53933.17
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.83
Nash Sutcliff	0.69







8	Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.13
9	T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
10	DD	3	K_1 (Reservior Par.)	0.13
11	FC (Field Capacity)	180.0	K_2 (Reservior Par.)	0.00
12	BETA	3.0	K_{perc}	0.22
13	C (Model param.)	0.03	PWP	105.00

15	Monthly $T_{ave.}$	PE_m	Daily PE_m
16	-1.4	5	0.161
17	-0.3	5	0.179
18	2.6	20	0.645
19	6.3	50	1.667
20	10.9	95	3.065
21	14.2	115	3.833
22	16.4	125	4.032
23	15.6	100	3.226
24	12.7	70	2.333
25	8.3	30	0.968
26	2.9	10	0.333
27	-0.4	5	0.161

Model Performance	
TOT. ETA.	5493.37
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Average $Q_{observ.}$	5.40
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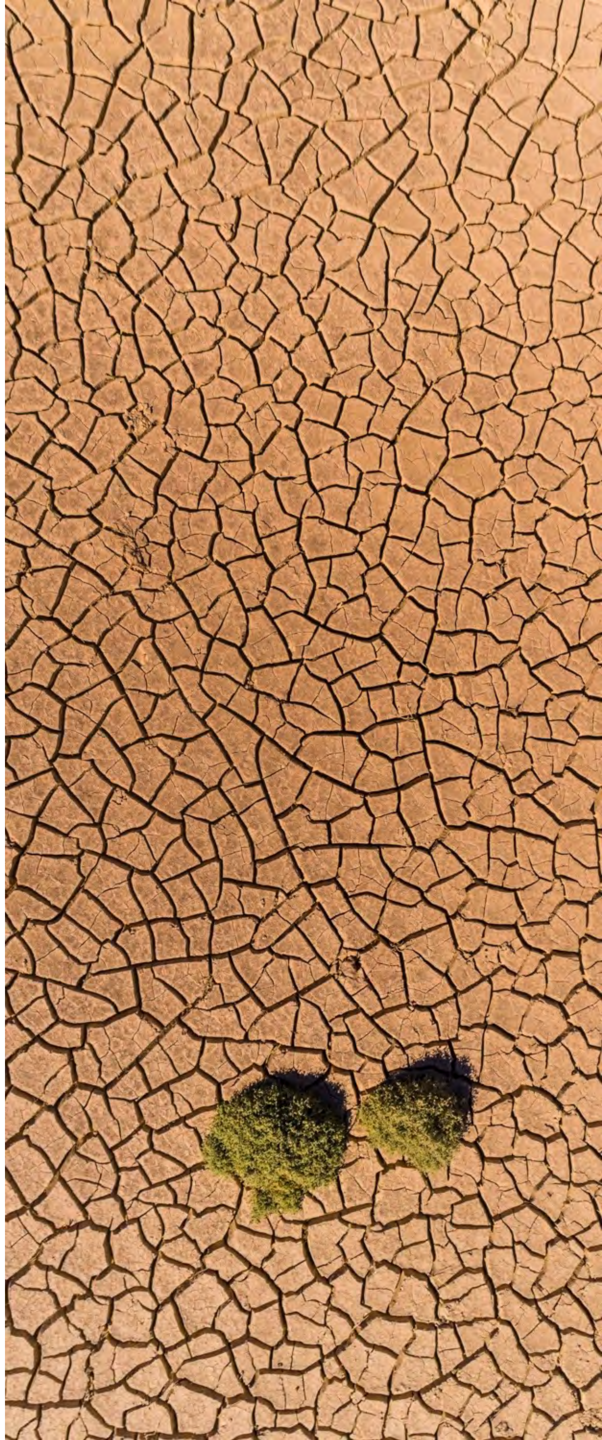
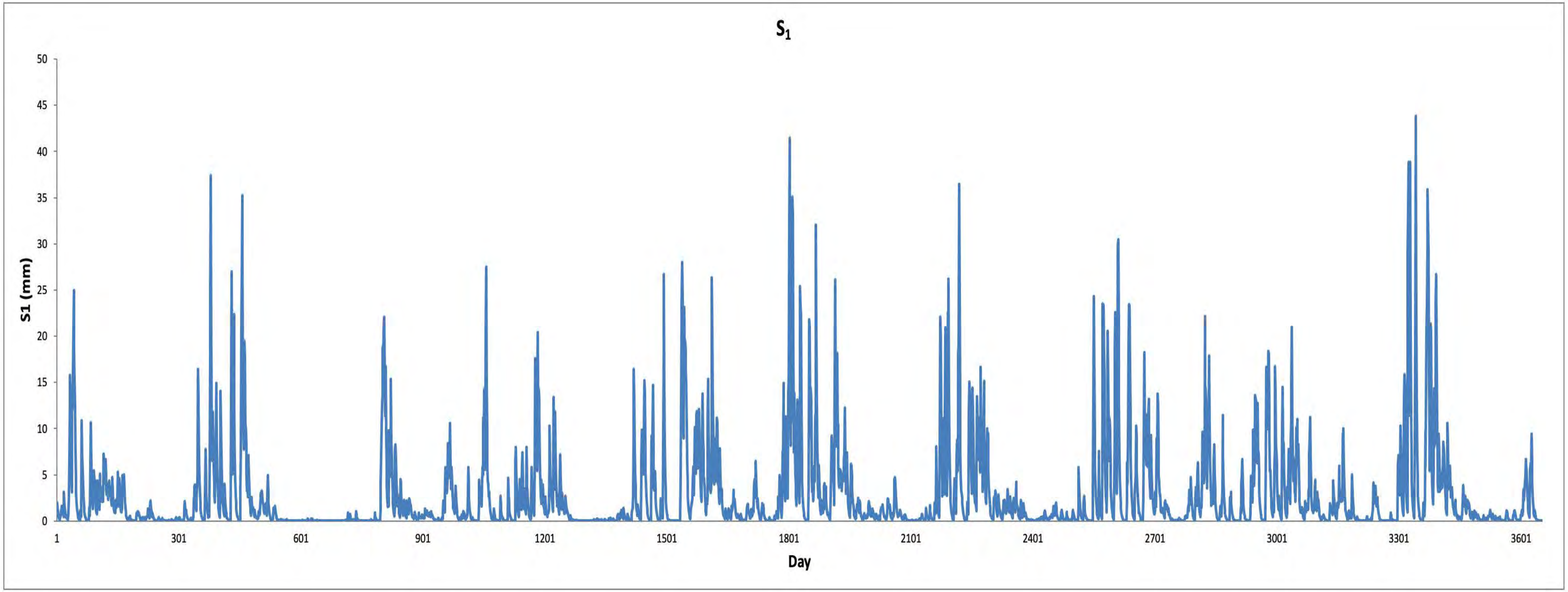
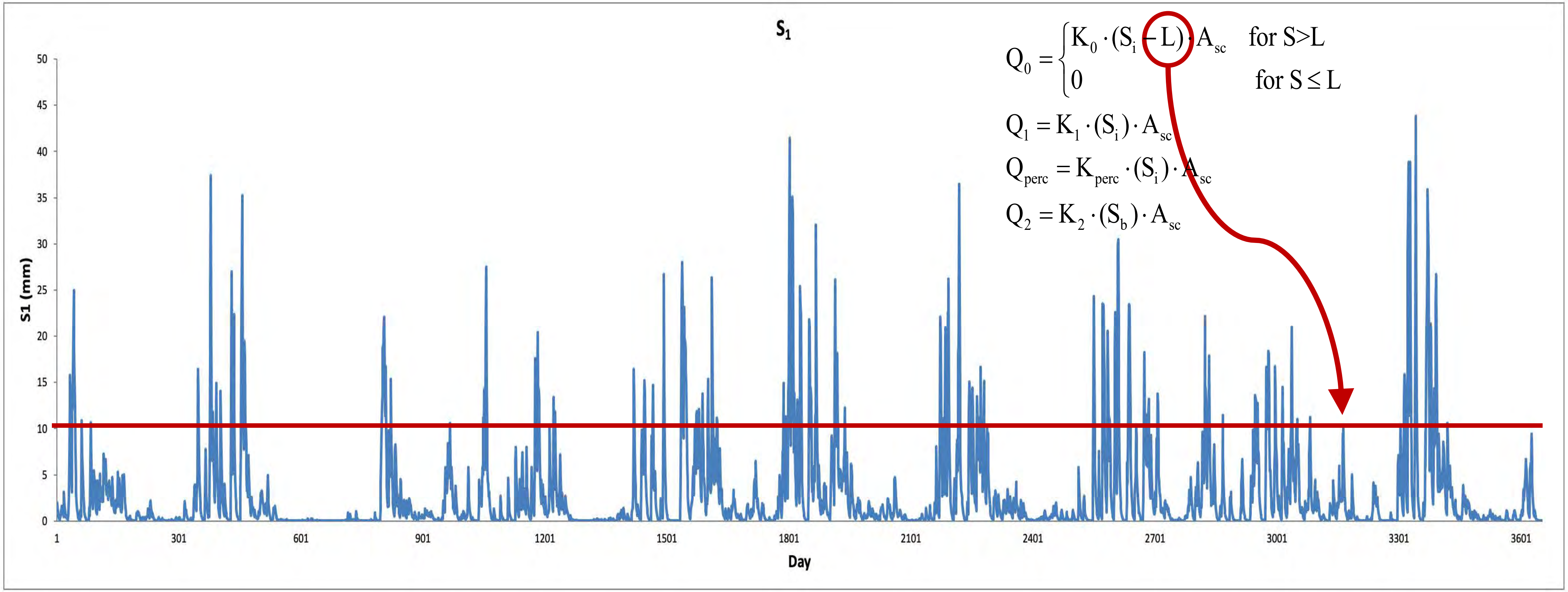
Correlation	0.83
Nash Sutcliff	0.69

$$S_1 = Q_{\text{initial}} + Q_{\text{surface}} - Q_0 - Q_1 - Q_{\text{perc}}$$

$$=\underbrace{K31}_{\text{Initial } S_1}+\underbrace{H32}_{P_{eff}}-\underbrace{MAX(0,K31-\$F\$9)*\$F\$8}_{(S_1-L)*\ K_0}-\underbrace{K31*\$F\$10}_{(S_1)*\ K_1}\ -\underbrace{K31*\$F\$12}_{(S_{perc})*\ K_{perc}}$$




S_1
S1 (mm)
0
5
10
15
20
25
30
35
40
45
50
Day
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
3301
3601

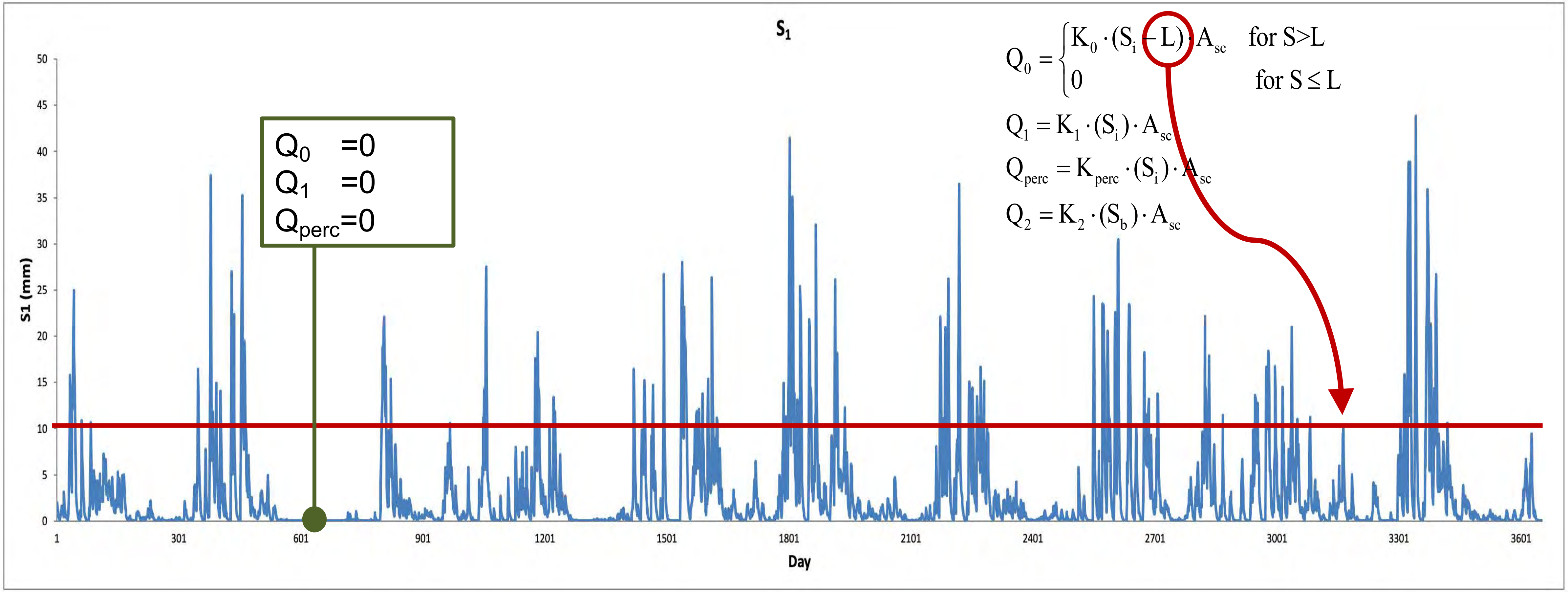


$$Q_0 = \begin{cases} K_0 \cdot (S_i - L) \cdot A_{sc} & \text{for } S > L \\ 0 & \text{for } S \le L \end{cases}$$

$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

$$Q_{perc} = K_{perc} \cdot (S_i) \cdot A_{sc}$$

$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$



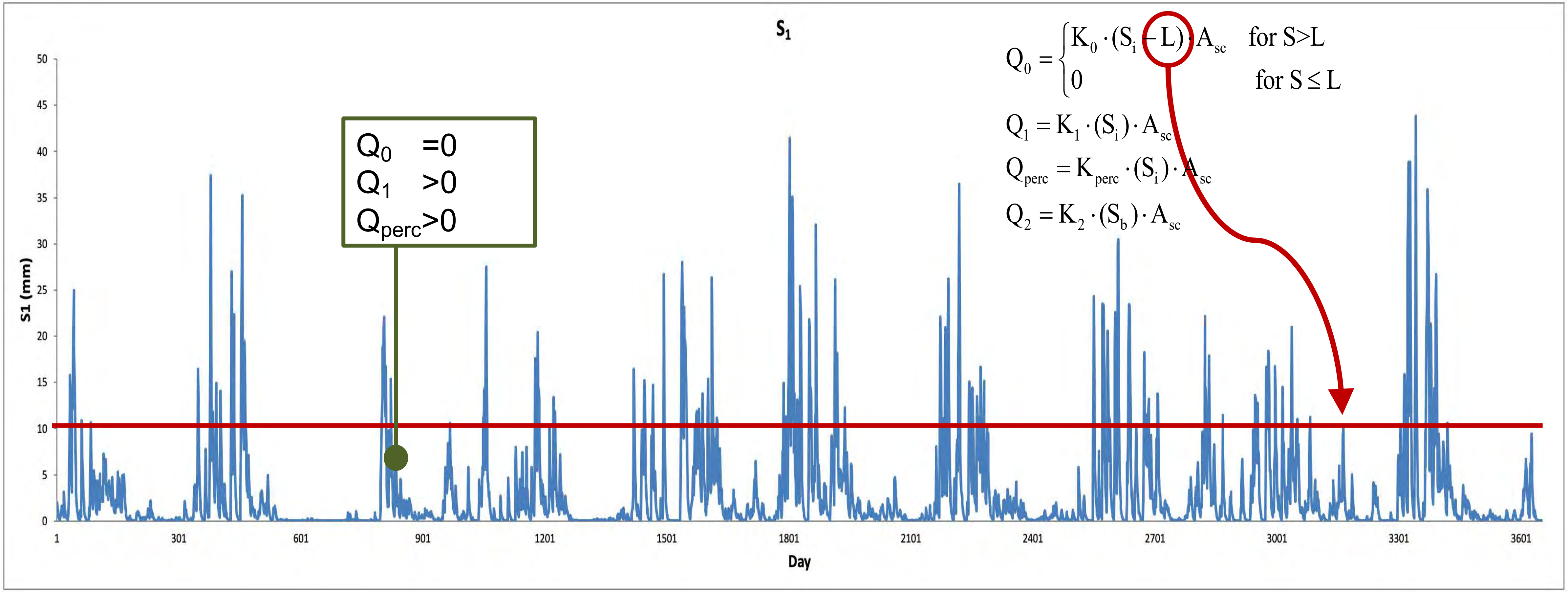
$Q_0 = 0$
$Q_1 = 0$
$Q_{perc} = 0$

$$Q_0 = \begin{cases} K_0 \cdot (S_i - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \le L \end{cases}$$

$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

$$Q_{perc} = K_{perc} \cdot (S_i) \cdot A_{sc}$$

$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$



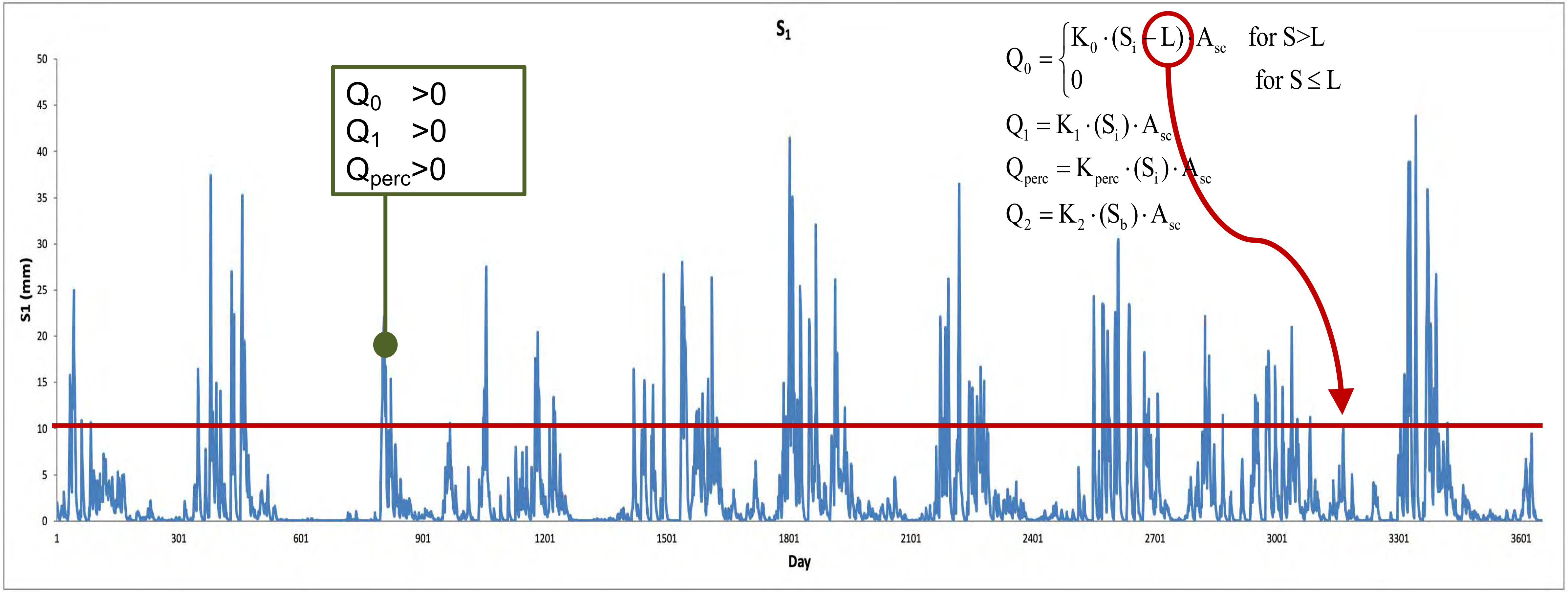
Q_0 =0
Q_1 >0
Q_{perc}>0

$$Q_0 = \begin{cases} K_0 \cdot (S_i - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \leq L \end{cases}$$

$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

$$Q_{perc} = K_{perc} \cdot (S_i) \cdot A_{sc}$$

$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$



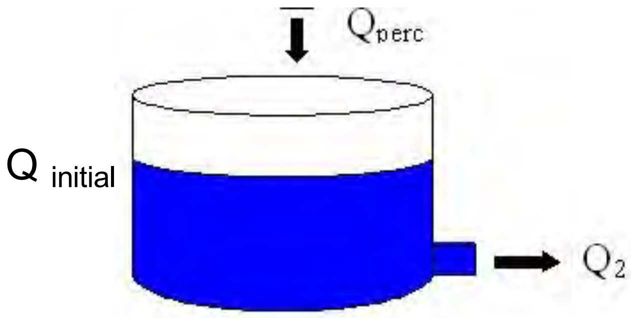
Q_0 >0
Q_1 >0
Q_{perc}>0

$$Q_0 = \begin{cases} K_0 \cdot (S_i \boxed{- L}) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \le L \end{cases}$$

$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

$$Q_{perc} = K_{perc} \cdot (S_i) \cdot A_{sc}$$

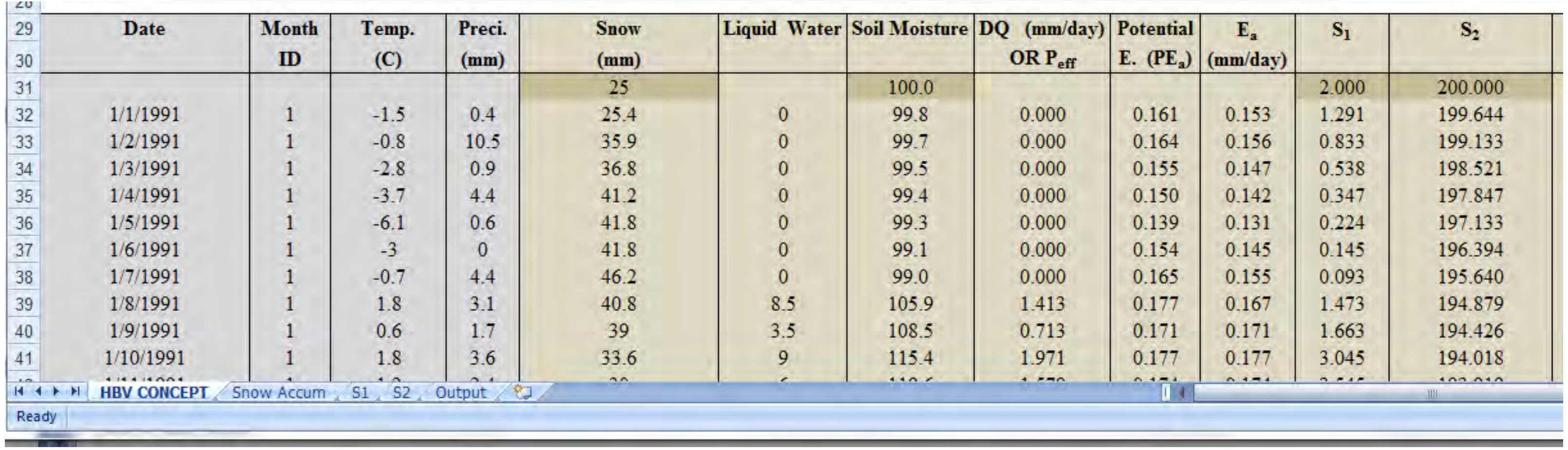
$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$



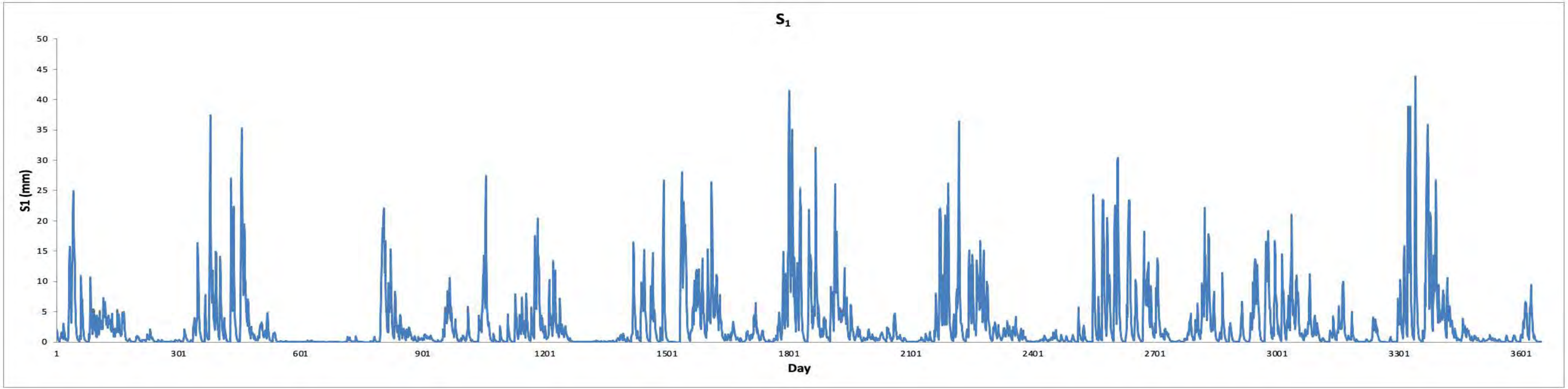
$$S_2 = Q_{initial} - Q_2 + Q_{perc}$$

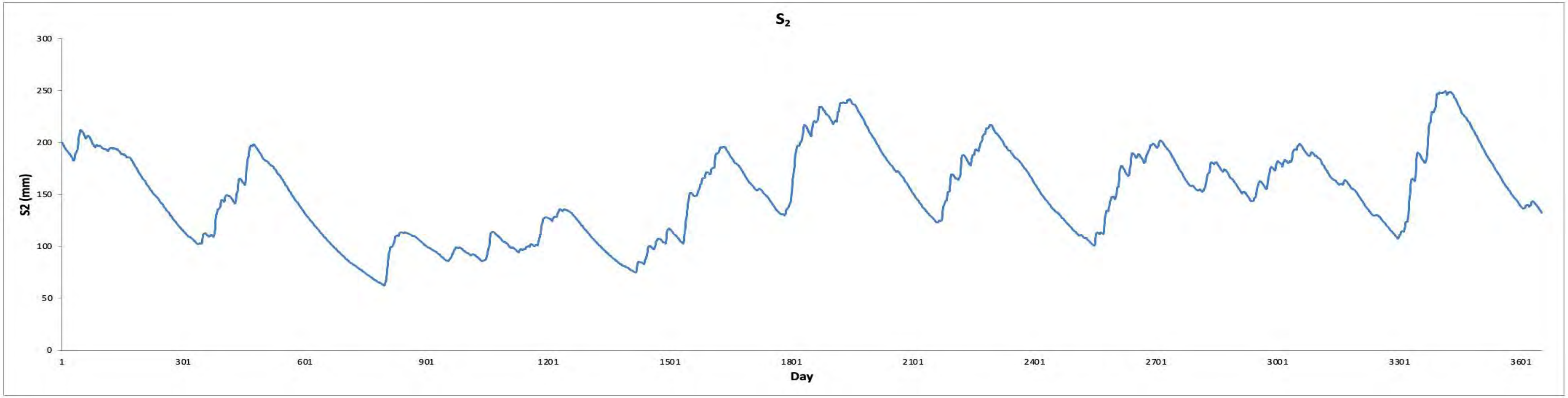
⇩

$$=\underbrace{L31}_{\text{Initial } S_2}+\underbrace{K31*\$F\$12}_{(S_1)^* K_{perc}}-\underbrace{L31*\$F\$11}_{(S_2)^* K_2}$$



29	Date	Month	Temp.	Preci.	Snow	Liquid Water	Soil Moisture	DQ (mm/day)	Potential	E_a	S_1	S_2
30		ID	(C)	(mm)	(mm)			OR P_{eff}	E. (PE_a)	(mm/day)		
31					25		100.0				2.000	200.000
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538	198.521
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347	197.847
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224	197.133
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145	196.394
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093	195.640
39	1/8/1991	1	1.8	3.1	40.8	8.5	105.9	1.413	0.177	0.167	1.473	194.879
40	1/9/1991	1	0.6	1.7	39	3.5	108.5	0.713	0.171	0.171	1.663	194.426
41	1/10/1991	1	1.8	3.6	33.6	9	115.4	1.971	0.177	0.177	3.045	194.018


S₁
S1 (mm)
50
45
40
35
30
25
20
15
10
5
0
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
3301
3601
Day

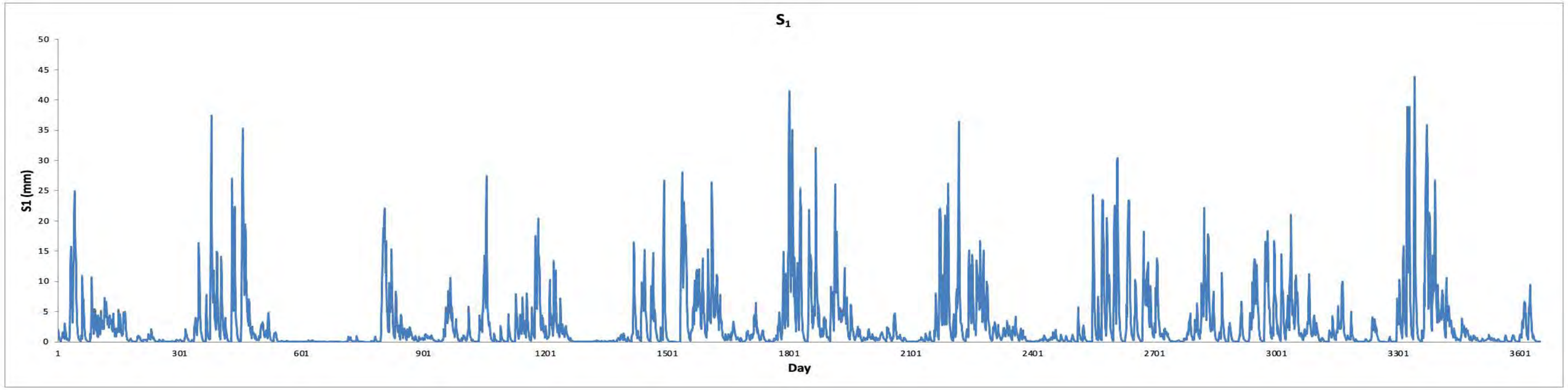

S₂
S2 (mm)
300
250
200
150
100
50
0
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
3301
3601
Day

$$Q_0 = K_0 .(S_1\text{-}L). A$$

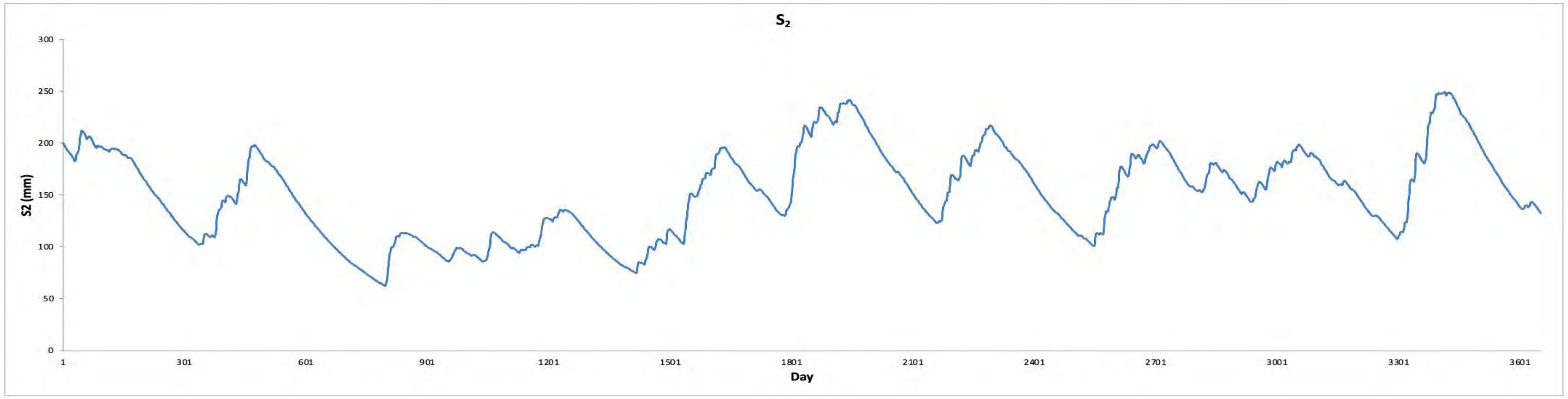
$$Q_1 = K_1 . S_1 . A$$

$$Q_2 = K_2 . S_2 . A$$

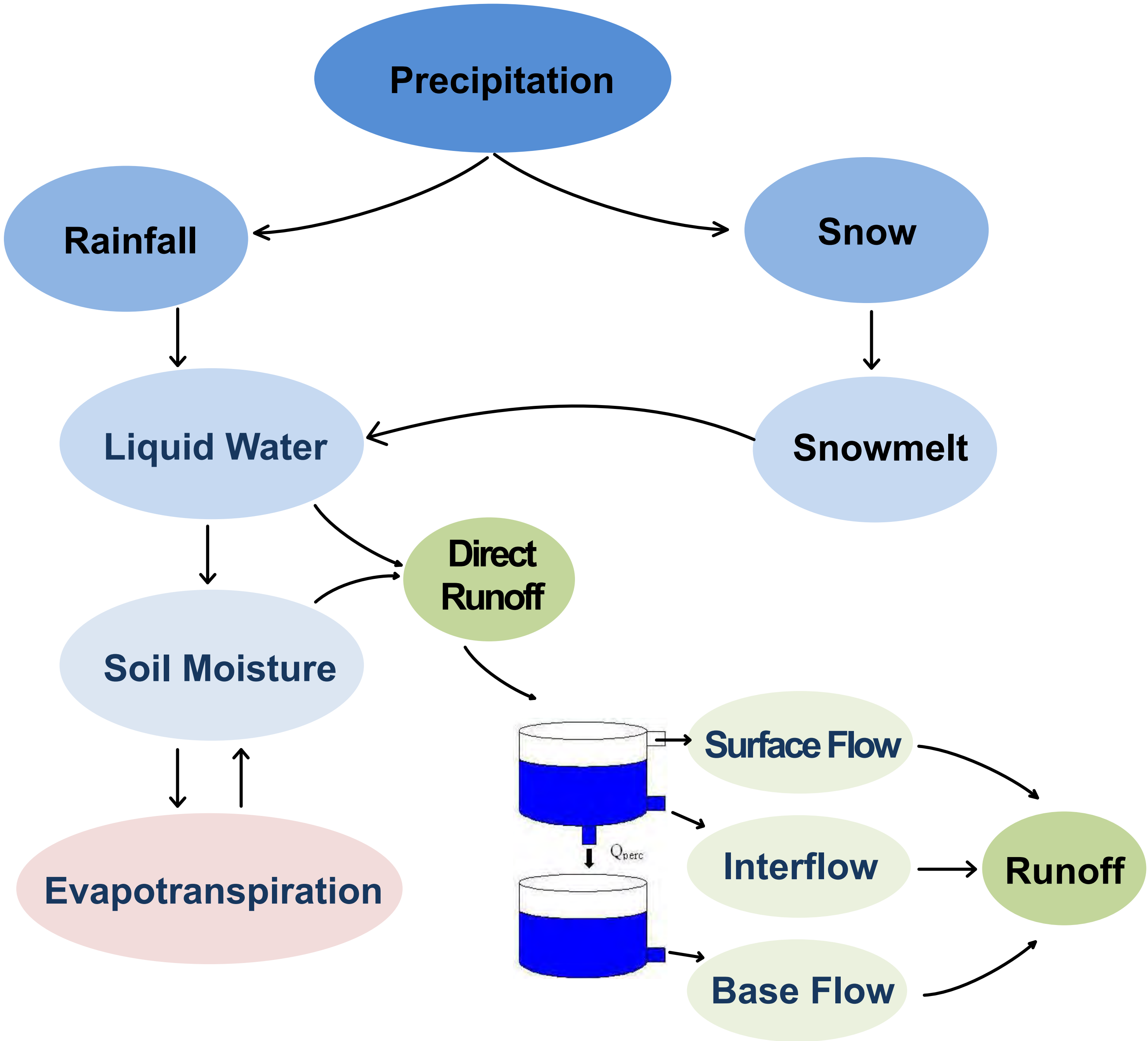
$$K_0 > K_1 > K_2$$



S_1



S_2



Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

Evapotranspiration

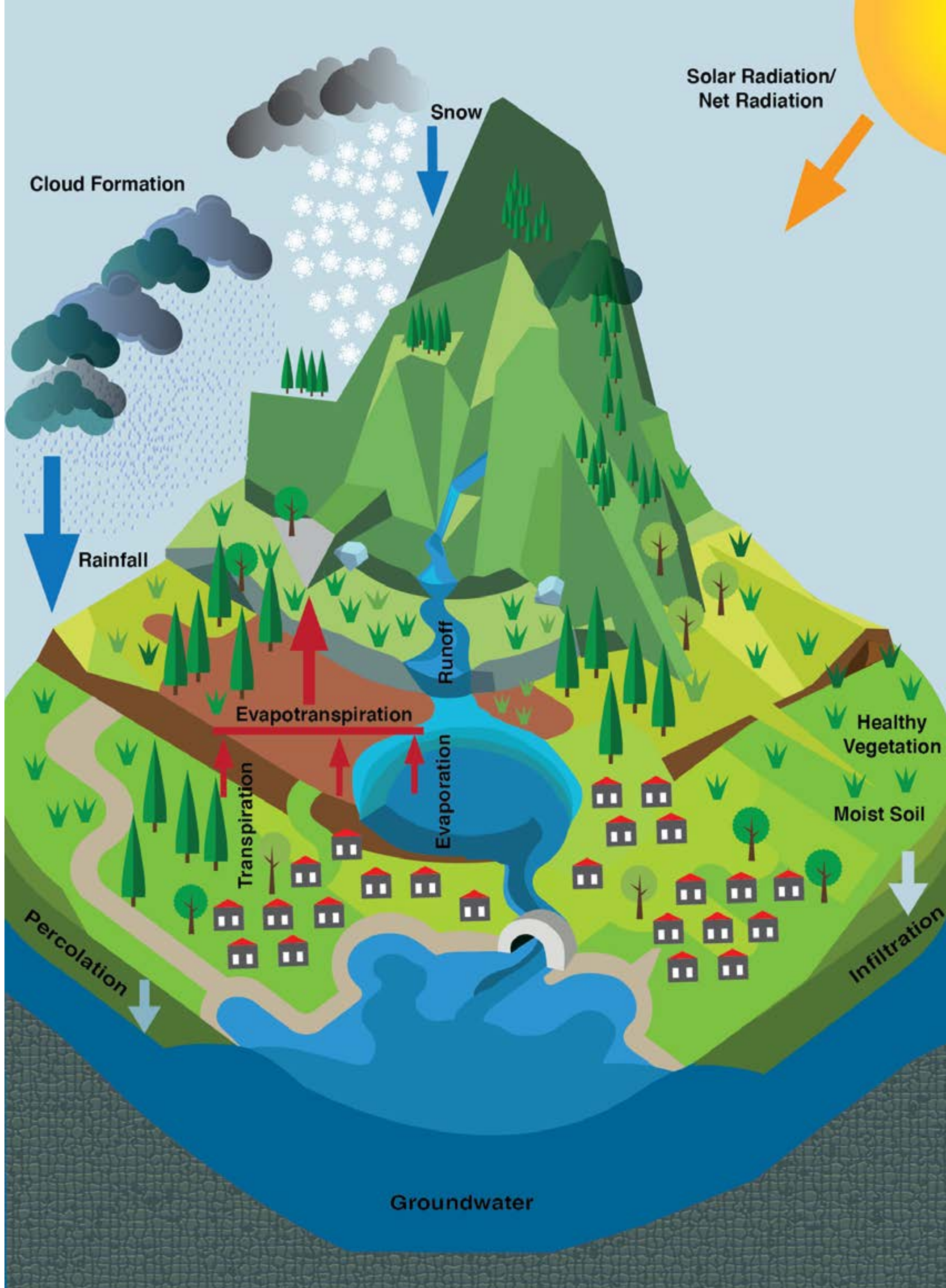
Surface Flow

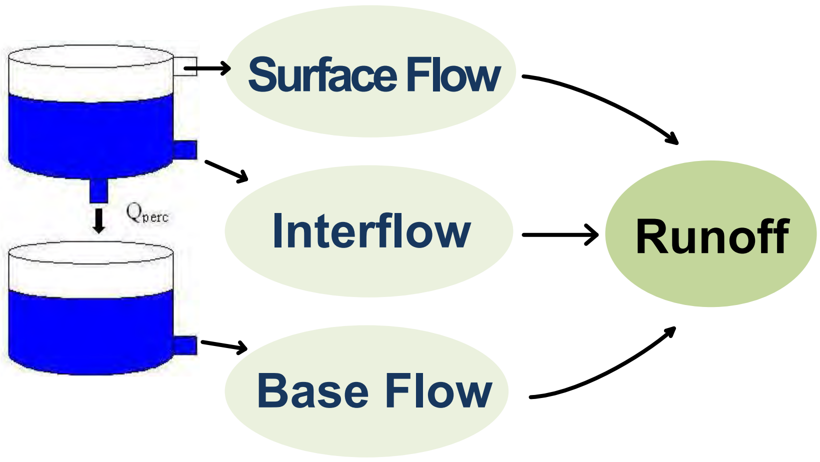
Q_{perc}

Interflow

Base Flow

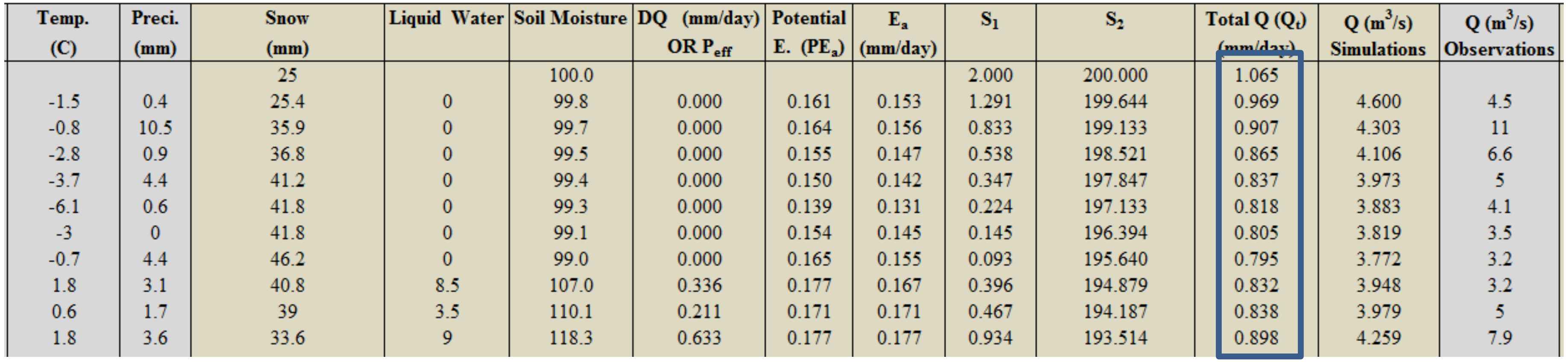
Runoff



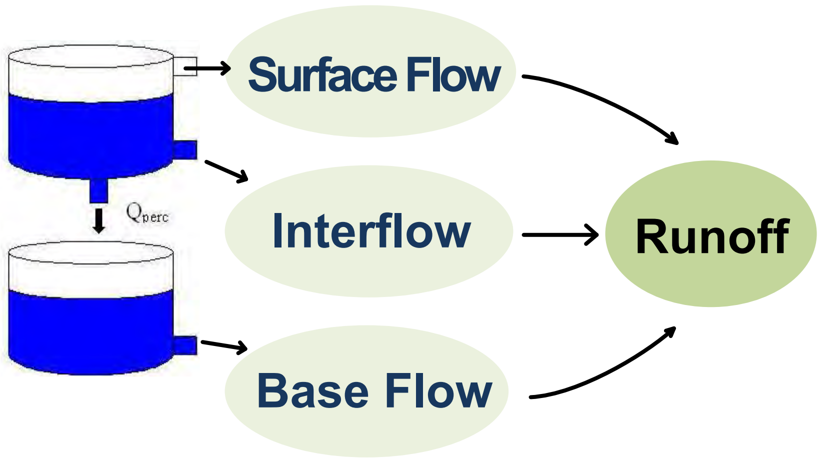


$$Q = Q_0 + Q_1 + Q_2$$

$$\underbrace{\texttt{=MAX(0,K31-\$F\$9)*\$F\$8}}_{K_0\ (S_1\text{-}L)}\underbrace{\texttt{+K31*\$F\$10}}_{K_1\ (S_1)}\underbrace{\texttt{+L31*\$F\$11}}_{K_2\ (S_2)}$$



Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations
		25		100.0				2.000	200.000	1.065		
-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5
-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133	0.907	4.303	11
-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538	198.521	0.865	4.106	6.6
-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347	197.847	0.837	3.973	5
-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224	197.133	0.818	3.883	4.1
-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145	196.394	0.805	3.819	3.5
-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093	195.640	0.795	3.772	3.2
1.8	3.1	40.8	8.5	107.0	0.336	0.177	0.167	0.396	194.879	0.832	3.948	3.2
0.6	1.7	39	3.5	110.1	0.211	0.171	0.171	0.467	194.187	0.838	3.979	5
1.8	3.6	33.6	9	118.3	0.633	0.177	0.177	0.934	193.514	0.898	4.259	7.9

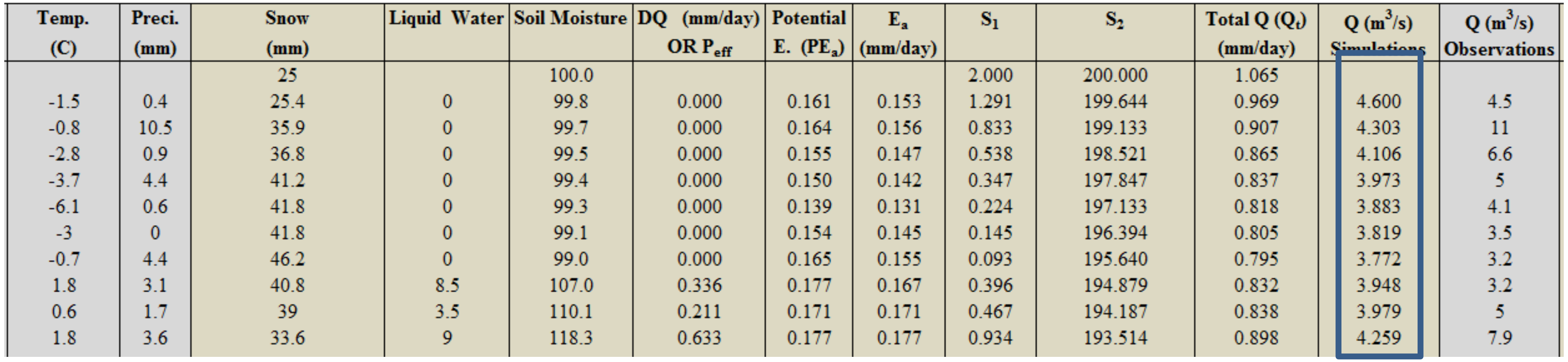


$$Q = Q_0 + Q_1 + Q_2$$

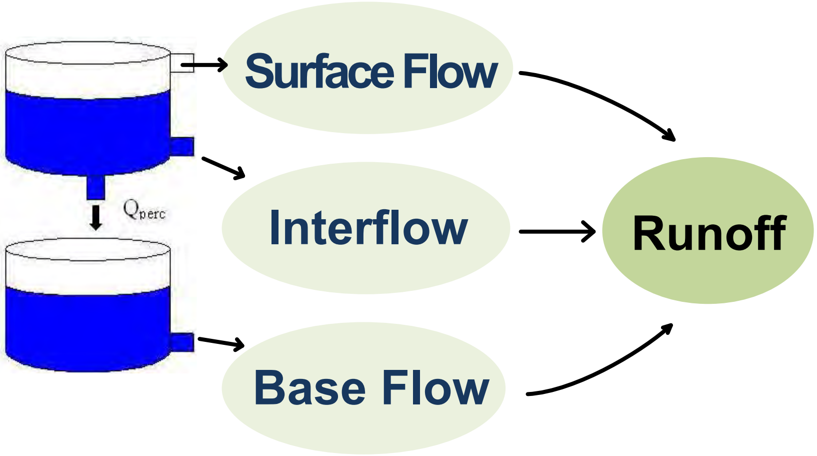
$$\underbrace{\texttt{=MAX(0,K31-\$F\$9)*\$F\$8}}_{K_0\,(S_1\text{-}L)}\texttt{+}\underbrace{\texttt{K31*\$F\$10}}_{K_1\,(S_1)}\texttt{+}\underbrace{\texttt{L31*\$F\$11}}_{K_2\,(S_2)}$$

Convert Q (mm/d) to Q (m^3/s)

$$\texttt{=}\underbrace{\texttt{M32}}_{Q\text{ (mm/day)}}\texttt{*}\underbrace{\texttt{\$C\$8}}_{\text{Watershed Area }(km^2)}\texttt{*1000/(24*3600)}$$



Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations
		25		100.0				2.000	200.000	1.065		
-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5
-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133	0.907	4.303	11
-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538	198.521	0.865	4.106	6.6
-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347	197.847	0.837	3.973	5
-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224	197.133	0.818	3.883	4.1
-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145	196.394	0.805	3.819	3.5
-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093	195.640	0.795	3.772	3.2
1.8	3.1	40.8	8.5	107.0	0.336	0.177	0.167	0.396	194.879	0.832	3.948	3.2
0.6	1.7	39	3.5	110.1	0.211	0.171	0.171	0.467	194.187	0.838	3.979	5
1.8	3.6	33.6	9	118.3	0.633	0.177	0.177	0.934	193.514	0.898	4.259	7.9



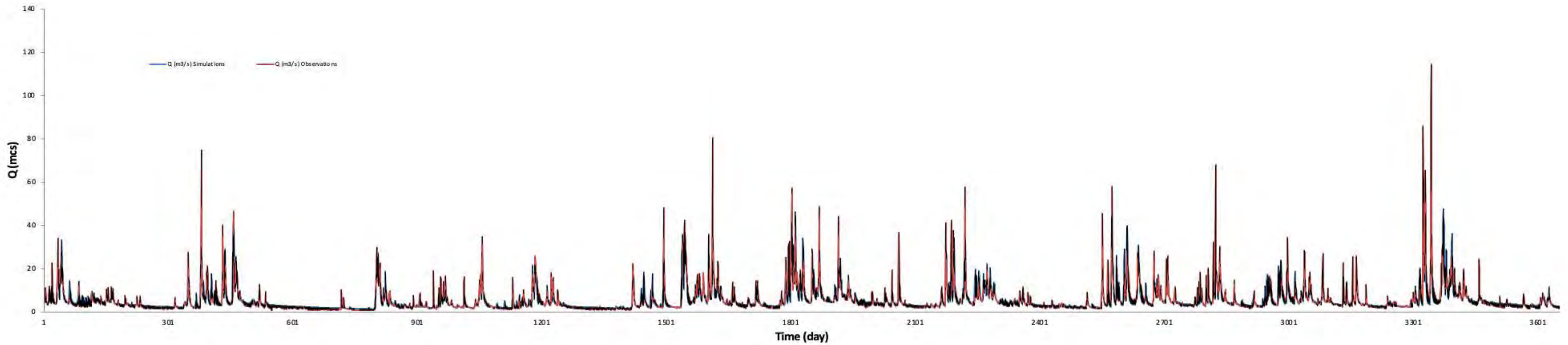
Surface Flow

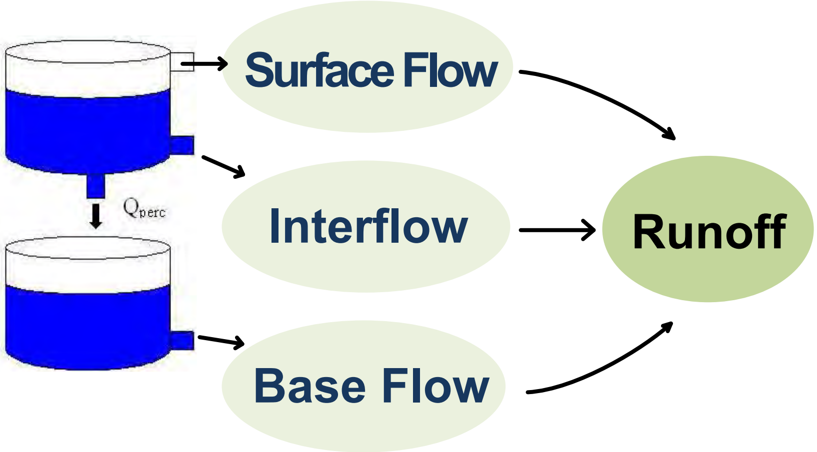
Interflow

Base Flow

Q_{perc}

Runoff



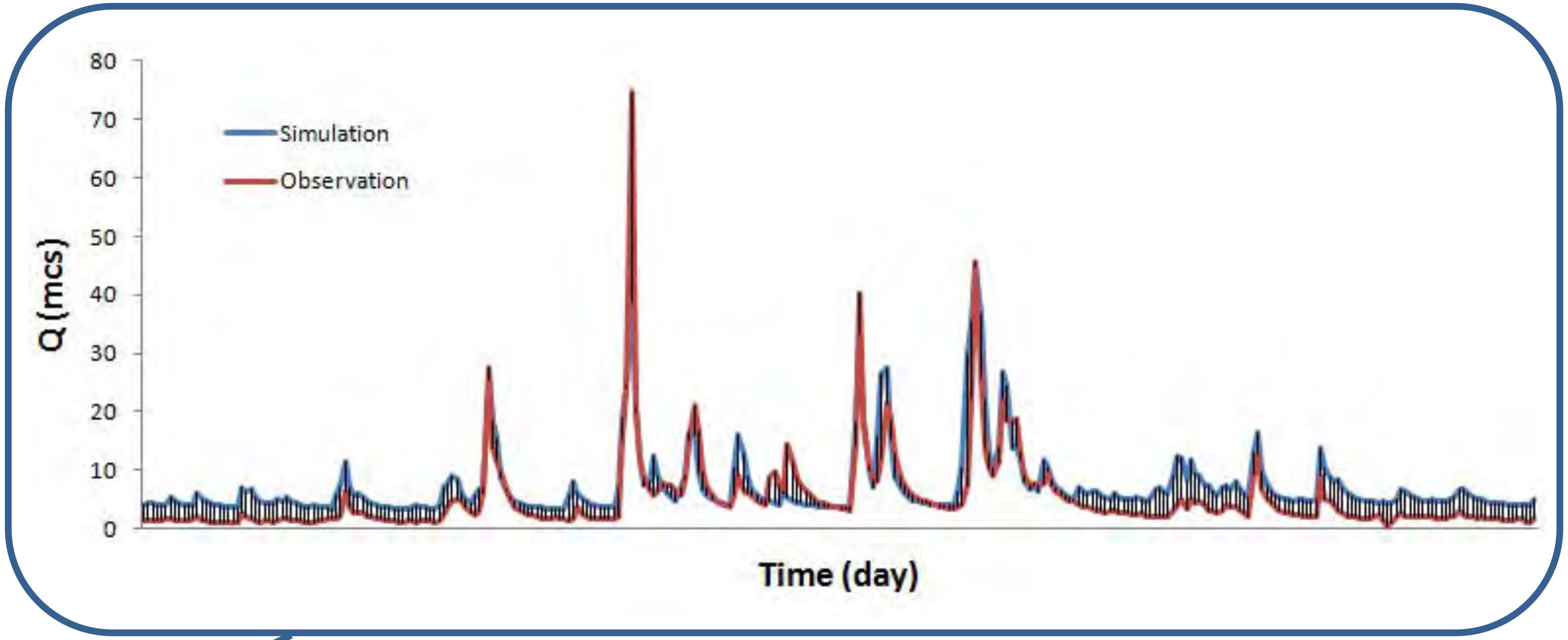


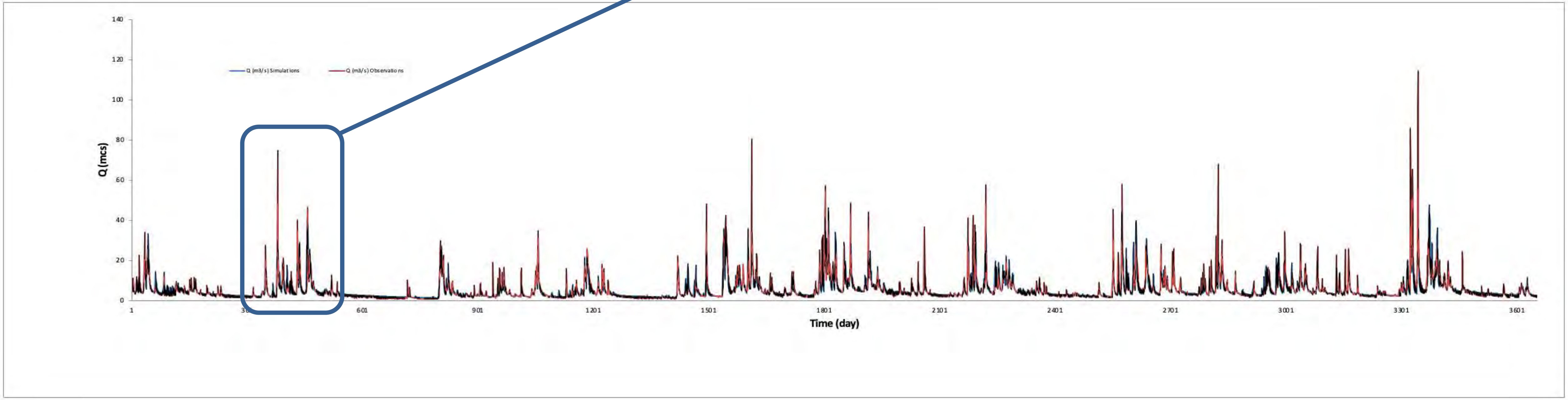
Surface Flow

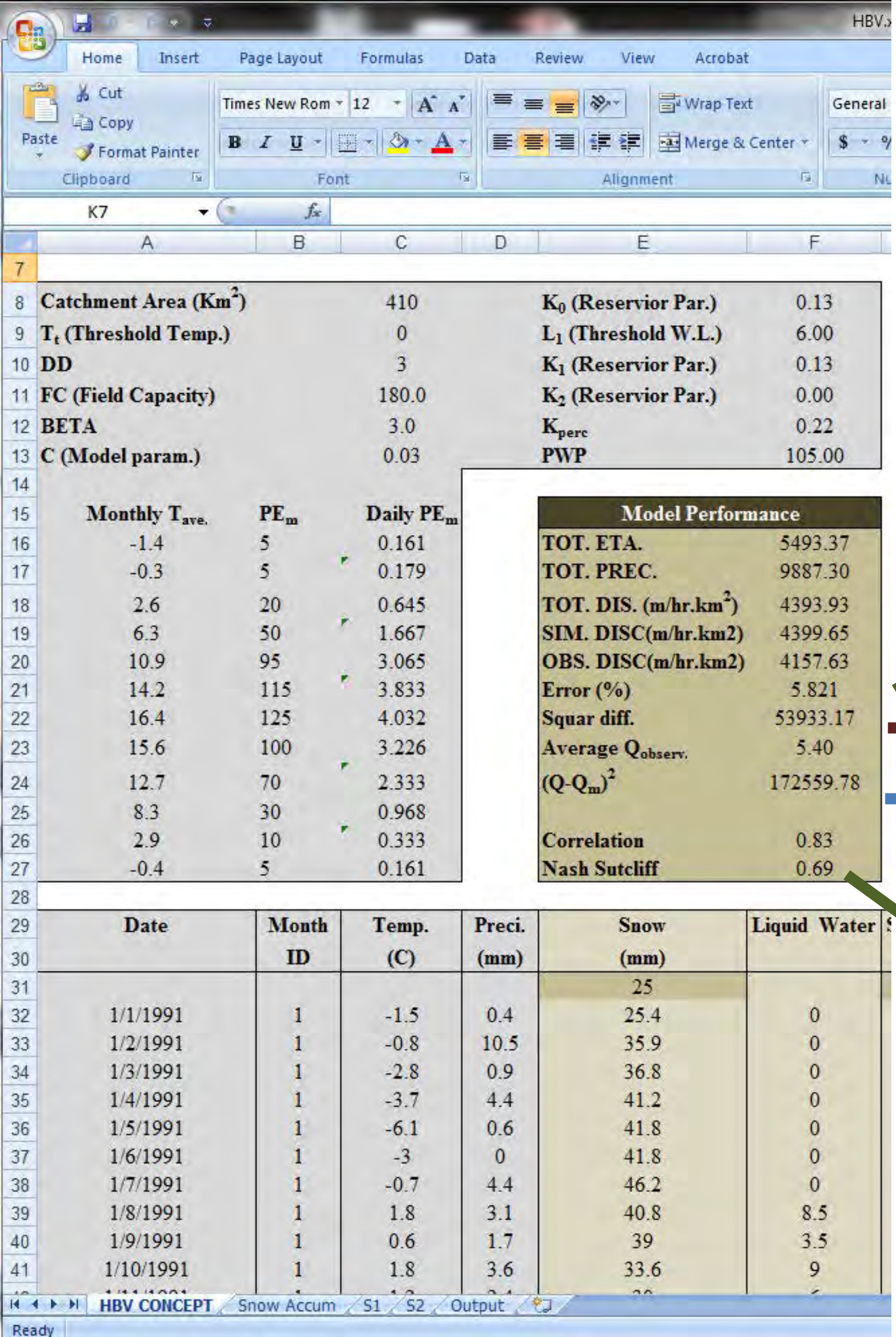
Interflow

Base Flow

Runoff







Catchment Area (Km^2)	410	K$_0$ (Reservior Par.)	0.13
T$_t$ (Threshold Temp.)	0	L$_1$ (Threshold W.L.)	6.00
DD	3	K$_1$ (Reservior Par.)	0.13
FC (Field Capacity)	180.0	K$_2$ (Reservior Par.)	0.00
BETA	3.0	K$_{perc}$	0.22
C (Model param.)	0.03	PWP	105.00

Monthly T$_{ave.}$	PE$_m$	Daily PE$_m$
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

Model Performance	
TOT. ETA.	5493.37
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	4393.93
SIM. DISC(m/hr.km2)	4399.65
OBS. DISC(m/hr.km2)	4157.63
Error (%)	5.821
Squar diff.	53933.17
Average Q$_{observ.}$	5.40
(Q-Q$_m$)^2	172559.78
Correlation	0.83
Nash Sutcliff	0.69

Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water
				25	
1/1/1991	1	-1.5	0.4	25.4	0
1/2/1991	1	-0.8	10.5	35.9	0
1/3/1991	1	-2.8	0.9	36.8	0
1/4/1991	1	-3.7	4.4	41.2	0
1/5/1991	1	-6.1	0.6	41.8	0
1/6/1991	1	-3	0	41.8	0
1/7/1991	1	-0.7	4.4	46.2	0
1/8/1991	1	1.8	3.1	40.8	8.5
1/9/1991	1	0.6	1.7	39	3.5
1/10/1991	1	1.8	3.6	33.6	9

$$\sum_{i=1}^{n} Q_s$$

$$\sum_{i=1}^{n} Q_o$$

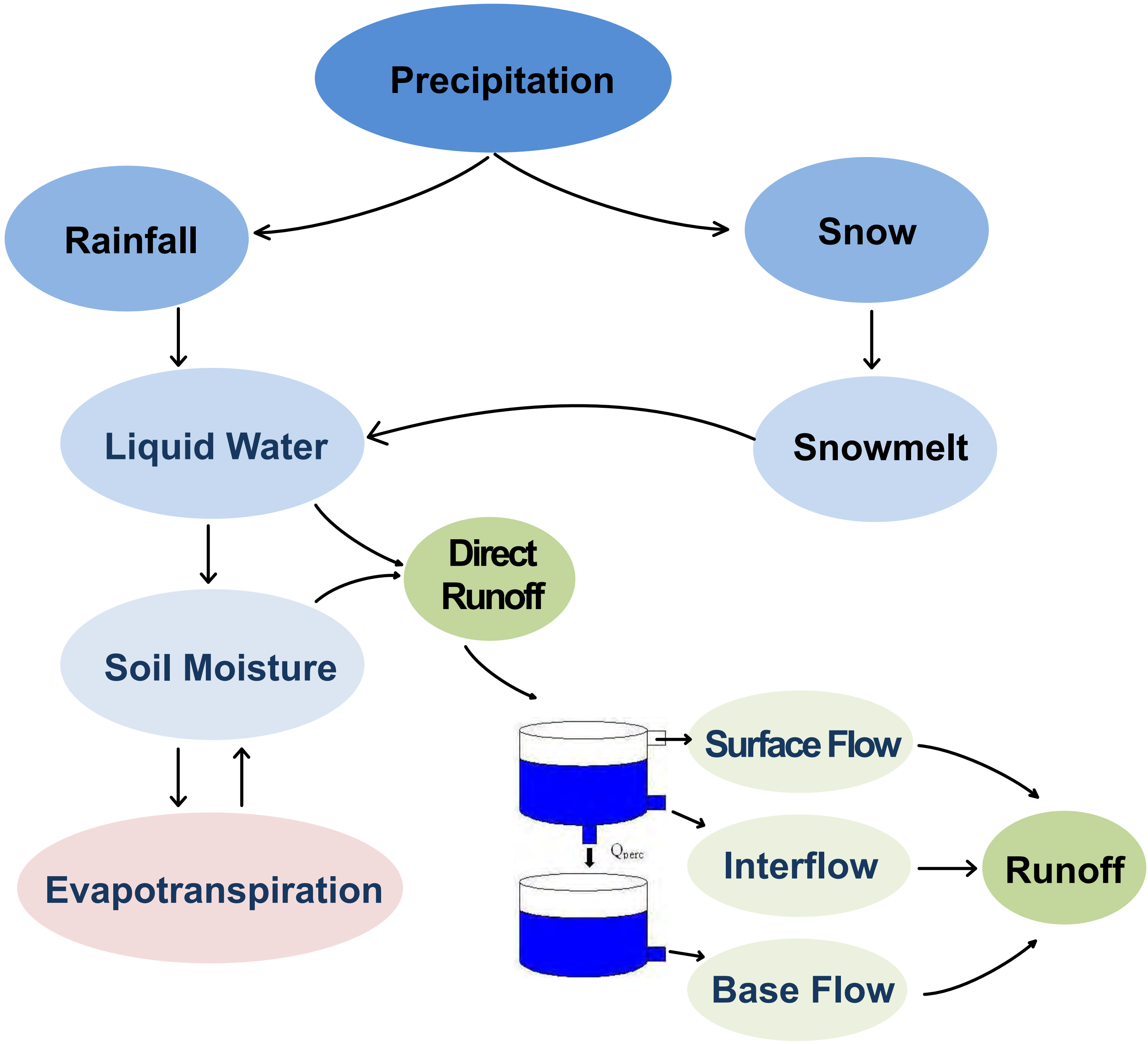
$$Bias = \frac{\sum_{i=1}^{n} Q_s}{\sum_{i=1}^{n} Q_o}$$

Error (%) of total runoff

$$\sum^{n} (Q_s^t - Q_o^t)^2$$

$$\sum_{t=1}^{n} (Q_o^t - \overline{Q}_o)^2$$

$$R_{NS} = 1 - \frac{\sum_{t=1}^{n} (Q_s^t - Q_o^t)^2}{\sum_{t=1}^{n} (Q_o^t - \overline{Q}_o)^2}$$



Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

Evapotranspiration

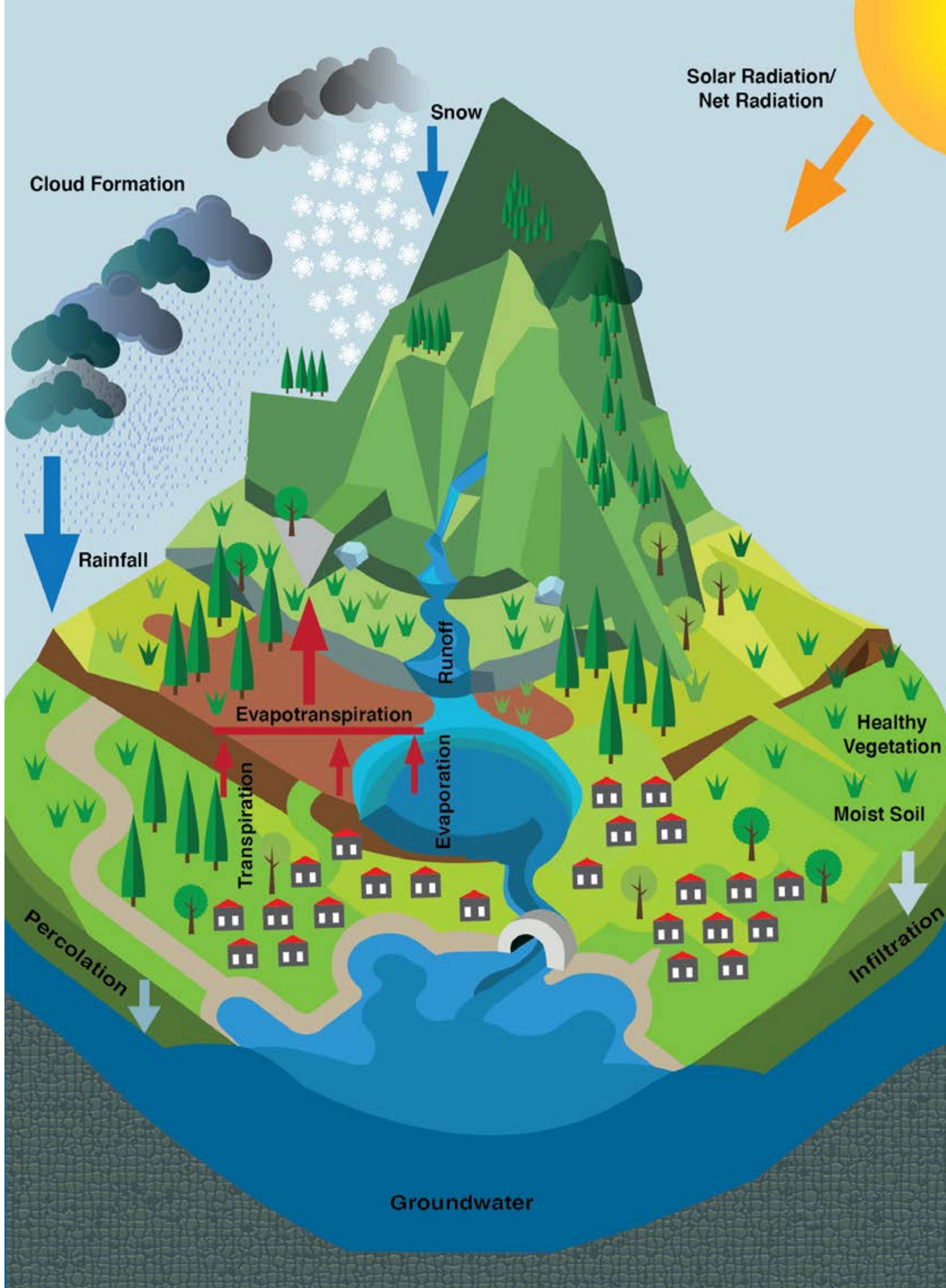
Q_{perc}

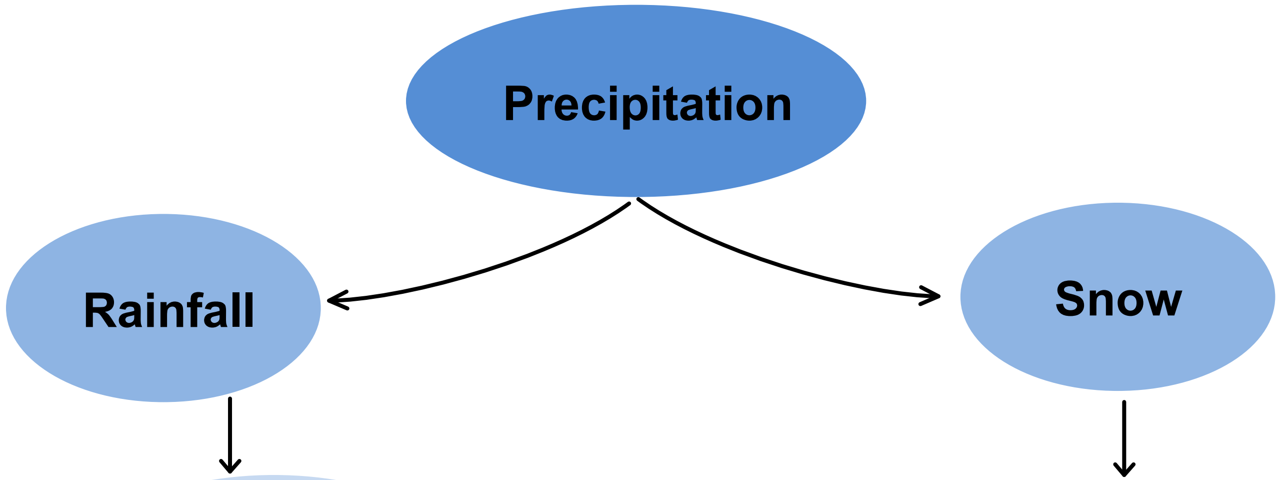
Surface Flow

Interflow

Base Flow

Runoff

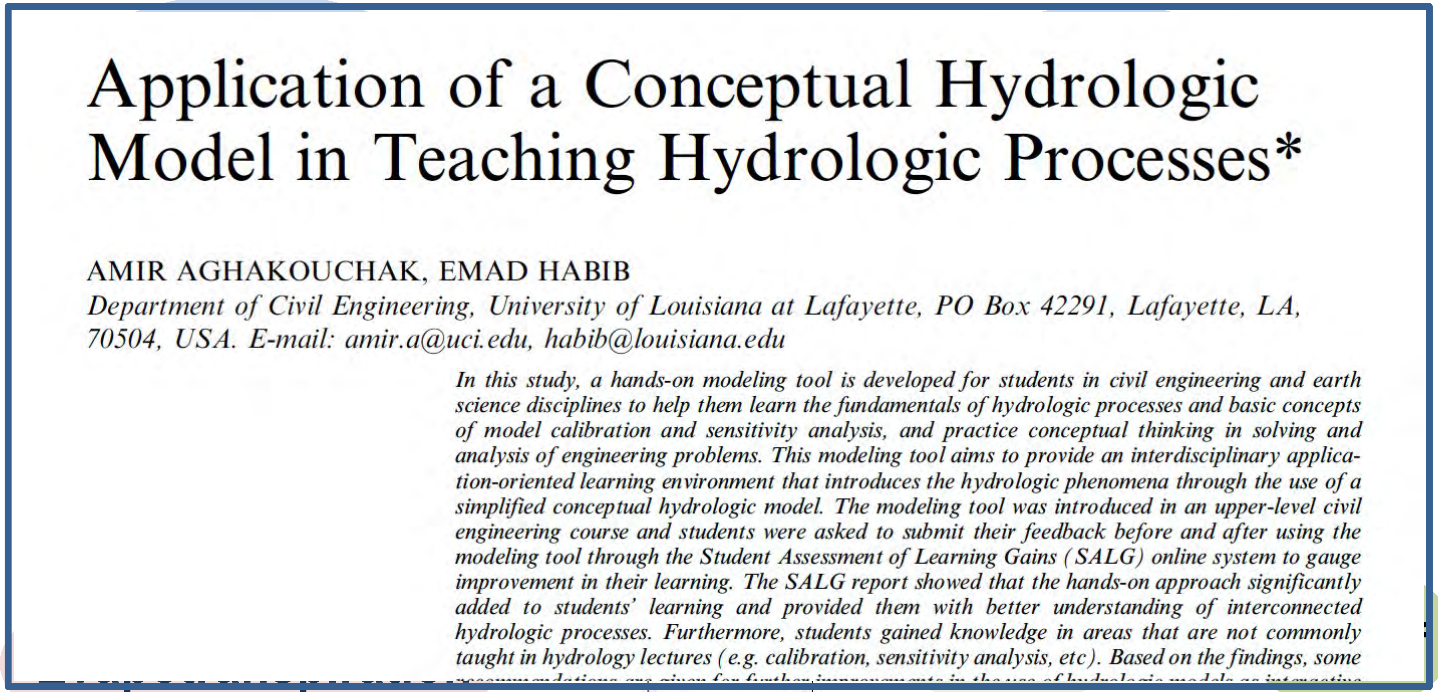




Precipitation

Rainfall

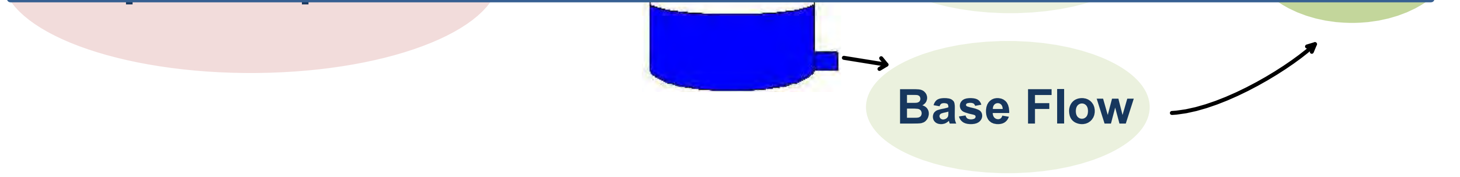
Snow



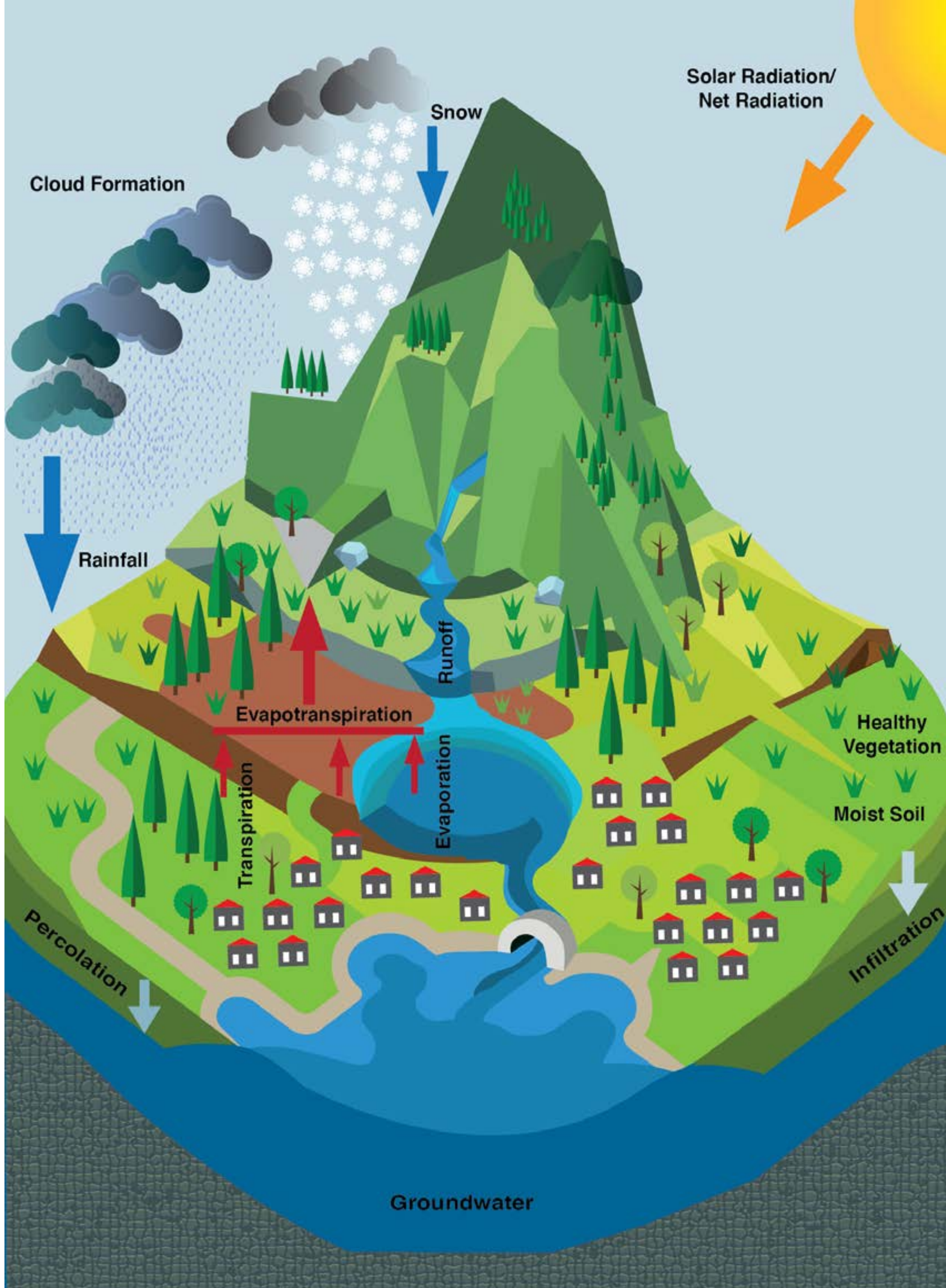
Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes*

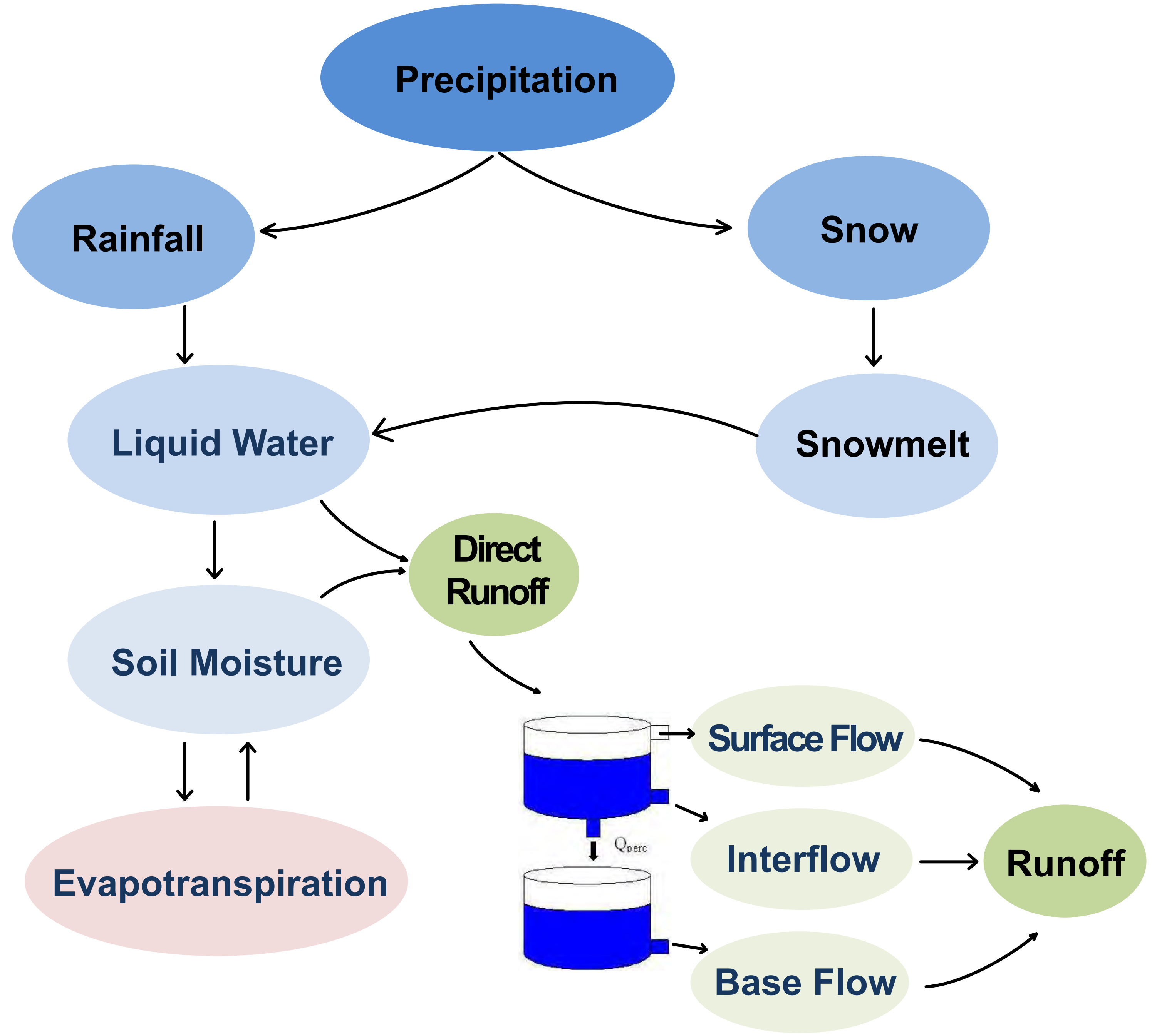
AMIR AGHAKOUCHAK, EMAD HABIB
Department of Civil Engineering, University of Louisiana at Lafayette, PO Box 42291, Lafayette, LA, 70504, USA. E-mail: amir.a@uci.edu, habib@louisiana.edu

In this study, a hands-on modeling tool is developed for students in civil engineering and earth science disciplines to help them learn the fundamentals of hydrologic processes and basic concepts of model calibration and sensitivity analysis, and practice conceptual thinking in solving and analysis of engineering problems. This modeling tool aims to provide an interdisciplinary application-oriented learning environment that introduces the hydrologic phenomena through the use of a simplified conceptual hydrologic model. The modeling tool was introduced in an upper-level civil engineering course and students were asked to submit their feedback before and after using the modeling tool through the Student Assessment of Learning Gains (SALG) online system to gauge improvement in their learning. The SALG report showed that the hands-on approach significantly added to students' learning and provided them with better understanding of interconnected hydrologic processes. Furthermore, students gained knowledge in areas that are not commonly taught in hydrology lectures (e.g. calibration, sensitivity analysis, etc). Based on the findings, some



Base Flow





Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

Evapotranspiration

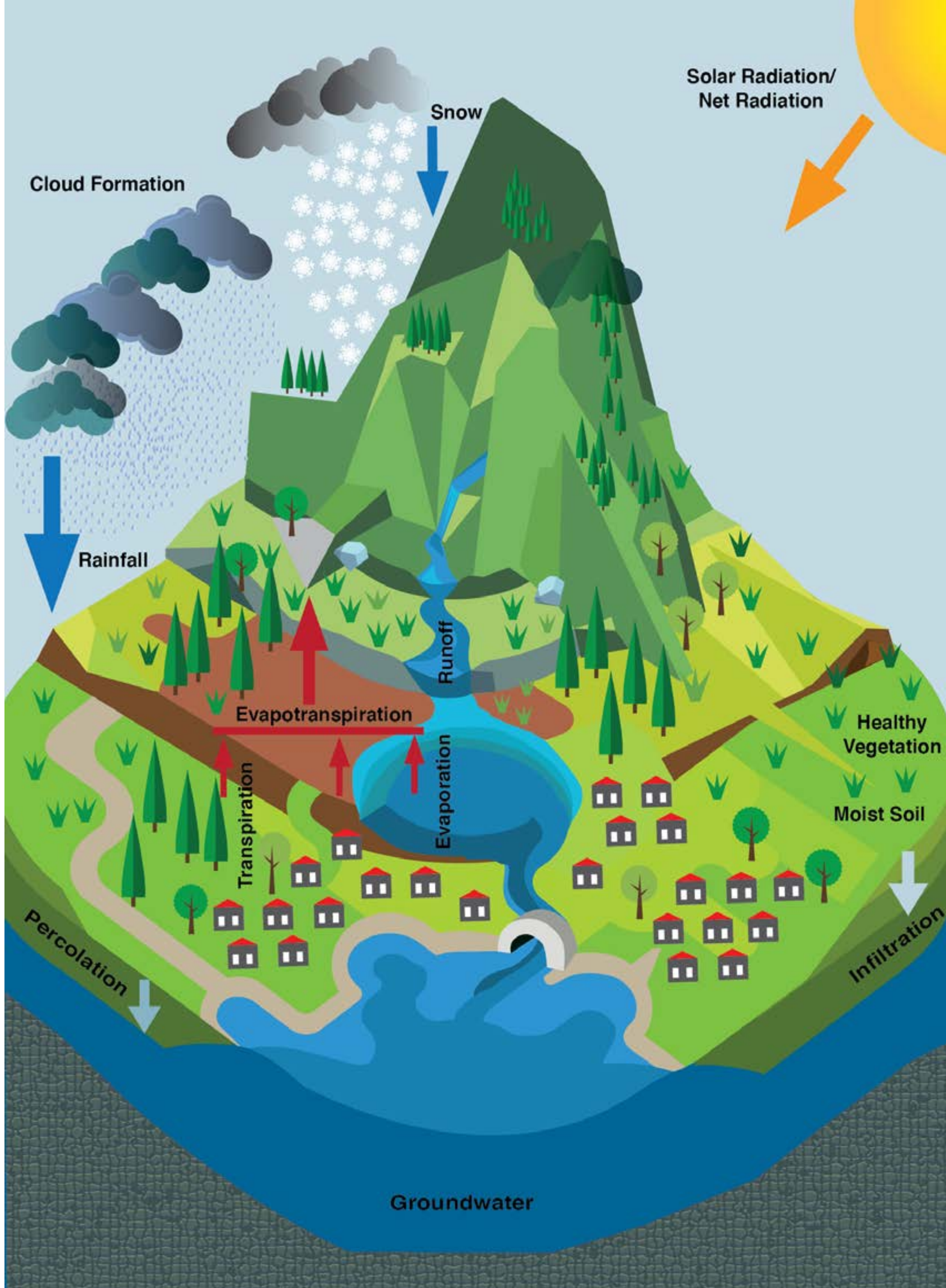
Surface Flow

Q_{perc}

Interflow

Base Flow

Runoff



Questions?

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Hydrologic Modeling

Part II

Amir AghaKouchak

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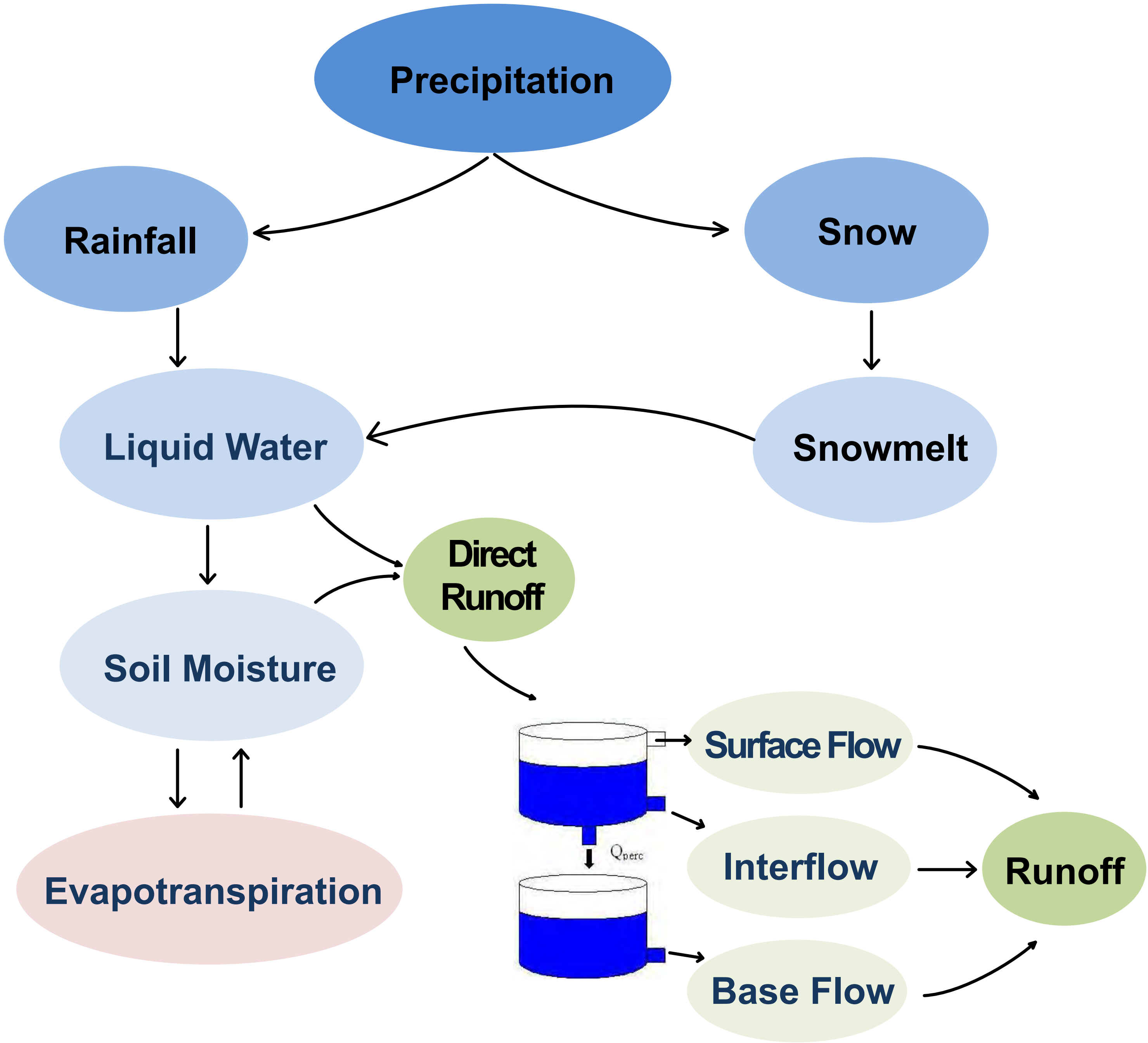

Precipitation

Rainfall

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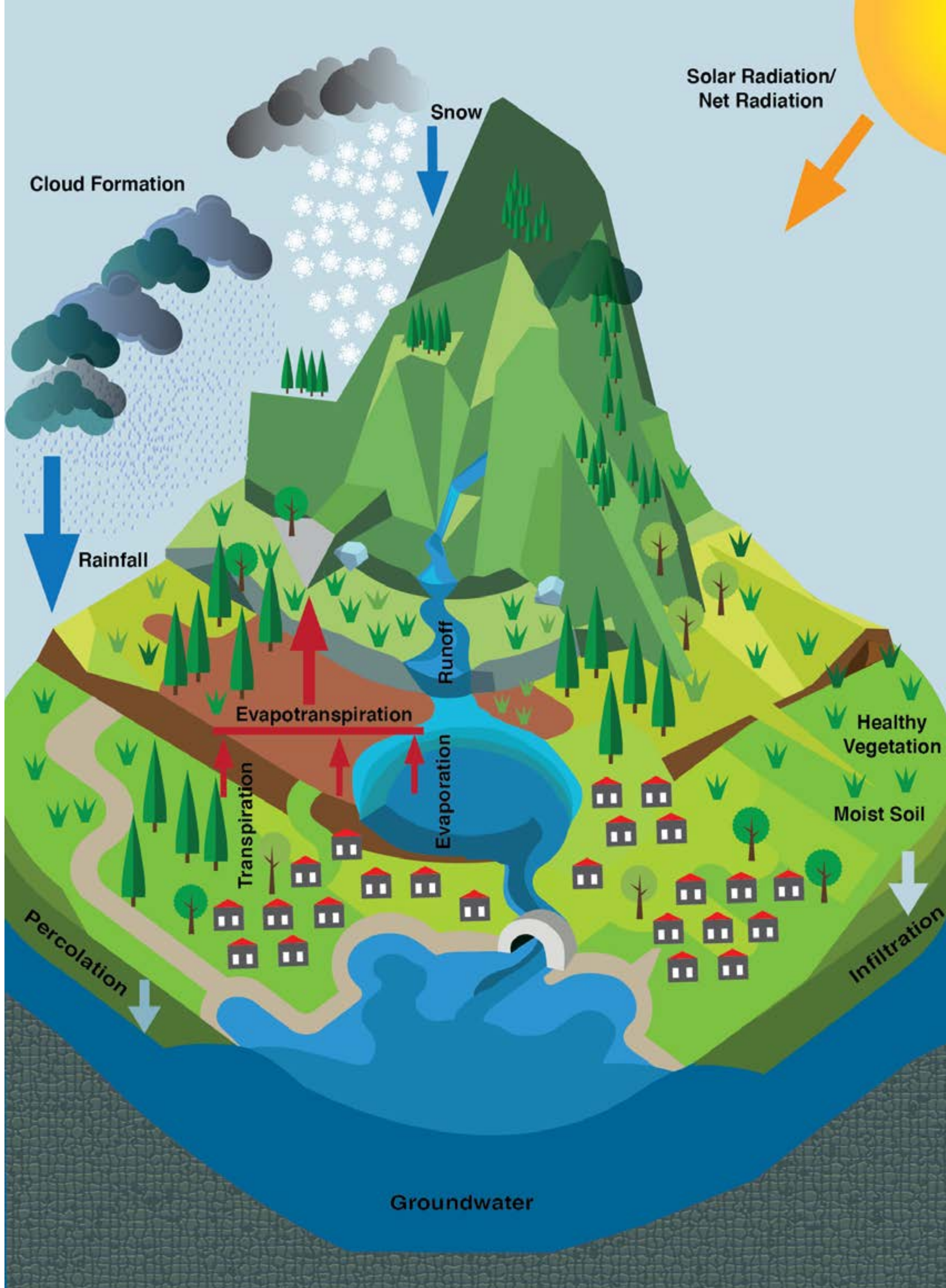
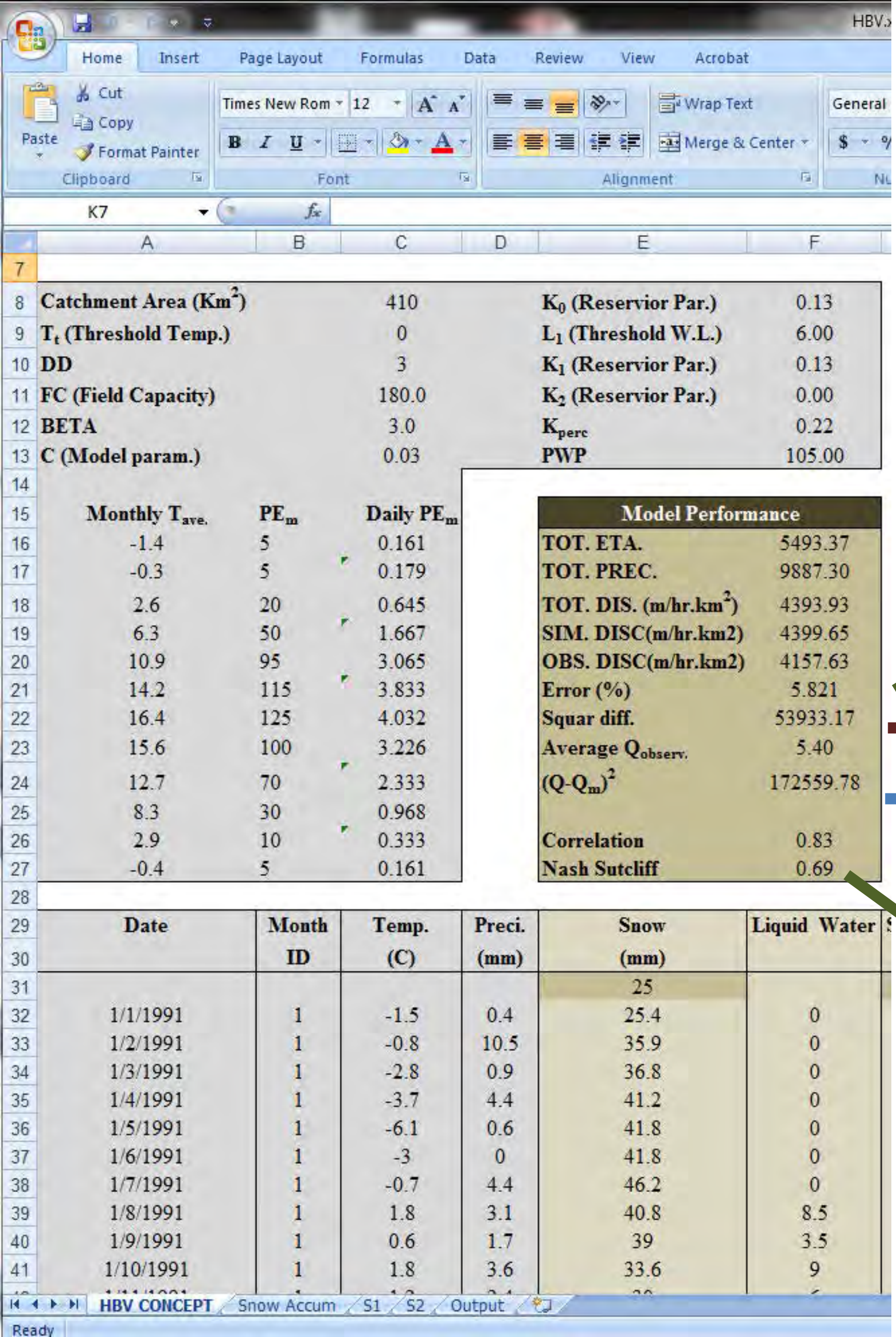
Q_{perc}





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FC (Field Capacity)	180.0	K$_2$ (Reservior Par.)	0.00
BETA	3.0	K$_{perc}$	0.22
C (Model param.)	0.03	PWP	105.00

Monthly T$_{ave.}$	PE$_m$	Daily PE$_m$
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
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-0.4	5	0.161

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TOT. PREC.	9887.30
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Error (%)	5.821
Squar diff.	53933.17
Average Q$_{observ.}$	5.40
(Q-Q$_m$)^2	172559.78
Correlation	0.83
Nash Sutcliff	0.69

Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water
				25	
1/1/1991	1	-1.5	0.4	25.4	0
1/2/1991	1	-0.8	10.5	35.9	0
1/3/1991	1	-2.8	0.9	36.8	0
1/4/1991	1	-3.7	4.4	41.2	0
1/5/1991	1	-6.1	0.6	41.8	0
1/6/1991	1	-3	0	41.8	0
1/7/1991	1	-0.7	4.4	46.2	0
1/8/1991	1	1.8	3.1	40.8	8.5
1/9/1991	1	0.6	1.7	39	3.5
1/10/1991	1	1.8	3.6	33.6	9

$$\sum_{i=1}^{n} Q_s$$

$$\sum_{i=1}^{n} Q_o$$

$$Bias = \frac{\sum_{i=1}^{n} Q_s}{\sum_{i=1}^{n} Q_o}$$

Error (%) of total runoff

$$\sum_{t=1}^{n} (Q_s^t - Q_o^t)^2$$

$$\sum_{t=1}^{n} (Q_o^t - \overline{Q}_o)^2$$

$$R_{NS} = 1 - \frac{\sum_{t=1}^{n} (Q_s^t - Q_o^t)^2}{\sum_{t=1}^{n} (Q_o^t - \overline{Q}_o)^2}$$

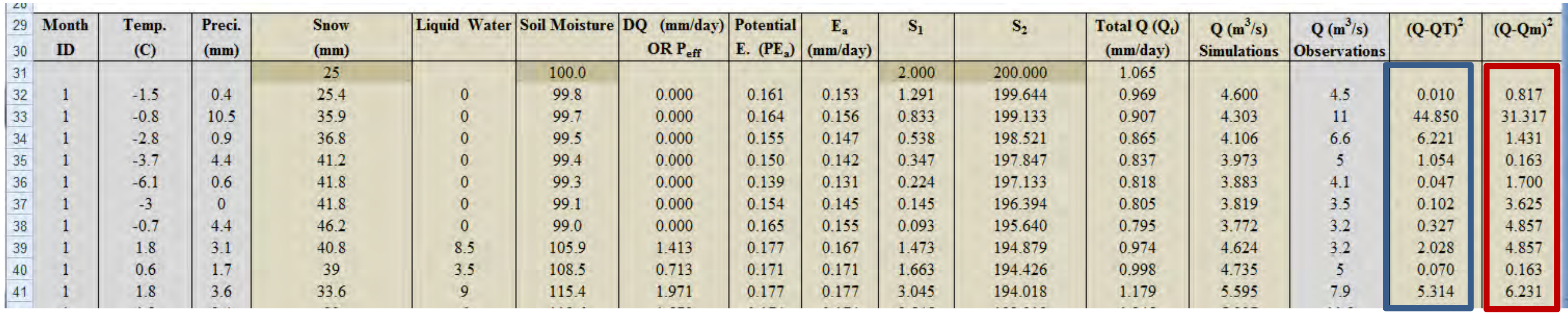
$$R_{NS} = 1 - \frac{\boxed{\sum_{t=1}^{n}(Q_s^t - Q_o^t)^2}}{\boxed{\sum_{t=1}^{n}(Q_o^t - \overline{Q}_o)^2}}$$

$\sum_{t=1}^{n}(Q_s^t - Q_o^t)^2 \longrightarrow$ **=(O32-N32)^2**

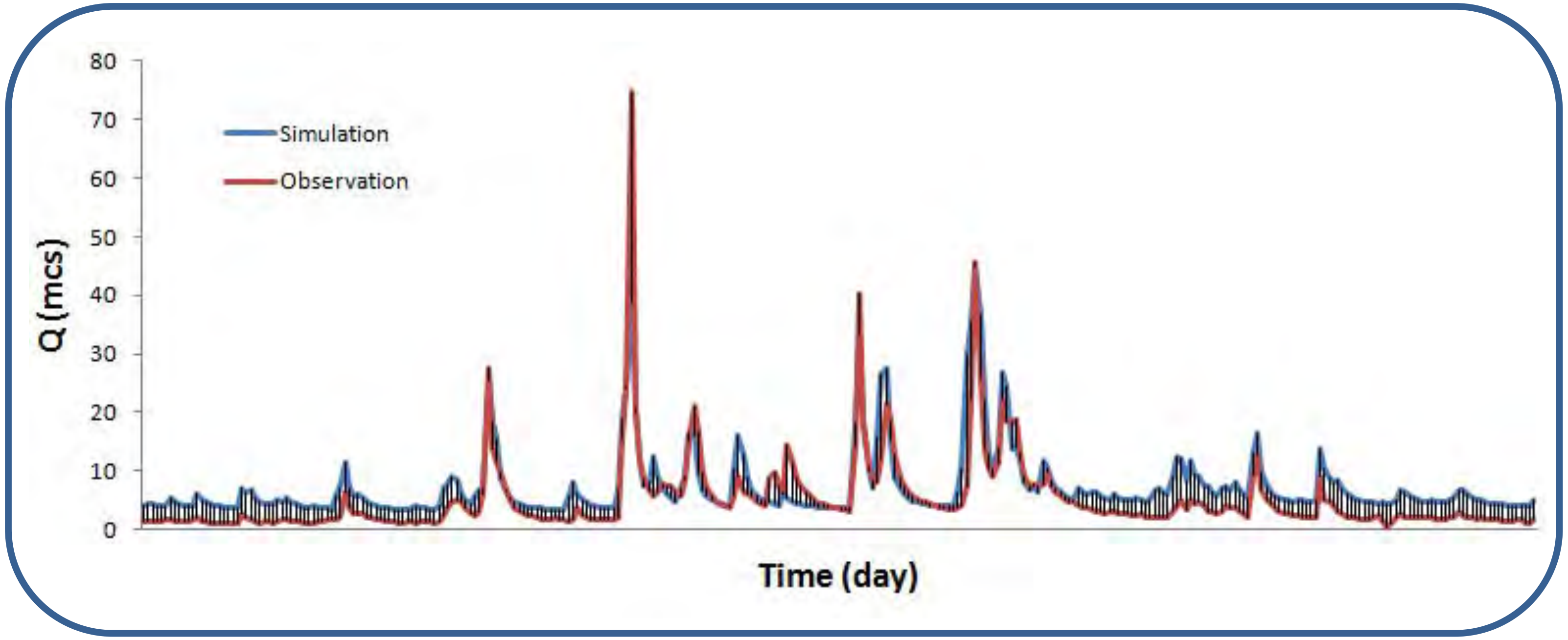
$\sum_{t=1}^{n}(Q_o^t - \overline{Q}_o)^2 \longrightarrow$ **=(O32-$F$23)^2**

where:

R_{NS}	Nash-Sutcliffe coefficient [-]
Q_s	simulated discharge [L^3T^{-1}]
Q_o	observed discharge [L^3T^{-1}]
$\bar{O}_o$	mean observed discharge [L^3T^{-1}]
n	number of time steps



29 30	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations	$(Q-QT)^2$	$(Q-Qm)^2$
31				25		100.0				2.000	200.000	1.065				
32	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5	0.010	0.817
33	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133	0.907	4.303	11	44.850	31.317
34	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538	198.521	0.865	4.106	6.6	6.221	1.431
35	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347	197.847	0.837	3.973	5	1.054	0.163
36	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224	197.133	0.818	3.883	4.1	0.047	1.700
37	1	-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145	196.394	0.805	3.819	3.5	0.102	3.625
38	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093	195.640	0.795	3.772	3.2	0.327	4.857
39	1	1.8	3.1	40.8	8.5	105.9	1.413	0.177	0.167	1.473	194.879	0.974	4.624	3.2	2.028	4.857
40	1	0.6	1.7	39	3.5	108.5	0.713	0.171	0.171	1.663	194.426	0.998	4.735	5	0.070	0.163
41	1	1.8	3.6	33.6	9	115.4	1.971	0.177	0.177	3.045	194.018	1.179	5.595	7.9	5.314	6.231



Error in Initial Conditions

- Error in the initial values of soil moisture, snow, field capacity, permanent wilting point

Error in Model Processes

- Unrealistic model assumptions
- Unrepresentative conceptual description of the system

Error in Observations

- Error in input data (e.g., precipitation, temperature, etc.)
- Error in observed discharge

Error in Model Parameterization

- Inability to obtain the optimal set of parameters.
- Deficiencies in parameter estimation scheme

Conceptual

- BETA (β)
- C
- L
- K_0
- K_1
- K_2
- K_{perc}

Conceptual & Measurable

- FC
- DD
- PWP
- T_t

Initial Conditions

- Snow
- Soil Moisture
- S_1
- S_2

Error in Initial Conditions

- Error in the initial values of soil moisture, snow, field capacity, permanent wilting point

Error in Model Processes

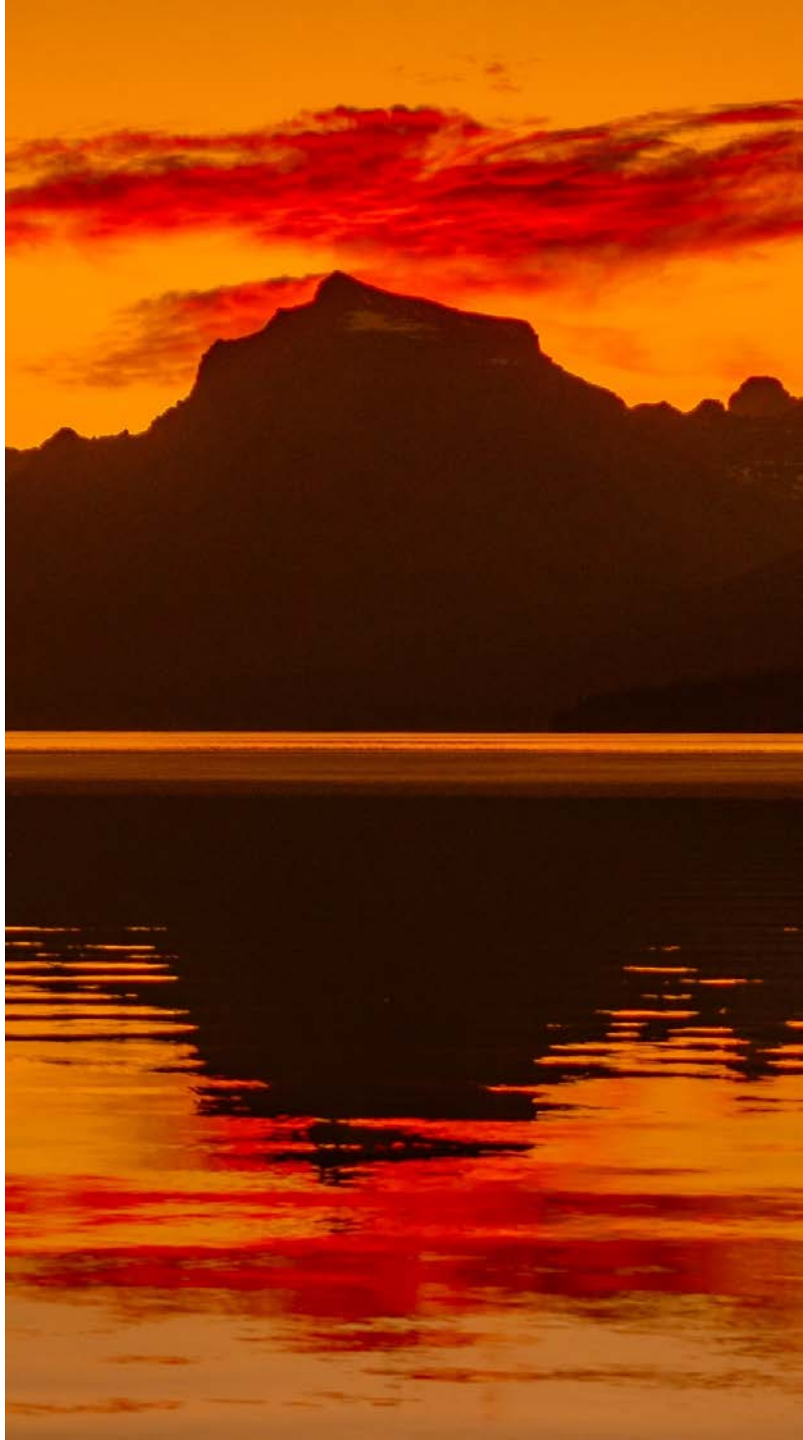
- Unrealistic model assumptions
- Unrepresentative conceptual description of the system

Error in Observations

- Error in input data (e.g., precipitation, temperature, etc.)
- Error in observed discharge

Error in Model Parameterization

- Inability to obtain the optimal set of parameters.
- Deficiencies in parameter estimation scheme



Conceptual

- BETA (β)
- C
- L
- K_0
- K_1
- K_2
- K_{perc}

Conceptual & Measurable

- FC
- DD
- PWP
- T_t

Initial Conditions

- Snow
- Soil Moisture
- S_1
- S_2

Error in Initial Conditions

- Error in the initial values of soil moisture, snow, field capacity, permanent wilting point

Error in Model Processes

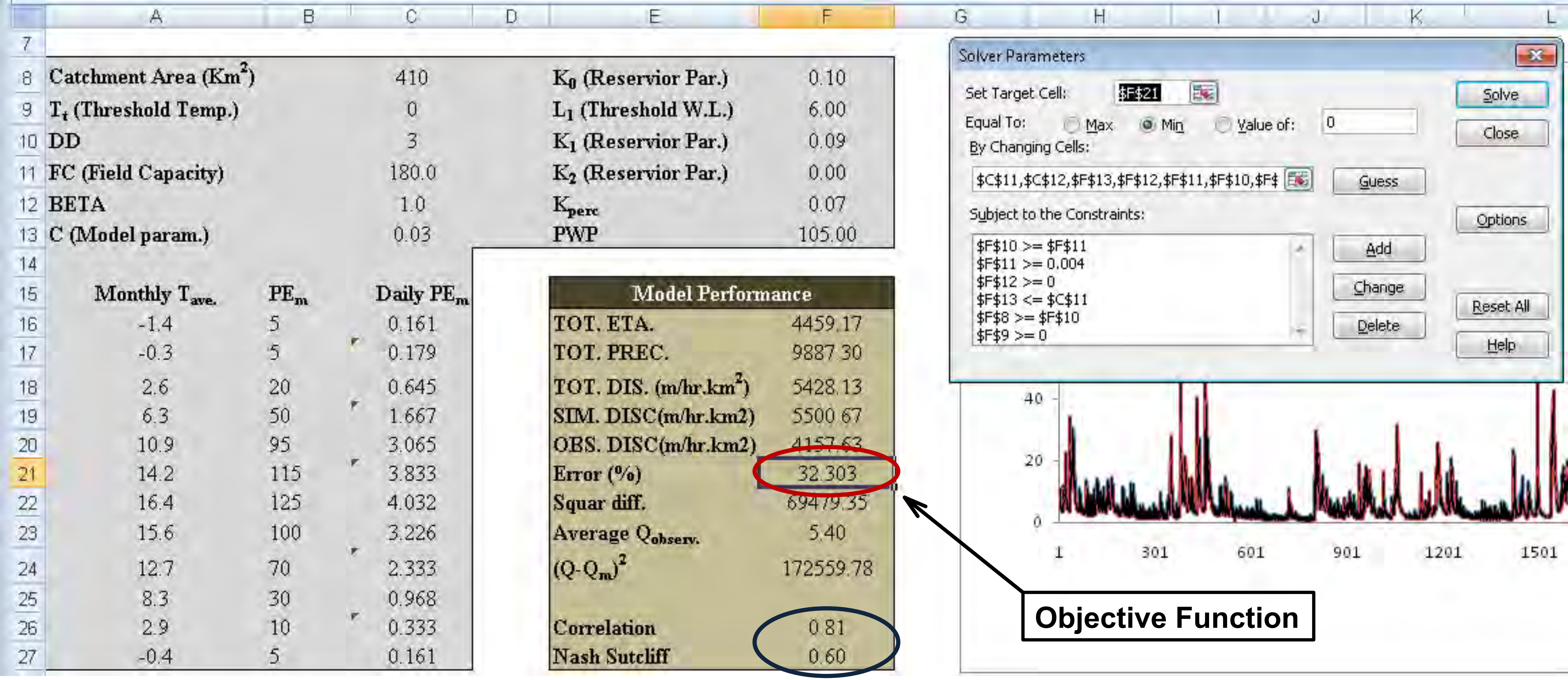
- Unrealistic model assumptions
- Unrepresentative conceptual description of the system

Error in Observations

- Error in input data (e.g., precipitation, temperature, etc.)
- Error in observed discharge

Error in Model Parameterization

- Inability to obtain the optimal set of parameters.
- Deficiencies in parameter estimation scheme



	A	B	C	D	E	F
7						
8	Catchment Area (Km^2)		410		K_0 (Reservior Par.)	0.10
9	T_t (Threshold Temp.)		0		L_1 (Threshold W.L.)	6.00
10	DD		3		K_1 (Reservior Par.)	0.09
11	FC (Field Capacity)		180.0		K_2 (Reservior Par.)	0.00
12	BETA		1.0		K_{perc}	0.07
13	C (Model param.)		0.03		PWP	105.00
14						
15	Monthly $T_{ave.}$	PE_m	Daily PE_m		Model Performance	
16	-1.4	5	0.161		TOT. ETA.	4459.17
17	-0.3	5	0.179		TOT. PREC.	9887.30
18	2.6	20	0.645		TOT. DIS. ($m/hr.km^2$)	5428.13
19	6.3	50	1.667		SIM. DISC(m/hr.km2)	5500.67
20	10.9	95	3.065		OBS. DISC(m/hr.km2)	4157.63
21	14.2	115	3.833		Error (%)	32.303
22	16.4	125	4.032		Squar diff.	69479.35
23	15.6	100	3.226		Average $Q_{observ.}$	5.40
24	12.7	70	2.333		$(Q-Q_m)^2$	172559.78
25	8.3	30	0.968			
26	2.9	10	0.333		Correlation	0.81
27	-0.4	5	0.161		Nash Sutcliff	0.60

Set Target Cell: $F$21

Equal To: ○ Max ● Min ○ Value of: 0

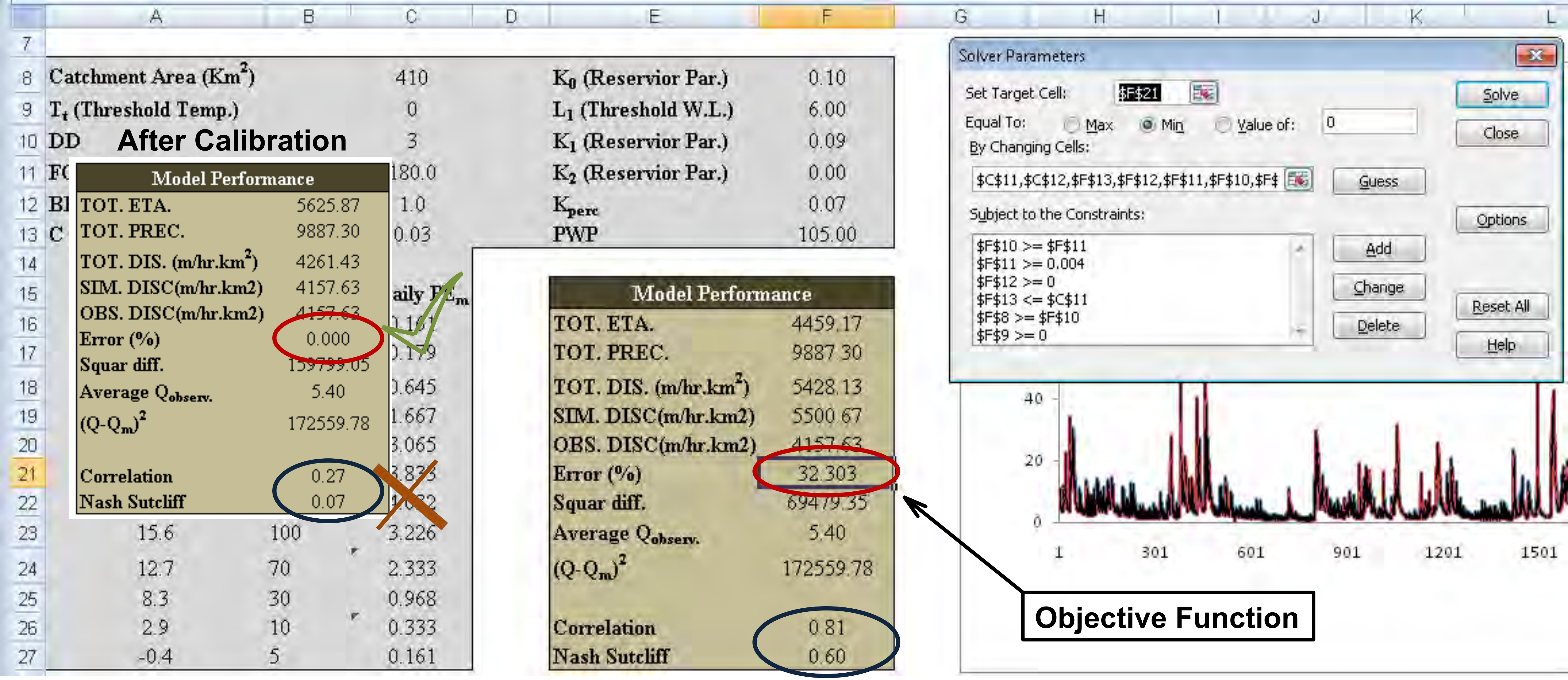
By Changing Cells:

$C$11,$C$12,$F$13,$F$12,$F$11,$F$10,F

Subject to the Constraints:

$F$10 >= $F$11
$F$11 >= 0.004
$F$12 >= 0
$F$13 <= $C$11
$F$8 >= $F$10
$F$9 >= 0

Objective Function



After Calibration

Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.10
T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
DD	3	K_1 (Reservior Par.)	0.09
FC	180.0	K_2 (Reservior Par.)	0.00
BI	1.0	K_{perc}	0.07
C	0.03	PWP	105.00

Model Performance	
TOT. ETA.	5625.87
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	4261.43
SIM. DISC(m/hr.km2)	4157.63
OBS. DISC(m/hr.km2)	4157.63
Error (%)	0.000
Squar diff.	159799.05
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.27
Nash Sutcliff	0.07

aily P_{E_m}

0.161
0.179
0.645
1.667
3.065
3.873
4.032

15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

Model Performance	
TOT. ETA.	4459.17
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	5428.13
SIM. DISC(m/hr.km2)	5500.67
OBS. DISC(m/hr.km2)	4157.63
Error (%)	32.303
Squar diff.	69479.35
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.81
Nash Sutcliff	0.60

Solver Parameters

Set Target Cell: $F$21

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells:

$C$11,$C$12,$F$13,$F$12,$F$11,$F$10,F

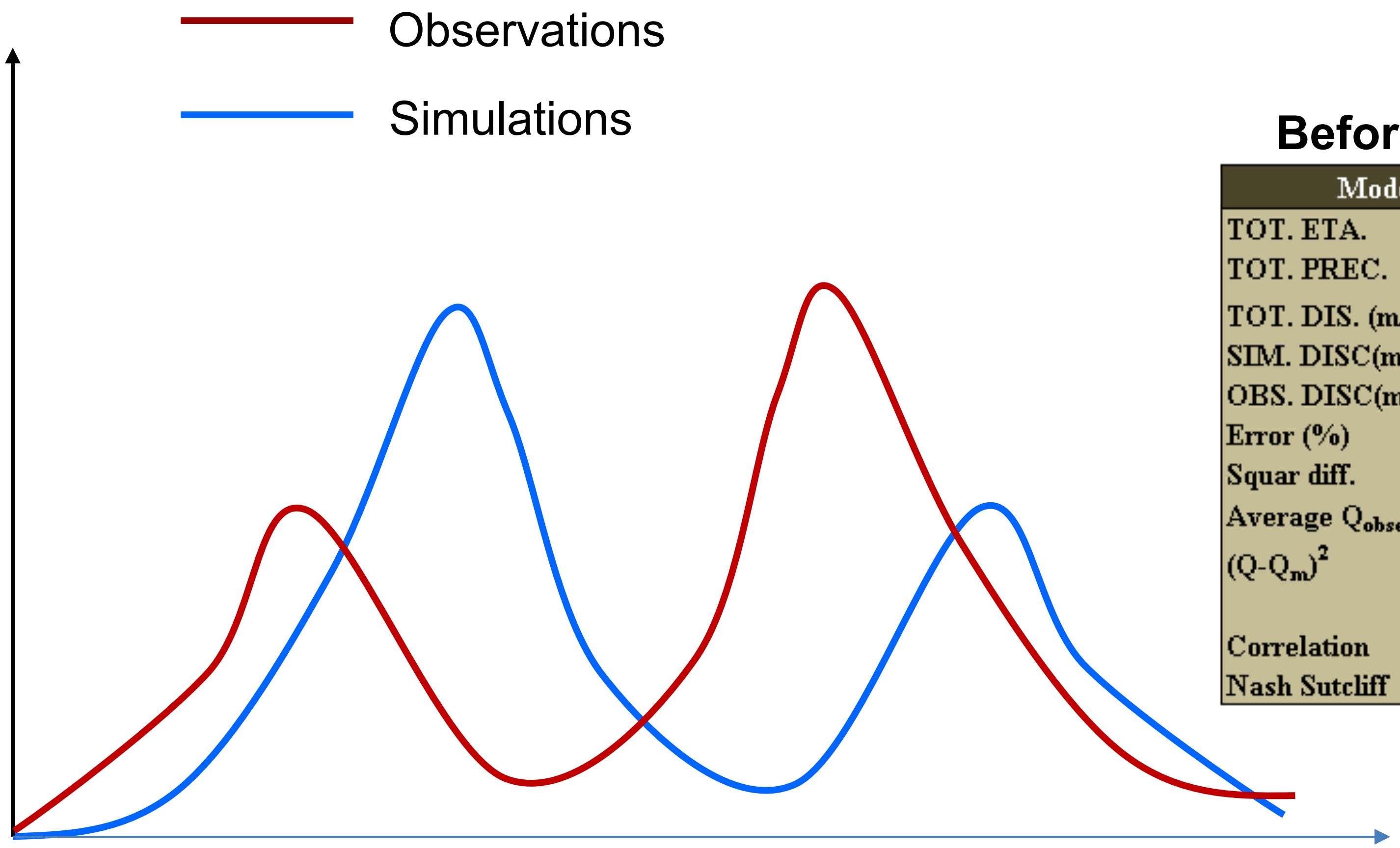
Subject to the Constraints:

$F$10 >= $F$11
$F$11 >= 0.004
$F$12 >= 0
$F$13 <= $C$11
$F$8 >= $F$10
$F$9 >= 0

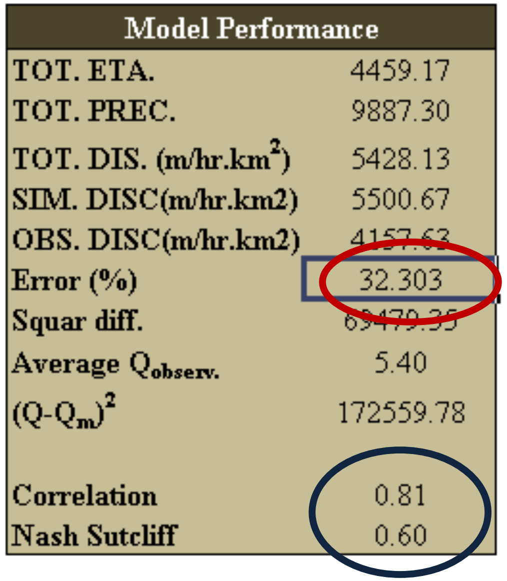
Objective Function

Objective Function 1:

Minimum total runoff error

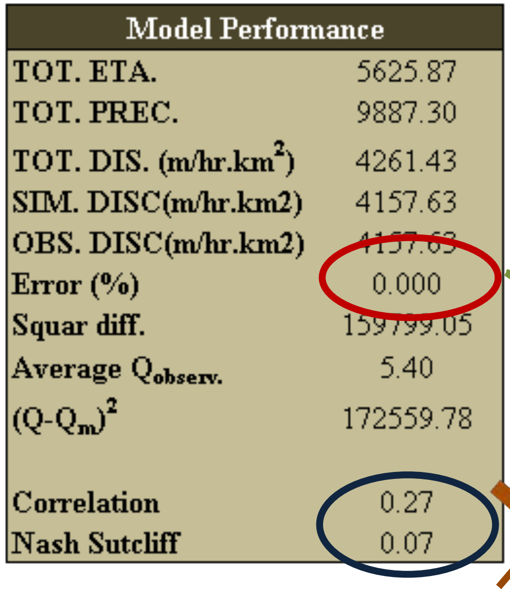


Before Calibration



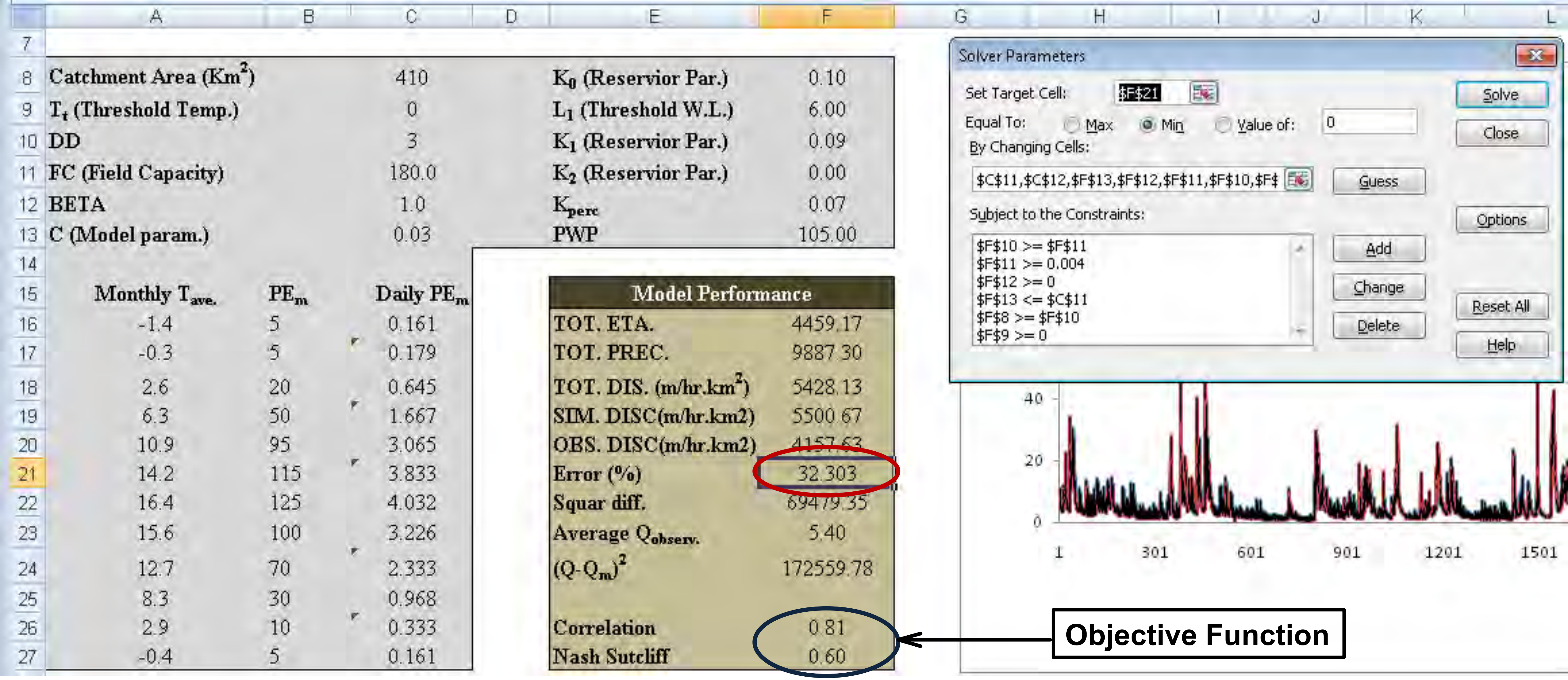
Model Performance	
TOT. ETA.	4459.17
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	5428.13
SIM. DISC(m/hr.km2)	5500.67
OBS. DISC(m/hr.km2)	4157.63
Error (%)	32.303
Squar diff.	69479.35
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.81
Nash Sutcliff	0.60

After Calibration



Model Performance	
TOT. ETA.	5625.87
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	4261.43
SIM. DISC(m/hr.km2)	4157.63
OBS. DISC(m/hr.km2)	4157.63
Error (%)	0.000
Squar diff.	159799.05
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.27
Nash Sutcliff	0.07

✓ ✗



Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.10
T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
DD	3	K_1 (Reservior Par.)	0.09
FC (Field Capacity)	180.0	K_2 (Reservior Par.)	0.00
BETA	1.0	K_{perc}	0.07
C (Model param.)	0.03	PWP	105.00

Monthly $T_{ave.}$	PE_m	Daily PE_m
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

Model Performance	
TOT. ETA.	4459.17
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	5428.13
SIM. DISC(m/hr.km2)	5500.67
OBS. DISC(m/hr.km2)	4157.63
Error (%)	32.303
Squar diff.	69479.35
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.81
Nash Sutcliff	0.60

Solver Parameters

Set Target Cell: $F$21

Equal To: ○ Max ● Min ○ Value of: 0

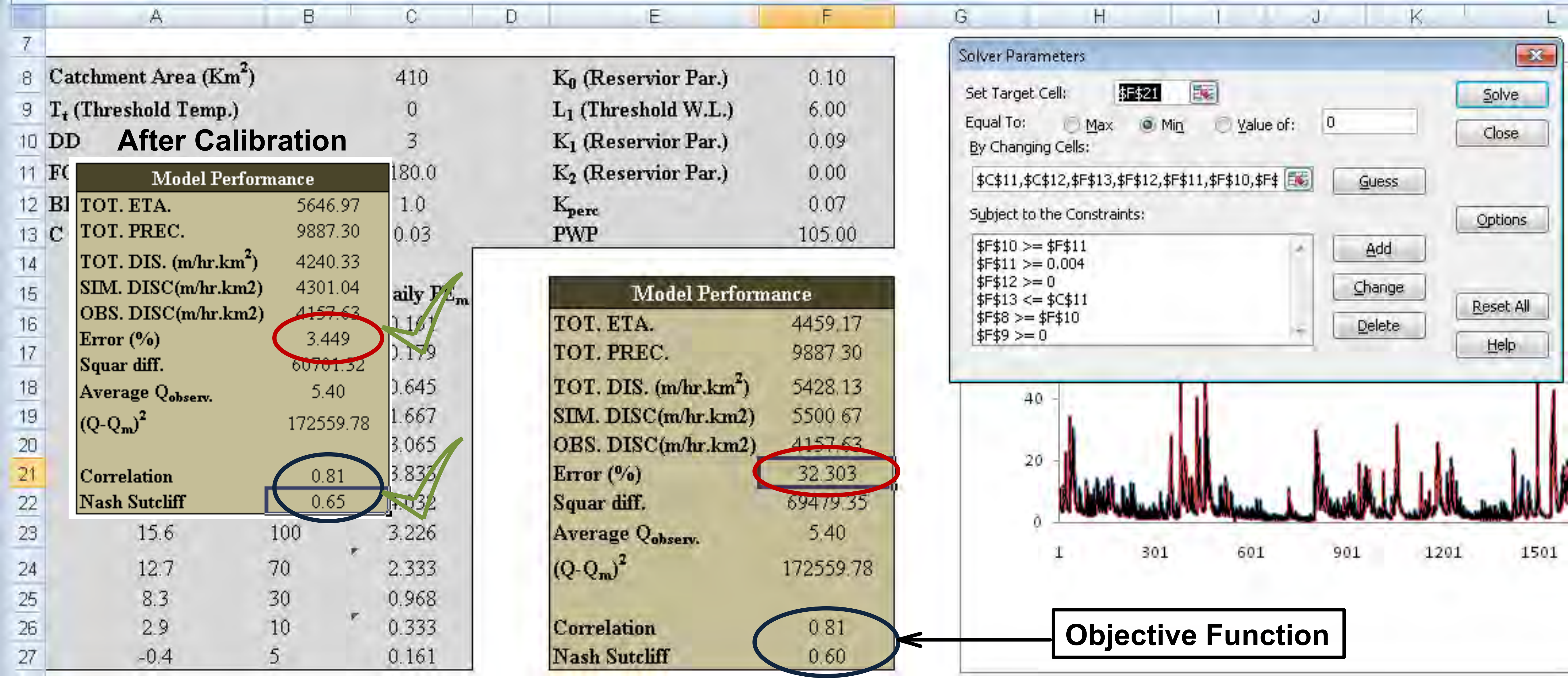
By Changing Cells:

$C$11,$C$12,$F$13,$F$12,$F$11,$F$10,F

Subject to the Constraints:

$F$10 >= $F$11
$F$11 >= 0.004
$F$12 >= 0
$F$13 <= $C$11
$F$8 >= $F$10
$F$9 >= 0

Objective Function



After Calibration

Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.10
T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
DD	3	K_1 (Reservior Par.)	0.09
FC	180.0	K_2 (Reservior Par.)	0.00
Bl	1.0	K_{perc}	0.07
C	0.03	PWP	105.00

Model Performance	
TOT. ETA.	5646.97
TOT. PREC.	9887.30
TOT. DIS. ($m/hr.km^2$)	4240.33
SIM. DISC(m/hr.km2)	4301.04
OBS. DISC(m/hr.km2)	4157.63
Error (%)	3.449
Squar diff.	60701.32
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.81
Nash Sutcliff	0.65

aily PE_m

		0.161
		0.179
		0.645
		1.667
		3.065
		3.833
		4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

Model Performance	
TOT. ETA.	4459.17
TOT. PREC.	9887.30
TOT. DIS. ($m/hr.km^2$)	5428.13
SIM. DISC(m/hr.km2)	5500.67
OBS. DISC(m/hr.km2)	4157.63
Error (%)	32.303
Squar diff.	69479.35
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.81
Nash Sutcliff	0.60

Objective Function

Solver Parameters

Set Target Cell: $F$21

Equal To: ○ Max ● Min ○ Value of: 0

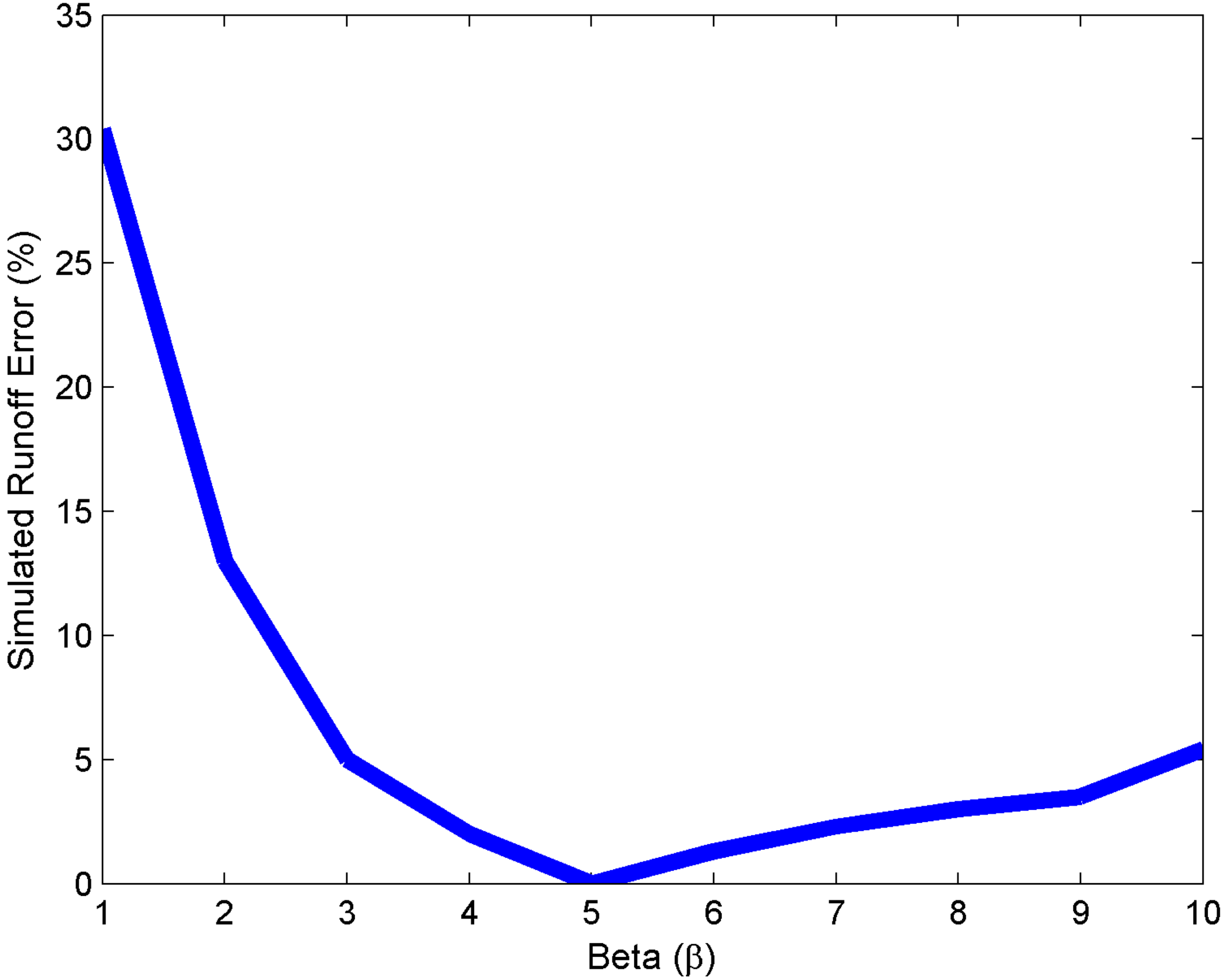
By Changing Cells:

$C$11,$C$12,$F$13,$F$12,$F$11,$F$10,F

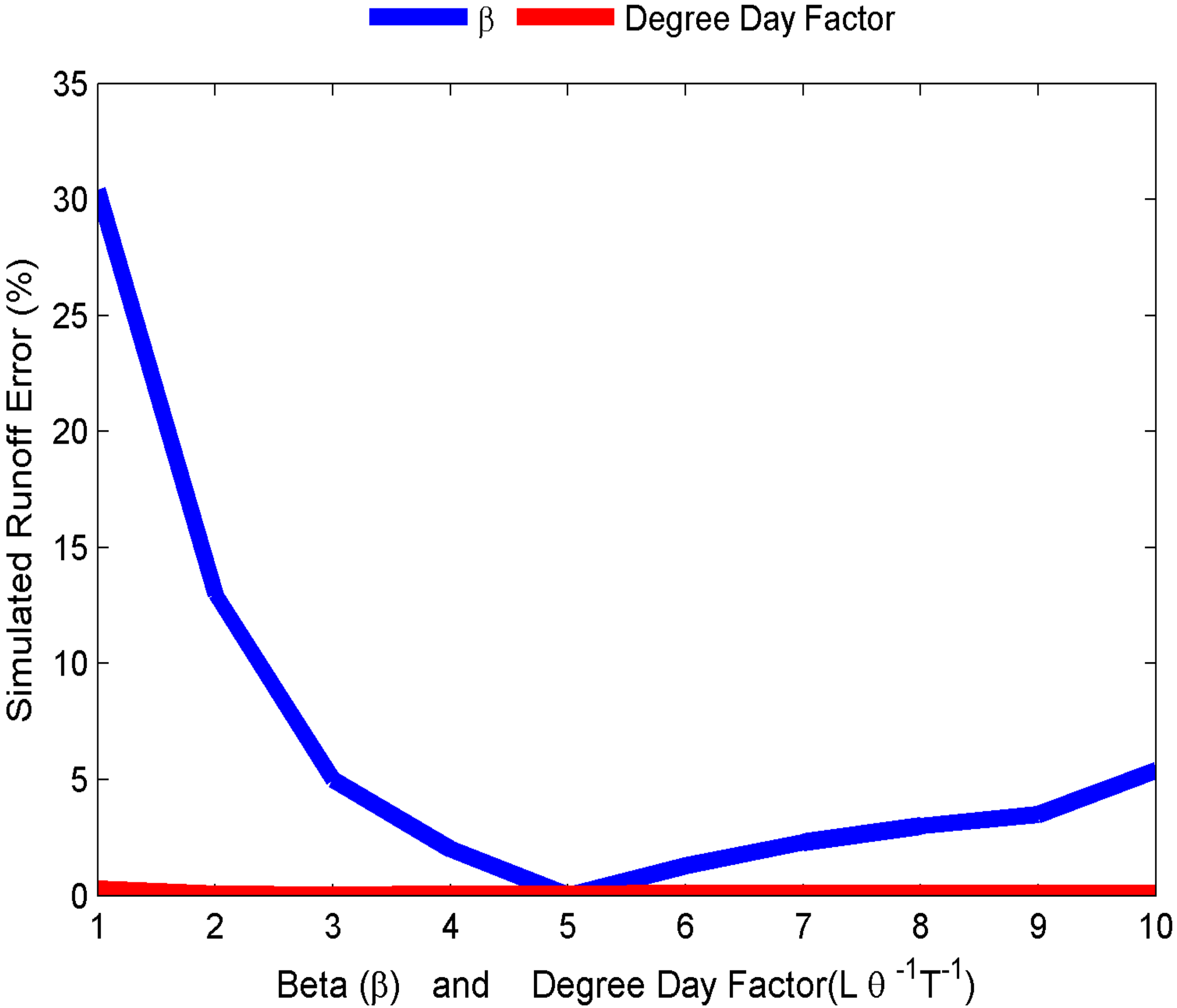
Subject to the Constraints:

$F$10 >= $F$11
$F$11 >= 0.004
$F$12 >= 0
$F$13 <= $C$11
$F$8 >= $F$10
$F$9 >= 0

Parameter Sensitivity



Parameter Sensitivity



Conceptual

- BETA (β)
- C
- L
- K_0
- K_1
- K_2
- K_{perc}

Conceptual & Measurable

- FC
- DD
- PWP
- T_t

Initial Conditions

- Snow
- Soil Moisture
- S_1
- S_2

Error in Initial Conditions

- Error in the initial values of soil moisture, snow, field capacity, permanent wilting point

Error in Model Processes

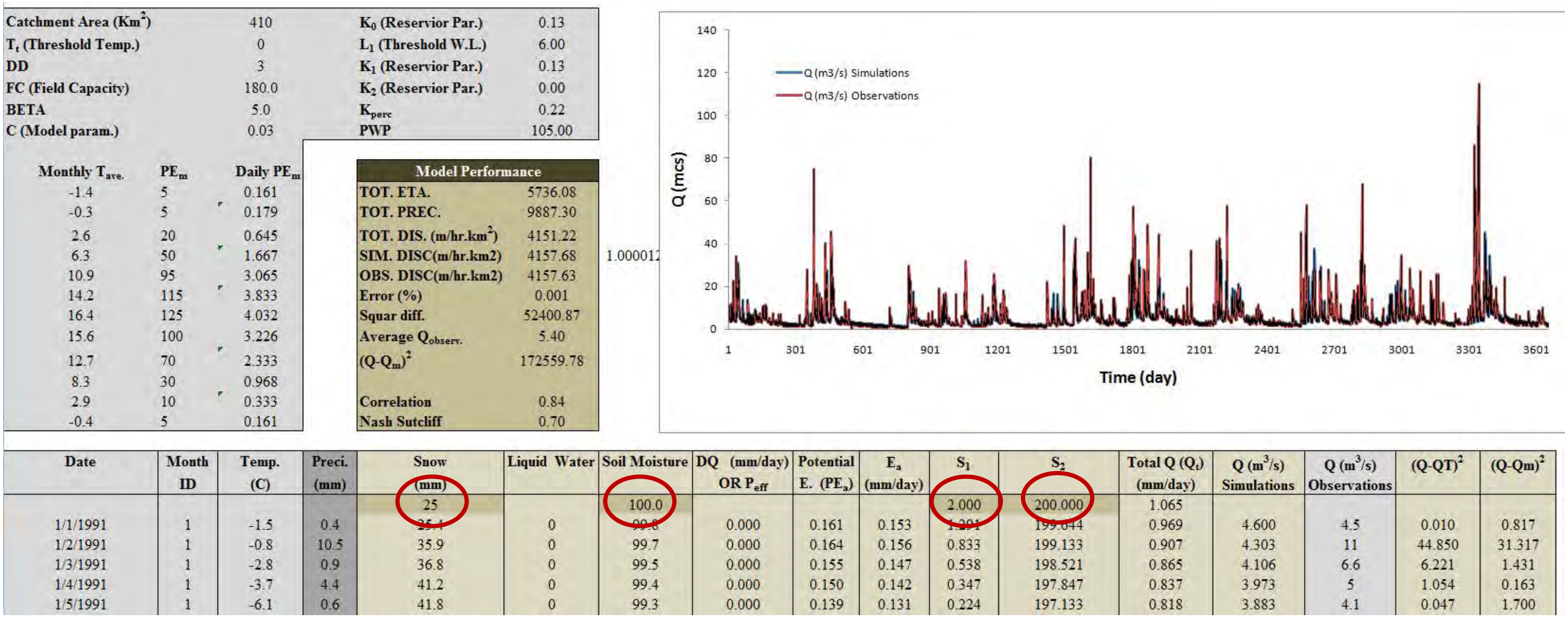
- Unrealistic model assumptions
- Unrepresentative conceptual description of the system

Error in Observations

- Error in input data (e.g., precipitation, temperature, etc.)
- Error in observed discharge

Error in Model Parameterization

- Inability to obtain the optimal set of parameters.
- Deficiencies in parameter estimation scheme



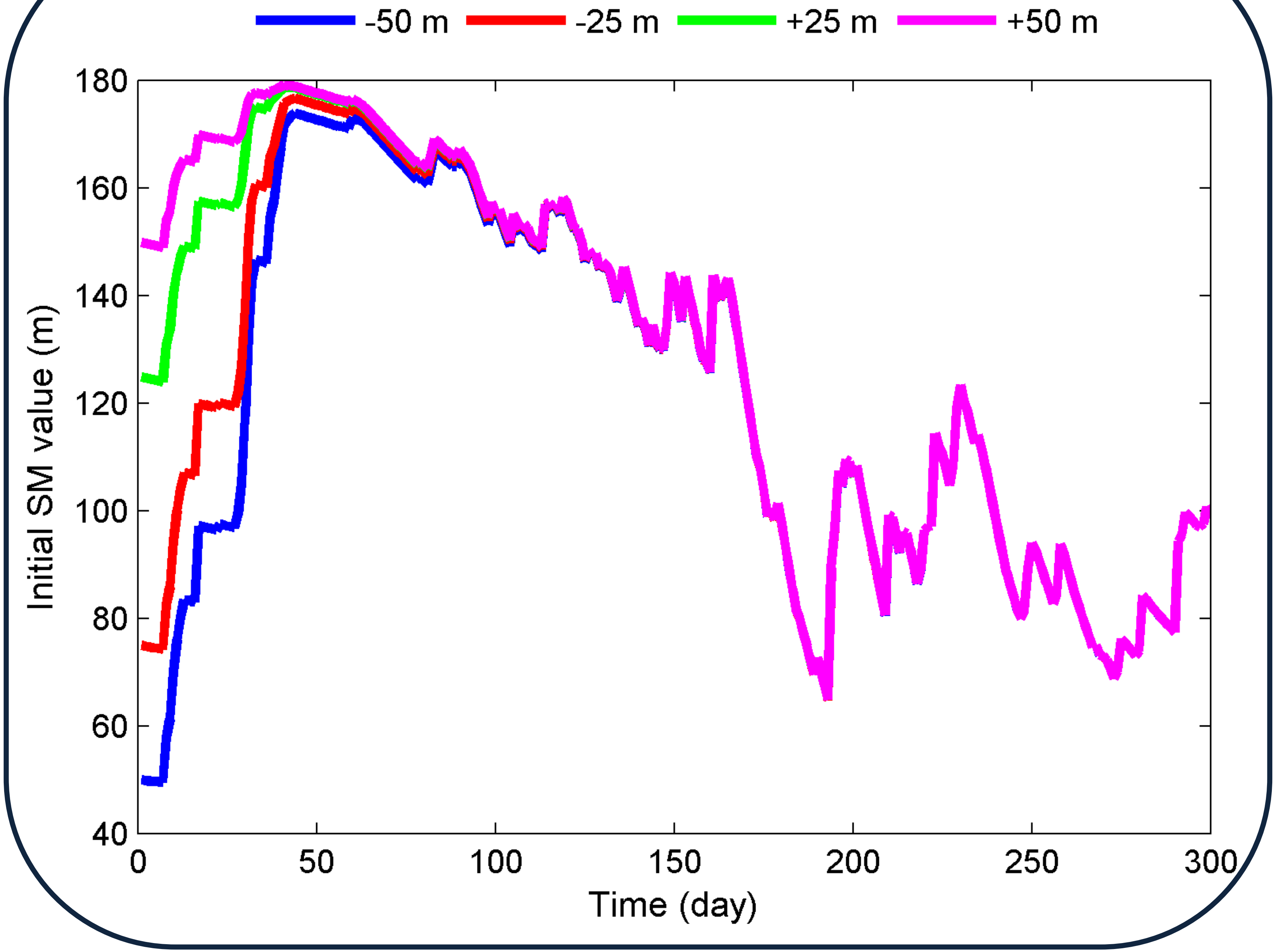
Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.13
T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
DD	3	K_1 (Reservior Par.)	0.13
FC (Field Capacity)	180.0	K_2 (Reservior Par.)	0.00
BETA	5.0	K_{perc}	0.22
C (Model param.)	0.03	PWP	105.00

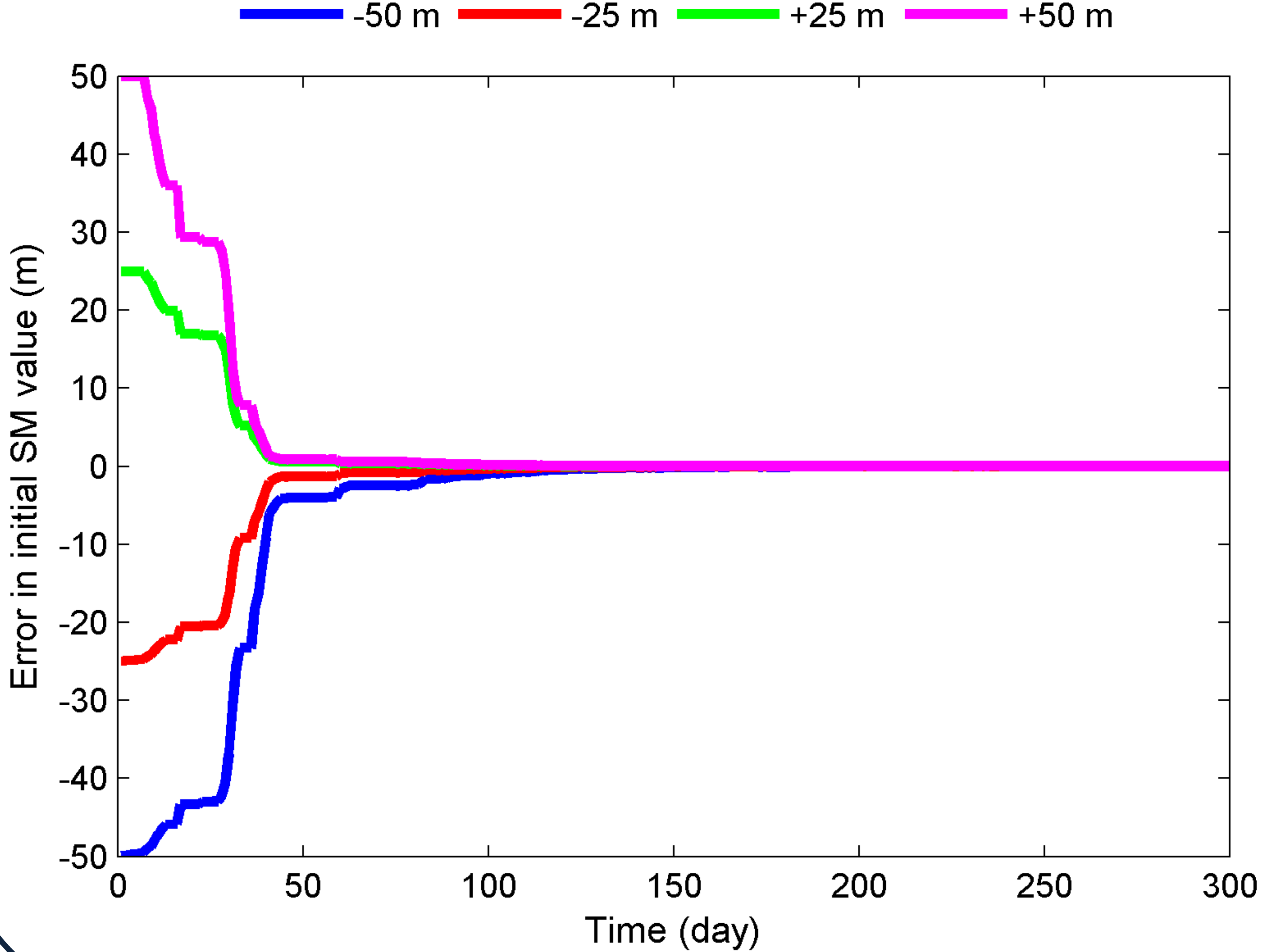
Monthly $T_{ave.}$	PE_m	Daily PE_m
-1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032
15.6	100	3.226
12.7	70	2.333
8.3	30	0.968
2.9	10	0.333
-0.4	5	0.161

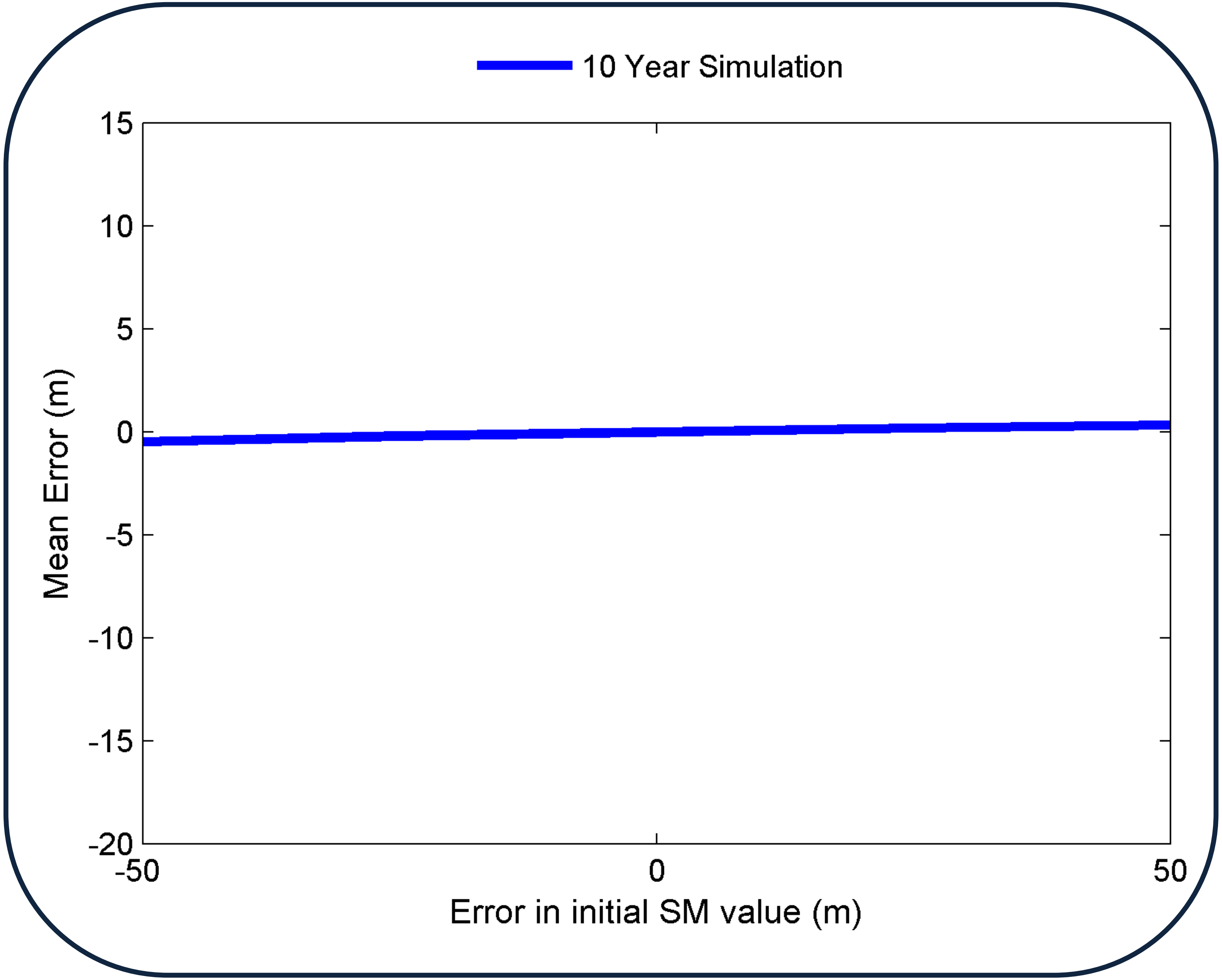
Model Performance	
TOT. ETA.	5736.08
TOT. PREC.	9887.30
TOT. DIS. ($m/hr.km^2$)	4151.22
SIM. DISC(m/hr.km2)	4157.68
OBS. DISC(m/hr.km2)	4157.63
Error (%)	0.001
Squar diff.	52400.87
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.84
Nash Sutcliff	0.70

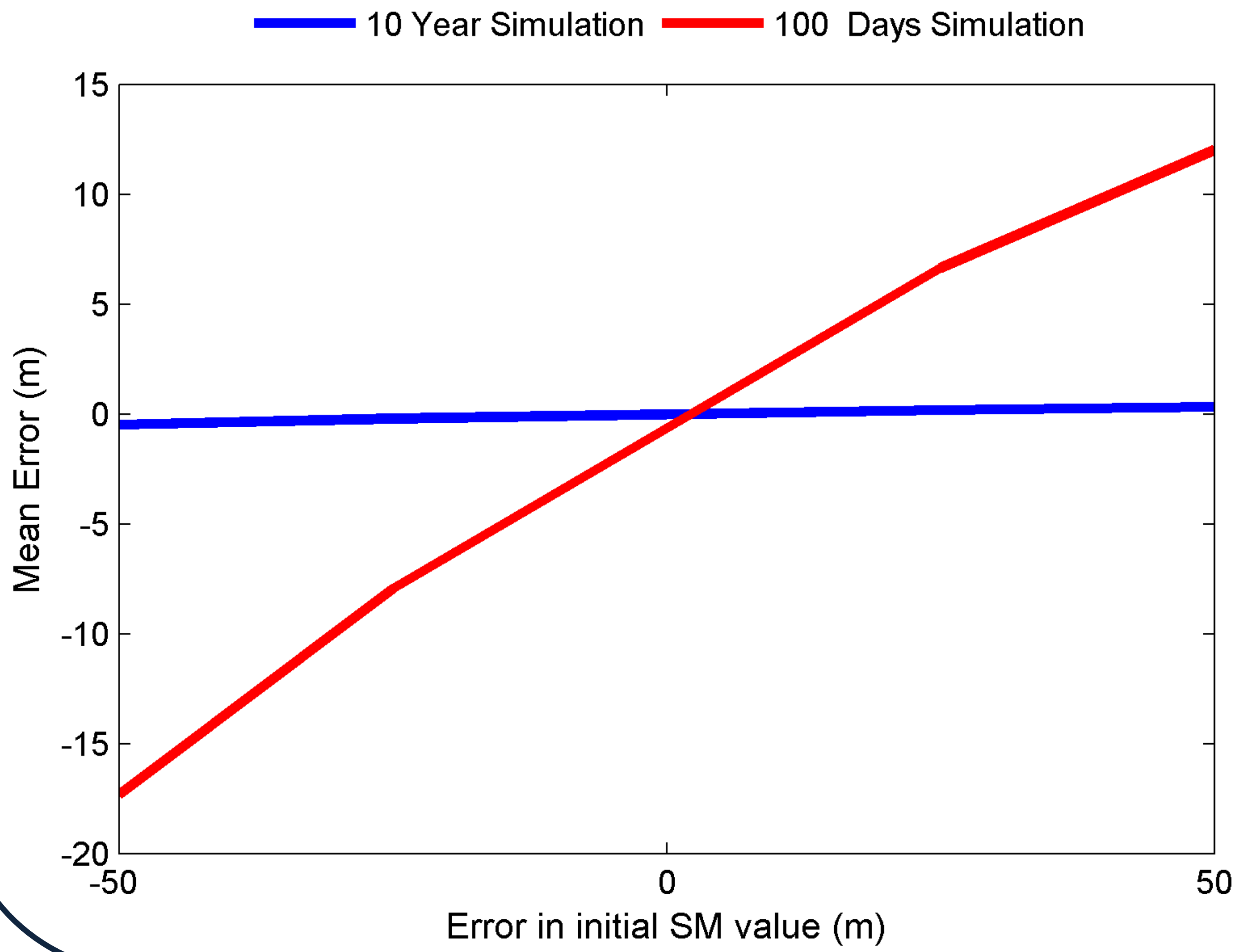
1.000012

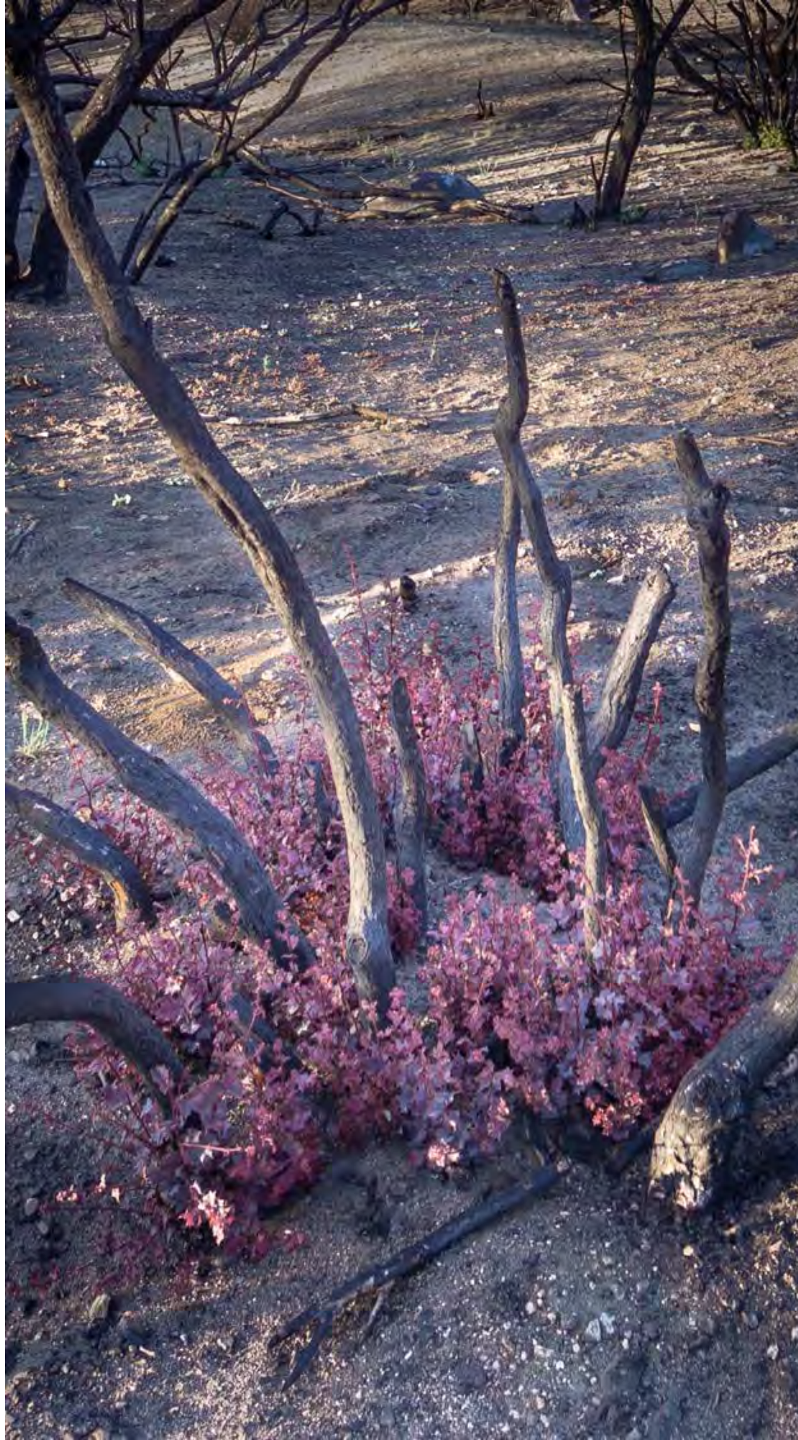
Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations	$(Q-QT)^2$	$(Q-Qm)^2$
				25		100.0				2.000	200.000	1.065				
1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5	0.010	0.817
1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133	0.907	4.303	11	44.850	31.317
1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538	198.521	0.865	4.106	6.6	6.221	1.431
1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347	197.847	0.837	3.973	5	1.054	0.163
1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224	197.133	0.818	3.883	4.1	0.047	1.700


-50 m
-25 m
+25 m
+50 m
Initial SM value (m)
180
160
140
120
100
80
60
40
0
50
100
150
200
250
300
Time (day)


-50 m
-25 m
+25 m
+50 m
Error in initial SM value (m)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
Time (day)

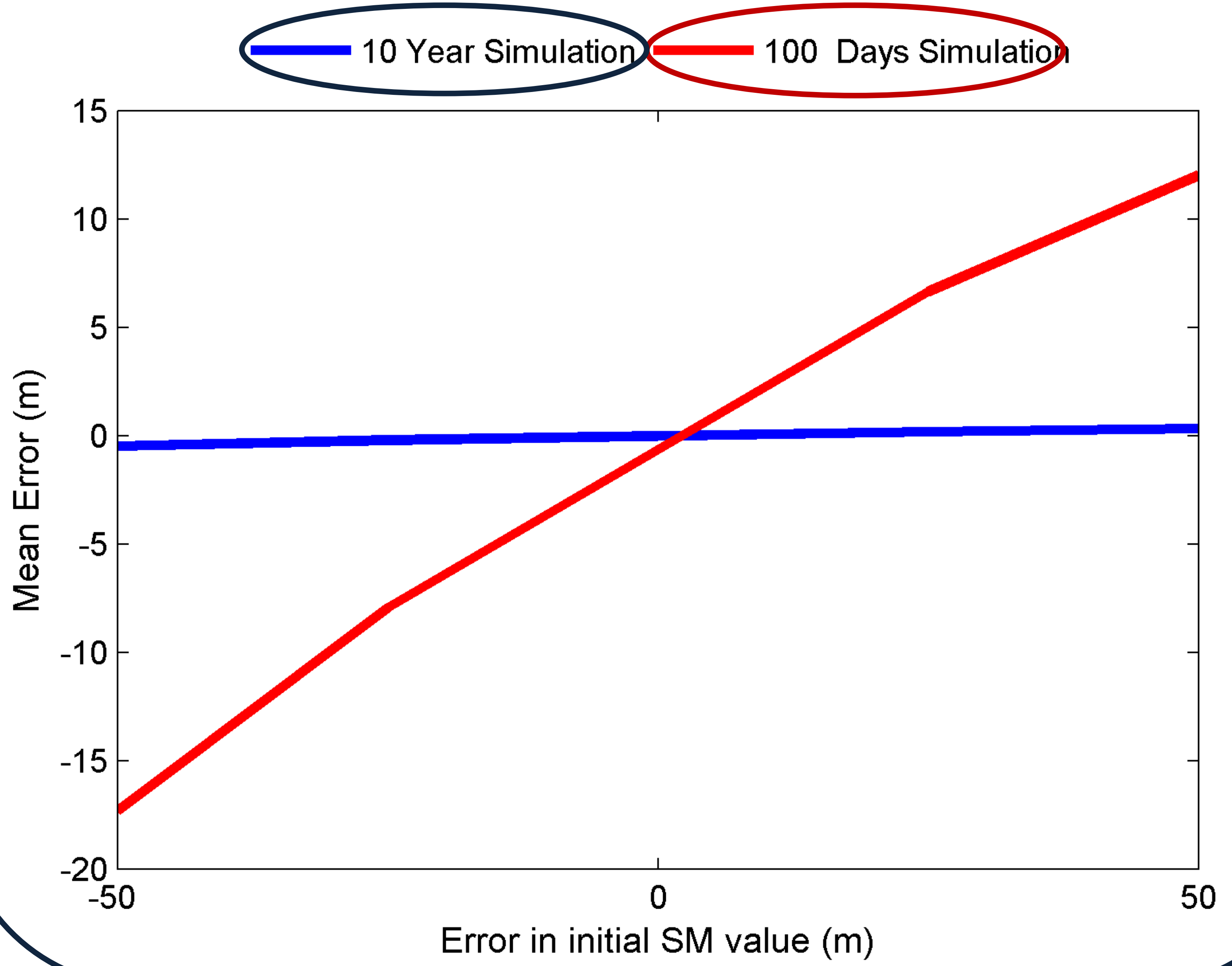

10 Year Simulation
15
10
5
0
-5
-10
-15
-20
Mean Error (m)
-50
0
50
Error in initial SM value (m)

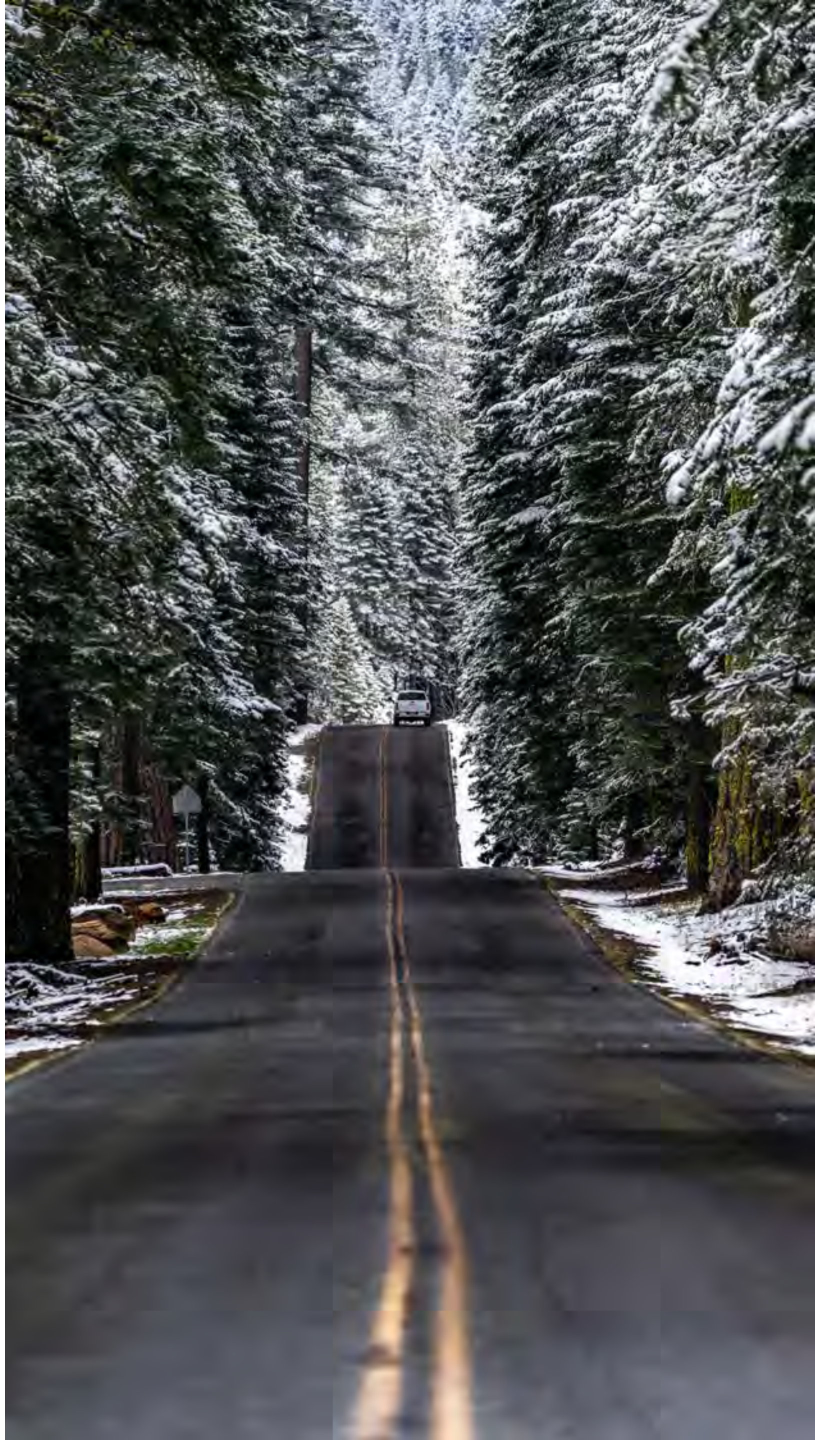

10 Year Simulation
100 Days Simulation
15
10
5
0
-5
-10
-15
-20
-50
0
50
Mean Error (m)
Error in initial SM value (m)

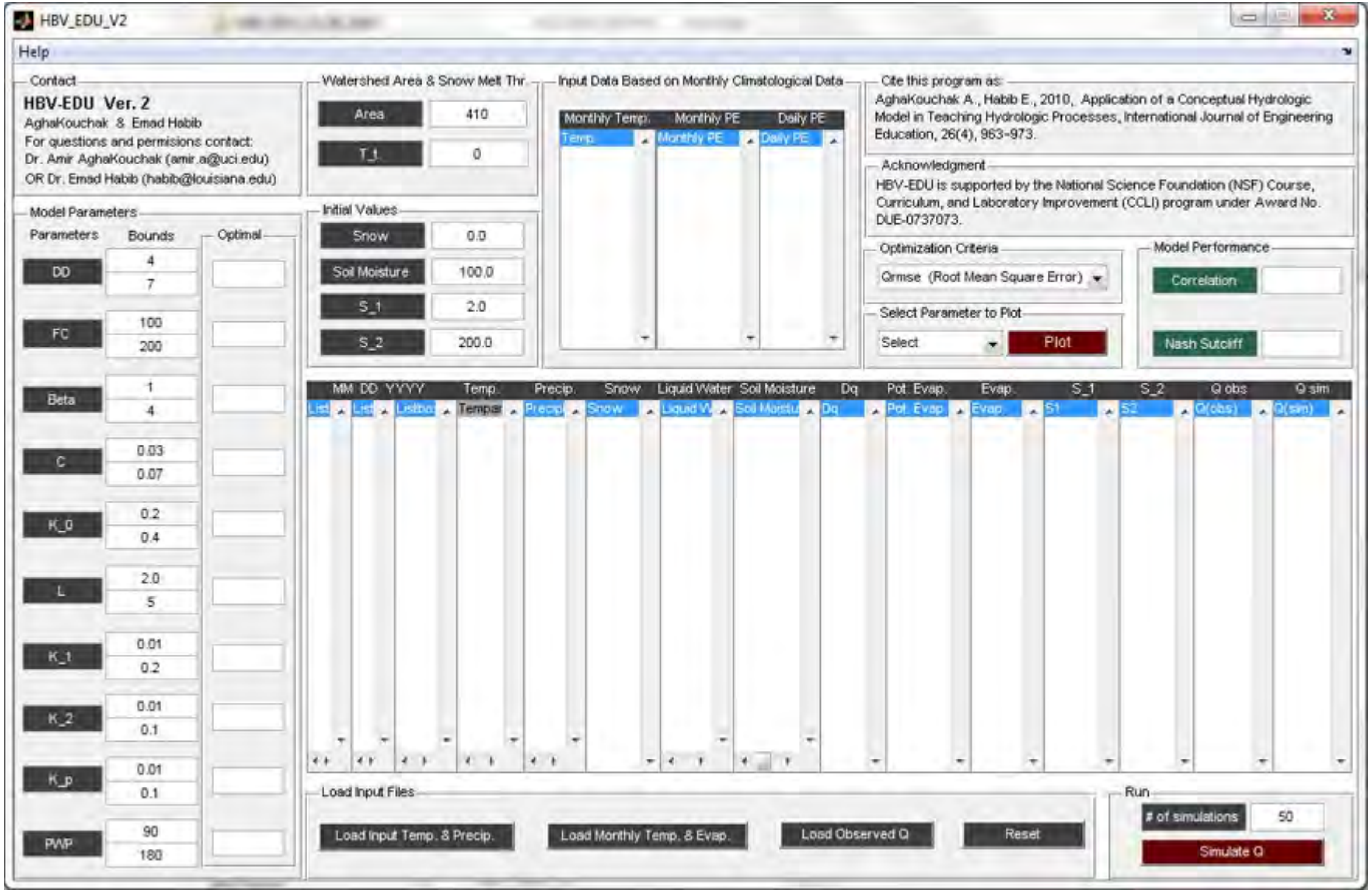


Insensitive to Initial Conditions

sensitive to Initial Conditions







Contact

HBV-EDU Ver. 2
AghaKouchak & Emad Habib
For questions and permisions contact:
Dr. Amir AghaKouchak (amir.a@uci.edu)
OR Dr. Emad Habib (habib@louisiana.edu)

Watershed Area & Snow Melt Thr.
Area: 410
T_t: 0

Input Data Based on Monthly Climatological Data

Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

Acknowledgment
HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Model Parameters

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

Initial Values
Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

Optimization Criteria: Qrmse (Root Mean Square Error)

Select Parameter to Plot: Select

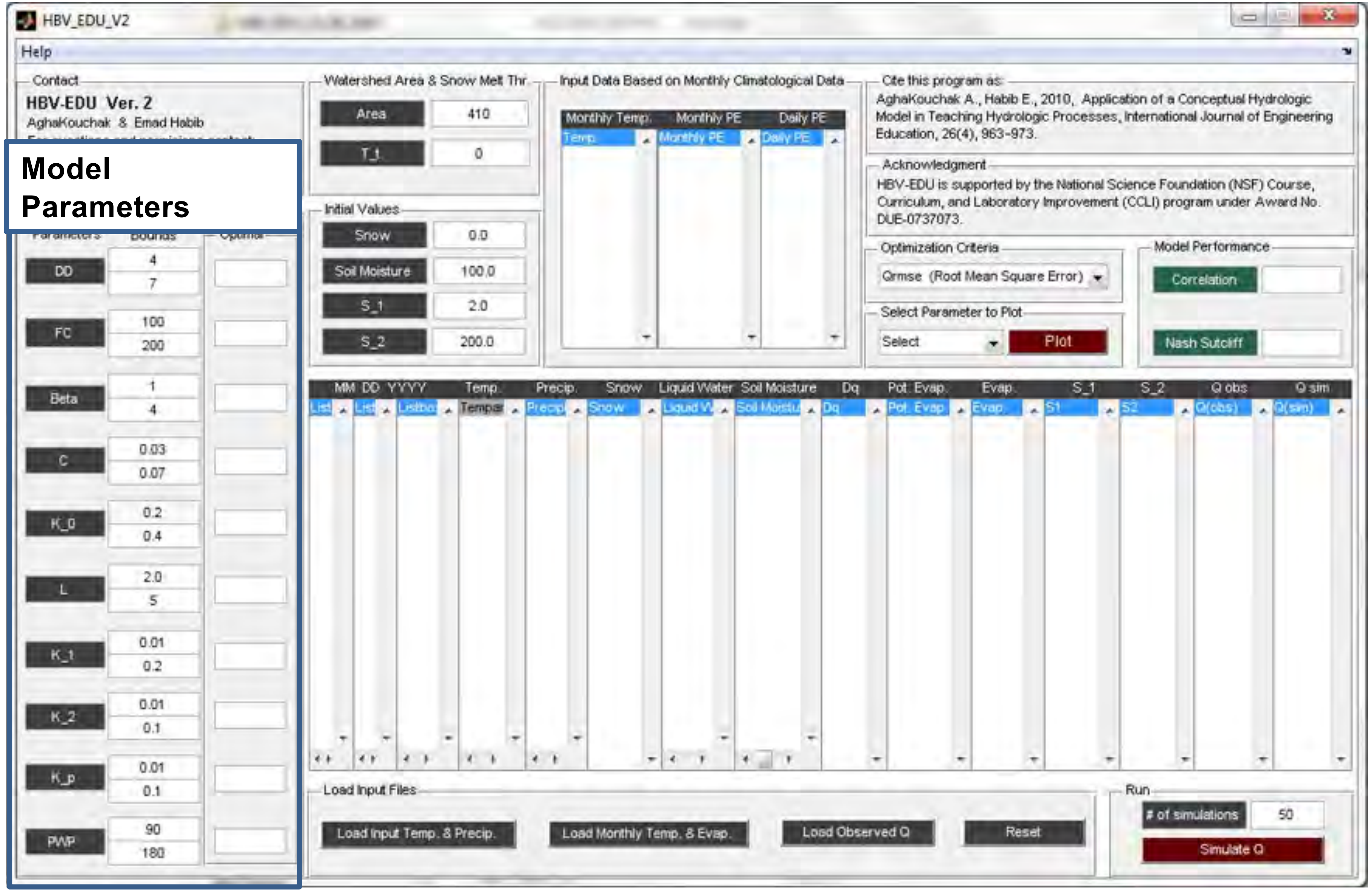
Model Performance

Load Input Files

Run
# of simulations: 50

http://amir.eng.uci.edu/education.php

Model Parameters



HBV-EDU Ver. 2

AghaKouchak & Emad Habib

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

Area: 410

T_t: 0

Snow: 0.0

Soil Moisture: 100.0

S_1: 2.0

S_2: 200.0

Cite this program as:
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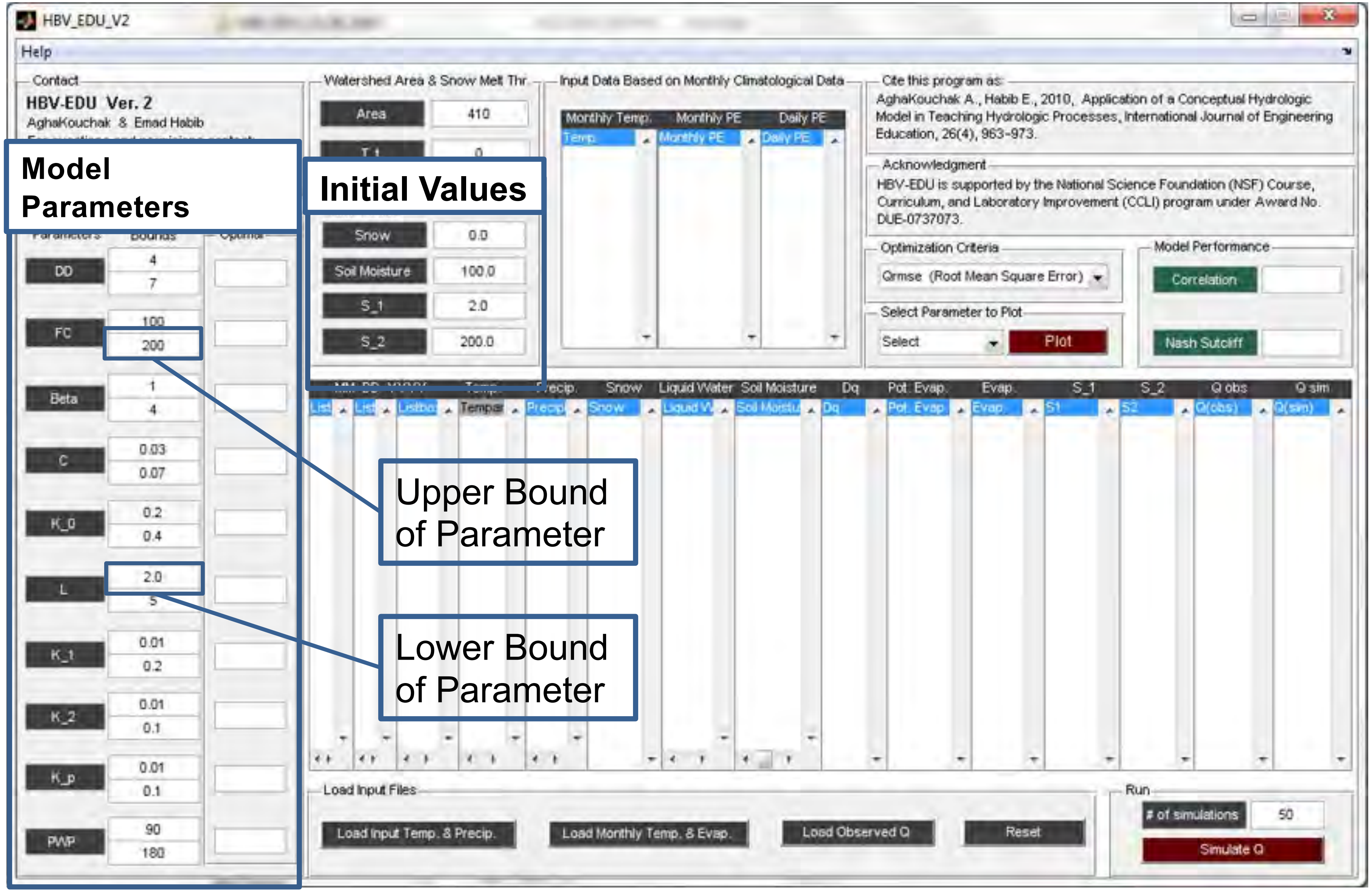
Optimization Criteria: Qrmse (Root Mean Square Error)

# of simulations: 50



HBV-EDU Ver. 2

AghaKouchak & Emad Habib

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Acknowledgment

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Area: 410

T_t: 0

Snow: 0.0

Soil Moisture: 100.0

S_1: 2.0

S_2: 200.0

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

Optimization Criteria: Qrmse (Root Mean Square Error)

Select Parameter to Plot: Select

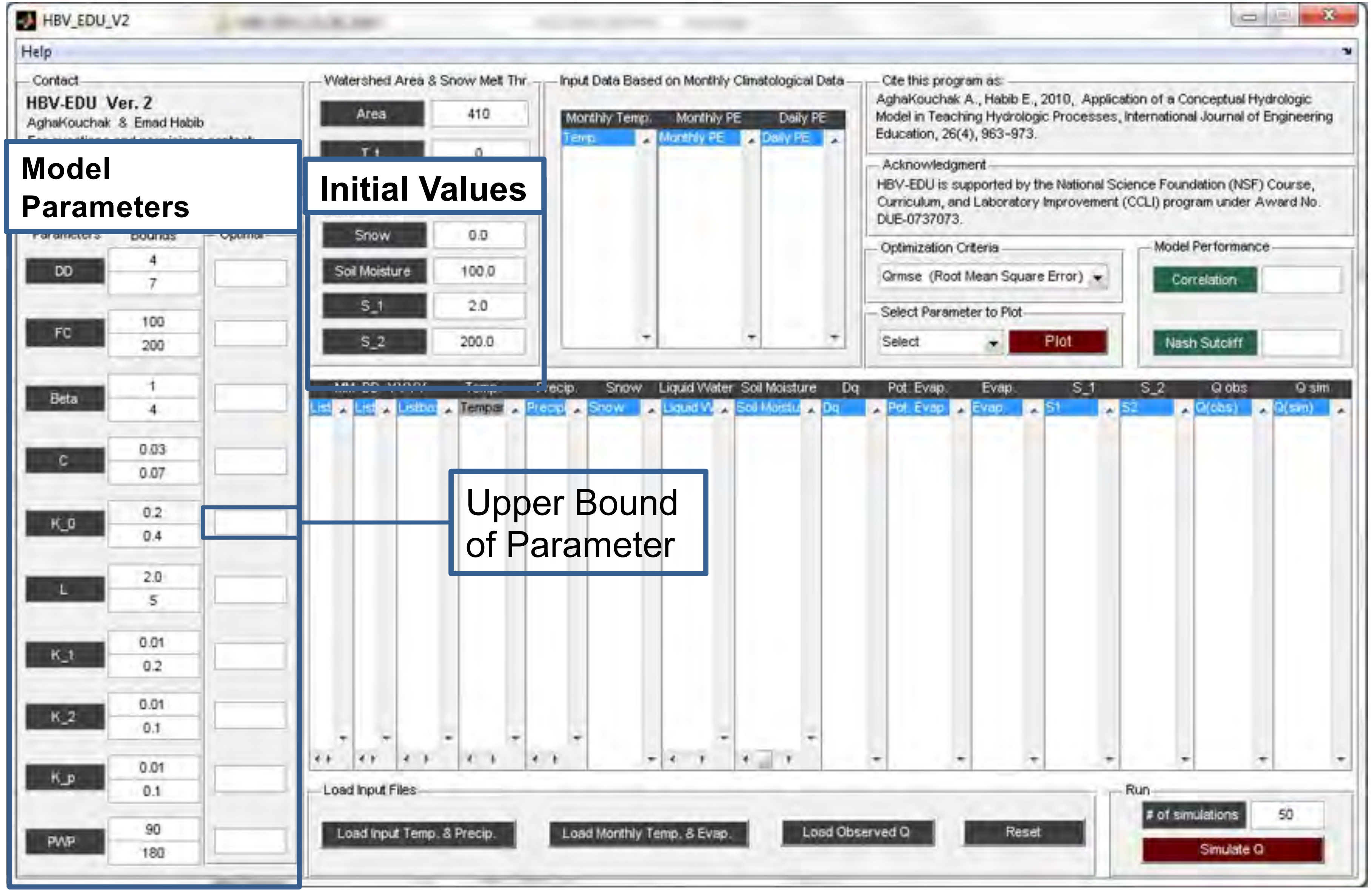
# of simulations: 50

Model Parameters

Initial Values

Upper Bound of Parameter

Lower Bound of Parameter



Model Parameters

Initial Values

Upper Bound of Parameter

Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

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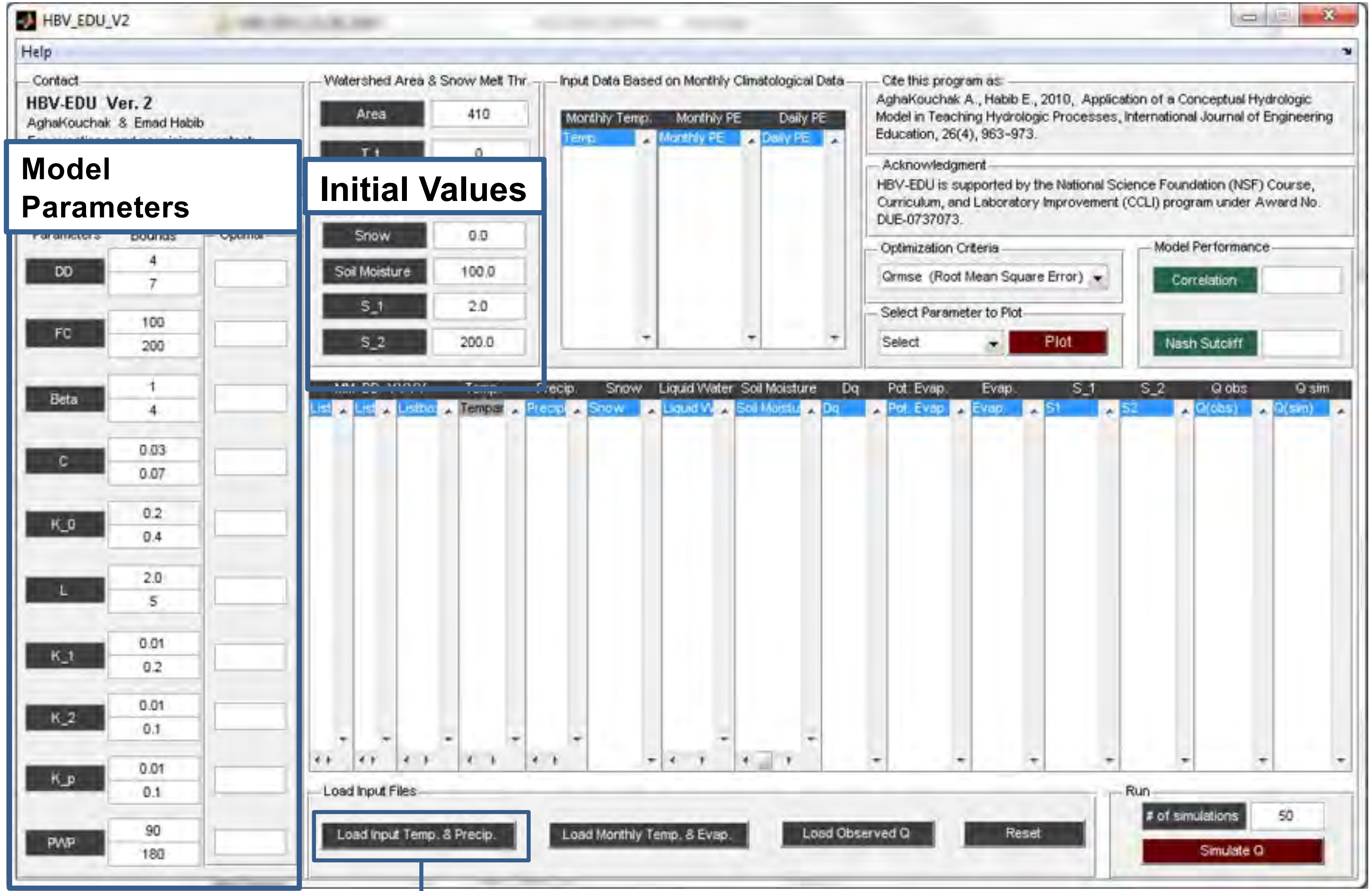
Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

Area: 410
T_t: 0
Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

Optimization Criteria: Qrmse (Root Mean Square Error)

# of simulations: 50



AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Optimization Criteria: Qrmse (Root Mean Square Error)

Area 410

T_t 0

# of simulations 50

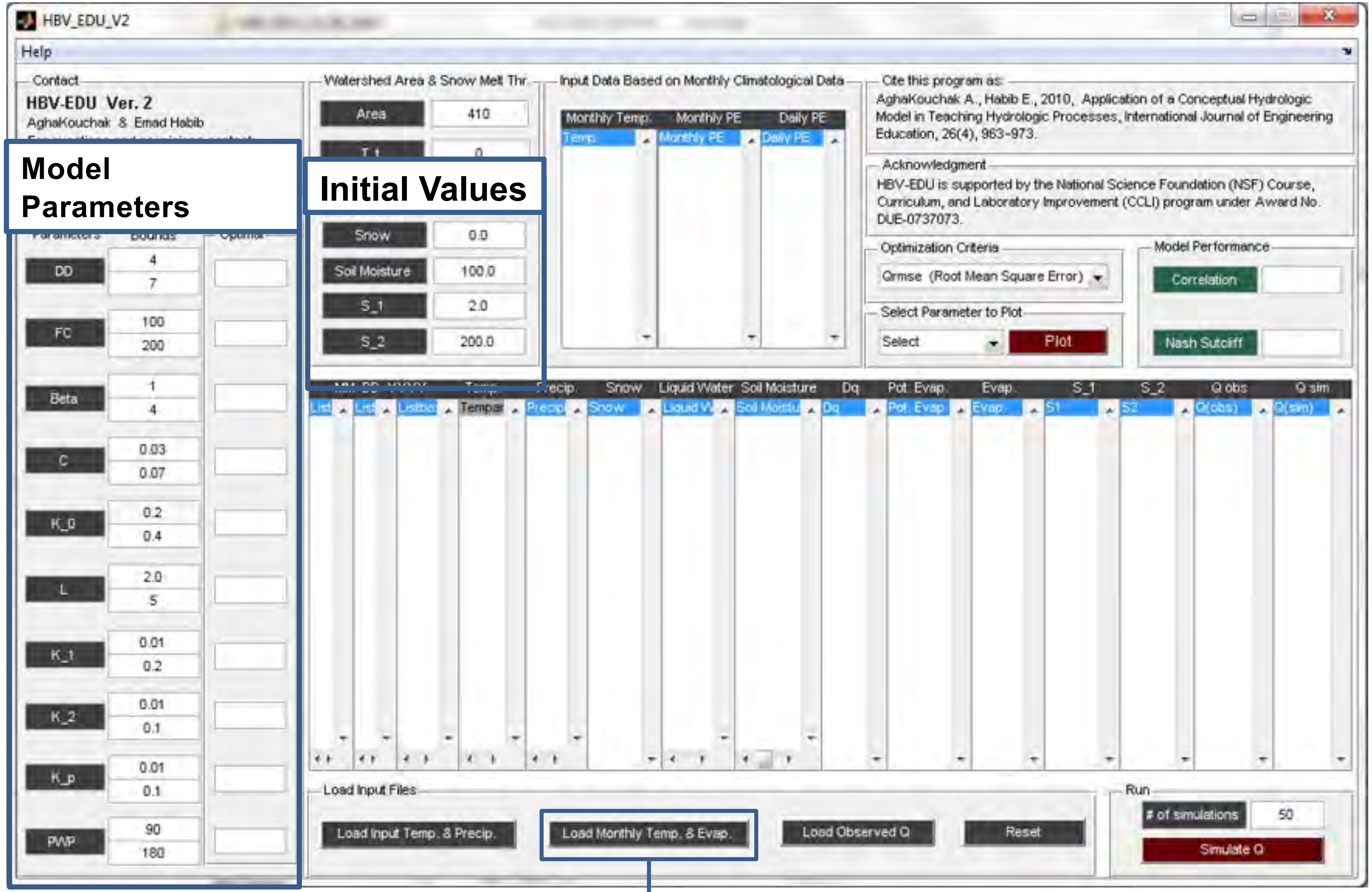
Model Parameters

DD	4	7
FC	100	200
Beta	1	4
C	0.03	0.07
K_0	0.2	0.4
L	2.0	5
K_1	0.01	0.2
K_2	0.01	0.1
K_p	0.01	0.1
PWP	90	180

Initial Values

Snow	0.0
Soil Moisture	100.0
S_1	2.0
S_2	200.0

Input Precipitation & Temperature Data



HBV-EDU Ver. 2
AghaKouchak & Emad Habib

Cite this program as:
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Acknowledgment
HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Area: 410
T_1: 0

Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

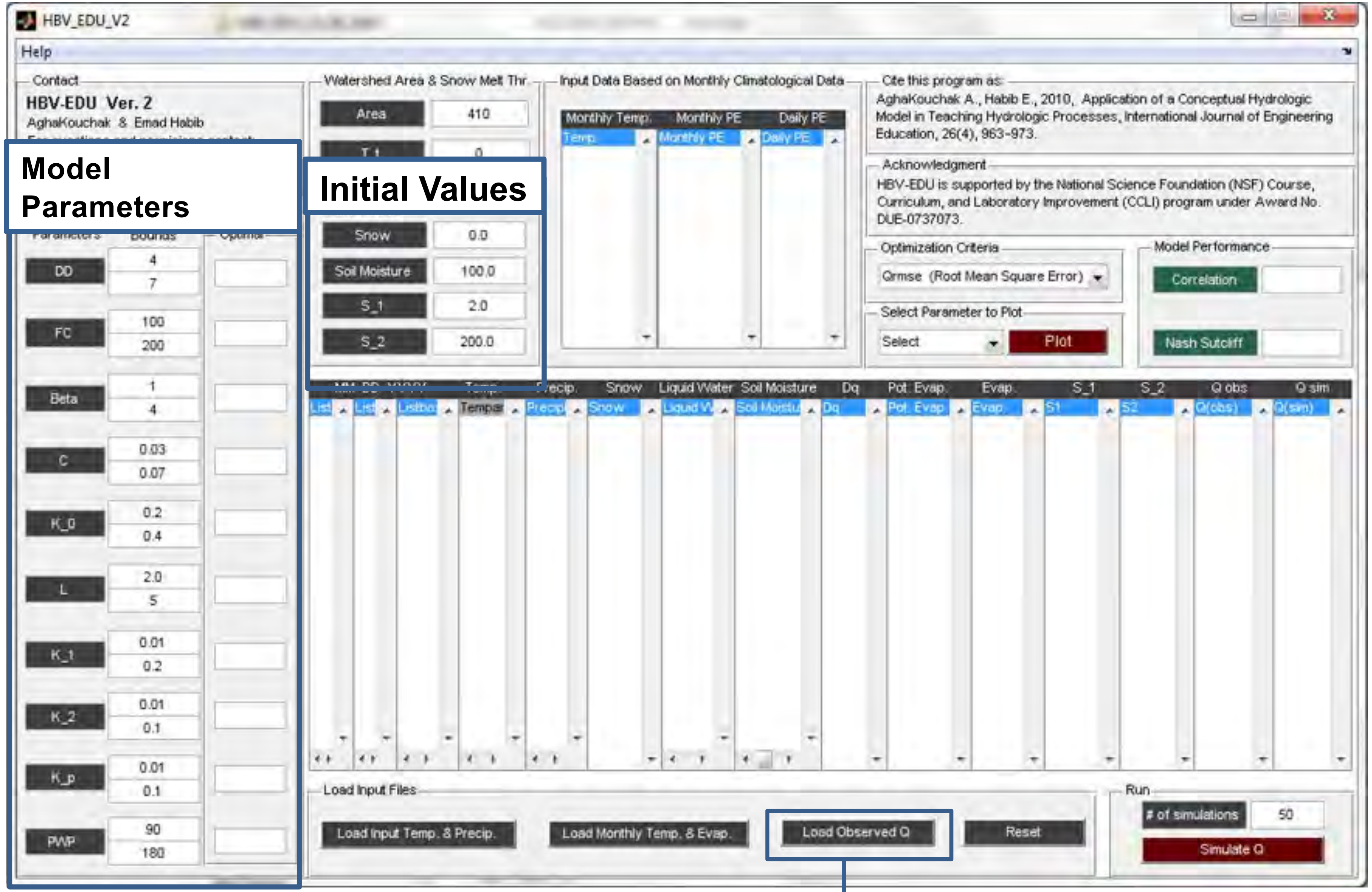
Optimization Criteria: Qrmse (Root Mean Square Error)

# of simulations: 50

Model Parameters

Initial Values

Monthly Temperature & Evapotranspiration



HBV-EDU Ver. 2
AghaKouchak & Emad Habib

AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Parameters	Bounds		Optimal
DD	4	7	
FC	100	200	
Beta	1	4	
C	0.03	0.07	
K_0	0.2	0.4	
L	2.0	5	
K_1	0.01	0.2	
K_2	0.01	0.1	
K_p	0.01	0.1	
PWP	90	180	

Area 410
T_t 0
Snow 0.0
Soil Moisture 100.0
S_1 2.0
S_2 200.0

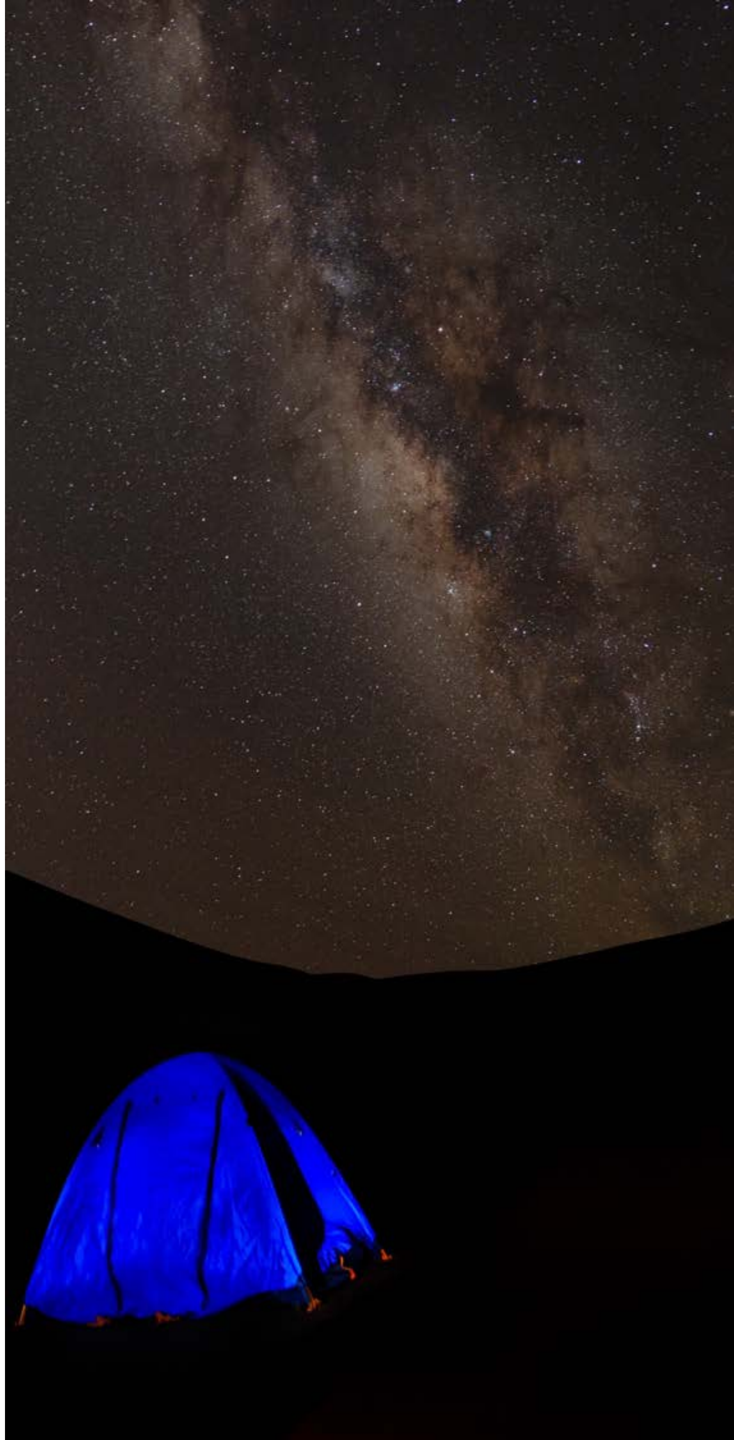
Qrmse (Root Mean Square Error)

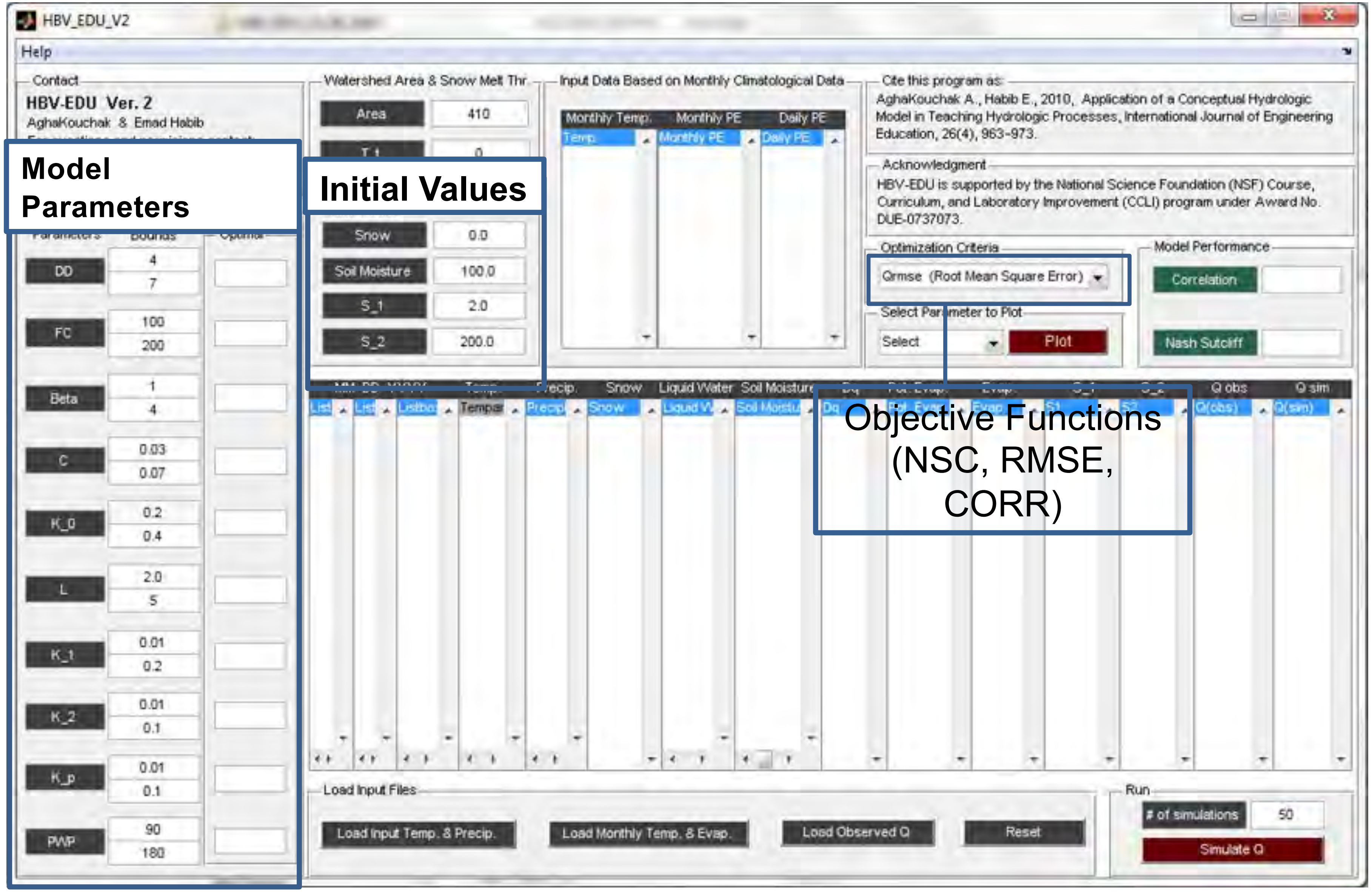
# of simulations 50

Model Parameters

Initial Values

Observed Discharge





Model Parameters

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

Initial Values

Area: 410
T_t: 0
Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

Acknowledgment
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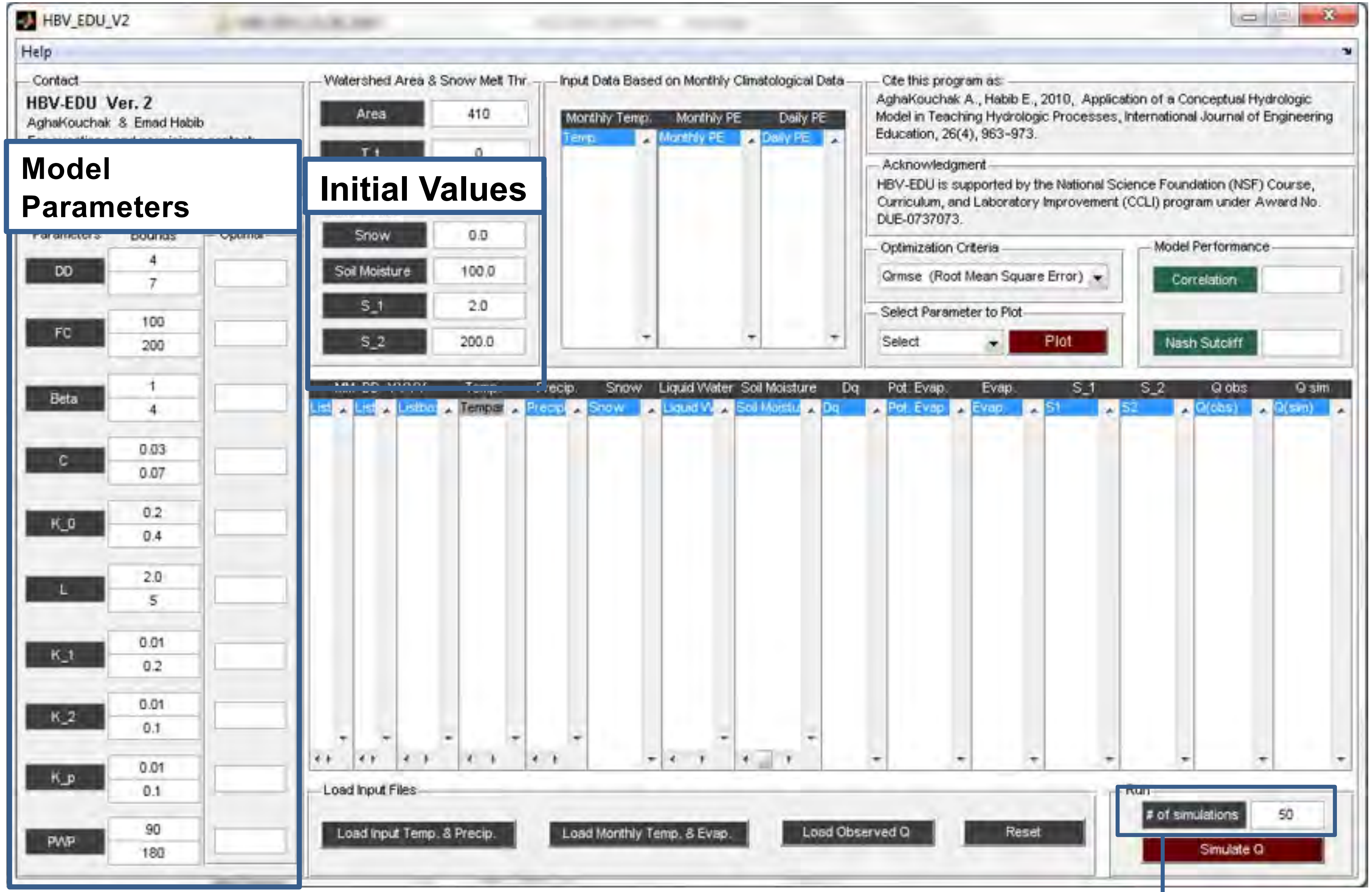
Optimization Criteria: Qrmse (Root Mean Square Error)

# of simulations: 50

Objective Functions (NSC, RMSE, CORR)



Cite this program as:
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Optimization Criteria: Qrmse (Root Mean Square Error)

Model Parameters

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

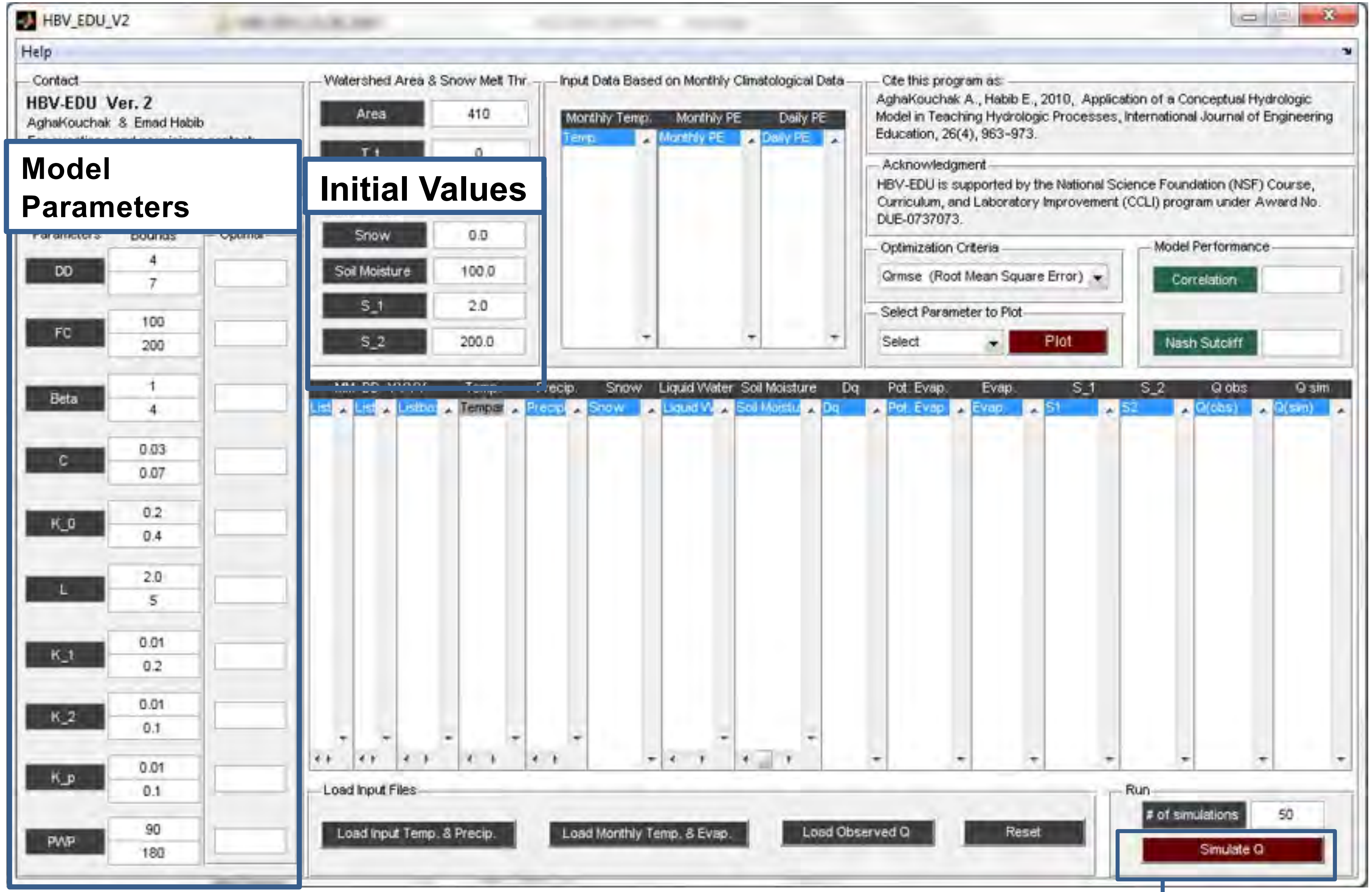
Area: 410
T_1: 0

Initial Values

Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

# of simulations: 50

Number of Simulations



HBV-EDU Ver. 2
AghaKouchak & Emad Habib

Model Parameters

Parameters	Bounds		Optimal
DD	4	7	
FC	100	200	
Beta	1	4	
C	0.03	0.07	
K_0	0.2	0.4	
L	2.0	5	
K_1	0.01	0.2	
K_2	0.01	0.1	
K_p	0.01	0.1	
PWP	90	180	

Area: 410
T_t: 0

Initial Values

Snow: 0.0
Soil Moisture: 100.0
S_1: 2.0
S_2: 200.0

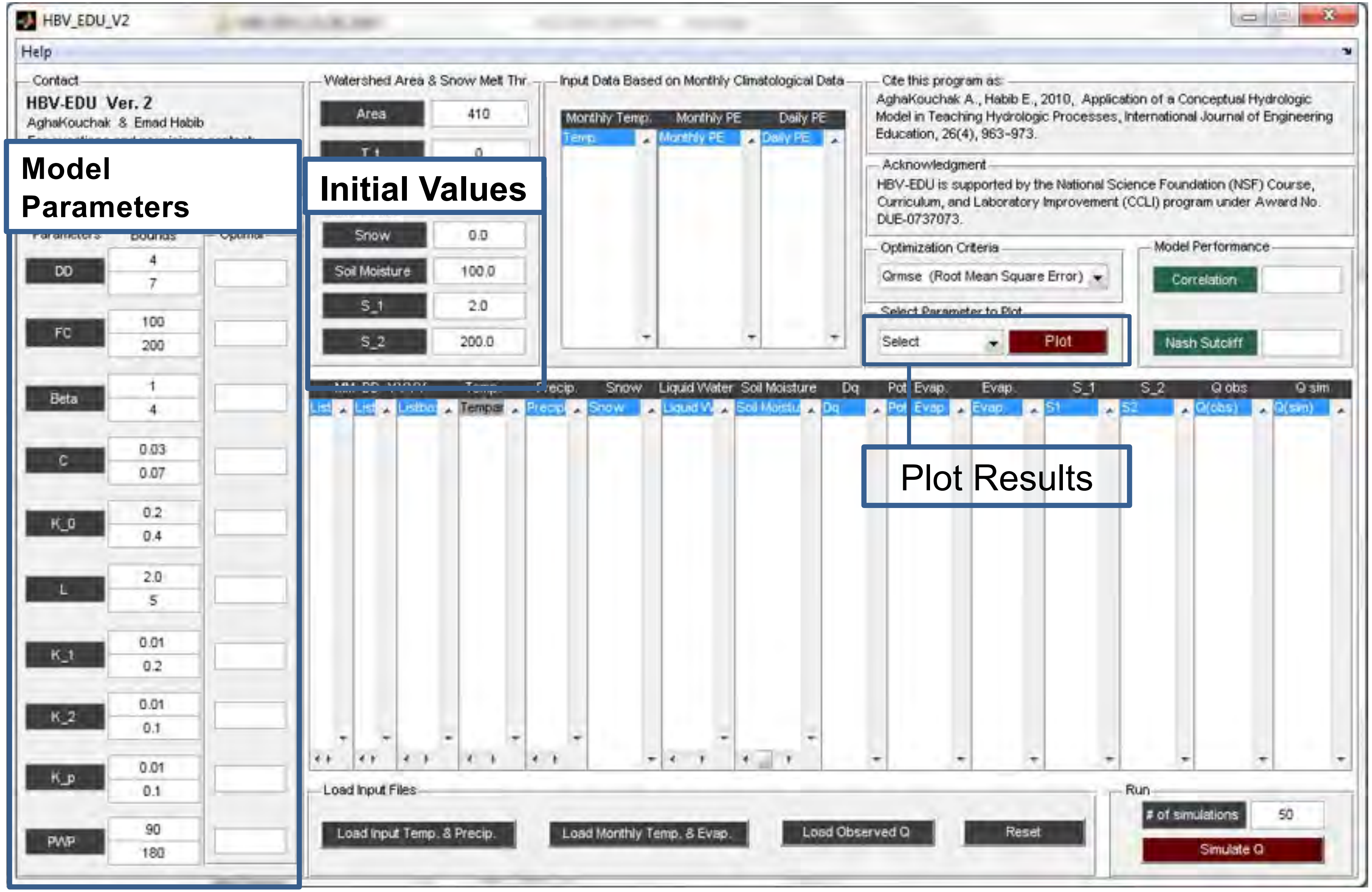
Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

Acknowledgment
HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Optimization Criteria: Qrmse (Root Mean Square Error)
Select Parameter to Plot: Select

# of simulations: 50

Run



Model Parameters

Initial Values

Plot Results

HBV-EDU Ver. 2
AghaKouchak & Emad Habib

Parameters	Bounds	Optimal
DD	4 7	
FC	100 200	
Beta	1 4	
C	0.03 0.07	
K_0	0.2 0.4	
L	2.0 5	
K_1	0.01 0.2	
K_2	0.01 0.1	
K_p	0.01 0.1	
PWP	90 180	

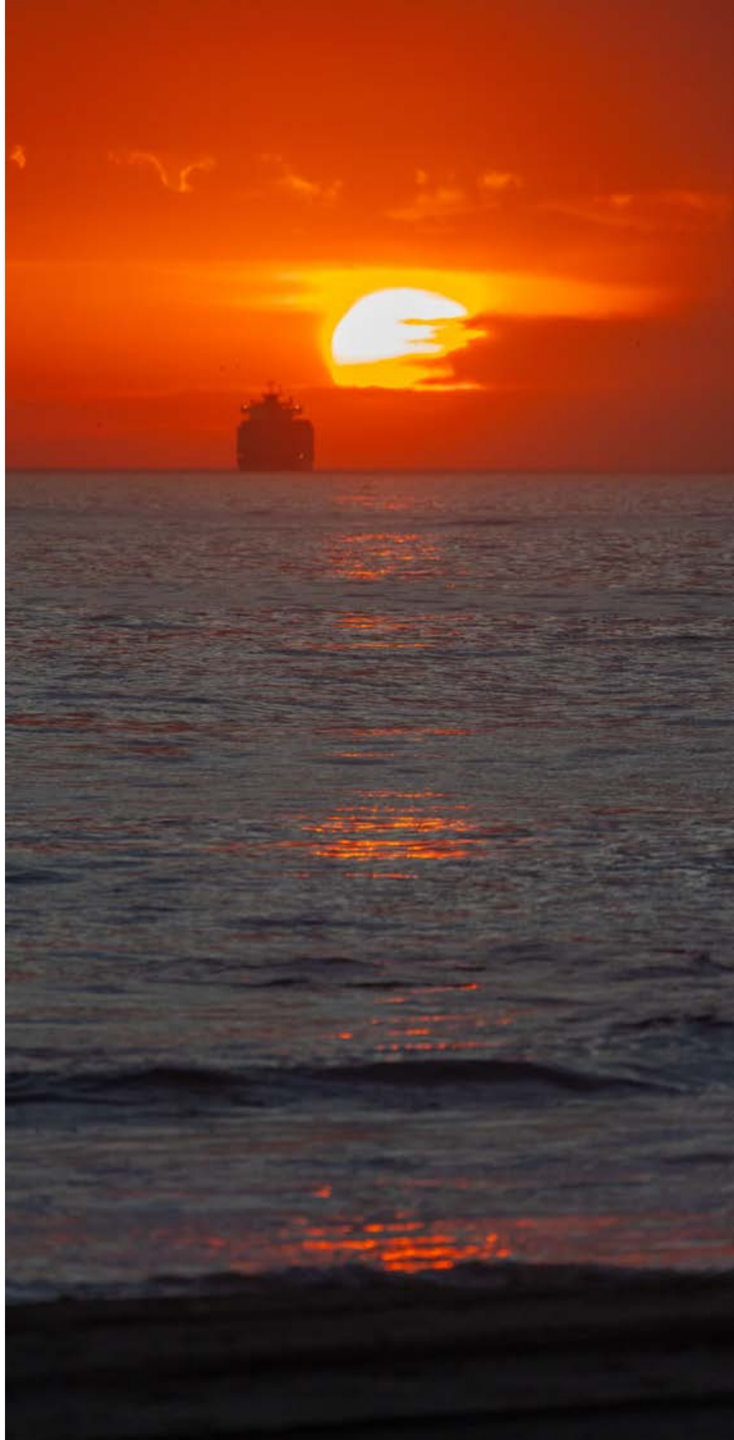
Watershed Area & Snow Melt Thr.
Area 410
T_1 0
Snow 0.0
Soil Moisture 100.0
S_1 2.0
S_2 200.0

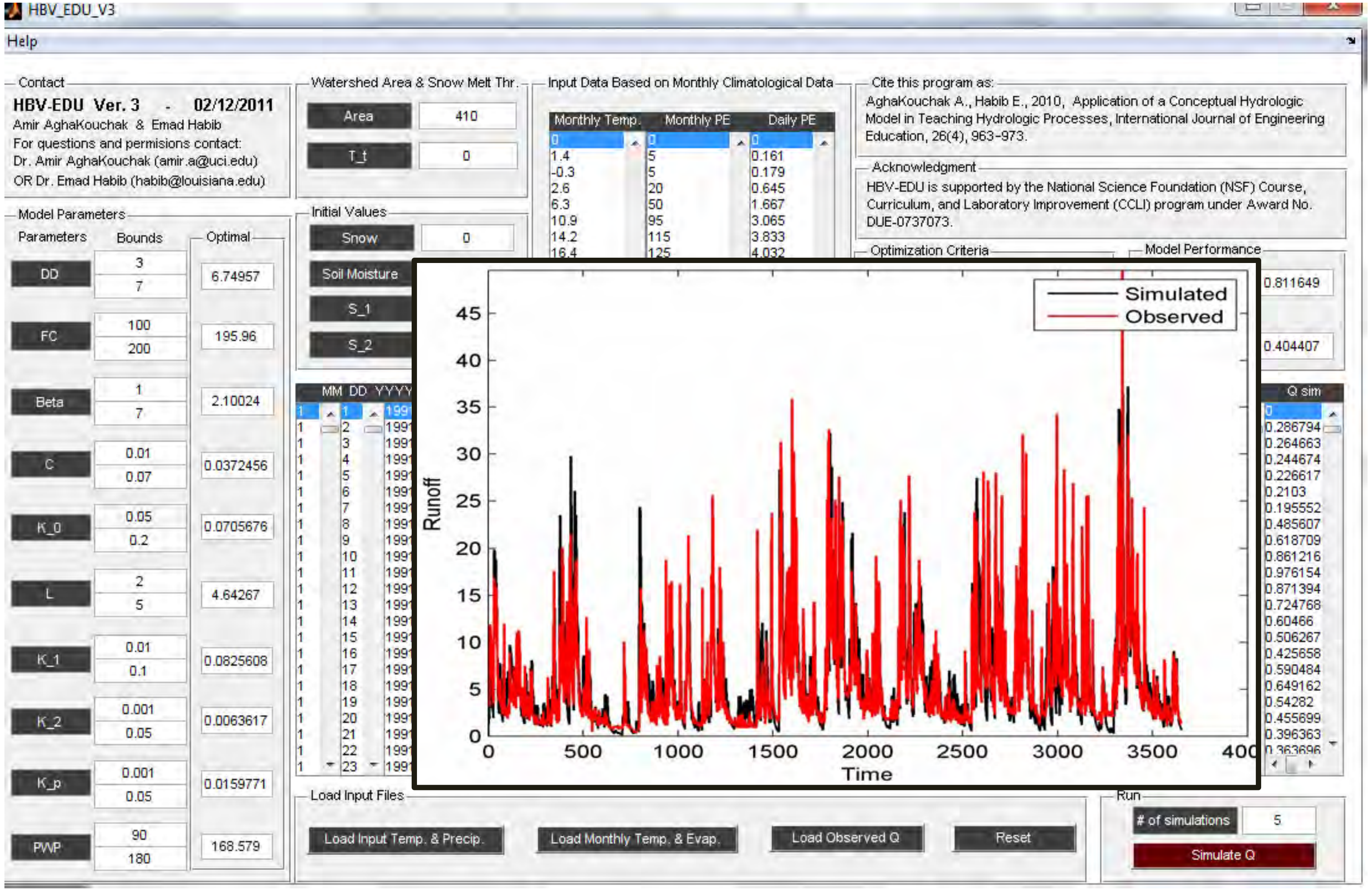
Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

Acknowledgment
HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Optimization Criteria: Qrmse (Root Mean Square Error)

\# of simulations 50





HBV-EDU Ver. 3 - 02/12/2011
Amir AghaKouchak & Emad Habib
For questions and permisions contact:
Dr. Amir AghaKouchak (amir.a@uci.edu)
OR Dr. Emad Habib (habib@louisiana.edu)

Area: 410
T_t: 0
Snow: 0

Monthly Temp.	Monthly PE	Daily PE
0	0	0
1.4	5	0.161
-0.3	5	0.179
2.6	20	0.645
6.3	50	1.667
10.9	95	3.065
14.2	115	3.833
16.4	125	4.032

Cite this program as:
AghaKouchak A., Habib E., 2010, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, International Journal of Engineering Education, 26(4), 963-973.

Acknowledgment
HBV-EDU is supported by the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. DUE-0737073.

Model Performance: 0.811649; 0.404407

Parameters	Bounds	Optimal
DD	3 7	6.74957
FC	100 200	195.96
Beta	1 7	2.10024
C	0.01 0.07	0.0372456
K_0	0.05 0.2	0.0705676
L	2 5	4.64267
K_1	0.01 0.1	0.0825608
K_2	0.001 0.05	0.0063617
K_p	0.001 0.05	0.0159771
PWP	90 180	168.579

MM	DD	YYYY
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1	2	1991
1	3	1991
1	4	1991
1	5	1991
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1	11	1991
1	12	1991
1	13	1991
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1	19	1991
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1	21	1991
1	22	1991
1	23	1991

Q sim
0
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0.264663
0.244674
0.226617
0.2103
0.195552
0.485607
0.618709
0.861216
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0.724768
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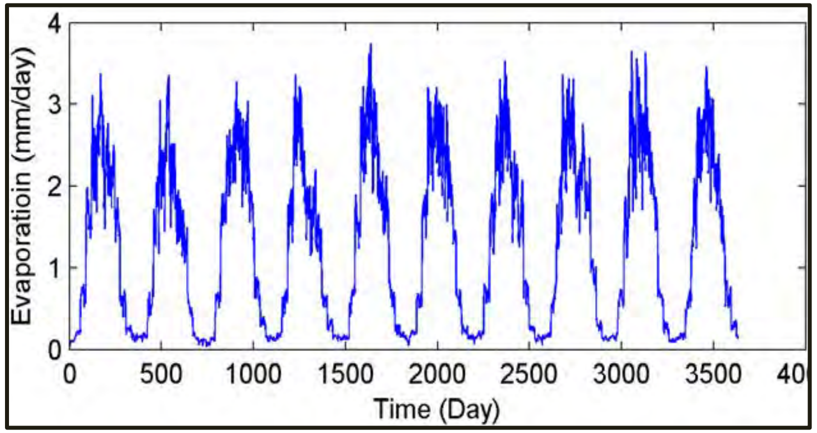
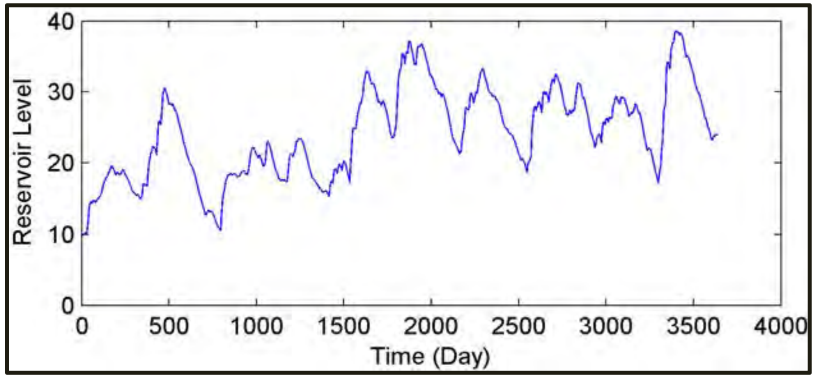
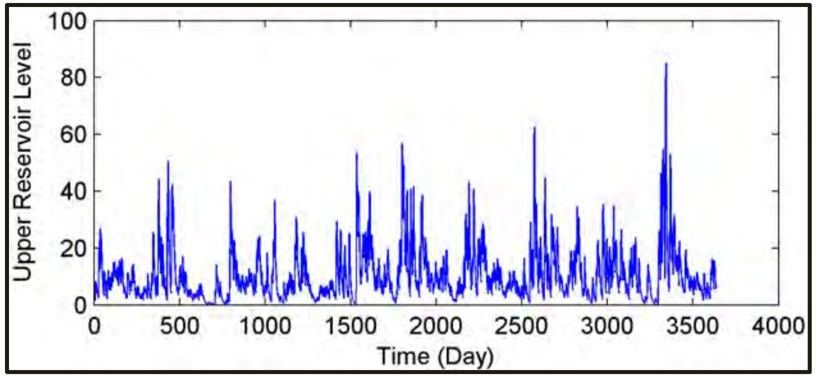
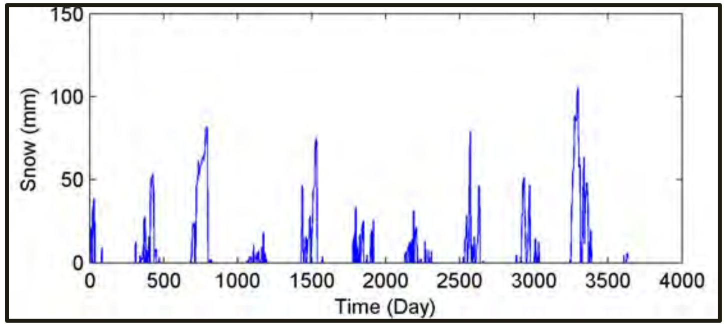
0.363696

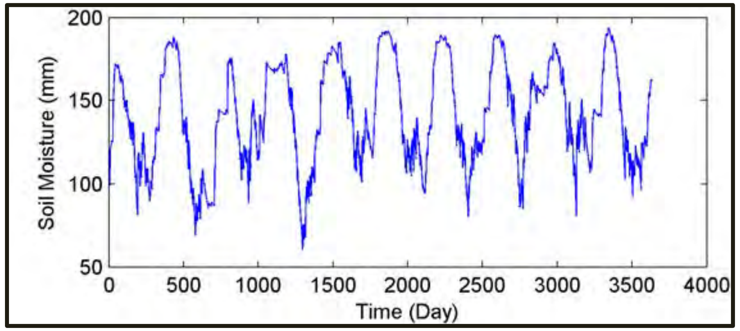
# of simulations: 5

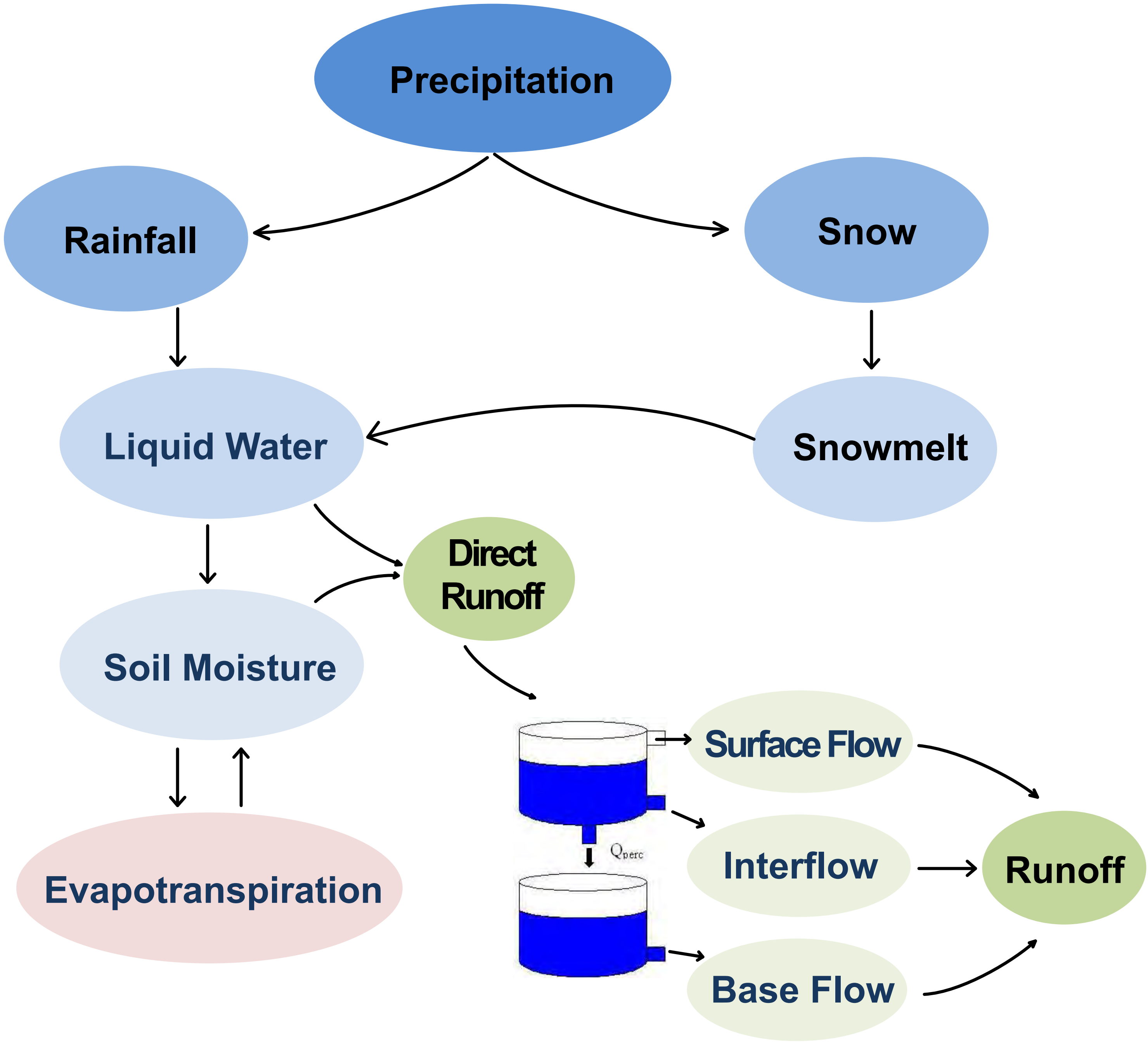












Precipitation

Rainfall

Snow

Liquid Water

Snowmelt

Direct Runoff

Soil Moisture

Evapotranspiration

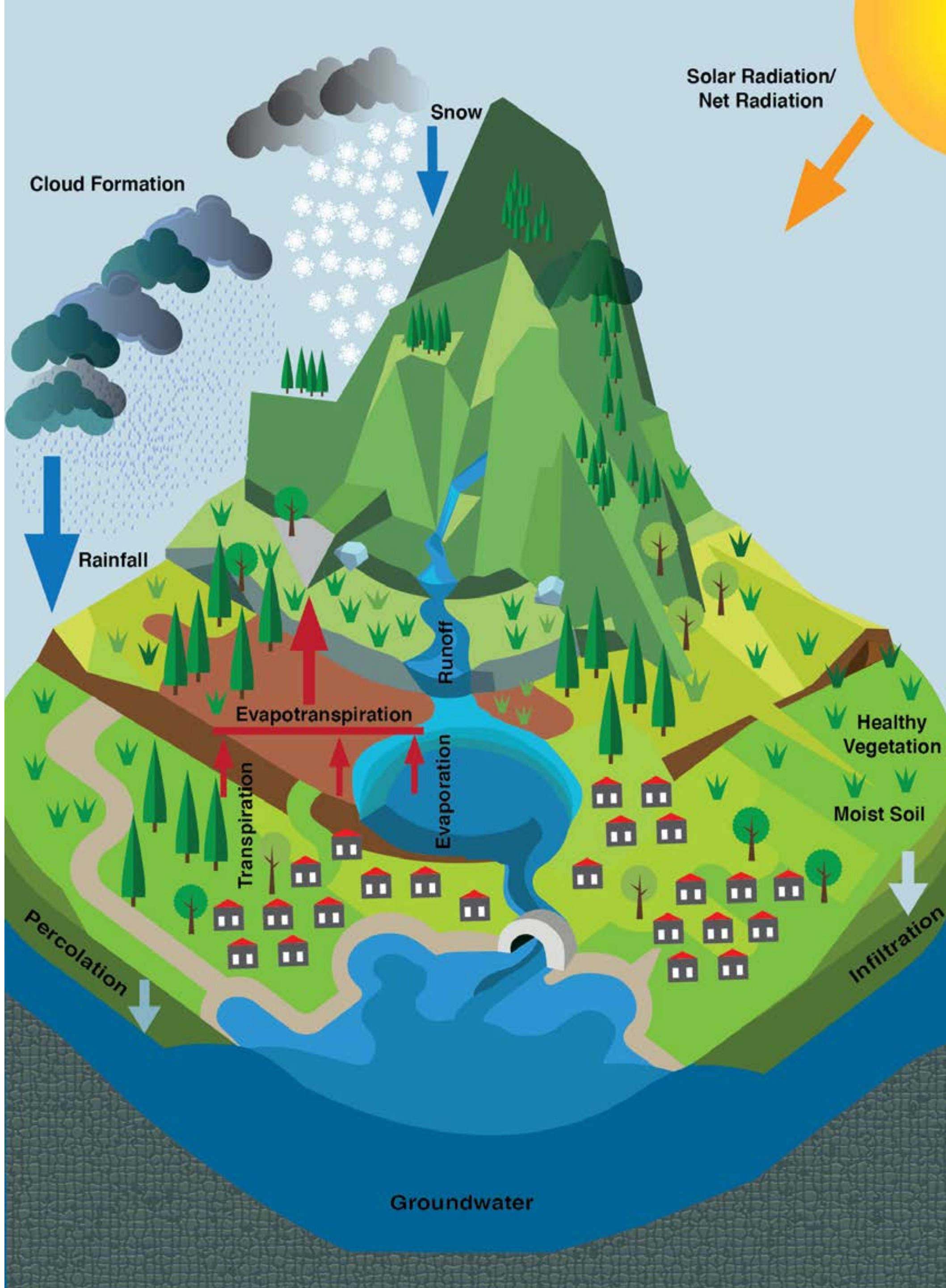
Surface Flow

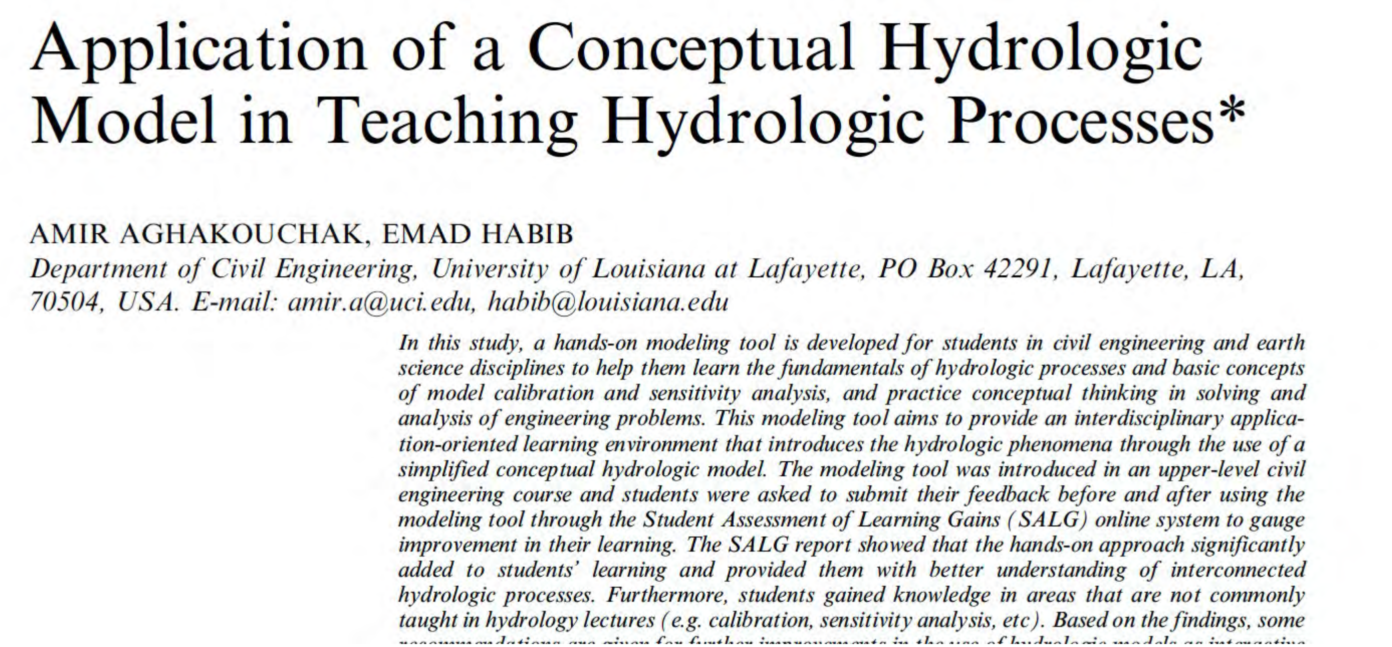
Interflow

Base Flow

Runoff

Q_{perc}





Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes*

AMIR AGHAKOUCHAK, EMAD HABIB
Department of Civil Engineering, University of Louisiana at Lafayette, PO Box 42291, Lafayette, LA, 70504, USA. E-mail: amir.a@uci.edu, habib@louisiana.edu

In this study, a hands-on modeling tool is developed for students in civil engineering and earth science disciplines to help them learn the fundamentals of hydrologic processes and basic concepts of model calibration and sensitivity analysis, and practice conceptual thinking in solving and analysis of engineering problems. This modeling tool aims to provide an interdisciplinary application-oriented learning environment that introduces the hydrologic phenomena through the use of a simplified conceptual hydrologic model. The modeling tool was introduced in an upper-level civil engineering course and students were asked to submit their feedback before and after using the modeling tool through the Student Assessment of Learning Gains (SALG) online system to gauge improvement in their learning. The SALG report showed that the hands-on approach significantly added to students' learning and provided them with better understanding of interconnected hydrologic processes. Furthermore, students gained knowledge in areas that are not commonly taught in hydrology lectures (e.g. calibration, sensitivity analysis, etc). Based on the findings, some

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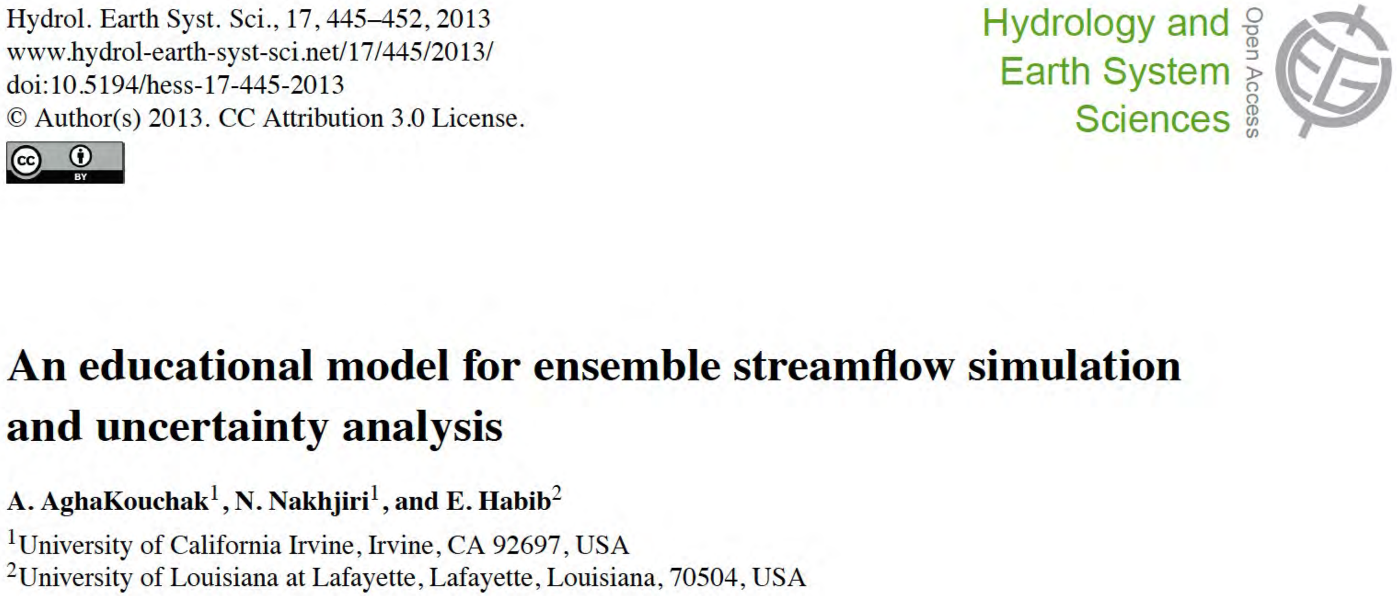


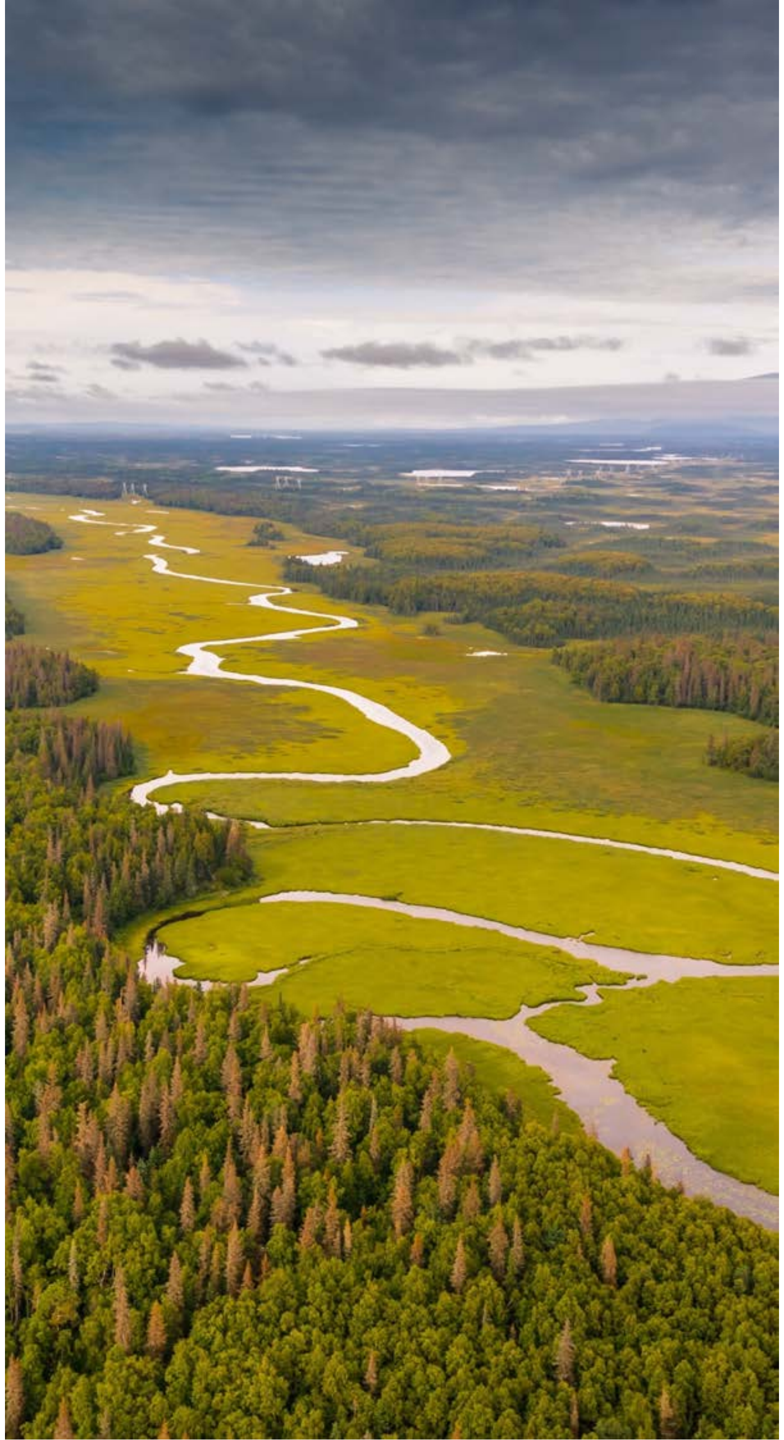
Hydrol. Earth Syst. Sci., 17, 445–452, 2013
www.hydrol-earth-syst-sci.net/17/445/2013/
doi:10.5194/hess-17-445-2013

Hydrology and Earth System Sciences
Open Access

An educational model for ensemble streamflow simulation and uncertainty analysis

A. AghaKouchak[1], N. Nakhjiri[1], and E. Habib[2]

[1]University of California Irvine, Irvine, CA 92697, USA
[2]University of Louisiana at Lafayette, Lafayette, Louisiana, 70504, USA



Part III: Other Tools, Data, & Models

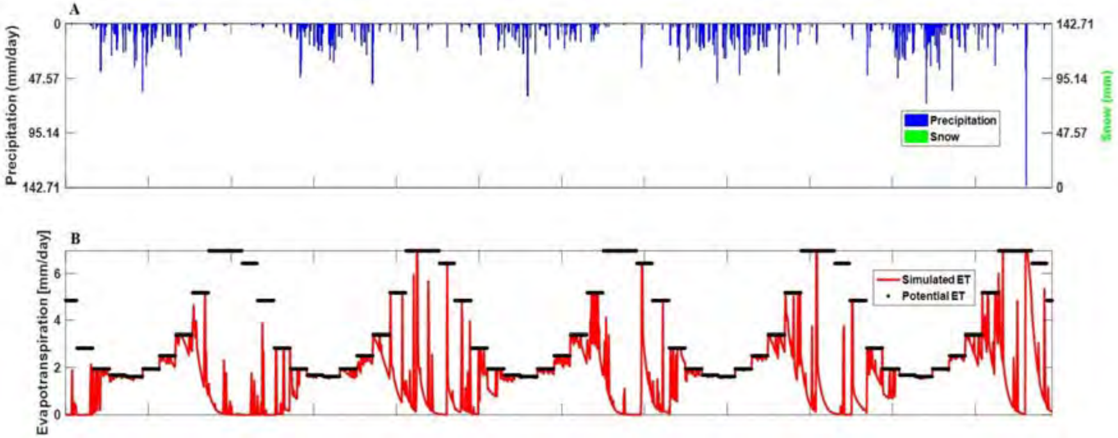
Amir AghaKouchak
University of California, Irvine

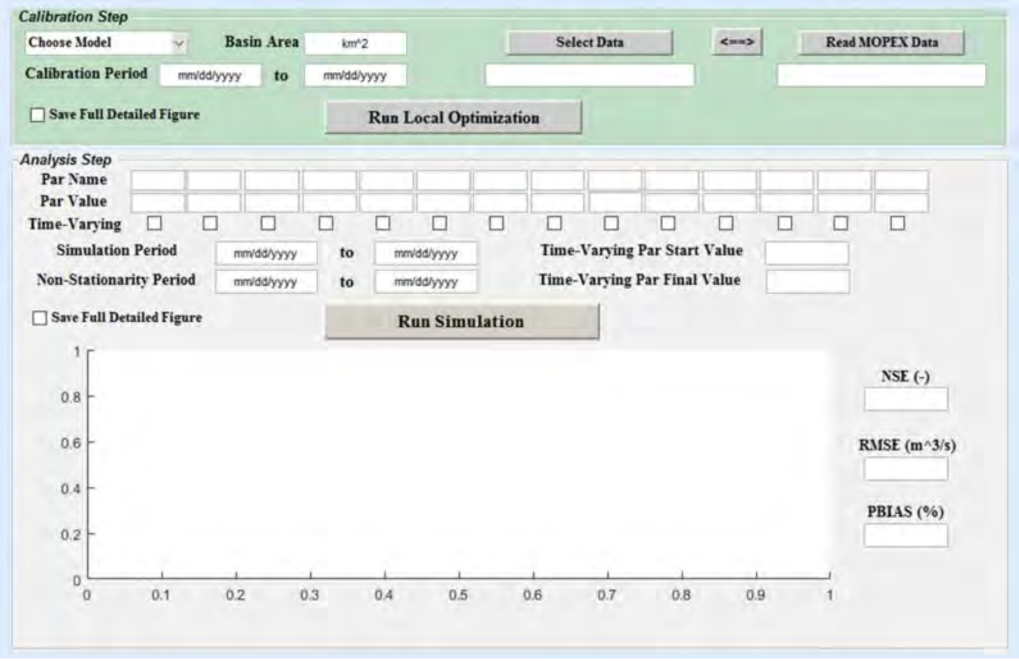
: @AghaKouchak

: @AmirAghaKouchak

A Multi-Model Nonstationary Rainfall-Runoff Modeling Framework: Analysis and Toolbox

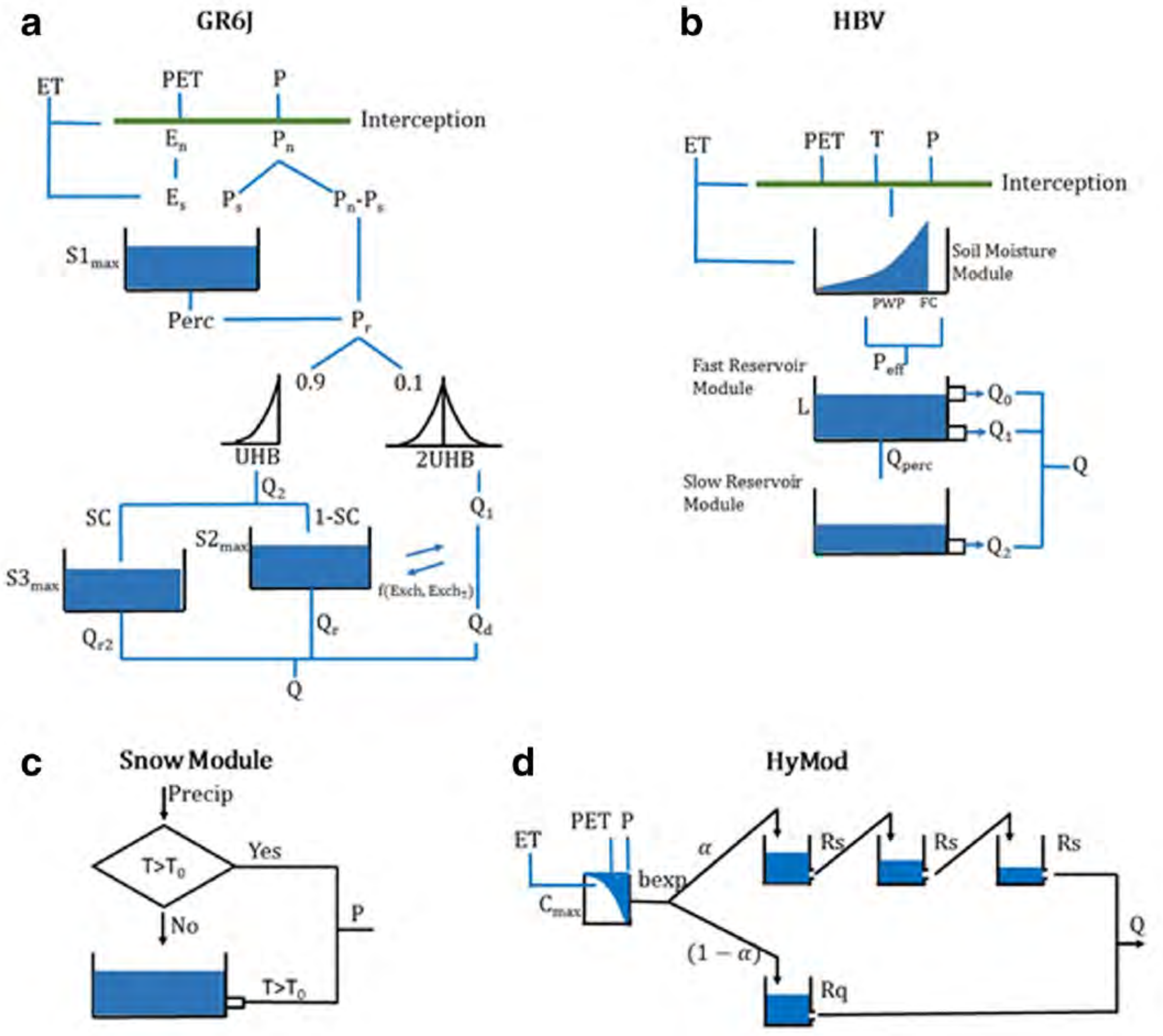
Mojtaba Sadegh[1,2] • Amir AghaKouchak[1] • Alejandro Flores[3] • Iman Mallakpour[1] • Mohammad Reza Nikoo[4]



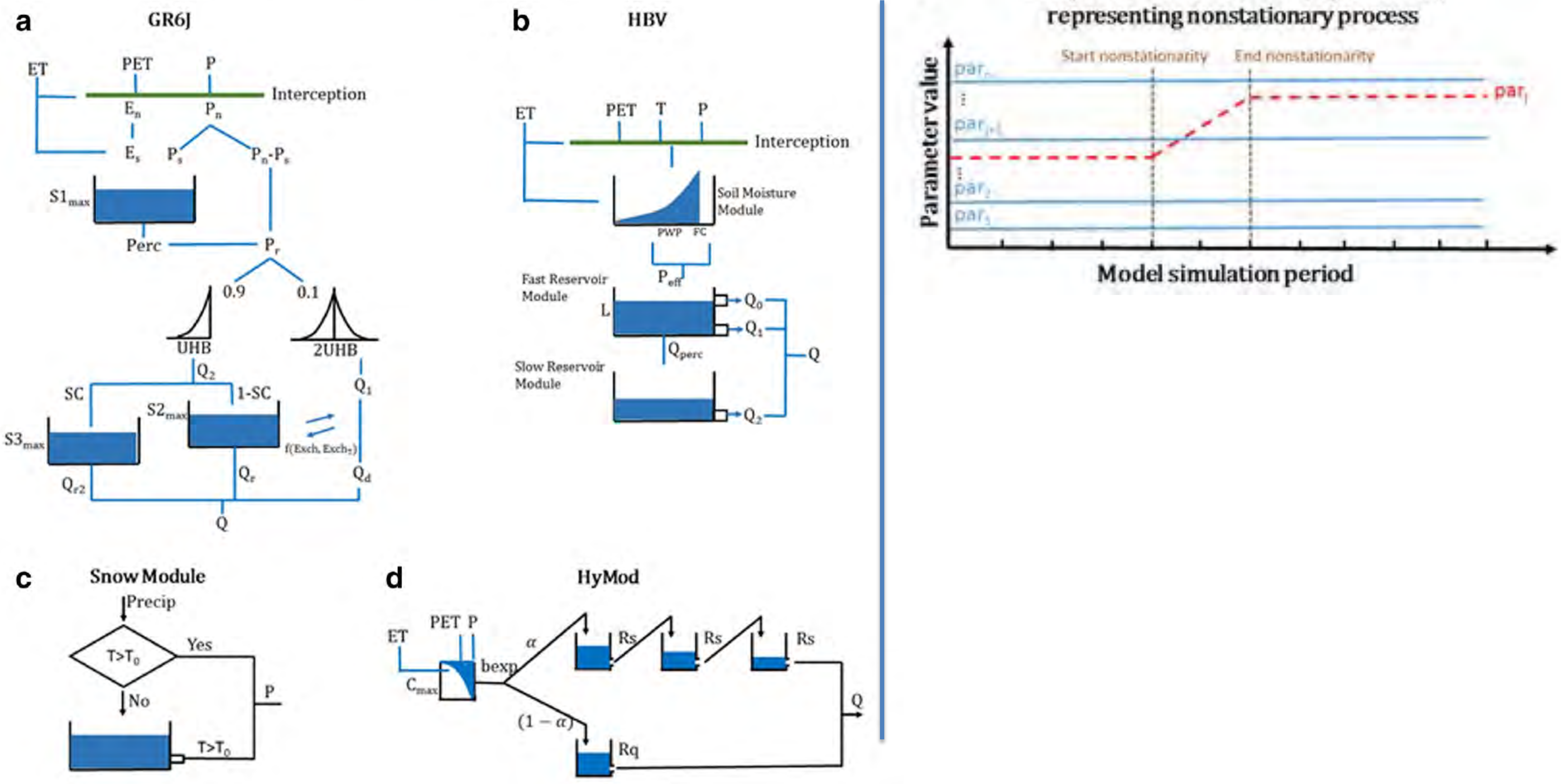


Click Here to Download Toolbox

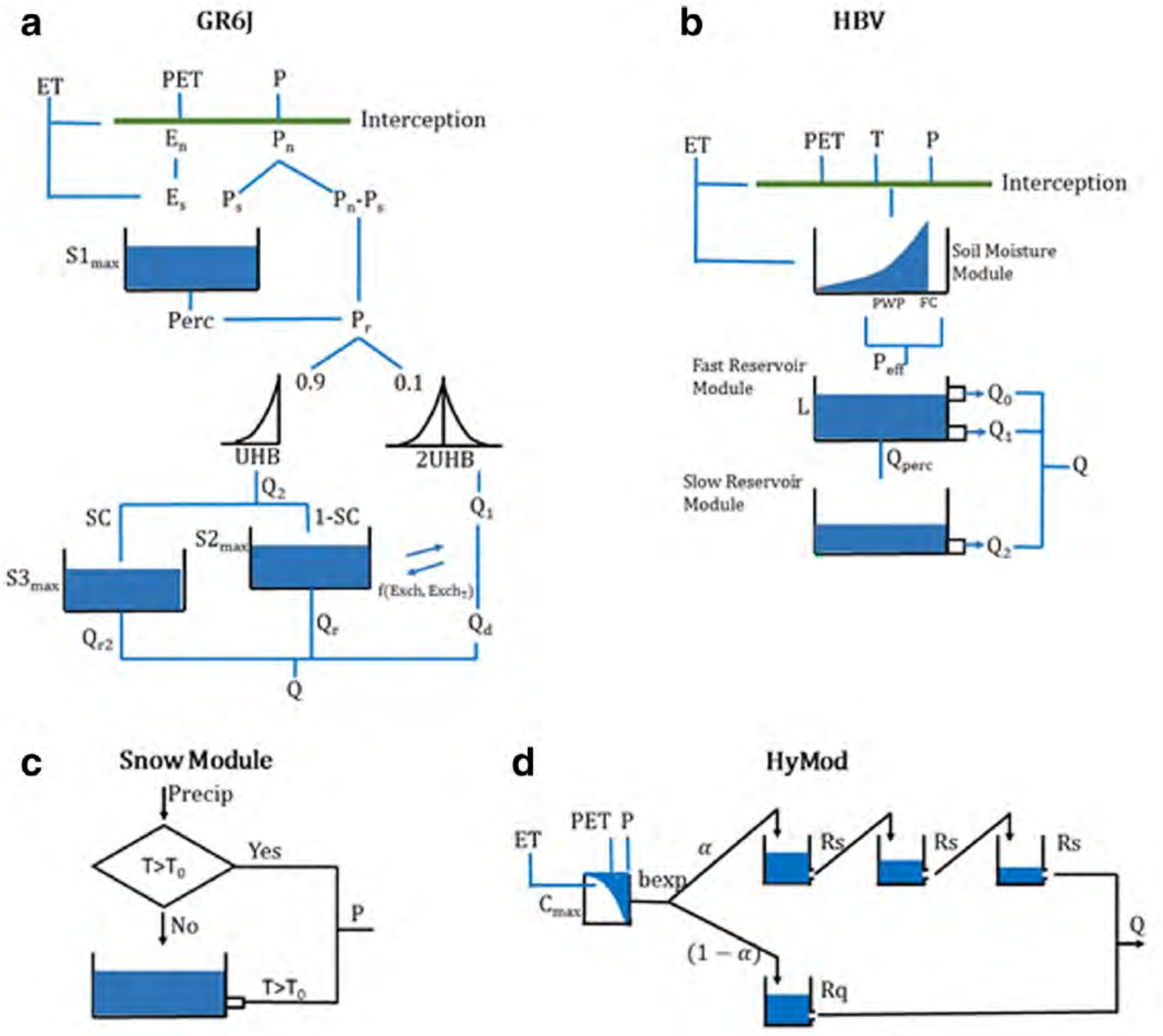
A Multi-Model Nonstationary Rainfall-Runoff Modeling Framework: Analysis and Toolbox

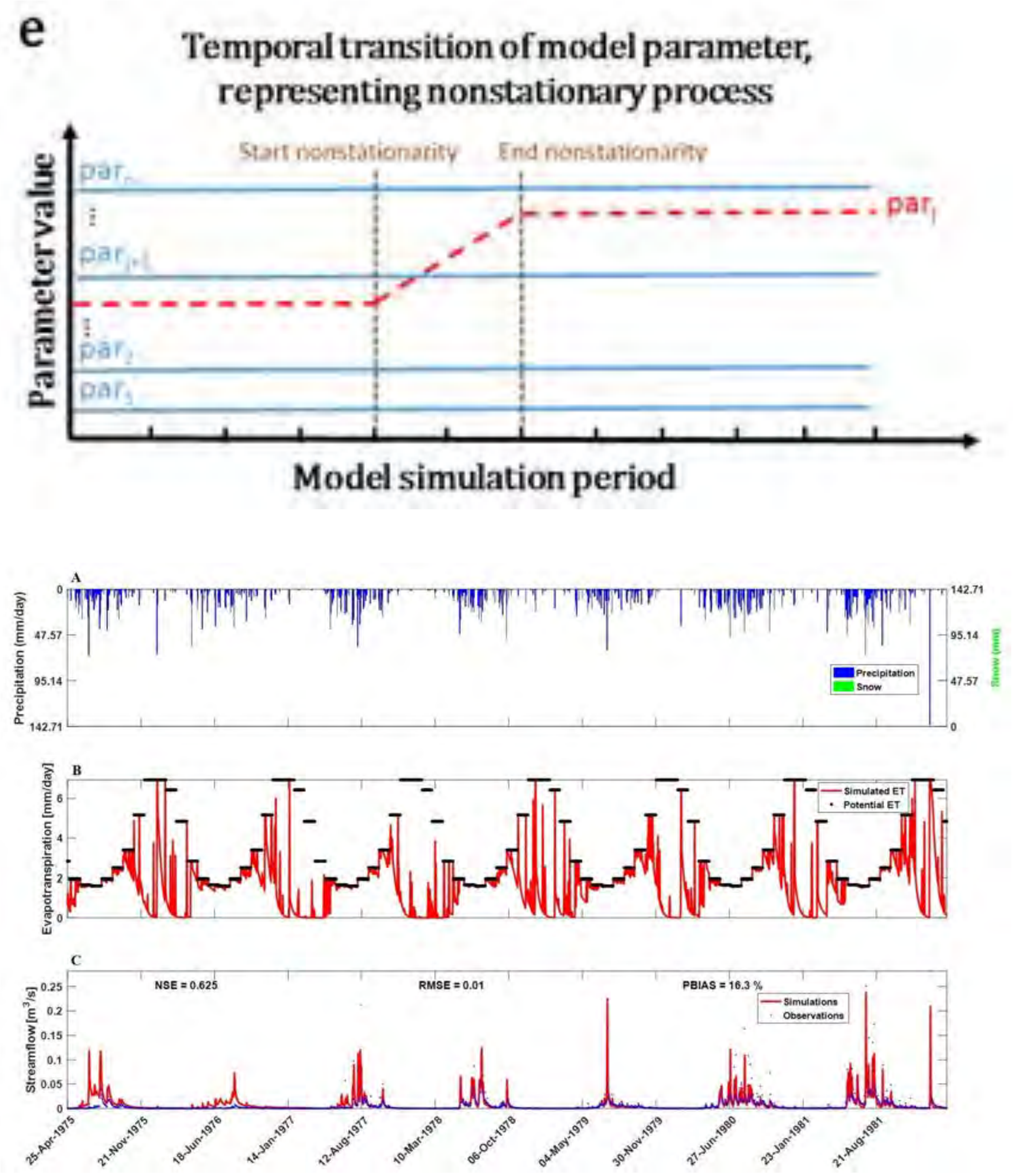


A Multi-Model Nonstationary Rainfall-Runoff Modeling Framework: Analysis and Toolbox



A Multi-Model Nonstationary Rainfall-Runoff Modeling Framework: Analysis and Toolbox





Data

Global Heat Wave Data:

https://www.nature.com/articles/sdata2018206

Global Drought Data:

http://www.nature.com/articles/sdata20141

Global Heat Wave Data:

https://www.nature.com/articles/sdata2018206

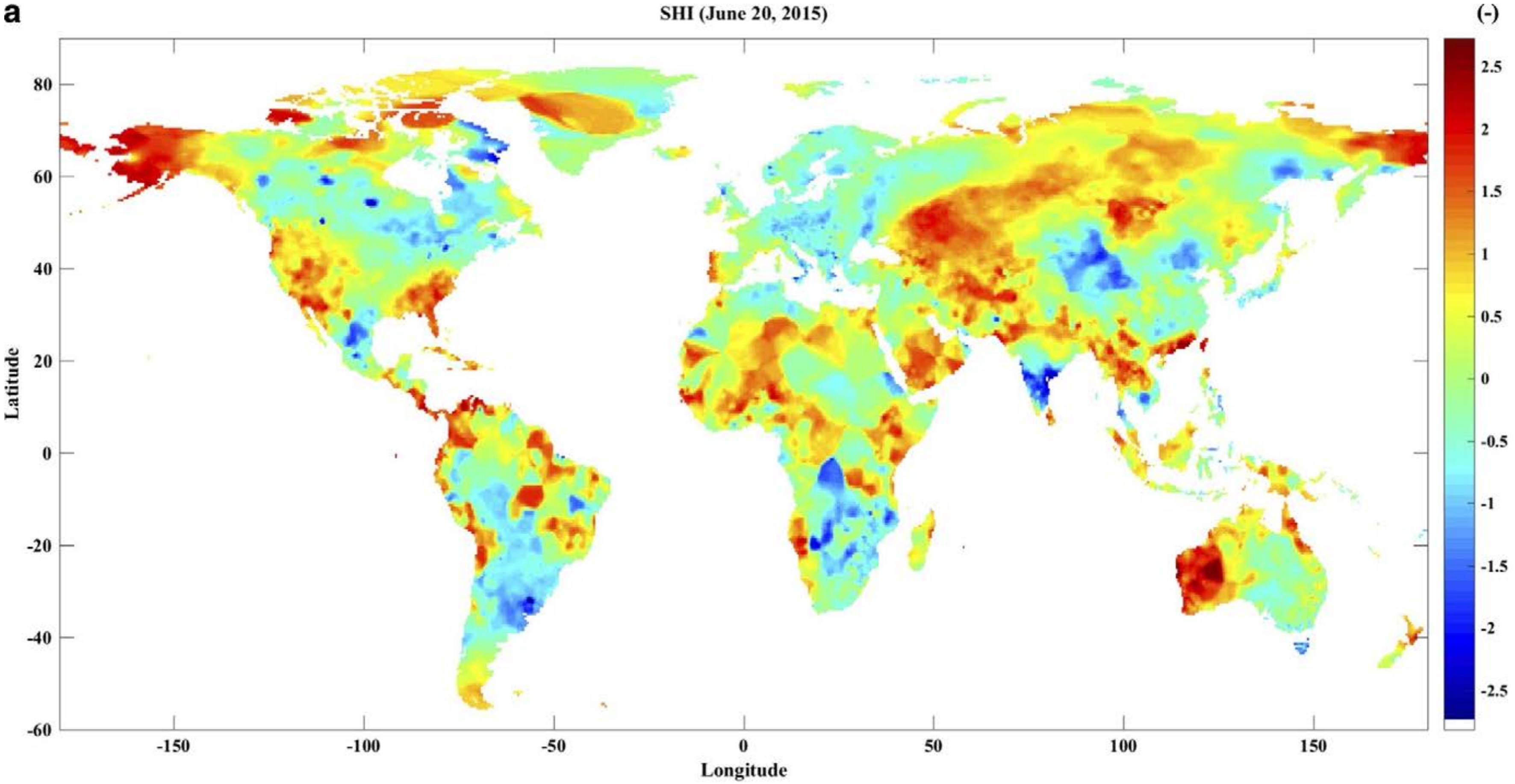
Global Drought Data:

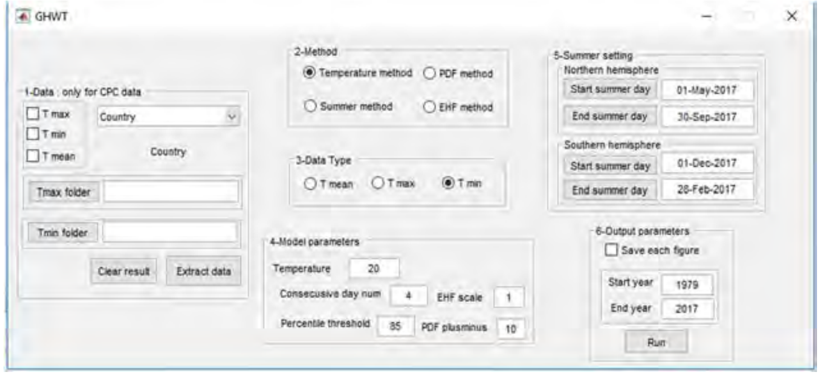
http://www.nature.com/articles/sdata20141

Global Snow Drought Data:

https://figshare.com/collections/Global_Snow_Drought_Data_Set/5055179

GHWR, A Multi-Method Global Heatwave and Warm-Spell Record and Toolbox





1-Data : only for CPC data
☐ T max
☐ T min
☐ T mean
Country: Country

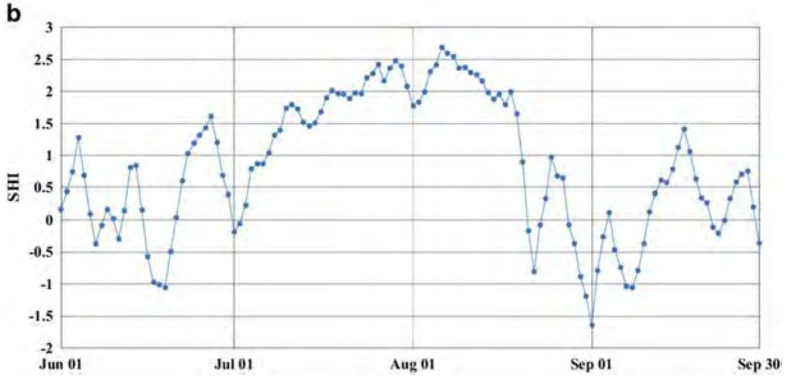
2-Method
● Temperature method ○ PDF method
○ Summer method ○ EHF method

3-Data Type
○ T mean ○ T max ● T min

4-Model parameters
Temperature: 20
Consecusive day num: 4
EHF scale: 1
Percentile threshold: 85
PDF plusminus: 10

5-Summer setting
Northern hemisphere
Start summer day: 01-May-2017
End summer day: 30-Sep-2017
Southern hemisphere
Start summer day: 01-Dec-2017
End summer day: 28-Feb-2017

6-Output parameters
☐ Save each figure
Start year: 1979
End year: 2017

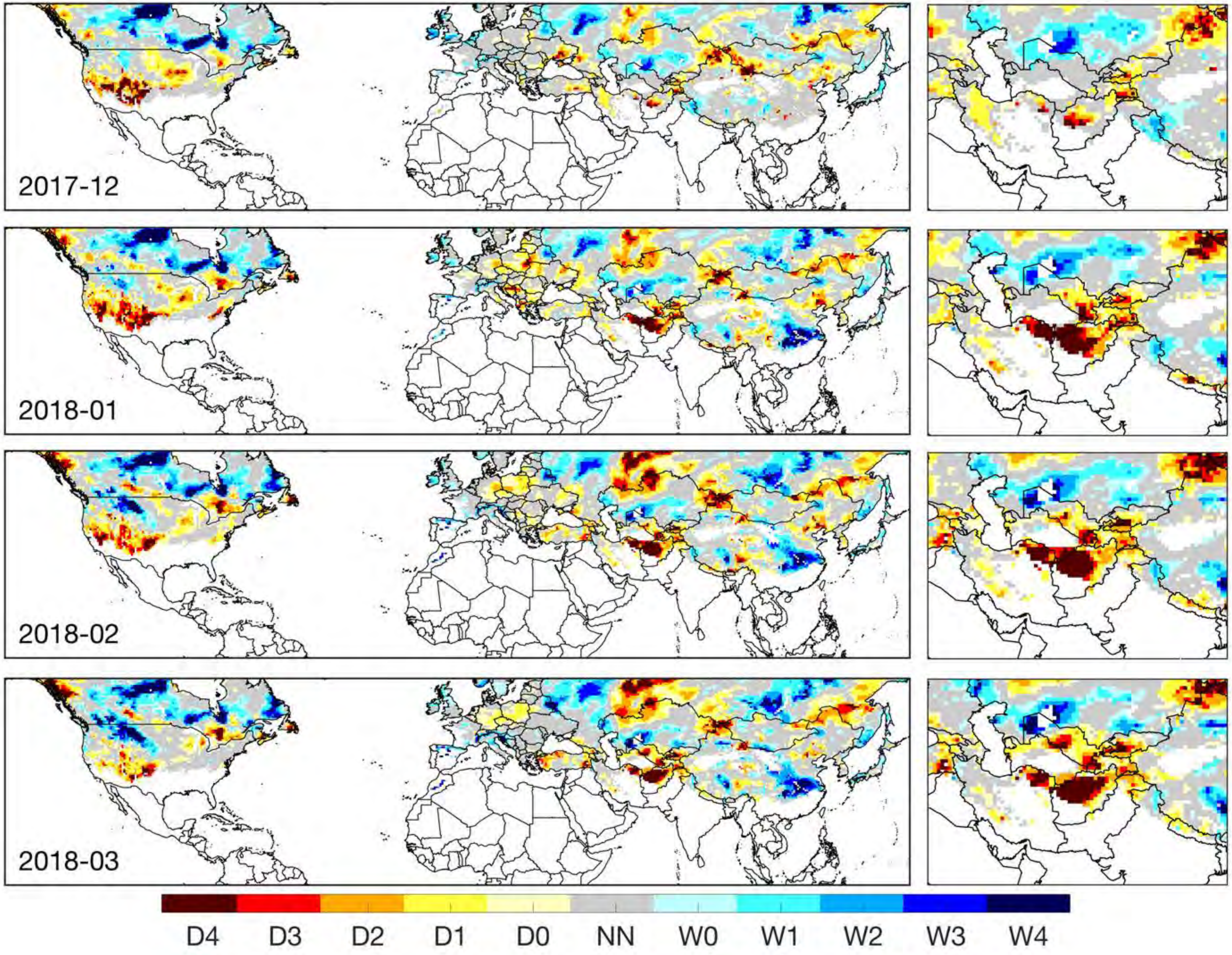


Overarching Question: we introduce a multi-method global heatwave and warm-spell data record and analysis toolbox (named GHWR)

Highlight: GHWR also introduces the standardized heat index (SHI) as a generalized statistical metric to identify heatwave/warm-spells.

Data Link: https://www.nature.com/articles/sdata2018206

Raei E., Nikoo M.R., AghaKouchak A., Mazdiyasni O., Sadegh M., 2018, GHWR, A Multi-Method Global Heatwave and Warm-Spell Record and Toolbox, *Scientific Data*, 119, 188-196



Global Snow Drought Hotspots and Characteristics

Overarching Question: How do snow drought characteristics vary across the globe over the last 40 years?

Highlight: Snow droughts or snow water equivalent (SWE) deficits became more prevalent, intensified, and lengthened across many parts of the world.

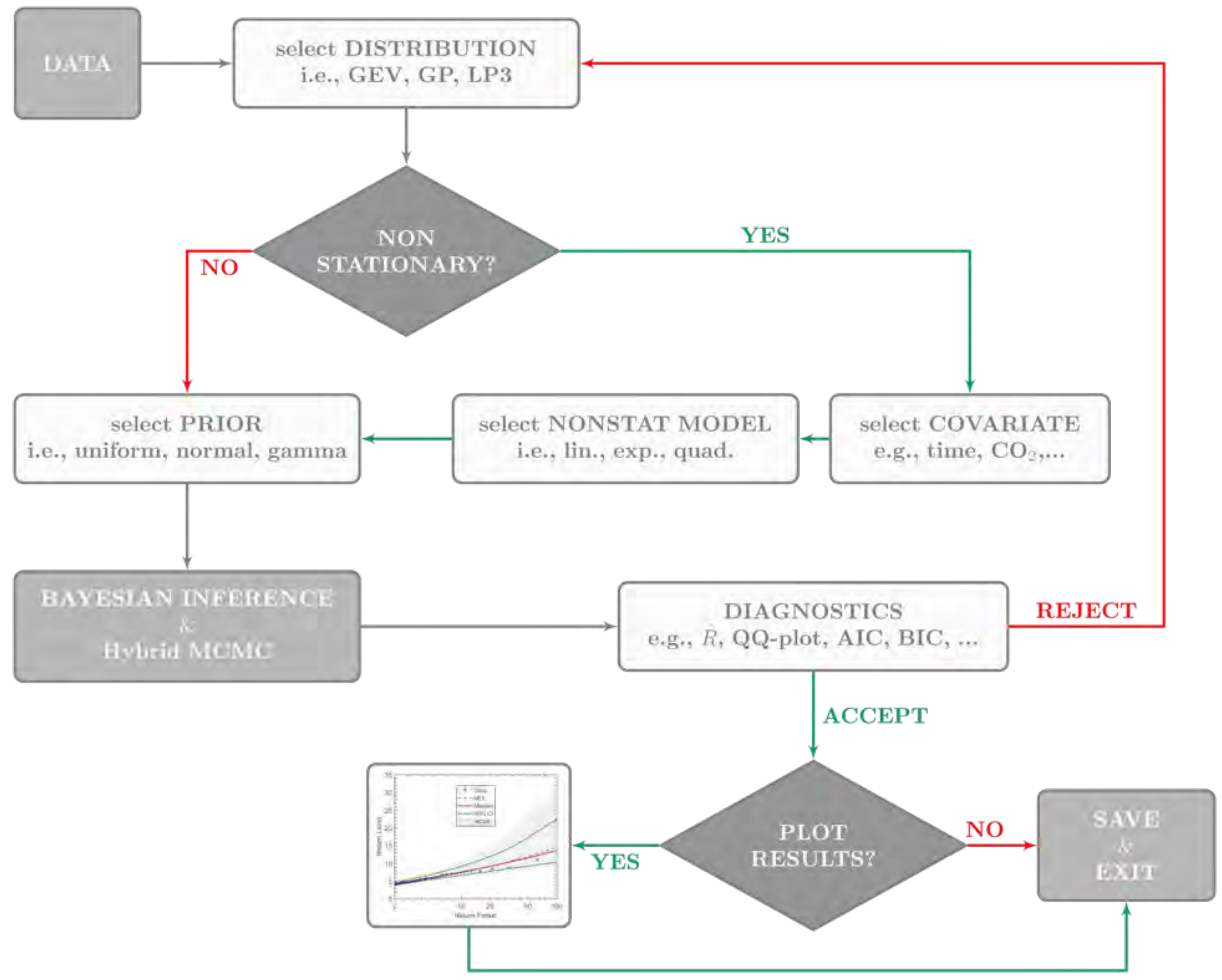
Data Link: https://figshare.com/collections/Global_Snow_Drought_Data_Set/5055179

Huning, L.S. and AghaKouchak, A., 2020. Global snow drought hot spots and characteristics. *Proceedings of the National Academy of Sciences*, *117*(33), pp.19753-19759.

Software & Tools

Process-informed **N**onstationaty **E**xtreme **V**alue **A**nalysis (**ProNEVA**)

ProNEVA Matlab Toolbox



DATA

select DISTRIBUTION
i.e., GEV, GP, LP3

NON STATIONARY?

NO

YES

select PRIOR
i.e., uniform, normal, gamma

select NONSTAT MODEL
i.e., lin., exp., quad.

select COVARIATE
e.g., time, CO_2,...

BAYESIAN INFERENCE
&
Hybrid MCMC

DIAGNOSTICS
e.g., $\hat{R}$, QQ-plot, AIC, BIC, ...

REJECT

ACCEPT

PLOT RESULTS?

YES

NO

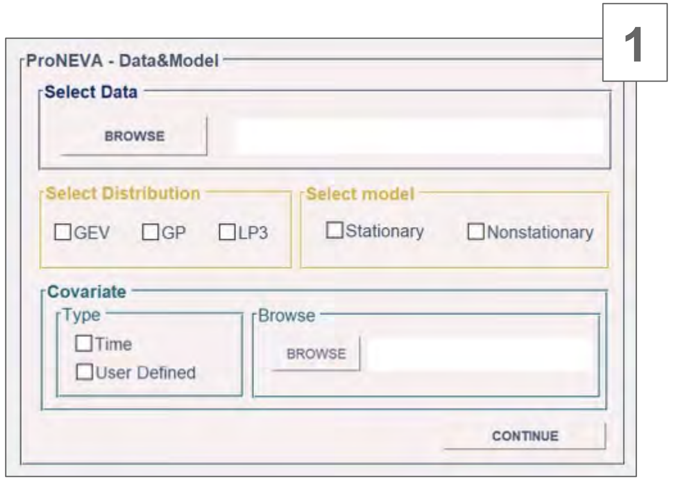
SAVE
&
EXIT

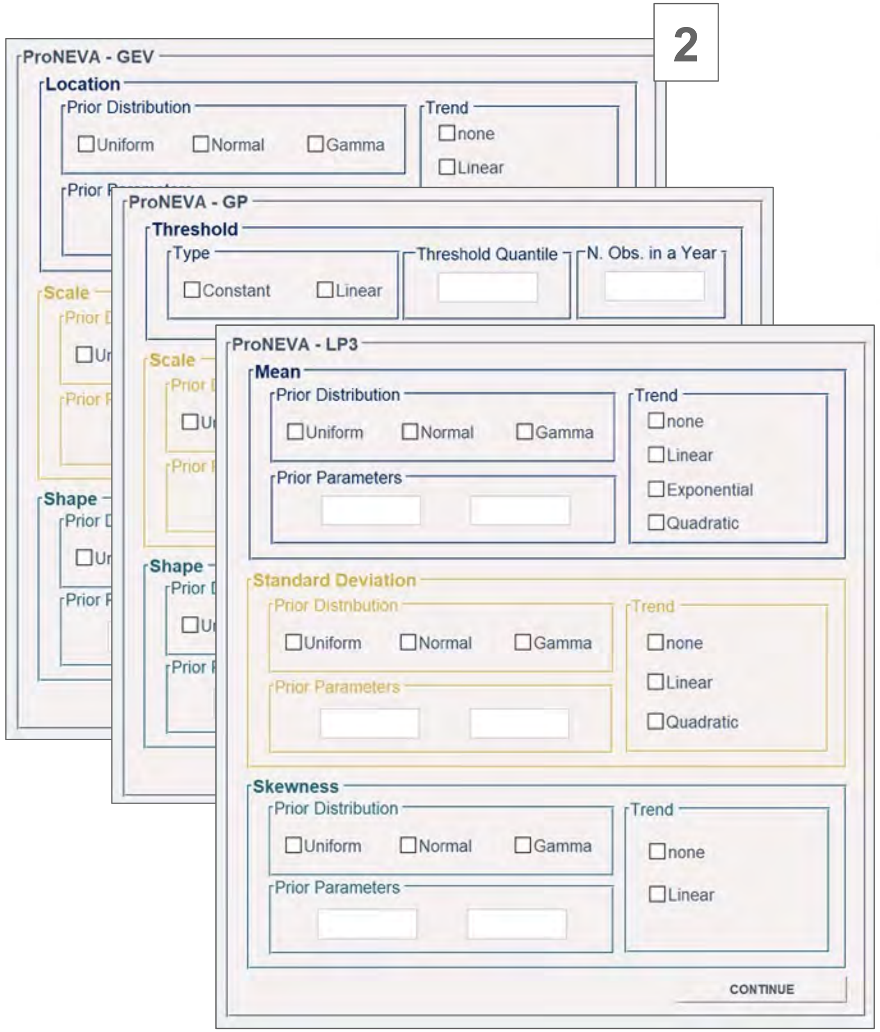
Process-informed Nonstationary Extreme Value Analysis (**ProNEVA**) is a software package designed to facilitate extreme value analysis under both stationary and nonstationary assumptions. The source code of the toolbox is freely available along with a Graphical User Interface (GUI) – Ragno et al., 2019, *AWR*.

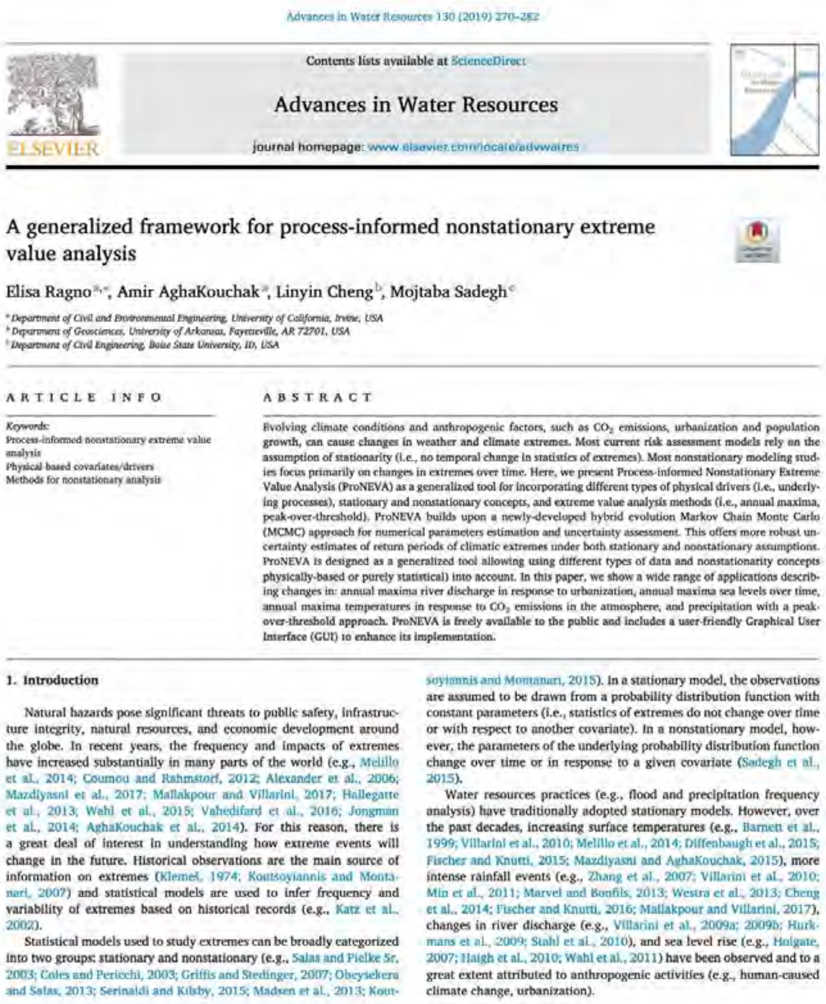
[Link to Download ProNEVA]

Process-informed **N**onstationaty **E**xtreme **V**alue **A**nalysis (ProNEVA)

ProNEVA Matlab Toolbox **GUI**







Advances in Water Resources 130 (2019) 270–282

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journal homepage: www.elsevier.com/locate/advwatres

A generalized framework for process-informed nonstationary extreme value analysis

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A R T I C L E   I N F O

Keywords:
Process-informed nonstationary extreme value analysis
Physical-based covariates/drivers
Methods for nonstationary analysis

A B S T R A C T

Evolving climate conditions and anthropogenic factors, such as CO_2 emissions, urbanization and population growth, can cause changes in weather and climate extremes. Most current risk assessment models rely on the assumption of stationarity (i.e., no temporal change in statistics of extremes). Most nonstationary modeling studies focus primarily on changes in extremes over time. Here, we present Process-informed Nonstationary Extreme Value Analysis (ProNEVA) as a generalized tool for incorporating different types of physical drivers (i.e., underlying processes), stationary and nonstationary concepts, and extreme value analysis methods (i.e., annual maxima, peak-over-threshold). ProNEVA builds upon a newly-developed hybrid evolution Markov Chain Monte Carlo (MCMC) approach for numerical parameters estimation and uncertainty assessment. This offers more robust uncertainty estimates of return periods of climatic extremes under both stationary and nonstationary assumptions. ProNEVA is designed as a generalized tool allowing using different types of data and nonstationarity concepts physically-based or purely statistical) into account. In this paper, we show a wide range of applications describing changes in: annual maxima river discharge in response to urbanization, annual maxima sea levels over time, annual maxima temperatures in response to CO_2 emissions in the atmosphere, and precipitation with a peak-over-threshold approach. ProNEVA is freely available to the public and includes a user-friendly Graphical User Interface (GUI) to enhance its implementation.

1. Introduction

Natural hazards pose significant threats to public safety, infrastructure integrity, natural resources, and economic development around the globe. In recent years, the frequency and impacts of extremes have increased substantially in many parts of the world (e.g., Melillo et al., 2014; Coumou and Rahmstorf, 2012; Alexander et al., 2006; Mazdiyasni et al., 2017; Mallakpour and Villarini, 2017; Hallegatte et al., 2013; Wahl et al., 2015; Vahedifard et al., 2016; Jongman et al., 2014; AghaKouchak et al., 2014). For this reason, there is a great deal of interest in understanding how extreme events will change in the future. Historical observations are the main source of information on extremes (Klemeš, 1974; Koutsoyiannis and Montanari, 2007) and statistical models are used to infer frequency and variability of extremes based on historical records (e.g., Katz et al., 2002).

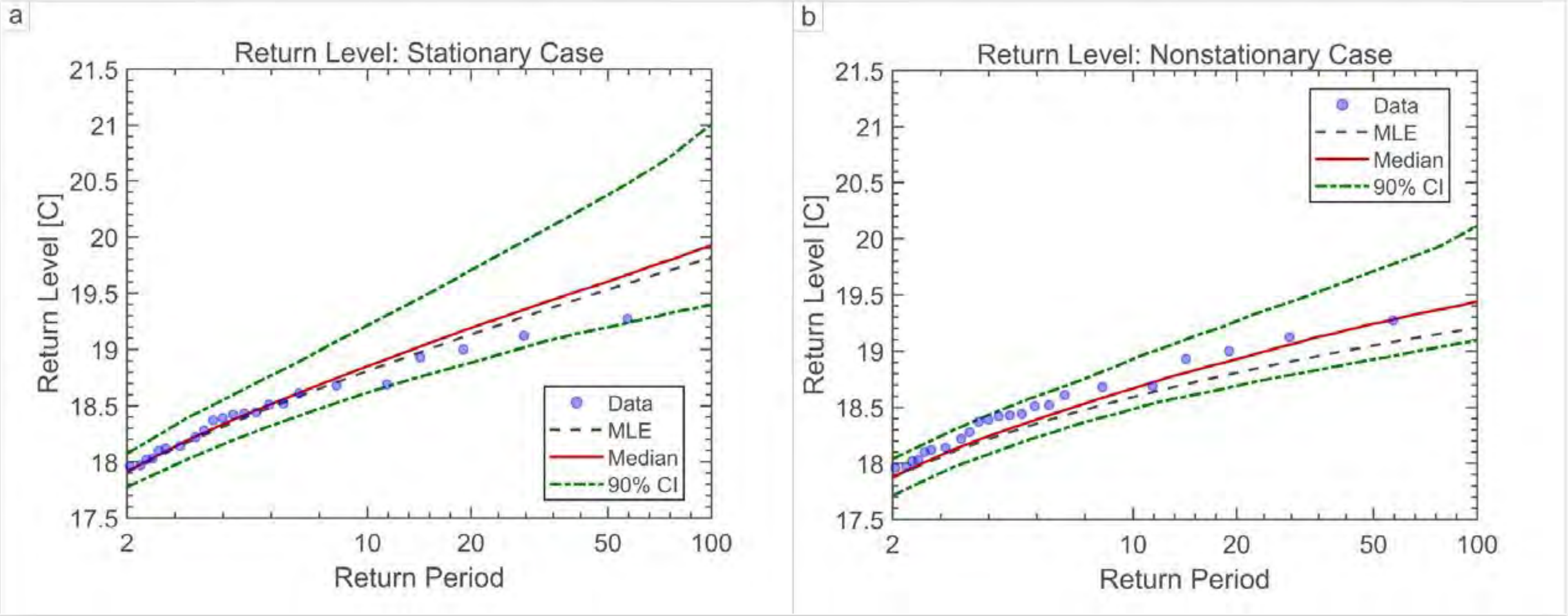
Statistical models used to study extremes can be broadly categorized into two groups: stationary and nonstationary (e.g., Salas and Pielke Sr, 2003; Coles and Pericchi, 2003; Griffis and Stedinger, 2007; Obeysekera and Salas, 2013; Serinaldi and Kilsby, 2015; Madsen et al., 2013; Koutsoyiannis and Montanari, 2015). In a stationary model, the observations are assumed to be drawn from a probability distribution function with constant parameters (i.e., statistics of extremes do not change over time or with respect to another covariate). In a nonstationary model, however, the parameters of the underlying probability distribution function change over time or in response to a given covariate (Sadegh et al., 2015).

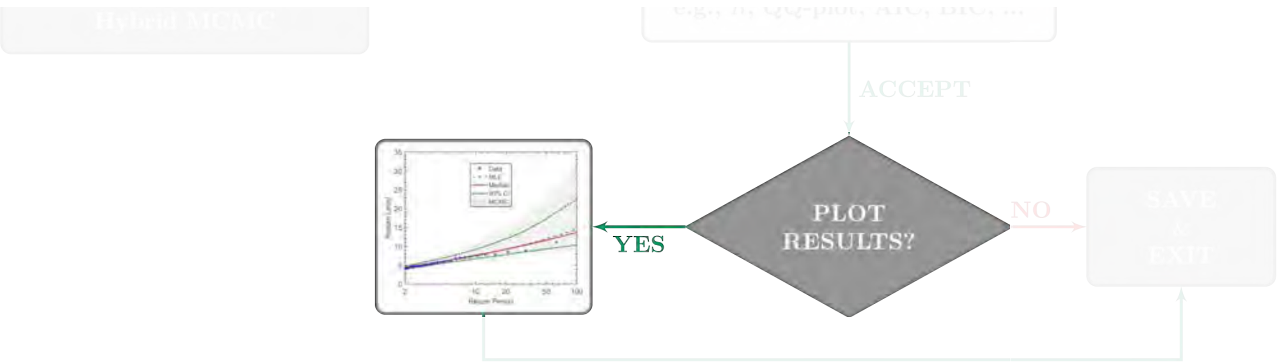
Water resources practices (e.g., flood and precipitation frequency analysis) have traditionally adopted stationary models. However, over the past decades, increasing surface temperatures (e.g., Barnett et al., 1999; Villarini et al., 2010; Melillo et al., 2014; Diffenbaugh et al., 2015; Fischer and Knutti, 2015; Mazdiyasni and AghaKouchak, 2015), more intense rainfall events (e.g., Zhang et al., 2007; Villarini et al., 2010; Min et al., 2011; Marvel and Bonfils, 2013; Westra et al., 2013; Cheng et al., 2014; Fischer and Knutti, 2016; Mallakpour and Villarini, 2017), changes in river discharge (e.g., Villarini et al., 2009a; 2009b; Hurkmans et al., 2009; Stahl et al., 2010), and sea level rise (e.g., Holgate, 2007; Haigh et al., 2010; Wahl et al., 2011) have been observed and to a great extent attributed to anthropogenic activities (e.g., human-caused climate change, urbanization).

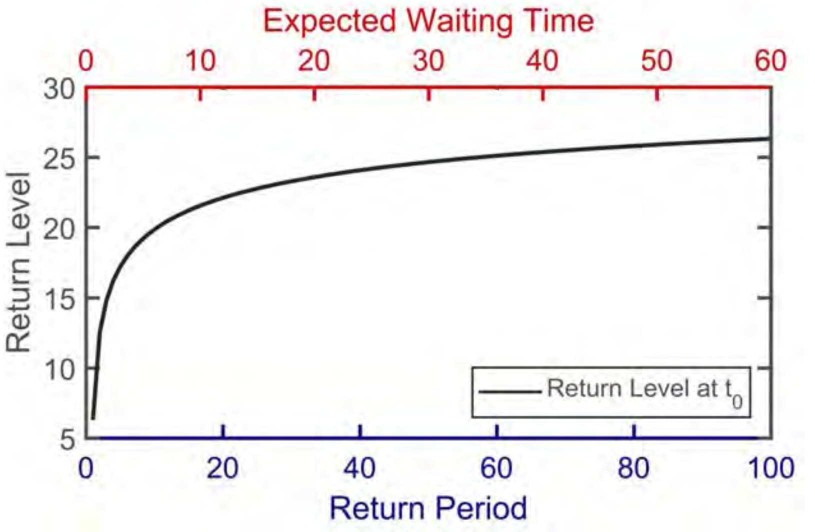
Link to Download ProNEVA

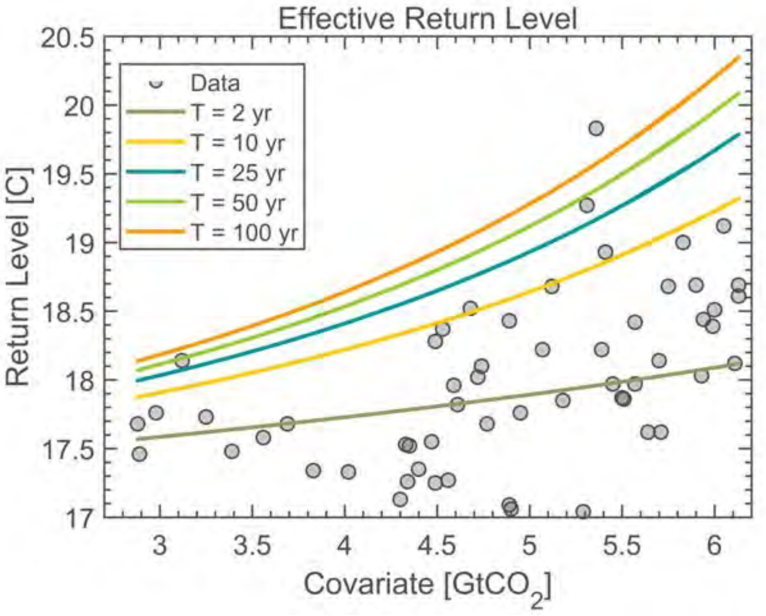
Process-informed **N**onstationaty **E**xtreme **V**alue **A**nalysis (**ProNEVA**)

ProNEVA Matlab Toolbox





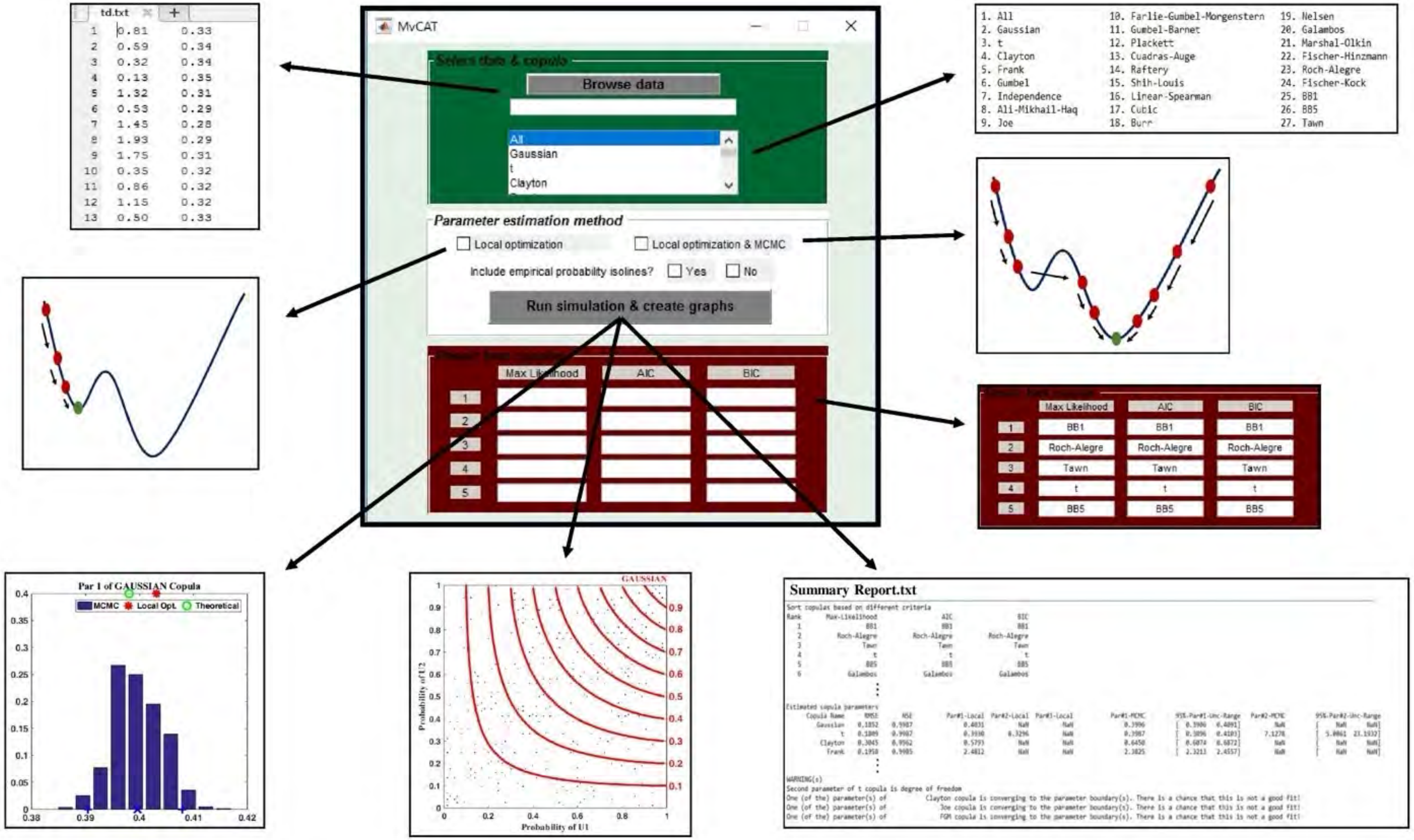




Ragno E., AghaKouchak A., Cheng L., Sadegh, M., 2019, A Generalized Framework for Process-informed Nonstationary Extreme Value Analysis, *Advances in Water Resources*, 130, 270-282.

Multivariate Copula Analysis Toolbox (MvCAT) Link to Download

Multi-hazard Scenario Analysis Toolbox (MhAST) Link to Download



```
0.81   0.33
0.59   0.34
0.32   0.34
0.13   0.35
1.32   0.31
0.53   0.29
1.45   0.28
1.93   0.29
1.75   0.31
0.35   0.32
0.86   0.32
1.15   0.32
0.50   0.33
```

```
1. All                 10. Farlie-Gumbel-Morgenstern   19. Nelsen
2. Gaussian            11. Gumbel-Barnet               20. Galambos
3. t                   12. Plackett                    21. Marshal-Olkin
4. Clayton             13. Cuadras-Auge                22. Fischer-Hinzmann
5. Frank               14. Raftery                     23. Roch-Alegre
6. Gumbel              15. Shih-Louis                  24. Fischer-Kock
7. Independence        16. Linear-Spearman             25. BB1
8. Ali-Mikhail-Haq     17. Cubic                       26. BB5
9. Joe                 18. Burr                        27. Tawn
```

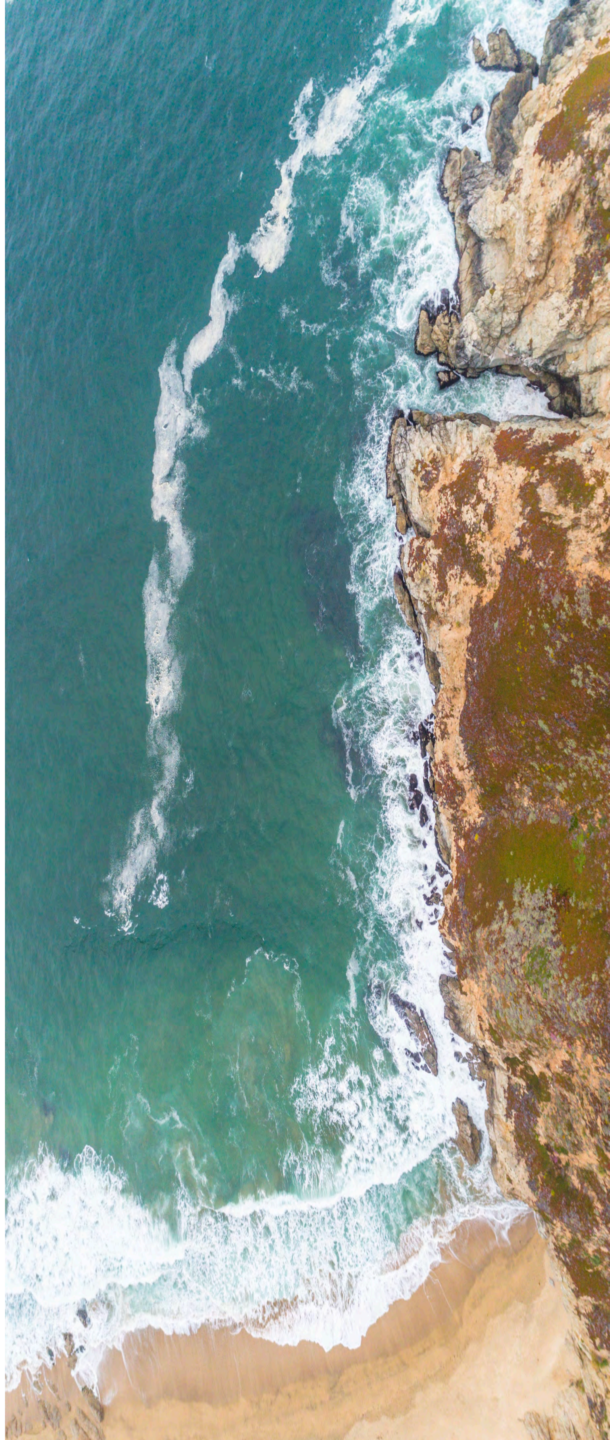
	Max Likelihood	AIC	BIC
1	BB1	BB1	BB1
2	Roch-Alegre	Roch-Alegre	Roch-Alegre
3	Tawn	Tawn	Tawn
4	t	t	t
5	BB5	BB5	BB5

Summary Report.txt

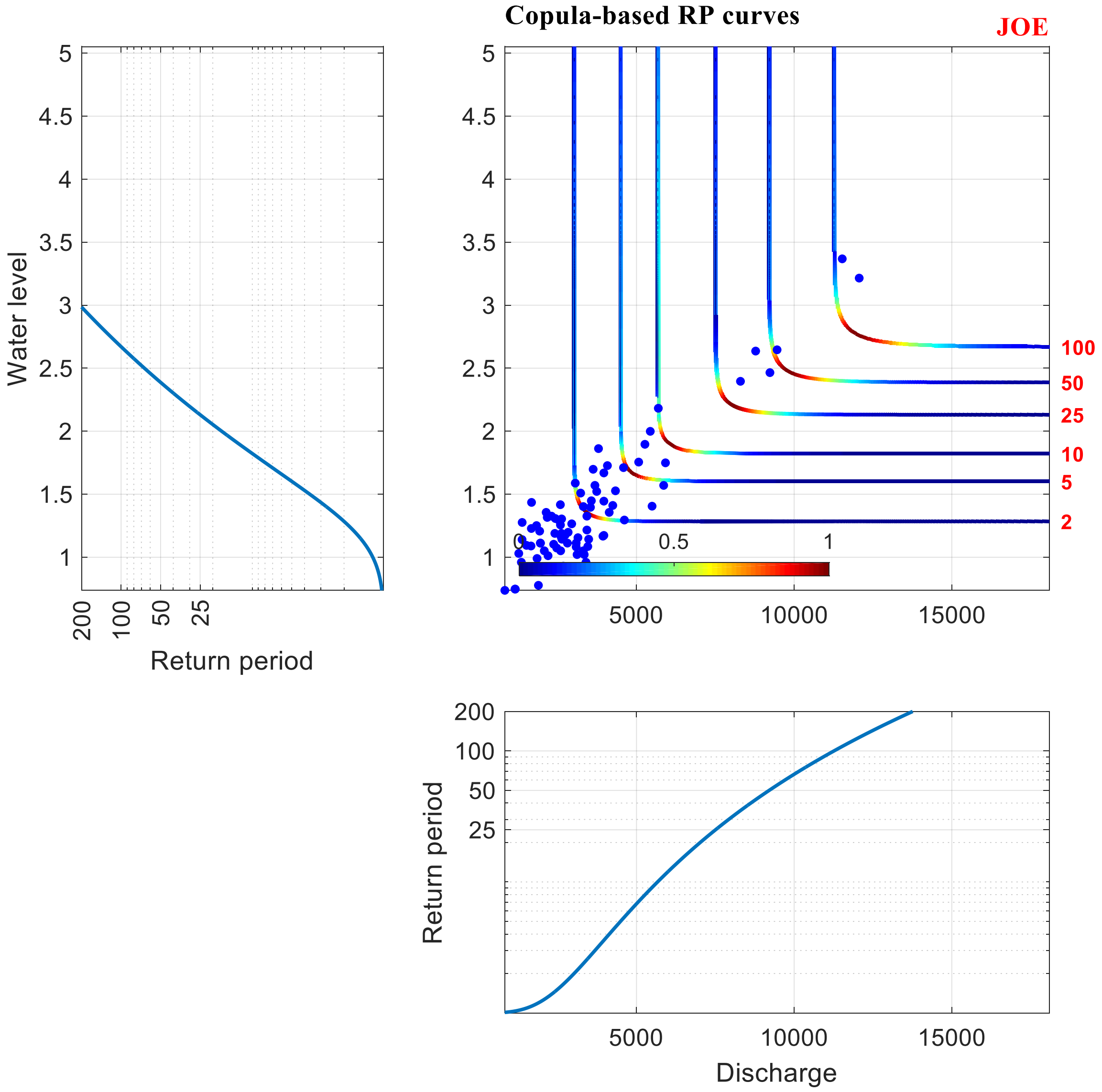
```
Sort copulas based on different criteria
Rank      Max-Likelihood          AIC             BIC
  1                  BB1          BB1             BB1
  2          Roch-Alegre  Roch-Alegre     Roch-Alegre
  3                 Tawn         Tawn            Tawn
  4                    t            t               t
  5                  BB5          BB5             BB5
  6             Galambos     Galambos        Galambos
                       :
Estimated copula parameters
    Copula Name    RMSE     NSE      Par#1-Local  Par#2-Local  Par#3-Local    Par#1-MCMC    95%-Par#1-Unc-Range   Par#2-MCMC    95%-Par#2-Unc-Range
       Gaussian  0.1852  0.9987           0.4031          NaN          NaN        0.3996    [  0.3906   0.4091]          NaN    [     NaN       NaN]
              t  0.1809  0.9987           0.3930       0.3296          NaN        0.3987    [  0.3896   0.4103]       7.1278    [  5.0061   23.1932]
        Clayton  0.3045  0.9962           0.5793          NaN          NaN        0.6450    [  0.6074   0.6872]          NaN    [     NaN       NaN]
          Frank  0.1958  0.9985           2.4812          NaN          NaN        2.3825    [  2.3211   2.4557]          NaN    [     NaN       NaN]
                       :
WARNING(s)
Second parameter of t copula is degree of freedom
One (of the) parameter(s) of          Clayton copula is converging to the parameter boundary(s). There is a chance that this is not a good fit!
One (of the) parameter(s) of              Joe copula is converging to the parameter boundary(s). There is a chance that this is not a good fit!
One (of the) parameter(s) of              FGM copula is converging to the parameter boundary(s). There is a chance that this is not a good fit!
```

Sadegh et al., 2017, *Water Resources Research*

Sadegh et al., 2018, *Geophysical Research Letters*



Multi-hazard Scenario Analysis Toolbox (MhAST)



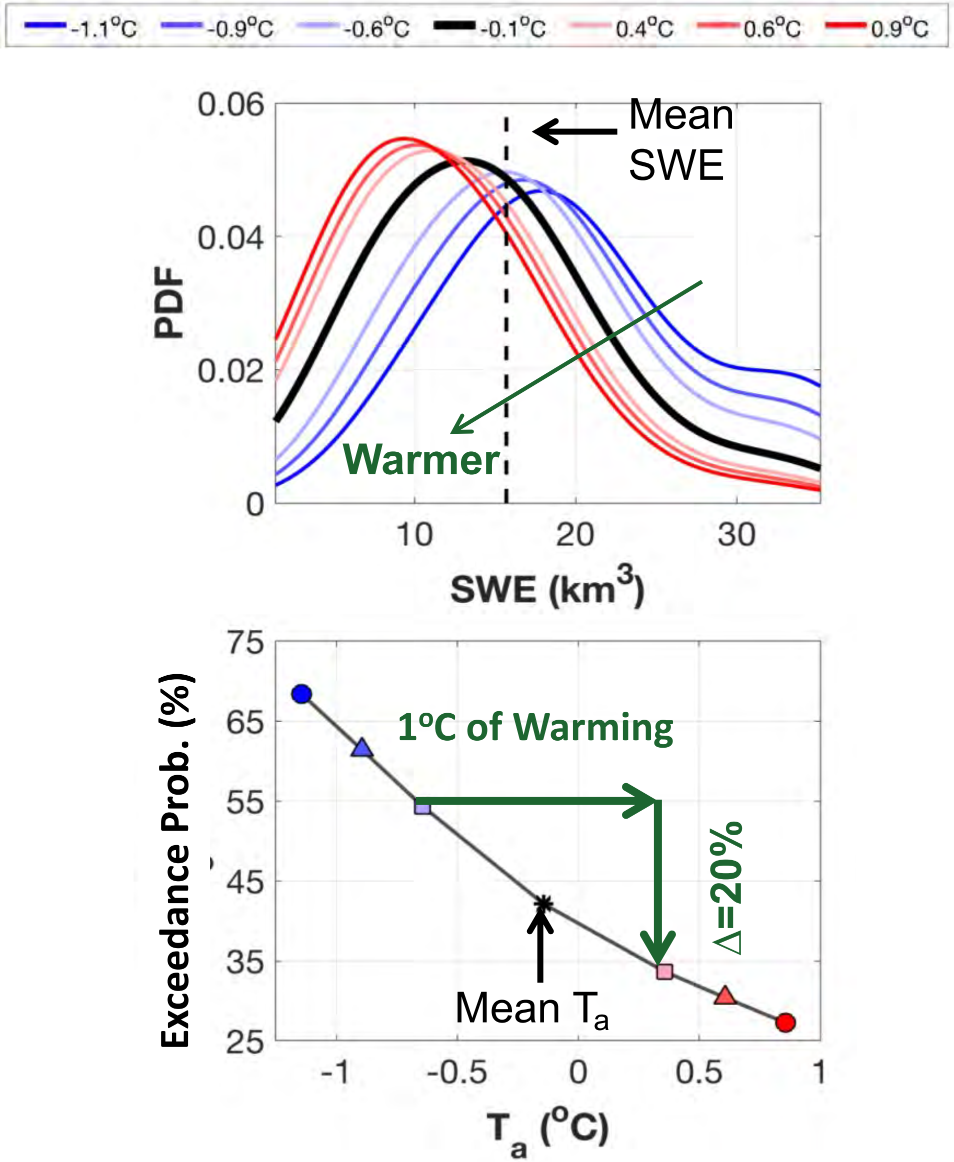
1. Estimates the most likely scenario on any critical layer (isoline): highest density on any critical layer

2. Includes different Hazard Scenarios (e.g., AND, OR, Kendall).

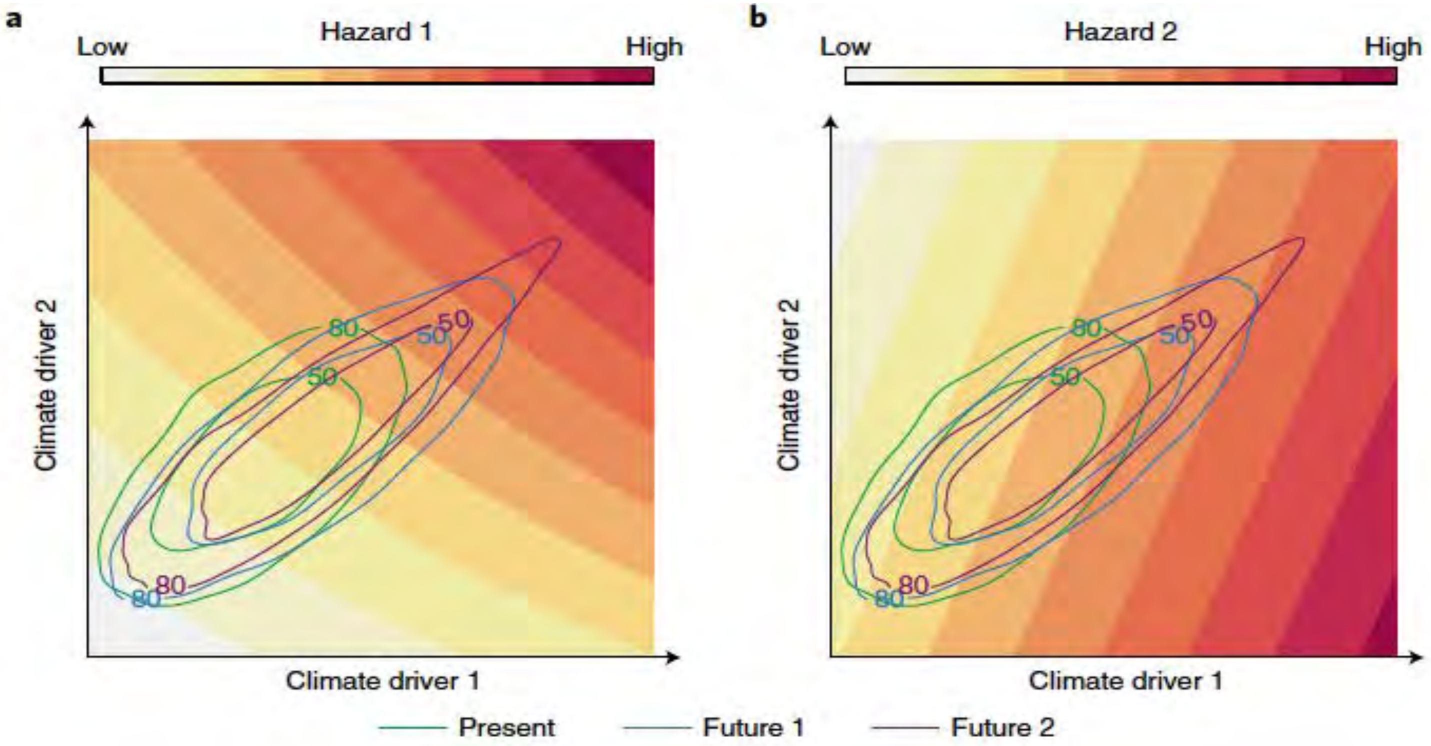
3. Uncertainty analysis and posterior distribution of the parameter using a Bayesian MCMC approach

Sadegh et al., 2018, *Geophysical Research Letters*

Mountain Snowpack Response to Different Levels of Warming



Huning and AghaKouchak, 2018, *PNAS*



Distribution of two climatic drivers in the present climate (green), a future climate with a shift in mean, variability and correlation between the drivers (Future 1, blue) and a future climate with an increase in dependence in the upper tail of both drivers (Future 2, purple) - Zscheischler J., et al., 2018.

Example for the left panel: Coastal flooding caused by extreme precipitation and surge (or fluvial flooding and ocean flooding)

Example for right panel: Wildfires with humidity (y-axis) and temperature/wind (x-axis).

Questions?

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