CE 3354 Engineering Hydrology

Lecture 17: Hydrograph Routing

Outline

- Routing Hydrographs
  - Background
  - Hydraulic Routing
  - Hydrologic Routing
- HEC-HMS Representations

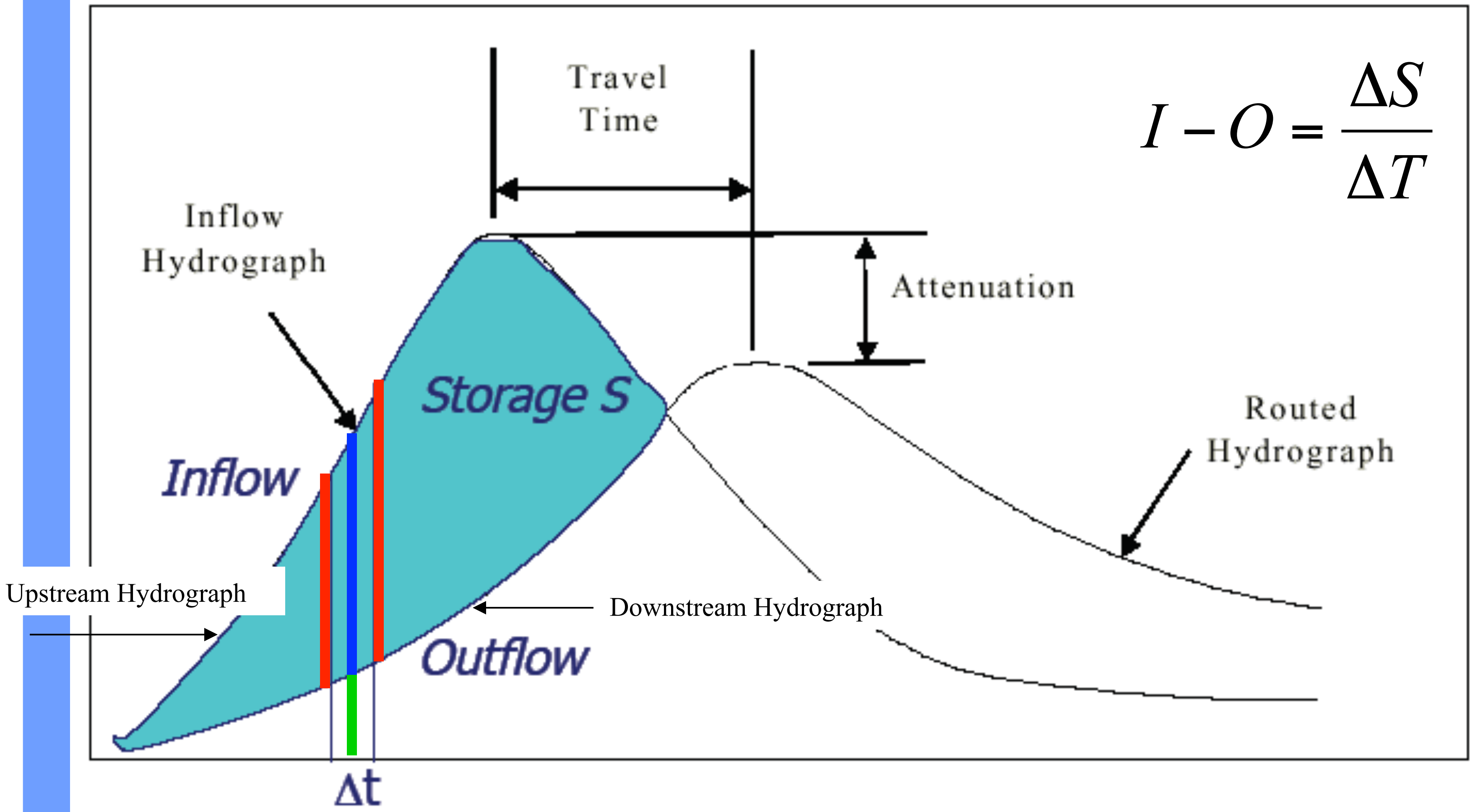
Routing

- Routing simulates movement of a discharge signal (flood wave) through reaches
  - Accounts for storage in the reach and flow resistance.
  - Allows modeling of a basin comprised of interconnected sub-basins
  - Hydraulic routing – uses continuity and momentum (St. Venant Equations)
  - Hydrologic routing – uses continuity equation

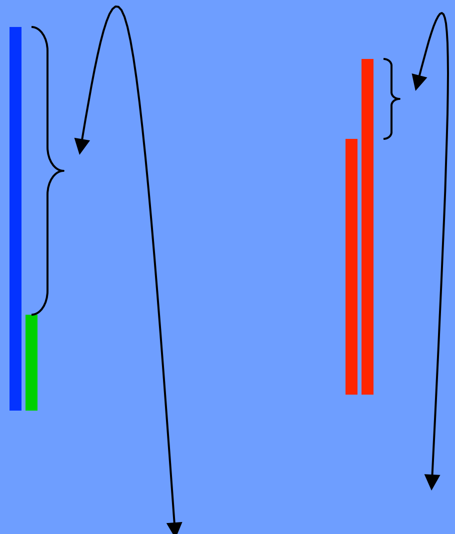
Routing-Hydrologic and Hydraulic

- Problem:
  - you have a hydrograph at one location (I)
  - you have reach characteristics (S = f(I,O))
- Need:
  - a hydrograph at different location (O)
- This is a "routing" situation.
- The "reach" can be a reservoir or some similar feature

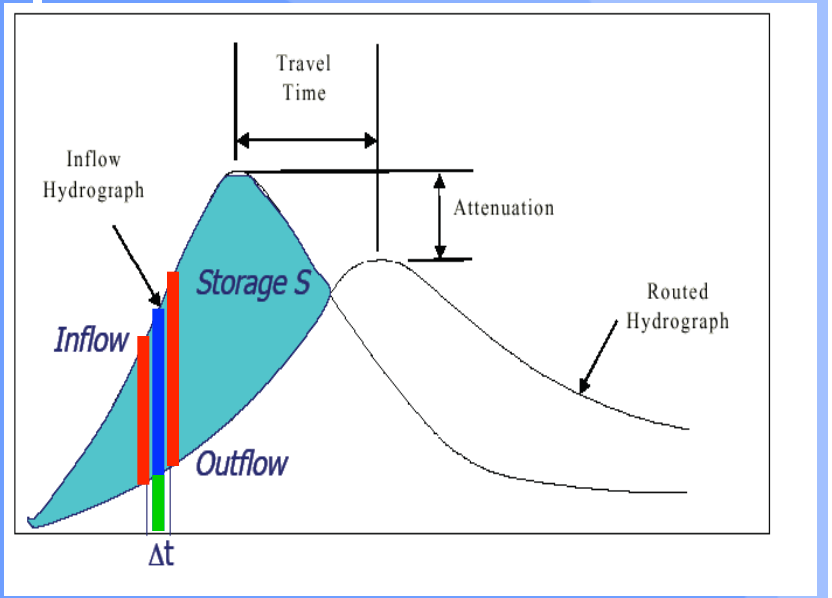
Routing Hydrographs



Routing Hydrographs



$$\Delta T(I - O) = \Delta S$$



- These "bar-heights" related by the routing table

Hydrologic Routing

- Hydrologic routing techniques use the equation of continuity and some linear or curvilinear relation between storage and discharge within the river.
- Methods include:
  - Lag Routing (no attenuation)
  - Modified Puls (level pool routing)
  - Muskingum-Cunge (almost a hydraulic model)

Level Pool Routing

- Technique to approximate the outflow hydrograph passing through a reservoir with the pool (water surface) always level.

- Uses a reach (reservoir) mass balance equation, and

$$Q_{\text{in}} - Q_{\text{out}} = \frac{\Delta S}{\Delta t}$$

- a storage-outflow relationship.

$$Q_{\text{out}} = f(S)$$

Level Pool Routing

- Variable names are typically changed:

$$Q_{\text{in}} \Rightarrow I_t$$

$$Q_{out} \Rightarrow O_t$$

- So the reach mass balance is

$$\bar{I} - \bar{O} = \frac{\Delta S}{\Delta t}$$

Level Pool Routing

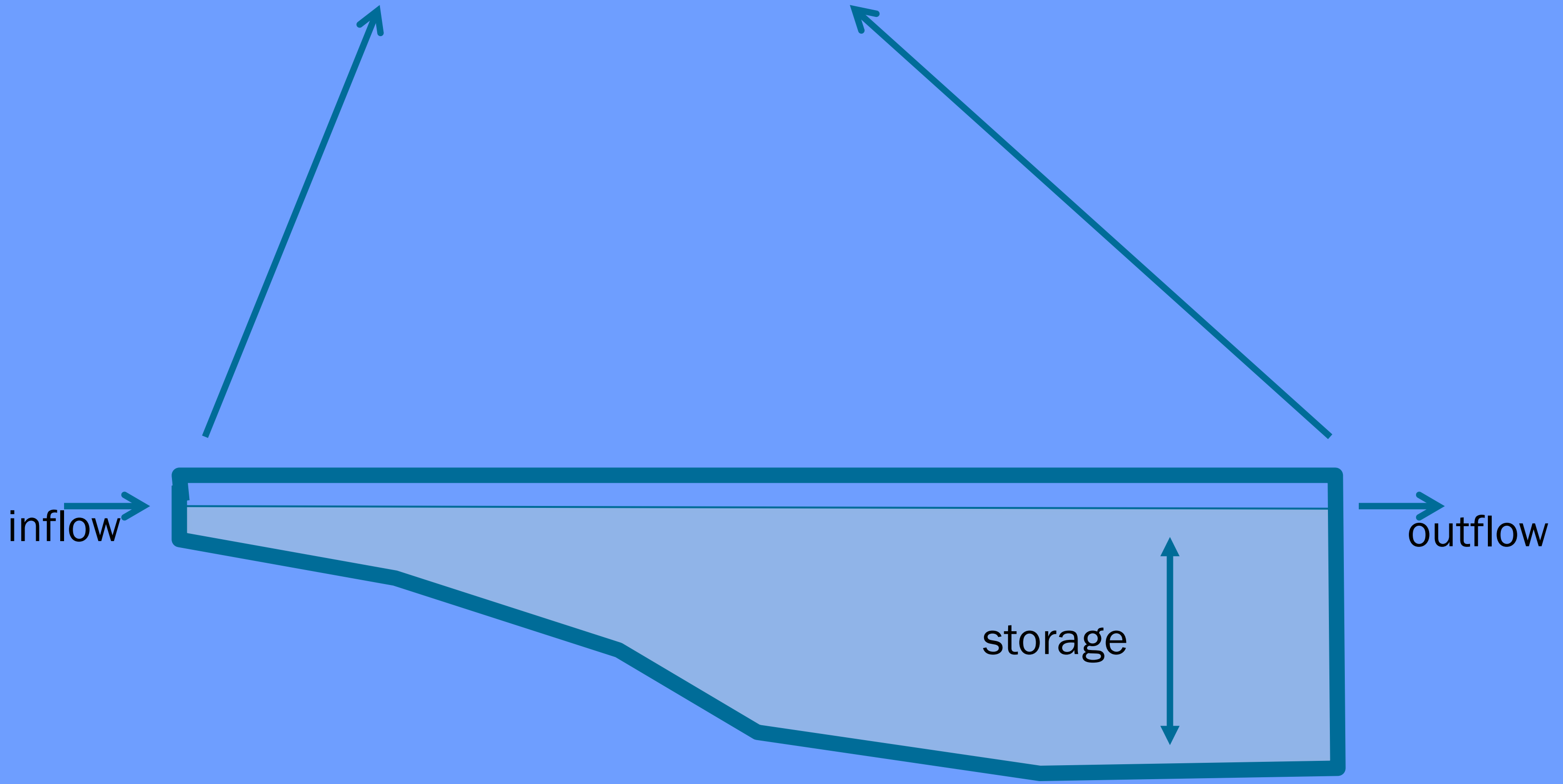
- The time averaged values are taken at the beginning and end of the time interval, and the first-order difference quotient is used to approximate the rate of change in storage.
- The reach mass balance is then

$$\frac{I_t + I_{t-\Delta t}}{2} - \frac{O_t + O_{t-\Delta t}}{2} = \frac{S_t - S_{t-\Delta t}}{\Delta t}$$

Level Pool Routing

- Then rearrange the reach mass balance to isolate the storage and outflow at the end of the time step

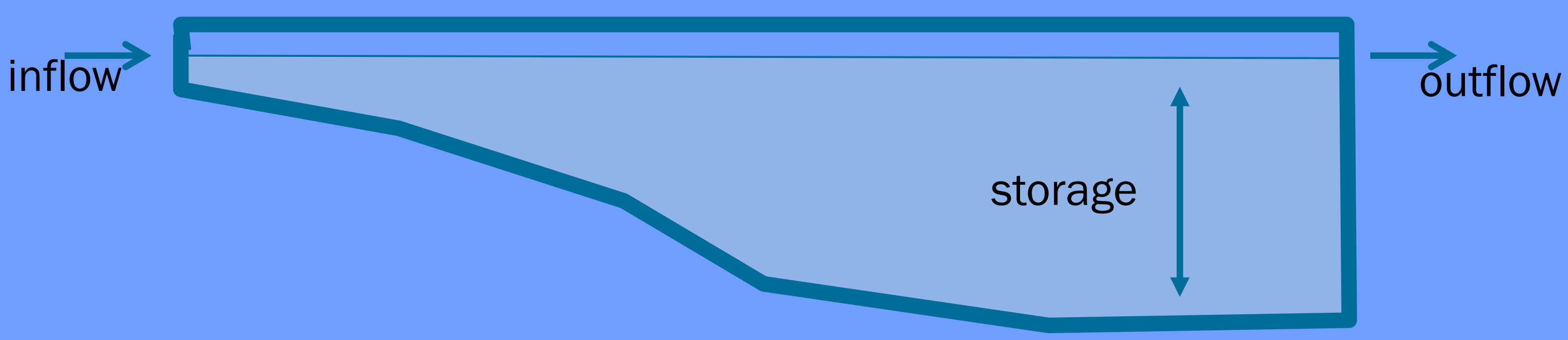
$$\left[I_{t-1} + I_t\right]\Delta t - \left[0_{t-1} + 0_t\right]\Delta t = 2S_t - 2S_{t-1}$$



Level Pool Routing

- Then rearrange the reach mass balance to isolate the storage and outflow at the end of the time step

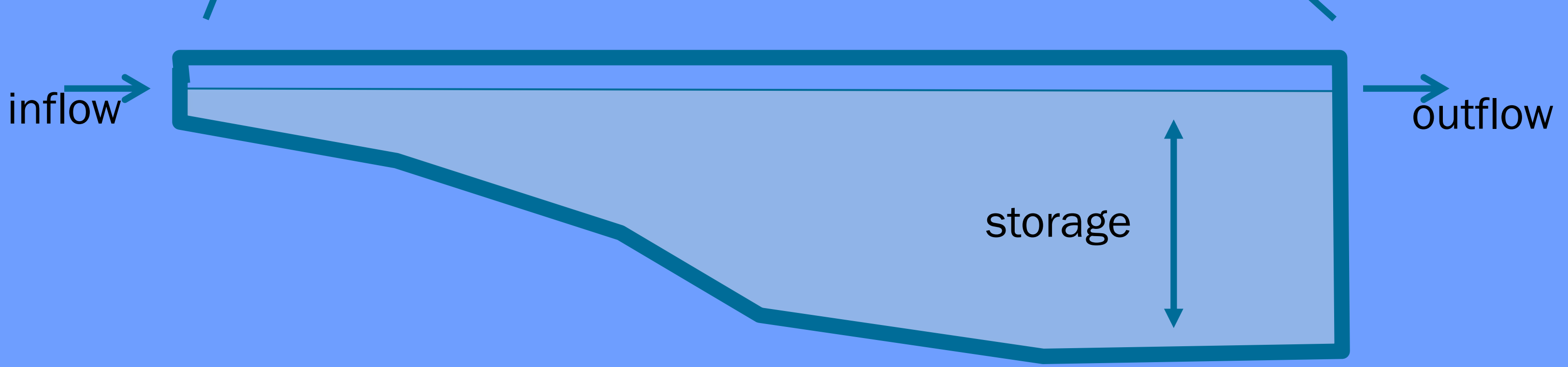
$$\left[I_{t-1} + I_t\right] + \left[0_{t-1}\right] + \frac{2S_{t-1}}{\Delta t} = \frac{2S_t}{\Delta t} + 0_t$$



Level Pool Routing

- A bit more algebra and we get Eqn 8.2.3 in CMM (pg. 246)

$$\left[I_{t-1}+I_{t}\right]+\left[\frac{2S_{t-1}}{\Delta t}-0_{t-1}\right]=\left[\frac{2S_{t}}{\Delta t}+0_{t}\right]$$

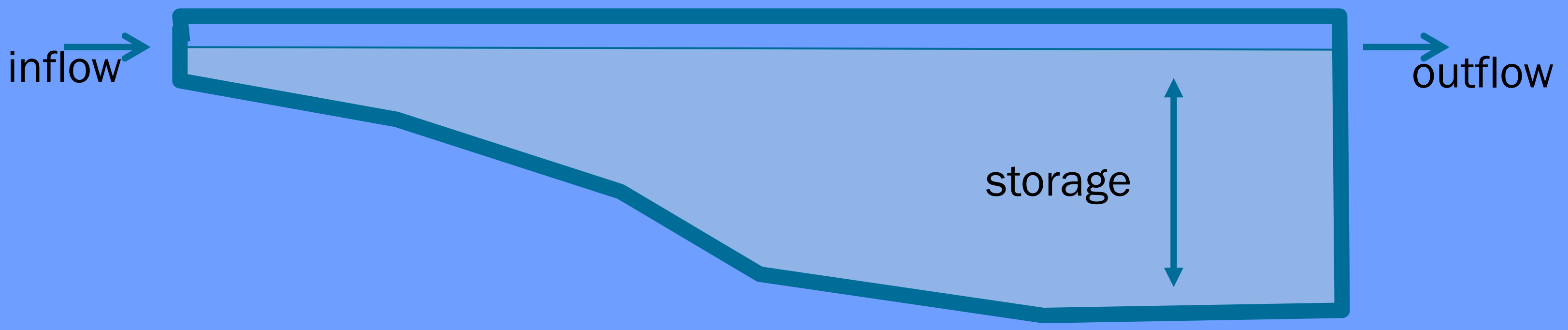


Level Pool Routing

- The equation has two unknowns, so need another relationship. That's where the Storage-Outflow function comes into play

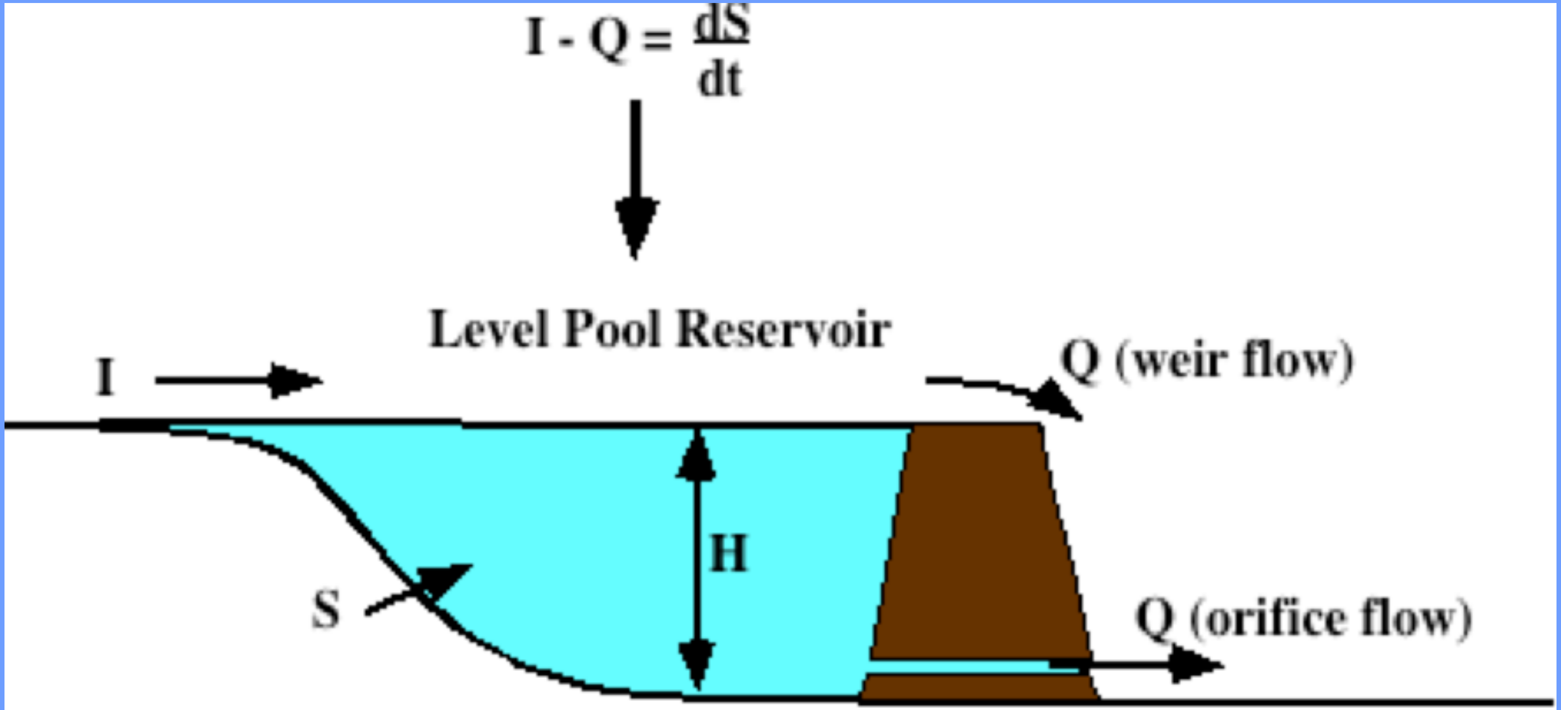
$$\left[I_{t-1} + I_t\right] + \left[\frac{2S_{t-1}}{\Delta t} - 0_{t-1}\right] = \left[\frac{2S_t}{\Delta t} + 0_t\right]$$

$$O = f(S)$$



Level Pool Routing

- Storage-Outflow Concepts



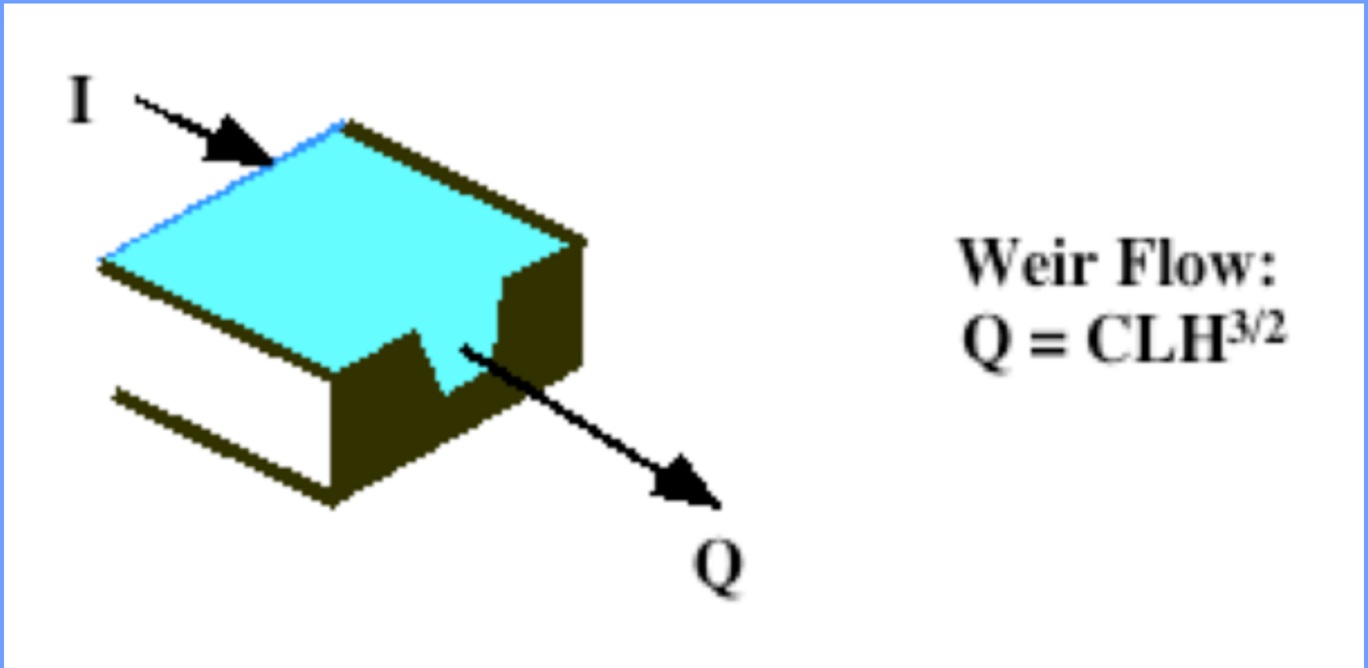
Storage α Depth $S = f(H)$

$Q = f(H)$ Outflow α Depth

Thus storage and outflow can be related into the Storage-Outflow function

Level Pool Routing

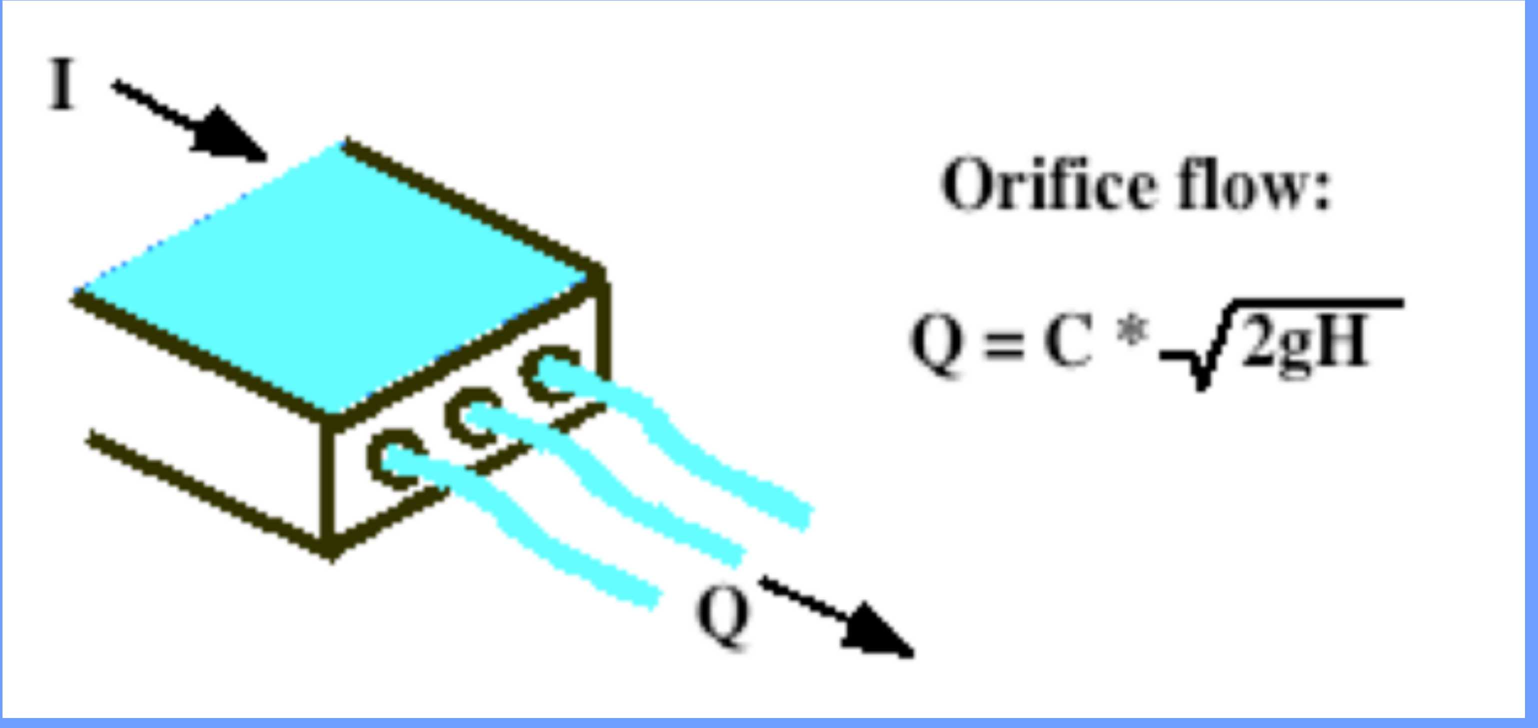
- Outflow over a weir (or spillway, or similar structure)



Weir flow; critical depth model

Level Pool Routing

- Outflow through orifice (culvert, or similar structure)



Orifice flow; energy loss model

Level Pool Routing

- Use outlet-works hydraulics, and depth-area-storage to build a storage-outflow function

$$O = f(S)$$

- Once we have that function, then build an auxiliary function (tabulation) called the storage-indication curve (function)

$$O = g(\frac{2S}{\Delta t} + O)$$

Level Pool Routing

- Once have the storage-indication curve then can use the reach mass balance to estimate the numerical value of :

$$\frac{2S_t}{\Delta t} + O_t$$

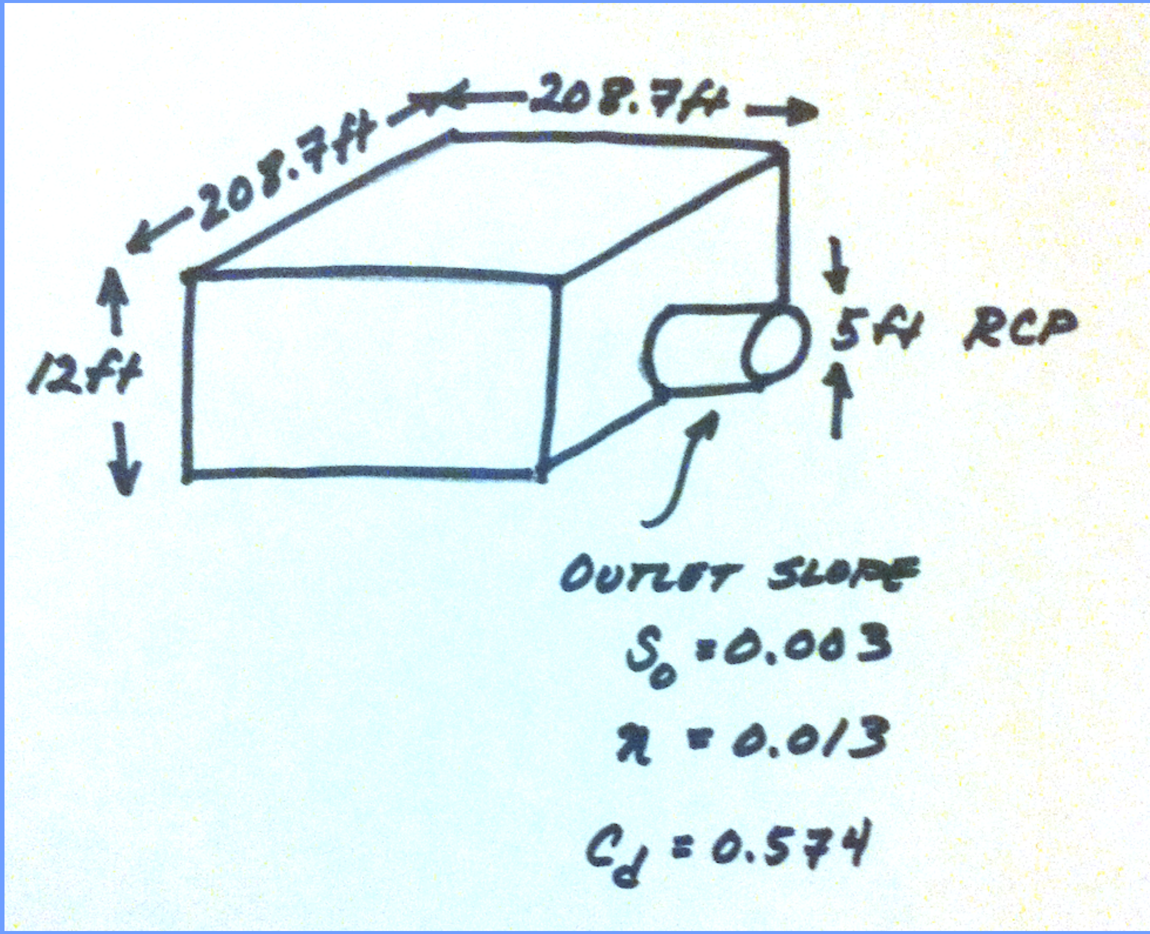
- Then use the storage-indication curve to find the value of outflow, subtract than from the result above, and now have both the end-of-interval outflow and storage.

Level Pool Routing

- Example – Similar to CMM 8.2.1 pg 247-252; but
  - Show how the storage-indication curve derived using hydraulics
  - Illustrate use of spreadsheet programming needed to make the actual computations

Level Pool Routing

- 1-acre detention basin.
  - Vertical walls
  - Drained by a 5-foot RCP
  - 12-foot maximum depth



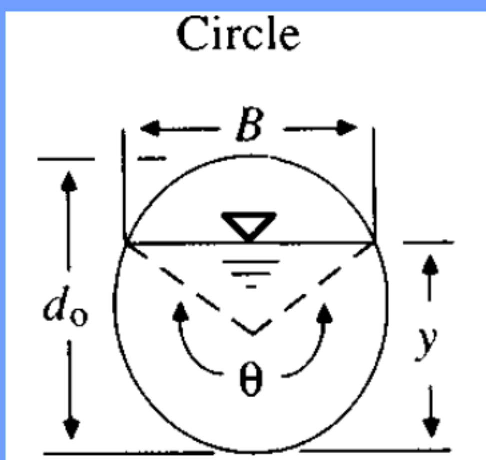
Level Pool Routing

- Tasks:
  - Build a depth-storage table
  - Build a depth-outflow table
    - From 0 -5 feet deep use Manning's equation in a circular conduit
    - From 5+ to 12 feet deep use Orifice equation (neglecting frictional losses)
  - Save a depth-storage-outflow table for use in storage-indication curve
  - Build the routing table (apply the reach mass balance)

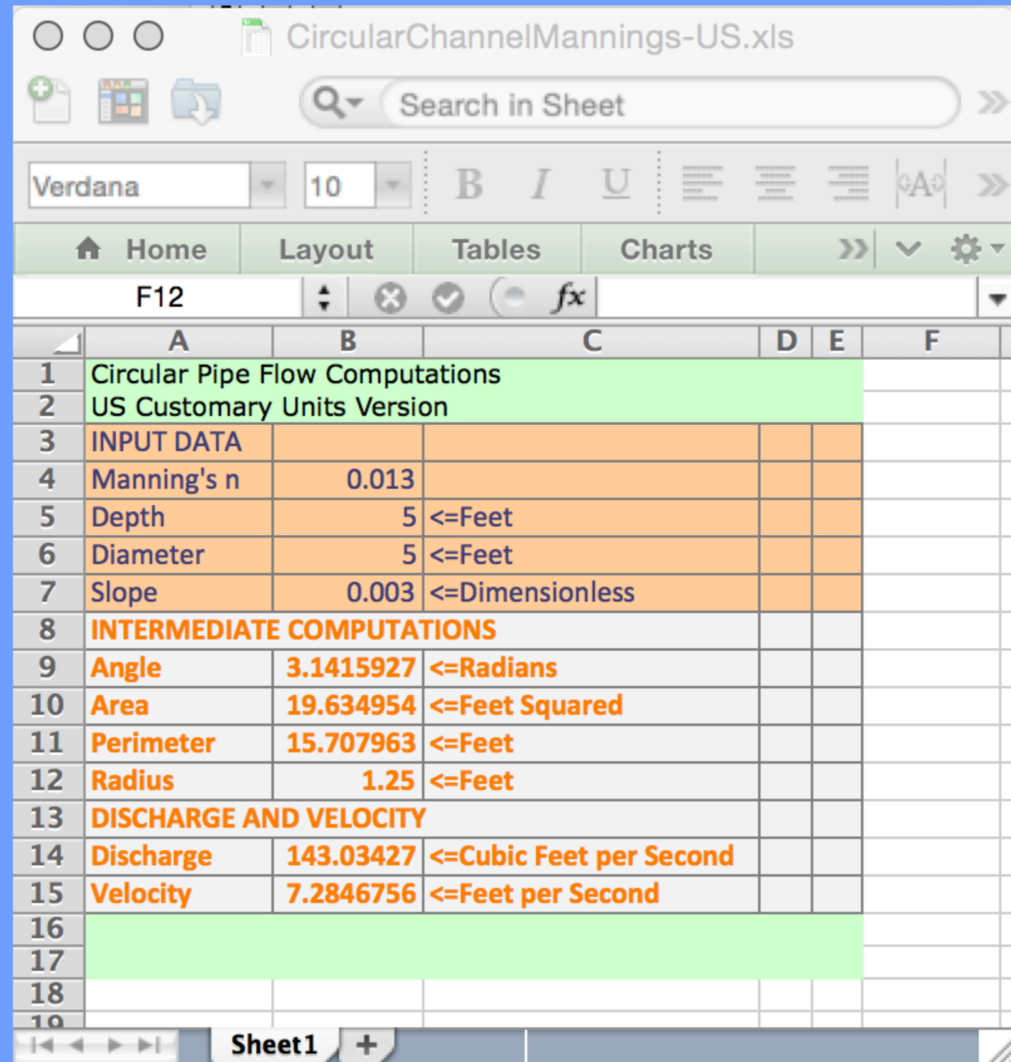
Level Pool Routing

- Manning's Equation Calculator

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$



CMM pg 162



	A	B	C
1	Circular Pipe Flow Computations		
2	US Customary Units Version		
3	INPUT DATA		
4	Manning's n	0.013	
5	Depth	5	<=Feet
6	Diameter	5	<=Feet
7	Slope	0.003	<=Dimensionless
8	INTERMEDIATE COMPUTATIONS		
9	Angle	3.1415927	<=Radians
10	Area	19.634954	<=Feet Squared
11	Perimeter	15.707963	<=Feet
12	Radius	1.25	<=Feet
13	DISCHARGE AND VELOCITY		
14	Discharge	143.03427	<=Cubic Feet per Second
15	Velocity	7.2846756	<=Feet per Second

Level Pool Routing

- Orifice Equation Calculator

$$Q = C_d A \sqrt{2gh}$$

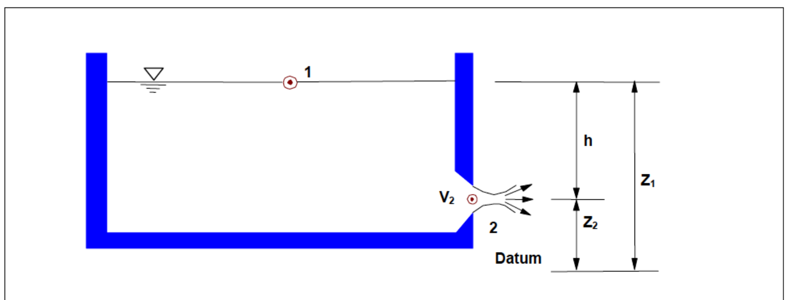
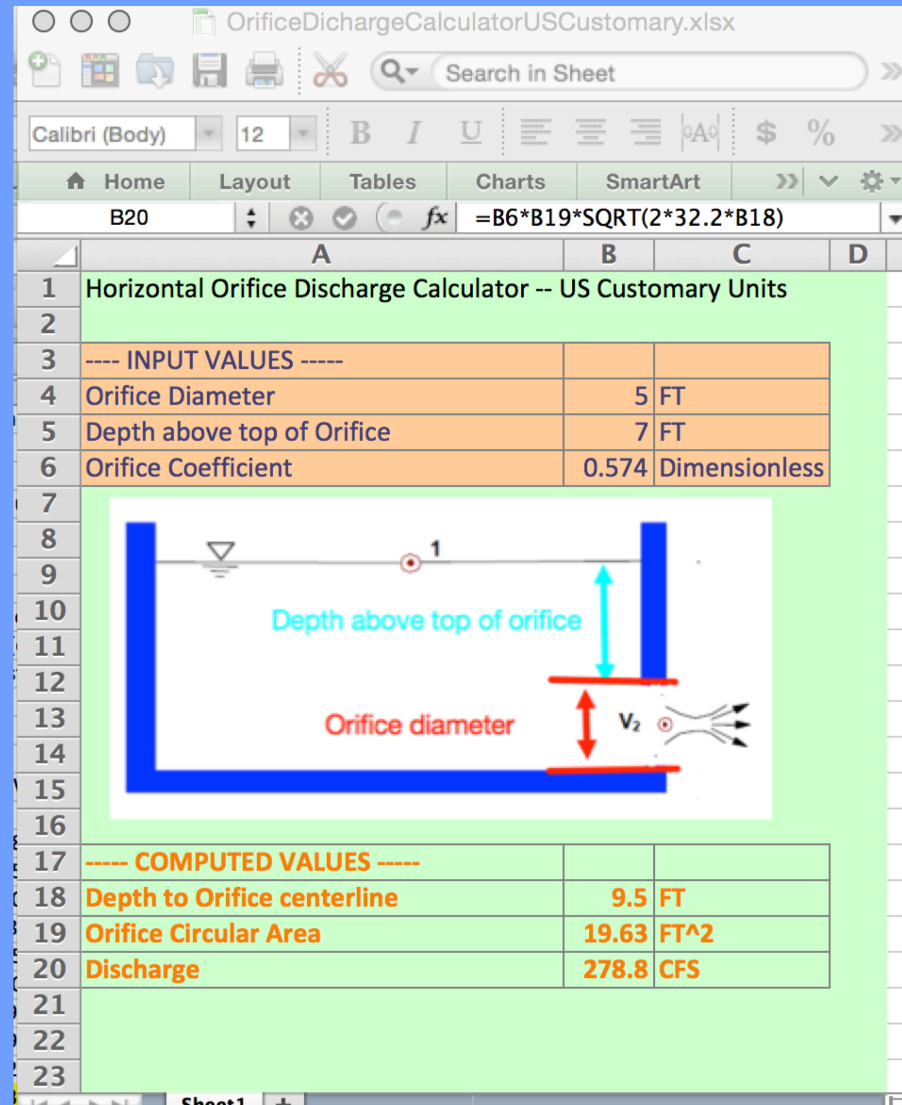


Figure 8.4. Schematic diagram of the flow through an orifice

This can be simplified by making the following assumptions: (1) the pressure at both points is atmospheric, therefore $p_1 = p_2$; (2) the surface area of the pool A_1 is very large relative to the

FHWA-NHI-02-001 pp. 8-9 – 8-10



	A	B	C
1	Horizontal Orifice Discharge Calculator -- US Customary Units		
2			
3	---- INPUT VALUES -----		
4	Orifice Diameter	5	FT
5	Depth above top of Orifice	7	FT
6	Orifice Coefficient	0.574	Dimensionless
17	----- COMPUTED VALUES -----		
18	Depth to Orifice centerline	9.5	FT
19	Orifice Circular Area	19.63	FT^2
20	Discharge	278.8	CFS

Level Pool Routing

- DEPTH-STORAGE-OUTFLOW

H18

	A	B	C	D	E	F	G
3	1-acre, vertical walls						
4	5-foot RCP outlet (assume short)						
5	10-foot max depth						
6							
7	Methods:						
8	Use Manning's equation in a circular channel for estimate Q vs Depth for 0 to 5 feet)						
9	Use Orifice equation (e.g. FHWA, TxDOT) for estimate Q vs Depth for 5 to 10 feet						
10	Use Depth*Area to estimate storage in cubic feet						
11					DELTA T	10	MIN
12							
13							
14	DEPTH(FT)	OUTFLOW(CFS)	DONE-HOW	STORAGE(FT^3)	2S/Dt + O (CFS)	REMARKS	
15	0	0	Mannings	0	0		
16	0.5	2.986243	Mannings	21780	75.586243		
17	1	12.5257	Mannings	43560	157.7257		
18	1.5	28.01057	Mannings	65340	245.81057		
19	2	48.2008	Mannings	87120	338.6008		
20	2.5	71.51714	Mannings	108900	434.51714		
21	3	96.09617	Mannings	130680	531.69617		
22	3.5	119.7537	Mannings	152460	627.95368		
23	4	139.8113	Mannings	174240	720.61126		
24	4.5	152.4455	Mannings	196020	805.84555	Recall max flow in circular is at 85-95% fill depth	
25	5	143.0343	Mannings	217800	869.03427		
26	5	143.0343	Orifice	217800	869.03427	Adjust Cd to match flow at 5ft deep	
27	5.5	156.6862	Orifice	239580	955.28619		
28	6	169.2404	Orifice	261360	1040.4404		
29	6.5	180.9256	Orifice	283140	1124.7256		
30	7	191.9006	Orifice	304920	1208.3006		
31	7.5	202.281	Orifice	326700	1291.281		

= 2*D16/(F11*60)+B16

Level Pool Routing

- Copy the depth-storage-outflow to the routing table (we are going to build) – we need it as a tabulation so we can use INDEX and MATCH to get values from the table for interpolation (Eq. at bottom CMM pg 249)

$$y = y_1 + \frac{(y_2 - y_1)}{(x_2 - x_1)}(x - x_1)$$

Level Pool Routing

- Copy of Outflow, 2S/DT+O and Storage Tabulations

	A	B	C
1	STORAGE-INDICATION-CURVE		
2	O (CFS)	2S/Dt + O (CFS)	STORAGE (FT^3)
3	0	0	0
4	2.98624343	75.5862434	21780
5	12.5256993	157.725699	43560
6	28.0105714	245.810571	65340
7	48.2007997	338.6008	87120
8	71.5171358	434.517136	108900
9	96.0961739	531.696174	130680
10	119.753679	627.953679	152460
11	139.811264	720.611264	174240
12	152.445547	805.845547	196020
13	143.034272	869.034272	217800
14	156.686194	955.286194	239580
15	169.240433	1040.44043	261360
16	180.925633	1124.72563	283140
17	191.900613	1208.30061	304920
18	202.281007	1291.28101	326700
19	212.15411	1373.75411	348480
20	221.587741	1455.78774	370260
21	230.635833	1537.43583	392040
22	239.342115	1618.74212	413820
23	247.742626	1699.74263	435600
24	255.867484	1780.46748	457380
25	263.742165	1860.94217	479160
26	271.388449	1941.18845	500940
27	278.825126	2021.22513	522720
28			

Level Pool Routing

- Routing Table
  - Left side are “known” values

E9

	A	B	C	D	E	F	G	H	I
29									
30	ROUTING-TABLE								
31									TABLE LOOKUP
32	INDEX	TIME(MIN)	TIME(SEC)	INFLOW(CFS	I_t + I_t-Dt	DT (MIN)	2S/DT-O	2S/DT+O	2S/DT+O_low
33	1	0	0	0	0	10	0	--	--
34	2	10	600	60	60	10	55.2590684	60	0
35	3	20	1200	120	180	10	182.947727	235.259068	157.7256993
36	4	30	1800	180	300	10	315.414811	482.947727	434.5171358
37	5	40	2400	240	420	10	451.403622	735.414811	720.6112637
38	6	50	3000	300	540	10	667.381692	991.403622	955.2861942
39	7	60	3600	360	660	10	914.176235	1327.38169	1291.281007
40	8	70	4200	320	680	10	1120.75304	1594.17624	1537.435833
41	9	80	4800	280	600	10	1221.03844	1720.75304	1699.742626
42	10	90	5400	240	520	10	1237.24044	1741.03844	1699.742626
43	11	100	6000	200	440	10	1186.42257	1677.24044	1618.742115
44	12	110	6600	160	360	10	1083.2263	1546.42257	1537.435833
45	13	120	7200	120	280	10	941.438711	1363.2263	1291.281007
46	14	130	7800	80	200	10	775.197957	1141.43871	1124.725633
47	15	140	8400	40	120	10	600.847057	895.197957	869.0342717
48	16	150	9000	0	40	10	395.757641	640.847057	627.9536787

Level Pool Routing

- Routing Table
  - Middle and right part is table lookup and calculations

	F	G	H	I	J	K	L	M	N	O	P
29											
30											
31				TABLE LOOKUP						INTERPOLATE FROM TABLE	
32	DT (MIN)	2S/DT-O	2S/DT+O	2S/DT+O_low	O_low	S_low	2S/DT + O_hi	O_hi	S_hi	O_interpolate	S_interpolate
33	10	0	--	--	--	--	--	--	--	0	0
34	10	55.2590684	60	0	0	0	75.58624343	2.986243427	21780	2.370465808	17288.86026
35	10	182.947727	235.259068	157.7256993	12.52569929	43560	245.8105714	28.01057136	65340	26.15567085	62731.01926
36	10	315.414811	482.947727	434.5171358	71.51713583	108900	531.6961739	96.09617392	130680	83.76645791	119754.3806
37	10	451.403622	735.414811	720.6112637	139.8112637	174240	805.8455468	152.4455468	196020	142.0055944	178022.7649
38	10	667.381692	991.403622	955.2861942	156.6861942	239580	1040.440433	169.2404326	261360	162.010965	248817.7971
39	10	914.176235	1327.38169	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480	206.6027284	336233.6891
40	10	1120.75304	1594.17624	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820	236.7115991	407239.3909
41	10	1221.03844	1720.75304	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380	249.8572979	441268.7218
42	10	1237.24044	1741.03844	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380	251.898999	446741.8327
43	10	1186.42257	1677.24044	1618.742115	239.3421151	413820	1699.742626	247.7426258	435600	245.408939	429549.4513
44	10	1083.2263	1546.42257	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820	231.5981329	394447.3297
45	10	941.438711	1363.2263	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480	210.8937941	345699.7516
46	10	775.197957	1141.43871	1124.725633	180.9256328	283140	1208.300613	191.9006128	304920	183.120377	287495.5003
47	10	600.847057	895.197957	869.0342717	143.0342717	217800	955.2861942	156.6861942	239580	147.1754502	224406.7521
48	10	395.757641	640.847057	627.9536787	119.7536787	152460	720.6112637	139.8112637	174240	122.5447079	155490.7047
49	10	271.567488	395.757641	338.6007997	48.2007997	87120	434.5171358	71.51713583	108900	62.09507651	100098.7694

	A	B	C
1	STORAGE-INDICATION-CURVE		
2	O (CFS)	2S/Dt + O (CFS)	STORAGE (FT^3)
3	0	0	0
4	2.98624343	75.5862434	21780
5	12.5256993	157.725699	43560
6	28.0105714	245.810571	65340
7	48.2007997	338.6008	87120
8	71.5171358	434.517136	108900
9	96.0961739	531.696174	130680
10	119.753679	627.953679	152460
11	139.811264	720.611264	174240
12	152.445547	805.845547	196020
13	143.034272	869.034272	217800
14	156.686194	955.286194	239580
15	169.240433	1040.44043	261360
16	180.925633	1124.72563	283140
17	191.900613	1208.30061	304920
18	202.281007	1291.28101	326700
19	212.15411	1373.75411	348480
20	221.587741	1455.78774	370260
21	230.635833	1537.43583	392040
22	239.342115	1618.74212	413820
23	247.742626	1699.74263	435600
24	255.867484	1780.46748	457380
25	263.742165	1860.94217	479160
26	271.388449	1941.18845	500940
27	278.825126	2021.22513	522720
28			

$$\left[I_{t-1}+I_t\right]+\left[\frac{2S_{t-1}}{\Delta t}-0_{t-1}\right]=\left[\frac{2S_t}{\Delta t}+0_t\right]$$

		G	H	I	J	K	L	M	N
				TABLE LOOKUP					
		…O	2S/DT+O	2S/DT+O_low	O_low	S_low	2S/DT + O_hi	O_hi	S_hi
		0	--	--	--	--	--	--	--
		…0684	60	0	0	0	75.58624343	2.986243427	21780
		…7727	235.259068	157.7256993	12.52569929	43560	245.8105714	28.01057136	65340
		…4811	482.947727	434.5171358	71.51713583	108900	531.6961739	96.09617392	130680
		…3622	735.414811	720.6112637	139.8112637	174240	805.8455468	152.4455468	196020
		…1692	991.403622	955.2861942	156.6861942	239580	1040.440433	169.2404326	261360
		…5235	1327.38169	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480
		…5304	1594.17624	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820
	10	…3844	1720.75304	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380
42	10	1237.24044	1741.03844	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380
43	10	1186.42257	1677.24044	1618.742115	239.3421151	413820	1699.742626	247.7426258	435600
44	10	1083.2263	1546.42257	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820
45	10	941.438711	1363.2263	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480
46	10	775.197957	1141.43871	1124.725633	180.9256328	283140	1208.300613	191.9006128	304920
47	10	600.847057	895.197957	869.0342717	143.0342717	217800	955.2861942	156.6861942	239580
48	10	395.757641	640.847057	627.9536787	119.7536787	152460	720.6112637	139.8112637	174240
49	10	271.567488	395.757641	338.6007997	48.2007997	87120	434.5171358	71.51713583	108900

$$y = y_1 + \frac{(y_2 - y_1)}{(x_2 - x_1)}(x - x_1)$$

	H	I	J	K	L	M	N	O	P
		TABLE LOOKUP						INTERPOLATE FROM TABLE	
	2S/DT+O	2S/DT+O_low	O_low	S_low	2S/DT + O_hi	O_hi	S_hi	O_interpolate	S_interpolate
0	--	--	--	--	--	--	--	0	0
584	60	0	0	0	75.58624343	2.986243427	21780	2.370465808	17288.86026
727	235.259068	157.7256993	12.52569929	43560	245.8105714	28.01057136	65340	26.15567085	62731.01926
311	482.947727	434.5171358	71.51713583	108900	531.6961739	96.09617392	130680	83.76645791	119754.3806
522	735.414811	720.6112637	139.8112637	174240	805.8455468	152.4455468	196020	142.0055944	178022.7649
592	991.403622	955.2861942	156.6861942	239580	1040.440433	169.2404326	261360	162.010965	248817.7971
235	1327.38169	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480	206.6027284	336233.6891
304	1594.17624	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820	236.7115991	407239.3909
344	1720.75304	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380	249.8572979	441268.7218
044	1741.03844	1699.742626	247.7426258	435600	1780.467484	255.8674837	457380	251.898999	446741.8327
257	1677.24044	1618.742115	239.3421151	413820	1699.742626	247.7426258	435600	245.408939	429549.4513
263	1546.42257	1537.435833	230.6358331	392040	1618.742115	239.3421151	413820	231.5981329	394447.3297
711	1363.2263	1291.281007	202.2810069	326700	1373.75411	212.1541099	348480	210.8937941	345699.7516
957	1141.43871	1124.725633	180.9256328	283140	1208.300613	191.9006128	304920	183.120377	287495.5003
057	895.197957	869.0342717	143.0342717	217800	955.2861942	156.6861942	239580	147.1754502	224406.7521
641	640.847057	627.9536787	119.7536787	152460	720.6112637	139.8112637	174240	122.5447079	155490.7047
488	395.757641	338.6007997	48.2007997	87120	434.5171358	71.51713583	108900	62.09507651	100098.7694

Level Pool Routing

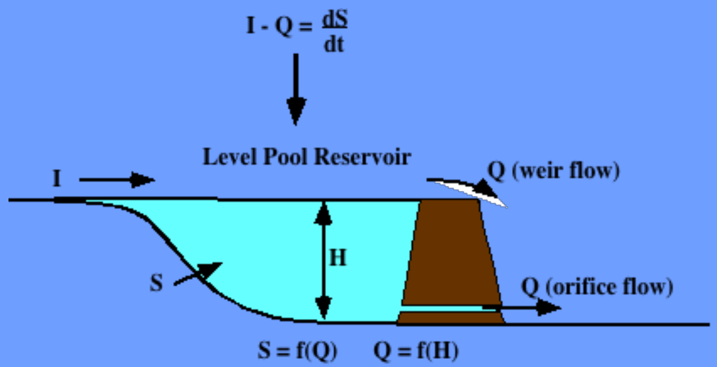
- The full spreadsheet, with the interpolation function as an Excel 94 macro sheet (you could code in place, will have a few more columns) is on server as Routing Example.
- Such computations are a lot easier to perform in HEC-HMS because it handles (1) building the routing table and (2) selecting a decent time step
- Can also use level pool routing for a stream reach (next meeting).

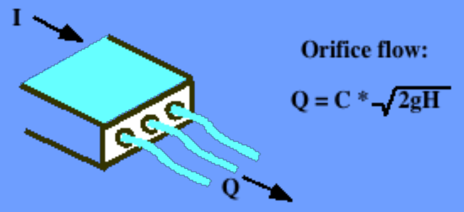
Reservoir Concepts

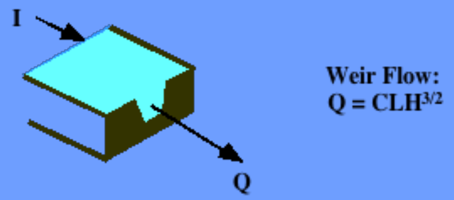
- Reservoir
  - A pond, lake, or basin, either natural or artificial, for the storage, regulation, and control of water.
    - Regulated reservoir
      - Outflow controlled by moveable gates and valves.
      - Head, and valve settings determine outflow.
    - Unregulated reservoir.
      - Outflow controlled by fixed weirs and orifices.
      - Head and constructed weir height determine outflow.

Reservoir Storage

- Storage Representations
  - Storage vs. Discharge
  - Storage vs. Elevation
  - Surface Area vs. Elevation
- Discharge Representations
  - Spillways, Weirs
  - Orifices, Sluice gates
  - Pumps
  - Dam Breach







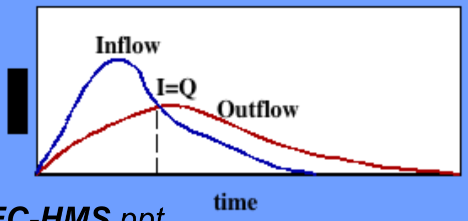
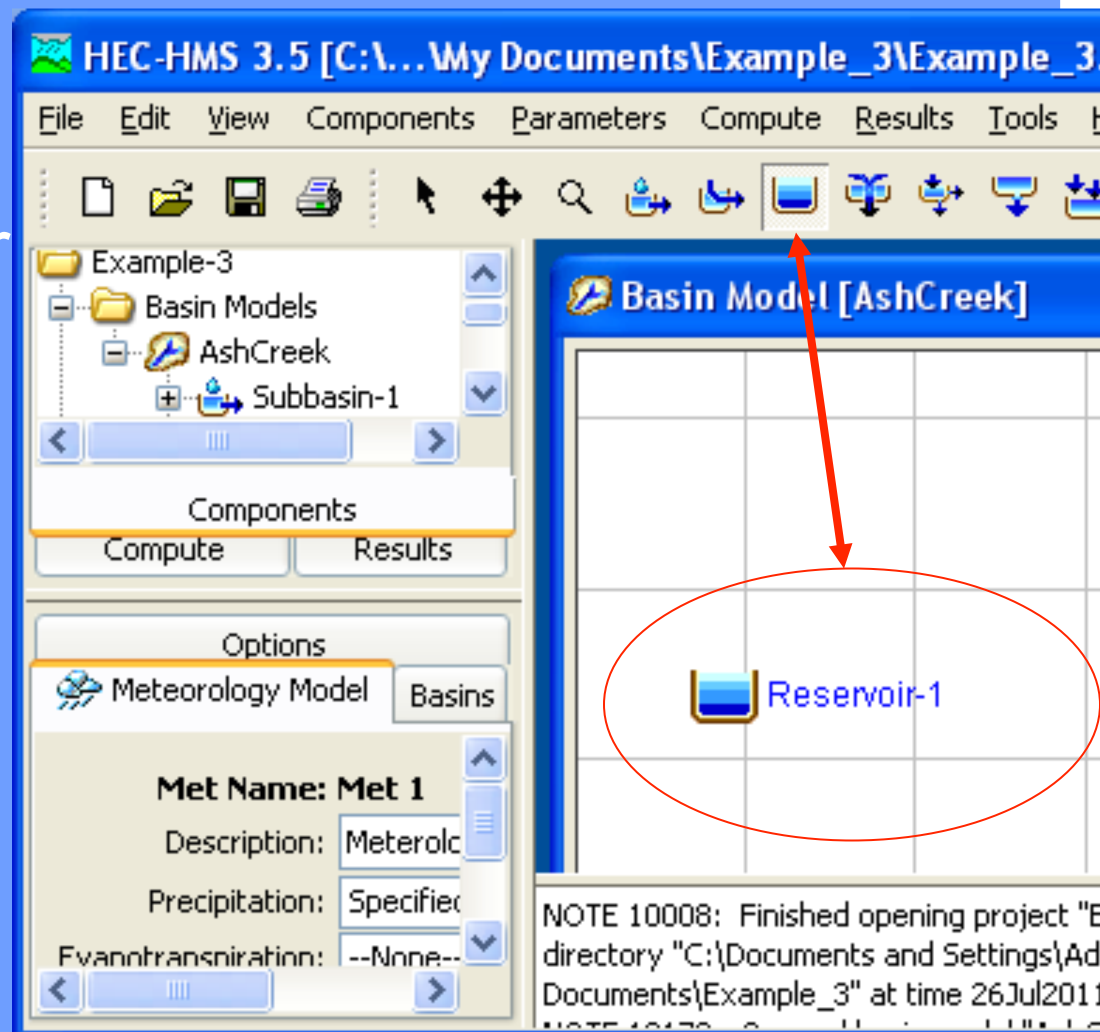


Image from *ftp://ftp.crwr.utexas.edu/pub/outgoing/Robayo/**HECHMS**.../**HEC-HMS**.ppt*

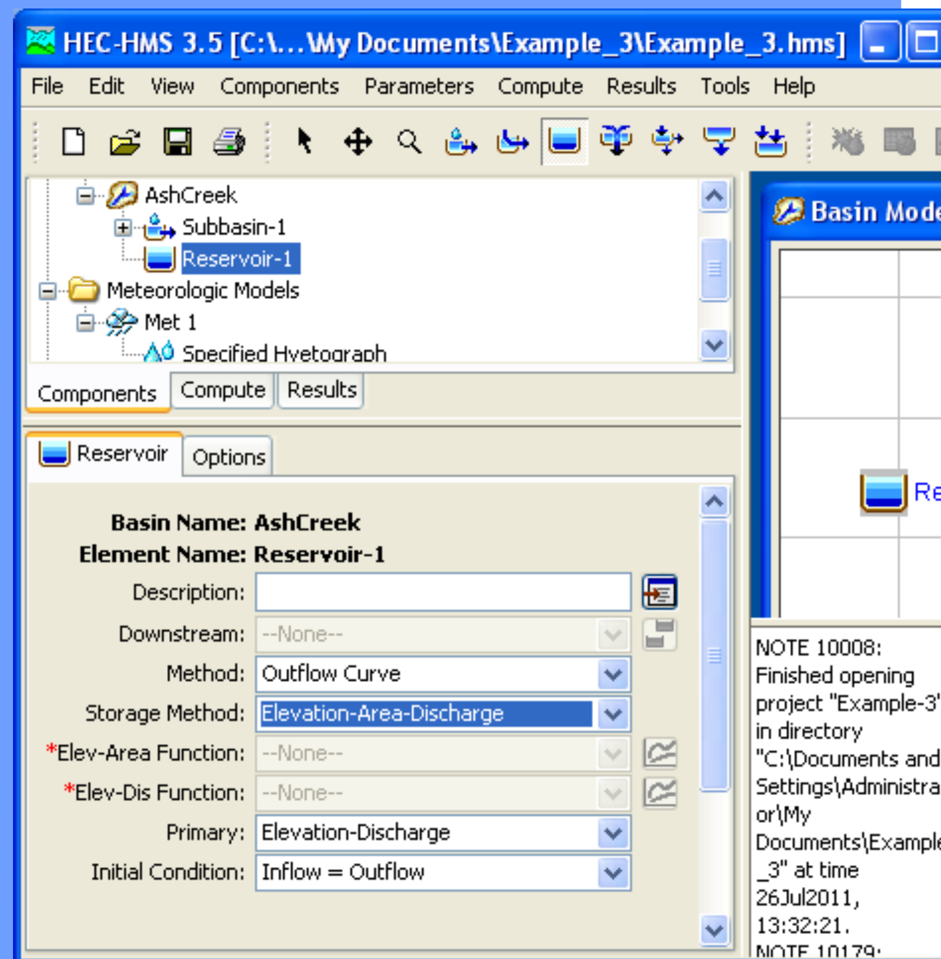
Reservoir Storage

- In HEC-HMS reservoirs (and detention basins) are treated as a hydrologic element in the basin model



Reservoir Storage

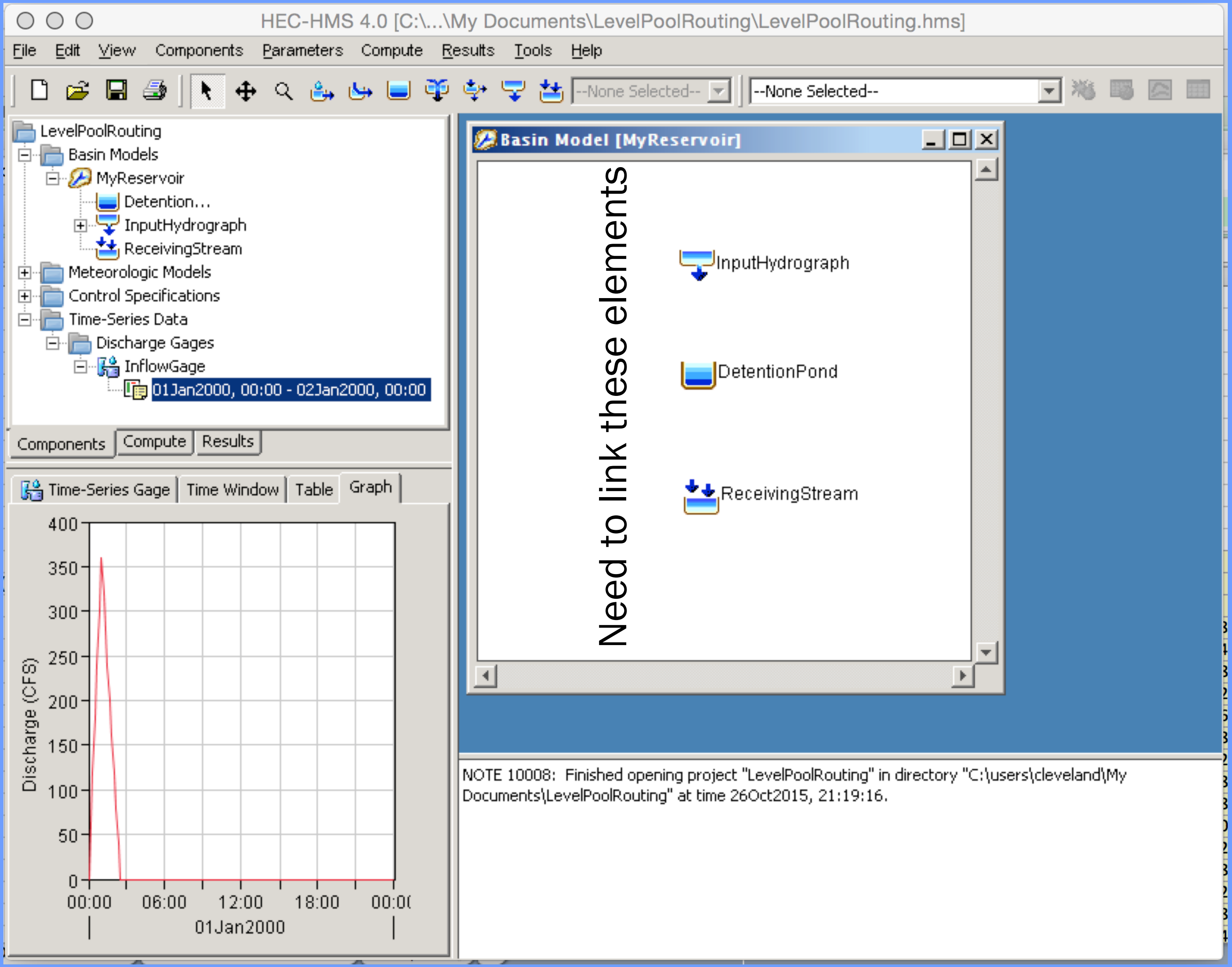
- Accounts for storage
- Flows are "routed" through a resrvoir
  - Level pool routing
  - Orifice flow
  - Weir flow



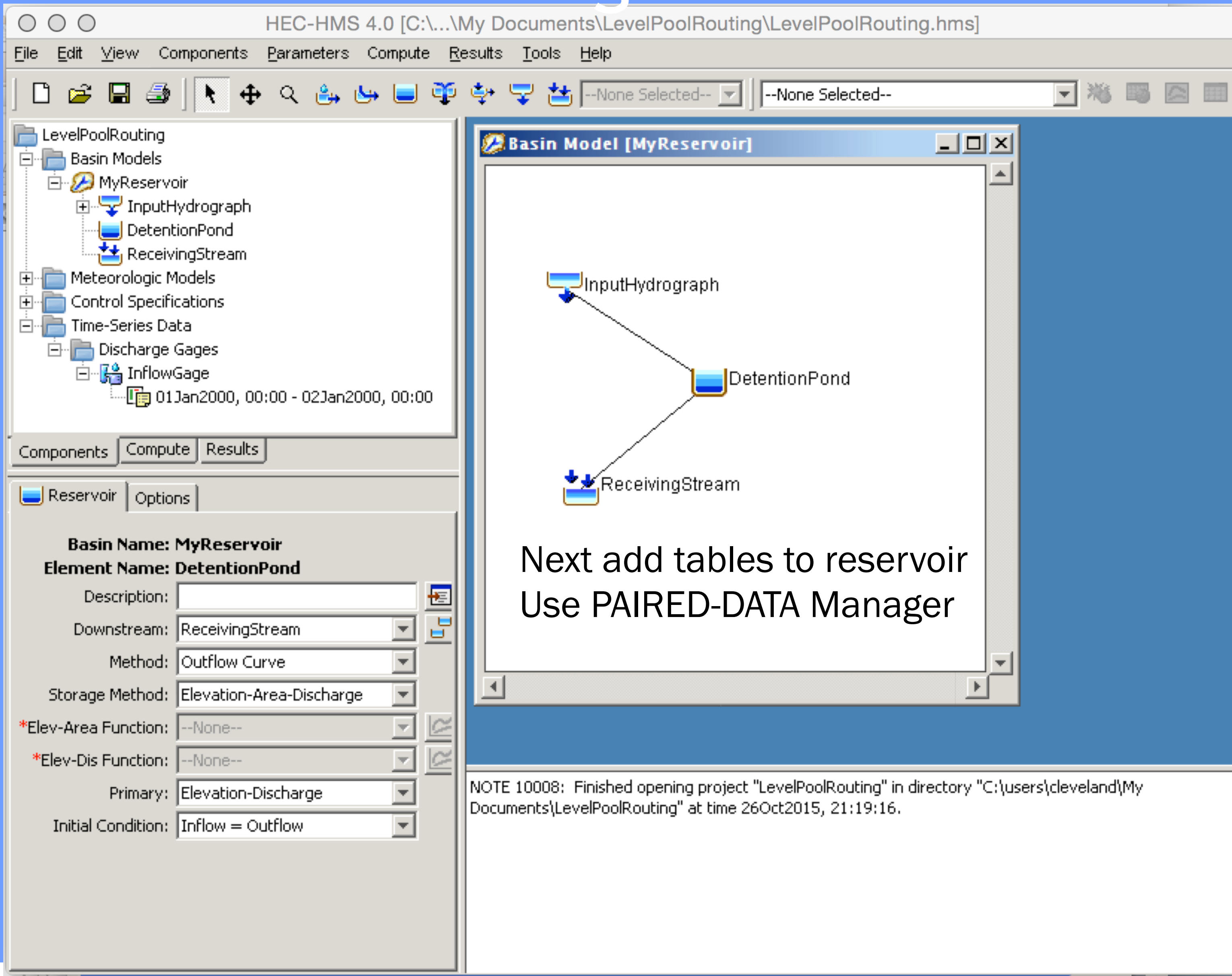
Level Pool Routing in HMS

- Repeat the example (we have done the hard work of building the storage-indication tables) in HMS
- Tasks:
  - Build an HMS Model – use Source, Reservoir, and Sink to capture the various inflow and outflow computations.
    - Time Series Manager to build a discharge gage for inflow
  - All the heavy lifting is in the reservoir specification
  - Met model is required, but type is –NONE—
  - Set time step to 10 minutes (to be same as example)

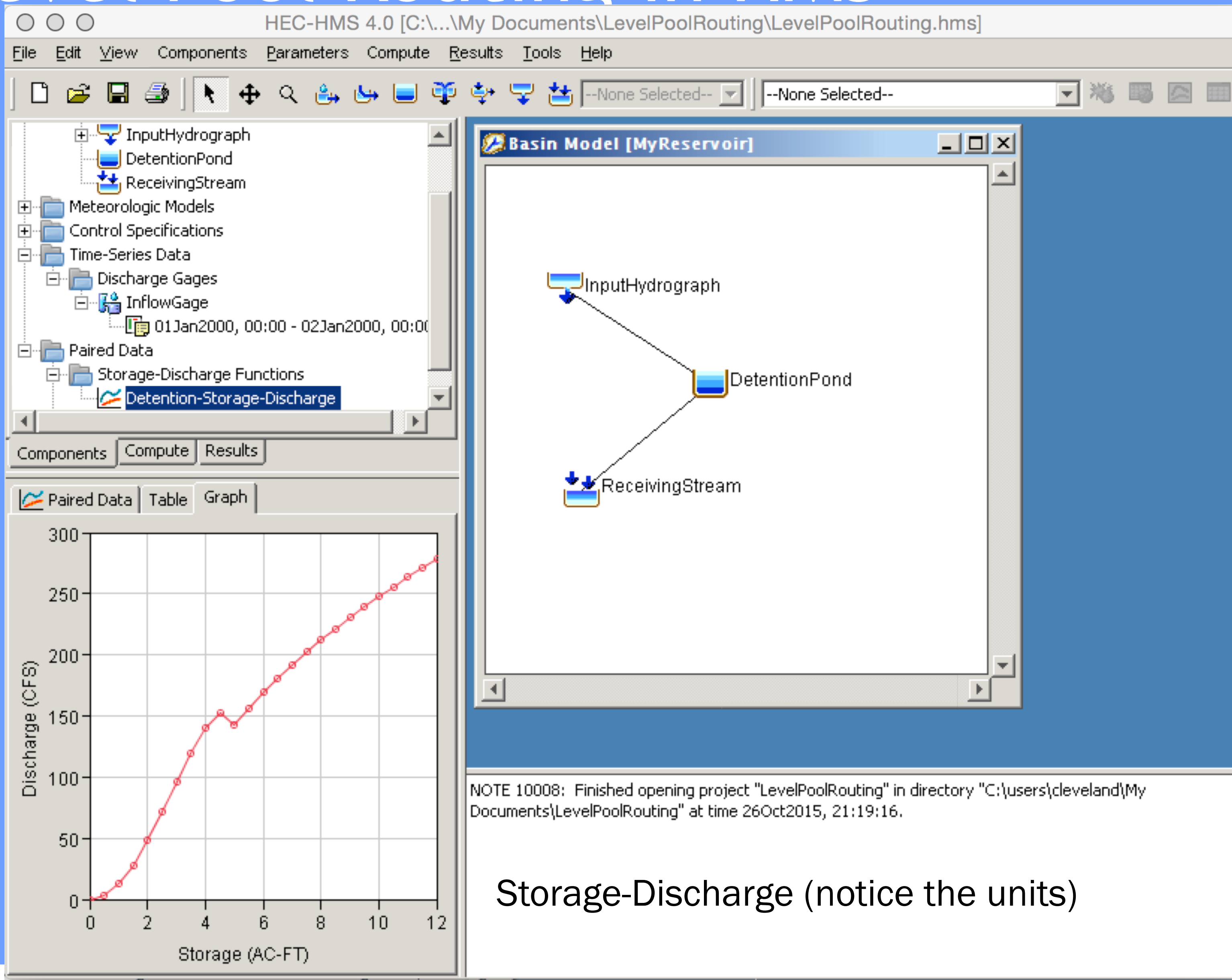
Level Pool Routing in HMS



Level Pool Routing in HMS

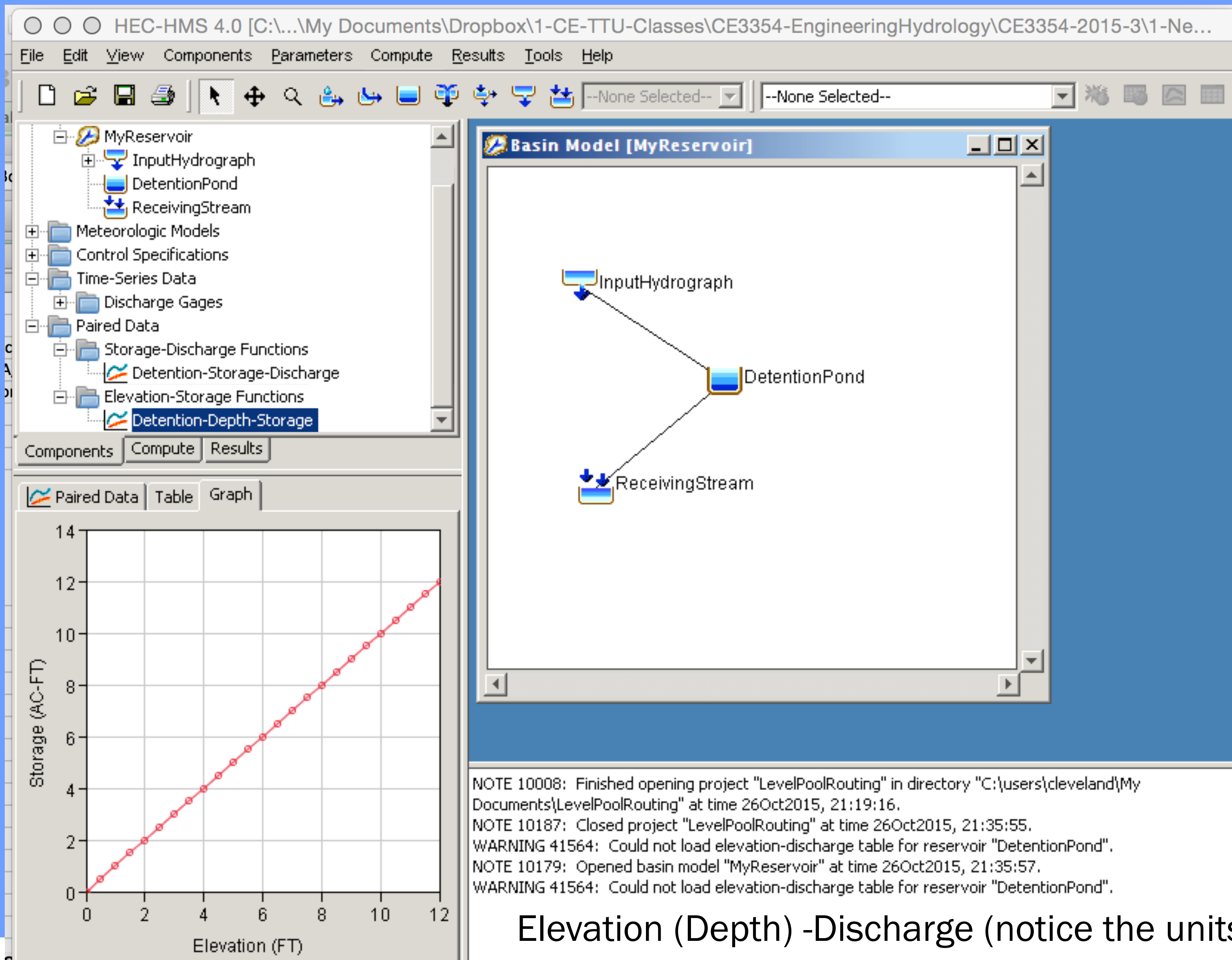


Level Pool Routing in HMS



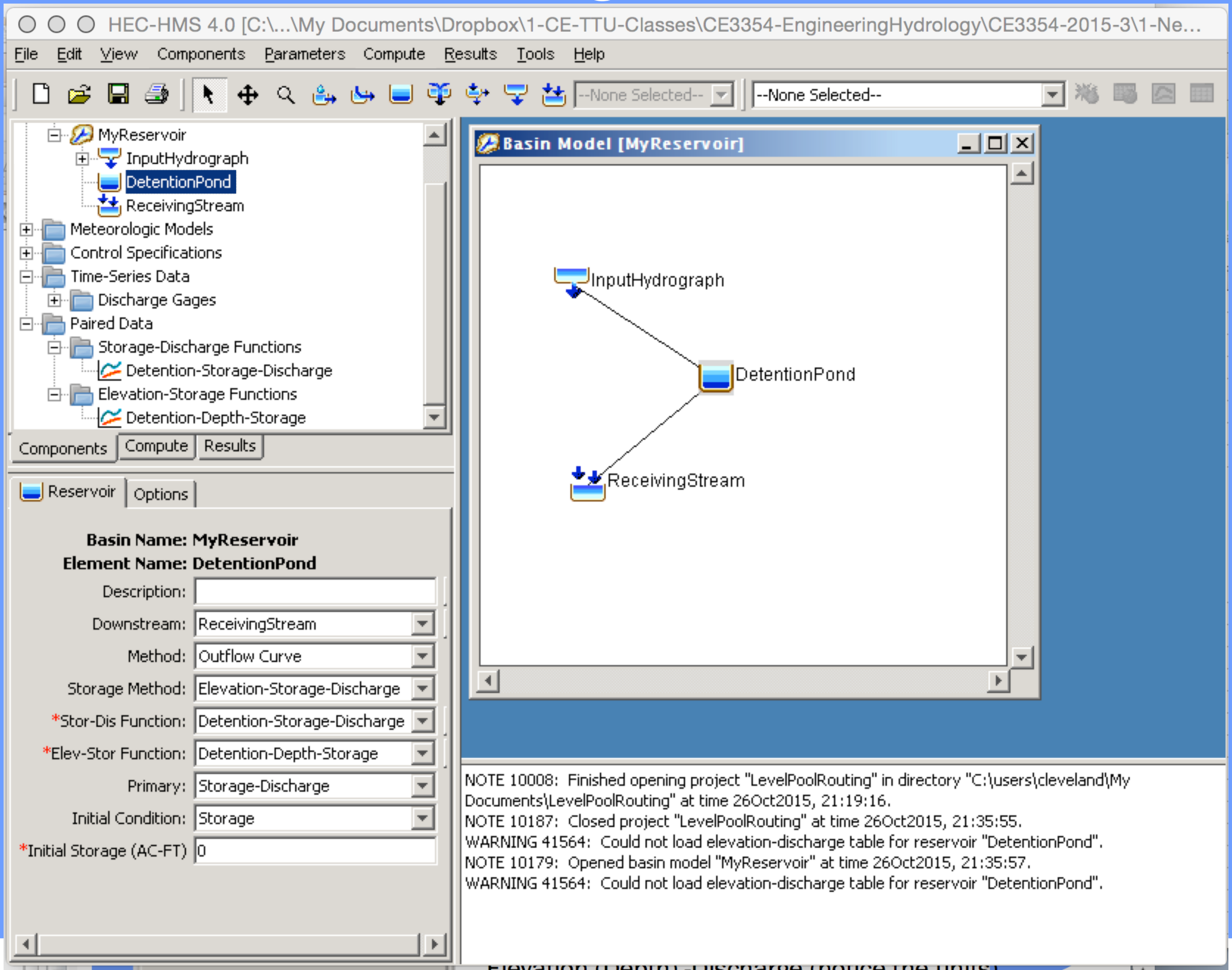
Storage-Discharge (notice the units)

Level Pool Routing in HMS



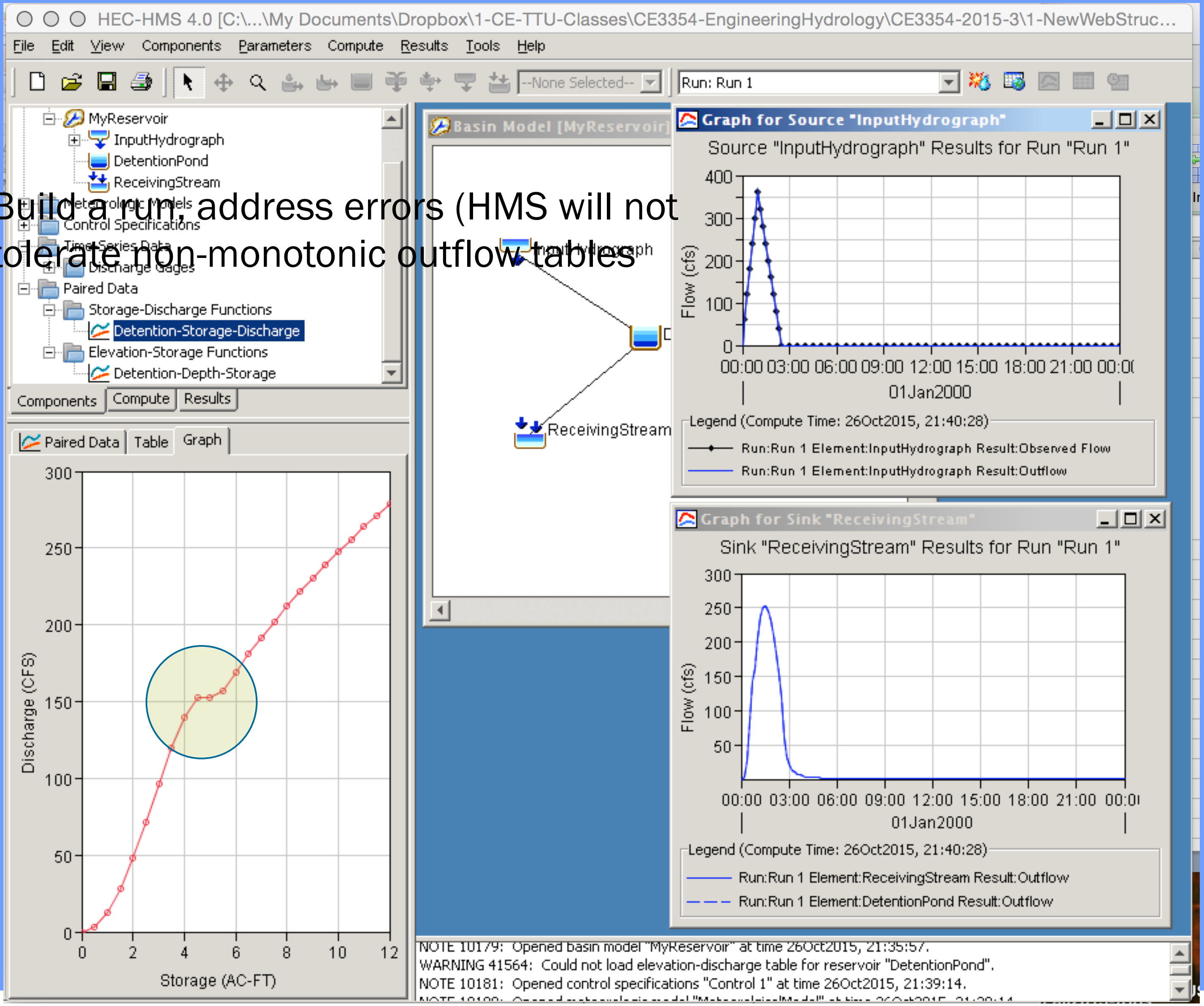
Elevation (Depth) -Discharge (notice the units)

Level Pool Routing in HMS



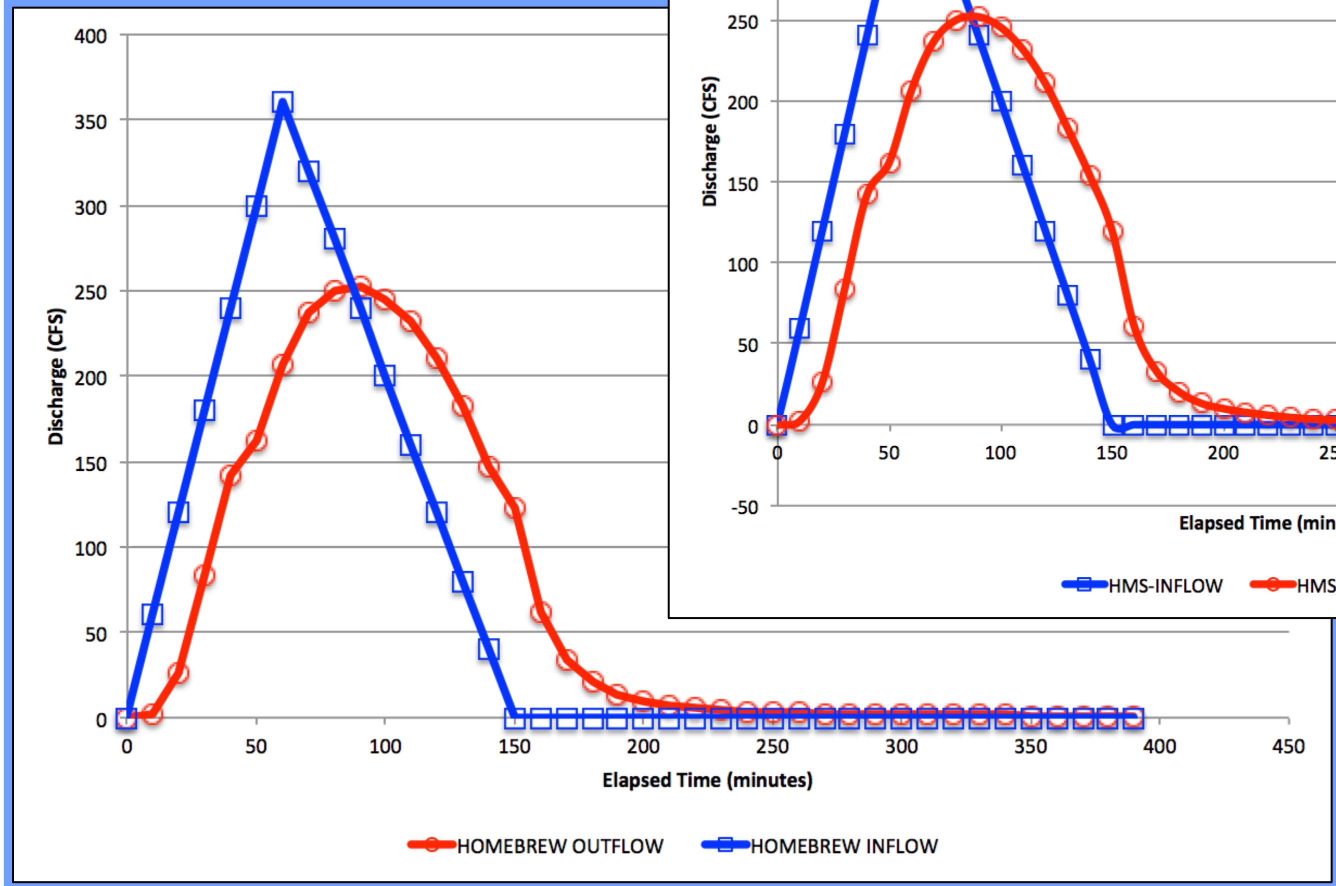
Level Pool Routing in HMS

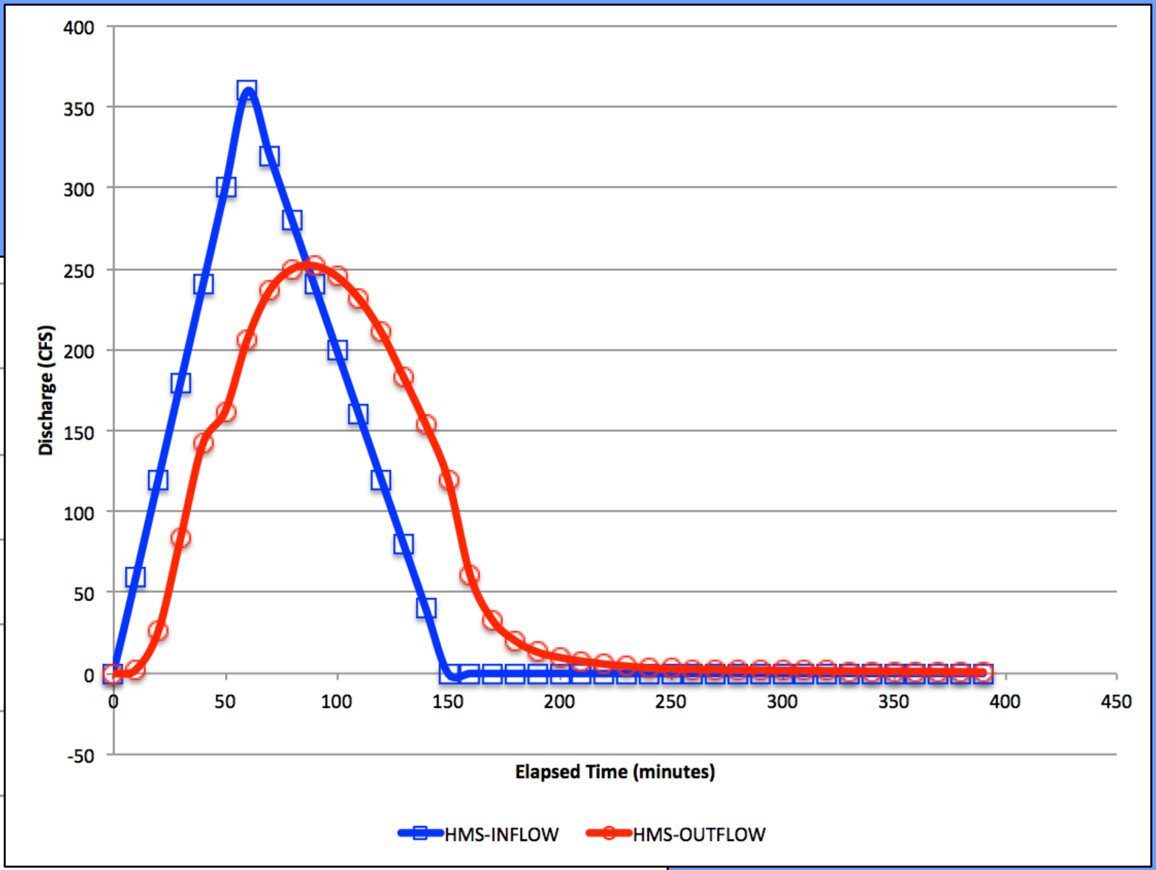
Build a run, address errors (HMS will not tolerate non-monotonic outflow tables



Level Pool Routing

- Compare Results





Routing-channel and reservoir

- Reservoir routing
  - Account for storage in a reservoir
  - Unique storage-discharge relationship
- Channel routing
  - Account for storage in channel as well as travel time
  - Storage-discharge relation in channel is non-unique
    - Can treat channel as a series of reservoirs to mitigate looped effect.

Next Time

- Level Pool Routing applied to a stream reach
  - Example
- Muskingum Routing Background
  - CMM pp. 257-260
- Muskingum-Cunge Routing applied to a stream reach
  - CMM pp. 302-304