A SunCam online continuing education course

Open Channel & Box Culvert Flow

The Manning Formula

and

“Manning-Channel”

A SunCam Software Tool for Engineers

by

William C. Dunn, P.E.

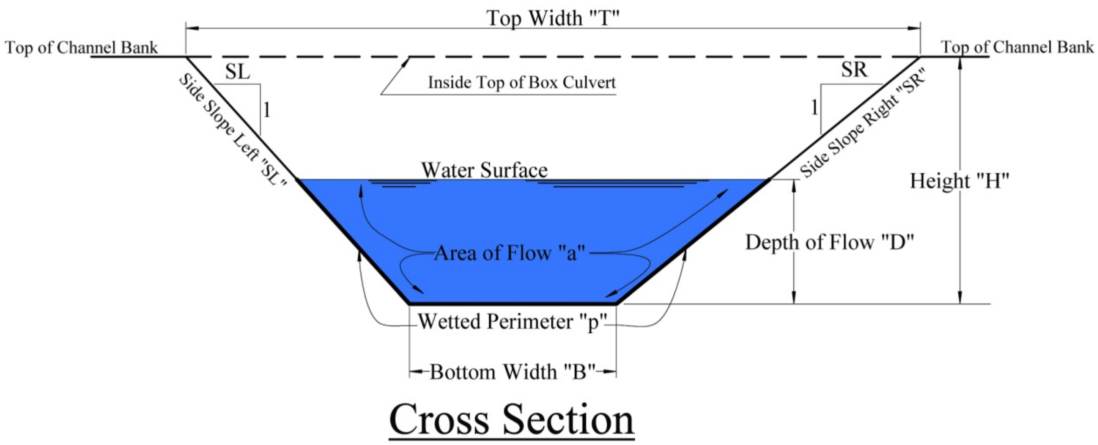

Figure 1 defining the variables

Purpose

Open channels, box culverts and pipes are common conduits for transporting water utilizing the force of gravity to create the flow. Flow in pipes is covered in the SunCam companion course, Gravity Flow in Pipes - The Manning Formula. This course will expand on that topic to cover open channel and box culvert flow.

The purpose of this course and the "Manning-Channel" software is to examine and understand the Manning formula approach to the hydraulic design of such conduits. The Manning formula is an empirical formula that science and engineering have developed to predict the velocity of gravity flow in a conduit. The person who completes this course will have an improved understanding of the hydraulics of gravity flow and the use of the Manning Formula as a design tool. The "Manning-Channel" software will allow users to speed the learning process by eliminating most of the monotonous calculations.

Introduction

Robert Manning (1816-1897) was an Irish accountant who spent more time studying engineering than accounting. In 1890 he developed the Manning formula which is still in common use today. The formula takes two basic forms as follows:

In U.S. Customary Units

(1) $V=\frac{1.486}{n}\times R^{2/3}\times S^{1/2}$

(2) $Q=aV=\frac{1.486}{n}a\times R^{2/3}\times S^{1/2}$

Where:

V=Mean velocity in feet per second

n=Manning coefficient of roughness

R=Hydraulic radius in feet (the cross-sectional area of flow divided by the wetted perimeter)

S=Hydraulic slope in feet per foot (or any other linear measure divided by the same linear measure). This is an indication of the loss of head in the system.

Q=Quantity of flow in cubic feet per second (Discharge)

a=Cross-sectional area of flow in square feet.

In Metric Units

$V=\frac{1}{n}\times R^{2/3}\times S^{1/2}$

$Q=aV=\frac{1}{n}a\times R^{2/3}\times S^{1/2}$

Where:

V=Mean velocity in meters per second

n=Manning coefficient of roughness

R=Hydraulic radius in meters (the cross-sectional area of flow divided by the wetted perimeter)

S=Hydraulic slope in meters per meter (or any other linear measure divided by the same linear measure). This is an indication of the loss of head in the system.

Q=Quantity of flow in cubic meters per second (Discharge)

a=Cross-sectional area of flow in square meters.

Formula (1) above may be restated as follows:

In U.S. Customary Units

(3) $n=\frac{1.486}{V}\times R^{2/3}\times S^{1/2}$

(4) $R=\left(\frac{Vn}{1.486\times S^{1/2}}\right)^{3/2}$

(5) $S=\left(\frac{Vn}{1.486\times R^{2/3}}\right)^{2}$

In Metric Units

$n=\frac{1}{V}\times R^{2/3}\times S^{1/2}$

$R=\left(\frac{Vn}{S^{1/2}}\right)^{3/2}$

$S=\left(\frac{Vn}{R^{2/3}}\right)^{2}$

See Appendix "A" for a complete listing of the 52 formulas used in Manning-Channel.

Manning-Channel software

The SunCam "Manning-Channel" software is a Microsoft Excel based program for solving the Manning Formula. It was developed using the formulae (1) - (5) and the geometry of the conduit. The program first reads the data inputs to determine which of the variables are known and then computes as many of the missing variables as possible with the given data.

There are exactly 16,384 possible data entry combinations of the 14 variables (2^{14}) ranging from no data entered to data entered for all 14 variables. Those combinations fall into four categories. The input tracking cell (row 38) prompts the user with one of these messages:

Software Precautions

A professional engineer should have a healthy skepticism about all software outputs, even the software that you write yourself. Most state engineering boards have adopted rules to guide engineers similar to the Florida rule which states:

"61G15-30.008 Use of Computer Software and Hardware.
> *The engineer shall be responsible for the results generated by any computer software and hardware that he or she uses in providing engineering services*."

We recommend the following best practices:

1. Test new software with known sets of data.
2. Always guess the outcome before you do the calculations (this is recommended for all calculations, not just software).
3. Ask yourself if the answer "looks right". (Also recommended for all calculations.)
4. When any of these cast doubt on the software output use hand calculations or alternative software to crosscheck and verify results.

Prompt	Meaning
Complete results	The input data allows the calculation of a complete set of results
Partial results	The input data allows the calculation of some but not all results
Need more data	There is insufficient data to calculate any results
Overdetermined	Too much data has been input

A typical "Complete Results" output is shown in Figure 2.

"Manning-Channel" v 1.0.0

SunCam Software for Computing Hydraulics in Open Channels and Box Culverts

No more than one entry in each of the alternating color blocks.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (✓ U.S. Units, ✓ Metric Units, ✓ English Units)
Manning Formula Elements	**Q**	Quantity of Flow (Discharge)	54	54	54	CFS (Cubic Feet/Sec)
				24236.88347	24236.88347	GPM (Gallons/Minute) [US]
				34.90111204	34.90111204	MGD (Million gal/day) [US]
				1.529109738	1.529109738	CMS (Cubic Meters/Sec)
				5504795.057	5504795.057	LPH (Liters/Hour)
				91746.58428	91746.58428	LPM (Liters/Minute)
				1529.109738	1529.109738	LPS (Liters/Second)
				132.1150814	132.1150814	MLD (Million Liters/day)
				20181.42718	20181.42718	GPM (Gallons/Minute) [UK]
				29.06125514	29.06125514	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.5	1.5	Feet/Sec
				0.4572	0.4572	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient		8.89758E-05	0.000219753	Feet/Foot or Meter/Meter
				0.00890%	0.02198%	% Slope
	R	Hydraulic Radius		1.45521375	0.738633754	Feet
				0.443549151	0.225135568	Meters
Channel Dimensions	**T**	Top Width	24	24	24	Feet
				7.3152	7.3152	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height	3	3	3	Feet
				0.9144	0.9144	Meters
	SL	Side Slope Left		4	4	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right		4	4	Any Unit (Horizontal/Vert.)
Section Properties	**%**	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		3	3	Feet
				0.9144	0.9144	Meters
	a	Area of Flow		36	36	Square Feet
				3.34450944	3.34450944	Square Meters
	p	Wetted Perimeter		24.73863375	48.73863375	Feet
				7.540335568	14.85553557	Meters

Complete Results

Side slopes assumed equal

Applegate Road Drainage District

Station 27+47.50 - 36+50.00

Finished concrete surface

1. Box Culvert Results will only be displayed when Channel/Box is flowing 100% full.
2. Entrance and exit losses are ignored.

by WC Dunn, P.E.

14-Jun-2012 4:47:54 PM

Figure 2 Typical Results

To help the user visualize the results of a calculation, Manning-Channel will highlight the computed results in the Channel Results column with a pale grey background. Any of the variables that were input by the user will be displayed with a white background in the Channel Results column. In the Box Culvert Results column, any results that differ from the Channel Results column will be highlighted.

Because there are many ways to compute each variable, results can often be ambiguous. Manning-Channel will fully display results only when the input data supports one and only one method of computing the value of a missing variable. When the input data combination produces ambiguous results, the program will display an "Over Determined" message in the input tracking cell.

"Manning-Channel" v 1.0.0

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SunCam Software for Computing Hydraulics in Open Channels and Box Culverts

No more than one entry in each of the alternating color blocks.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (☑ U.S. Units ☑ Metric Units ☑ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)	54	54	54	CFS (Cubic Feet/Sec)
				24236.88347	24236.88347	GPM (Gallons/Minute) [US]
				34.90111204	34.90111204	MGD (Million gal/day) [US]
				1.529109738	1.529109738	CMS (Cubic Meters/Sec)
				5504795.057	5504795.057	LPH (Liters/Hour)
				91746.58428	91746.58428	LPM (Liters/Minute)
				1529.109738	1529.109738	LPS (Liters/Second)
				132.1150814	132.1150814	MLD (Million Liters/day)
				20181.42718	20181.42718	GPM (Gallons/Minute) [UK]
				29.06125514	29.06125514	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.5	1.5	Feet/Sec
				0.4572	0.4572	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient		8.89758E-05	0.000219753	Feet/Foot or Meter/Meter
				0.00890%	0.02198%	% Slope
	R	Hydraulic Radius		1.45521375	0.738633754	Feet
				0.443549151	0.225135568	Meters
Channel Dimensions	T	Top Width	24	24	24	Feet
				7.3152	7.3152	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height	3	3	3	Feet
				0.9144	0.9144	Meters
	SL	Side Slope Left		4	4	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right		4	4	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow	3	3	3	Feet
				0.9144	0.9144	Meters
	a	Area of Flow		36	36	Square Feet
				3.34450944	3.34450944	Square Meters
	p	Wetted Perimeter		24.73863375	48.73863375	Feet
				7.540335568	14.85553557	Meters

OVERDETERMINED

Delete one or more entries

Figure 3 - Too much input

In addition to the "OVERDETERMINED" prompt, the output cells will be partially obscured when the results are ambiguous and a red stripe will display along the right edge of one or more input cells as an indication of which variables are overdetermined.

WARNING: *Depending on the processing speed of your computer, these overdetermined indicators may appear momentarily while the software is processing a new entry of data.*

The input tracking prompt at row 39 will display additional messages alerting the user about any assumptions that are made or when there may be alternative solutions. Here are examples:

Side slopes must be parallel. Assumed vertical.

A possible alternative solution for B = 9.31125 feet

Using "Manning-Channel" is intuitive. You simply enter the variables that you know in the "Inputs" cells and the program will:

1. Instantly calculate that variable amount in all of the other measurement units shown.
2. Use the combination of all of the input data to calculate any of the missing variables

As a simple example, enter the number 1 in the input cell for "Q", Quantity of Flow in CFS(Cubic Feet/Second) and the

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (✓ U.S. Units, ✓ Metric Units, ✓ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)	1	1		CFS (Cubic Feet/Sec)
				448.8311753		GPM (Gallons/Minute) [US]
				0.64631689		MGD (Million gal/day) [US]
				0.028316847		CMS (Cubic Meters/Sec)
				101940.6492		LPH (Liters/Hour)
				1699.01082		LPM (Liters/Minute)
				28.316847		LPS (Liters/Second)
				2.446575581		MLD (Million Liters/day)
				373.7301329		GPM (Gallons/Minute) [UK]
				0.538171391		MGD (Million Gal/day) [UK]
	V	Velocity of Flow	2	2		Feet/Sec
				0.6096		Meters/Sec
	n	Roughness Coeff.				No Units
	S	Hydraulic Gradient				Feet/Foot or Meter/Meter
						% Slope
	R	Hydraulic Radius				Feet
						Meters
Channel Dimensions	T	Top Width				Feet
						Meters
	B	Bottom Width				Feet
						Meters
	H	Height				Feet
						Meters
	SL	Side Slope Left				Any Unit (Horizontal/Vert.)
	SR	Side Slope Right				Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)				% Full
	D	Depth of Flow				Feet
						Meters
	a	Area of Flow		0.5		Square Feet
				0.04645152		Square Meters
	p	Wetted Perimeter				Feet
						Meters

Partial Results

Figure 4

program instantly calculates that 1 CFS is equal to 448.8 gallons per minute, 28.3 liters per second, etc. Now enter a 2 in the input cell for "V", Velocity in Feet/Sec and you will see that the cross sectional area "a" is calculated at 0.5 square feet (0.0464 square meters) and the velocity is also calculated at 0.61 meters per second (Figure 4).

The Manning Formula

This formula uses three variables ("n", "R" & S) to calculate the velocity of flow in a conduit. When the cross-sectional area of flow is known it can be multiplied by the velocity to determine the quantity of flow (Q=aV). This course will cover flow through rectangular, trapezoidal and "V" conduit shapes. Circular pipe is covered in the companion course, "Gravity Flow in Pipes".

The Variables

Coefficient of Roughness (n) - There is one and only one formula for calculating a value for the coefficient of roughness "n". Formula (3) on page 3 may be used when velocity, hydraulic gradient and hydraulic radius are known.

Of the three variables "n", the coefficient of roughness, is the most difficult for the engineer to determine with accuracy and therefore should be the most carefully examined of the three. The engineer should select the roughness coefficient that best represents the condition of the conduit walls keeping in mind that conditions may change over time. Post installation factors that affect the value of the roughness coefficient include:

1. Solids collecting in the bottom of the channel or on its walls.
2. Uneven settlement.
3. Vegetation growth.
4. Erosion of the walls and floor of the channel.

Manning-Channel makes it easy to test a range of values before making the final decision. For this course, we will use the following values for *n*:

Concrete paved	0.012
Asphalt paved	0.016
Grassy channel	0.022-0.025
Natural streams	0.035
Corrugated steel sheet piling	0.050-0.060
Heavily vegetated floodplains	0.075

Sensitivity Analysis:

The Manning coefficient of roughness is inversely proportional to velocity (V) and discharge (Q). If you design a channel to be concrete paved (n=0.012) but change the surface to grass (n=0.024) the velocity and discharge will be reduced by exactly half. This relationship is true for any channel or box culvert size or shape and can be easily demonstrated with Manning-Channel software. (See Figures 5 and 6)

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		61.40181844	39.07054536	CFS (Cubic Feet/Sec)
				27559.05033	17536.07879	GPM (Gallons/Minute) [US]
				39.68503231	25.25195336	MGD (Million gal/day) [US]
				1.738705898	1.106354655	CMS (Cubic Meters/Sec)
				6259341.234	3982876.758	LPH (Liters/Hour)
				104322.3539	66381.27931	LPM (Liters/Minute)
				1738.705898	1106.354655	LPS (Liters/Second)
				150.2241896	95.58904221	MLD (Million Liters/day)
				22947.70977	14601.84011	GPM (Gallons/Minute) [UK]
				33.04470206	21.02664976	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		3.837613652	2.441909085	Feet/Sec
				1.169704641	0.744293889	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient		0.001	0.001	Feet/Foot or Meter/Meter
			0.10000%	0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		0.9701425	0.492422502	Feet
				0.295699434	0.150090379	Meters
Channel Dimensions	T	Top Width		16	16	Feet
				4.8768	4.8768	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height	2	2	2	Feet
				0.6096	0.6096	Meters
	SL	Side Slope Left	4	4	4	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	4	4	4	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		2	2	Feet
				0.6096	0.6096	Meters
	a	Area of Flow		16	16	Square Feet
				1.48644864	1.48644864	Square Meters
	p	Wetted Perimeter		16.4924225	32.4924225	Feet
				5.026890379	9.903690379	Meters

Complete Results

Figure 5 - Concrete surface (n=0.012)

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		30.70090922	19.53527268	CFS (Cubic Feet/Sec)
				13779.52517	8768.039396	GPM (Gallons/Minute) [US]
				19.84251616	12.62597668	MGD (Million gal/day) [US]
				0.869352949	0.553177328	CMS (Cubic Meters/Sec)
				3129670.617	1991438.379	LPH (Liters/Hour)
				52161.17695	33190.63965	LPM (Liters/Minute)
				869.3529491	553.1773276	LPS (Liters/Second)
				75.1120948	47.7945211	MLD (Million Liters/day)
				11473.85488	7300.920055	GPM (Gallons/Minute) [UK]
				16.52235103	10.51332488	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.918806826	1.220954542	Feet/Sec
				0.584852321	0.372146945	Meters/Sec
	n	Roughness Coeff.	0.024	0.024	0.024	No Units
	S	Hydraulic Gradient		0.001	0.001	Feet/Foot or Meter/Meter
			0.10000%	0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		0.9701425	0.492422502	Feet
				0.295699434	0.150090379	Meters
Channel Dimensions	T	Top Width		16	16	Feet
				4.8768	4.8768	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height	2	2	2	Feet
				0.6096	0.6096	Meters
	SL	Side Slope Left	4	4	4	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	4	4	4	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		2	2	Feet
				0.6096	0.6096	Meters
	a	Area of Flow		16	16	Square Feet
				1.48644864	1.48644864	Square Meters
	p	Wetted Perimeter		16.4924225	32.4924225	Feet
				5.026890379	9.903690379	Meters

Complete Results

Figure 6 - Grassy surface (n=0.024)

Excel Percentages

You can set Excel to display percentages as either a whole number (5=5%) or a decimal (.05=5%).

For Excel 2007:

1. Click the office button in the upper left of the screen
2. Click Excel Options at the bottom of the dropdown
3. Click Advanced
4. In "Editing Options" check or uncheck the box labeled "Enable automatic percent entry" to make the change.

If you are using another version of Excel you can use "Help" to find where to make the changes.

Hydraulic Radius (R) - can be an input into Manning-Channel but for almost all design problems, the hydraulic radius will be a software output rather than an input. The hydraulic radius is defined as the cross sectional area of the stream of water ("a") divided by the wetted perimeter ("p"). In U.S. customary units, the hydraulic radius is always measured in feet. So, for a 10-foot by 10-foot box culvert flowing half full, "R" would be calculated as follows:

(6) $a = 5 \times 10 = 50.0\ square\ feet$
(7) Wetted Perimeter$= 5 + 10 + 5 = 20\ feet$
(8) $R = \frac{50.0\ square\ feet}{20.0\ ft} = 2.5\ feet$

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)				CFS (Cubic Feet/Sec)
						GPM (Gallons/Minute) [US]
						MGD (Million gal/day) [US]
						CMS (Cubic Meters/Sec)
						LPH (Liters/Hour)
						LPM (Liters/Minute)
						LPS (Liters/Second)
						MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow				Feet/Sec
						Meters/Sec
	n	Roughness Coeff.				No Units
	S	Hydraulic Gradient				Feet/Foot or Meter/Meter
						% Slope
	R	Hydraulic Radius		2.5		Feet
				0.762		Meters
Channel Dimensions	T	Top Width		10		Feet
				3.048		Meters
	B	Bottom Width	10	10		Feet
				3.048		Meters
	H	Height	10	10		Feet
				3.048		Meters
	SL	Side Slope Left	0	0		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	50.00000%	50.00000%		% Full
	D	Depth of Flow		5		Feet
				1.524		Meters
	a	Area of Flow		50		Square Feet
				4.645152		Square Meters
	p	Wetted Perimeter		20		Feet
				6.096		Meters

Partial Results
A possible alternative solution for SR = 0.00000

Figure 7

Use the Manning-Channel software to verify these results (Figure 7). Enter:

- [10] in the input cell for Channel/Box Bottom Width "B"
- [10] in the input cell for Channel/Box Height "H"
- [0] in the input cells for Side Slope Left and Right "SL" & "SR" (Vertical walls have a side slope of 0.0)
- [50] in the input cell for % full ("%")Full ***(or [0.50] depending on your Excel setup, See Excel Percentage note on page 9)***

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)				CFS (Cubic Feet/Sec)
						GPM (Gallons/Minute) [US]
						MGD (Million gal/day) [US]
						CMS (Cubic Meters/Sec)
						LPH (Liters/Hour)
						LPM (Liters/Minute)
						LPS (Liters/Second)
						MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow				Feet/Sec
						Meters/Sec
	n	Roughness Coeff.				No Units
	S	Hydraulic Gradient				Feet/Foot or Meter/Meter
						% Slope
	R	Hydraulic Radius		3.333333333	2.5	Feet
				1.016	0.762	Meters
Channel Dimensions	T	Top Width		10	10	Feet
				3.048	3.048	Meters
	B	Bottom Width	10	10	10	Feet
				3.048	3.048	Meters
	H	Height	10	10	10	Feet
				3.048	3.048	Meters
	SL	Side Slope Left	0	0	0	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0	0	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		10	10	Feet
				3.048	3.048	Meters
	a	Area of Flow		100	100	Square Feet
				9.290304	9.290304	Square Meters
	p	Wetted Perimeter		30	40	Feet
				9.144	12.192	Meters

Partial Results
A possible alternative solution for SR = 0.00000

Figure 8

Now change the % full to 100% (Figure 8) and you see that Box Culvert Results appear in addition to the Open Channel Results. The Box Culvert Results will only appear when the conduit is flowing 100% full (the water surface is touching the ceiling of the box culvert). Notice that the area of flow is the same in both cases but the wetted perimeter is 30 feet for the open channel and 40 feet for the box culvert because the width of the culvert top has been added to the bottom and walls for the box culvert results.

For a box culvert with vertical side walls, the hydraulic radius flowing full is always identical to the hydraulic radius flowing half full.

Sensitivity Analysis:

Velocity (V) and discharge (Q) increase by approximately 63% each time the hydraulic radius is doubled. Site constraints will usually control the design of a channel but it is generally more desirable, from the standpoint of maximizing velocity and discharge, to keep the channel cross-section as compact as possible. To illustrate this point we will compare two "V" shape channel designs that differ only in their side slopes. Here are the inputs:

Variable	Design "A"	Design "B"
Roughness Coeff. (n)	0.012	0.012
Hydraulic Gradient (S)	0.1%	0.1%
Bottom Width (B)	0	0
Side Slope Left (SL)	2	4
Side Slope Right (SR)	2	4
% Full (%)	100%	100%
Area of Flow (a)	32 Square feet	32 Square feet

This comparison demonstrates that the more compact Design "A" (Figure 9) produces a discharge capacity (and velocity) that is about 19% higher for the open channel and 22% higher for the box culvert than the flatter, shallower Design "B" (Figure 10) solely as a result of the fact that the wetted perimeter is 30% higher for the flatter section.

The engineer should be thinking about construction costs throughout any design process, making cost a consideration in every decision. As this example demonstrates, the wetted perimeter serves as a useful proxy for the cost of paving the slopes with "B" costing 30% more than "A" because of the increased length of wetted perimeter.

Likewise, the end area of a channel serves as a useful proxy for the quantity of excavated material. In this example the quantity of excavated material would be the same for both designs.

	Scroll down for sketch and definition of terms		Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		184.6591652	120.6106308	CFS (Cubic Feet/Sec)
				82880.79013	54133.81116	GPM (Gallons/Minute) [US]
				119.3483373	77.95268775	MGD (Million gal/day) [US]
				5.228965327	3.415312778	CMS (Cubic Meters/Sec)
				18824275.18	12295126	LPH (Liters/Hour)
				313737.9196	204918.7667	LPM (Liters/Minute)
				5228.965327	3415.312778	LPS (Liters/Second)
				451.7826043	295.083024	MLD (Million Liters/day)
				69012.69434	45075.82707	GPM (Gallons/Minute) [UK]
				99.37827985	64.90919098	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		5.770598911	3.769082212	Feet/Sec
				1.758878548	1.148816258	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient		0.001	0.001	Feet/Foot or Meter/Meter
			0.10000%	0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		1.788854382	0.94427191	Feet
				0.545242816	0.287814078	Meters
Channel Dimensions	T	Top Width		16	16	Feet
				4.8768	4.8768	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height		4	4	Feet
				1.2192	1.2192	Meters
	SL	Side Slope Left	2	2	2	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	2	2	2	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		4	4	Feet
				1.2192	1.2192	Meters
	a	Area of Flow	32	32	32	Square Feet
				2.97289728	2.97289728	Square Meters
	p	Wetted Perimeter		17.88854382	33.88854382	Feet
				5.452428156	10.32922816	Meters

Figure 9 - Design "A"

	Scroll down for sketch and definition of terms		Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		154.7228871	98.45160506	CFS (Cubic Feet/Sec)
				69444.45526	44188.14961	GPM (Gallons/Minute) [US]
				100.0000152	63.63093517	MGD (Million gal/day) [US]
				4.381264321	2.787839037	CMS (Cubic Meters/Sec)
				15772551.56	10036220.53	LPH (Liters/Hour)
				262875.8593	167270.3422	LPM (Liters/Minute)
				4381.264321	2787.839037	LPS (Liters/Second)
				378.5412374	240.8692928	MLD (Million Liters/day)
				57824.60516	36794.33144	GPM (Gallons/Minute) [UK]
				83.26743144	52.98383728	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		4.835090222	3.076612658	Feet/Sec
				1.4737355	0.937751538	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient		0.001	0.001	Feet/Foot or Meter/Meter
			0.10000%	0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		1.371988681	0.696390581	Feet
				0.41818215	0.212259849	Meters
Channel Dimensions	T	Top Width		22.627417	22.627417	Feet
				6.896836701	6.896836701	Meters
	B	Bottom Width	0	0	0	Feet
				0	0	Meters
	H	Height		2.828427125	2.828427125	Feet
				0.862104588	0.862104588	Meters
	SL	Side Slope Left	4	4	4	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	4	4	4	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		2.828427125	2.828427125	Feet
				0.862104588	0.862104588	Meters
	a	Area of Flow	32	32	32	Square Feet
				2.97289728	2.97289728	Square Meters
	p	Wetted Perimeter		23.32380758	45.95122458	Feet
				7.10909655	14.00593325	Meters

Figure 10 - Design "B"

Hydraulic Gradient (S) – Is defined as the total head loss divided by the length of conduit. For open channel flow, the hydraulic slope will usually be the same as the physical slope of the channel but for closed channels such as pipes and box culverts, the conduit may be completely submerged and subject to surcharging. In either case the hydraulic slope is calculated as:

$$\frac{\text{Upper end water elevation - Lower end water elevation}}{\text{Length of run}}$$

Sensitivity Analysis:

Velocity (V) and discharge (Q) increase by approximately 41% each time the hydraulic gradient is doubled.

V	Velocity of Flow		1		Feet/Sec
			0.3048		Meters/Sec
n	Roughness Coeff.	0.025	0.025		No Units
S	Hydraulic Gradient	0.001	0.001		Feet/Foot or Meter/Meter
			0.10000%		% Slope
R	Hydraulic Radius	0.388044738	0.388044738		Feet
			0.118276036		Meters

Figure 11

V	Velocity of Flow		1.414213562		Feet/Sec
			0.431052294		Meters/Sec
n	Roughness Coeff.	0.025	0.025		No Units
S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
			0.20000%		% Slope
R	Hydraulic Radius	0.388044738	0.388044738		Feet
			0.118276036		Meters

Figure 12

Natural terrain and the need to limit scour caused by high water velocity will usually limit the engineer's choice of slopes but it is generally more desirable in areas of flat terrain to maximize discharge quantity (Q) by using as steep a gradient as possible. Likewise, in areas of steep terrain it is a greater challenge to keep gradients as flat as possible in order to minimize scour caused by high velocities.

Velocity (V) – The Manning Formula is a mathematical model for predicting velocity of flow in a conduit or channel. Based on Manning, the velocity of flow in a gravity system is dependent on only three things:

1. The geometry of the conduit ("R")
2. The slope of the conduit ("S")
3. The roughness of the walls of the conduit ("n")

If you know "R", "S" and "n", you can calculate velocity. In fact, using the variations of the Manning Formula shown in the beginning of this course (formulae 3, 4 & 5), any one of these variables may be calculated if the other three are known. To illustrate, using Manning-Channel enter the following:

- [0.012] in the input cell for roughness coefficient ("n")
- [0.2] in the input cell for Hydraulic Gradient ("S") ***(or [0.002] depending on your Excel setup, See Excel Percentage note on page 9)***
- [0.2] in the input cell for Hydraulic Radius in feet ("R")

V	Velocity of Flow		1.893967657		Feet/Sec
			0.577281342		Meters/Sec
n	Roughness Coeff.	0.012	0.012		No Units
S	Hydraulic Gradient		0.002		Feet/Foot or Meter/Meter
		0.20000%	0.20000%		% Slope
R	Hydraulic Radius	0.2	0.2		Feet
			0.06096		Meters

Figure 13 - Calculating Velocity (V)

The resulting velocity is 1.894 feet per second. Now delete the entry for Roughness coefficient and enter the following:

- [1.894] in the input cell for Velocity in feet per second ("V")

V	Velocity of Flow	1.894	1.894		Feet/Sec
			0.5772912		Meters/Sec
n	Roughness Coeff.		0.011999795		No Units
S	Hydraulic Gradient		0.002		Feet/Foot or Meter/Meter
		0.20000%	0.20000%		% Slope
R	Hydraulic Radius	0.2	0.2		Feet
			0.06096		Meters

Figure 14 - Calculating Roughness Coefficient (n)

Note that the value of "n" is now calculated at 0.01200, matching the original entry. Testing the remaining variables gives similar results.

V	Velocity of Flow	1.894	1.894		Feet/Sec
			0.5772912		Meters/Sec
n	Roughness Coeff.	0.012	0.012		No Units
S	Hydraulic Gradient		0.002000068		Feet/Foot or Meter/Meter
			0.20001%		% Slope
R	Hydraulic Radius	0.2	0.2		Feet
			0.06096		Meters

Figure 15 - Calculating Hydraulic Gradient (S)

V	Velocity of Flow	1.894	1.894		Feet/Sec
			0.5772912		Meters/Sec
n	Roughness Coeff.	0.012	0.012		No Units
S	Hydraulic Gradient		0.002		Feet/Foot or Meter/Meter
		0.20000%	0.20000%		% Slope
R	Hydraulic Radius		0.200005123		Feet
			0.060961562		Meters

Figure 16 - Calculating Hydraulic Radius (R)

Alternate Formula for Velocity - When the discharge (Q) and the area of flow (a) are known, the velocity may be calculated as:

$$V = \frac{Q}{a}$$

Sensitivity Analysis:

Velocity is directly proportional to discharge (Q) and inversely proportional to area of flow (a). Velocity will double whenever discharge is doubled or when area of flow is halved.

Quantity of Flow ("Q") is calculated as the product of velocity (V) and the cross sectional area of the stream of flow (a).

$$Q = aV$$

To illustrate use the entries in figure 13 and add:

- [8] in the input cell for area of flow (a) in square feet.

The resulting quantity of flow (Q) is 15.152 CFS (Figure 17).

Note that in addition to calculating the quantity of flow, Manning-Channel also calculates the wetted perimeter by dividing the area of flow "a" by the hydraulic radius.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (✓ U.S. Units ✓ Metric Units ✓ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		15.15174125		CFS (Cubic Feet/Sec)
				6800.573835		GPM (Gallons/Minute) [US]
				9.792826281		MGD (Million gal/day) [US]
				0.429049539		CMS (Cubic Meters/Sec)
				1544578.34		LPH (Liters/Hour)
				25742.97233		LPM (Liters/Minute)
				429.0495389		LPS (Liters/Second)
				37.06988016		MLD (Million Liters/day)
				5662.662273		GPM (Gallons/Minute) [UK]
				8.154233674		MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.893967657		Feet/Sec
				0.577281342		Meters/Sec
	n	Roughness Coeff.	0.012	0.012		No Units
	S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
				0.20000%		% Slope
	R	Hydraulic Radius	0.2	0.2		Feet
				0.06096		Meters
Channel Dimensions	T	Top Width				Feet
						Meters
	B	Bottom Width				Feet
						Meters
	H	Height				Feet
						Meters
	SL	Side Slope Left				Any Unit (Horizontal/Vert.)
	SR	Side Slope Right				Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)				% Full
	D	Depth of Flow				Feet
						Meters
	a	Area of Flow	8	8		Square Feet
				0.74322432		Square Meters
	p	Wetted Perimeter		40		Feet
				12.192		Meters

Figure 17 - Calculating Quantity of Flow (Q)

Sensitivity Analysis:

Discharge "Q" is directly proportional to Velocity "V" and area of flow "a". Discharge will double whenever velocity or area of flow is doubled.

Channel Dimensions ("T", "B","H","SL", & "SR") define the size and shape of the cross-section of the channel or box culvert. Manning-Channel software allows any shape for the channel cross-section with only a restriction against non-horizontal tops and bottoms. A sampling of allowable shapes is shown in Figure 18.

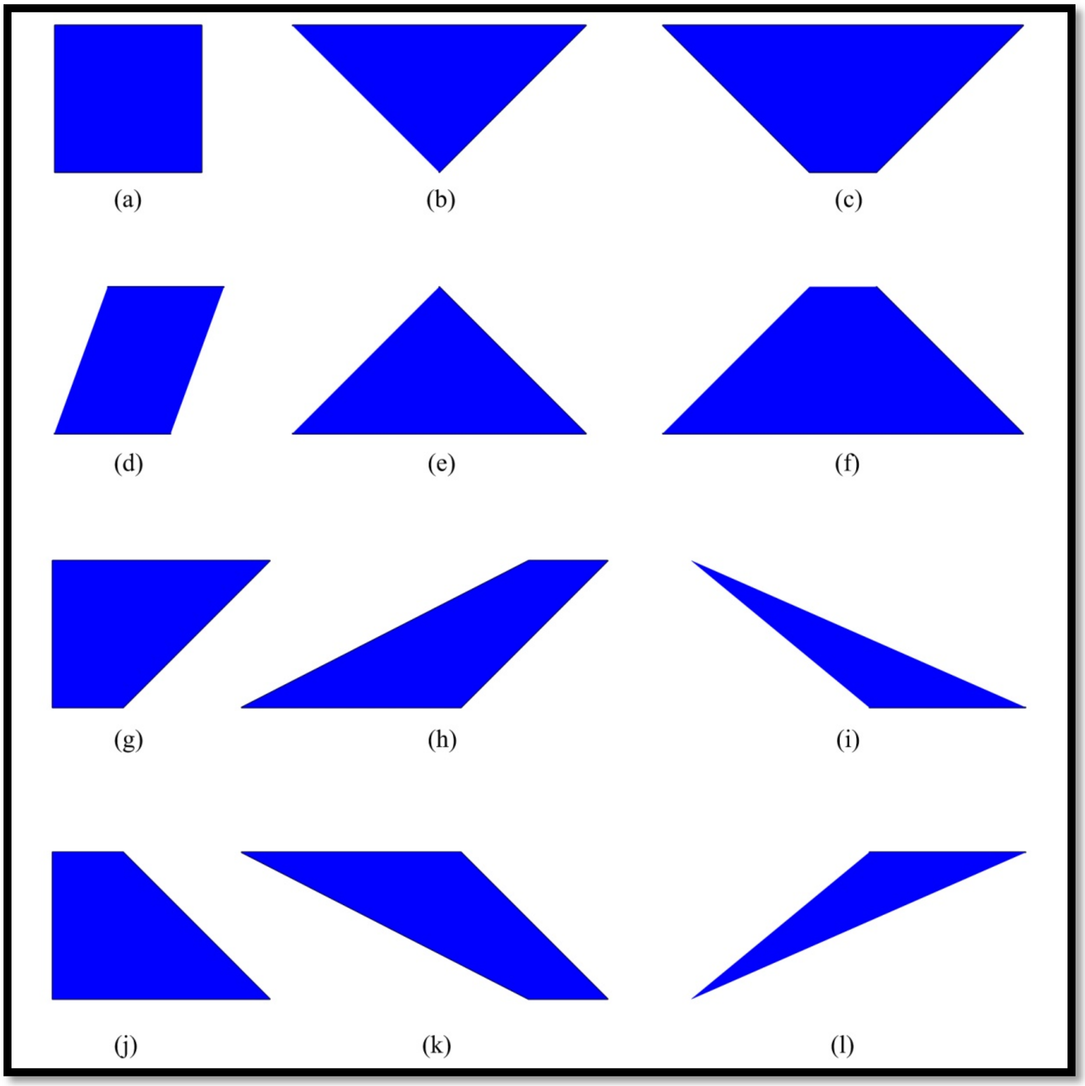

Figure 18 - Manning-Channel allowable shapes

Sections (a), (b), (c), and (g) are all common shapes for channels that engineers are likely to encounter on engineering projects. Although less commonplace, the other shapes will doubtless find uses where space is severely constrained.

Section Properties ("%", "D", "a", & "p") define the properties of the water in the channel. Although any of these variables may be inputs to the Manning-Channel software they will more commonly be calculated outputs. When these variables *are* inputs they can sometimes produce more than one solution for the output variables. Although there are several reasons for this phenomenon, the most common cause is the quadratic equation:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Whenever a solution relies on the quadratic equation, there will always be two values for the unknown variable depending on which sign is used to replace the ± symbol. Here's a simple example:

R	Hydraulic Radius		0.833333333		Feet
			0.254		Meters
T	Top Width		10		Feet
			3.048		Meters
B	Bottom Width		10		Feet
			3.048		Meters
H	Height		2		Feet
			0.6096		Meters
SL	Side Slope Left	0	0		Any Unit (Horizontal/Vert.)
SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
%	% Full (D/H)	50.00000%	50.00000%		% Full
D	Depth of Flow		1		Feet
			0.3048		Meters
a	Area of Flow	10	10		Square Feet
			0.9290304		Square Meters
p	Wetted Perimeter	12	12		Feet
			3.6576		Meters

Partial Results

A possible alternative solution for B = 2.00000 feet

Figure 19 - Example of an alternate solution

The primary result is a rectangular section, 10 feet wide and 2 feet high. The suggested alternate has a bottom width of 2 feet. The alternate solution can be tested by deleting the input for either the area of flow or the wetted perimeter and entering 2 feet for the bottom width.

R	Hydraulic Radius		0.833333333		Feet
			0.254		Meters
T	Top Width		2		Feet
			0.6096		Meters
B	Bottom Width	2	2		Feet
			0.6096		Meters
H	Height		10		Feet
			3.048		Meters
SL	Side Slope Left	0	0		Any Unit (Horizontal/Vert.)
SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
%	% Full (D/H)	50.00000%	50.00000%		% Full
D	Depth of Flow		5		Feet
			1.524		Meters
a	Area of Flow		10		Square Feet
			0.9290304		Square Meters
p	Wetted Perimeter	12	12		Feet
			3.6576		Meters

Partial Results

A possible alternative solution for SR = 0.00000

Figure 20 - Testing the alternate solution

This demonstrates that a 10 foot wide by 2 foot high rectangular section is identical in hydraulic radius, area of flow, wetted perimeter and hydraulic performance to a 2 foot wide by 10 foot high rectangular section.

The primary and alternate solution will always be mathematically valid even in cases like this one where the primary and alternate solutions are identical (both solutions of the quadratic equation are the same). When the alternative solution is a negative dimension, it will not be displayed.

Sample Problems

The following series of sample problems will illustrate the use of the Manning Formula and Manning-Channel software.

Sample Problem 1

Alice graduated with a degree in civil engineering and accepted a job offer as an Engineer-in-Training for the Department of Transportation. Her first assignment on her first day at work was to redesign a storm drainage outfall utilizing an environmentally friendly dry grassy swale instead of the 30 inch diameter concrete pipe that had been included in the original design. The design parameters for the pipe:

Quantity of flow	13 CFS
Width of easement	25 feet
Hydraulic Gradient	0.10%
Pipe diameter	30 inches

Alice used Manning-Channel to do the hydraulic design. She first tested a 1-foot deep "V" shaped swale. She will use a 1.0 foot per second velocity to avoid scour and set the depth of flow at 80% full to insure that the channel is not overtopped. She entered:

- [13] in the input cell for Quantity of Flow in cubic feet per second ("Q")
- [1] in the input cell for Velocity of Flow (V) in Feet/Sec

  (The Area of Flow is displayed after these entries)
- [0.025] in the input cell for roughness coefficient (n)

  (The Wetted Perimeter and Hydraulic Radius are displayed after these entries)
- [0] in the input cell for Channel Bottom Width (B) in feet
- [1] in the input cell for Channel Height (H) in feet
- [80] in the input cell for % full ("%")Full ***(or [0.80] depending on your Excel setup, See Excel Percentage note on page 9)***

See figure 21 for the results.

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units, Metric Units, English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)	13	13		CFS (Cubic Feet/Sec)
				5834.805279		GPM (Gallons/Minute) [US]
				8.402119566		MGD (Million gal/day) [US]
				0.368119011		CMS (Cubic Meters/Sec)
				1325228.44		LPH (Liters/Hour)
				22087.14066		LPM (Liters/Minute)
				368.119011		LPS (Liters/Second)
				31.80548255		MLD (Million Liters/day)
				4858.491728		GPM (Gallons/Minute) [UK]
				6.996228088		MGD (Million Gal/day) [UK]
	V	Velocity of Flow	1	1		Feet/Sec
				0.3048		Meters/Sec
	n	Roughness Coeff.	0.025	0.025		No Units
	S	Hydraulic Gradient		0.0009619		Feet/Foot or Meter/Meter
				0.09619%		% Slope
	R	Hydraulic Radius		0.399516146		Feet
				0.121772521		Meters
Channel Dimensions	T	Top Width		40.625		Feet
				12.3825		Meters
	B	Bottom Width	0	0		Feet
				0		Meters
	H	Height	1	1		Feet
				0.3048		Meters
	SL	Side Slope Left		20.3125		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right		20.3125		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	80.00000%	80.00000%		% Full
	D	Depth of Flow		0.8		Feet
				0.24384		Meters
	a	Area of Flow		13		Square Feet
				1.20773952		Square Meters
	p	Wetted Perimeter		32.53936078		Feet
				9.917997166		Meters
		Complete Results				
		Side slopes assumed equal				

Figure 21 - Sample Problem 1

This solution meets all of the criteria for the channel except the top width is too wide for the easement.

Next, she changed the entries as follows:

- deleted the entry for % full
- [25] in the input cell for Top Width (T) in feet.

This produced a more constrained design so the predictable result was that the depth of flow exceeded the 1 foot height of the channel. (Figure 22)

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (☑ U.S. Units ☑ Metric Units ☑ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)	13	Overtopping		CFS (Cubic Feet/Sec)
				Overtopping		GPM (Gallons/Minute) [US]
				Overtopping		MGD (Million gal/day) [US]
				Overtopping		CMS (Cubic Meters/Sec)
				Overtopping		LPH (Liters/Hour)
				Overtopping		LPM (Liters/Minute)
				Overtopping		LPS (Liters/Second)
				Overtopping		MLD (Million Liters/day)
				Overtopping		GPM (Gallons/Minute) [UK]
				Overtopping		MGD (Million Gal/day) [UK]
	V	Velocity of Flow	1	Overtopping		Feet/Sec
				Overtopping		Meters/Sec
	n	Roughness Coeff.	0.025	Overtopping		No Units
	S	Hydraulic Gradient		Overtopping		Feet/Foot or Meter/Meter
				Overtopping		% Slope
	R	Hydraulic Radius		Overtopping		Feet
				Overtopping		Meters
Channel Dimensions	T	Top Width	25	Overtopping		Feet
				Overtopping		Meters
	B	Bottom Width	0	Overtopping		Feet
				Overtopping		Meters
	H	Height	1	Overtopping		Feet
				Overtopping		Meters
	SL	Side Slope Left		Overtopping		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right		Overtopping		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)		Overtopping		% Full
	D	Depth of Flow		Overtopping		Feet
				Overtopping		Meters
	a	Area of Flow		Overtopping		Square Feet
				Overtopping		Square Meters
	p	Wetted Perimeter		Overtopping		Feet
				Overtopping		Meters

The % full exceeds 100%

Figure 22 - Overtopping

Alice experimented with different values for Bottom Width and Height to find a configuration that best fit her criteria. She settled on a trapezoidal cross-section with a bottom width of 5 feet and a depth of 1.25 feet. See figure 23 for the results.

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units, Metric Units, English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)	13	13		CFS (Cubic Feet/Sec)
				5834.805279		GPM (Gallons/Minute) [US]
				8.402119566		MGD (Million gal/day) [US]
				0.368119011		CMS (Cubic Meters/Sec)
				1325228.44		LPH (Liters/Hour)
				22087.14066		LPM (Liters/Minute)
				368.119011		LPS (Liters/Second)
				31.80548255		MLD (Million Liters/day)
				4858.491728		GPM (Gallons/Minute) [UK]
				6.996228088		MGD (Million Gal/day) [UK]
	V	Velocity of Flow	1	1		Feet/Sec
				0.3048		Meters/Sec
	n	Roughness Coeff.	0.025	0.025		No Units
	S	Hydraulic Gradient		0.000540713		Feet/Foot or Meter/Meter
				0.05407%		% Slope
	R	Hydraulic Radius		0.61539873		Feet
				0.187573533		Meters
Channel Dimensions	T	Top Width	25	25		Feet
				7.62		Meters
	B	Bottom Width	5	5		Feet
				1.524		Meters
	H	Height	1.25	1.25		Feet
				0.381		Meters
	SL	Side Slope Left		8		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right		8		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)		80.00000%		% Full
	D	Depth of Flow		1		Feet
				0.3048		Meters
	a	Area of Flow		13		Square Feet
				1.20773952		Square Meters
	p	Wetted Perimeter		21.1245155		Feet
				6.438752323		Meters
Complete Results *Side slopes assumed equal*						

Figure 23 - Final Design

This solution used only about half of the available hydraulic slope while meeting all other criteria exactly. The side slopes at 1:8 are gentle enough that a vehicle could safely traverse the area without tipping and rolling over. The slopes are also flat enough to operate mowing and maintenance equipment in the channel obviating the need for a separate maintenance road within the easement.

Sample Problem 2

John Mapleton, P.E. has been hired by a farm cooperative to design a work road through an orange grove to be used for grove maintenance and harvesting. The road will cross a drainage canal which John will enclose in a single barrel box culvert. He uses Manning Channel and the existing canal dimensions to calculate a hypothetical existing hydraulic capacity of the canal:

Bottom width	6-feet
Side slopes	1:1
Height	5-feet

John does not know the hydraulic gradient for the existing canal and without the gradient he cannot calculate the "actual" capacity. He assumes a gradient value of 0.1% for the canal and he will use the same value for the box culvert. In that way he can be assured that the capacity of the canal and culvert will match regardless of the hydraulic gradient. He enters:

- [0.025] in the input cell for roughness coefficient (n)
- [0.001] in the input cell for Hydraulic Gradient (S) in feet/foot
- [6] in the input cell for Channel Bottom Width (B) in feet
- [5] in the input cell for Channel Height (H) in feet
- [1] in each of the side slope input cells (SL & SR)
- [100] in the input cell for % full ("%")Full ***(or [1.0] depending on your Excel setup, See Excel Percentage note on page 9)***

The calculated hypothetical capacity of the existing canal (assuming a 0.1% gradient and ignoring the possible alternate value for "SR") is 202 CFS (see figure 24). Although Manning-Channel also computes box culvert results, John ignores those results because the new box culvert will have vertical side slopes and a different bottom width.

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No more than one entry in each of the alternating color blocks.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		201.966624	136.7752159	CFS (Cubic Feet/Sec)
				90648.91721	61388.98091	GPM (Gallons/Minute) [US]
				130.5344402	88.40013215	MGD (Million gal/day) [US]
				5.71905799	3.873042863	CMS (Cubic Meters/Sec)
				20588608.76	13942954.31	LPH (Liters/Hour)
				343143.4794	232382.5718	LPM (Liters/Minute)
				5719.05799	3873.042863	LPS (Liters/Second)
				494.1266104	334.6309033	MLD (Million Liters/day)
				75481.01323	51117.01963	GPM (Gallons/Minute) [UK]
				108.692659	73.60850827	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		3.672120436	2.486822108	Feet/Sec
				1.119262309	0.757983378	Meters/Sec
	n	Roughness Coeff.	0.025	0.025	0.025	No Units
	S	Hydraulic Gradient	0.001	0.001	0.001	Feet/Foot or Meter/Meter
				0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		2.730594264	1.521769509	Feet
				0.832285132	0.463835346	Meters
Channel Dimensions	T	Top Width		16	16	Feet
				4.8768	4.8768	Meters
	B	Bottom Width	6	6	6	Feet
				1.8288	1.8288	Meters
	H	Height	5	5	5	Feet
				1.524	1.524	Meters
	SL	Side Slope Left	1	1	1	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	1	1	1	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		5	5	Feet
				1.524	1.524	Meters
	a	Area of Flow		55	55	Square Feet
				5.1096672	5.1096672	Square Meters
	p	Wetted Perimeter		20.14213562	36.14213562	Feet
				6.139322938	11.01612294	Meters

Complete Results

A possible alternative solution for SR = 0.21895

Figure 24 - Hypothetical capacity of existing canal

To calculate the box culvert results John enters the following:

- [0.012] in the input cell for roughness coefficient (n) for concrete finish
- [0.001] in the input cell for Hydraulic Gradient (S) in feet/foot
- [5] in the input cell for Channel Height (H) in feet
- [0] in each of the side slope input cells (SL & SR)
- [100] in the input cell for % full ("%")Full ***(or [1.0] depending on your Excel setup, See Excel Percentage note on page 9)***

He then experiments with different values for bottom width to find a culvert width that will produce at least 202 CFS in the box culvert column. John finds that an 8 foot width gives a capacity of 209 CFS (about 3% higher than the canal capacity) but he selects a 9 foot width (Figure 25) yielding a 242 CFS capacity which is a comfortable 20% greater capacity than the canal itself.

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		Scroll down for sketch and definition of terms	**Inputs**	**Channel Results**	**Box Culvert Results**	**Units** (U.S. Units / Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		313.104531	241.7796431	CFS (Cubic Feet/Sec)
				140531.0746	108518.2414	GPM (Gallons/Minute) [US]
				202.3647466	156.2662669	MGD (Million gal/day) [US]
				8.866133098	6.84643716	CMS (Cubic Meters/Sec)
				31918079.15	24647173.78	LPH (Liters/Hour)
				531967.9859	410786.2296	LPM (Liters/Minute)
				8866.133098	6846.43716	LPS (Liters/Second)
				766.0338997	591.5321707	MLD (Million Liters/day)
				117016.598	90360.33814	GPM (Gallons/Minute) [UK]
				168.5039011	130.1188869	MGD (Million Gal/day) [UK]
	V	Velocity of Flow		6.957878466	5.372880957	Feet/Sec
				2.120761356	1.637654116	Meters/Sec
	n	Roughness Coeff.	0.012	0.012	0.012	No Units
	S	Hydraulic Gradient	0.001	0.001	0.001	Feet/Foot or Meter/Meter
				0.10000%	0.10000%	% Slope
	R	Hydraulic Radius		2.368421053	1.607142857	Feet
				0.721894737	0.489857143	Meters
Channel Dimensions	T	Top Width		9	9	Feet
				2.7432	2.7432	Meters
	B	Bottom Width	9	9	9	Feet
				2.7432	2.7432	Meters
	H	Height	5	5	5	Feet
				1.524	1.524	Meters
	SL	Side Slope Left	0	0	0	Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0	0	Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	100.00000%	100.00000%	100.00000%	% Full
	D	Depth of Flow		5	5	Feet
				1.524	1.524	Meters
	a	Area of Flow		45	45	Square Feet
				4.1806368	4.1806368	Square Meters
	p	Wetted Perimeter		19	28	Feet
				5.7912	8.5344	Meters
Complete Results *A possible alternative solution for SR = 0.00000*						

Figure 25 - Hypothetical capacity of proposed box culvert

To verify that his premise about the hydraulic gradient is correct John reruns both calculations with a gradient of 0.005 feet/foot. The resulting calculated capacity for the canal was 452 CFS while the box culvert had a capacity of 541 CFS, the same 20% higher.

Sample Problem 3

A giant US retailer "Z.inc" (fictional, of course) has purchased land and is planning its first retail store in Eastern Europe. The site occupies the space between a motorway and the Grand Canal which is used for barge traffic and for drainage. The site is significantly smaller than Z.inc's typical US store but company executives hope to utilize a portion of the canal right-of-way for additional customer parking.

Z.inc retained local chartered engineer Luc Dumas to plan the site and study the potential for encroaching on the canal. Luc explained that the Grand Canal Council would not allow any work within the canal except work related to barge traffic and drainage but that a small barge port could solve many logistic problems including the parking shortage and the small size of local delivery trucks. He promised to conduct the study and meet again with the executives in 2-weeks.

Luc started with the existing cross-section and Grand Canal Council rules for making modifications to the canal:

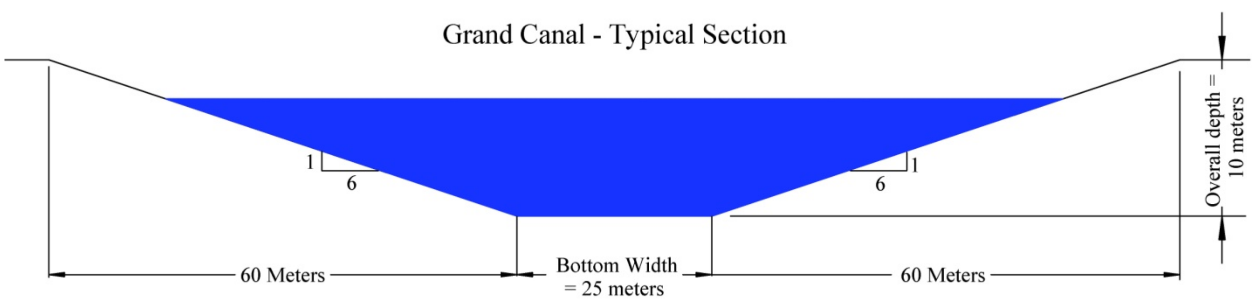

Figure 26 Existing Cross-Section

Grand Canal Council Rules:

1. No encroachments in the middle 25 meters of the canal by improvements or berthed vessels.
2. No changes in the overall depth in the middle 25 meters of the canal.
3. Maintain the hydraulic equivalent of the existing canal which is defined as: a discharge rate of 387 cubic meters per second when the canal is 85% full (water depth = 8.5 meters), a velocity of no more than 1.0 meters per second and no increase in the hydraulic gradient.

Luc uses Manning-Channel for the hydraulic calculations. He normally restricts the outputs to metric units but he adds the "U.S. Units" check-box for the benefit of his clients.

Figure 27 - Selecting units of measure

He enters the following:

- [387] in the input cell for Quantity of Flow in cubic meters per second ("Q")
- [0.025] in the input cell for roughness coefficient ("n") for an earth/grassy channel
- [25] in the input cell for Channel Bottom Width (B) in Meters
- [10] in the input cell for Channel Height (H) in meters
- [6] in each of the side slope cells
- [85] in the input cell for % full ("%")Full ***(or [0.85] depending on your Excel setup, See Excel Percentage note on page 9)***

Results are shown in Figure 28.

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No more than one entry in each of the alternating color blocks.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (☑ U.S. Units ☑ Metric Units ☐ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		13666.77582		CFS (Cubic Feet/Sec)
				6134075.056		GPM (Gallons/Minute) [US]
				8833.068043		MGD (Million gal/day) [US]
			387	387		CMS (Cubic Meters/Sec)
				1393200000		LPH (Liters/Hour)
				23220000		LPM (Liters/Minute)
				387000		LPS (Liters/Second)
				33436.8		MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.965456689		Feet/Sec
				0.599071199		Meters/Sec
	n	Roughness Coeff.	0.025	0.025		No Units
	S	Hydraulic Gradient		2.60174E-05		Feet/Foot or Meter/Meter
				0.00260%		% Slope
	R	Hydraulic Radius		16.50551125		Feet
				5.030879828		Meters
Channel Dimensions	T	Top Width		475.7217848		Feet
				145		Meters
	B	Bottom Width		82.02099738		Feet
			25	25		Meters
	H	Height		32.80839895		Feet
			10	10		Meters
	SL	Side Slope Left	6	6		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	6	6		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	85.00000%	85.00000%		% Full
	D	Depth of Flow		27.88713911		Feet
				8.5		Meters
	a	Area of Flow		6953.486129		Square Feet
				646		Square Meters
	p	Wetted Perimeter		421.2826871		Feet
				128.406963		Meters

Complete Results

Figure 28 - Grand Canal existing condition

The hydraulic gradient of 0.00260% would be the basis for designing a new cross section that is the hydraulic equivalent of the existing canal. He used the cross section shown in figure 29 and Manning-Channel to solve for a bottom width that would produce a hydraulic gradient that would be equal to or flatter than 0.00260%.

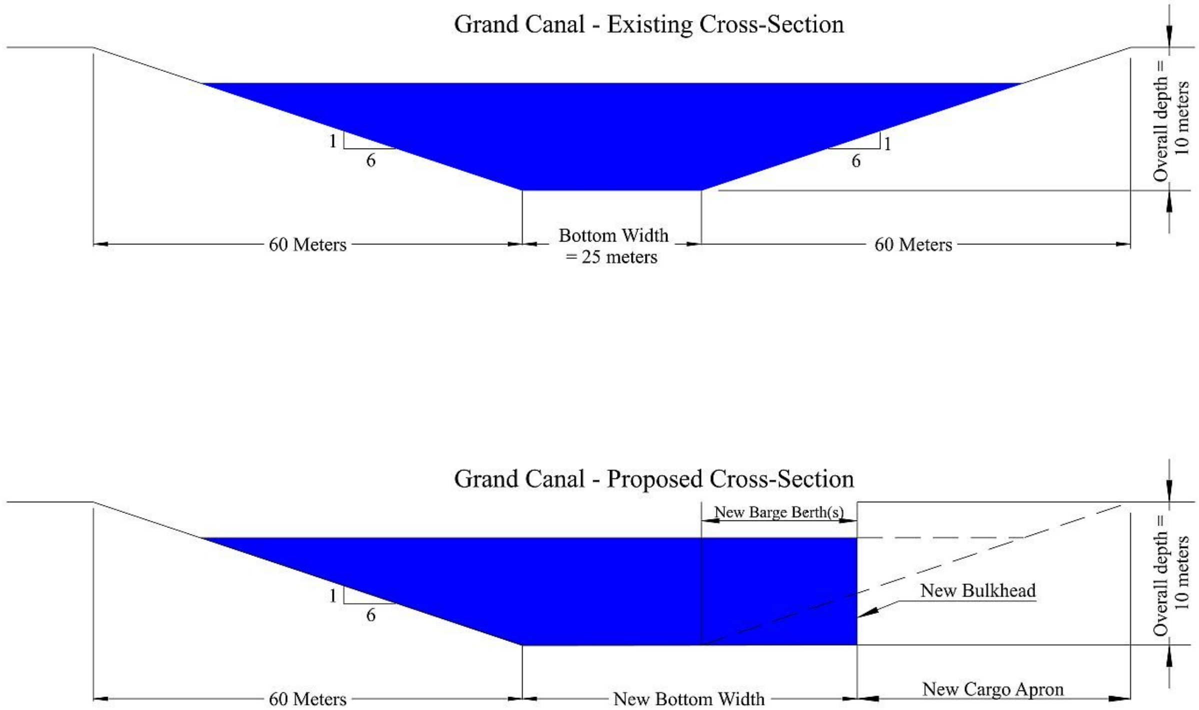

Figure 29 Existing and Proposed Cross-Section

Luc changes the input for Side Slope Right to 0.0 and then experiments with the bottom width to find a width that will result in a hydraulic gradient equal to or flatter than 0.00260%. He finds that a bottom width of 45 meters will produce a gradient of 0.00256%. (See Figure 30)

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SunCam Software for Computing Hydraulics in Open Channels and Box Culverts

No more than one entry in each of the alternating color blocks.

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (✓ U.S. Units, ✓ Metric Units, English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		13666.77582		CFS (Cubic Feet/Sec)
				6134075.056		GPM (Gallons/Minute) [US]
				8833.068043		MGD (Million gal/day) [US]
			387	387		CMS (Cubic Meters/Sec)
				1393200000		LPH (Liters/Hour)
				23220000		LPM (Liters/Minute)
				387000		LPS (Liters/Second)
				33436.8		MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow		2.11879019		Feet/Sec
				0.64580725		Meters/Sec
	n	Roughness Coeff.	0.025	0.025		No Units
	S	Hydraulic Gradient		2.56213E-05		Feet/Foot or Meter/Meter
				0.00256%		% Slope
	R	Hydraulic Radius		18.68800613		Feet
				5.696104268		Meters
Channel Dimensions	T	Top Width		344.488189		Feet
				105		Meters
	B	Bottom Width		147.6377953		Feet
			45	45		Meters
	H	Height		32.80839895		Feet
			10	10		Meters
	SL	Side Slope Left	6	6		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	85.00000%	85.00000%		% Full
	D	Depth of Flow		27.88713911		Feet
				8.5		Meters
	a	Area of Flow		6450.273317		Square Feet
				599.25		Square Meters
	p	Wetted Perimeter		345.1557792		Feet
				105.2034815		Meters

Complete Results

A possible alternative solution for SR = 0.00000

Figure 30 - First-Round Calculation of the New Bottom Width

Luc knows that the bottom width will be greater than 45 meters because the roughness coefficient for the bulkhead could be much higher than the grassy bottom. The coefficient for the new bulkhead could be as high as 0.060 depending on the material selected for its construction. He calculates a blended coefficient as follows:

$$(8)\ \frac{(p1)(n1) + (p2)(n2)}{p}$$

Where p1 and n1 are the wetted perimeter and coefficient for the grassy perimeter and p2 and n2 are the wetted perimeter and coefficient for the bulkhead portion of the perimeter and p is the total wetted perimeter. He uses empty cells next to the Manning-Channel template to do this quick calculation:

p1=	=45+((8.5)^2+(8.5*6)^2)^0.5 = 96.70348151
n1=	0.025
p2=	8.5
n2=	0.06
p=	p1+p2 = 105.2034815
Blended Coefficient=	(p1*n1+p2*n2)/p = .027828

The blended coefficient for the 45 meter bottom width calculates to 0.027828. He rounds up to 0.028 and then adjusts the bottom width to match the hydraulic gradient to be equal to or flatter than 0.00260% (the existing canal gradient). The new bottom width is now 52 meters (See Figures 31 & 32). He recalculates the blended coefficient and finds that the 0.028 value is still valid.

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No more than one entry in each of the alternating color blocks.

	Scroll down for sketch and definition of terms		Inputs	Channel Results	Box Culvert Results	Units (☑ U.S. Units, ☑ Metric Units, ☐ English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		13666.77582		CFS (Cubic Feet/Sec)
				6134075.056		GPM (Gallons/Minute) [US]
				8833.068043		MGD (Million gal/day) [US]
			387	387		CMS (Cubic Meters/Sec)
				1393200000		LPH (Liters/Hour)
				23220000		LPM (Liters/Minute)
				387000		LPS (Liters/Second)
				33436.8		MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow		1.927415592		Feet/Sec
				0.587476272		Meters/Sec
	n	Roughness Coeff.	0.028	0.028		No Units
	S	Hydraulic Gradient		2.55445E-05		Feet/Foot or Meter/Meter
				0.00255%		% Slope
	R	Hydraulic Radius		19.26190927		Feet
				5.871029946		Meters
Channel Dimensions	T	Top Width		367.4540682		Feet
				112		Meters
	B	Bottom Width		170.6036745		Feet
			52	52		Meters
	H	Height		32.80839895		Feet
			10	10		Meters
	SL	Side Slope Left	6	6		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	85.00000%	85.00000%		% Full
	D	Depth of Flow		27.88713911		Feet
				8.5		Meters
	a	Area of Flow		7090.725987		Square Feet
				658.75		Square Meters
	p	Wetted Perimeter		368.1216585		Feet
				112.2034815		Meters

Complete Results

A possible alternative solution for SR = 0.00000

Figure 31 - Final Design

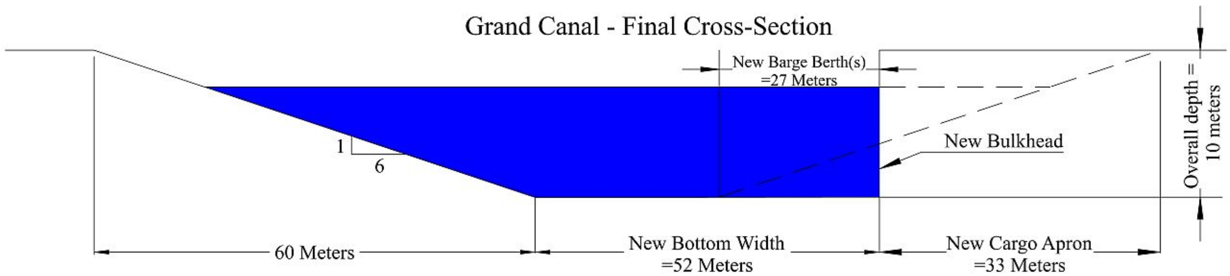

Figure 32 - Final Cross Section

The Grand Canal Council approved the plan and Z.inc actually completed construction of the barge port prior to developing the remainder of the site. The port was used as a delivery and staging area for construction of the store and parking lot. After the store was completed it used the port for delivery of most of its merchandise and as a tourist stop for river cruises.

Sample Problem 4

Enzo Como is an engineering student at The Sapienza University of Rome. Enzo's final assignment in his "History of Engineering" class is to answer a simple question:

What is the hydraulic capacity of "Aqua Marcia", Rome's longest aqueduct?

His professor, Dr. Mona Rosci has been making the same seemingly easy final assignment for many years. Like all of his predecessors, Enzo found that the answer was easily obtained from internet research. The facts are:

Overall Length	91.424 km
Gradient	318m to 59m (total fall of 259m)
Rectangular Channel Dimensions	0.6m wide by 1.35m high
Percent Full	66.67%
Capacity	187,600m^3/day

After completing a short 2-page paper on the subject Enzo decided to use Manning-Channel to verify these results. He made the following entries:

- [=187600/24/60/60] in the input cell for Quantity of Flow in cubic meters per second ("Q")
- [=(318-59)/91424] in the input cell for Hydraulic Gradient (S) in meter/meter
- [0.6] in the input cell for Bottom Width (B) in meters
- [1.35] in the input cell for Channel Height (H) in meters
- [0] in each of the input cells for Side Slope (SL & SR)
- [66.67] in the input cell for % full ("%")Full ***(or [0.6667] depending on your Excel setup, See Excel Percentage note on page 9)***

Results are shown in Figure 33.

		Scroll down for sketch and definition of terms	Inputs	Channel Results	Box Culvert Results	Units (U.S. Units / ✓ Metric Units / English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)				CFS (Cubic Feet/Sec)
						GPM (Gallons/Minute) [US]
						MGD (Million gal/day) [US]
			2.171296296	2.171296296		CMS (Cubic Meters/Sec)
				7816666.667		LPH (Liters/Hour)
				130277.7778		LPM (Liters/Minute)
				2171.296296		LPS (Liters/Second)
				187.6		MLD (Million Liters/day)
						GPM (Gallons/Minute) [UK]
						MGD (Million Gal/day) [UK]
	V	Velocity of Flow		13.19133193		Feet/Sec
				4.020717973		Meters/Sec
	n	Roughness Coeff.		0.004897396		No Units
	S	Hydraulic Gradient	0.002832954	0.002832954		Feet/Foot or Meter/Meter
				0.28330%		% Slope
	R	Hydraulic Radius		0.738198203		Feet
				0.225002812		Meters
Channel Dimensions	T	Top Width		1.968503937		Feet
				0.6		Meters
	B	Bottom Width				Feet
			0.6	0.6		Meters
	H	Height				Feet
			1.35	1.35		Meters
	SL	Side Slope Left	0	0		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	66.67000%	66.67000%		% Full
	D	Depth of Flow		2.952903543		Feet
				0.900045		Meters
	a	Area of Flow		5.812802251		Square Feet
				0.540027		Square Meters
	p	Wetted Perimeter		7.874311024		Feet
				2.40009		Meters

Complete Results

A possible alternative solution for SR = 0.00000

Figure 33

Enzo found the results troubling because the calculated roughness coefficient seemed much too low. He expected the coefficient to be in the range of 0.014-0.018 which is 280% to 360% higher than the calculated value. Suspecting a software error he verified the software output with hand calculations and got the same results. Perhaps the historic capacity measurement was based on the channel flowing full. He used Manning-Channel again to see how the results would change if the percent full was changed to 100%. Flowing full, the coefficient increased to 0.008 which is still smoother than glass and was therefore still suspect. He decided to recalculate the capacity of Aqua Marcia using the original 66.67% full and a coefficient of 0.014 (see Figure 34).

Scroll down for sketch and definition of terms			Inputs	Channel Results	Box Culvert Results	Units (U.S. Units; ✓ Metric Units; English Units)
Manning Formula Elements	Q	Quantity of Flow (Discharge)		26.82325126		CFS (Cubic Feet/Sec)
				12039.11139		GPM (Gallons/Minute) [US]
				17.33632032		MGD (Million gal/day) [US]
				0.759549902		CMS (Cubic Meters/Sec)
				2734379.647		LPH (Liters/Hour)
				45572.99411		LPM (Liters/Minute)
				759.5499018		LPS (Liters/Second)
				65.62511152		MLD (Million Liters/day)
				10024.65726		GPM (Gallons/Minute) [UK]
				14.43550645		MGD (Million Gal/day) [UK]
	V	Velocity of Flow		4.614512949		Feet/Sec
				1.406503547		Meters/Sec
	n	Roughness Coeff.	0.014	0.014		No Units
	S	Hydraulic Gradient	0.002832954	0.002832954		Feet/Foot or Meter/Meter
				0.28330%		% Slope
	R	Hydraulic Radius		0.738198203		Feet
				0.225002812		Meters
Channel Dimensions	T	Top Width		1.968503937		Feet
				0.6		Meters
	B	Bottom Width				Feet
			0.6	0.6		Meters
	H	Height				Feet
			1.35	1.35		Meters
	SL	Side Slope Left	0	0		Any Unit (Horizontal/Vert.)
	SR	Side Slope Right	0	0		Any Unit (Horizontal/Vert.)
Section Properties	%	% Full (D/H)	66.67000%	66.67000%		% Full
	D	Depth of Flow		2.952903543		Feet
				0.900045		Meters
	a	Area of Flow		5.812802251		Square Feet
				0.540027		Square Meters
	p	Wetted Perimeter		7.874311024		Feet
				2.40009		Meters

Figure 34 Quantity of flow for "Aqua Marcia"

The resulting calculated quantity of flow (0.76*24*60*60=65,664 m^3/day) was only about 1/3 of the historical estimate made by Sextus Julius Frontinus in 97 AD and still widely regarded as fact throughout the world. This discovery would also go a long way toward dispelling the myth that the average ancient Roman used a cubic meter of water every day (about three times the modern rate).

Enzo received a grade of 30 points (the highest mark in the Italian University system and equal to an A+). Dr. Rosci posted the grades outside her office along with a note saying that after seven years, a student had finally given the correct answer to the final assignment and that the question would now be retired.

--End of Course--

Appendix "A"
(This is supplemental information, not a part of the course or the test.)

Formulas used in Manning-Channel software:

Variable	Formula (In U.S. Customary Units)
Q	$= aV$
V	$= \frac{1.486}{n}\left(R^{2/3}\right)\left(S^{1/2}\right)$
V	$= \frac{Q}{a}$
n	$= \frac{1.486}{V}\left(R^{2/3}\right)\left(S^{1/2}\right)$
S	$= \left(\frac{Vn}{1.486 \times R^{2/3}}\right)^2$
R	$= \left(\frac{Vn}{1.486 \times S^{1/2}}\right)^{3/2}$
R	$= \frac{a}{p}$
T	$= B + H(SL + SR)$
T Parallel sides (SL=SR)	$= B$
B	$= T - H(SL + SR)$

B	$= \left(\frac{a}{D}\right) - D\left(\frac{SL+SR}{2}\right)$
B	$= p - D\left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)$
B	$= -\left(\frac{SL+SR}{2}\right)\left(D - \frac{a}{D}\right)$
B	$= p - \frac{-p + \left((p^2) - 4\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)}\left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)$
B	$= p - \frac{-p - \left((p^2) - 4\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)}\left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)$
B Parallel sides (SL=SR)	$= T$
H Nonparallel sides B≠T	$= \frac{T-B}{SL+SR}$
H	$= \frac{D}{\%}$
SL Nonparallel sides B≠T	$= \frac{T-B}{H} - SR$
SL	$= \left(\frac{-2B}{D}\right) + \left(\frac{2a}{D^2}\right) - SR$
SL	$= \left(\left(\left(\frac{p-B}{D}\right) - (SR^2+1)^{\frac{1}{2}}\right)^2 - 1\right)^{\frac{1}{2}}$

SL Parallel sides (B=T)	$= -SR$
SL Nonparallel sides B≠T sides assumed equal	$= \frac{T - B}{2H}$
SL Sides assumed equal	$= \frac{-\left(2\frac{B}{D}\right) + \left(2\frac{a}{(D)^2}\right)}{2}$
SL Sides assumed equal	$= \left(\frac{\left(\left(\frac{p - B}{2}\right)^2\right) - D^2}{D^2}\right)^{\frac{1}{2}}$
SL	$= \frac{4\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right) + \left(16\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right)^2 + 48\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right)^2 - 48\right)^{\frac{1}{2}}}{6}$
SL	$= \frac{4\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right) - \left(16\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right)^2 + 48\left(\frac{p}{D} - (SR^2+1)^{\frac{1}{2}} + \frac{SR}{2} - \frac{a}{D^2}\right)^2 - 48\right)^{\frac{1}{2}}}{6}$
SL	$= \frac{2B}{D} + \frac{2a}{D^2} - SR$
SR Nonparallel sides B≠T	$= \frac{T - B}{H} - SL$
SR	$= \left(\frac{-2B}{D}\right) + \left(\frac{2a}{D^2}\right) - SL$
SR	$= \left(\left(\left(\frac{p - B}{D}\right) - (SL^2 + 1)^{\frac{1}{2}}\right)^2 - 1\right)^{\frac{1}{2}}$
SR Parallel sides (B=T)	$= -SL$

SR Nonparallel sides B≠T sides assumed equal	$= \frac{T - B}{2H}$
SR Sides assumed equal	$= \frac{-\left(2\frac{B}{D}\right) + \left(2\frac{a}{(D)^2}\right)}{2}$
SR Sides assumed equal	$= \left(\frac{\left(\left(\frac{p-B}{2}\right)^2\right) - D^2}{D^2}\right)^{\frac{1}{2}}$
SR	$= \frac{4\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right) + \left(16\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right)^2 + 48\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right)^2 - 48\right)^{\frac{1}{2}}}{6}$
SR	$= \frac{4\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right) - \left(16\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right)^2 + 48\left(\frac{p}{D} - (SL^2+1)^{\frac{1}{2}} + \frac{SL}{2} - \frac{a}{D^2}\right)^2 - 48\right)^{\frac{1}{2}}}{6}$
SR	$= \frac{2B}{D} + \frac{2a}{D^2} - SL$
%	$= \frac{D}{H}$
D SL+SR=0	$= \frac{a}{B}$
D SL=SR≠0	$= \frac{-B + \left((B^2) - 2(SL+SR)(-a)\right)^{\frac{1}{2}}}{SL+SR}$
D SL+SR=0	$= \frac{p - B}{2}$
D SL+SR≠0	$= \frac{p - B}{(SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}}$

D	$= \frac{\%}{H}$
D SL+SR≠0	$= \frac{-T - \left((T^2) - 4\frac{\% - 2}{2\%}(SL+SR)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{\% - 2}{2\%}\right)(SL+SR)}$
D SL+SR≠0	$= \frac{-T + \left((T^2) - 4\frac{\% - 2}{2\%}(SL+SR)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{\% - 2}{2\%}\right)(SL+SR)}$
D	$= \frac{-p + \left((p^2) - 4\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)}$
D	$= \frac{-p - \left((p^2) - 4\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)(-a)\right)^{\frac{1}{2}}}{2\left(\frac{SL+SR}{2} - \left((SL^2+1)^{\frac{1}{2}} + (SR^2+1)^{\frac{1}{2}}\right)\right)}$
a	$= \frac{Q}{V}$
a	$= DB + D^2\left(\frac{SL+SR}{2}\right)$
a	$= Rp$
p	$= B + ((SLD)^2 + D^2)^{\frac{1}{2}} + ((SRD)^2 + D^2)^{\frac{1}{2}}$
p	$= \frac{a}{R}$
P For Box Culverts	$= T + B + ((SLD)^2 + D^2)^{\frac{1}{2}} + ((SRD)^2 + D^2)^{\frac{1}{2}}$