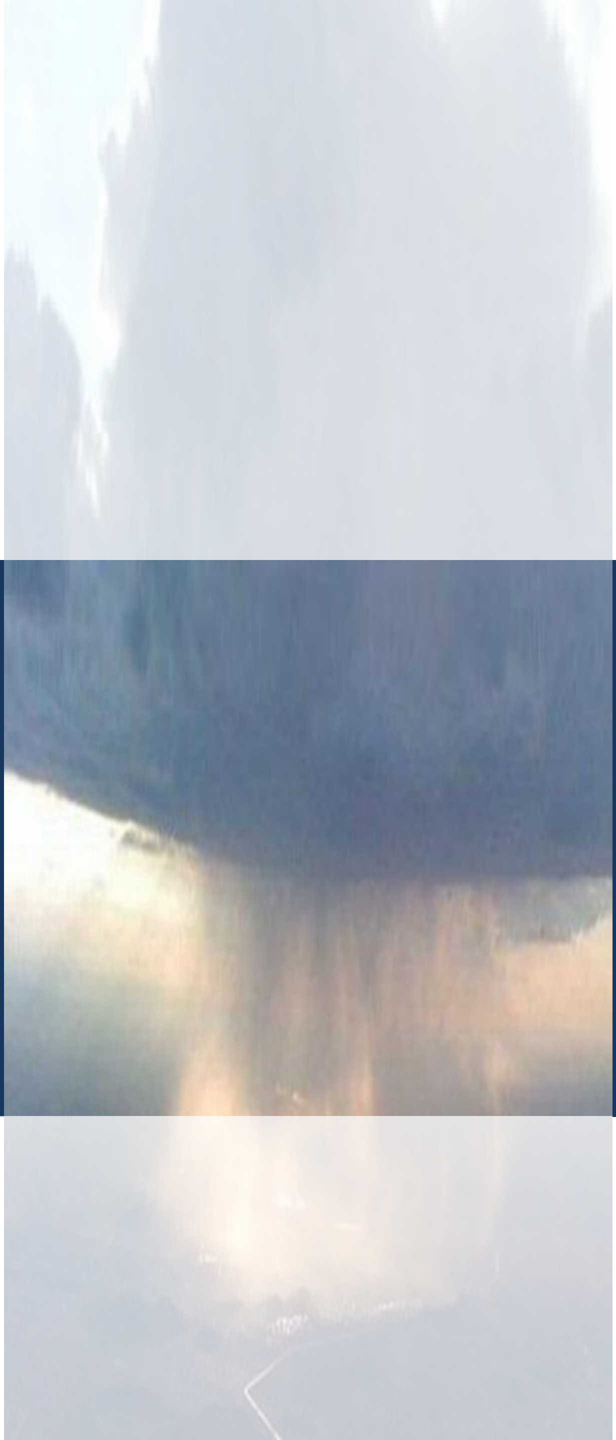
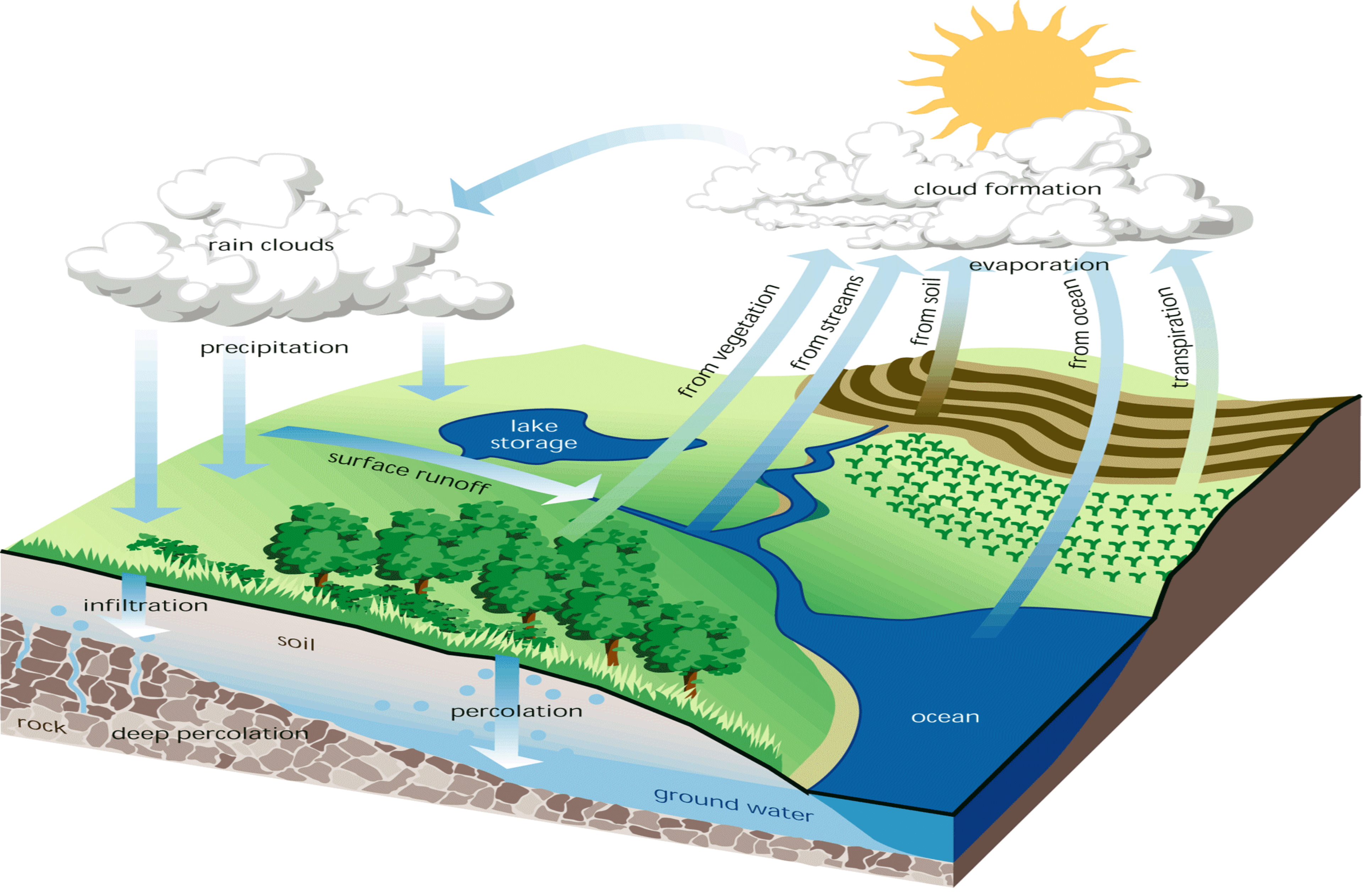


Integrated Water Cycle Analysis I

Amir AghaKouchak
University of California, Irvine
Email: amir.a@uci.edu

2nd Workshop on Water Resources in Developing Countries: Planning and Management in a Climate Change Scenario, 6-17 May 2013, Trieste, Italy.

Hydrologic Processes



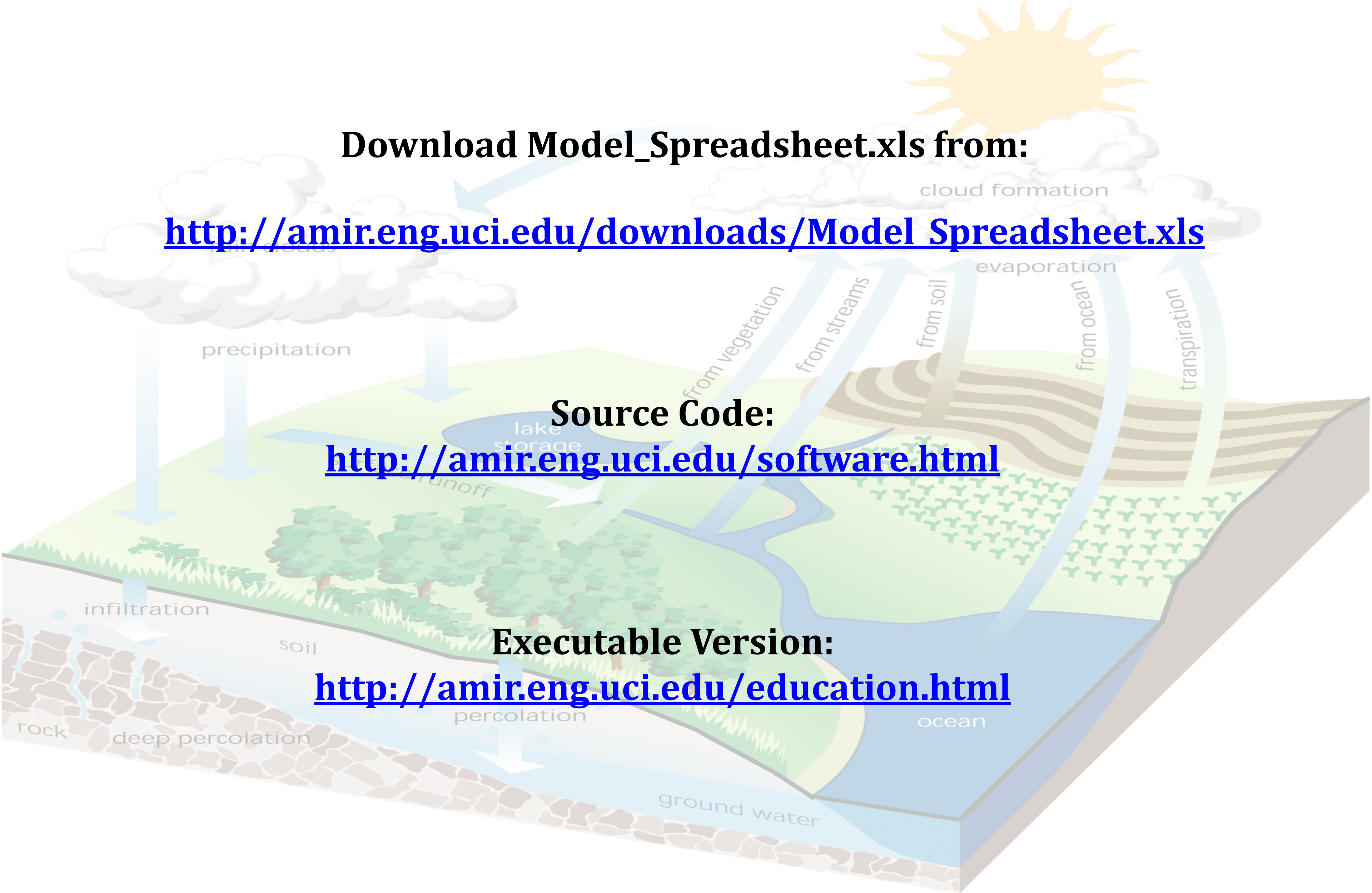
Hydrologic Processes

Download Model_Spreadsheet.xls from:

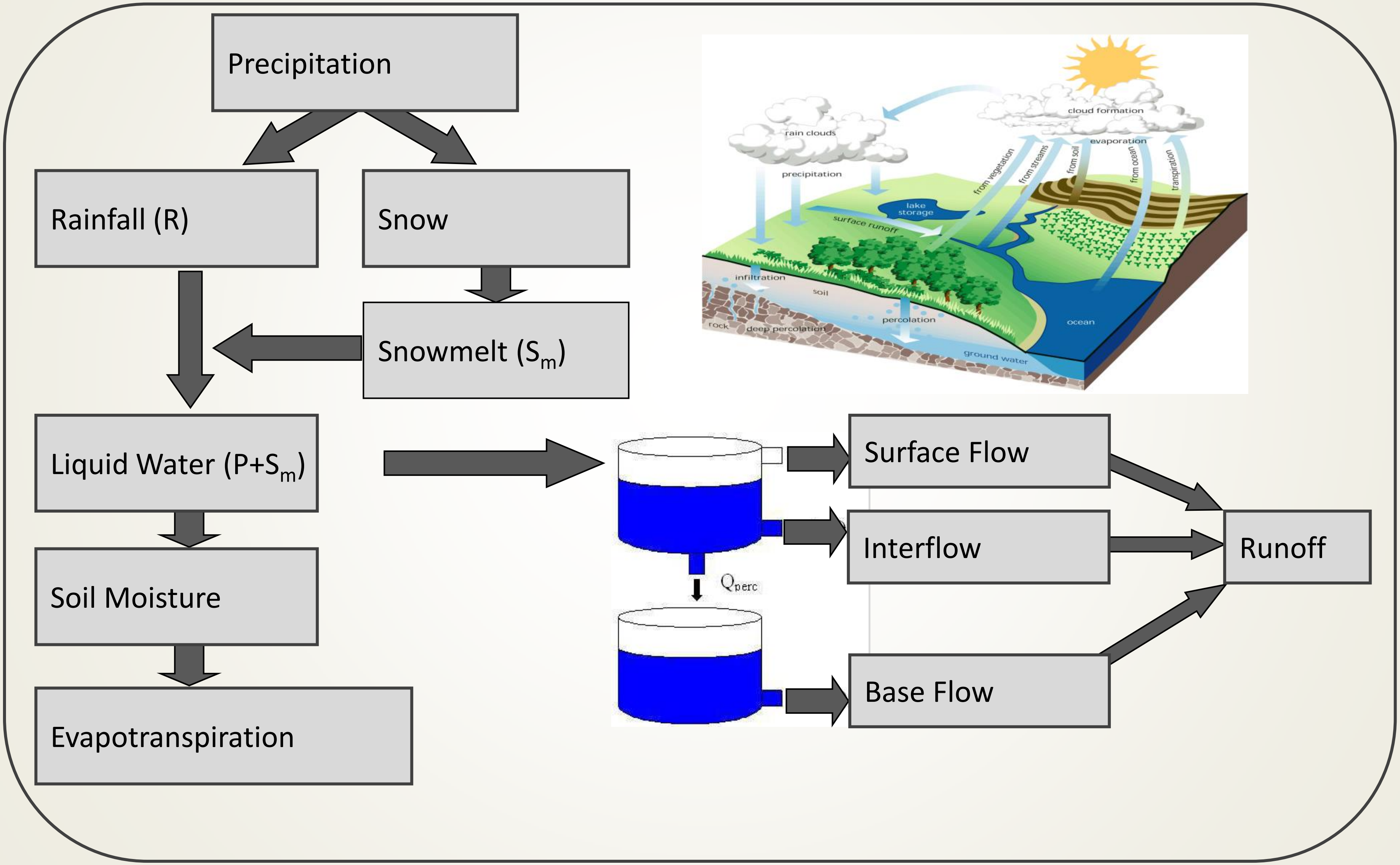
http://amir.eng.uci.edu/downloads/Model_Spreadsheet.xls

Source Code:
http://amir.eng.uci.edu/software.html

Executable Version:
http://amir.eng.uci.edu/education.html



Model Structure



Precipitation

Rainfall (R)

Snow

Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

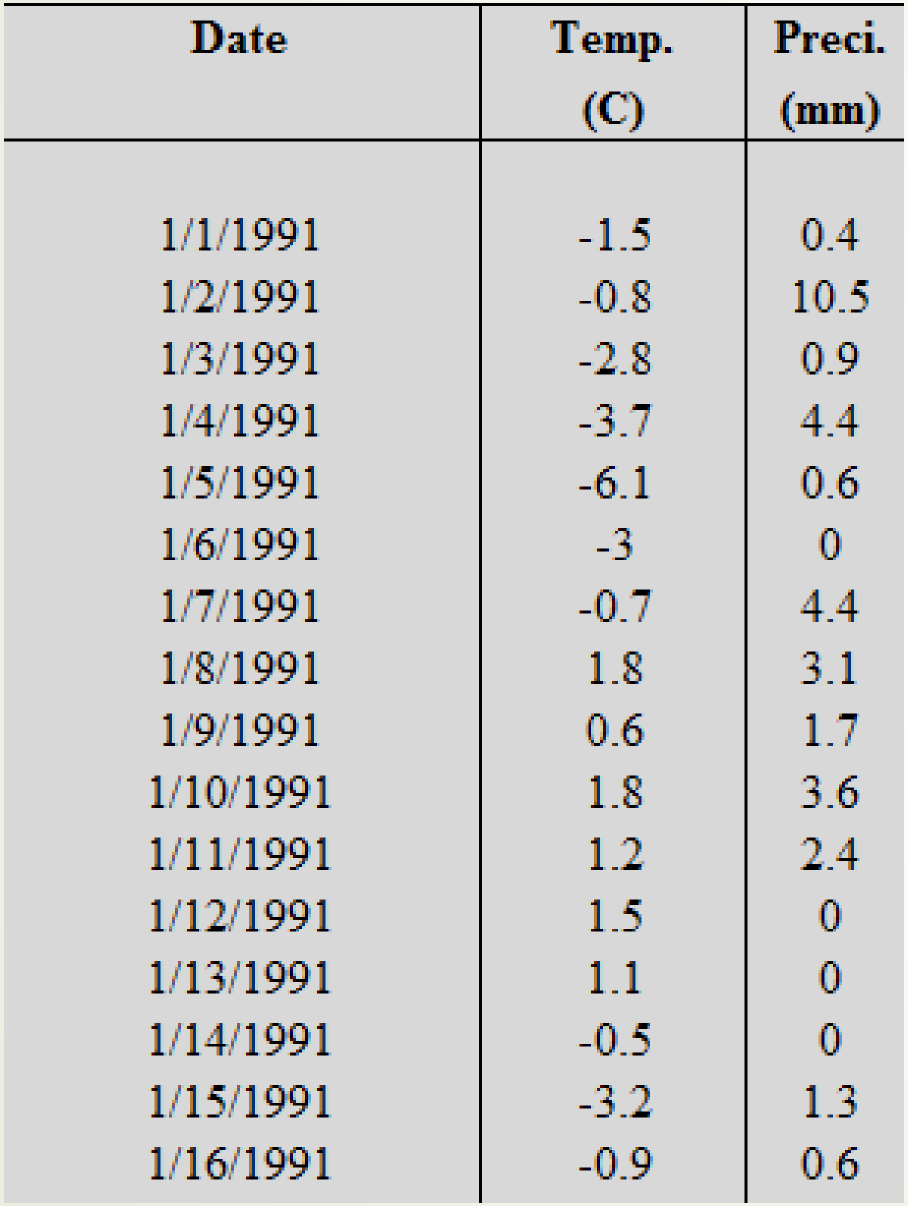
Surface Flow

Interflow

Base Flow

Runoff

Hydrologic Modeling



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

First Step?

Precipitation Separation: Rainfall & Snow

Rainfall

- Infiltration
- Direct Runoff

Snow

- Snowmelt
- Snow Accumulation

Precipitation Separation: Rainfall & Snow

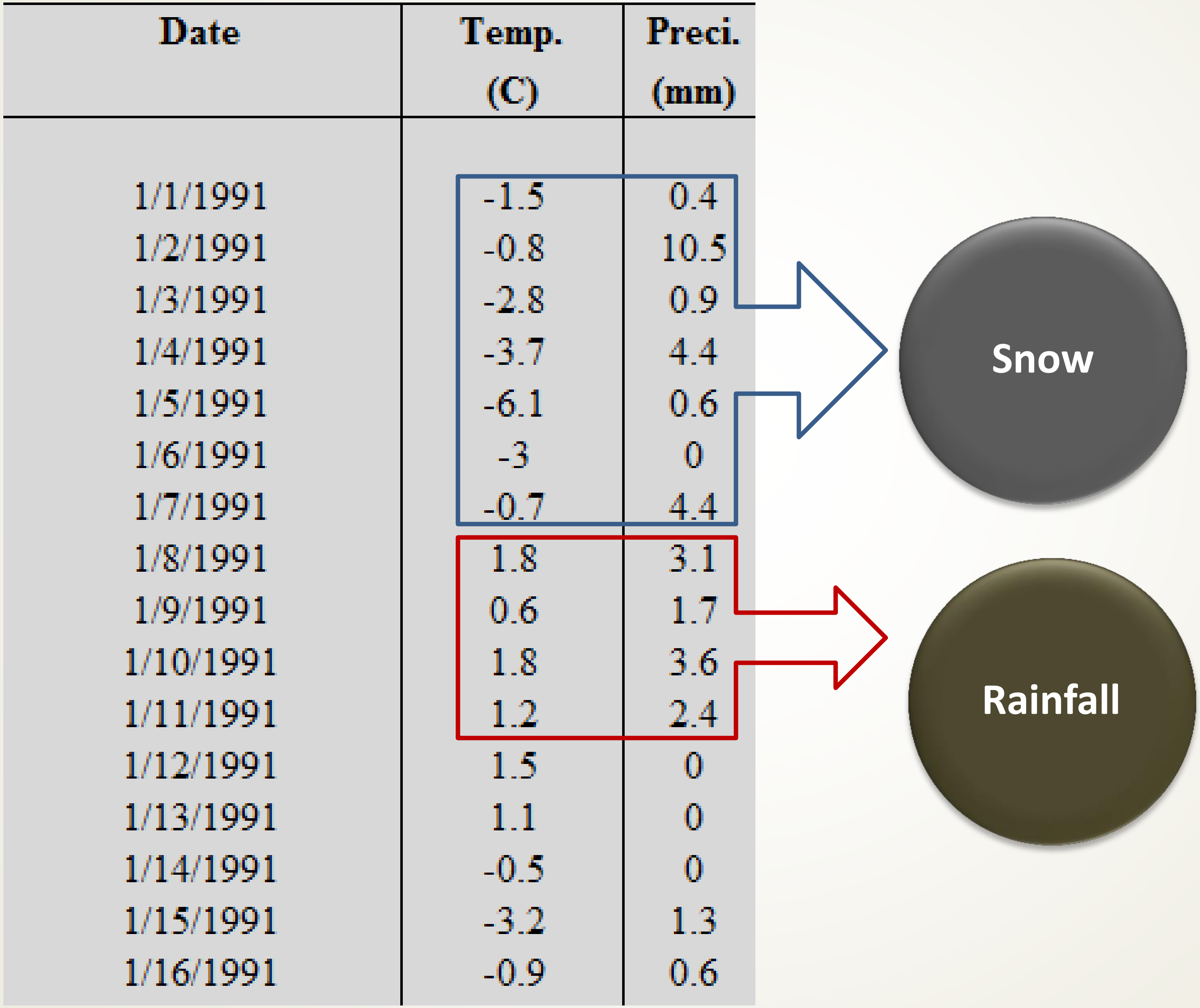
Precipitation separation into rainfall and snow based on ground temperature:

If $T > T_t$: Rainfall

If $T \leq T_t$: Snow

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

Precipitation Separation: Rainfall & Snow



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 Separation: Rainfall & Snow

Snowmelt and accumulation is proportional to the temperature:

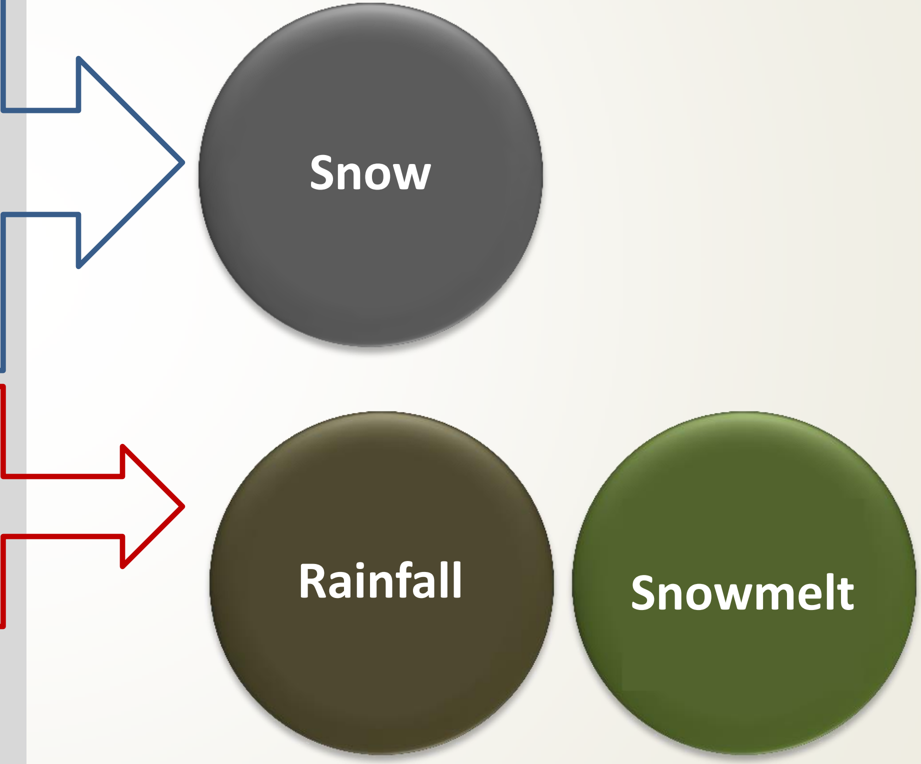
If $T > T_t$: snow melts

If $T \leq T_t$: snow accumulates

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

Precipitation Separation: Rainfall & Snow

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



Snowmelt

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

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

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

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

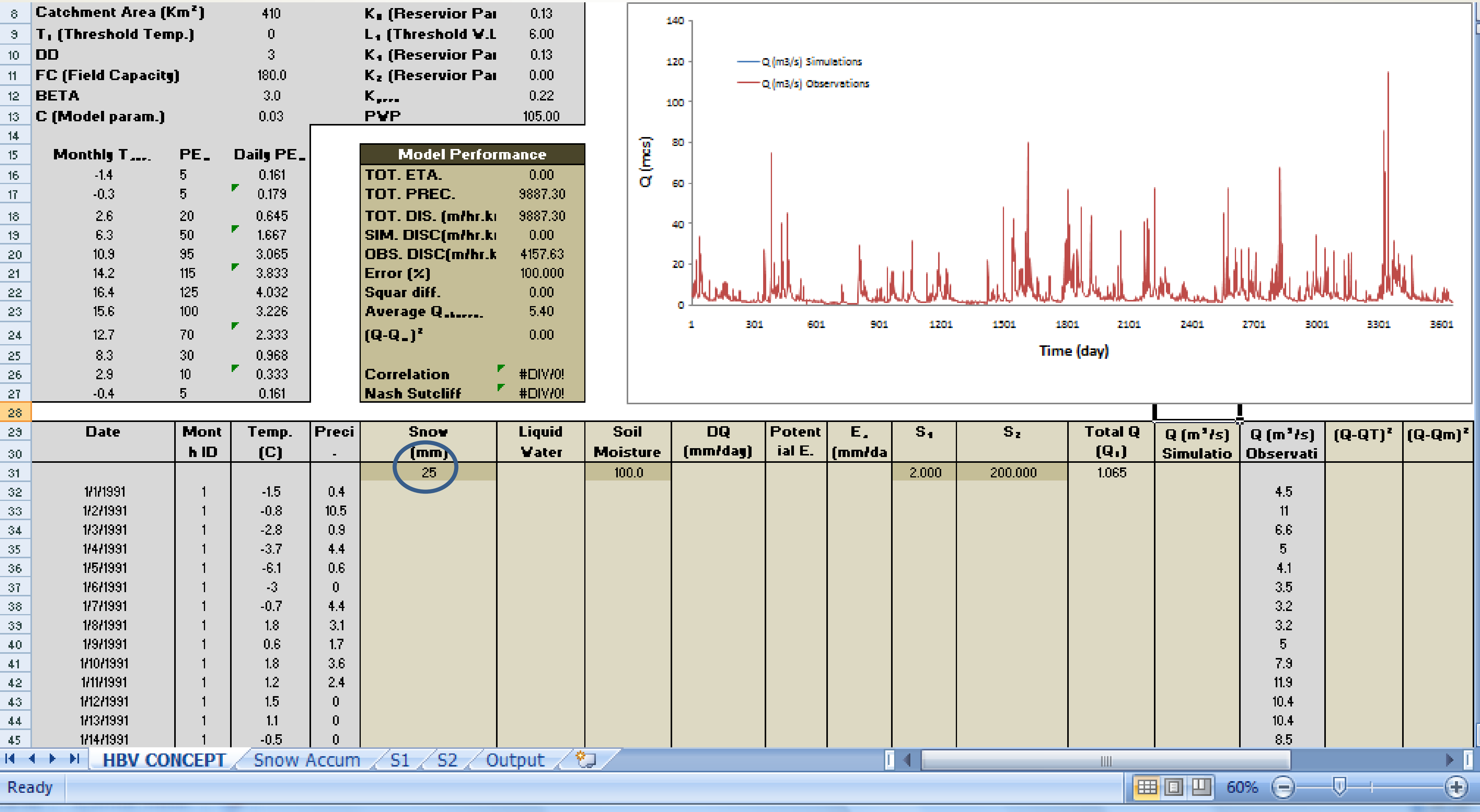
T_t ($[\theta]$): threshold temperature

Degree-Day-Factor $[L\theta^{-1}T^{-1}]$: snowmelt depth resulting from 1 degree day (1 degree temperature deviation from freezing point).

Degree-Day: a day with a mean temperature of 5 degrees represents 5 degree days above a threshold of 0 degrees.

Download Model_Spreadsheet.xls from:

http://amir.eng.uci.edu/downloads/Model_Spreadsheet.xls



Catchment Area (Km²)	410	K_0 (Reservior Pa	0.13
T_1 (Threshold Temp.)	0	L_1 (Threshold V.L	6.00
DD	3	K_1 (Reservior Pa	0.13
FC (Field Capacity)	180.0	K_2 (Reservior Pa	0.00
BETA	3.0	K	0.22
C (Model param.)	0.03	PWP	105.00

Monthly T	PE	Daily PE
-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.	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	S_1	S_2	Total Q (Q_t)	Q (m³/s) Simulatio	Q (m³/s) Observati	(Q-QT)²	(Q-Qm)²
				25		100.0				2.000	200.000	1.065				
1/1/1991	1	-1.5	0.4											4.5		
1/2/1991	1	-0.8	10.5											11		
1/3/1991	1	-2.8	0.9											6.6		
1/4/1991	1	-3.7	4.4											5		
1/5/1991	1	-6.1	0.6											4.1		
1/6/1991	1	-3	0											3.5		
1/7/1991	1	-0.7	4.4											3.2		
1/8/1991	1	1.8	3.1											3.2		
1/9/1991	1	0.6	1.7											5		
1/10/1991	1	1.8	3.6											7.9		
1/11/1991	1	1.2	2.4											11.9		
1/12/1991	1	1.5	0											10.4		
1/13/1991	1	1.1	0											10.4		
1/14/1991	1	-0.5	0											8.5		

Snowmelt

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

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

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

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

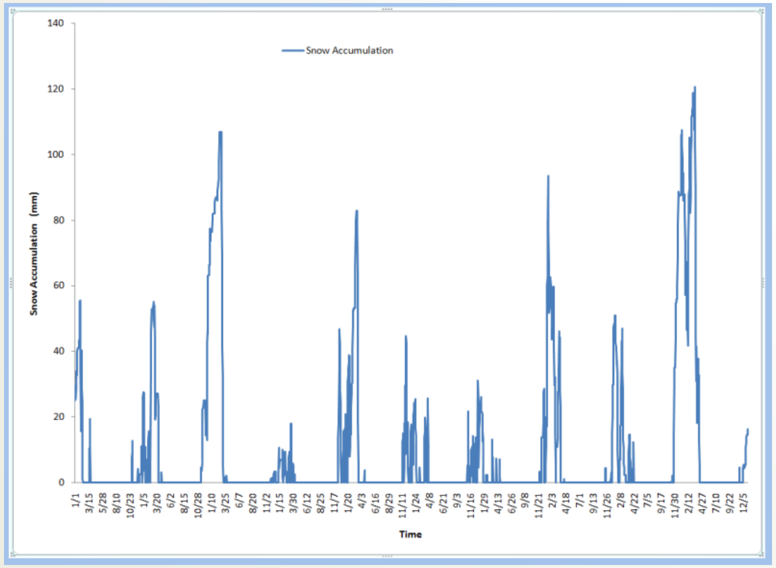
NOTE: The MAX function in the above statement is used to prevent negative values of snow height!

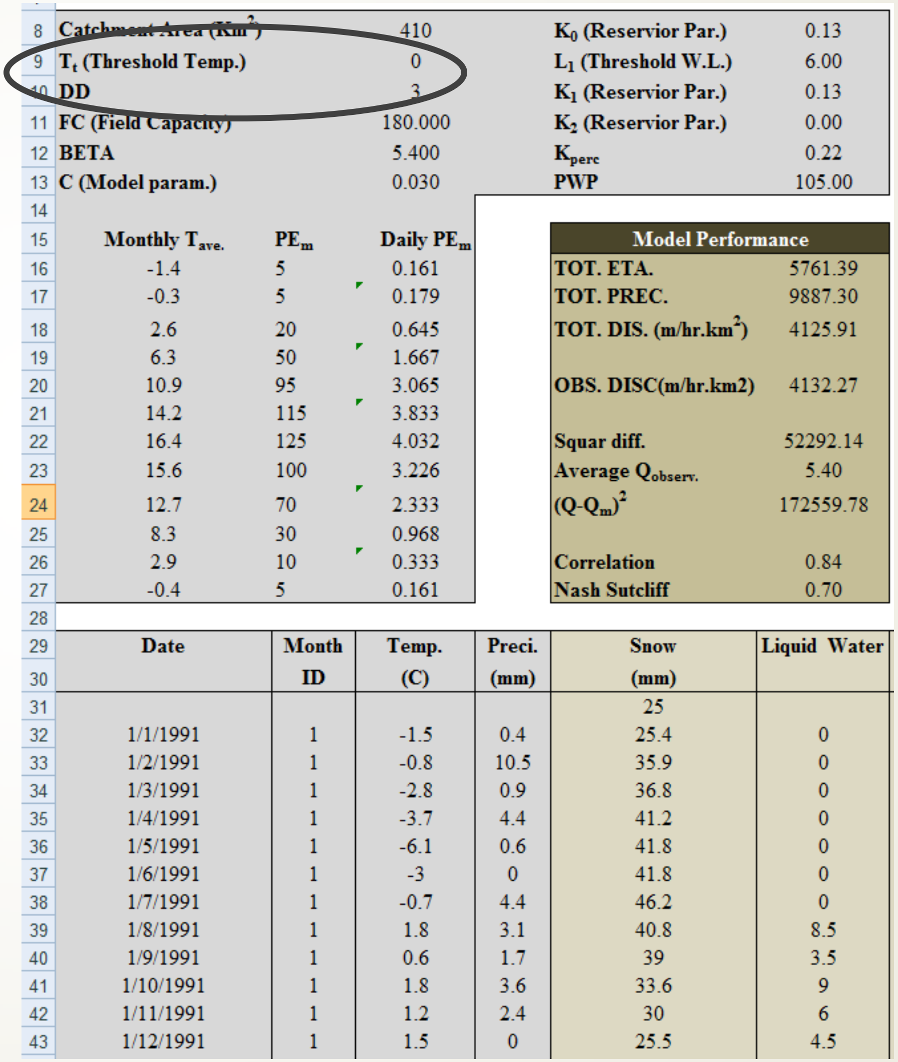
Snowmelt

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!





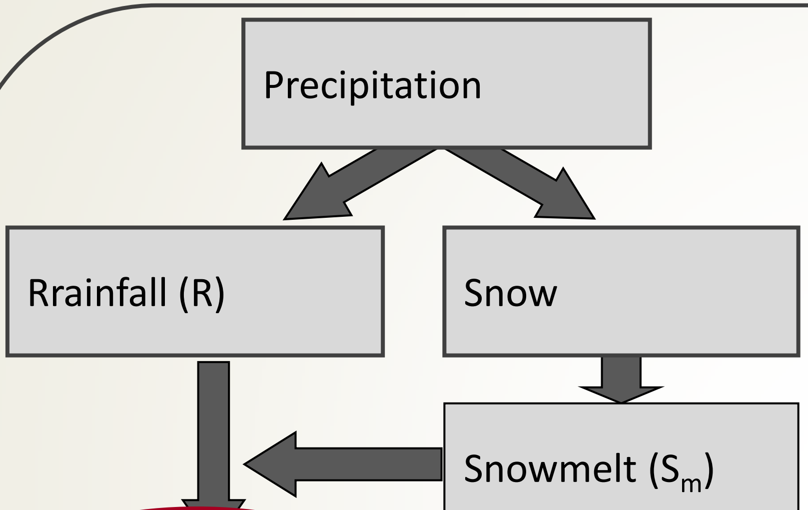
8	Catchment Area (Km²)	410	K_0 (Reservior Par.)	0.13
9	T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
10	DD	3	K_1 (Reservior Par.)	0.13
11	FC (Field Capacity)	180.000	K_2 (Reservior Par.)	0.00
12	BETA	5.400	K_{perc}	0.22
13	C (Model param.)	0.030	PWP	105.00
14				

15	Monthly $T_{ave.}$	PE_m	Daily PE_m
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
28			

Model Performance	
TOT. ETA.	5761.39
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km²)	4125.91
OBS. DISC(m/hr.km2)	4132.27
Squar diff.	52292.14
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.84
Nash Sutcliff	0.70

29 30	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water
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

Model Structure

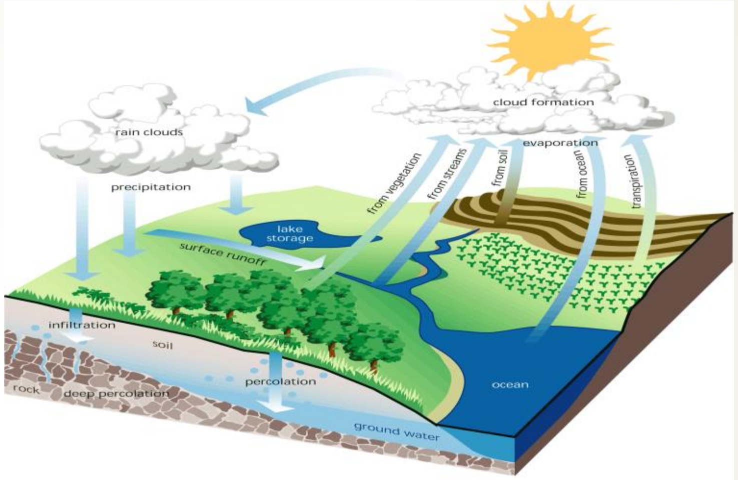


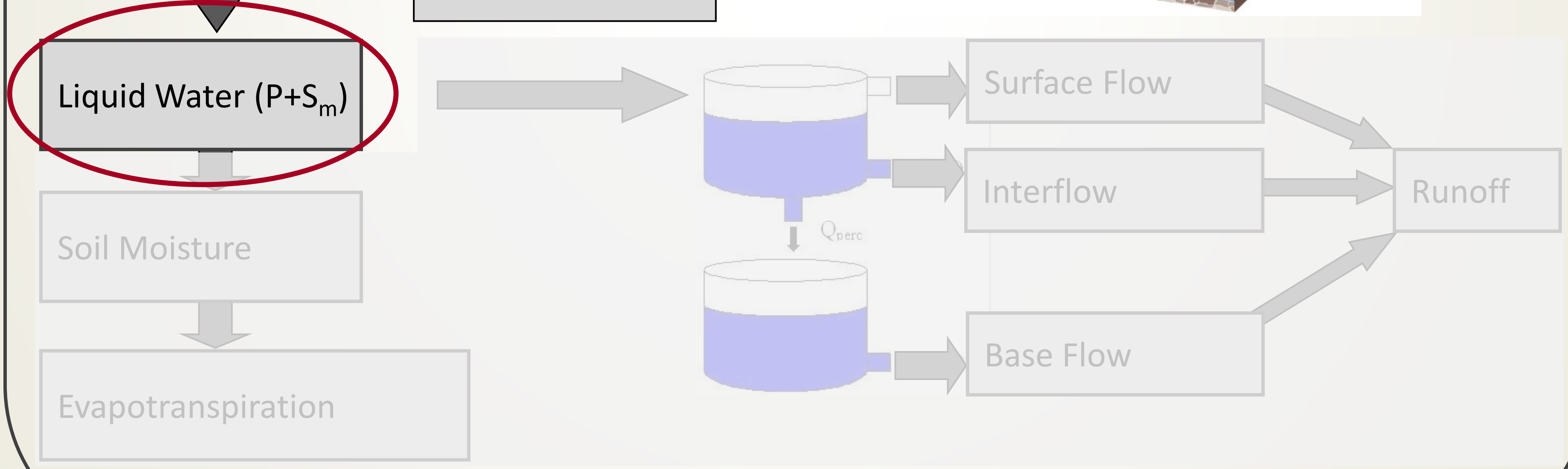
Precipitation

Rrainfall (R)

Snow

Snowmelt (S_m)





Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

Surface Flow

Interflow

Base Flow

Runoff

Liquid Water Equivalent

$$\text{Liquid Water} = P+S_m$$

P= Precipitation
S_m= Snowmelt

If $T < T_t$: Liquid Water = 0
If $T > T_t$: Liquid Water = $P+S_m$
$T_{t.}$: Threshold temperature (0 °C / 32 °F)

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

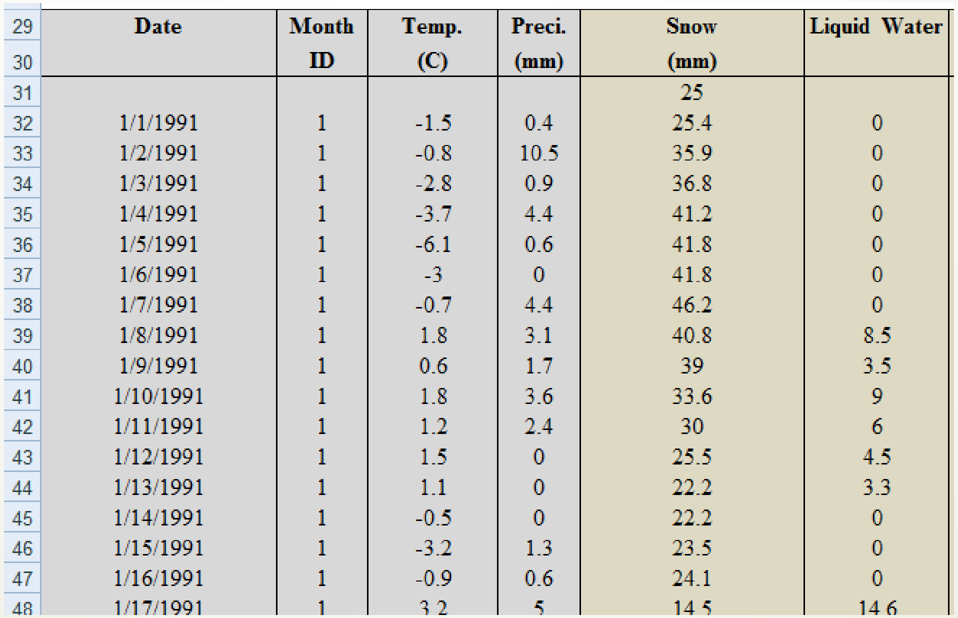
NOTE: The MIN function in the above statement is used to prevent negative values

Liquid Water Equivalent

$$\text{Liquid Water} = P + S_m$$

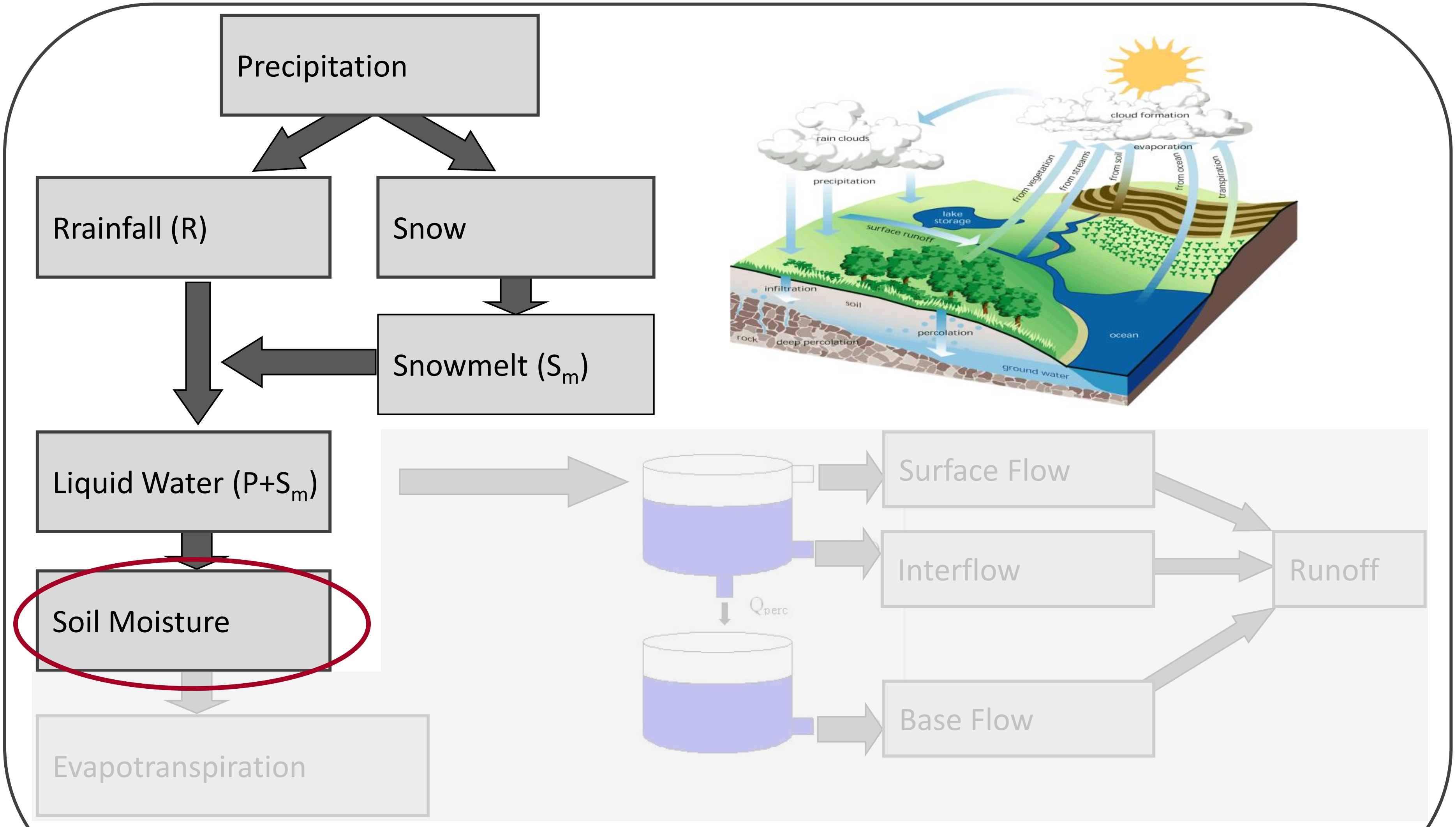
IF(C32>$C$9,D32+MIN(E31,$C$10*(C32-$C$9)),0)

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



29 30	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water
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
44	1/13/1991	1	1.1	0	22.2	3.3
45	1/14/1991	1	-0.5	0	22.2	0
46	1/15/1991	1	-3.2	1.3	23.5	0
47	1/16/1991	1	-0.9	0.6	24.1	0
48	1/17/1991	1	3.2	5	14.5	14.6

Model Structure



Precipitation

Rrainfall (R)

Snow

Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

Surface Flow

Interflow

Base Flow

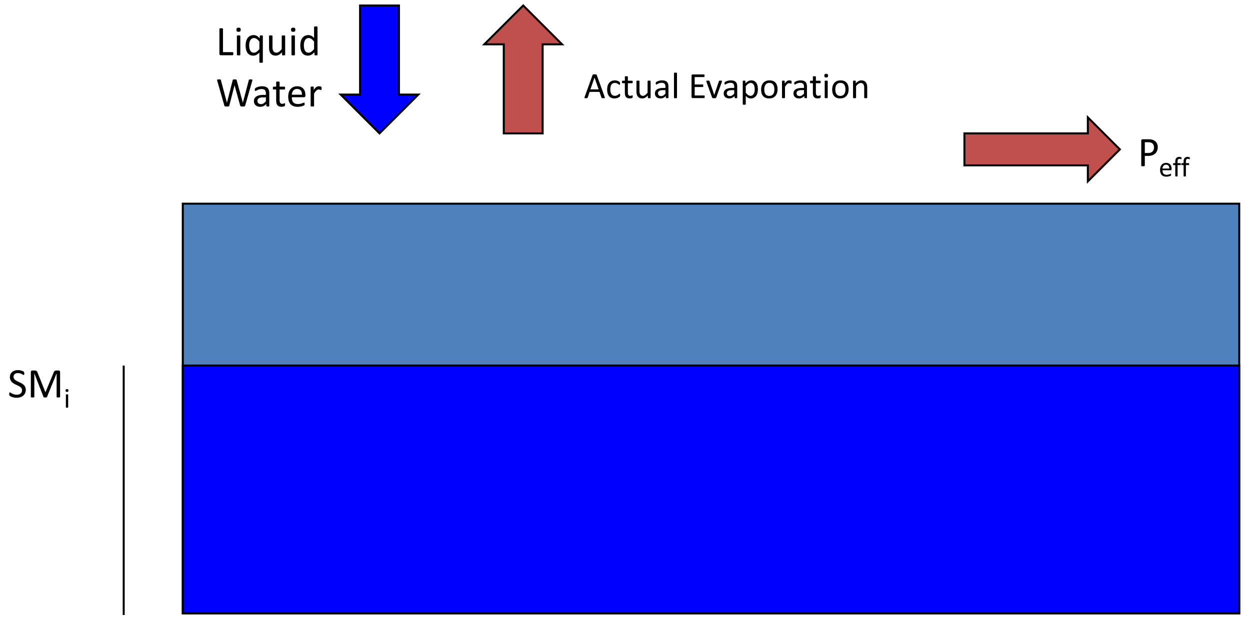
Runoff

Q_{perc}

Soil Moisture

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

In the following, Effective Precipitation and Actual Evapotranspiration are addressed.

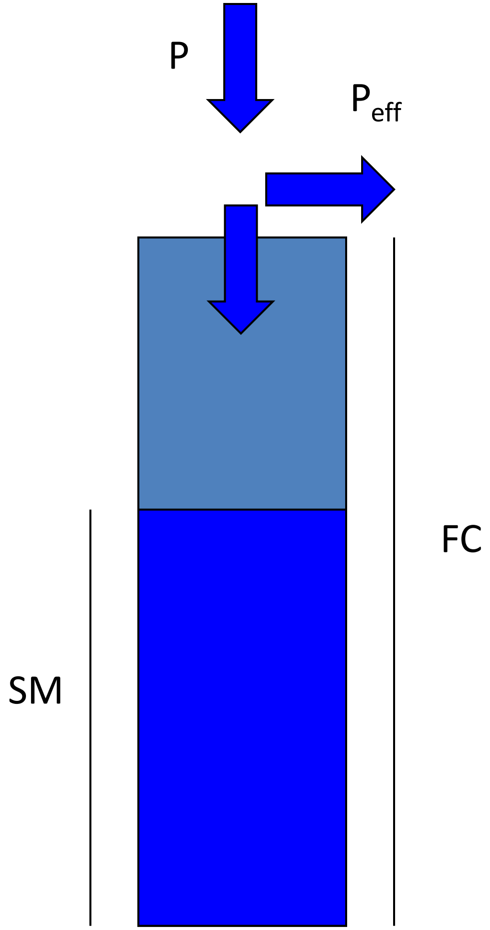


Effective Precipitation

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

$Peff$	([L])	effective precipitation
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.



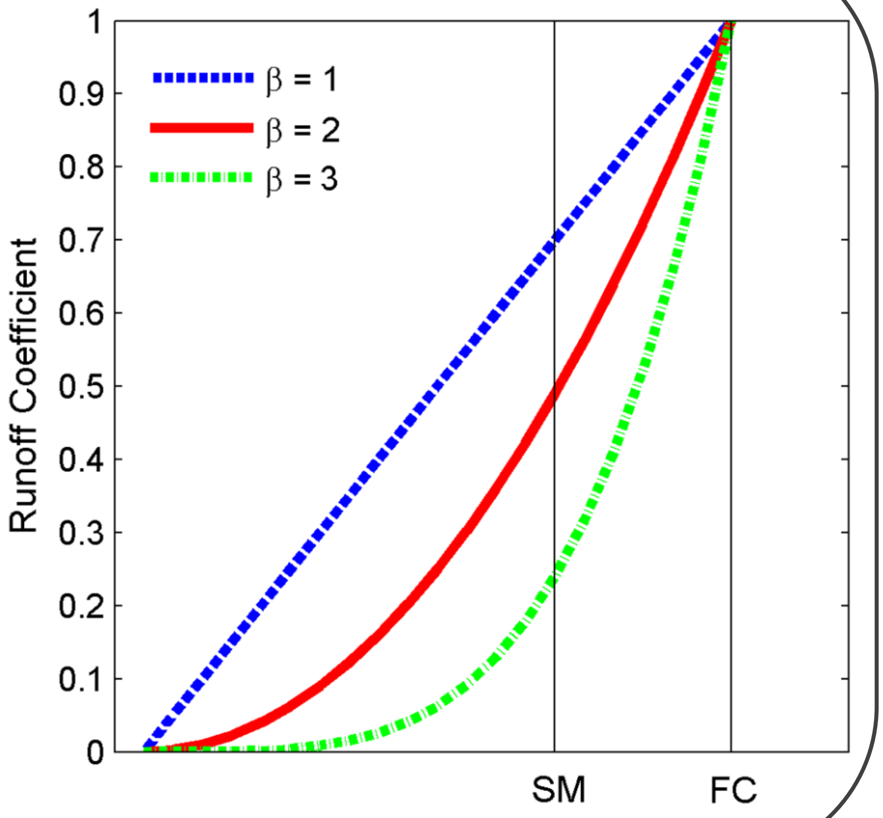
Effective Precipitation

Liquid Water

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

Runoff Coefficient

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

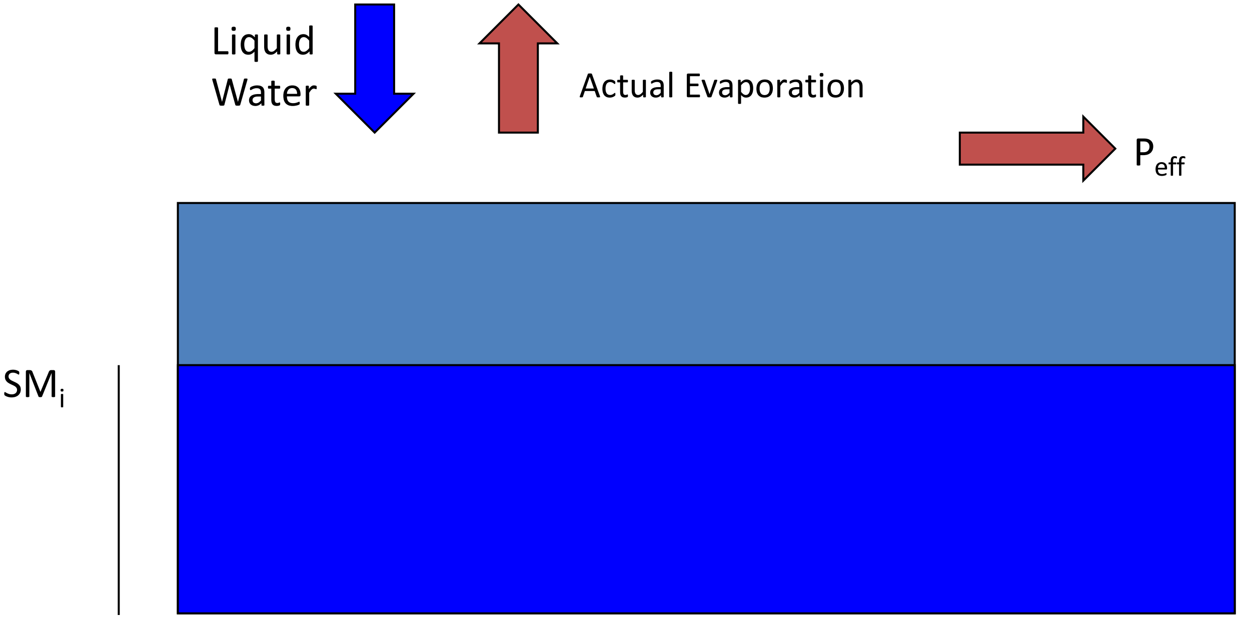


For a given soil-moisture deficit, β determines the amount of rain or snowmelt which contributes to runoff. The graph shows that for a specific soil moisture, the higher the β, the lower the runoff coefficient. Further, as the soil moisture (*SM*) approaches the field capacity (*FC*); the runoff coefficient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

Soil Moisture

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

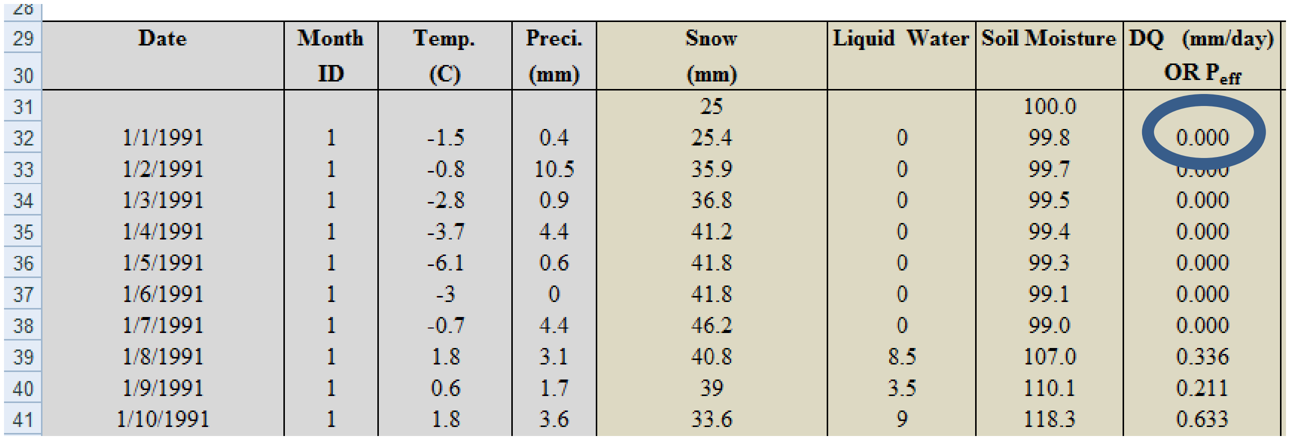
In the following, Effective Precipitation and Actual Evapotranspiration are addressed.



Effective Precipitation

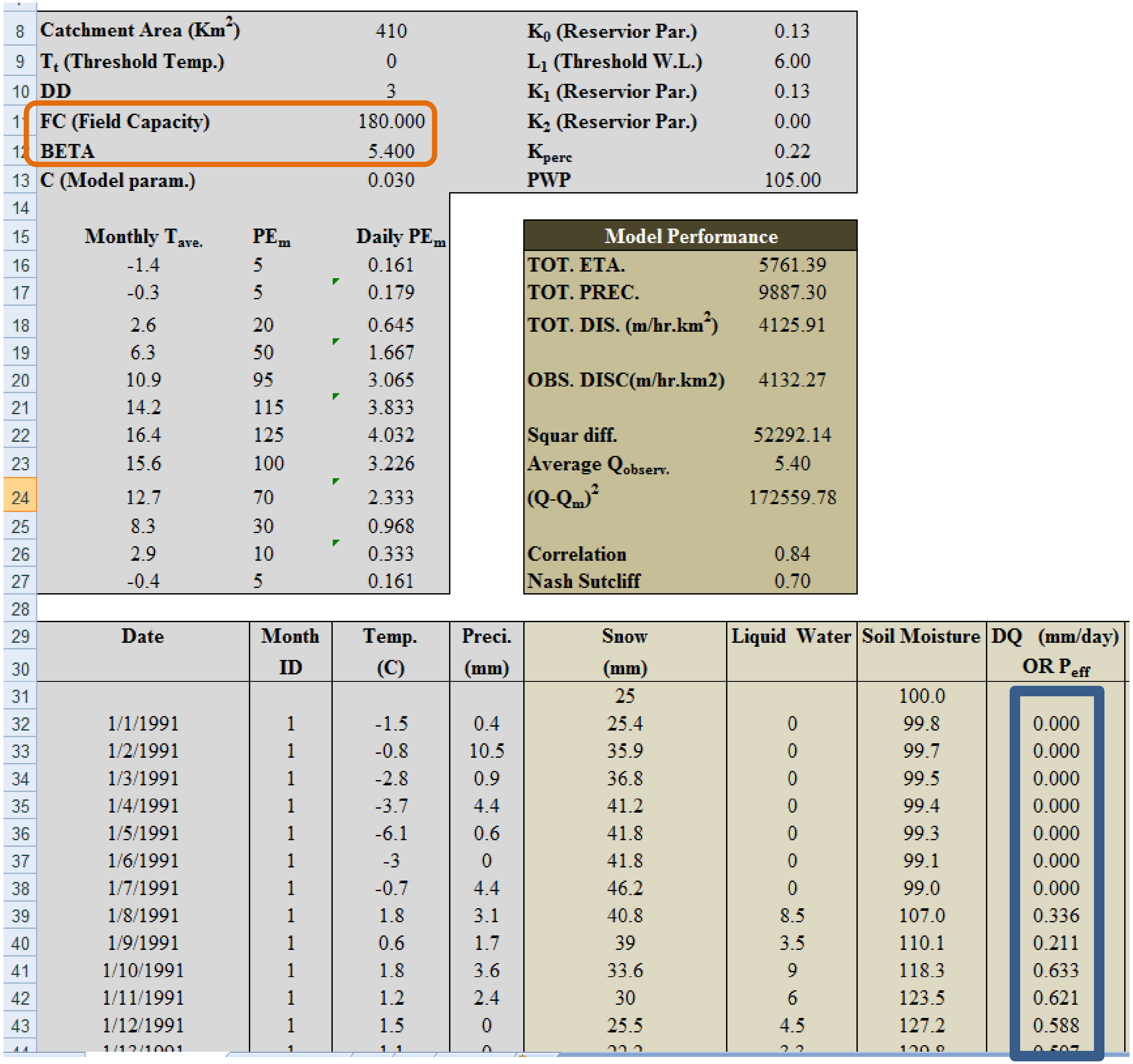
$$P_{eff} = \left[\frac{SM}{FC}\right]^{\beta} \left(P + SNOWMELT\right)$$

=(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

Effective Precipitation



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)	180.000	**K_2 (Reservior Par.)**	0.00
BETA	5.400	**K_{perc}**	0.22
C (Model param.)	0.030	**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.	5761.39
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	4125.91
OBS. DISC(m/hr.km2)	4132.27
Squar diff.	52292.14
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.84
Nash Sutcliff	0.70

Date	**Month ID**	**Temp. (C)**	**Preci. (mm)**	**Snow (mm)**	**Liquid Water**	**Soil Moisture**	**DQ (mm/day) OR P_{eff}**
				25		100.0	
1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000
1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000
1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000
1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000
1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000
1/6/1991	1	-3	0	41.8	0	99.1	0.000
1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000
1/8/1991	1	1.8	3.1	40.8	8.5	107.0	0.336
1/9/1991	1	0.6	1.7	39	3.5	110.1	0.211
1/10/1991	1	1.8	3.6	33.6	9	118.3	0.633
1/11/1991	1	1.2	2.4	30	6	123.5	0.621
1/12/1991	1	1.5	0	25.5	4.5	127.2	0.588

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, PWP.

Evapotranspiration

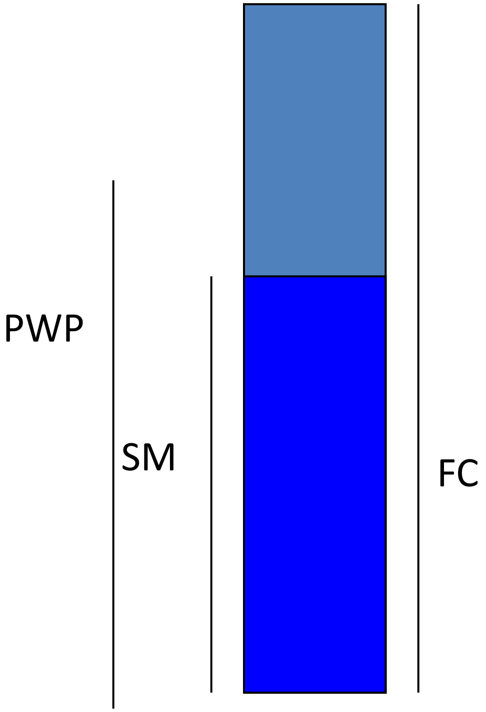
$$E_a = PE_a \cdot \frac{SM}{PWP} \quad \text{for} \quad SM < PWP$$

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

E_a ([L]) Actual evapotranspiration

PWP ([L]) Soil Permanent Wilting Point

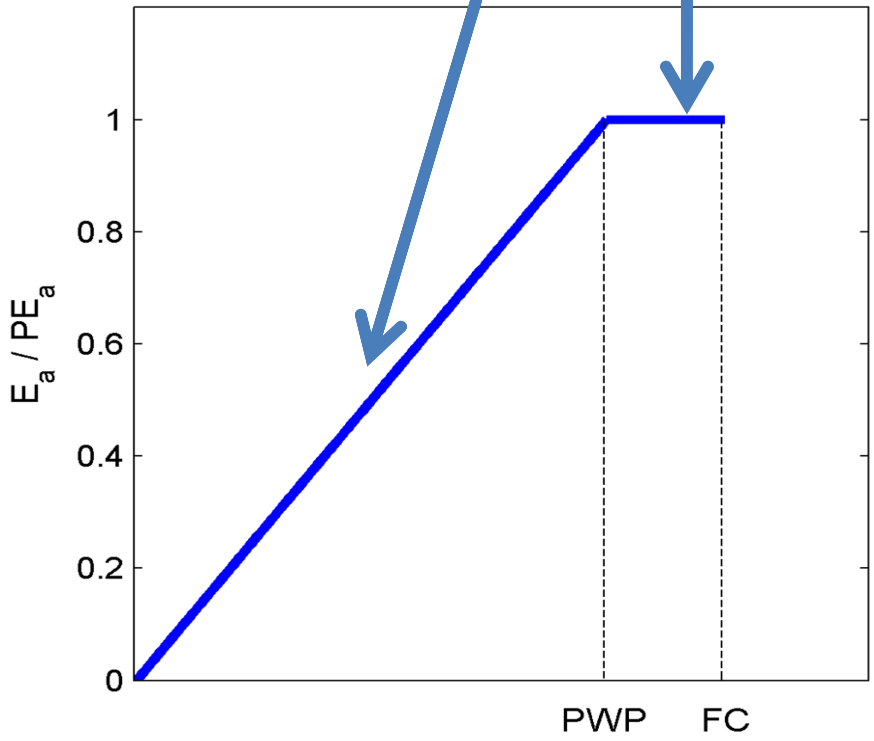
When the soil moisture is above the PWP, actual evapotranspiration occurs at the same rate as potential evapotranspiration. PWP is the soil-moisture limit for evapotranspiration decrease meaning that when the soil moisture is less than PWP, the actual evapotranspiration is less then the adjusted evapotranspiration.



Evapotranspiration

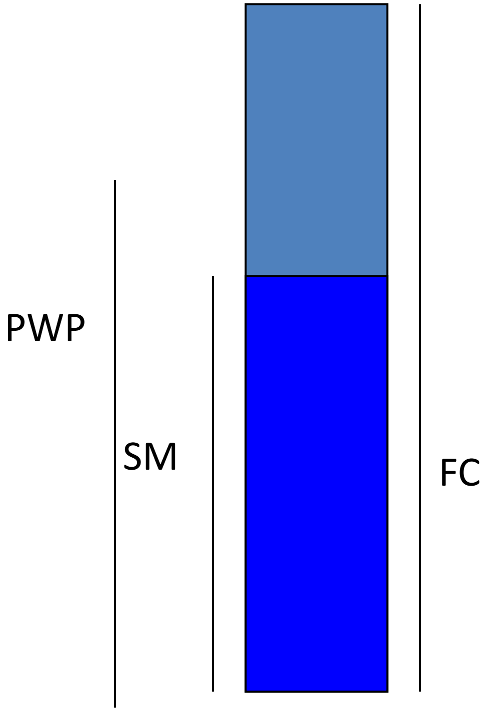
$$E_a = PE_a \cdot \frac{SM}{PWP} \quad \text{for } SM < PWP$$

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



PEa ([L]) : adjusted potential evapotranspiration

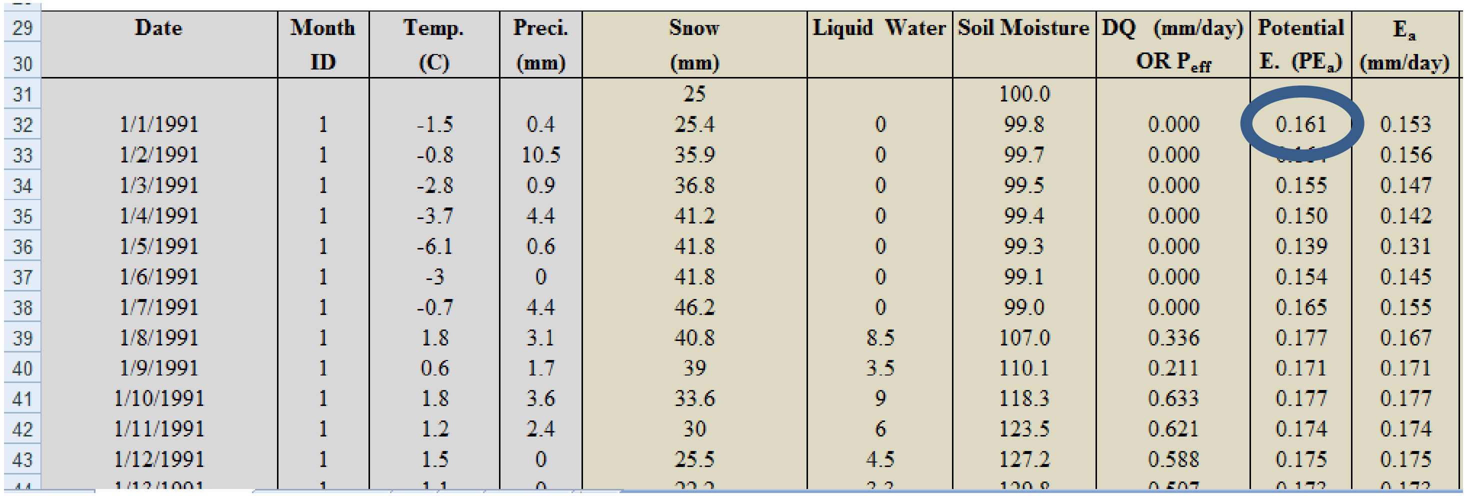
Ea   ([L]) : actual evapotranspiration



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)



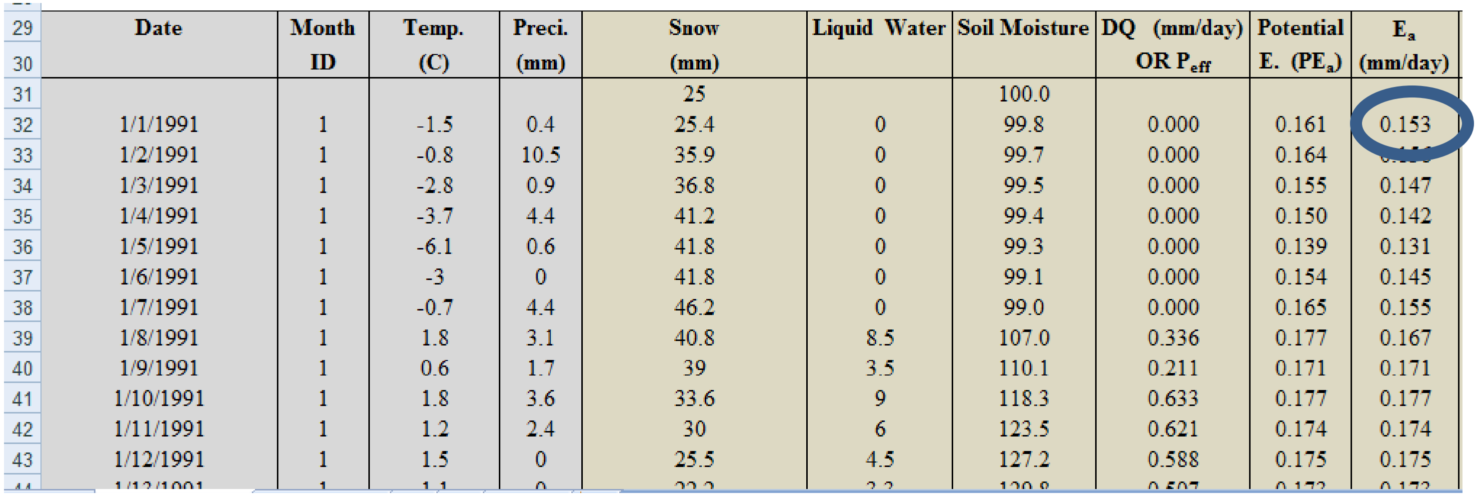
29	Date	Month	Temp.	Preci.	Snow	Liquid Water	Soil Moisture	DQ (mm/day)	Potential	E_a
30		ID	(C)	(mm)	(mm)			OR P_{eff}	E. (PE_a)	(mm/day)
31					25		100.0			
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	[illegible]	0.156
34	1/3/1991	1	-2.8	0.9	36.8	0	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

Evapotranspiration

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

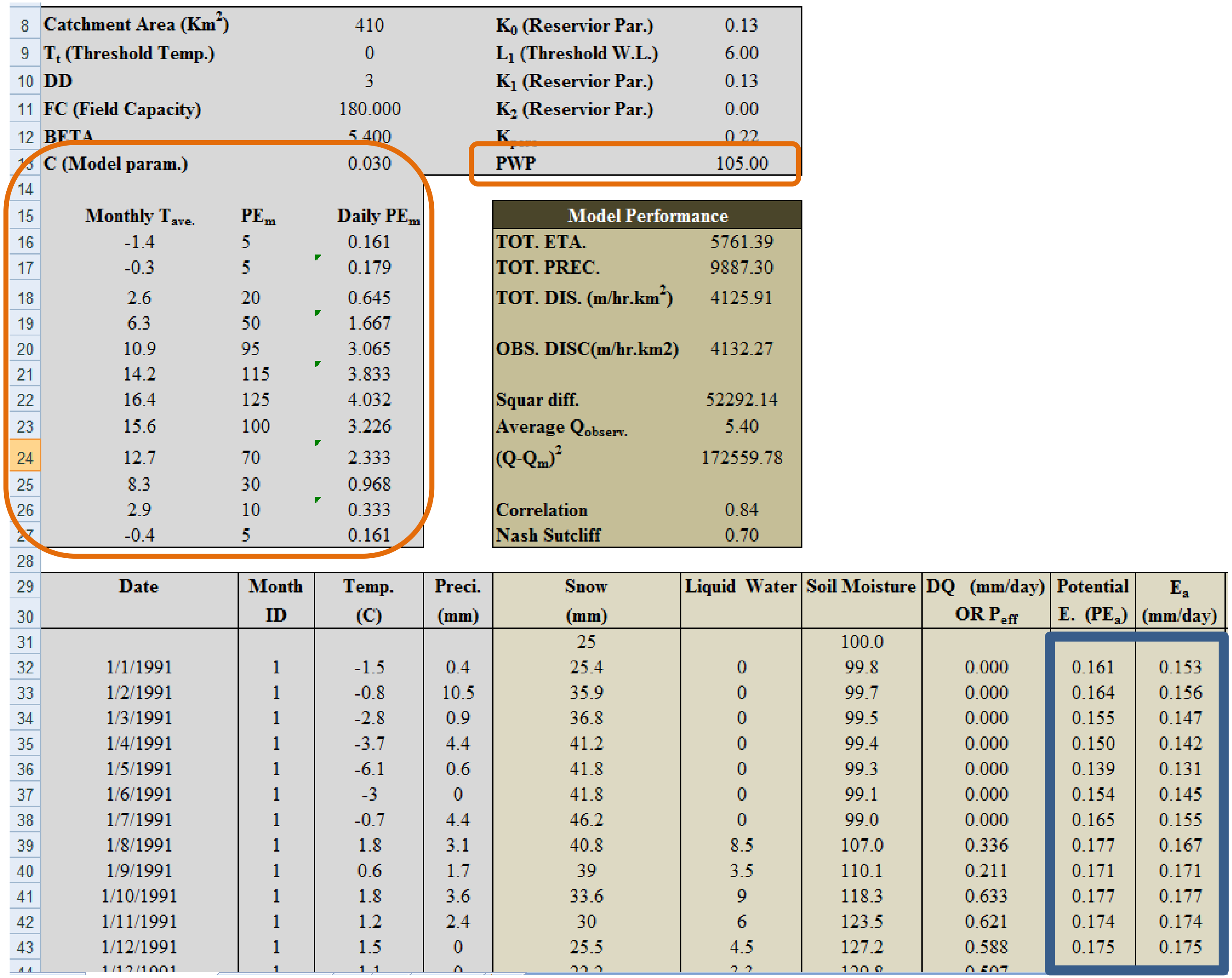
$$E_a = PE_a \quad \text{for} \quad SM \geq PWP$$

=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)
29										
30										
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	[illegible]
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

Evapotranspiration



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)	180.000	**K_2 (Reservior Par.)**	0.00
BETA	5.400	**K_{perc}**	0.22
C (Model param.)	0.030	**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

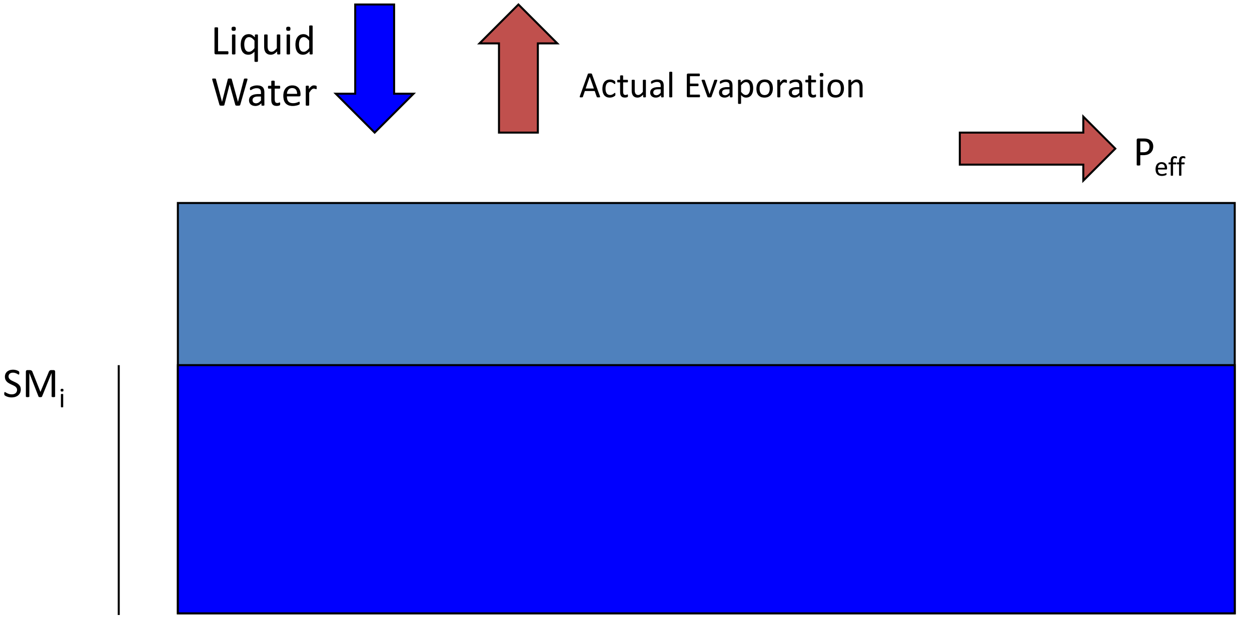
Model Performance	
TOT. ETA.	5761.39
TOT. PREC.	9887.30
TOT. DIS. (m/hr.km^2)	4125.91
OBS. DISC(m/hr.km2)	4132.27
Squar diff.	52292.14
Average $Q_{observ.}$	5.40
$(Q-Q_m)^2$	172559.78
Correlation	0.84
Nash Sutcliff	0.70

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			
1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153
1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156
1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147
1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142
1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131
1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145
1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155
1/8/1991	1	1.8	3.1	40.8	8.5	107.0	0.336	0.177	0.167
1/9/1991	1	0.6	1.7	39	3.5	110.1	0.211	0.171	0.171
1/10/1991	1	1.8	3.6	33.6	9	118.3	0.633	0.177	0.177
1/11/1991	1	1.2	2.4	30	6	123.5	0.621	0.174	0.174
1/12/1991	1	1.5	0	25.5	4.5	127.2	0.588	0.175	0.175

Soil Moisture

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

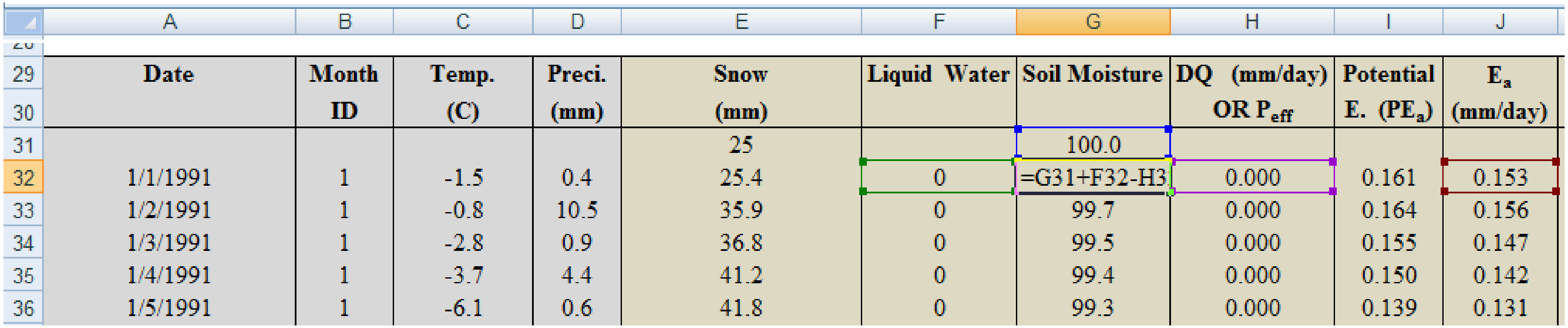
In the following, Effective Precipitation and Actual Evapotranspiration are addressed.



Soil Moisture

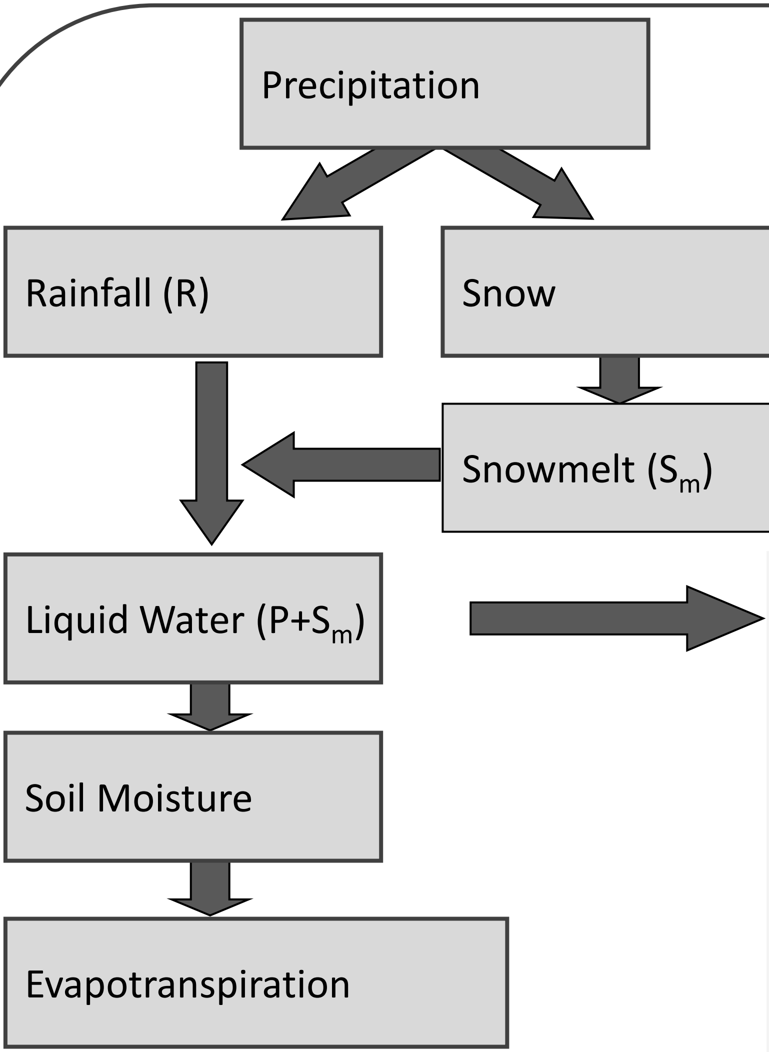
Soil Moisture = Initial Soil Moisture (SM_i) + Liquid Water – Effective Precipitation (P_{eff}) – Actual Evapotranspiration

=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

Model Structure



Precipitation

Rainfall (R)

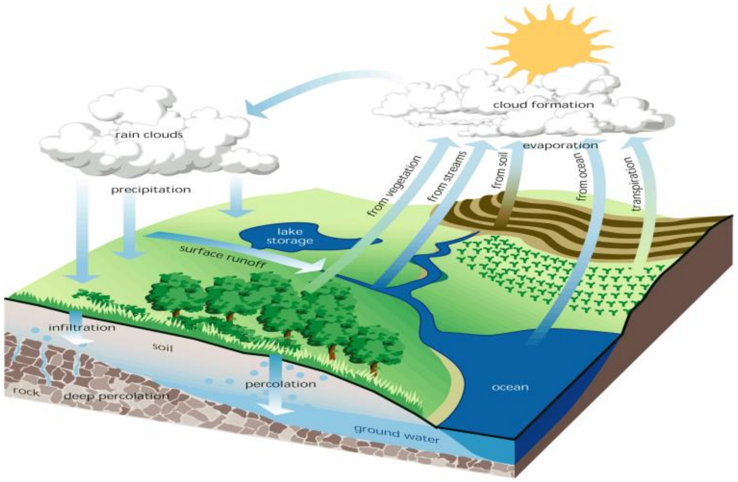
Snow

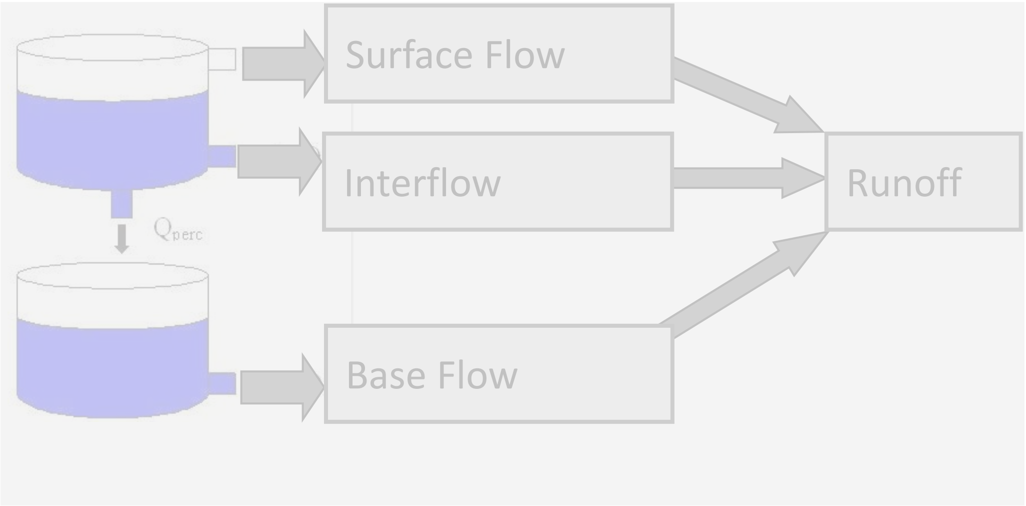
Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration





Surface Flow

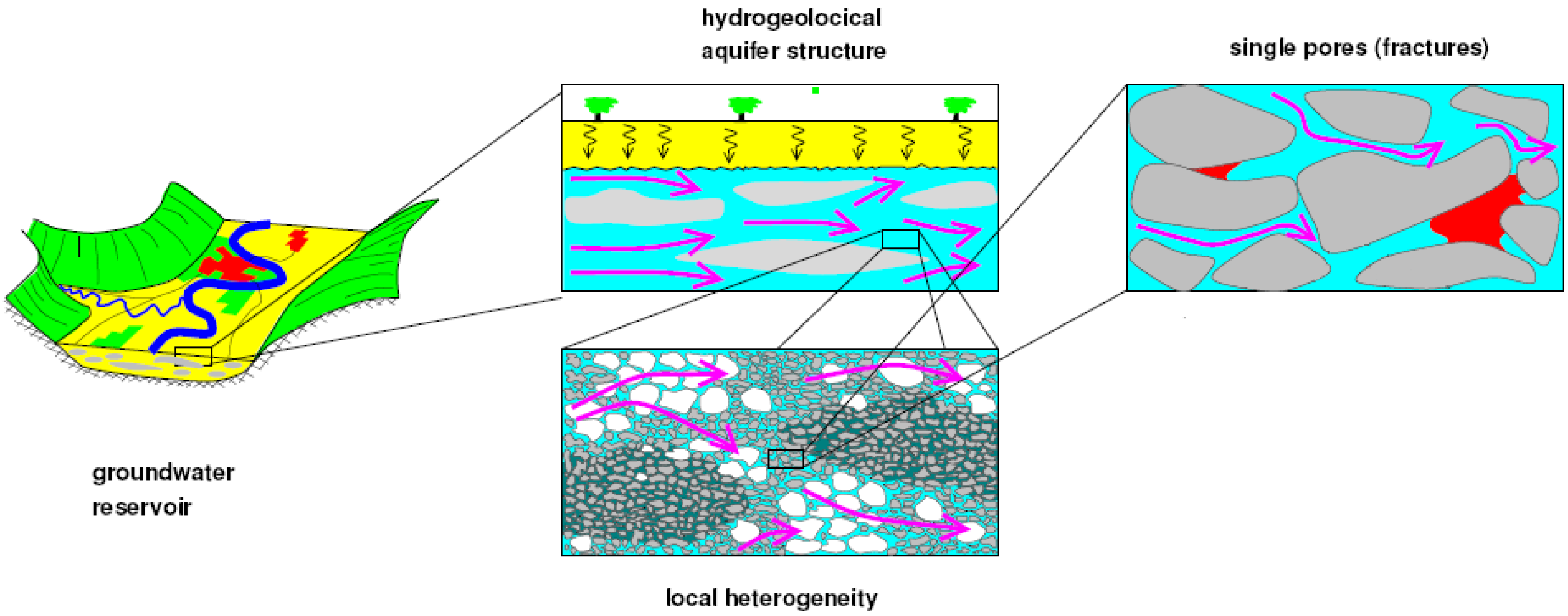
Interflow

Runoff

Q_{perc}

Base Flow

Conceptualization of Subsurface Flow

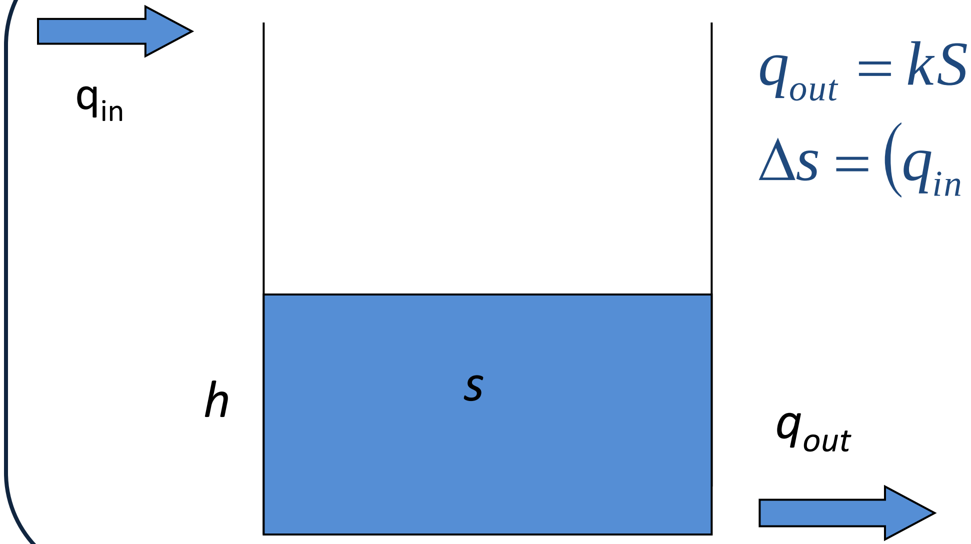


Modified after Kobus & Harr 1995

Linear reservoir model can be used to model subsurface flow

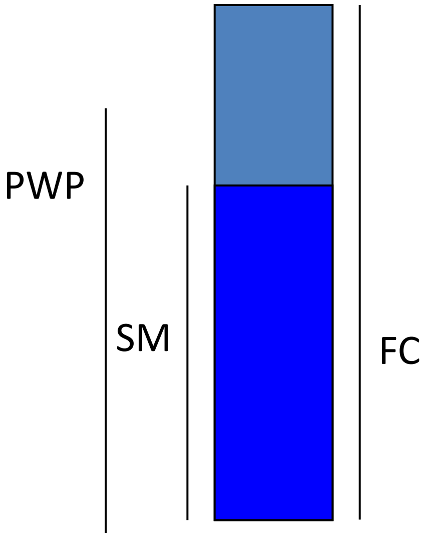
Linear Reservoir Model

Example: linear reservoir model



$$q_{out} = kS$$

$$\Delta s = \left(q_{in} - kS\right)\Delta t$$



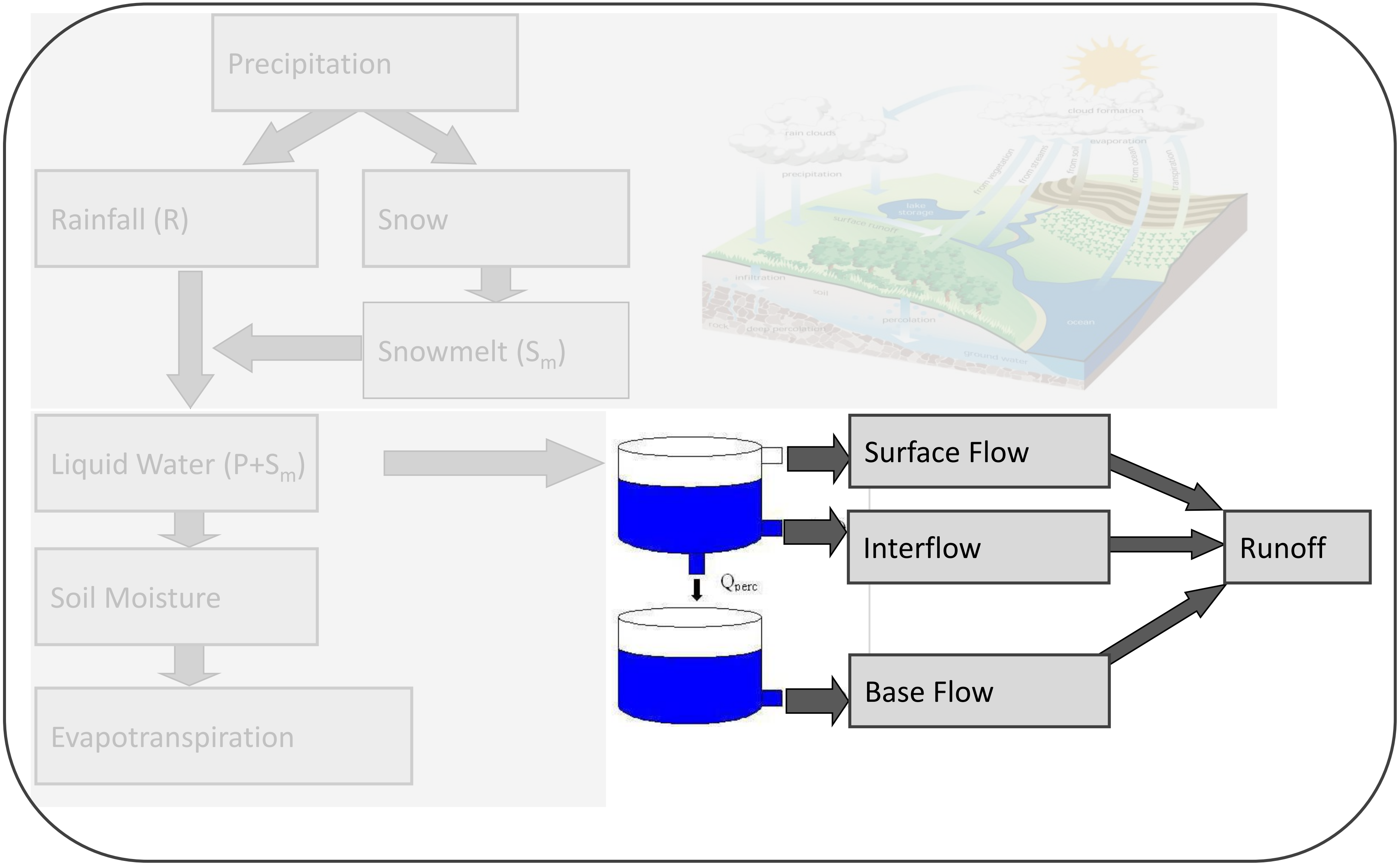
Real world analogy to variables & parameters

storage S ⇔ soil moisture

reservoir depth h ⇔ field capacity of the soil

reservoir constant k ⇔ retention capacity/hydraulic conductivity

Model Structure



Precipitation

Rainfall (R)

Snow

Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

Surface Flow

Interflow

Base Flow

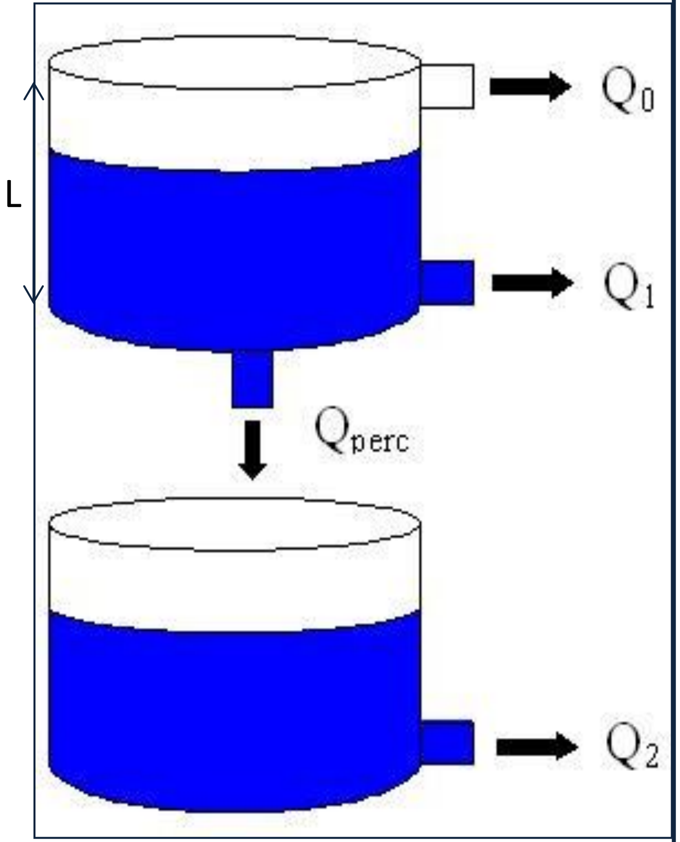
Runoff

Reservoir Concept

This module estimates the runoff at the catchment outlet based on the reservoir concept. The system consists of two conceptual reservoirs one above the other.

The first reservoir is used to model the near surface and sub-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}).



Reservoir Concept

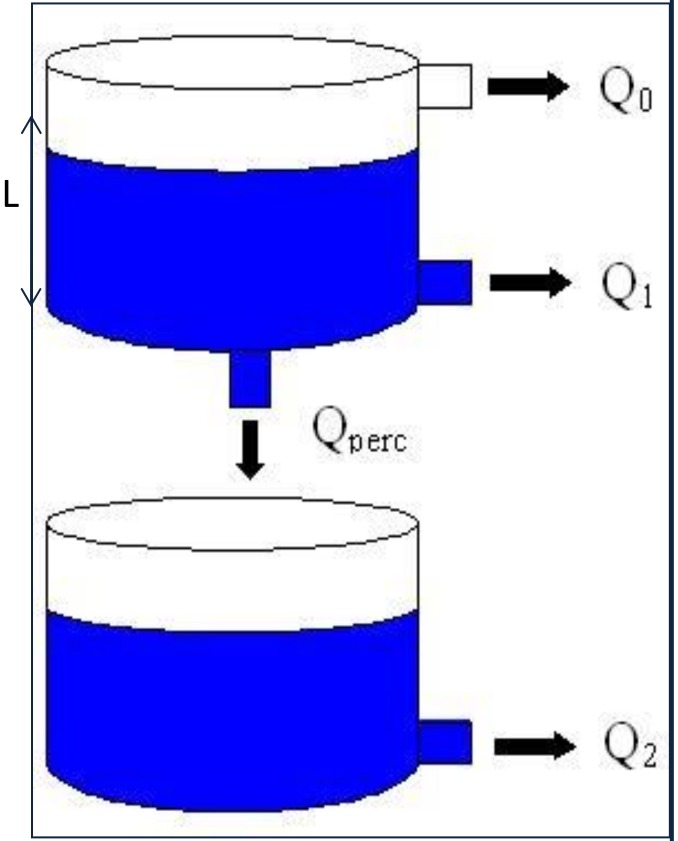
$$Q_0 = \begin{cases} K_0 \cdot (S_i - L) \cdot A_{sc} & \text{for } S > L \\ 0 & \text{for } S \leq L \end{cases}$$

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

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

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

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



Reservoir Concept

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

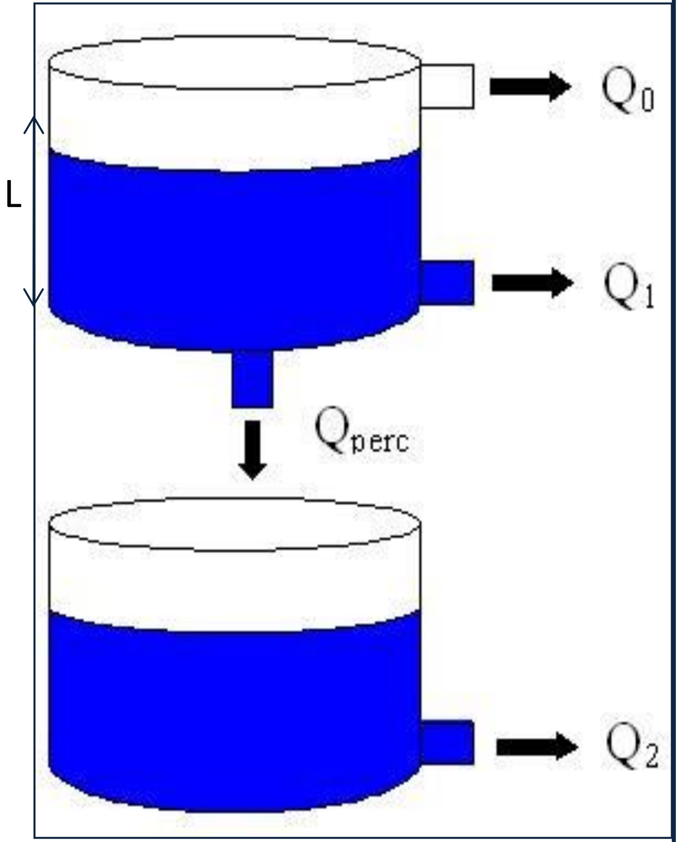
$$Q_1 = K_1 \cdot (S_i) \cdot A_{sc}$$

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

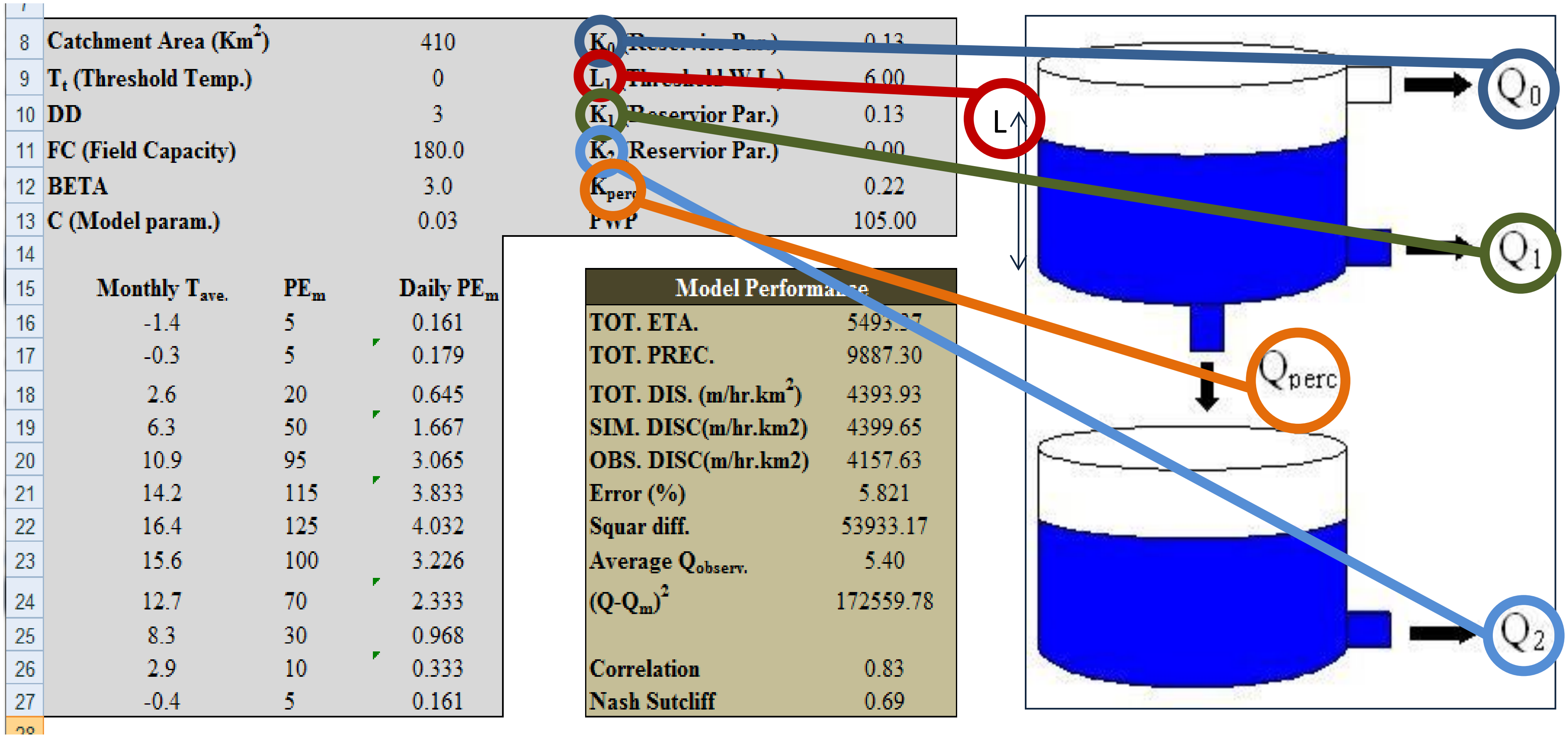
$$Q_2 = K_2 \cdot (S_b) \cdot A_{sc}$$

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

When the water level in the upper reservoir exceeds the threshold value *L*, runoff quickly occurs from the upper reservoir. The flow response of its other two outlets is relatively slower. Recession coefficients K0, K1, K2, represent the response function.



Reservoir Concept



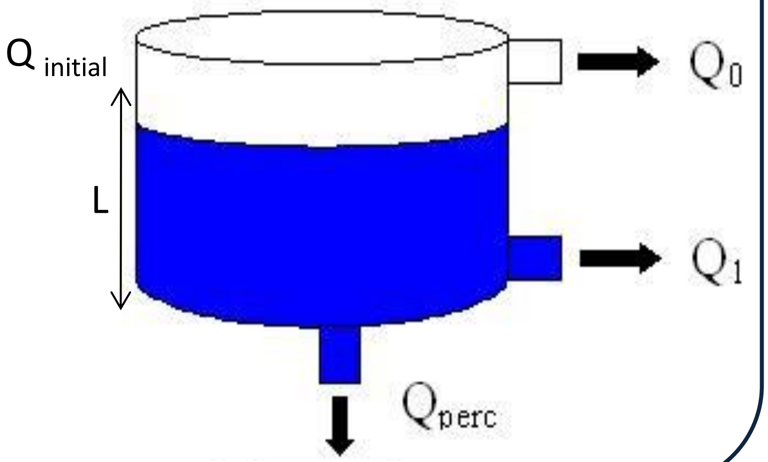
8	Catchment Area (Km^2)	410	K_0 (Reservior Par.)	0.13
9	T_t (Threshold Temp.)	0	L_1 (Threshold W.L.)	6.00
10	DD	3	K_1 (Reservior Par.)	0.13
11	FC (Field Capacity)	180.0	K_2 (Reservior Par.)	0.00
12	BETA	3.0	K_{perc}	0.22
13	C (Model param.)	0.03	PWP	105.00
14				

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
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

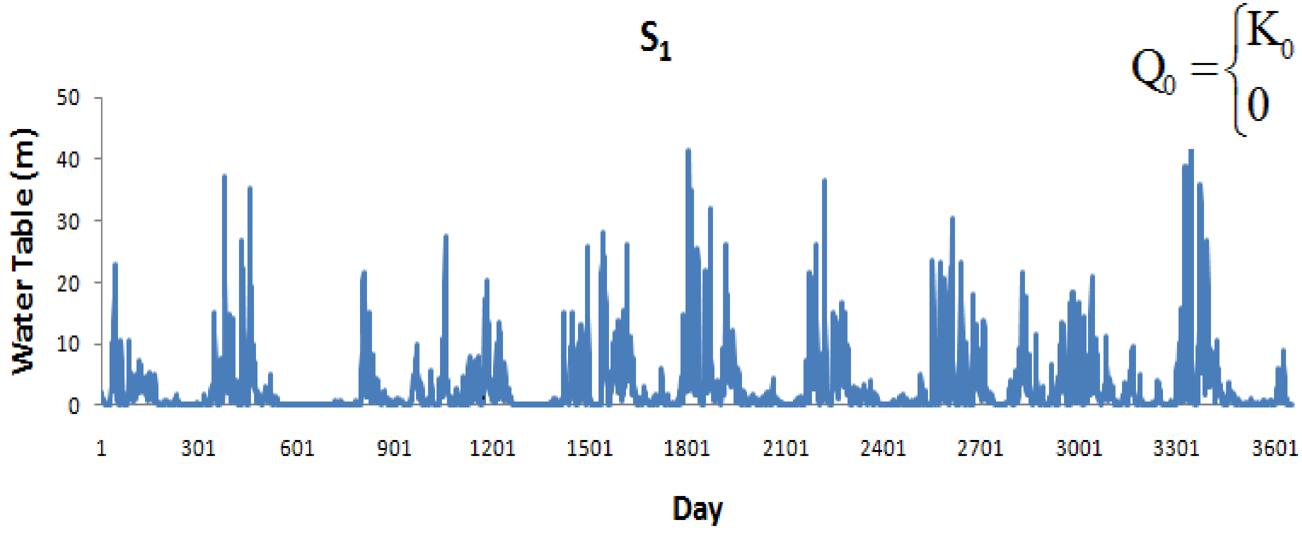
Reservoir Concept

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

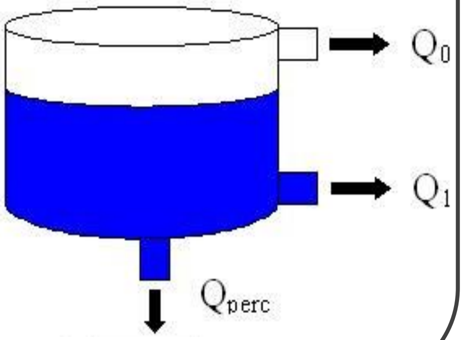


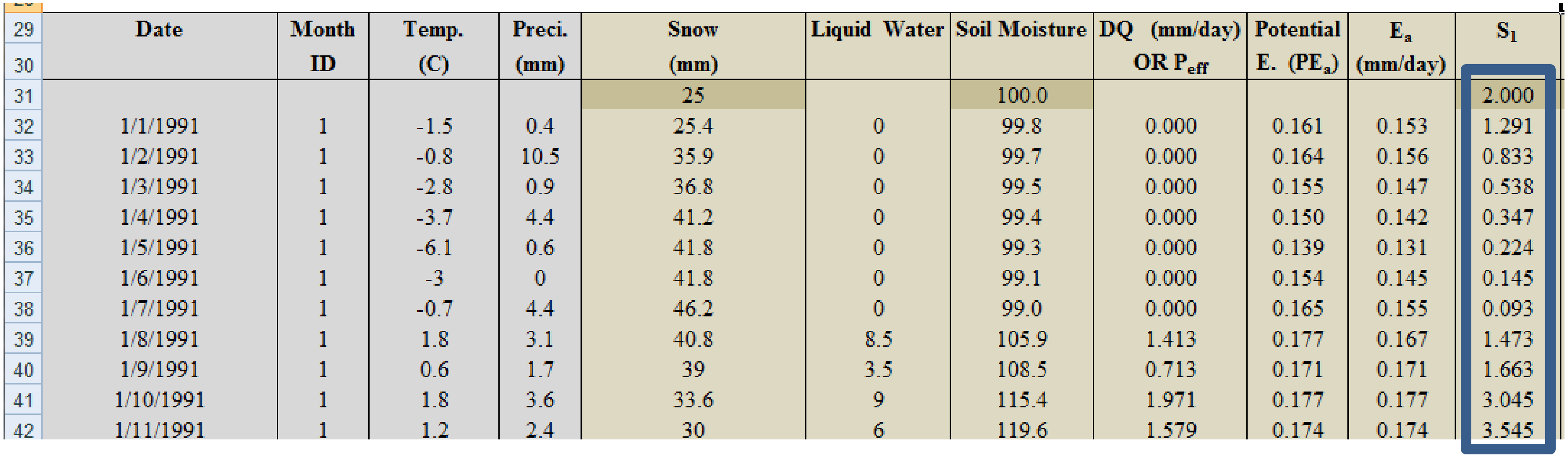
$$=\underbrace{K31}_{\text{Initial } S_1}+\underbrace{H32}_{P_{eff}}-\underbrace{MAX(0,K31-\$F\$9)*\$F\$8}_{(S_1-L)*\ K_0}-\underbrace{K31*\$F\$10}_{(S_1)*\ K_1}\ -\underbrace{K31*\$F\$12}_{(S_{perc})*\ K_{perc}}$$

Reservoir Concept



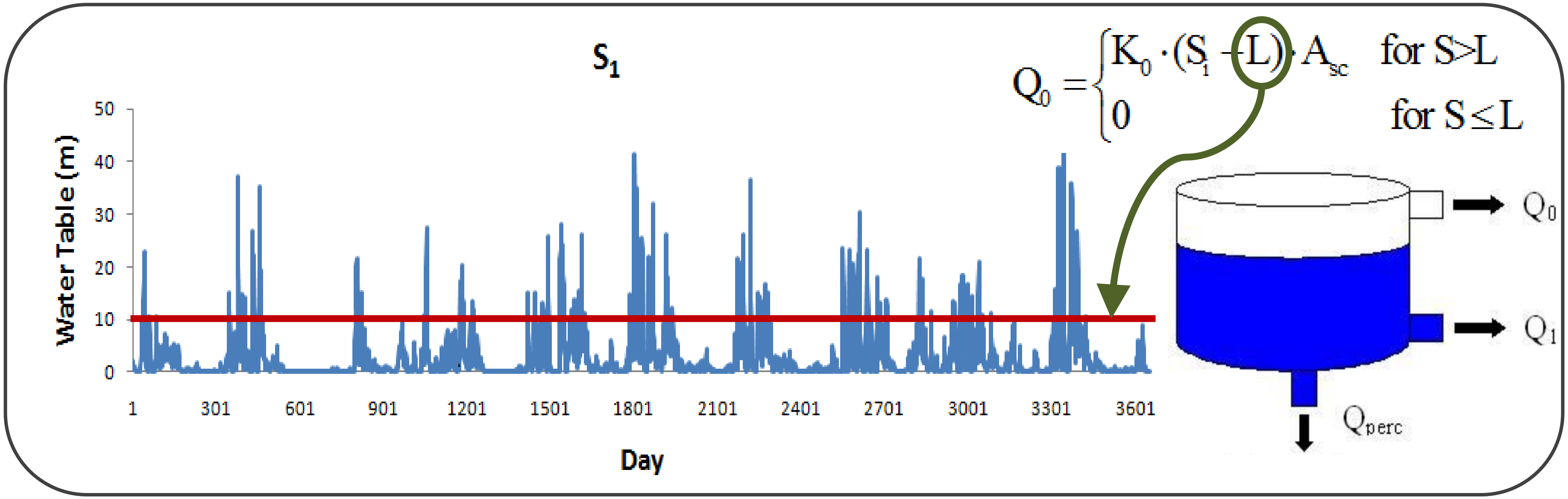
$$Q_0 = \begin{cases} K_0 \cdot (S_1 - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \le L \end{cases}$$



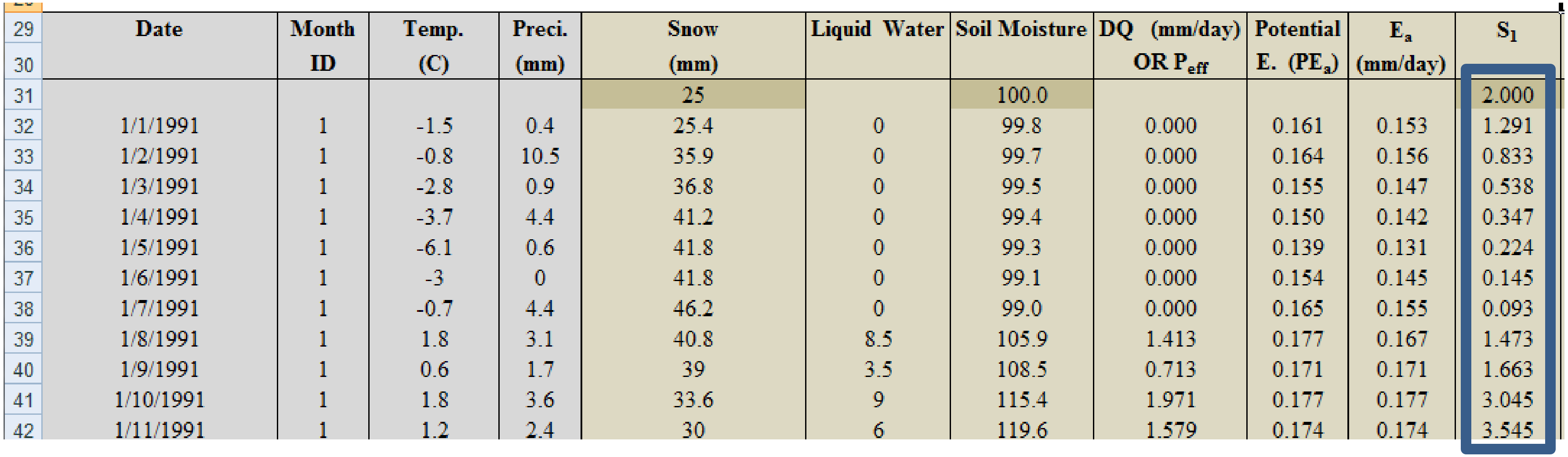


	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1
31					25		100.0				2.000
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093
39	1/8/1991	1	1.8	3.1	40.8	8.5	105.9	1.413	0.177	0.167	1.473
40	1/9/1991	1	0.6	1.7	39	3.5	108.5	0.713	0.171	0.171	1.663
41	1/10/1991	1	1.8	3.6	33.6	9	115.4	1.971	0.177	0.177	3.045
42	1/11/1991	1	1.2	2.4	30	6	119.6	1.579	0.174	0.174	3.545

Reservoir Concept

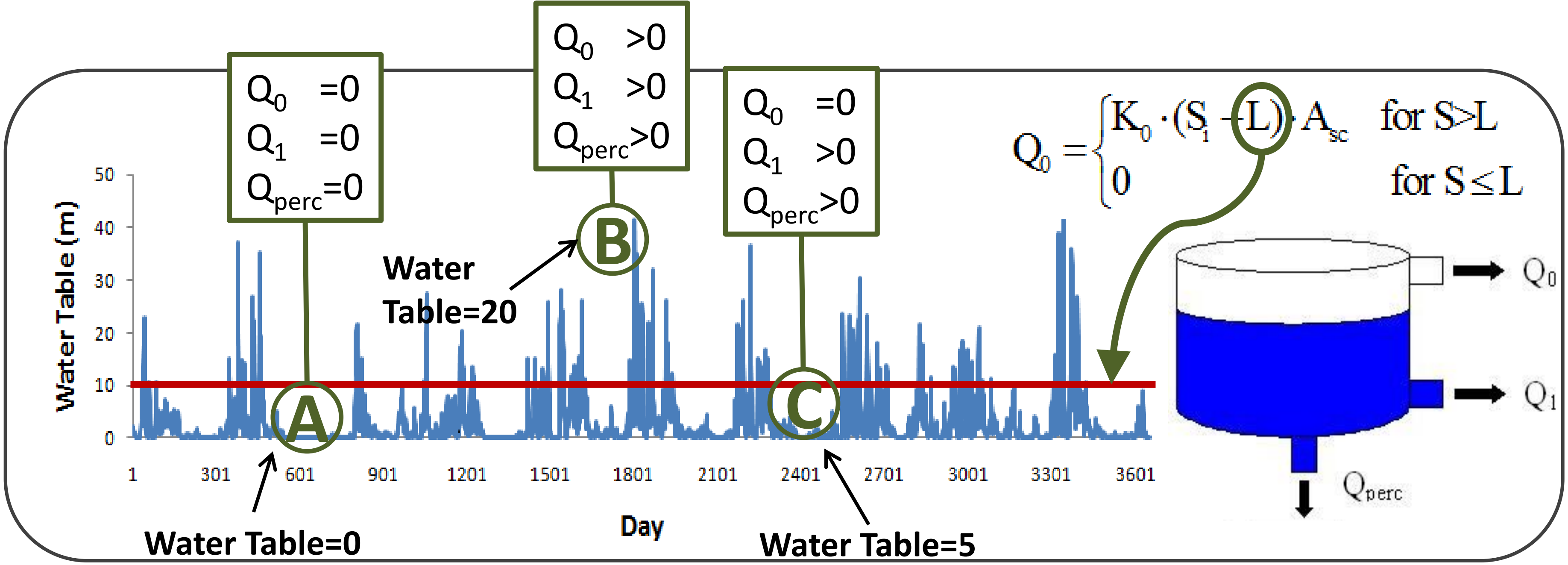


$$Q_0 = \begin{cases} K_0 \cdot (S_1 - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \le L \end{cases}$$

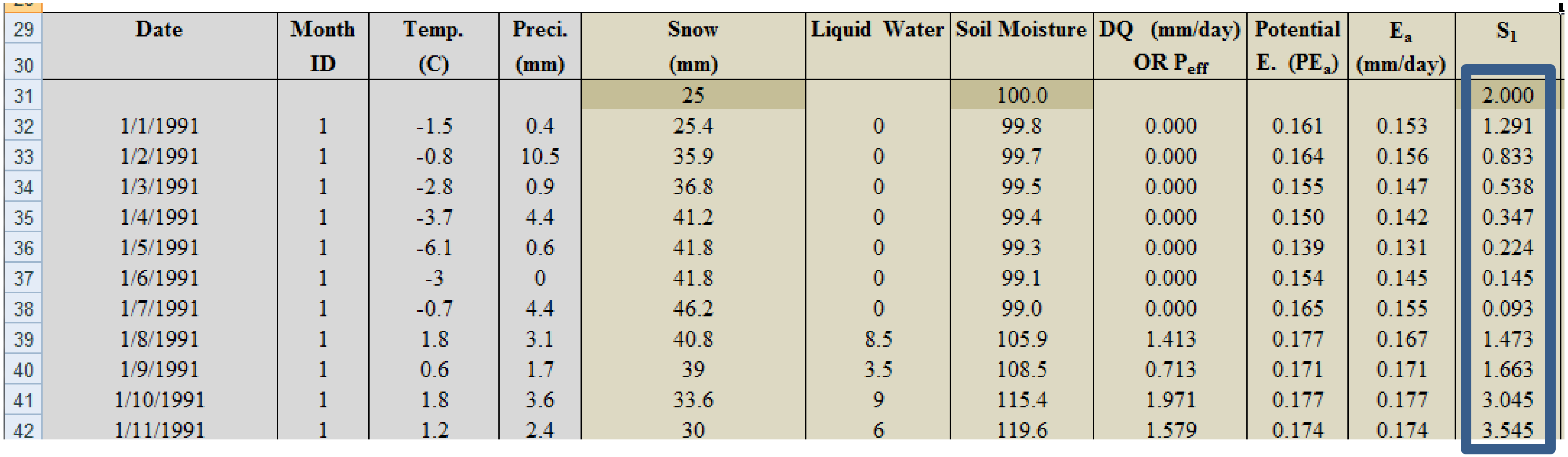


	Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1
31					25		100.0				2.000
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093
39	1/8/1991	1	1.8	3.1	40.8	8.5	105.9	1.413	0.177	0.167	1.473
40	1/9/1991	1	0.6	1.7	39	3.5	108.5	0.713	0.171	0.171	1.663
41	1/10/1991	1	1.8	3.6	33.6	9	115.4	1.971	0.177	0.177	3.045
42	1/11/1991	1	1.2	2.4	30	6	119.6	1.579	0.174	0.174	3.545

Reservoir Concept



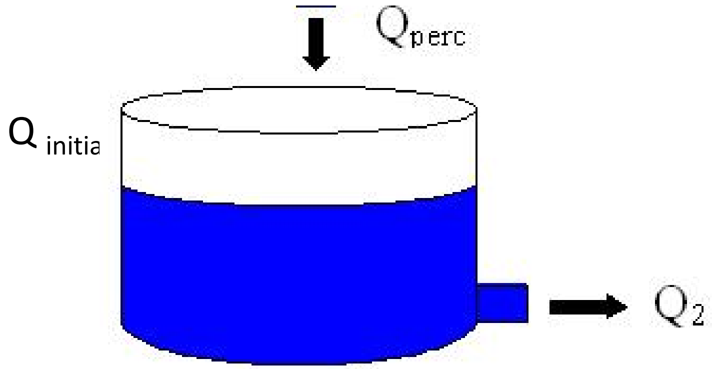
$$Q_0 = \begin{cases} K_0 \cdot (S_1 - L) \cdot A_{sc} & \text{for } S>L \\ 0 & \text{for } S \le L \end{cases}$$



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)	S_1
31					25		100.0				2.000
32	1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291
33	1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833
34	1/3/1991	1	-2.8	0.9	36.8	0	99.5	0.000	0.155	0.147	0.538
35	1/4/1991	1	-3.7	4.4	41.2	0	99.4	0.000	0.150	0.142	0.347
36	1/5/1991	1	-6.1	0.6	41.8	0	99.3	0.000	0.139	0.131	0.224
37	1/6/1991	1	-3	0	41.8	0	99.1	0.000	0.154	0.145	0.145
38	1/7/1991	1	-0.7	4.4	46.2	0	99.0	0.000	0.165	0.155	0.093
39	1/8/1991	1	1.8	3.1	40.8	8.5	105.9	1.413	0.177	0.167	1.473
40	1/9/1991	1	0.6	1.7	39	3.5	108.5	0.713	0.171	0.171	1.663
41	1/10/1991	1	1.8	3.6	33.6	9	115.4	1.971	0.177	0.177	3.045
42	1/11/1991	1	1.2	2.4	30	6	119.6	1.579	0.174	0.174	3.545

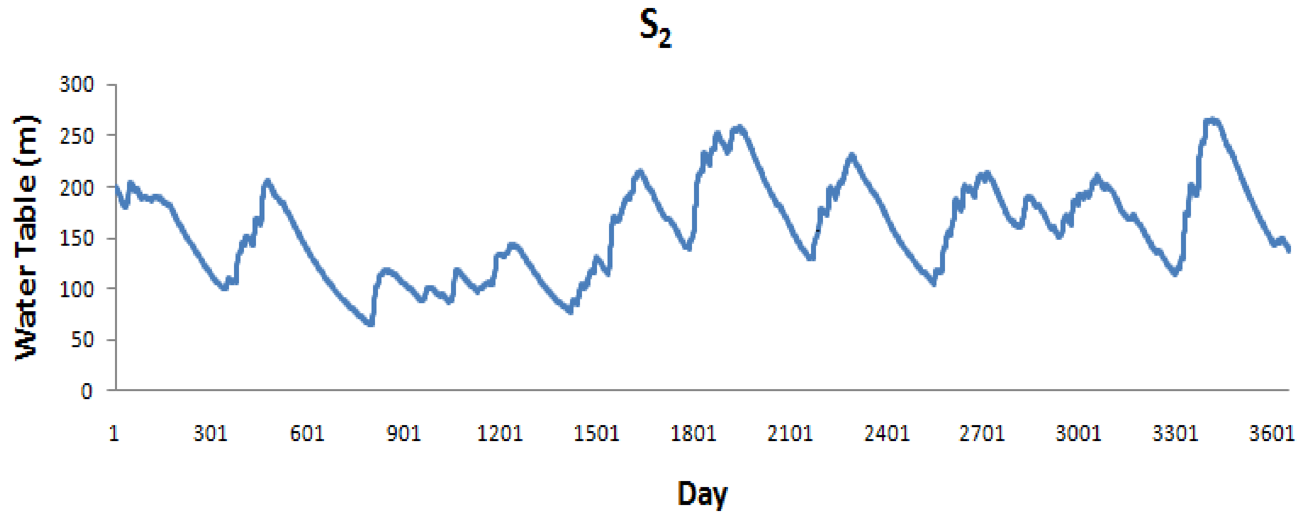
Reservoir Concept

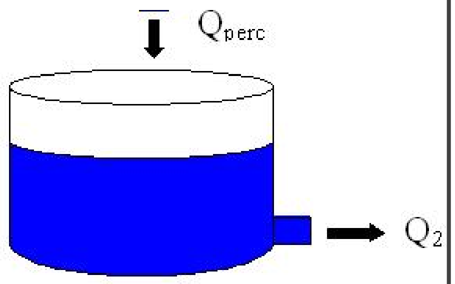
$$S_2 = Q_{\text{initial}} - Q_2 + Q_{perc}$$

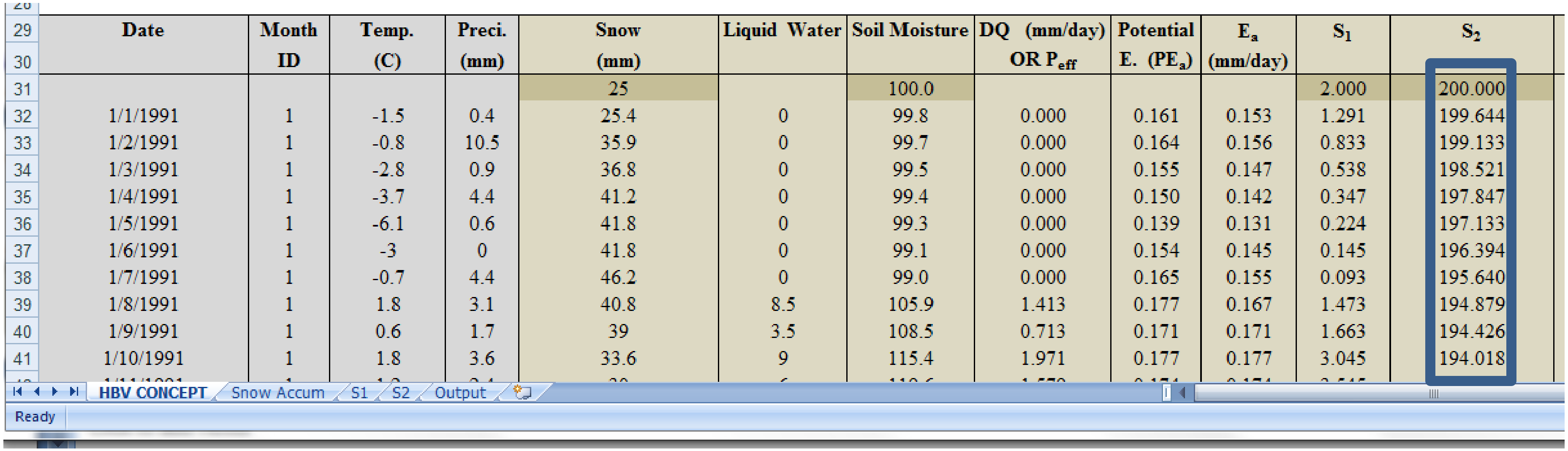


$$=\underbrace{L31}_{\text{Initial } S_2}+\underbrace{K31*\$F\$12}_{(S_1)*\ K_{perc}}\underbrace{-L31*\$F\$11}_{(S_2)*\ K_2}$$

Reservoir Concept

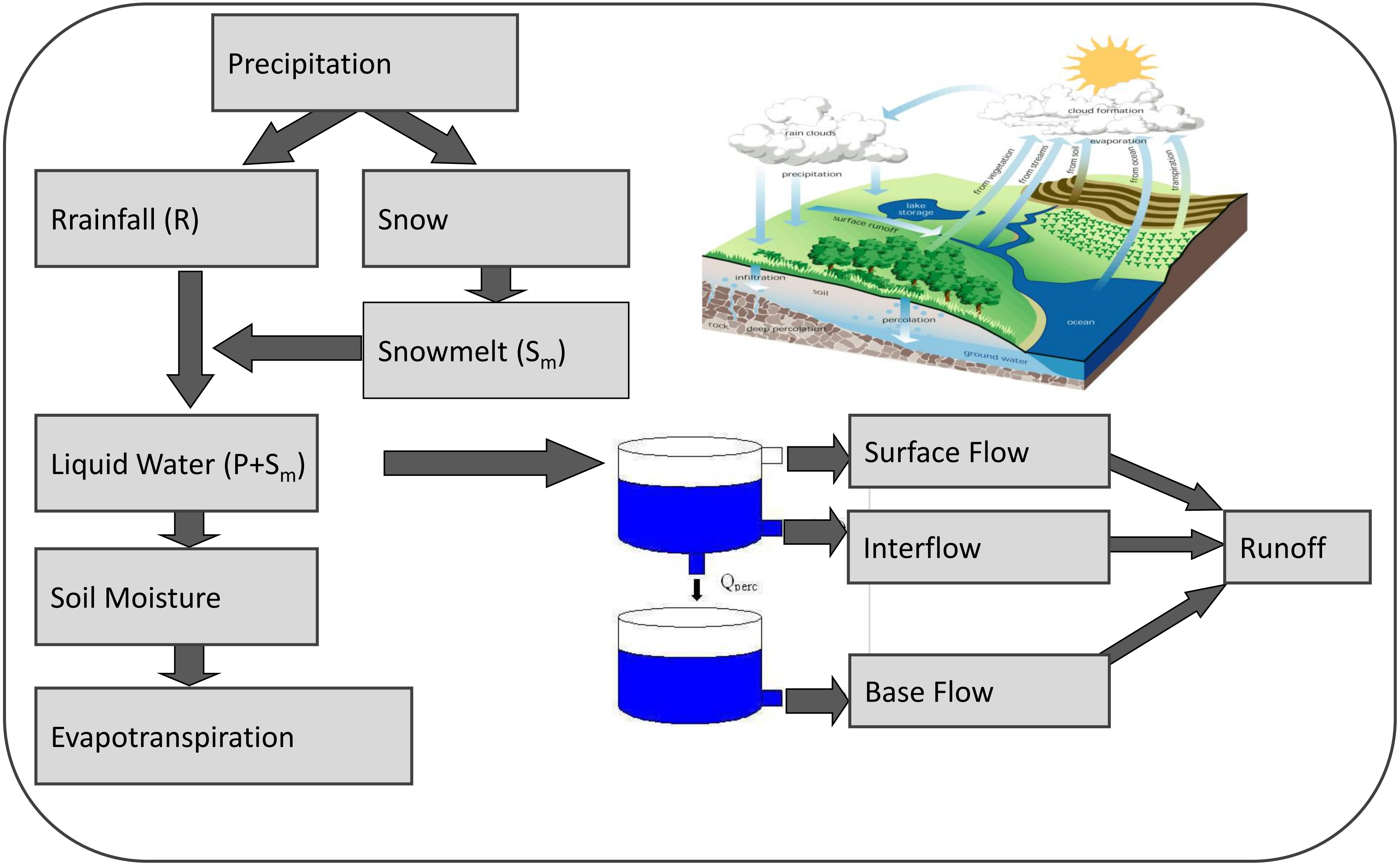






Date	Month ID	Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2
				25		100.0				2.000	200.000
1/1/1991	1	-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644
1/2/1991	1	-0.8	10.5	35.9	0	99.7	0.000	0.164	0.156	0.833	199.133
1/3/1991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

Model Structure



Precipitation

Rrainfall (R)

Snow

Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

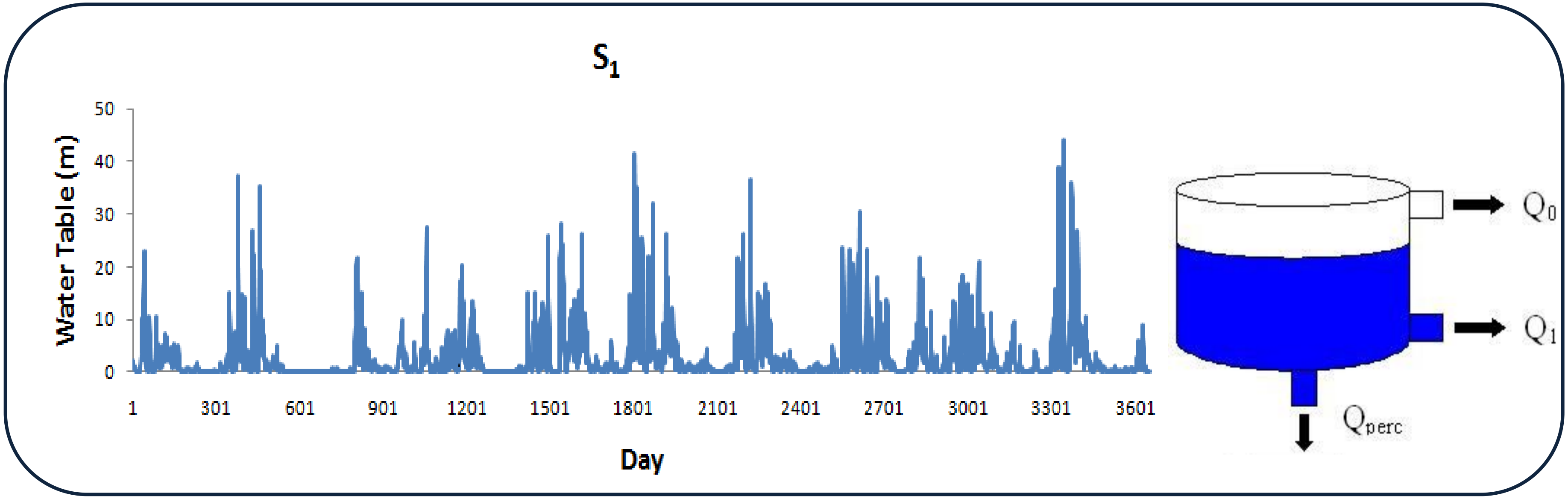
Surface Flow

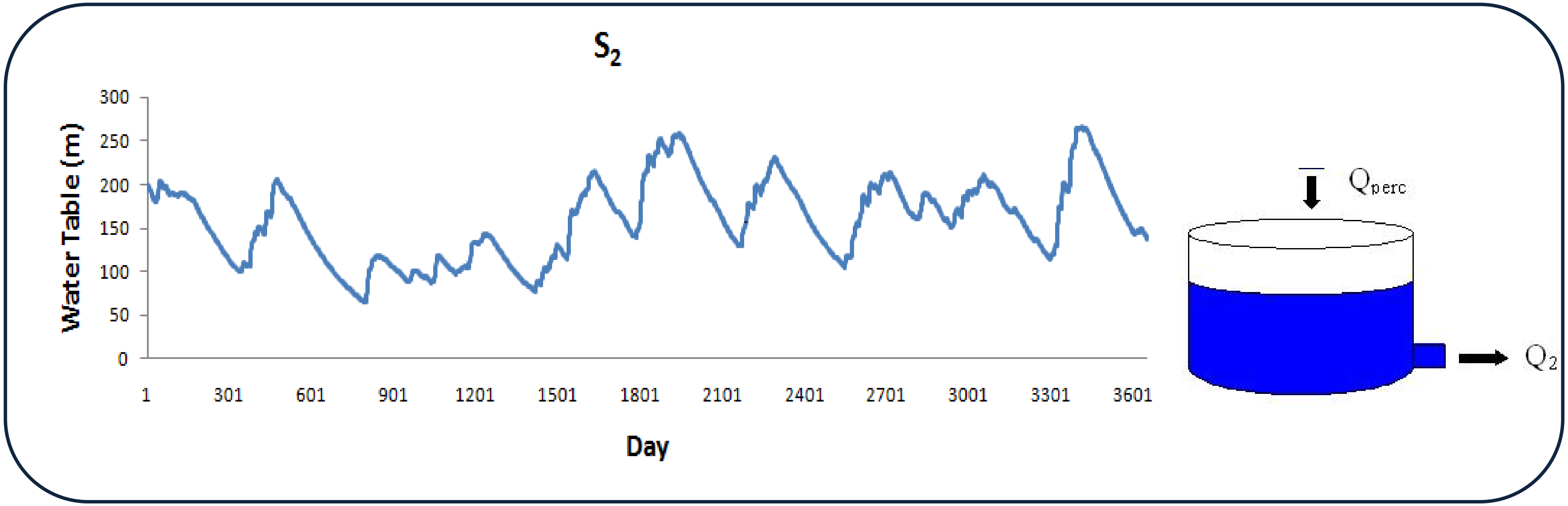
Interflow

Base Flow

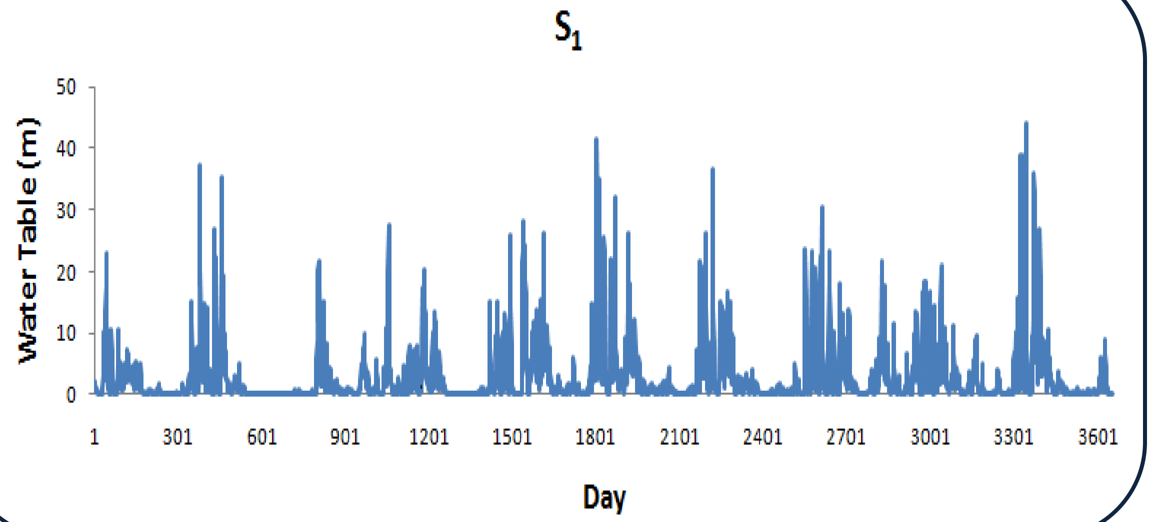
Runoff

Reservoir Concept





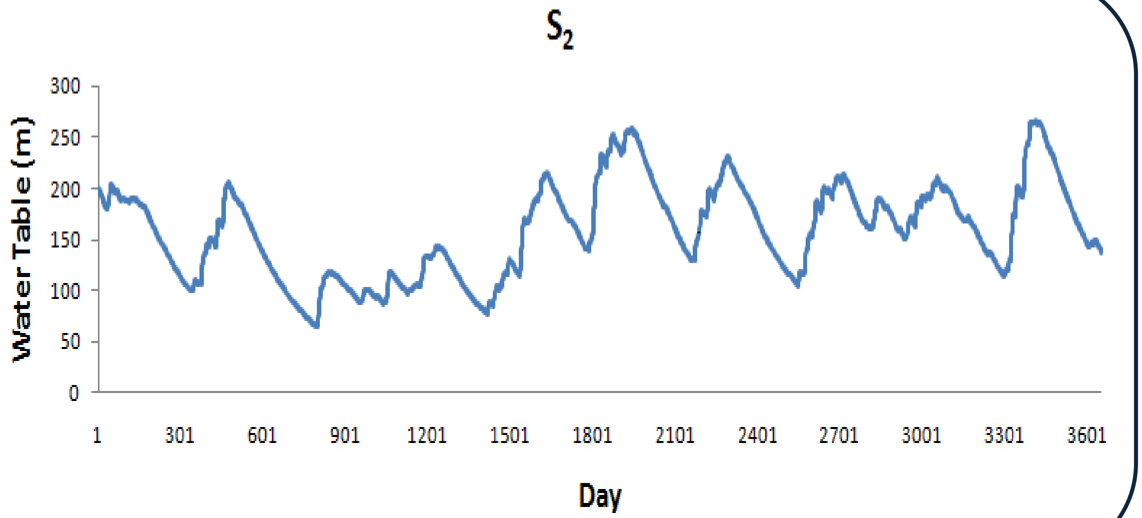
Reservoir Concept



$$Q_0 = K_0 .(S_1 - L). A$$

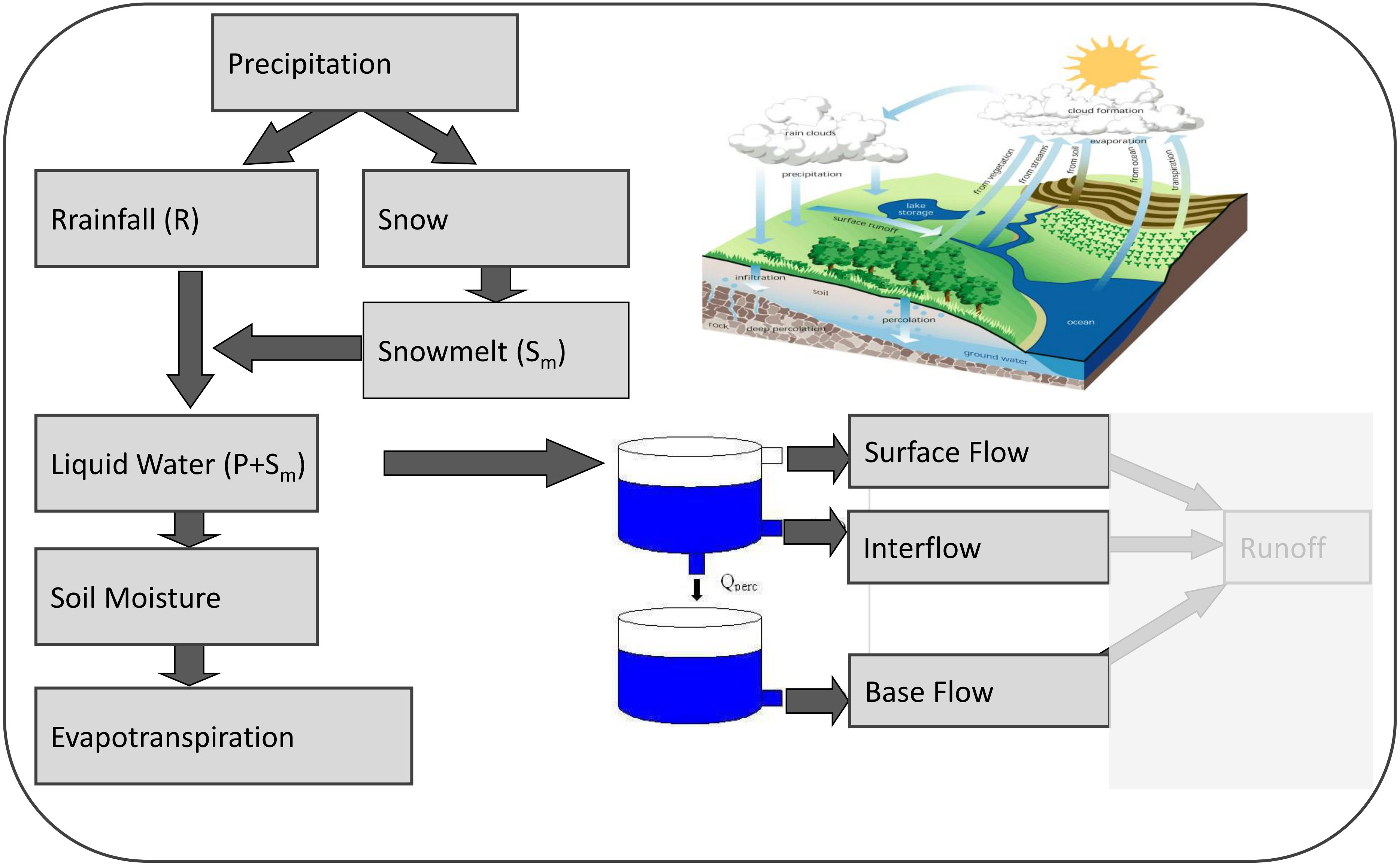
$$Q_1 = K_1 . S_1 . A$$

$$Q_2 = K_2 . S_2 . A$$



$$K_0 > K_1 > K_2$$

Model Structure



Precipitation

Rrainfall (R)

Snow

Snowmelt (S_m)

Liquid Water ($P+S_m$)

Soil Moisture

Evapotranspiration

Surface Flow

Interflow

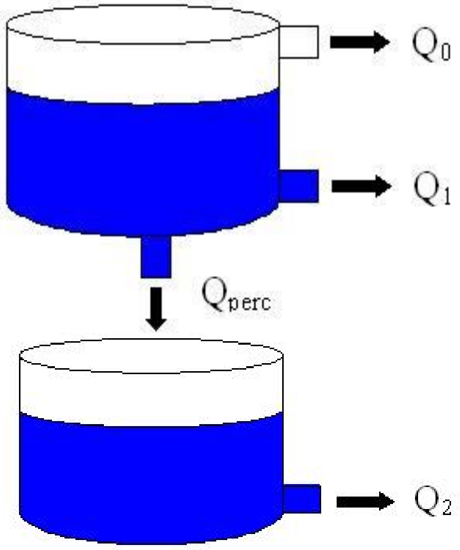
Base Flow

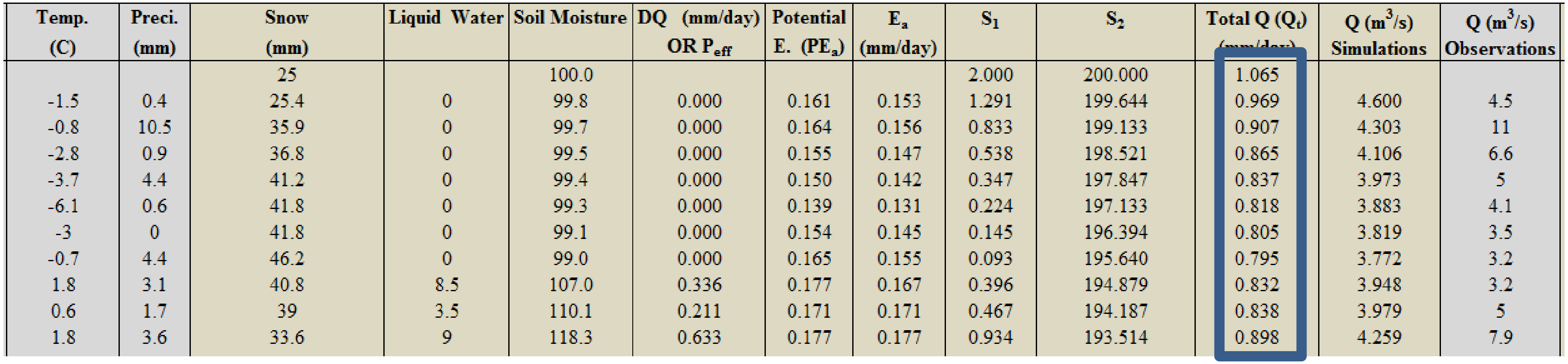
Runoff

Runoff Response

$$Q = Q_0 + Q_1 + Q_2$$

=MAX(0,K31-$F$9)*$F$8+K31*$F$10+L31*$F$11



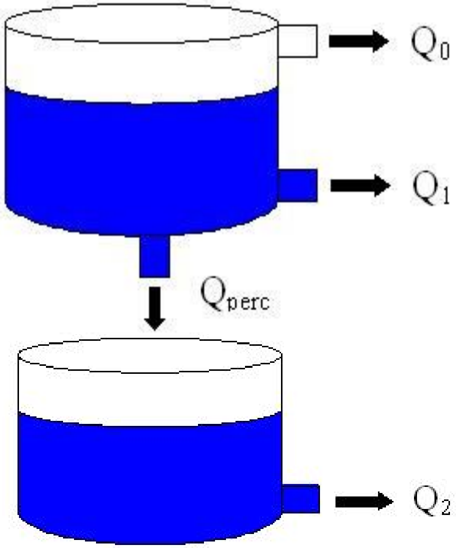


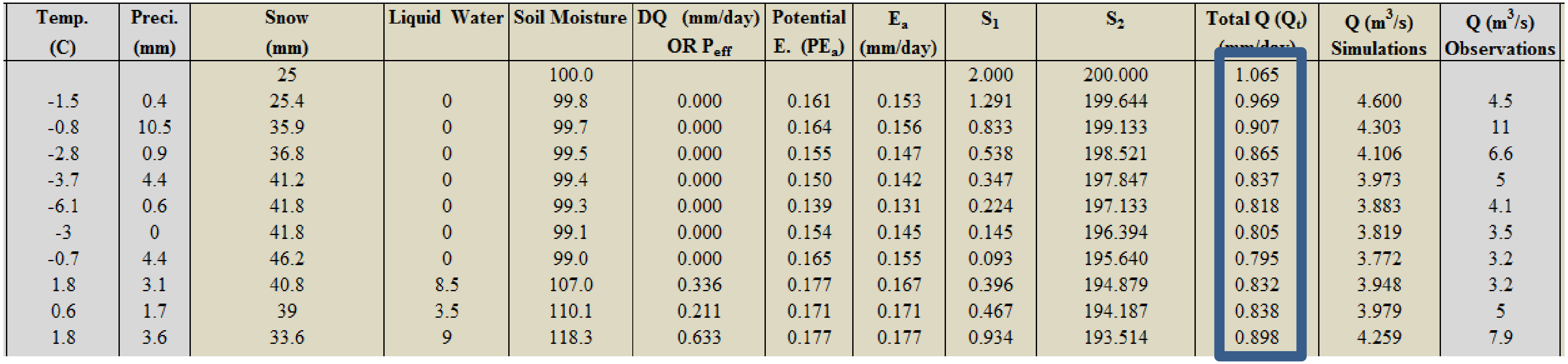
Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations
		25		100.0				2.000	200.000	1.065		
-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5
-0.8	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

Runoff Response

$$Q = Q_0 + Q_1 + Q_2$$

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



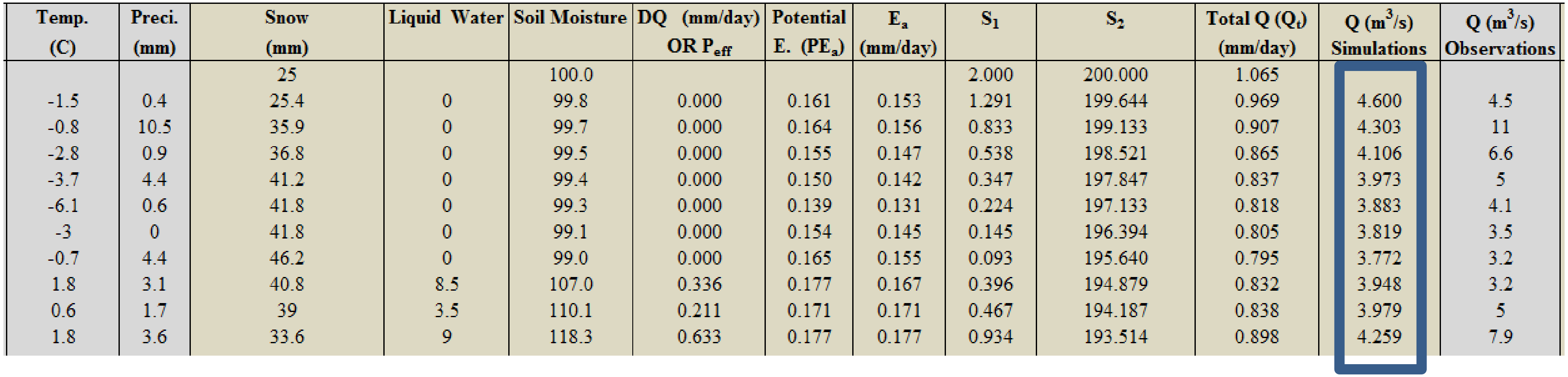


Temp. (C)	Preci. (mm)	Snow (mm)	Liquid Water	Soil Moisture	DQ (mm/day) OR P_{eff}	Potential E. (PE_a)	E_a (mm/day)	S_1	S_2	Total Q (Q_t) (mm/day)	Q (m^3/s) Simulations	Q (m^3/s) Observations
		25		100.0				2.000	200.000	1.065		
-1.5	0.4	25.4	0	99.8	0.000	0.161	0.153	1.291	199.644	0.969	4.600	4.5
-0.8	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

Runoff Response

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

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



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

Runoff Response