A SunCam online continuing education course

Gravity Flow in Pipes

The Manning Formula

and

SunCam "Manning-Pipe"

A Software Tool for Engineers

by

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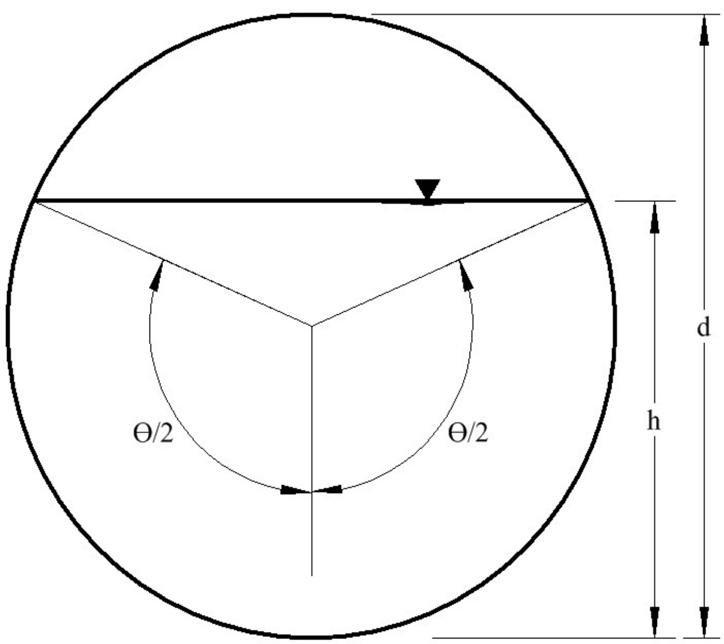
Note: This course covers circular pipe conduits.
Future courses will address other conduit shapes.



Purpose

Although the force of gravity is nearly constant in magnitude and direction, we can redirect gravity's vertical force to power the transport of liquids in a sloped pipe over great distances. The purpose of this course and the companion software is to examine and understand one approach to the hydraulic design of such pipelines. The Manning formula is one of many empirical formulae 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 pipelines and the use of the Manning Formula as a design tool. The Manning-Pipe software will allow users to speed the learning by eliminating most of the monotonous calculation.

Introduction

The Manning Formula, developed in 1890 by the Irish accountant turned engineer, Robert Manning, was a refinement of the 1867 formula developed by French engineer Philippe Gauckler. Although Manning had no formal education in engineering or hydraulics, he was a methodical mathematician and a keen observer. In addition to Gauckler, his formula was derived as a compilation of seven other empirical formulae (see inset) that were in use during the period. Common uses for Manning's formula are the design of gravity flow conduits such as storm sewers, sanitary sewers, swales, ditches and rivers. The formula takes two basic forms as follows:

Manning's Formula is a compilation of these formulae:

- Du Buat (1786)
- Eyelwein (1814)
- Weisbach (1845)
- St. Venant (1851)
- Neville (1860)
- Darcy and Bazin (1865)
- Ganguillet & Kutter (1869)

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-

In Metric Units

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

(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-

In U.S. Customary Units	In Metric Units
sectional area of flow divided by the wetted perimeter)	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.	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 feet per second	Q=Quantity of flow in cubic meters per second
A=Cross-sectional area of flow in square feet.	A=Cross-sectional area of flow in square meters.

Formula (1) above may be restated as follows:

In U.S. Customary Units / In Metric Units

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

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

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

The SunCam “Manning-Pipe” software was developed using these formulae and the geometry of a circle. Iterative approximation methods have been utilized to find some solutions. Solutions utilizing these methods are generally accurate to within ±0.01%.

The input tracking cells (rows 33 & 34) prompt the user about the status of inputs. The tracking cell at row 33 will always display one of the following prompts:

Let's Get Started! – When no input data has been entered.

Complete Results – When the user has input sufficient data to generate complete results.

Need More Data – When data input is insufficient to generate any results.

Partial Results! – When the input data is sufficient to generate some (but not all) results.

Over Determined – When too many input cells have input.

The tracking cell at row 34 will remain blank or display one of the following prompts:

Please Input Your Known Data - When no input data has been entered.

A second solution will display when % full is at or above XX.xx% - When the input data could result in 2-possible solutions. The percentage displayed depends on which combination of variables you input. (More on that later)

Too Much Input Data (Q, V, a) – When too much data has been input. (The variables in parentheses are the input combinations that make the problem over determined.)

Percentages

A note about entering percentages in an Excel spreadsheet:

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

Manning-Pipe

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Fleming Island, Florida 32003
www.suncam.com
800-735-4449 or 904-215-9345

v 1.0.0 **Help?**

Gravity Flow in Pipes

Input what you know into the "Inputs" column. No more than one entry in each of 10 color blocks.

	Variable	Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow	7.24	7.24	7.24	Cubic Foot/Sec
			3249.537709	3249.537709	Gallons/Minute [US]
			4.679334281	4.679334281	MGD (Million gal/day) [US]
			0.205013972	0.205013972	Cubic Meters/Sec
			738050.3002	738050.3002	Liters/Hour
			12300.83834	12300.83834	Liters/Minute
			205.0139723	205.0139723	Liters/Second
			17.7132072	17.7132072	MLD (Million Liters/day)
			2705.806162	2705.806162	Gallons/Minute [UK]
			3.896360874	3.896360874	MGD (Million Gal/day) [UK]
V	Velocity of flow	3.5	3.5	3.5	Foot/Sec
			1.0668	1.0668	Meters/Sec
n	Roughness coefficient	0.013	0.013	0.013	No Units
S	Hydraulic Gradient	0.002	0.002	0.002	Feet/Foot or Meter/Meter
			0.20000%	0.20000%	% Slope
R	Hydraulic Radius (a/p)		0.566521484	0.566521484	Feet
			0.172677848	0.172677848	Meters
d	Pipe Diameter		33.00688659	23.96415401	Inches
			838.3765962	608.6907293	Millimeters
%	% Full		37.95429%	62.73862%	% Full
h	Depth of Flow		12.52752989	15.03478016	Inches
			318.1998956	381.8841799	Millimeters
a	Area of Flow		2.068571429	2.068571429	Square Feet
			0.192174975	0.192174975	Square Meters
p	Wetted Perimeter		3.651355663	3.651355663	Feet
			1.112946739	1.112946739	Meters

Complete Results!

A second solution will display when % full is at or above 6.1735%

Project Name	Jamestown Road Drainage District
Proj. #	54123
By	WCD
Notes	CB23 to MH25, Concrete Pipe Alternative

 NOTE: All data is for round pipe.

Figure 1 Sample inputs and results using Manning-Pipe

Manning Formula

This empirical formula uses three variables ("n", "R" & S) to calculate the velocity of flow in a pipe. When the cross-sectional area of flow is known it can be multiplied by the velocity to determine the quantity of flow (Q=aV). Although this course will be limited to circular pipe, the conduit could also be a box culvert, a ditch or a river. Flow through a conduit with a free water surface such as ditches, rivers and partially filled pipes and culverts is generally called "open channel flow" while flow through full pipes and culverts is called "closed channel flow".

The Variables

Coefficient of Roughness (n) - Of the three variables ("*n*", "R" & S), "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. For new pipe, the manufacturer will supply the most accurate value for "n" but the engineer would be wise to consider how the roughness coefficient will change over the years following installation. Post installation factors that affect the value of the roughness coefficient include:

1. Solids collecting in the bottom (obvert) of the pipe or on its walls
2. Settlement or deflection of the pipe
3. Tree roots growing into the pipe through pipe joints or cracks
4. Erosion of the pipe interior surface

As the design engineer, you will use your own judgment to select the most appropriate coefficient for your project. We encourage you to test a range of values before making your decision. For this course, we will use the following values for *n*:

Polyethylene (smooth)	0.009
PVC	0.010
Asbestos cement	0.011
Cast iron	0.012
Concrete	0.012 or 0.013
Clay	0.014
Corrugated metal	0.022

Hydraulic Radius (R) - 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 24-inch diameter pipe flowing full, "R" would be calculated as follows:

(7) $a = \pi \left(\frac{r}{12}\right)^2 = 3.14159\, ft^2$

(8) Wetted Perimeter$= \pi \frac{d}{12} = 6.28318\, ft$

(9) $R = \frac{3.14159\, ft^2}{6.28318\, ft} = 0.5\, ft$

For the same pipe flowing half full, the calculation of (R) would similarly be:

(10) $R = \frac{\frac{3.14159\, ft^2}{2}}{\frac{6.28318\, ft}{2}} = 0.5\, ft$

Use the Manning-Pipe software to verify these results. Enter:

- [24] in the input cell for pipe diameter ("d")in inches (don’t enter the [brackets])
- [100] in the input cell for "%" Full ***(or [1.0] depending on your Excel setup, See Percentage note on page 4)***

Figure 2 below shows the solution.

R	Hydraulic Radius (a/p)		0.5		Feet
			0.152401853		Meters
d	Pipe Diameter	24	24		Inches
			609.6012192		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		24		Inches
			609.6012192		Millimeters
a	Area of Flow		3.141592654		Square Feet
			0.291861079		Square Meters
p	Wetted Perimeter		6.283185307		Feet
			1.91513817		Meters

Figure 2 Computing "R" for pipe flowing full

Now change the percentage full entry to:

- [50] in the input cell for "%" Full **(or [0.5] depending on your Excel setup, See Percentage note on page 4)**
- Figure 3 below shows the solution.

Hydraulic Radius (a/p)		0.5		Feet
		0.152401853		Meters
Pipe Diameter	24	24		Inches
		609.6012192		Millimeters
% Full	50.00000%	50.00000%		% Full
Depth of Flow		12		Inches
		304.8006096		Millimeters
Area of Flow		1.570796327		Square Feet
		0.145930539		Square Meters
Wetted Perimeter		3.141592654		Feet
		0.957569085		Meters

Figure 3- Computing "R" for pipe flowing half full

The hydraulic radius for a full pipe is always identical to that of a pipe flowing half full, which means the velocity will be the same if "n" and "S" are constant. Likewise, the quantity of flow, "Q", for a full pipe will always be twice the flow of a half-full pipe because the cross sectional area of flow doubles when the pipe is full.

Exploring hydraulic radius further, we will build a table of values for area ("a"), wetted perimeter ("p") and hydraulic radius ("R") using various percentages full and the same 24-inch diameter pipe:

% Full	a	p	R
10%	0.1635	1.2870	0.1270
20%	0.4473	1.8546	0.2412
30%	0.7927	2.3186	0.3419
40%	1.1735	2.7389	0.4285
50%	1.5708	3.1416	0.5000
60%	1.9681	3.5443	0.5553
70%	2.3489	3.9646	0.5925
80%	2.6943	4.4286	0.6084
90%	2.9781	4.9962	0.5961
100%	3.1416	6.2832	0.5000

Table 1 - "%" full vs. Hydraulic Radius

You will notice that "R" values increase with the percentage full up to 80% and then decrease to 0.5 at 100%. Actually, the maximum value for "R" for any size round pipe occurs when the pipe is 81.28% full.

% Full	a	p	R
10%	0.1635	1.2870	0.1270
20%	0.4473	1.8546	0.2412
30%	0.7927	2.3186	0.3419
40%	1.1735	2.7389	0.4285
50%	1.5708	3.1416	0.5000
60%	1.9681	3.5443	0.5553
70%	2.3489	3.9646	0.5925
80%	2.6943	4.4286	0.6084
81.28%	2.7348	4.4934	**0.6086**
90%	2.9781	4.9962	0.5961
100%	3.1416	6.2832	0.5000

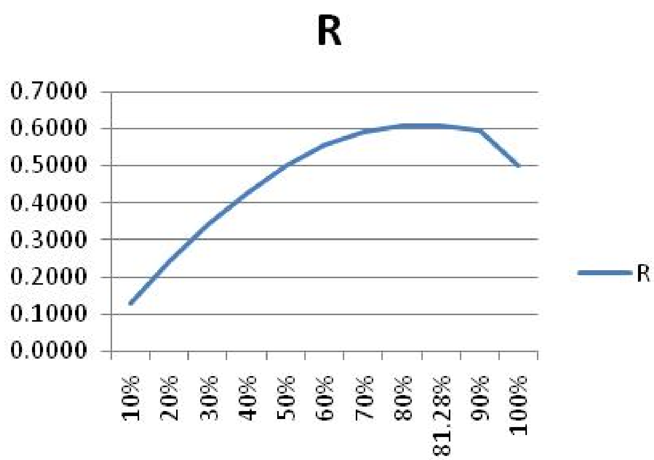

Table 2 - The maximum value of R

This would also be the point of maximum velocity (but not the point of maximum quantity of flow).

The shape of the chart in Table 2 above demonstrates the reason that there are sometimes two sets of results for a given set of input data. Use Manning-Pipe to illustrate this point by entering:

- [24] in the input cell for pipe diameter ("d") in inches
- [0.55] in the input cell for "R" in feet

R	Hydraulic Radius (a/p)	0.55	0.55	0.55	Feet
			0.167642039	0.167642039	Meters
d	Pipe Diameter	24	24	24	Inches
			609.6012192	609.6012192	Millimeters
%	% Full		97.73800%	58.88800%	% Full
h	Depth of Flow		23.45712	14.13312	Inches
			595.8120396	358.981966	Millimeters
a	Area of Flow		3.12357209	1.924435027	Square Feet
			0.290186928	0.178784376	Square Meters
p	Wetted Perimeter		5.679296009	3.499012112	Feet
			1.731070473	1.066511861	Meters
Partial Results					
A second solution will display when % full is at or above 50%					

Figure 4 - Two solutions for a single value of R

These two solutions (59% and 98% full) correspond to the intercepts of a horizontal line drawn at 0.55 on the Figure 5 chart below.

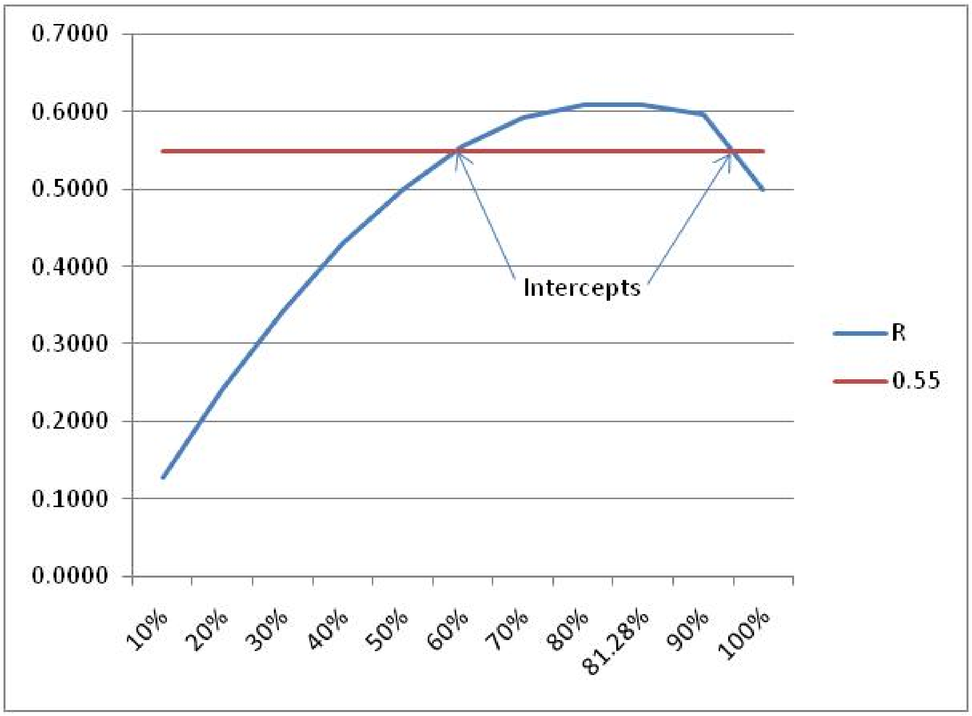

Figure 5 - Two solutions for R=0.55

Problems with two valid solutions will be covered in greater detail later in the course.

Hydraulic Slope (S) – Is defined as the total head loss divided by the length of pipe. Figure 6 illustrates a longitudinal-section view of four different system configurations each with an identical hydraulic slope of 0.002 (0.2%). As illustrated by these examples, the hydraulic slope and the slope of the pipe need not be the same. Although all of these cases have identical hydraulic slope, only Cases 3 and 4 are also equal in velocity and quantity of flow. The so-called "inverted siphon" in Case 4 is undesirable from a maintenance standpoint but it is hydraulically the equal of Case 3.

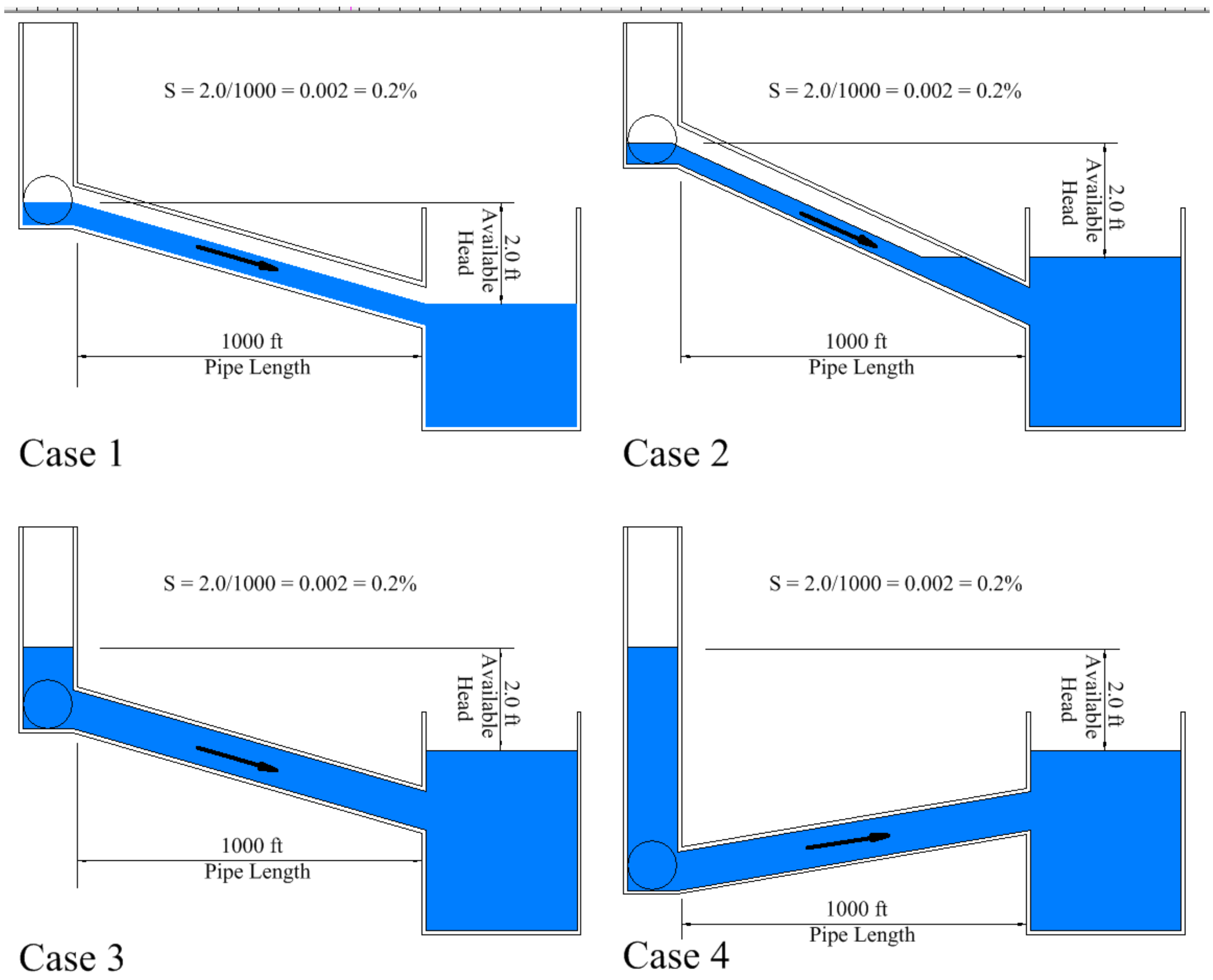

Figure 6 - Four systems with identical 0.2% hydraulic slope

The available head is the power that drives a gravity flow pipe system and it is the friction of the pipe walls that resists that power.

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-Pipe enter the following:

- [0.011] in the input cell for roughness coefficient ("n")
- [0.002] in the input cell for Hydraulic Gradient ("S")
- [0.35] in the input cell for Hydraulic Radius in feet ("R")

V	Velocity of flow		3.000450629		Foot/Sec
			0.914537352		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
			0.20000%		% Slope
R	Hydraulic Radius (a/p)	0.35	0.35		Feet
			0.106681297		Meters

Figure 7 - Calculating Velocity (V)

The resulting velocity is 3.000 feet per second. Now delete the entry for Roughness coefficient and enter the following:

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

V	Velocity of flow	3	3		Foot/Sec
			0.9144		Meters/Sec
n	Roughness coefficient		0.011001652		No Units
S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
			0.20000%		% Slope
R	Hydraulic Radius (a/p)	0.35	0.35		Feet
			0.106681297		Meters

Figure 8 - Calculating Roughness Coefficient (n)

Note that the value of "n" is now calculated at 0.01100, matching the original entry. Testing the remaining variables gives similar results.

V	Velocity of flow	3	3		Foot/Sec
			0.9144		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient		0.001999399		Feet/Foot or Meter/Meter
			0.19994%		% Slope
R	Hydraulic Radius (a/p)	0.35	0.35		Feet
			0.106681297		Meters

Figure 9 - Calculating Hydraulic Gradient (S)

V	Velocity of flow	3	3		Foot/Sec
			0.9144		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
			0.20000%		% Slope
R	Hydraulic Radius (a/p)		0.349921155		Feet
			0.106657265		Meters

Figure 10 - Calculating Hydraulic Radius (R)

Quantity of Flow ("Q") is calculated as the product of velocity and the cross sectional area of the stream of flow. For pipes flowing full the calculation of area is simply $a = \pi r^2$ and for partially full pipes the calculation is just slightly more complex. We won't do the math here but will illustrate this by using Manning-Pipe and entering:

- [24] in the input cell for diameter in inches ("d")
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

R	Hydraulic Radius (a/p)		0.5		Feet
			0.152401853		Meters
d	Pipe Diameter	24	24		Inches
			609.6012192		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		24		Inches
			609.6012192		Millimeters
a	Area of Flow		3.141592654		Square Feet
			0.291861079		Square Meters
p	Wetted Perimeter		6.283185307		Feet
			1.91513817		Meters

Figure 11 - Area of flow for a full pipe

The area of flow in square feet is 3.14159. Now change the entry for "%" full to:

- [80] in the input cell for % full ("%")Full **(or [0.8] depending on your Excel setup, See Percentage note on page 4)**

R	Hydraulic Radius (a/p)		0.608386523		Feet
			0.185438467		Meters
d	Pipe Diameter	24	24		Inches
			609.6012192		Millimeters
%	% Full	80.00000%	80.00000%		% Full
h	Depth of Flow		19.2		Inches
			487.6809754		Millimeters
a	Area of Flow		2.694297436		Square Feet
			0.250306339		Square Meters
p	Wetted Perimeter		4.428594871		Feet
			1.349852131		Meters

Figure 12 - Area of flow for a pipe 80% full

Now, to calculate "Q", all that is needed is to multiply the area of flow by the velocity or, using Manning-Pipe enter:

- [10] in the input cell for Velocity in feet per second. ["V"]
- [24] in the input cell for diameter in inches ("d")
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

Q	Quantity of Flow		31.41592654		Cubic Foot/Sec
			14100.44723		Gallons/Minute [US]
			20.30464393		MGD (Million gal/day) [US]
			0.889599985		Cubic Meters/Sec
			3202559.946		Liters/Hour
			53375.9991		Liters/Minute
			889.5999851		Liters/Second
			76.86143871		MLD (Million Liters/day)
			11741.0784		Gallons/Minute [UK]
			16.9071529		MGD (Million Gal/day) [UK]
V	Velocity of flow	10	10		Foot/Sec
			3.048		Meters/Sec
n	Roughness coefficient				No Units
S	Hydraulic Gradient				Feet/Foot or Meter/Meter
					% Slope
R	Hydraulic Radius (a/p)		0.5		Feet
			0.152401853		Meters
d	Pipe Diameter	24	24		Inches
			609.6012192		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		24		Inches
			609.6012192		Millimeters
a	Area of Flow		3.141592654		Square Feet
			0.291861079		Square Meters
p	Wetted Perimeter		6.283185307		Feet
			1.91513817		Meters
			Partial Results		

Figure 13 - Calculating Q

The resulting quantity of flow is 31.4159 cubic feet per second or 14,100 gallons per minute.

We saw earlier that the maximum hydraulic radius and velocity (but not quantity of flow) occur when a pipe is flowing 81.28% full. Now we will examine the quantity of flow to find the maximum Q. Using Manning-Pipe, we enter:

- [0.011] in the input cell for roughness coefficient ("n")

- [0.002] in the input cell for Hydraulic Gradient ("S")
- [24] in the input cell for diameter in inches ("d")
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		11.95650724		Cubic Foot/Sec
			5366.453195		Gallons/Minute [US]
			7.727692568		MGD (Million gal/day) [US]
			0.338570586		Cubic Meters/Sec
			1218854.11		Liters/Hour
			20314.23516		Liters/Minute
			338.5705861		Liters/Second
			29.25249864		MLD (Million Liters/day)
			4468.507039		Gallons/Minute [UK]
			6.434650136		MGD (Million Gal/day) [UK]
V	Velocity of flow		3.805874457		Foot/Sec
			1.160030535		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient	0.002	0.002		Feet/Foot or Meter/Meter
			0.20000%		% Slope
R	Hydraulic Radius (a/p)		0.5		Feet
			0.152401853		Meters
d	Pipe Diameter	24	24		Inches
			609.6012192		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		24		Inches
			609.6012192		Millimeters
a	Area of Flow		3.141592654		Square Feet
			0.291861079		Square Meters
p	Wetted Perimeter		6.283185307		Feet
			1.91513817		Meters
			Complete Results!		

Figure 14 - Finding the "%" full that produces the maximum Q

The resulting quantity of flow is 11.9565 cubic feet per second. By changing the "%" full, we can construct Table 3 where we see that the maximum quantity of flow occurs at about 94% full. Actually, the maximum "Q" for any size circular pipe occurs when the pipe is 93.82% full. The actual quantity of flow for a pipe operating at 93%-95% full is about 7.5% greater than a full pipe. The reason for this somewhat counterintuitive condition is that filling that last 6% of the pipe increases the area of flow by only 2.6% while increasing the wetted perimeter by 19%. The large added wetted perimeter increases the friction loss by more than the small increase in flow area can increase the quantity of flow.

%	R	a	p	V	Q
100.00000%	0.5000000000	3.1415926536	6.2831853072	3.8058744574	11.9565072360
99.00000%	0.5331520646	3.1362753489	5.8825156225	3.9722982805	12.4582211759
98.00000%	0.5470292072	3.1265985444	5.7155970888	4.0409312850	12.6343698736
97.00000%	0.5574033289	3.1141306080	5.5868532646	4.0918605772	12.7425882670
96.00000%	0.5658234953	3.0994417021	5.4777536240	4.1329654386	12.8098854340
95.00000%	0.5729030486	3.0828667467	5.3811316836	4.1673682404	12.8474409697
94.00000%	**0.5789631222**	**3.0646353687**	**5.2933170545**	**4.1967044933**	**12.8613690221**
93.00000%	0.5841983412	3.0449188676	5.2121319986	4.2219653861	12.8555420623
92.00000%	0.5887380173	3.0238521240	5.1361590983	4.2438091293	12.8326512496
91.00000%	0.5926737078	3.0015454327	5.0644146911	4.2627012508	12.7946914700
90.00000%	0.5960733407	2.9780915448	4.9961830896	4.2789865471	12.7432136561
80.00000%	0.6083865230	2.6942974356	4.4285948712	4.3377133138	11.6870898578
70.00000%	0.5924692578	2.3489192285	3.9646263457	4.2617208808	10.0104381231
60.00000%	0.5552884095	1.9681134270	3.5443084952	4.0815036994	8.0328622331
50.00000%	0.5000000000	1.5707963268	3.1415926536	3.8058744574	5.9782536180
40.00000%	0.4284527225	1.1734792266	2.7388768120	3.4335475007	4.0291966656
30.00000%	0.3418819354	0.7926734251	2.3185589615	2.9538734911	2.3414570176
20.00000%	0.2411827481	0.4472952180	1.8545904360	2.3408411768	1.0470470645
10.00000%	0.1270402697	0.1635011088	1.2870022176	1.5267528056	0.2496257766
0.01000%	0.0001333271	0.0000053332	0.0400006667	0.0157671585	0.0000000841

Table 3 - Finding Max "Q"

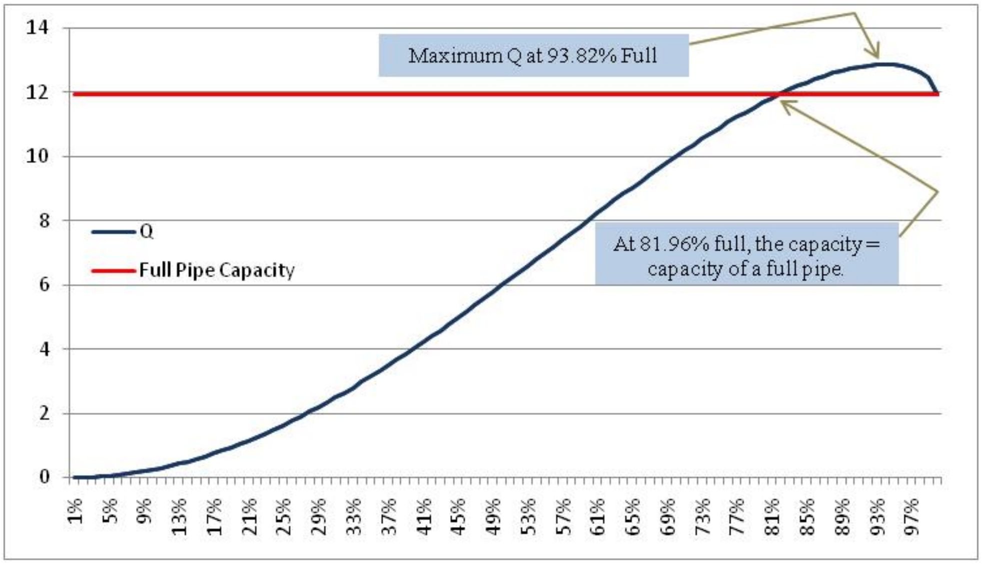

Figure 15 - Charting "Q" vs. "%" full

Figure 15 shows a plot of the values of "Q" from Table 3. The red line is a plot of the full pipe capacity, which intersects the graph of "Q" at two locations (81.96% and 100%). In other words, a pipe designed to flow full will produce the identical quantity of flow when the pipe is flowing only 81.96% full. This is true for all pipe sizes, hydraulic slopes and roughness coefficients. More on this point later.

Manning-Pipe Software is a Microsoft Excel ® based program for solving the Manning Formula. 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 data given. Because there are many ways to compute each variable, results can often be ambiguous. Manning-Pipe will not display results when the input data supports more than one method of computing the value of a missing variable. When the input data combination produces such an ambiguity, the program will display an "Over Determined" message in the tracking cell.

A Word of Caution

Designing pipelines to flow 94% full in order to capture that 7.5% capacity bonus is very tempting but risky and should probably be avoided except in the most controlled environment such as a constant flow feed pipe in an industrial plant. In a public storm or sanitary sewer system, even a slight increase in the quantity of flow above the design flow condition will fill the pipe immediately and push the system into surcharge. By designing for a full pipe on the other hand, the system capacity will actually be achieved when the pipe is only 82% full (see Figure 15) leaving a safety margin of 7.5% and a useful air gap at the top of the pipe.

An air gap at the top of the pipe can often be an important part of a gravity pipeline. For example, full pipes in a sanitary sewer can often block the escape of gas, severely restricting hydraulic capacity and creating undesirable odor control conditions such as splashing, bubbling and "burping" of the venting gas into manholes. This is particularly true when manholes are sealed to prevent the inflow of surface water.

Alternate Solutions - There are a total of 1024 (2^{10}) possible combinations of data inputs in the 10 input categories ("Q", "V", "n", "S", "R", "d", "%", "h", "a", "p"). A few of these combinations can produce two different but equally accurate sets of results. In those cases, the program will display results in both the **Solution #1** column and the **Solution #2** column to give the user the option of selecting the results that are best suited for the particular application. There are three different cases where specific input combinations can result in two solutions. You do not have to remember these cases when using Manning-Pipe because both solutions will always display when they exist. Each of the three cases is described below:

Case 1

This case is perhaps the most common way that a designer will encounter alternate solutions because it involves one of the most common sets of input data, ("Q", "n", "S" & "d"). Of the 1024 possible input combinations, only this one will produce Case 1 results. A design engineer will frequently use this combination of inputs to find the depth of flow (or "%" full) in a pipe. When the "%" Full is at or above 81.96% there will be two solutions. If the "%" Full is exactly 93.82% the two solutions will be equal. Figure 16 illustrates Case 1.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow	10.17	10.17	10.17	Cubic Foot/Sec
			4564.613053	4564.613053	Gallons/Minute [US]
			6.573042768	6.573042768	MGD (Million gal/day) [US]
			0.287982334	0.287982334	Cubic Meters/Sec
			1036736.402	1036736.402	Liters/Hour
			17278.94004	17278.94004	Liters/Minute
			287.982334	287.982334	Liters/Second
			24.88167366	24.88167366	MLD (Million Liters/day)
			3800.835452	3800.835452	Gallons/Minute [UK]
			5.473203051	5.473203051	MGD (Million Gal/day) [UK]
V	Velocity of flow		3.670506554	3.55518535	Foot/Sec
			1.118770398	1.083620495	Meters/Sec
n	Roughness coefficient	0.013	0.013	0.013	No Units
S	Hydraulic Gradient	0.002	0.002	0.002	Feet/Foot or Meter/Meter
			0.20000%	0.20000%	% Slope
R	Hydraulic Radius (a/p)		0.608419778	0.579972884	Feet
			0.185448603	0.176777885	Meters
d	Pipe Diameter	24	24	24	Inches
			609.6012192	609.6012192	Millimeters
%	% Full		82.44600%	99.98600%	% Full
h	Depth of Flow		19.78704	23.99664	Inches
			502.5918212	609.515875	Millimeters
a	Area of Flow		2.770734734	2.860610348	Square Feet
			0.257407538	0.265757186	Square Meters
p	Wetted Perimeter		4.553985313	4.932317402	Feet
			1.388071602	1.503388625	Meters
Complete Results! *A second solution will display when % full is at or above 81.96%*					

Figure 16- Alternate Solutions Case 1

Figure 17 is a plot of the Quantity of flow vs. the percentage full for a fixed diameter pipe. The red line represents the quantity of flow for the pipe at 100% full. Any horizontal line drawn below the red line intercepts the curve only once while a horizontal line drawn above the red line and below the maximum value of "Q" will intercept the curve twice thereby yielding two alternate solutions. The shape of the curve and the percentages are the same for any pipe size.

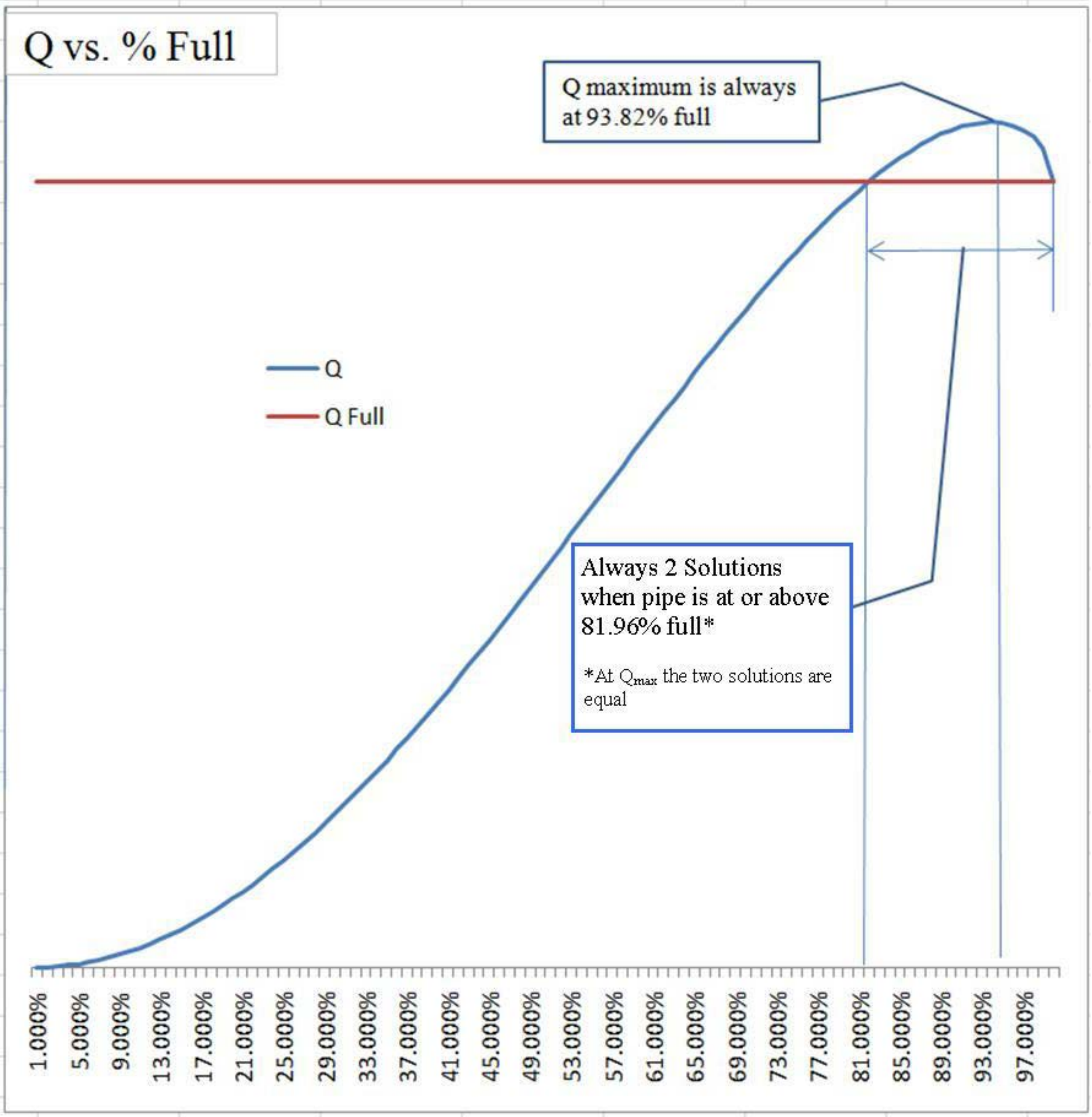

Figure 17 - – Case 1, charting "Q" vs. "%" Full

Case 2

Eleven of the 1024 possible input combinations will produce Case 2 results. Ten of these combinations involve inputs for both "R" and "d" (see Figure 18). This combination of inputs is unlikely to occur in a typical hydraulics problem because it involves the input of hydraulic radius ("R") which is seldom a known variable. Nonetheless, when a user enters data into the input cells for hydraulic radius ("R") and pipe diameter ("d") there will be two solutions whenever the pipe is calculated to be at or above half full.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow				Cubic Foot/Sec
					Gallons/Minute [US]
					MGD (Million gal/day) [US]
					Cubic Meters/Sec
					Liters/Hour
					Liters/Minute
					Liters/Second
					MLD (Million Liters/day)
					Gallons/Minute [UK]
					MGD (Million Gal/day) [UK]
V	Velocity of flow				Foot/Sec
					Meters/Sec
n	Roughness coefficient				No Units
S	Hydraulic Gradient				Feet/Foot or Meter/Meter
					% Slope
R	Hydraulic Radius (a/p)	0.6	0.6	0.6	Feet
			0.182882224	0.182882224	Meters
d	Pipe Diameter	24	24	24	Inches
			609.6012192	609.6012192	Millimeters
%	% Full		88.61200%	73.15600%	% Full
h	Depth of Flow		21.26688	17.55744	Inches
			540.1798324	445.9598679	Millimeters
a	Area of Flow		2.943783637	2.462769783	Square Feet
			0.273484173	0.228796895	Square Meters
p	Wetted Perimeter		4.90631137	4.104617142	Feet
			1.49546189	1.251102518	Meters
Partial Results					
A second solution will display when % full is at or above 50%					

Figure 18 - Alternate Results Case 2a

In Figure 19, we see the eleventh Case 2 combination, which involves inputs for "V", "n", "S" & "d". Design engineers will frequently use this combination of inputs to evaluate an existing pipe to determine its capacity and depth of flow when operating at a minimum or maximum allowable velocity.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		10.84308128	7.233991576	Cubic Foot/Sec
			4866.712914	3246.840941	Gallons/Minute [US]
			7.008066567	4.675450935	MGD (Million gal/day) [US]
			0.307041874	0.204843833	Cubic Meters/Sec
			1105350.745	737437.7975	Liters/Hour
			18422.51241	12290.62996	Liters/Minute
			307.0418736	204.8438326	Liters/Second
			26.52841788	17.69850714	MLD (Million Liters/day)
			4052.386208	2703.560633	Gallons/Minute [UK]
			5.835436139	3.893127312	MGD (Million Gal/day) [UK]
V	Velocity of flow	3.5	3.5	3.5	Foot/Sec
			1.0668	1.0668	Meters/Sec
n	Roughness coefficient	0.013	0.013	0.013	No Units
S	Hydraulic Gradient	0.002	0.002	0.002	Feet/Foot or Meter/Meter
			0.20000%	0.20000%	% Slope
R	Hydraulic Radius (a/p)		0.566521484	0.566521484	Feet
			0.172677848	0.172677848	Meters
d	Pipe Diameter	24	24	24	Inches
			609.6012192	609.6012192	Millimeters
%	% Full		95.91000%	62.53400%	% Full
h	Depth of Flow		23.0184	15.00816	Inches
			584.6685293	381.2080264	Millimeters
a	Area of Flow		3.098023222	2.066854736	Square Feet
			0.28781338	0.19201549	Square Meters
p	Wetted Perimeter		5.46850086	3.648325429	Feet
			1.666819331	1.112023113	Meters
Complete Results!					
A second solution will display when % full is at or above 50%					

Figure 19 Alternate Results Case 2b

Figure 20 is a plot of the Hydraulic Radius vs. the percentage full for a fixed diameter pipe. The shape of the curve will be identical for any pipe size. The red line represents the hydraulic radius for the pipe at 100% full. Any horizontal line drawn below the red line intercepts the curve only once while a horizontal line drawn above the red line and below the maximum value of "R" will intercept the curve twice thereby yielding two alternate solutions. If the % Full is 81.28 the two solutions will be equal.

Variations of this case may be seen by adding entries for "Q", "V", "n" or "S" (but not "Q" and "V" together). As shown in Figure 19, inputs for the three variables "V", "n" & "S" can also combine as a replacement for "R".

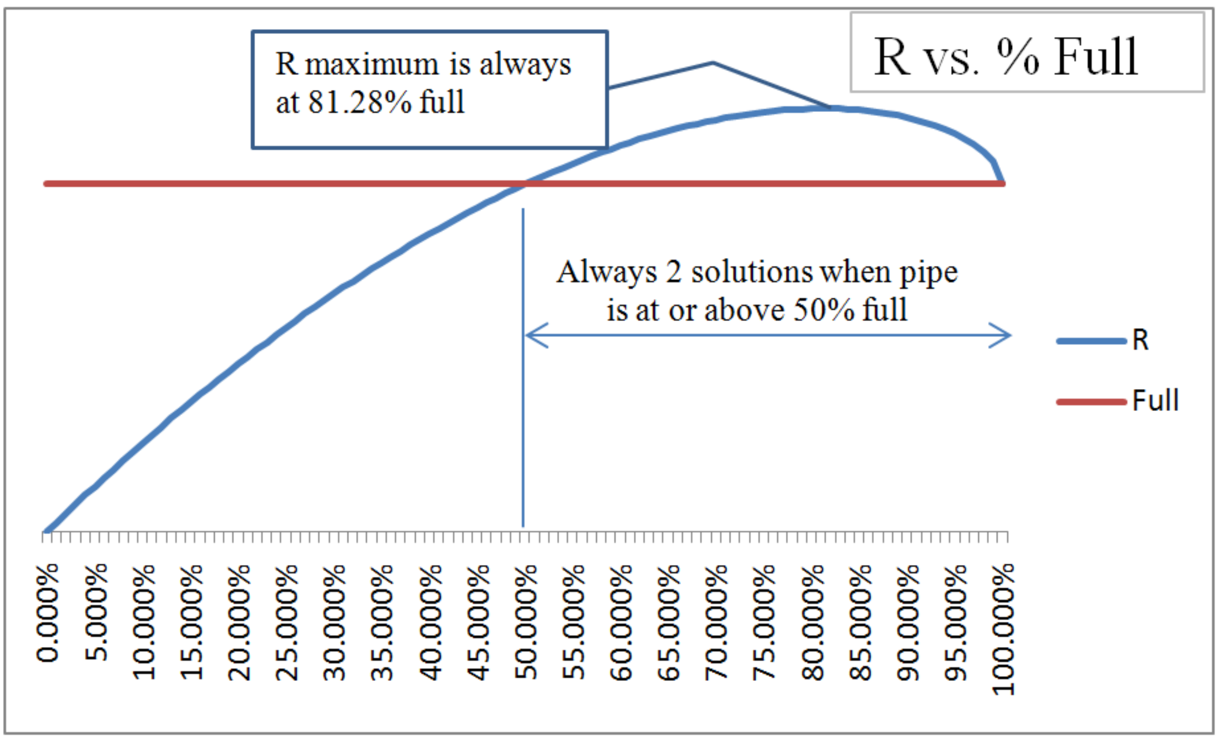

Figure 20 – Case 2, charting "R" vs. "%" Full (holding "d" fixed)

Case 3

A total of 41 of the 1024 possible input combinations will produce Case 3 results. All 41 of these involve entries for any two of the hydraulic radius ("R"), cross sectional area of the stream of water ("a") or the wetted perimeter ("p") or for other input variables that can be used to calculate "R", "a" or "p"**.** There will be two solutions whenever the pipe is calculated to be at or above 6.1735% full. Figure 21 illustrates this point with entries for area and wetted perimeter.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow				Cubic Foot/Sec
					Gallons/Minute [US]
					MGD (Million gal/day) [US]
					Cubic Meters/Sec
					Liters/Hour
					Liters/Minute
					Liters/Second
					MLD (Million Liters/day)
					Gallons/Minute [UK]
					MGD (Million Gal/day) [UK]
V	Velocity of flow				Foot/Sec
					Meters/Sec
n	Roughness coefficient				No Units
S	Hydraulic Gradient				Feet/Foot or Meter/Meter
					% Slope
R	Hydraulic Radius (a/p)		0.6	0.6	Feet
			0.182882224	0.182882224	Meters
d	Pipe Diameter		72.68288811	24.11878981	Inches
			1846.14905	612.6184864	Millimeters
%	% Full		16.09066%	89.68570%	% Full
h	Depth of Flow		11.69515576	21.63110653	Inches
			297.0575504	549.4312047	Millimeters
a	Area of Flow	3	3	3	Square Feet
			0.2787068	0.2787068	Square Meters
p	Wetted Perimeter	5	5	5	Feet
			1.524018532	1.524018532	Meters
Partial Results					
A second solution will display when % full is at or above 6.1735%					

Figure 21 Alternative Results Case 3

Figure 22 is a plot of the hydraulic radius vs. the percentage full of the pipe. This plot was created by calculating the hydraulic radius while holding either "p" or "a" fixed and allowing the pipe diameter to vary. Note that the curve is identical whether "p" or "a" is held constant.

Any horizontal line drawn below the red line intercepts the blue "R" curve only once while a horizontal line drawn above the red line and below the minimum value of "R" will intercept the curve twice. When the %Full is exactly 50% the two solutions will be equal.

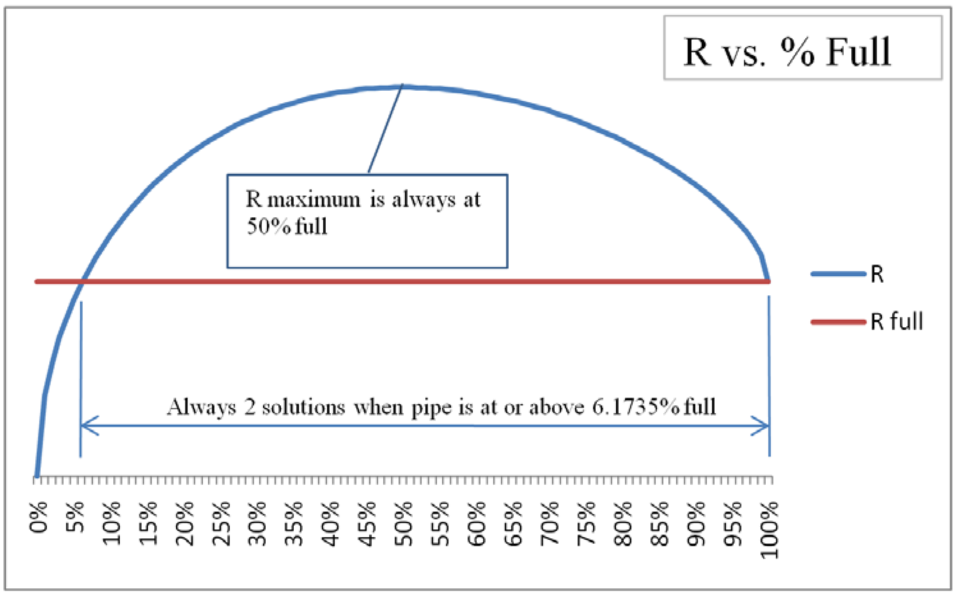

Figure 22 - Case 3, charting "R" vs. "%" Full (holding "p" or "a" fixed)

Tools – Old and New

In Robert Manning's time, the slide rule was nearly 3-centuries old and still it was the latest in computing technology. Raising a number to a $^{2}/_{3}$ power was an arduous task then but now the simplest electronic calculator can perform the calculation in an instant and to a degree of accuracy that would have been all but unattainable in 1890.

The Manning Formula has not changed in 120 years but advances in our computing tools now make it possible for us to perform thousands of calculations faster than we can input data. Our modern computing devices give today's engineer the power to better utilize and apply those time tested tools like The Manning Formula. Whether you use the Manning-Pipe software that is the companion to this course, a simple hand calculator or a computing tool of your own making, you will be capable of performing calculations faster and more accurately than Manning could have imagined.

Sample Problems

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

Sample Problem 1

A storm sewer catch basin is planned for a public park. The design information is:

Quantity of flow	3.6 CFS
Outfall lake surface elevation	120.00 ft
Catch basin grate elevation	124.50 ft
Allowed flooding above the grate	1.5 ft.
The total available head is calculated as: (124.50-120.00+1.5)	6.0’
Length of pipe	500 ft.
The hydraulic gradient is (6.0/500)	0.012 feet per foot

The entire pipe will be constructed below the water surface elevation of the lake therefore, the pipe will be considered as flowing full.

Using Manning-Pipe enter:

- [3.6] in the input cell for Quantity of Flow in cubic feet per second ("Q")
- [0.022] in the input cell for roughness coefficient for CMP (corrugated metal pipe) ("n")
- [0.012] in the input cell for Hydraulic Gradient in feet per foot ("S")
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

The resulting diameter is 14.18 inches for corrugated metal pipe (see figure 23). The next nominal size greater than the calculated diameter is 15 inches.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow	3.6	3.6		Cubic Foot/Sec
			1615.792231		Gallons/Minute [US]
			2.326740803		MGD (Million gal/day) [US]
			0.101940649		Cubic Meters/Sec
			366986.3371		Liters/Hour
			6116.438952		Liters/Minute
			101.9406492		Liters/Second
			8.807672091		MLD (Million Liters/day)
			1345.428479		Gallons/Minute [UK]
			1.937417009		MGD (Million Gal/day) [UK]
V	Velocity of flow		3.28188225		Foot/Sec
			1.00031771		Meters/Sec
n	Roughness coefficient	0.022	0.022		No Units
S	Hydraulic Gradient	0.012	0.012		Feet/Foot or Meter/Meter
			1.20000%		% Slope
R	Hydraulic Radius (a/p)		0.295395833		Feet
			0.090037745		Meters
d	Pipe Diameter		14.179		Inches
			360.1473203		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		14.179		Inches
			360.1473203		Millimeters
a	Area of Flow		1.096525143		Square Feet
			0.101869671		Square Meters
p	Wetted Perimeter		3.71205352		Feet
			1.131447671		Meters
Complete Results!					

Figure 23 Sample Problem 1

By changing the roughness coefficient (n) to 0.013 (for concrete pipe) we see that the diameter is reduced to 11.64 inches. This means a nominal 12-inch diameter concrete pipe and a 15-inch corrugated metal pipe would be approximate hydraulic equivalents.

Now, for the concrete pipe (n=0.013), we will recalculate the hydraulic gradient using the actual pipe size by deleting the hydraulic gradient input and entering:

- [12] in the input cell for diameter in inches ("d")

The recalculated hydraulic gradient is 1.021% therefore the total headloss for the system is 0.01021*500 = 5.105 feet, a reduction of .895 feet in the allowed flooding above the grate. Now the allowable flooding will be slightly over 7 inches (1.5 ft - .895 ft = 0.605 ft = 7.26 in).

Using the corrugated metal pipe alternative (d=15, n=0.022), the hydraulic gradient would be 0.88946% therefore the total head loss for the system using CMP is 0.0088946*500=4.45 feet, a reduction of 1.55 feet in the allowed flooding above the grate. With the CMP alternative, the design storm will not cause any ponding above the grate (1.50 ft – 1.55 ft = -0.5 ft).

Sample Problem 2

This problem was taken from our course on Hazen Williams formula. This will give us the opportunity to compare the results of Hazen Williams with Manning. *(The original Hazen Williams question appears in red italic)*

A small historic town exists within a perimeter levy on land that lies slightly below sea level. It uses a central canal system to collect storm water from the town and convey it to the intake side of a pump station on the perimeter of town at the levy. The pump station utilizes 3 pumps to maintain a constant elevation of water in the collector canal of 3.0 feet below mean high water. The discharge of the pump station empties into a 500-foot long pipe that in turn empties into a wide canal where the water is carried to the Gulf of Mexico for discharge.

Pump #1	*Operates continuously even in drought conditions to maintain the low water elevation.*	*90 Cubic Feet/Second (CFS)*
Pump #2	*Operates along with Pump #1 during routine rainfall events*	*90 CFS*
Pump #3	*Operates along with Pumps # 1 & 2 during extreme rainfall events*	*200 CFS*

A federal judge has issued a ruling that the town discontinue the direct discharge into the Gulf of Mexico except in extreme rainfall events. Under the court order, pumps # 1 & 2 will pump discharge water through a 6,000-foot long pipe to a polishing pond with water surface elevation of +5.0 above mean high water and marsh filter system. Pump #3 will continue to operate without change.

Arnold de Gerabon, the design engineer for the project, evaluates the existing Pumps # 1 & 2 and determines that they are capable of producing the design volume of flow at 10 feet of head. The 3 feet of suction lift plus 5 feet for the receiving waters means the available head-loss for the new pipe would be 2-feet. He uses the Hydro-Calc tool to size the pipe by entering:

- *=90+90 in the input cell for "Q" in Cubic Feet/Sec*

- *120 in the input cell for "C", roughness coefficient (for concrete pipe)*
- *=2/6000 in the input cell for "S", Feet/Foot or Meter/Meter*

The resulting calculated pipe size is 99.67 inches. The nearest standard pipe size would be 108-inches (9-feet) diameter.

Here we will use Manning-Pipe to replicate the calculation using the Manning Formula. We enter:

- [=90+90] in the input cell for "Q" in Cubic Feet/Sec
- [0.013] in the input cell for "n", roughness coefficient (for concrete pipe)
- [=2/6000] in the input cell for "S", Feet/Foot or Meter/Meter
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

6		Variable	Inputs	Solution #1	Solution #2	Units
7	Q	Quantity of Flow	180.00000	180.00000		Cubic Feet/Sec
8		Quantity of Flow		80789.60692		US Gallons/Minute
9		Quantity of Flow		116.33694		MGD (Million gal/day)
10		Quantity of Flow		5.09703		Cubic Meters/Sec
11		Quantity of Flow		305821.94771		Liters/Minute
12	V	Velocity of flow		3.37791218		Feet/Sec
13		Velocity of flow		1.029587633		Meters/Sec
14	n	Roughness coefficient	0.013	0.013		No Units
15	S	Hydraulic Gradient	0.000333333	0.000333333		Feet/Foot or Meter/Meter
16		Hydraulic Gradient		0.03333%		% Slope
17	R	Hydraulic Radius (a/p)		2.059208333		Feet
18		Hydraulic Radius (a/p)		62.76543323		Centimeters
19	d	Pipe Diameter		98.8420		Inches
20		Pipe Diameter		251.0591821		Centimeters
21	%	% Full	100.00%	100.00000%		% Full
22	h	Depth of Flow		98.842		Inches
23		Depth of Flow		251.0591821		Centimeters
24	a	Area of Flow		53.2856709		Square Feet
25		Area of Flow		49502.38827		Square Centimeters
26	p	Wetted Perimeter		25.87677509		Feet
27		Wetted Perimeter		788.7336957		Centimeters
28			Complete Results!			

Figure 24 Pipe size using existing pumps

The manning resulting calculated pipe size is 98.84 inches which is less than 1 inch or 0.8% smaller than the same calculation using Hazen Williams. Even changing the roughness coefficient to 0.012 yields a pipe size of 95.92 inches, still within 3% of the Hazen Williams results.

He then checks to see how much he could reduce the pipe size if he selects new, higher head pumps to replace Pumps # 1 & 2. Each of the new pumps is rated at 90 CFS at 28 feet of head.

He uses the Hydro-Calc tool to size the pipe by entering:

- *=90+90 in the input cell for "Q" in Cubic Feet/Sec*
- *120 in the input cell for "C", roughness coefficient (for concrete pipe)*
- *=(28-8)/6000 in the input cell for "S", Feet/Foot or Meter/Meter*

The resulting calculated pipe size is 62.12 inches. The nearest standard pipe size would be 66-inches (5.5-feet) diameter.

Using Manning-Pipe we enter:

- [=90+90] in the input cell for "Q" in Cubic Feet/Sec
- [0.013] in the input cell for "n", roughness coefficient (for concrete pipe)
- [=(28-8)/6000] in the input cell for "S", Feet/Foot or Meter/Meter
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

The calculated pipe size using Manning is 64.19 inches as compared with 62.12 inches using Hazen-Williams. The results differ by only about 3%.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow	180	180		Cubic Foot/Sec
			80789.61155		Gallons/Minute [US]
			116.3370401		MGD (Million gal/day) [US]
			5.09703246		Cubic Meters/Sec
			18349316.86		Liters/Hour
			305821.9476		Liters/Minute
			5097.03246		Liters/Second
			440.3836045		MLD (Million Liters/day)
			67271.42393		Gallons/Minute [UK]
			96.87085046		MGD (Million Gal/day) [UK]
V	Velocity of flow		8.010277213		Foot/Sec
			2.441532494		Meters/Sec
n	Roughness coefficient	0.013	0.013		No Units
S	Hydraulic Gradient	0.003333333	0.003333333		Feet/Foot or Meter/Meter
			0.33333%		% Slope
R	Hydraulic Radius (a/p)		1.337208333		Feet
			0.407586056		Meters
d	Pipe Diameter		64.186		Inches
			1630.327661		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow		64.186		Inches
			1630.327661		Millimeters
a	Area of Flow		22.47025561		Square Feet
			2.087537682		Square Meters
p	Wetted Perimeter		16.80385551		Feet
			5.12187744		Meters
Complete Results!					

Figure 25 Pipe size using new high-head pumps

He then checks the capacity of this design by entering:

- *120 in the input cell for "C", roughness coefficient (for concrete pipe)*
- *66 in the input cell for Diameter in Inches*
- *=(28-8)/6000 in the input cell for "S", Feet/Foot or Meter/Meter*

The resulting calculated Quantity of flow is 211 CFS which yields a 17% factor of safety. This alternative is selected for lower initial cost and lower life cycle cost.

We use Manning-Pipe to make a similar calculation by entering:

- 0.013 in the input cell for "n", roughness coefficient (for concrete pipe)

- 66 in the input cell for Diameter ("d") in Inches
- =(28-8)/6000 in the input cell for "S", Feet/Foot or Meter/Meter
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		193.879499		Cubic Foot/Sec
			87019.16342		Gallons/Minute [US]
			125.3075948		MGD (Million gal/day) [US]
			5.490056111		Cubic Meters/Sec
			19764202		Liters/Hour
			329403.3666		Liters/Minute
			5490.056111		Liters/Second
			474.340848		MLD (Million Liters/day)
			72458.61095		Gallons/Minute [UK]
			104.3403998		MGD (Million Gal/day) [UK]
V	Velocity of flow		8.160497358		Foot/Sec
			2.487319595		Meters/Sec
n	Roughness coefficient	0.013	0.013		No Units
S	Hydraulic Gradient	0.003333333	0.003333333		Feet/Foot or Meter/Meter
			0.33333%		% Slope
R	Hydraulic Radius (a/p)		1.375		Feet
			0.419105096		Meters
d	Pipe Diameter	66	66		Inches
			1676.403353		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow	.	66		Inches
			1676.403353		Millimeters
a	Area of Flow		23.75829444		Square Feet
			2.207199409		Square Meters
p	Wetted Perimeter		17.27875959		Feet
			5.266629967		Meters
			Complete Results!		

Figure 26 Checking capacity of 66 inch pipe

The resulting quantity of flow using Manning is 193.88 CFS, just 8% lower than Hazen Williams. The comparison becomes almost identical when a roughness coefficient of 0.012 is used for the concrete pipe.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		210.036124		Cubic Foot/Sec
			94270.76037		Gallons/Minute [US]
			135.7498944		MGD (Million gal/day) [US]
			5.947560787		Cubic Meters/Sec
			21411218.83		Liters/Hour
			356853.6472		Liters/Minute
			5947.560787		Liters/Second
			513.869252		MLD (Million Liters/day)
			78496.82853		Gallons/Minute [UK]
			113.0354331		MGD (Million Gal/day) [UK]
V	Velocity of flow		8.840538805		Foot/Sec
			2.694596228		Meters/Sec
n	Roughness coefficient	0.012	0.012		No Units
S	Hydraulic Gradient	0.003333333	0.003333333		Feet/Foot or Meter/Meter
			0.33333%		% Slope
R	Hydraulic Radius (a/p)		1.375		Feet
			0.419105096		Meters
d	Pipe Diameter	66	66		Inches
			1676.403353		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow	.	66		Inches
			1676.403353		Millimeters
a	Area of Flow		23.75829444		Square Feet
			2.207199409		Square Meters
p	Wetted Perimeter		17.27875959		Feet
			5.266629967		Meters
			Complete Results!		

Figure 27 Capacity calculation using n=0.012

Sample Problem 3

The St. Cloud Development Company is planning a 40-story high-rise condominium building with 400 - 1, 2 & 3 bedroom units. The water & sewer utility has determined that neither of the gravity sewer systems nearest the building have the available capacity to serve the project. Instead, they outline a plan that requires the developer to construct a pump station and 3,000 foot force main to connect to a regional master pump station. The utility will require that the pump station and force main be oversized to accommodate other nearby properties with similar development potential.

Barbara Johnson, P.E., the consulting engineer for the project calculates that the peek sewer flow from the building is 175 gallons per minute (gpm) and she is not convinced that the pump station and force main is really necessary. She persuades the developer to allow her to conduct a capacity study on the nearby gravity sewers to calculate the available capacity and verify or refute the utility determination.

Ms. Johnson first contacts the chief engineer for the utility company to obtain record drawings for the two systems and to establish the establish the peak day of week and hour of day for the two systems. She plans four inspections to measure the depth of flow in each of the sewer lines. Three of the inspections are scheduled at the peak day/hour for the following 3-weeks and one is planned for measuring flows at 2:00 AM after rainstorms have increased the elevation of groundwater. This fourth inspection will help distinguish between the normal domestic flow and flow caused by the infiltration of groundwater. (At 2:00 AM a gravity sewer that does not suffer groundwater infiltration will usually have very low flows.)

The findings are:

	System "A"	System "B"
Pipe Size	8"	16"
Pipe Material	Asbestos Cement	Ductile Iron
Average daytime flow depth (in)	7.0"	12.5"
Slope (downstream)	0.4%	0.14%
Average 2:00 AM flow depth (in)	4.5	1.2

She uses Manning-Pipe software to calculate the flow for each of the systems. For System "A", she enters:

- [0.011] in the input cell for "n", roughness coefficient (don't enter the [brackets])
- [.004] in the input cell for "S", Hydraulic gradient (ft/ft)
- [8] in the input cell for pipe diameter "d" (in)
- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

The resulting capacity at 100% full is 405 gpm.

She then changes the "%" Full input cell to [=7/8] and thus calculates the average peak hour flow at 426 gpm which is 21 gpm higher than the capacity of the pipe flowing full.

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		0.949046981		Cubic Foot/Sec
			425.9618718		Gallons/Minute [US]
			0.613385093		MGD (Million gal/day) [US]
			0.026874018		Cubic Meters/Sec
			96746.46533		Liters/Hour
			1612.441089		Liters/Minute
			26.87401815		Liters/Second
			2.321915168		MLD (Million Liters/day)
			354.6874543		Gallons/Minute [UK]
			0.510749934		MGD (Million Gal/day) [UK]
V	Velocity of flow		2.930225758		Foot/Sec
			0.893132811		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient	0.004	0.004		Feet/Foot or Meter/Meter
			0.40000%		% Slope
R	Hydraulic Radius (a/p)		0.200847968		Feet
			0.061219205		Meters
d	Pipe Diameter	8	8		Inches
			203.2004064		Millimeters
%	% Full	87.50000%	87.50000%		% Full
h	Depth of Flow	.	7		Inches
			177.8003556		Millimeters
a	Area of Flow		0.323881864		Square Feet
			0.030089359		Square Meters
p	Wetted Perimeter		1.612572271		Feet
			0.491518005		Meters
Complete Results!					

Figure 28 System "A" Average daytime flow volume (gpm)

(For round pipe, the maximum quantity of flow occurs at approximately 93.82% full and any pipe flowing greater than 81.96% and less than 100% full will have a greater capacity than the same pipe flowing 100% full. See Figure 15)

To calculate the amount of flow attributable to infiltration she changes the "%" Full input cell to [=4½ / 8] to calculate 246 gpm (see Figure 29).

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		0.548509093		Cubic Foot/Sec
			246.187981		Gallons/Minute [US]
			0.354510691		MGD (Million gal/day) [US]
			0.015532048		Cubic Meters/Sec
			55915.37307		Liters/Hour
			931.9228844		Liters/Minute
			15.53204807		Liters/Second
			1.341968954		MLD (Million Liters/day)
			204.9943764		Gallons/Minute [UK]
			0.295191902		MGD (Million Gal/day) [UK]
V	Velocity of flow		2.712193385		Foot/Sec
			0.826676544		Meters/Sec
n	Roughness coefficient	0.011	0.011		No Units
S	Hydraulic Gradient	0.004	0.004		Feet/Foot or Meter/Meter
			0.40000%		% Slope
R	Hydraulic Radius (a/p)		0.178853235		Feet
			0.054515129		Meters
d	Pipe Diameter	8	8		Inches
			203.2004064		Millimeters
%	% Full	56.25000%	56.25000%		% Full
h	Depth of Flow	.	4.5		Inches
			114.3002286		Millimeters
a	Area of Flow		0.202238195		Square Feet
			0.018788387		Square Meters
p	Wetted Perimeter		1.130749439		Feet
			0.34465662		Meters
			Complete Results!		

Figure 29 – Calculating Infiltration

She follows the same procedure for the System "B" pipe using a roughness coefficient of 0.012 with the following results:

	System "A"	System "B"
Pipe Size	8"	16"
Pipe Material	Asbestos Cement	Ductile Iron
Average daytime flow depth (in)	7"	12.5"
Slope (downstream)	0.4%	0.14%
Total capacity (gpm)	405	1396
Average daytime flow volume (gpm)	426	1332
Available capacity (gpm)	-21	64
Average 2:00 AM flow depth (in)	4.5	1.2
Average 2:00 AM flow volume (gpm)	246	16
Available capacity plus infiltration	225	80

Table 4 - Calculating Available Capacity

In her report to the developer, Johnson confirmed that the existing gravity systems did not have sufficient available capacity for the project unless repairs were made to stop the infiltration into System "A". The cost of those repairs was significantly lower than pump station and force main alternative and the benefit to the utility would be greater because the repairs would eliminate the cost of treating the infiltrated groundwater.

Sample Problem 4

The James River Public Utilities Authority is retiring the ancient water treatment operation at their Alpha Water Treatment Plant and relocating that function to the new Lambda Water Treatment Plant 3,000 feet away. The ground storage tanks and high service distribution pumps at the Alpha Plant are to remain in service receiving finished (treated) water from Lambda at a constant rate of 80 million gallons per day (MGD) through two low service transfer pumps at Lambda and a 36" diameter prestressed concrete pressure pipe connecting the two plants.

Ed Davis is the new chief engineer for the utility and it is his job to build the new plant and complete the changeover. As he reviewed the plans on his first day on the job he noticed that the new plant site has a ground elevation that is 40 feet above the old plant which means there is a possibility that the feed from Lambda to Alpha could be by gravity flow. He uses Manning-Pipe and enters:

- [80] in the input cell for "Q", quantity of flow in MGD
- [012] in the input cell for "n", roughness coefficient (for concrete pipe)
- [=40/3000] in the input cell for "S", Feet/Foot or Meter/Meter

- [100] in the input cell for % full ("%")Full **(or [1.0] depending on your Excel setup, See Percentage note on page 4)**

Variable		Inputs	Solution #1	Solution #2	Units
Q	Quantity of Flow		123.7782909		Cubic Foot/Sec
			55555.55579		Gallons/Minute [US]
		80	80		MGD (Million gal/day) [US]
			3.505010926		Cubic Meters/Sec
			12618039.33		Liters/Hour
			210300.6556		Liters/Minute
			3505.010926		Liters/Second
			302.832944		MLD (Million Liters/day)
			46259.67712		Gallons/Minute [UK]
			66.61393505		MGD (Million Gal/day) [UK]
V	Velocity of flow		13.02647548		Foot/Sec
			3.970469726		Meters/Sec
n	Roughness coefficient	0.012	0.012		No Units
S	Hydraulic Gradient	0.013333333	0.013333333		Feet/Foot or Meter/Meter
			1.33333%		% Slope
R	Hydraulic Radius (a/p)		0.869520833		Feet
			0.265033173		Meters
d	Pipe Diameter		41.737		Inches
			1060.12192		Millimeters
%	% Full	100.00000%	100.00000%		% Full
h	Depth of Flow	.	41.737		Inches
			1060.12192		Millimeters
a	Area of Flow		9.501011592		Square Feet
			0.882665514		Square Meters
p	Wetted Perimeter		10.92672105		Feet
			3.330505075		Meters
Complete Results!					

Figure 30 Sizing a gravity alternative

The resulting calculated pipe size is 41.7 inches in diameter or 42 inches nominal pipe size. This plain reinforced 42-inch concrete pipe, Davis reasons, will actually be less costly and more reliable than the pressure rated 36-inch pre-stressed concrete pipe that was shown on the plans, plus the utility will be able to eliminate purchasing, installing, maintaining and operating the two low service transfer pumps.

End of Course

