CWEMF
IWFM v4.0 Workshop

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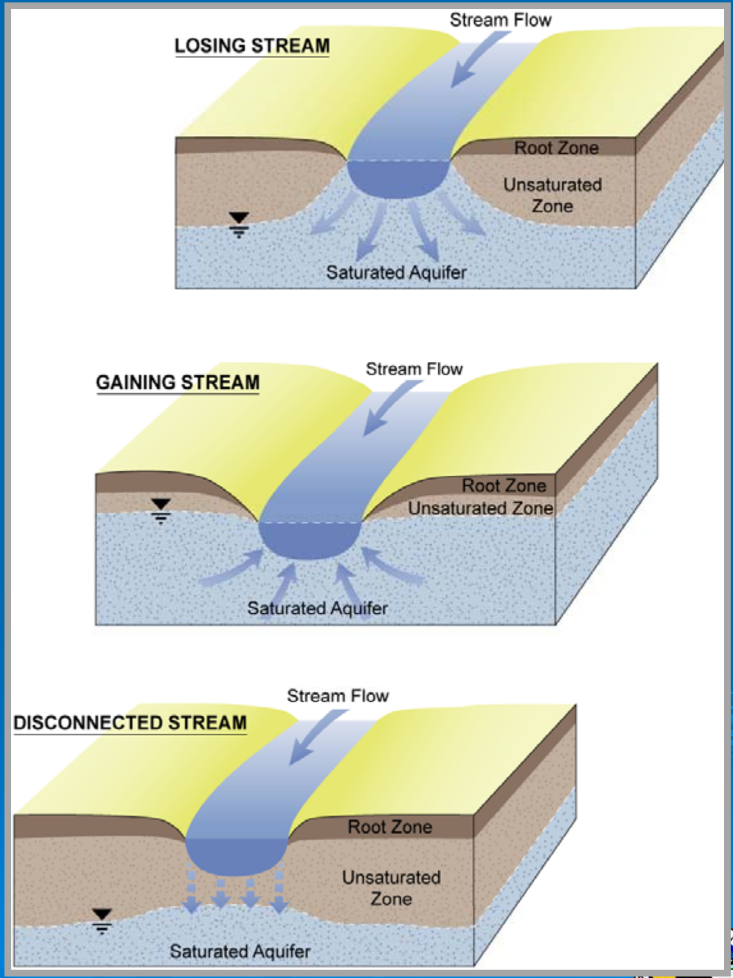
Session 2:
Stream Flow and Lake Routing

Stream Flow

- Continuous interaction with the groundwater system
- Contributes water to groundwater in wet periods
- Gains water from groundwater in dry periods
- Used as a source of water supply to meet agricultural and urban demands



Stream Flow

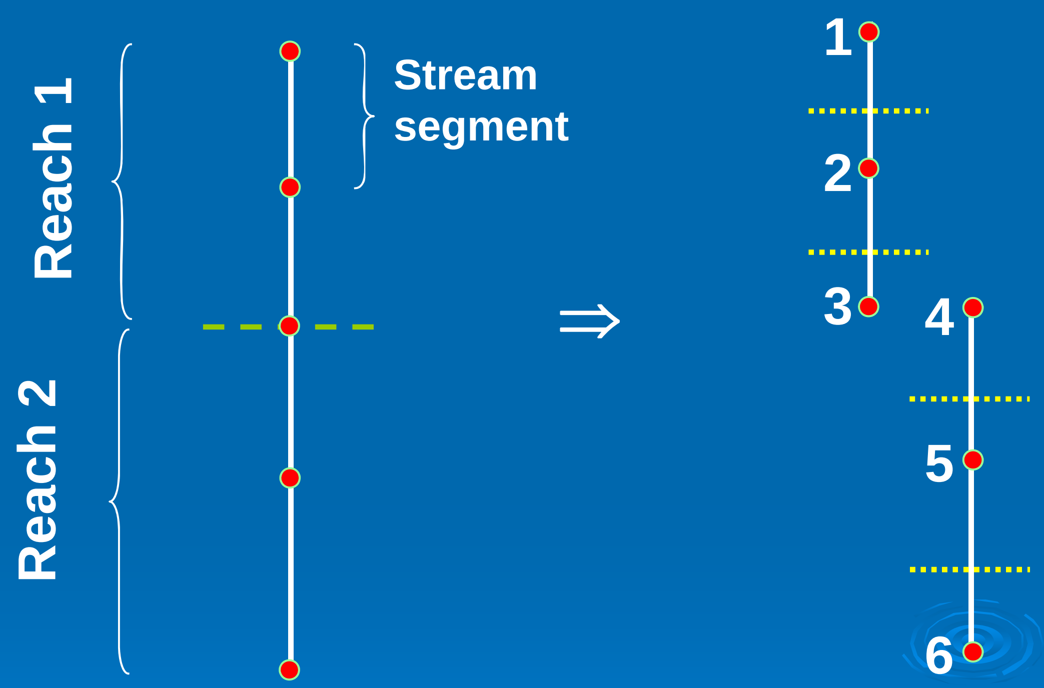
- Assumption of zero storage at a stream node (requires simulation time step to be large enough for stream flow to travel from upstream to downstream in a single time step)

$$\mathbf{Q_s - Q_{sin} + Q_{sout} = 0} \Rightarrow \begin{cases} Q_s & = \text{stream flow, } (L^3/T) \\ Q_{sin} & = \text{total inflows into stream, } (L^3/T) \\ Q_{sout} & = \text{total outflows from stream, } (L^3/T) \end{cases}$$

Inflows	Outflows
Flow from upstream nodes	Diversions
Irrigation return flow	Bypasses
Rainfall runoff	*Stream-aquifer interactions*
Inflows from small watersheds	
Tile drains	
Lake outflow	
Bypasses	
User-specified inflows	

Construction of a Stream Network

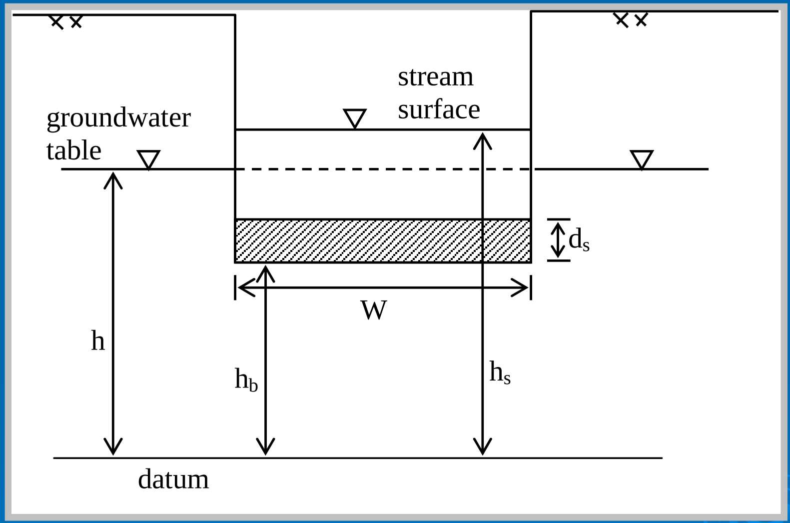
- Iteration over reaches first, then stream nodes
- Flow direction and stream network configuration are specified through reach and stream node numbering (reach 1 is the most upstream reach, stream node 1 is the most upstream node in reach 1)
- Each stream node is assigned to a groundwater node



Stream-Groundwater Interaction

$$Q_{sint} = C_s \left[\max\left(h_s, h_b\right) - \max\left(h, h_b\right) \right] \quad ; \quad C_s = \frac{K_s}{d_s} LW$$

- Q_{sint} = stream-aquifer interaction, (L^3/T)
- h = groundwater head, (L)
- h_s = stream surface elevation, (L)
- h_b = stream bottom elevation, (L)
- K_s = stream bed hydraulic conductivity, (L/T)
- d_s = stream bed thickness, (L)
- L = length of stream segment, (L)
- W = channel width, (L)



Solution of Stream Flow Equation

- Stream flow equations are linearized using Newton-Raphson method
- Stream flow and groundwater equations are fully coupled and solved simultaneously

$$\left.\begin{array}{l}\left[\mathbf{X}_s^{t+1}\right]\left\{\mathbf{h}_s^{t+1}\right\}+\left\{\mathbf{F}_s^{t+1}\right\}=0\\[2em]\left[\mathbf{X}_g^{t+1}\right]\left\{\mathbf{h}_g^{t+1}\right\}+\left\{\mathbf{F}_g^{t+1}\right\}=0\end{array}\right\}\Rightarrow\left[\mathbf{X}^{t+1}\right]\left\{\mathbb{H}^{t+1}\right\}+\left\{\mathbf{F}^{t+1}\right\}=0$$

$$\left\{\mathbb{H}^{t+1}\right\}^{T}=\left\{\mathbf{h}_{s_1}^{t+1},\cdots,\mathbf{h}_{s_{NS}}^{t+1},\mathbf{h}_1^{t+1},\cdots,\mathbf{h}_{N\times N_L}^{t+1}\right\}$$

- Stream-aquifer interaction is a by-product of the simultaneous solution of stream and groundwater equations

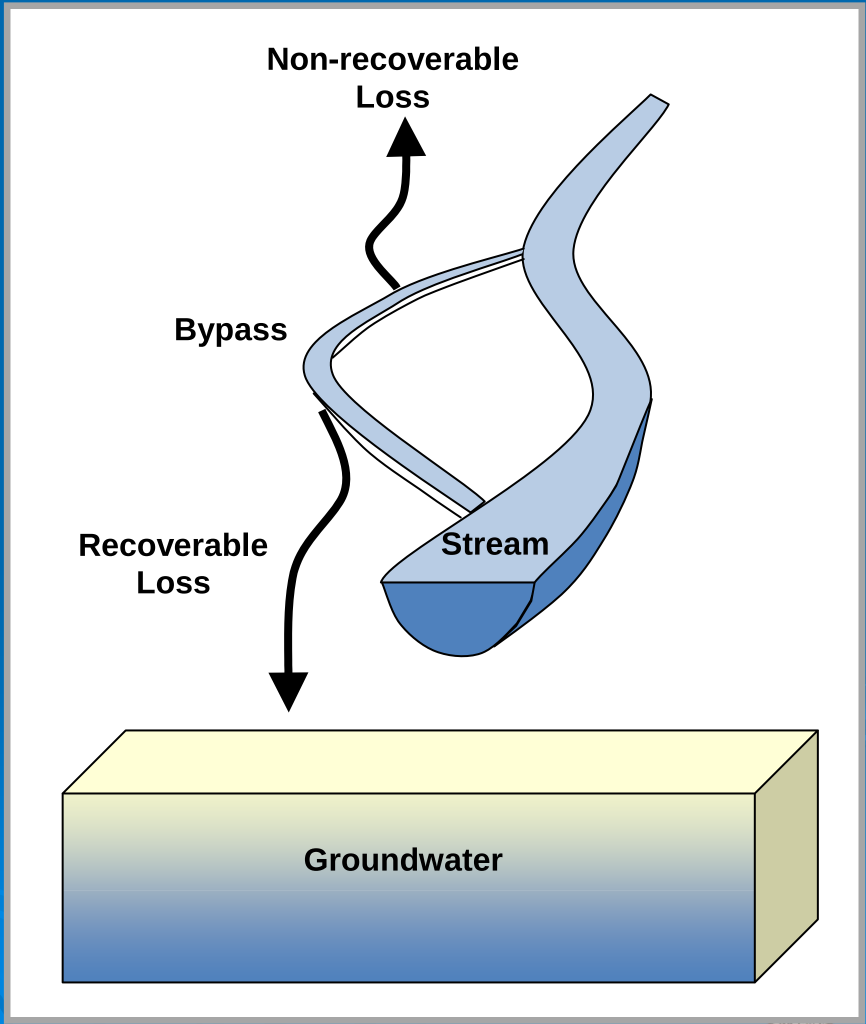
Solution of Stream Flow Equation

- Convergence criteria for the Newton-Raphson method:

$$\sqrt{\sum_{i}\left\{\left(\mathbb{H}_{i}^{t+1}\right)^{k+1}-\left(\mathbb{H}_{i}^{t+1}\right)^{k}\right\}^{2}}\leq\varepsilon \quad ; \quad i=1,\cdots\cdots,NS+N\times N_{L}$$

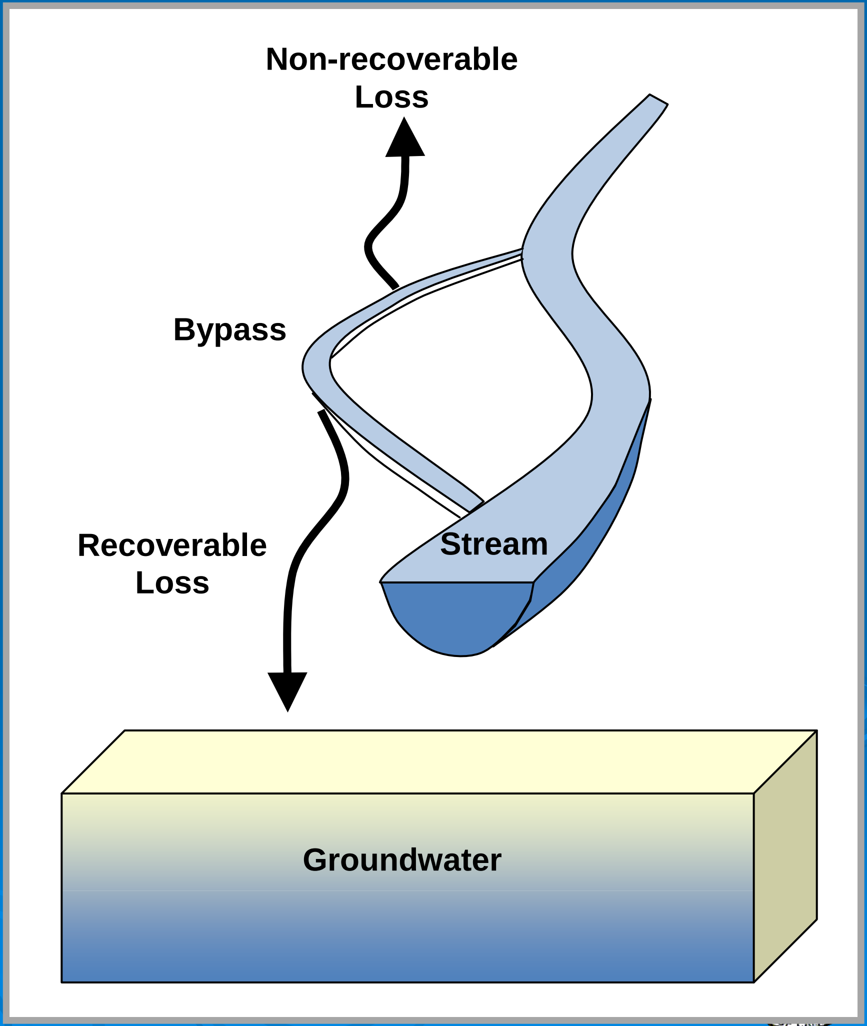
Stream Flow Bypasses

- Bypasses are generally used as flood control facilities
- Each bypass originates from a stream node and gets delivered to another stream node or a lake
- A portion of each bypass is lost as non-recoverable (evaporation) and recoverable (seepage from bypass canals into groundwater) losses; the fractions for recoverable and non-recoverable losses are specified by the user



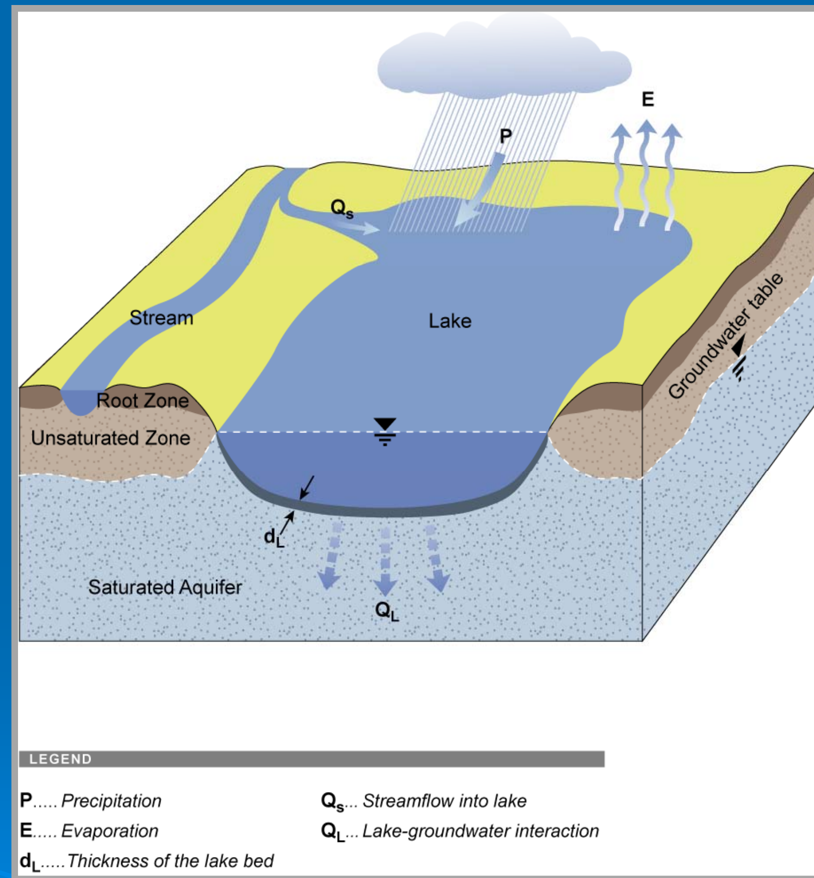
Stream Flow Bypasses

- Bypass flow amounts can be specified as a rating table (stream flow vs. bypass flow) or as a pre-defined time-series data
- Bypasses can be used to simulate artificial aquifer recharge operations through the use of recoverable loss
- In IWFM bypasses must be used to simulate stream network bifurcations



Lakes

- Interact with streams and aquifer system
- Can be hydraulically connected or disconnected to the aquifer system
- Lake storage is a function of precipitation, evaporation, inflows from upstream lakes and streams, lake-groundwater interaction and lake outflow
- One or more elements can be specified as lake elements



Lakes

- Conservation equation for lake storage:

$$\frac{\partial S_{lk}}{\partial t} - \sum_{i=1}^{N_{lk}} \left(P_{lk_i} A_{lk_i} - EV_{lk_i} A_{lk_i} - Q_{lkint_i} \right) - Q_{brlk} - Q_{inlk} + Q_{lko} = 0$$

S_{lk} = Lake storage, (L^3);
P_{lk} = Precipitation rate at lake node i, (L / T);
EV_{lk} = Evaporation rate at lake node i, (L/T);
Q_{lkint} = Lake-groundwater interaction, (L^3 / T);
Q_{brlk} = Inflow from bypass flows, (L^3 / T);
Q_{inlk} = Inflow from upstream lakes, (L^3 / T);
Q_{lko} = Outflow from lake, (L^3 / T);
A_{lk} = Area associated with lake node i, (L^2);
N_{lk} = Number of lake nodes for a lake.

Lakes

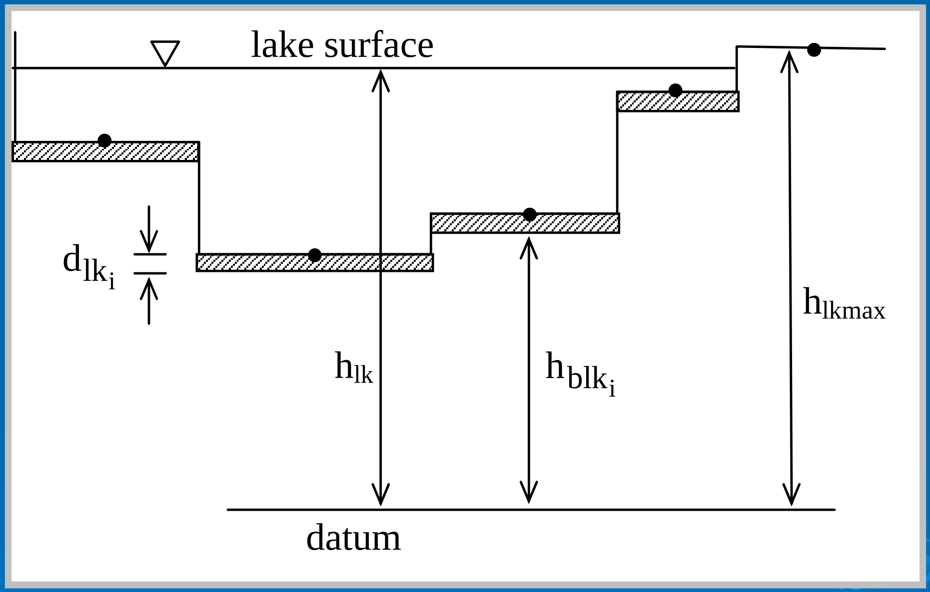
- Lake storage is a function of lake elevation computed internally in IWFM:

$$S_{lk} = S_{lk}\left(h_{lk}\right)$$

- Lake outflow is computed when lake surface elevation exceeds maximum lake elevation:

$$h_{lk} \leq h_{lk\,max}$$

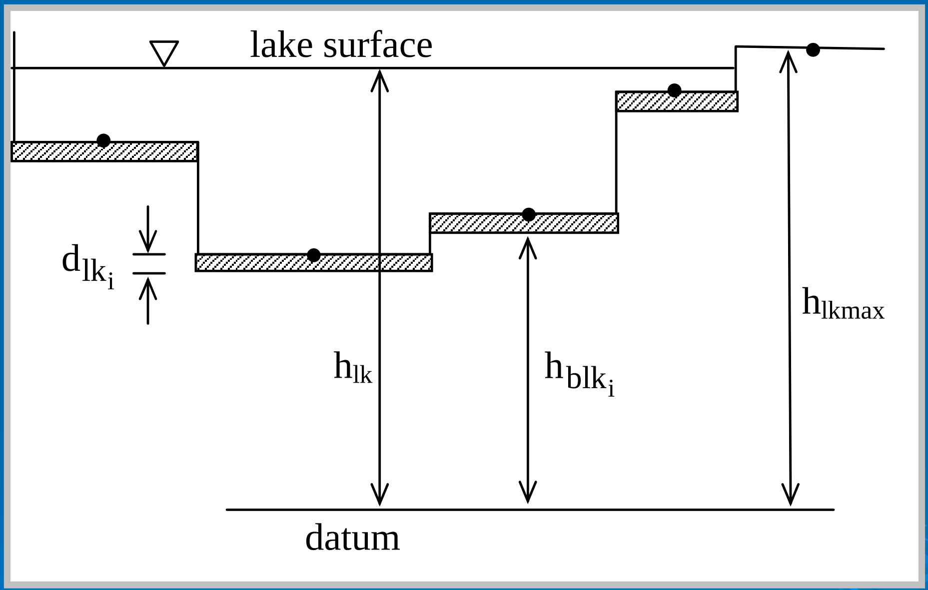
- Lake outflow can be directed to a stream node or a downstream lake



Lake-Groundwater Interaction

$$\mathbf{Q_{lkint} = C_{lk}\left[\max\left(h_{lk}, h_{blk}\right) - \max\left(h, h_{blk}\right)\right]} \; ; \quad \mathbf{C_{lk} = \frac{K_{lk}}{d_{lk}} A_{lk}}$$

Q_{lkint}	=	lake-aquifer interaction, (L^3/T)
h	=	groundwater head, (L)
h_{lk}	=	lake surface elevation, (L)
h_{blk}	=	lake bottom elevation, (L)
K_{lk}	=	lake bed hydraulic conductivity, (L/T)
d_{lk}	=	lake bed thickness, (L)
A_{lk}	=	area of lake, (L)



Computation of Lake Storage

- Lake equations are linearized using Newton-Raphson method
- Stream flow, lake and groundwater equations are fully coupled and solved simultaneously

$$\left.\begin{aligned} \left[\mathbf{X}_s^{t+1}\right]\left\{\mathbf{h}_s^{t+1}\right\}+\left\{\mathbf{F}_s^{t+1}\right\}=0 \\ \left[\mathbf{X}_{lk}^{t+1}\right]\left\{\mathbf{h}_{lk}^{t+1}\right\}+\left\{\mathbf{F}_{lk}^{t+1}\right\}=0 \\ \left[\mathbf{X}_g^{t+1}\right]\left\{\mathbf{h}_g^{t+1}\right\}+\left\{\mathbf{F}_g^{t+1}\right\}=0 \end{aligned}\right\} \Rightarrow \left[\mathbf{X}^{t+1}\right]\left\{\mathbb{H}^{t+1}\right\}+\left\{\mathbf{F}^{t+1}\right\}=0$$

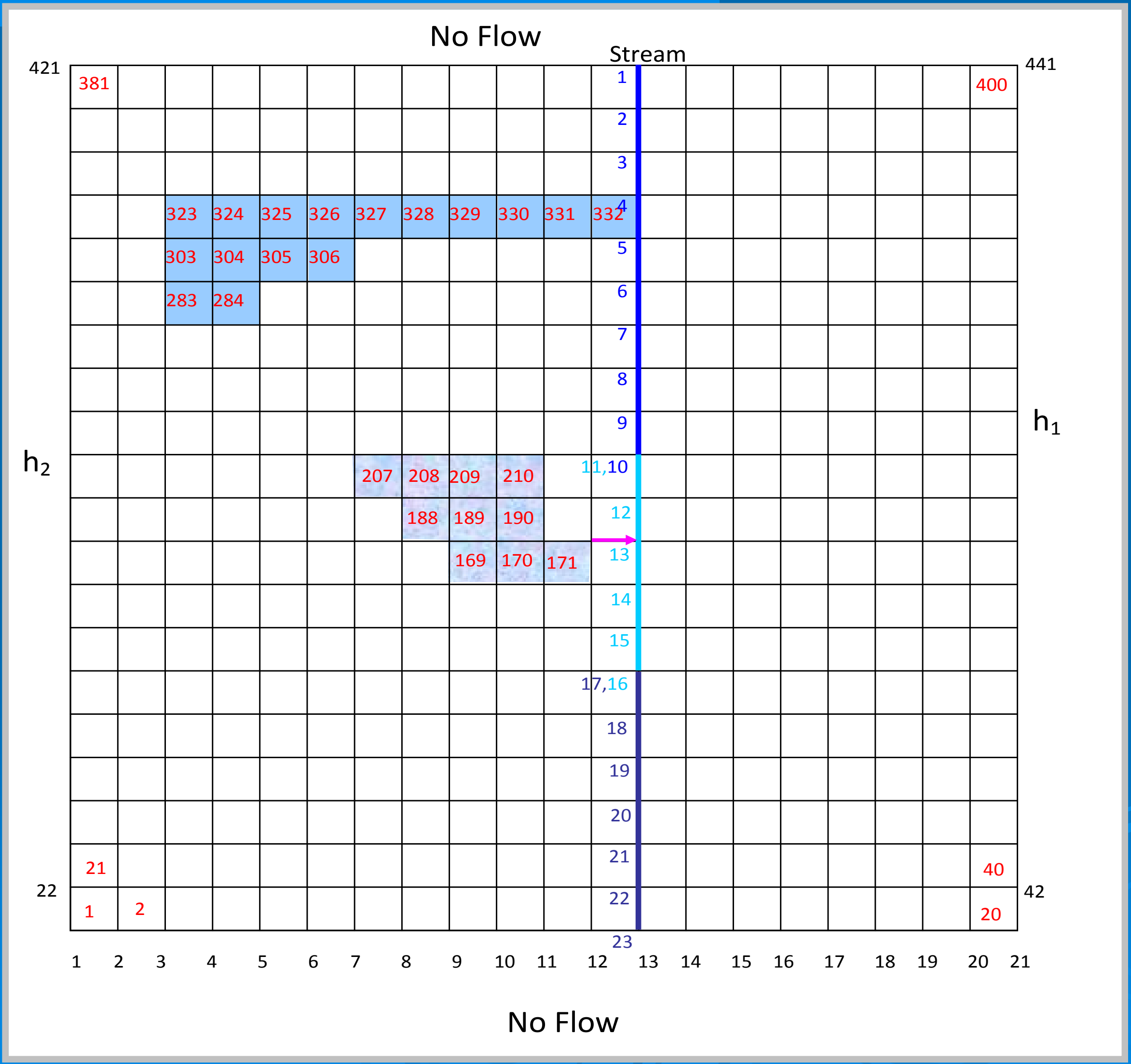
$$\left\{\mathbb{H}^{t+1}\right\}^T=\left\{\mathbf{h}_{s_1}^{t+1},\cdots,\mathbf{h}_{s_{NS}}^{t+1},\mathbf{h}_{lk_1}^{t+1},\cdots,\mathbf{h}_{lk_{NLK}}^{t+1},\mathbf{h}_1^{t+1},\cdots,\mathbf{h}_{N\times N_L}^{t+1}\right\}$$

Computation of Lake Storage

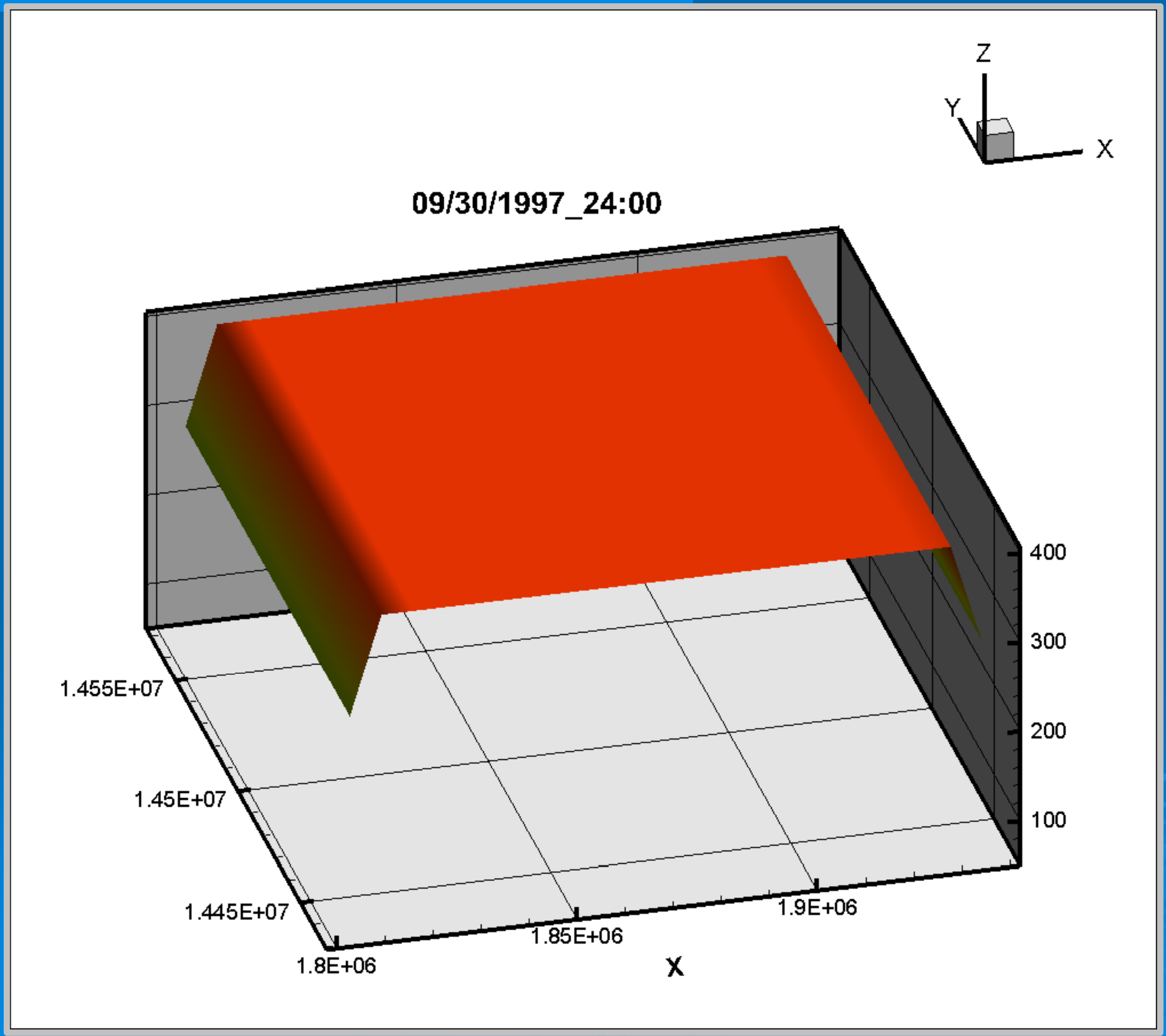
- Convergence criteria for the Newton-Raphson method

$$\sqrt{\sum_{\mathbf{i}}\left\{\left(\mathbb{H}_{\mathbf{i}}^{\mathbf{t+1}}\right)^{\mathbf{k+1}}-\left(\mathbb{H}_{\mathbf{i}}^{\mathbf{t+1}}\right)^{\mathbf{k}}\right\}^{\mathbf{2}}} \le \varepsilon \quad ; \quad \mathbf{i}=\mathbf{1}, \cdots\cdots, \mathbf{NS}+\mathbf{NLK}+\mathbf{N}\times\mathbf{N_L}$$

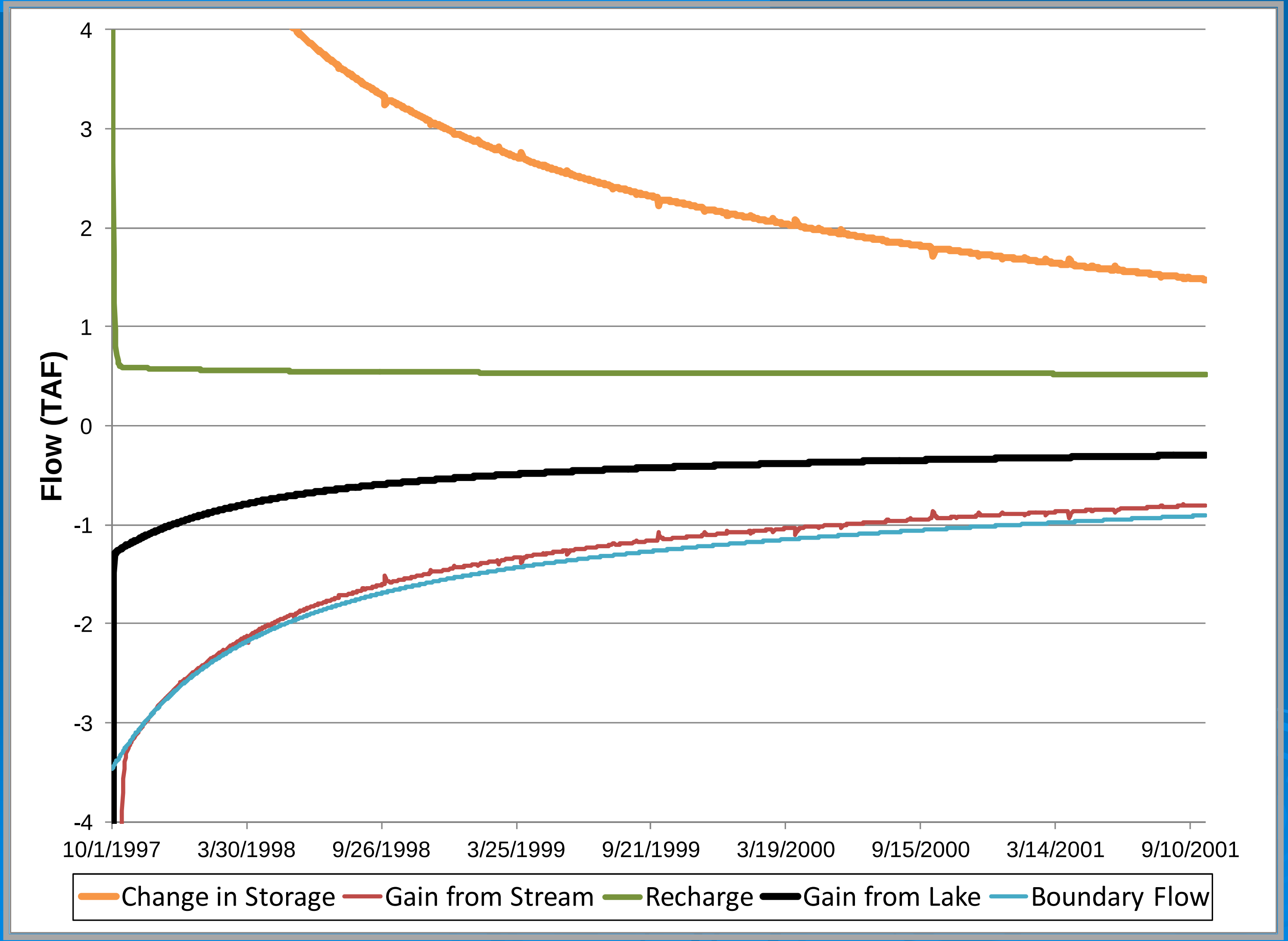
Example 2:
Streams and Lakes



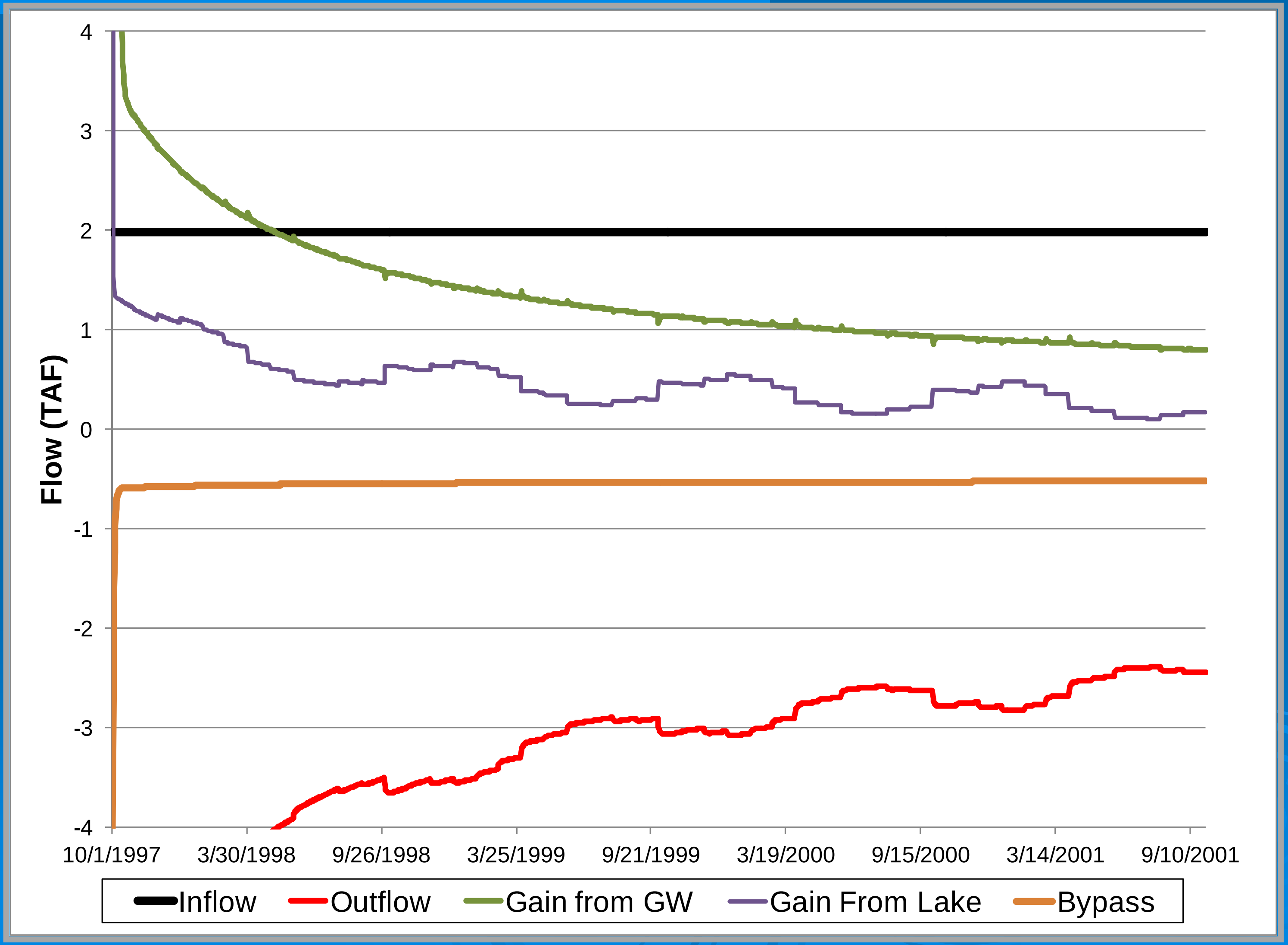
Example 2:
Streams and Lakes – Results



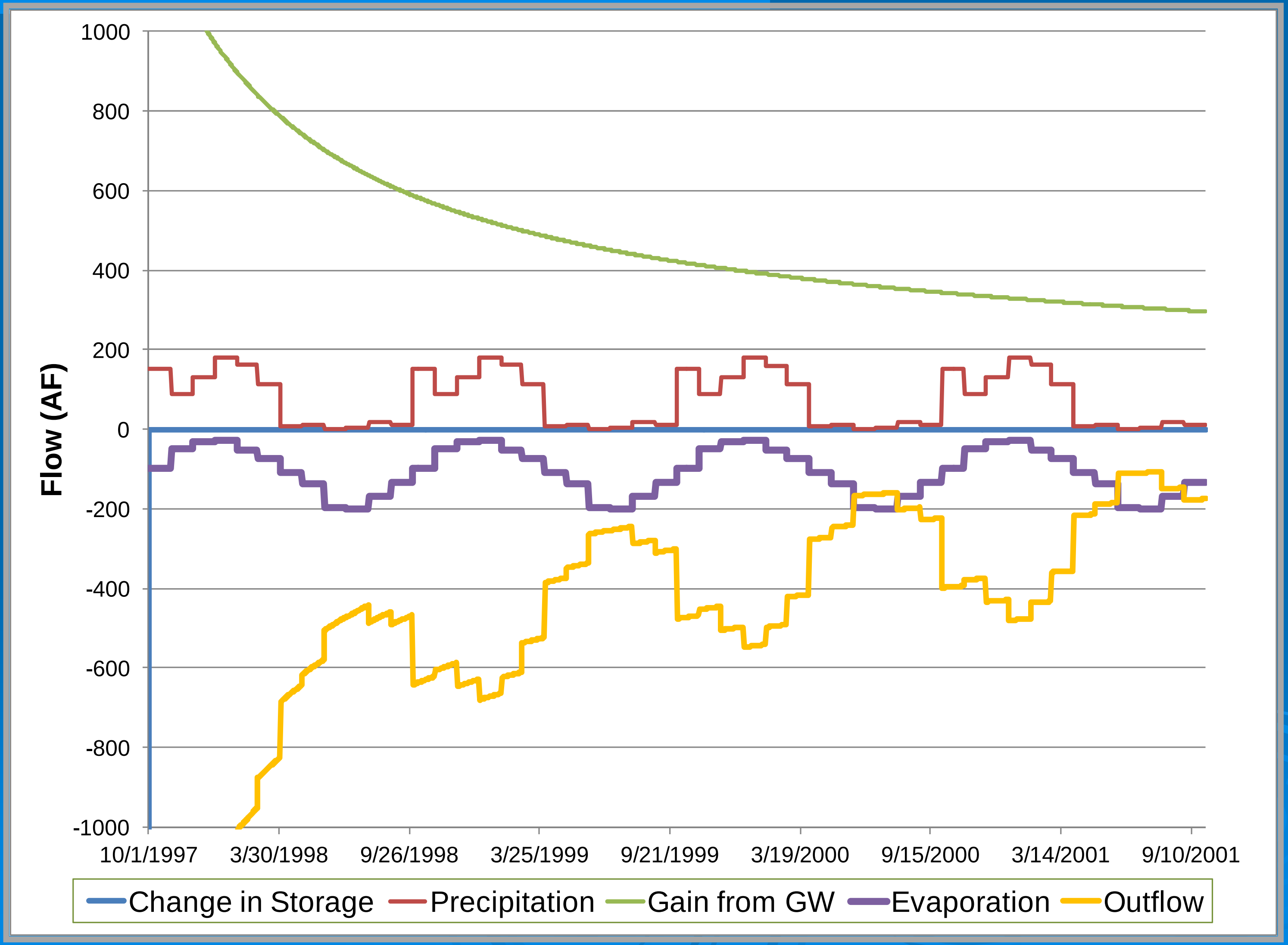
Example 2:
Streams and Lakes – Groundwater Mass Balance



Example 2:
Streams and Lakes – Stream Flow Mass Balance



Example 2:
Streams and Lakes – Lake Mass Balance



Example 2:
Streams and Lakes – Water Budget Cross Terms