Improving the Senior Level Hydraulic Engineering Design Course (CE 474) By Means of Computer Assisted Instruction

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Abstract- This paper presents the development of spreadsheet software at SIUC for the design of pipes, pipes systems, pipe networks, uniform flow in open channels, critical flow in open channels, and gradually-varied flow in open channels and the modules developed. Each module has relevant course material such as examples, projects, handouts, and notes, all key factors in the implementation of a computer-assisted method of instruction in the classroom. The overall design concept is to provide a user-friendly format for studying the application of the design theory presented in lecture. Most of the design problems assigned in the Hydraulic Engineering Design course (CE 474) involve tedious and time-consuming calculations; many require numerous trial-and-error procedures. Additionally, just a small change in the configuration of the problem to be analyzed requires repetition of the original procedure. These are some of the reasons why a computer-assisted method is so critical in enabling students to simulate a variety of realistic problems.

Keywords: Computer-Assisted, Hydraulic Design, Design Modules

MODULES

The following spreadsheet computer software modules for the simulation and analysis of Hydraulic Engineering Systems were created and distributed to the students enrolled in the course CE 474 Hydraulic Engineering Design starting the fall 2005.

- friction losses in pipe flow,
- parallel systems in pipes,
- branching pipes,
- pipe networks,
- unsteady flow in pipes,
- uniform flow in open channel flow,
- critical flow in open channel flow,
- gradually varied flow in open channel flow.

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A brief description of some of these modules [Bravo, 2005], its importance, and application is described below.

1. Calculation of friction losses

The module developed allows the calculation of the friction factor using equation 1and the plot of the friction factor versus the Reynolds Number. Multiple values of the relative roughness can create a graph like the one presented in figure 1.

$$10^{-5} < \frac{e}{D} < 2\times10^{-2} \qquad 4\times10^{3} < N_R < 10^{8}$$

$$f = \frac{0.25}{\left[\log\left(\frac{e}{3.7\,D} + \frac{5.74}{N_R^{0.9}}\right)\right]^2} \tag{1}$$

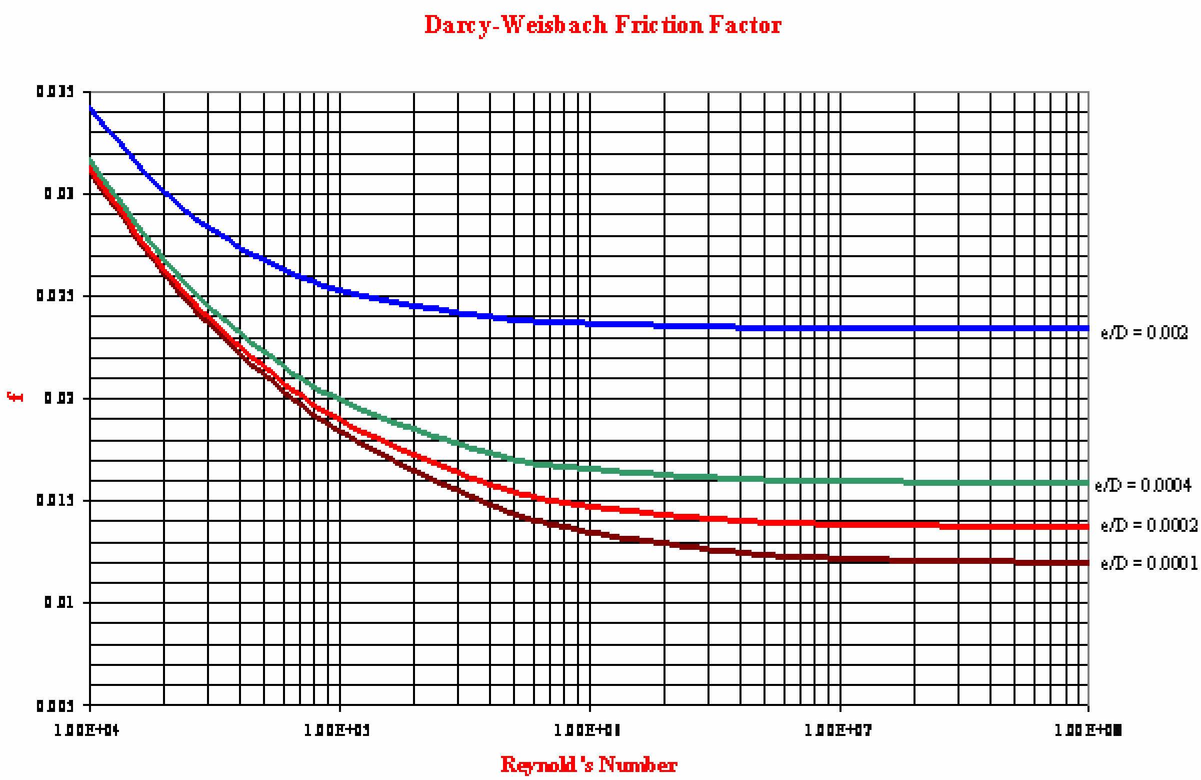


Figure 1. Plotting of the friction factor f vs. Reynold's number

The students benefit for the quick calculation, no need to have a textbook handy, and for reviewing many aspects about plotting such as the logarithmic scale.

2. Pipes connected in series

At this point the concept of the K factor for pipe flow is introduced to simplify the calculation and avoid the cumbersome writing of long equations. The "K" factor is a measure of the capacity of the cross section to convey a fluid. To factor K using the Darcy Weisbach approach is calculated using equation 2:

DARCY-WEISBACH FORMULAS: $h_f = K\,Q^2 \qquad K = f\,\dfrac{L}{D\,2g\,A^2}$ (2)

For complete turbulent flow the friction factor is considered constant and is calculated using equation 3:

$$f = \frac{0.25}{\left[\log\left(\dfrac{e}{3.7\,D}\right)\right]^2} \qquad (3)$$

For the Hazen-Williams formula in the Metric system, the factor K is calculated using equation 4:

$$h_f = \frac{L}{(1.318\times A)^{1.85}\,C_{HW}^{1.85}}\,Q^{1.85} \qquad K = \frac{L}{(1.318AC_{HW})^{1.85}} \qquad (4)$$

For the Hazen-Williams formula in the English system, the factor K is calculated using equation 5:

$$h_f = \frac{L}{(1.318\times A)^{1.85}\,C_{HW}^{1.85}}\,Q^{1.85} \qquad K = \frac{L}{(1.318AC_{HW})^{1.85}} \qquad (5)$$

The module for the pipe in series allows the calculation of the K factors. In many practical problems the discharge is unknown and the friction factor is initially approximated. The spreadsheets developed for the calculations are presented in figure 2and figure 3. The students benefit for the speedy calculation, and the possibilities to study the effects of changing the geometry of the pipes.

1	B	C	D	E	F	G	H	I	J	K	L
2	The following spreadsheet calculates the values of the K factors for friction and local losses for simulations										
3	where the discharge is known										
4	Q =	0.4	m^3/s		Input in cells C4 to C7 the parameters for your particular problem						
5	e =	1.25	mm =	0.00125	m						
6	S =	0.81									
7	ν =	4.00E-07	m^2/s								
8	Pipe	L	D	A	V	N_R	f	K_f	ΣK	K_L	K_T
9		m	m	m^2	m/s			s^2/m^5		s^2/m^5	s^2/m^5
10	1	4000	0.5	0.19635	2.037183	2.55E+06	0.024973	264.1224	2	2.644059	266.7665
11	2	1000	0.5	0.19635	2.037183	2.55E+06	0.024973	66.03061	2	2.644059	68.67467
12	3	500	0.5	0.19635	2.037183	2.55E+06	0.024973	33.0153	4	5.288119	38.30342
13											
14	The values of the properties of the pipes				Input in this column the loss coefficients for the fittings						
15	in these columns can be modified.				and valves in the corresponding pipes						
16	Note: You can change the number of pipes according to your specific requirements										

Figure 2. Determination of the K factors when discharge Q is known

3. Pipe systems connected in parallel

The module developed for this unit consists of spreadsheet to calculate the percentage of flow passing through each branch. Using the proportions of the flow assuming a head loss, the actual flow is determined. Both cases, when the discharge is known, and when the discharge is unknown, are covered in the examples. The students benefit by the speedy calculation, verification of assumption, and introduction of the relative error as a measure of acceptance or tolerance of the approximation. Figure 3, shows the calculation of the flow rate in a system of three parallel pipes.

The following spreadsheet calculates the values of the K factors for friction and local losses for simulations where the discharge is unknown

e =	1.25	mm	=	0.00125 m
S =	0.81			
ν =	4.00E-07	m²/s		

$$f = \frac{0.25}{\left[\log\left(\frac{e}{3.7D}\right)\right]^2}$$

Input in this column the loss coefficients for the fittings and valves in the corresponding pipes

The values of the properties of the pipes in these columns can be modified.

Pipe	L	D	A	e	f	K_f	ΣK	K_L	K_T
	m	m	m²	mm	assumed	s²/m⁵		s²/m⁵	s²/m⁵
1	1000	0.5	0.19625	0.00125	0.024874	65835.7	0	0	65835.7
2	7500	0.75	0.441563	0.00125	0.022325	58359.71	2	0.522813	58360.24
3	5000	1	0.785	0.00125	0.020747	8580.043	10	0.827107	8580.87

Note: You can change the number of pipes according to your specific requirements

Figure 3. Determination of the K factors when discharge Q is unknown

$Q =$ 0.2 m³/s

Assuming Complete Turbulence

Assume any value for the head loss in the parallel system

$h_T =$ **10 m**

$$Q = \sqrt{\frac{h_T}{K_T}}$$

Pipe	L	D	e	A	f (initial)	K_f	ΣK	K_L	K_T	$Q_{assumed}$	%	Q_{actual}
	m	m	m	m²		s²/m⁵		s²/m⁵	s²/m⁵	m³/s		m³/s
1	100	0.05	0.0001	0.001963	0.02342	1215.898	10	132203	133418.9	0.008657	9.03281	0.018066
2	150	0.075	0.0002	0.004418	0.02532	584.2273	3	7834.25	8418.477	0.034465	35.9596	0.071919
3	200	0.085	0.0001	0.005675	0.02044	431.8958	2	3165.742	3597.638	0.052722	55.0076	0.110015
									SUM	0.095845	100	0.2

The values of the properties of the pipes in these columns can be modified.

$$f = \frac{0.25}{\left[\log\left(\frac{e}{3.7D}\right)\right]^2}$$

Calculating the actual value of "f"

Pipe	L	D	e	A	f (initial)	Q	V	N_R	f (actual)	Δf	error %
	m	m	m	m²		m³/s	m/s				
1	100	0.05	0.0001	0.001963	0.02342	0.018066	9.20074	460037.2	0.023421	6.59E-07	0.00281
2	150	0.075	0.0002	0.004418	0.02532	0.071919	16.2792	1220938	0.02532	3.08E-07	0.00122
3	200	0.085	0.0001	0.005675	0.020436	0.110015	19.3876	1647950	0.020436	1.7E-07	0.00083

$$error = \frac{f_{actual} - f_{initial}}{f_{actual}} x100$$

Figure 4. Calculation of the flow in a parallel system of three pipes

4. Pipe branching

Based on the principles of mass conservation and that at any junction all the pipes converging to that junction must have the same piezometric head at that junction, spreadsheets to determine the discharges in the branching pipes system were developed.

For example, a system of branching pipes as the one shown in figure 5 can be solved in a graphical form as shown in figure 6, figure 7, and figure 8.

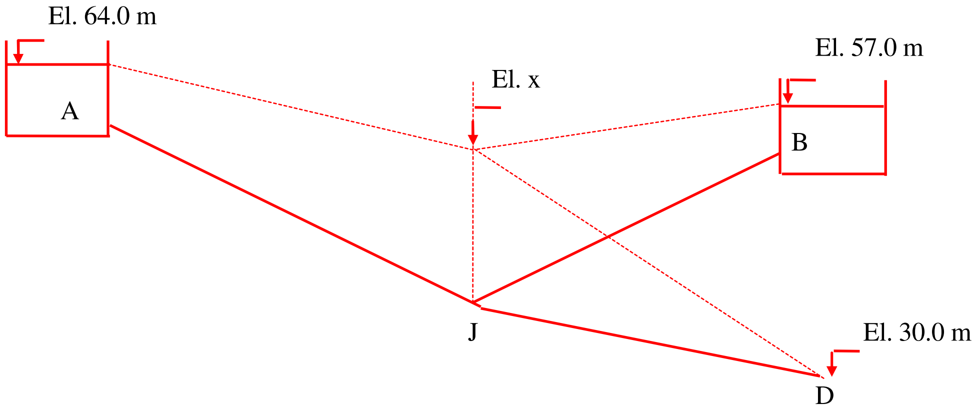


Figure 5. System of branching pipes

	Elev. (m)
Res A	64
Res B	57
Outlet D	30

$$h_f = \frac{L}{\left(A0.85C_{HW}R_H^{0.63}\right)^{1.85}}Q^{1.85}$$

$$K = \frac{L}{\left(0.85AC_{HW}R_H^{0.63}\right)^{1.85}}$$

Pipe	L	D	C_{HW}	A	R_H	K
	m	m		m^2	m	$s^{1.85}/m^{4.55}$
AJ	2400	0.6	100	0.2826	0.15	61.14816
BJ	1200	0.4	100	0.1256	0.1	219.8495
JD	1200	0.3	100	0.07065	0.075	891.2814

The values of the properties of the pipes in these colums can be modified

$$Q = \left(\frac{h_f}{K}\right)^{0.54}$$

A sign (positive for inflow and negative for outflow) is assigned automatically to the flows according to piezometric heads using the conditional function "if"

Assume x = 57 | x = 60

Pipe	K	h_L	Q	using	h_L	Q	using
	s^2/m^5	m	m^3/s	cond.	m	m^3/s	cond.
AJ	61.14816	7	0.310246	0.310246	4	0.229332	0.229332
BJ	219.8495	0	0	0	-3	0.098378	-0.09838
JD	891.2814	-27	0.151331	-0.15133	-30	0.160191	-0.16019
		ΣQ =	0.158915	0.158915		-0.02924	-0.02924

H_J	Qin	Qout
57	0.310246	0.151331
60	0.229332	0.258569

Figure 6. Determination of the flow rate in branching pipes

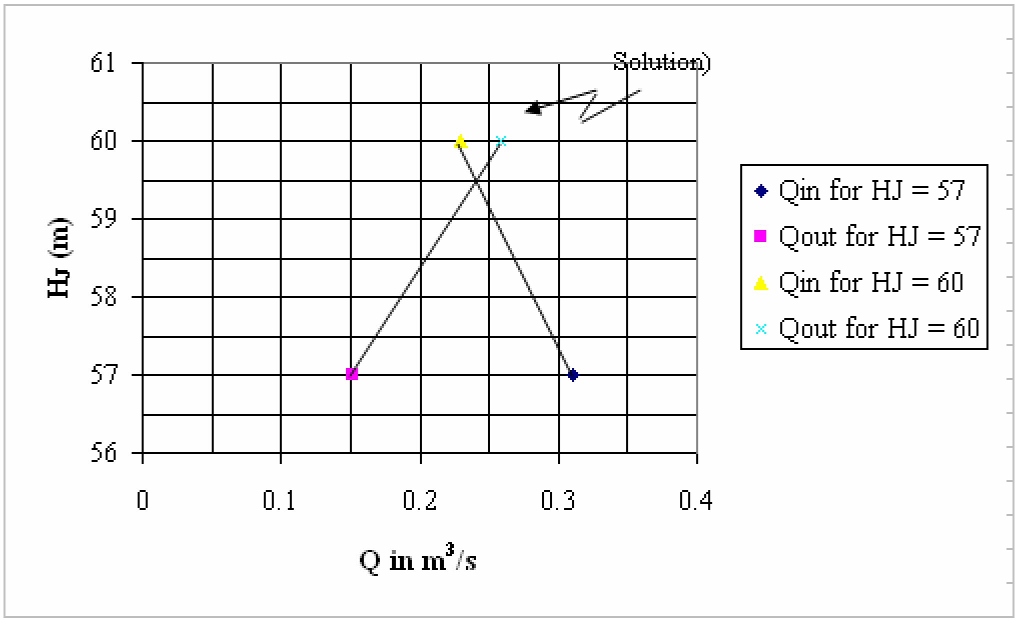


Figure 7. Graphical Solution using Q in and Q out

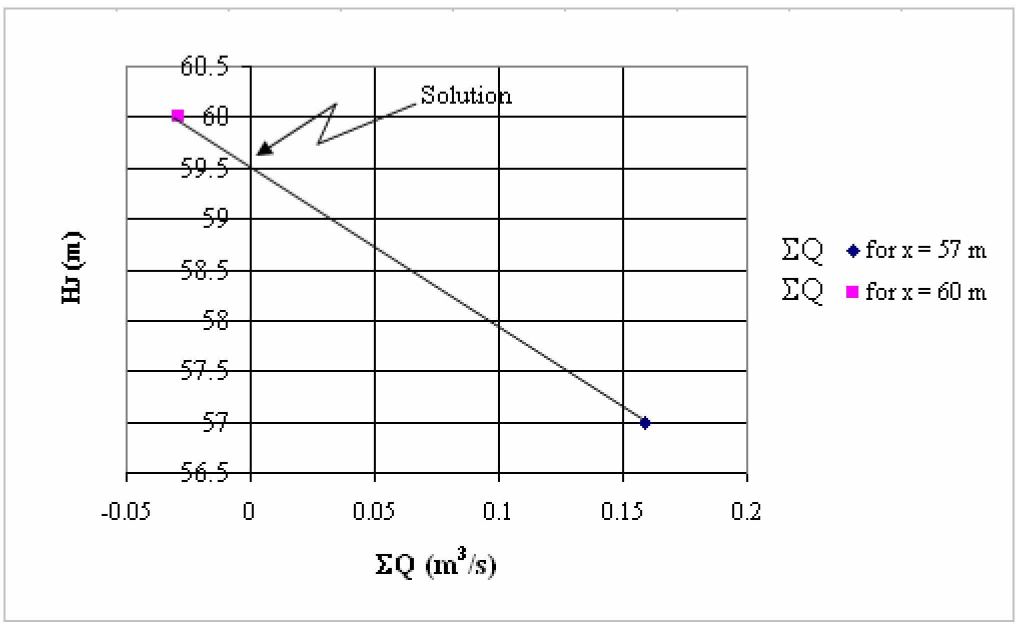


Figure 8. Graphical solution using the ΣQ at the node

5. Pipe networks (including fix grade nodes and pumps)

The spreadsheets modules were developed to determine the discharge in pipe networks. For simplicity only the first iteration of a simple pipe network as the one shown in figure 9, is presented in this paper. The file created contains four iterations. Also the pipes that are common to two loops are presented colored in the original file to help the students to recognize the problem of applying the correction for both loops. Similar files were created to include fix grade nodes and pumps with constant head.

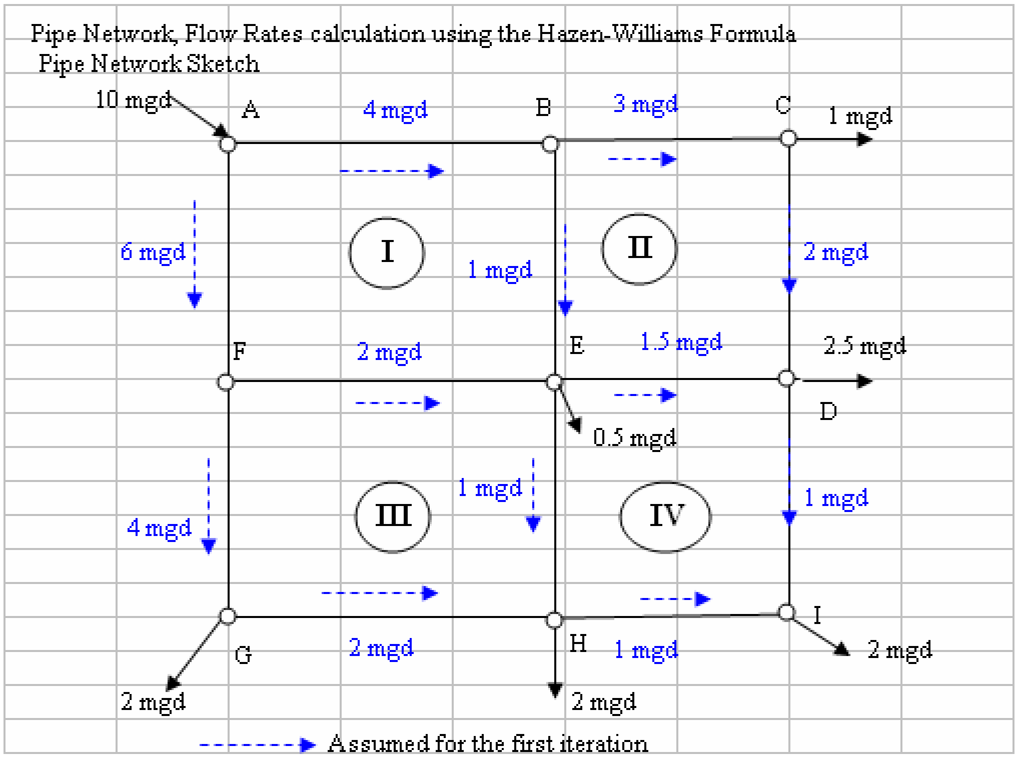


Figure 9. Pipe network example

Table 1. Pipe properties for the network of figure 9

Pipe	L (ft)	D (in)	C_{HW}
AB	3000	20	120
BE	4000	16	120
EF	3000	16	120
AF	4000	24	120
BC	3000	20	120
CD	4000	16	120
DE	3000	12	120
EB	4000	12	120
FE	3000	16	120
EH	4000	16	120
HG	4000	12	120
GF	3000	12	120
ED	3000	12	120
DI	4000	12	120
IH	3000	12	120
HE	4000	12	120

First Iteration										
Pipe	**L**	**D**	**A**	**R_H**	**C_{HW}**	**K**	**Q_0**	**$KQ^{1.85}$**	**$1.85KQ^{0.85}$**	**Q_1**
	ft	**in**	**ft^2**	**ft**		**$s^{1.85}/ft^{4.55}$**	**(assumed)**			**mgd**
AB	3000	20	2.181662	0.416667	120	0.167947	4	2.1826	1.0095	4.3175
BE	4000	16	1.396263	0.333333	120	0.663172	1	0.6632	1.2269	1.0694
EF	3000	16	1.396263	0.333333	120	0.497379	-2	-1.7931	1.6586	-3.2252
FA	4000	24	3.141593	0.5	120	0.092226	-6	-2.5377	0.7824	-5.6825
Sum							Σ =	-1.4849	4.6774	
								Δ Q_I=	-0.3175	
BC	3000	20	2.181662	0.416667	120	0.167947	3	1.2819	0.7905	3.2481
CD	4000	16	1.396263	0.333333	120	0.663172	2	2.3907	2.2114	2.2481
DE	3000	12	0.785398	0.25	120	2.016402	-1.5	-4.2692	5.2653	-1.1330
EB	4000	12	0.785398	0.25	120	2.688536	-1	-2.6885	4.9738	-1.0694
Sum							Σ =	-3.2851	13.2411	
								Δ Q_{II}=	-0.2481	
FE	3000	16	1.396263	0.333333	120	0.497379	2	1.7931	1.6586	3.2252
EH	4000	16	1.396263	0.333333	120	0.663172	1	0.6632	1.2269	2.6616
HG	3000	12	0.785398	0.25	120	2.016402	-2	-7.2691	6.7239	-0.4573
GF	4000	12	0.785398	0.25	120	2.688536	-4	-34.9403	16.1599	-2.4573
Sum							Σ =	-39.7532	25.7693	
								Δ Q_{III}=	-1.5427	
ED	3000	12	0.785398	0.25	120	2.016402	1.5	4.2692	5.2653	1.1330
DI	4000	12	0.785398	0.25	120	2.688536	1	2.6885	4.9738	0.8811
IH	3000	12	0.785398	0.25	120	2.016402	-1	-2.0164	3.7303	-1.1189
HE	4000	12	0.785398	0.25	120	2.688536	-1	-2.6885	4.9738	-2.6616
Sum							Σ =	2.2528	18.9433	
								Δ Q_{IV}=	0.1189	

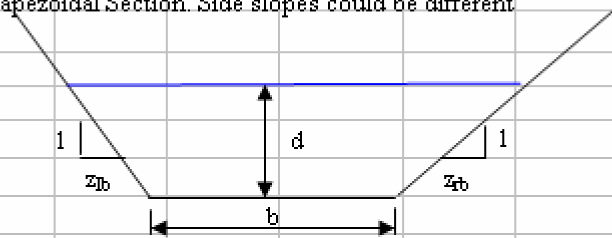
Figure 10. First iteration of the pipe network shown in figure 9

6. Uniform and critical flow in open channel

The Depth of the Channel that satisfies the equation is called Uniform or Normal Depth (d_n). Calculating the Normal Depth requires the solution of an equation that many times is done by the traditional trial and error procedure. The spreadsheets developed allow the calculation of the normal depth by approximation, using the Goal Seek tool, and using the Solver tool in Excel. The determination of the critical depth (d_c) also requires most of the time the trail and error procedure. The spreadsheets developed allow the calculation of the normal and critical depth by approximation, using the Goal Seek tool, and using the Solver tool in Excel. The example presented in figure 11 illustrate the iteration procedure, figure 12 illustrates the use of goal seek and solver for the determination of the normal depth, and figure 13 illustrates the use of goal seek and solver for the determination of the critical depth. The figures of the cross sections are embedded in the spreadsheet.

Calculation of Normal Depth for a Trapezoidal Section. Side slopes could be different

Q =	6	m^3/s
n =	0.012	
b =	2.4	m
z_{lb} =	2	
z_{rb} =	2	
S_o =	0.0001	



For Normal Depth, the following equation needs to be satisfied

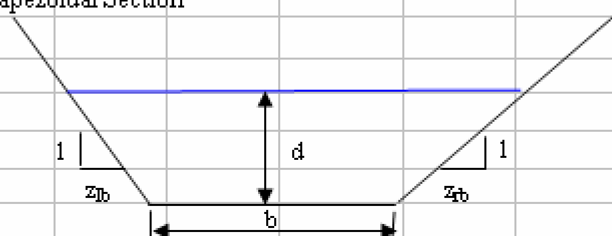
$$\frac{Qn}{S_o^{1/2}} = AR_H^{2/3}$$

Change the value of the normal depth (in red) until the difference is as close as zero (tolerance)

$\frac{Qn}{S_o^{1/2}}$	d_n	A	P	R_H	$AR_H^{2/3}$	Difference
7.2	1.48	7.9328	9.018761	0.879589	7.282485	-0.082485

Calculation of Critical Depth for a Trapezoidal Section

Q =	6	m^3/s
b =	2.4	m
z_{lb} =	2	
z_{rb} =	2	



For Critical Depth, the following equation needs to be satisfied

$$\frac{Q}{\sqrt{g}} = A\sqrt{\frac{D}{T}} = \frac{A^{3/2}}{T^{1/2}}$$

Change the value of the critical depth (in red) until the difference is as close as zero (tolerance)

$\frac{Q}{\sqrt{g}}$	d_c	A	T	D	$A\sqrt{D}$	Difference
1.915653	0.7	2.66	5.2	0.511538	1.902483	0.0131696

Figure 11. Example of the calculation of normal and critical depth of a trapezoidal cross section channel using iteration procedure.

Normal Depth Calculation

Trapezoidal Section

$$Q = A\frac{1}{n}R_H^{2/3}S_0^{1/2}$$

Q =	20	m^3/s		
n =	0.013			
S_o =	0.001			
b =	10	m		
z =	2			
Using Solver			**Using Goal Seek**	
d_n =	0.864002		0.863998	
Q =	20		19.99985	← Input Formula

Write here the Manning's formula for the discharge in terms of d_n (refer to the cell where d_n is placed)

Figure 12. Example determination of normal depth in a trapezoidal cross section channel with the same side slope using the tools solver and goal seek.

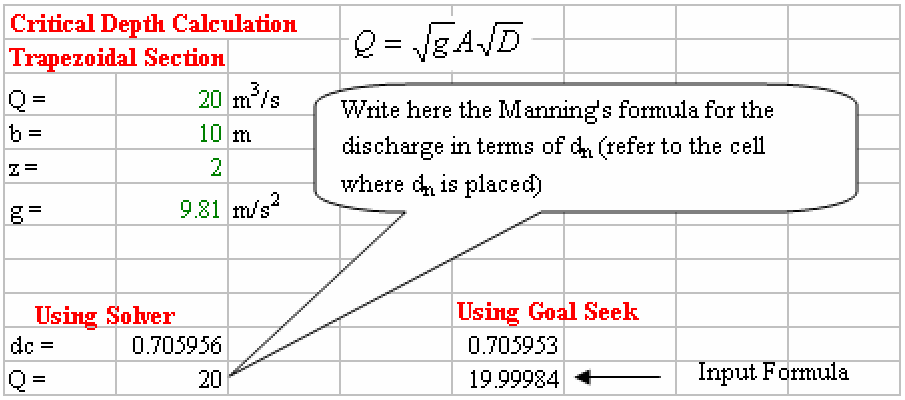


Figure 13. Example determination of critical depth in a trapezoidal cross section channel with the same side slope using the tools solver and goal seek.

7. Gradually Varied Flow in Open Channel

The study of gradually varied flow and the water surface profile calculation is done using two methods:

a. Direct Step Method

b. Standard Step Method

Spreadsheets for each one of these methods were developed. The calculation of the water surface profile using the Direct Step Method for a trapezoidal section channel that empties to a lake with a given depth is presented as a sample of the module developed. Figure 14 shows the first step of the calculation, that is, the determination of the type of flow in the channel by the calculation of the normal and critical depth. Figure 15 presents the calculation of the water surface profile performed with steps increments of 0.2 m. Figure 16 shows the calculation procedure in one step. The results of the calculation are better described in a graph; figure 17 presents the calculation of the water surface profile for the sample problem, and figure 18 shows the plotting of the water surface profile.

CONCLUSIONS

Since the fall semester of 2005, the modules developed have been delivered to the students enrolled in CE 474 as part of the course material. The students have responded very enthusiastically to this insertion as reflected in the exit senior evaluation for the instructor of the course. Also, the modules were used for the students for solving assignments close to real problems and the students have shown more interest in the subject. The insertion of the modules has motivated the students to create similar spreadsheets for other type of calculations in other areas such as structures, concrete, etc. Currently, a survey questionnaire is being developed to quantify the success of the insertion of the modules in the course.

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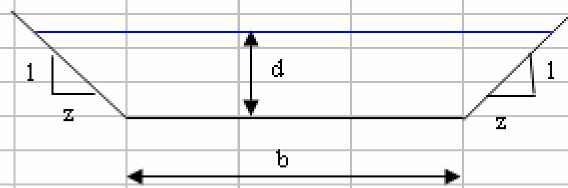
Direct Step Method

Calculation for the backwater curve of a prismatic channel of trapezoidal section which empties into a lake. The depth of water in the channel where it empties into the lake is given (d)

The propertties of the channel are:

$$A = bd + zd^2 \qquad P = b + 2d\sqrt{1+z^2}$$

$d =$	6	ft
$Q =$	350	cfs
$b =$	20	ft
$z =$	2	
$n =$	0.014	
$S_o =$	0.0002	



Calculation Normal Depth $\frac{Qn}{1.49 S_o^{1/2}} = A R_H^{2/3}$

$\frac{Qn}{1.49 S_o^{1/2}} =$ 232.5385

$d_n =$ 4.017516 m — Using Goal Seek

$A R_H^{2/3} =$ 232.5383

Calculation Critical Depth $\frac{Q}{\sqrt{g}} = A\sqrt{D}$

$\frac{Q}{\sqrt{g}} =$ 61.6794

$d_c =$ 1.976783 — Using Goal Seek

$A\sqrt{D} =$ 61.67886

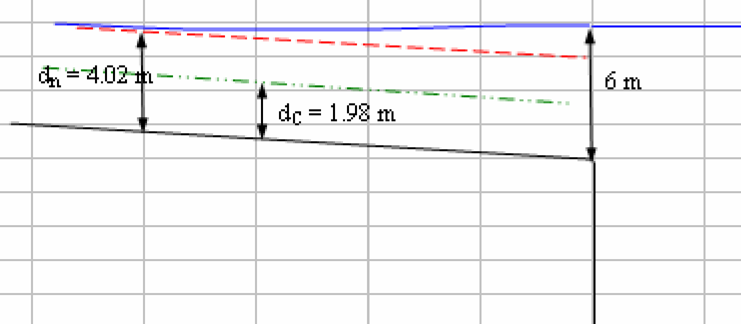


Figure 14. Determination of the type of flow

d	A	P	R_H	V	$\frac{V^2}{2g}$	E	ΔE	S_f	$\bar{S}_f$	$S_o - \bar{S}_f$	ΔX	L
ft	ft^2	ft	ft	ft/s		ft	ft				ft	ft
6	192.00	46.83	4.10	1.82	0.05	6.05		4.47E-05				0.00
5.8	183.28	45.94	3.99	1.91	0.06	5.86	0.19	5.09E-05	4.78E-05	1.52E-04	1281.01	1281.01
5.6	174.72	45.04	3.88	2.00	0.06	5.66	0.19	5.81E-05	5.45E-05	1.45E-04	1335.56	2616.57
5.4	166.32	44.15	3.77	2.10	0.07	5.47	0.19	6.67E-05	6.24E-05	1.38E-04	1406.75	4023.32
5.2	158.08	43.26	3.65	2.21	0.08	5.28	0.19	7.69E-05	7.18E-05	1.28E-04	1502.59	5525.91
5	150.00	42.36	3.54	2.33	0.08	5.08	0.19	8.91E-05	8.30E-05	1.17E-04	1637.03	7162.94
4.8	142.08	41.47	3.43	2.46	0.09	4.89	0.19	1.04E-04	9.64E-05	1.04E-04	1836.80	8999.75
4.6	134.32	40.57	3.31	2.61	0.11	4.71	0.19	1.21E-04	1.13E-04	8.74E-05	2160.25	11159.99
4.4	126.72	39.68	3.19	2.76	0.12	4.52	0.19	1.43E-04	1.32E-04	6.77E-05	2763.64	13923.64
4.2	119.28	38.78	3.08	2.93	0.13	4.33	0.18	1.70E-04	1.57E-04	4.34E-05	4255.05	18178.69
4	112.00	37.89	2.96	3.13	0.15	4.15	0.18	2.03E-04	1.87E-04	1.34E-05	13579.26	31757.95

Figure 15. Direct Step Method Calculation with a depth changing every 0.2 m

d	A	P	R_H	V	$\frac{V^2}{2g}$	E	ΔE	S_f	$\bar{S}_f$	$S_o - \bar{S}_f$	ΔX
ft	ft^2	ft	ft	ft/s		ft	ft				ft
6	192.00	46.83	4.10	1.82	0.05	6.05		4.47E-05			
4	112.00	37.89	2.96	3.13	0.15	4.15	1.90	2.03E-04	1.24E-04	7.60E-05	24990.27

Figure 16. Direct Step Method Calculation in one Step

x	-x	$y = xS_o$	d	$d + xS_o$
0.00	0	0	6	6
1281.01	-1281.01	0.256202	5.8	6.056202
2616.57	-2616.57	0.523314	5.6	6.123314
4023.32	-4023.32	0.804665	5.4	6.204665
5525.91	-5525.91	1.105182	5.2	6.305182
7162.94	-7162.94	1.432589	5	6.432589
8999.75	-8999.75	1.799949	4.8	6.599949
11159.99	-11160	2.231999	4.6	6.831999
13923.64	-13923.6	2.784727	4.4	7.184727
18178.69	-18178.7	3.635738	4.2	7.835738
31757.95	-31758	6.35159	4	10.35159

Water surface elevation respect to the control section where d is given

Elevation of the channel bed

The value of negative x is neccesary because the calculations go upstream of the control section

Figure 17. Calculation for drawing the water surface profile

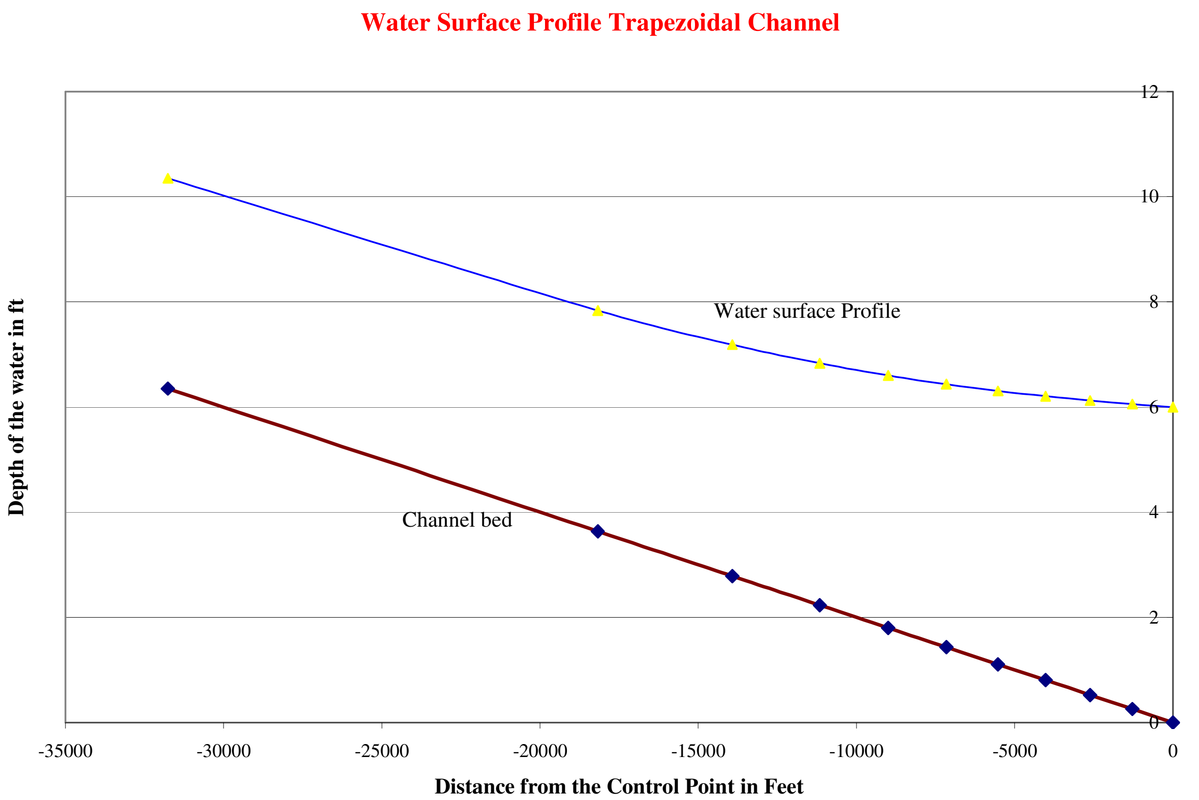


Figure 18. Water surface profile graph

References

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