PDHonline Course H147 (2 PDH)

Use of RATIONAL FORMULA for HYDRAULIC ANALYSIS & DESIGN

Instructor: Lester A. Tinkham, PE, PS

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

Use of the RATIONAL FORMULA For HYDRAULIC ANALYSIS & DESIGN

NOTE: All Tables and Figures provided in these lessons are extracted from standard engineering design manuals or leading professional publications.

CHAPTER 1 OVERVIEW

- Use and limitations of the Rational Formula
- Government Regulations - Federal, State and local
- Defining Drainage Area Boundaries
- Determining Watershed Characteristics
- The FORMULA: Q= CIA
- Define each parameter
- Parameter Units
- Derivation of Parameters
- Sample Computation

Learning Objectives

- To understand the background of the Rational Formula
- To recognize the formula's applicability and limitations
- To be introduced to a practical approach to solving the Rational Formula
- To be able to derive appropriate parameter values
- To calculate peak quantities of rainfall runoff for use in design of storm water management systems

INTRODUCTION

Since the beginning of time, man has been aware of the importance of water for survival. It is one of the staffs of life. We capture it and use it, recycle it, struggle with it through droughts, and fight it during floods, storms and hurricanes. Multiple studies have been undertaken to address a variety of considerations such as its relationship to climate, rainfall patterns, soil characteristics, vegetation, urban development, military maneuvers, etc. and, of course, land development, which usually modifies these relationships.

A major effort in studies related to storm water management has been directed to the understanding and ability to determine the quantity of storm water runoff at specific locations and the use of that determination to plan, design, construct, operate and maintain storm water collection and disposal facilities. Since water flows over land both as sheet flow and through channels, ravines and other depressions in the land, the handling of storm water runoff can be complicated. Runoff velocity is also of concern since as velocity increases the ability of the runoff to cause erosion and to pick up and carry sediments and any other contaminant also increases.

A combination of two major engineering disciplines has evolved to deal with these matters, specifically Hydrology, which relates to the quantity and patterns of rainfall runoff, and Hydraulics, which relates to means and methods to capture and dispose of storm water. Hydrology is always a prerequisite for Hydraulics, and the Rational Formula provides and satisfies the hydrology needs for certain conditions.

As it relates to the Rational Formula, in storm water studies the goal of the Hydrologist is to define the storm characteristics which produce a peak quantity of rainfall runoff which if controlled will provide an acceptable degree of protection from residual flooding damages along with a degree of comfort that the damages from any larger storm event would be either of nuisance consequence or are worth the risk in not protecting. The goal of the Hydraulic Engineer is to design a system to capture and/or control every drop of that runoff and either provide for re-cycling or convey it to an adequate point of disposal.

It must be noted that Hydrology should not be considered an exact science as its' analysis depends on a large number of variables such as watershed boundaries, topography, soil types, percolation rates, vegetation, rainfall intensities and distribution, and antecedent precipitation conditions, and many of these variables can have dramatic changes even within a single watershed. In order to reasonably define the necessary components for these analyses a substantial amount of engineering judgment is usually required and great care must be taken to assure a reasonably correct approximation of the quantity of storm water runoff is made.

Studies and experiments have developed several methods and their related formulae for determining the specific quantity of storm runoff at a selected point. Most deal with large, complex drainage basins of rivers and major streams with many tributaries. The formulas range from the widely used Rational Formula, developed circa 1889 to the more recently developed computer models that are being continually updated. The Rational Formula has survived the test of time and remains applicable for use in small, simple drainage basins, and its simplicity and ease of utilizing has made it a popular design formula among engineers for small site development projects.

Government Regulations - Federal, State and local

In the 1960's and early 1970's in response to increased public concern, Congress passed several laws relating to environmental matters. Of these there are 3 Federal Laws which currently require Hydraulic Analysis.

The Federal Flood Insurance Act The technical aspects of this Act are administered by the Federal Emergency Management Agency (FEMA), which has developed maps of all floodplains in the US (Flood Insurance Rate Maps, known as FIRM) and set standards for land development in floodplains. These studies usually apply to rivers and streams too large for use of the Rational Formula The formula, however, can and is routinely used in engineering analysis needed for application of floodplain regulatory requirements, for example for smaller construction projects which impact on FIRM designated flood hazard areas.

The Federal Water Pollution Control Act This Act established the National Pollution Discharge Elimination System (NPDES) and regulation rules are established by the Environmental Protection Agency (EPA).

EPA's first efforts deal with rules and regulations for protecting water quality from sanitary sewage collection and treatment. EPA has passed the responsibility of compliance to the States. All proposals and designs for upgrading and/or modifying existing facilities or additions to sanitary sewer systems must be approved by the State Environmental Department. There are no significant applications for use of the Rational Formula in this phase.

In 1972 Congress amended the Federal Water Pollution Control Act and named the amendments the Federal Clean Waters Act (CWA). This Act deals with rules and regulations for handling storm water with the primary purpose of preventing storm water pollution from entering the Nation's waterways. The State's are charged with the administration of this phase and have established regulations for handling storm water runoff. In many areas, local agencies have adopted additional regulations.

Each proposed project that disturbs one (1) acre or more land must apply for a Permit from the State and if necessary, also from the local agency. The EPA published this manual: http://www.epa.gov/npdes/pubs/sw_swppp_guide.pdf.
A primary requirement of these permits is to develop a "Storm Water Pollution Prevention Plan" (SWPPP). Each SWPPP must specify the "Best Management Practices" (BMP) for preventing construction generated sediment and other contaminants from reaching a natural stream. BMP facilities usually considered include silt fences, temporary construction entrances (to assure mud and debris is not tracked onto public road by construction vehicles and equipment), provisions for temporary and permanent seeding on bare earth, control of fugitive dust, storm water collection and conveyance to a satisfactory point of disposal (often a natural stream), handling spills and good housekeeping during construction. More recently the evaluation of use of bio-swales and rain gardens has become a popular consideration for managing storm water runoff.

Following construction, in many instances, new paving, landscaping and rainwater harvesting and re-cycling are expected to prevent further production of significant quantities of sediment, silt, dust and debris which could escape to a natural waterway. In other more complex storm water management systems, a combination of structural and non-structural methods must be developed to insure long-term continuation a functional system.

The Rational Formula is readily adaptable for use in determining the quantities of storm water needed for the development of all systems for collection, recycling and/or disposal of storm water for small watersheds (up to 200 acres).

In 1987 Congress amended the CWA to require EPA to establish a program to specifically address direct storm water discharges into the Nation's waterways. In response EPA promulgated the NPDES storm water application regulations. These regulations require facilities with the following storm water discharges apply for an NPDES permit associated with discharges from (1) an industrial activity; (2) large or medium size municipal storm water system; or (3) one which EPA determines contributes to a violation of a water quality standard which is a significant contributor to pollutants of US waters.

Regarding municipal storm water systems, their primary thrust deals with rules and regulations for assuring the elimination of combined sewers, which carry both sanitary sewage and storm water. In earlier days, as municipalities became established and grew, it became essential to solve problems generated by both sanitary and storm water. Local agencies at that time decided to kill two birds with one stone by capturing both types of untreated water in a single pipe and to carry it untreated to the nearest stream where it was carried on downstream by the natural flow. This was – at that time - an acceptable procedure as the contaminants thus disposed were diluted by the natural steam flows and had little effect on downstream areas. Over time, as municipalities grew and more were established, dilution was no longer the solution to pollution, and adverse effects downstream became a serious concern. Treatment of sewage was initiated and the objective of EPA's efforts to date – as described above - is to assure clean water is discharged into the Nation's streams. This objective is hampered by the fact that where combined sewers exist, the storm water component is also going through the sanitary sewage treatment facilities, requiring unnecessary treatment capacity and during storms often overloading those treatment facilities causing by-passes of raw sewage into our rivers and creeks. The separation of sanitary sewage and storm water sewage into separate collection and conveyance systems – while very expensive – is considered an important component of measures to solve these problems.

EPA has established the M -1 program for handling this phase. It provides that municipalities will establish plans to separate the two systems and to monitor the quantity and quality of outflow from storm sewers to assure no contaminants are being released. Design of these new systems can effectively use the Rational Formula to determine storm water flows.

Also, many local agencies are now requiring that - to prevent flooding damages in their communities – there can be no increase in the amount of existing flow in a stream caused by new developments. This requires that the increased flow caused by new developments must be either recycled or retained on-site and released at a rate that is no greater than the original pre-project flow. The Rational Formula can be used to develop and compare pre-project flows with post-project flows to determine the quantity of storm water that must be harvested for re-use or detained on-site. It is not well suited for design of a Detention Pond since it deals only with peak discharges and does not consider the timing of inflow or outflow requirements. It does, however, have substantial use in developing designs for rainwater gardens and bio swales which must characteristically address peak flows. More information on design of rain gardens is available at: http://learningstore.uwex.edu/assets/pdfs/GWQ037.pdf.

State Highway Departments and local Public Works Departments usually have standard specifications for design of roads, streets, driveways, parking areas, etc, including drainage. The Rational Formula is widely used in their analysis of drainage requirements.

Use and limitations of the Rational Formula

The Rational Formula can be used to determine the peak quantity of rainfall runoff at a specific location, from a selected size storm over a small drainage area. To begin, a specific location must be selected as the point of analysis, usually the site of a proposed drain pipe, a rain garden or a break in the topography where runoff patterns would be changing. Acceptability for use of the Rational Formula lies in the consideration of "Time of Concentration" a term that is defined as the time required for runoff from the most distant point of the drainage area to reach the point of consideration along with the assumption that rainfall intensity is uniform over the entire drainage area during the entire storm Since the runoff quantity at the selected point for analysis varies as the storm progresses, this time is highly important for large basins and depends largely on the slope of the stream channel carrying the runoff. The Rational Formula assumes that the length of the storm is equal to or longer than the "Time of Concentration", and thus all runoff will reach the selected point for analysis during the storm's runoff period. The timing of peak flow is therefore not encumbered by the time of concentration, and its inherent delay is no longer a consideration. This situation is always a factor of the size and character of the drainage basin, and the Rule of Thumb is that the all relevant factors for use of the Rational Formula can be satisfied if the drainage area is no more than 200 acres.

In addition to the size of drainage area the formula's use is limited to a single specified point of analysis and selected storm intensity. Each modification of any parameter requires a separate calculation. This is seldom a problem due to the simplicity of the formula and its ease of calculation.

The Rational Formula does not deal with Water Quality.

Defining Drainage Area Boundaries

Drainage areas are defined by topography and include all areas where runoff for rainfall will drain to the point of analysis.

Determining Watershed Characteristics

A careful consideration of the characteristics of the watershed is always important in determining the runoff quantity which will reach the point of analysis. These characteristics include such abstraction factors as topography, soil types, vegetation, and antecedent conditions.

The FORMULA: Q= CIA

The formula is based on a simple intensity-runoff relationship. The formula's parameters and their units (English units) are as follow:

"Q" is the peak storm water runoff quantity arriving at the point of analysis from the selected storm. It is measured in "cubic feet per second" (cfs).

"C" is the runoff coefficient. It is the only manipulative, variable factor in the formula, and it is expressed as a pure number with no units. Judgment must be used in selecting the values as it incorporates most of the hydrologic abstractions.

"I" is the intensity of the selected storm. It is expressed in "inches per hour".

"A" is area expressed in "acres".

Derivation of Parameters

- Parameter "C"

The determination of "C" is based on the character of the drainage area including type of soils, type and amount of vegetation, and developments on the land. A wealth of information on soil types, their locations and uses is available in Soil Surveys produced for most counties of the US by the US Department of Agriculture, Natural Resources Conservation Service (NRSC).For many counties in the US, navigating through the NRCS web site will lead to a "Custom Soil Resource Report" for a specific project location (www.websoilsurvey.nrsc.us.gov). Also for specific projects there is usually a Soil Investigation conducted by a geotechnical consultant. Vegetation types and limits must usually be determined by field investigation, but the USGS Quadrangles (available in many retail outlets) and aerial photos of the area also are helpful. Land development includes all items on the surface that affect the flow of water such as buildings, roads, ditches, swales, dams, etc. Since data presented below in Tables are average values, in addition to data developed through research of available detail, it is incumbent that - before selecting values for "C " - the engineer make a field investigation of the project site to determine the ***existing*** characteristics of the watershed to assure his/her engineering judgment adequately considers the appropriate factors influencing the determination of an appropriate "C" for the watershed. Also, inasmuch as the Rational Formula will be used for design of the Storm Drainage System, it is important to note that a different ***future*** "C" must be developed to determine the proper "Q" for sizing of drainage features, e.g. pipes, ditches, etc. considering the land use changes created by the project.

While engineering judgment will always be required in the selection of values for "C", the following provides information regarding soil groups (Table 1), land use (Table 2) and a composite coefficient for more complex watersheds (Table 3).

Regarding **Soil types**, the NRCS data (available in each US County's Soil Survey) provides information on infiltration rates and has divided soil groups into 4 hydrologic categories, as follows:

Group A – Soils with ***low*** runoff potential due to high infiltration rates- primarily deep well drained ***sands and gravels***.

Group B – Soils *with* ***moderately low*** runoff potential due to moderate infiltration rates – primarily moderately deep to deep, moderately well drained with moderately fine to moderately coarse textures, e.g. ***silt or sandy silt.***

Group C – Soils having ***moderately high*** runoff potential due to slow infiltration rates – primarily of soils where the a layer exists near the surface that impedes the infiltration of water or soils with moderately fine to fine texture,. E.g*.* ***sandy clay or silty clay.***

Group D – Soils having ***high*** runoff potential due to very slow infiltration rates – ***clays*** with high swelling potential, soils with permanently high water tables, soils with a claypan or clay liner near the surface and shallow soils over nearly impervious parent material.

TABLE 1

Recommended “C” values by Soil Groups

Slopes	A	B	C	D
Flat (0-1%)	0.04-0.09	0.07- 0.12	0.11-0.16	0.15-0.20
Average (2-6%)	0.09-0.14	0.12-0.17	0.16-0.21	0.20-0.25
Steep (over 6%)	0.12-0.16	0.16-0.20	0.19-0.25	0.24-0.30

This table is quite valuable and is usually used in the design of cross culverts, channels or interceptor ditches for roads.

Regarding **Land Use** - As unimproved areas are developed, increased runoff can be expected due to loss of vegetative cover, the reduction of retention by surface depressions and the increase of impervious surface areas.

TABLE 2

Recommended “C” Values by Selected Land Uses

Description of Area	Coefficients
Business: Downtown	0.70 – 0.95
Neighborhood areas	0.50 – 0.70
Residential: Single family	0.30 – 0.50
Multi units (detached)	0.40 – 0.60
Multi units (attached)	0.60 – 0.75
Suburban	0.25 – 0.40
Residential (1.2 ac, lots or more)	0.30 – 0.45
Apartment dwelling areas	0.50 – 0.70
Industrial: Light areas	0.50 – 0.80
Heavy Areas	0.60 – 0.90
Parks, Cemeteries	0.10 – 0.25
Playgrounds	0.20 – 0.40
Railroad yards areas	0.20 – 0.40
Unimproved areas	0.10 – 0.30

Regarding **Complex Watersheds**, studies to define “C” have determined typical values of relative imperviousness relative to the type of surface, as shown in Table 3.

TABLE 3

Values of Runoff Coefficient (C) for Rational Formula

Land Use	C	Land Use	C
Business: Downtown areas Neighborhood areas	0.70 - 0.95 0.50 - 0.70	***Lawns:*** Sandy soil, flat, 2% Sandy soil, avg., 2-7% Sandy soil, steep, 7% Heavy soil, flat, 2% Heavy soil, avg., 2-7% Heavy soil, steep, 7%	0.05 - 0.10 0.10 - 0.15 0.15 - 0.20 0.13 - 0.17 0.18 - 0.22 0.25 - 0.35

Residential:
Single-family areas
Multi units, detached
Multi units, attached
Suburban
	0.30 - 0.50
	0.40 - 0.60
	0.60 - 0.75
	0.25 - 0.40
		Agricultural land:
		Bare packed soil
		*Smooth
		*Rough
		Cultivated rows
		*Heavy soil, no crop
		*Heavy soil, with crop
		*Sandy soil, no crop
		*Sandy soil, with crop
		Pasture
		*Heavy soil
		*Sandy soil
		Woodlands
			0.30 - 0.60
			0.20 - 0.50
			0.30 - 0.60
			0.20 - 0.50
			0.20 - 0.40
			0.10 - 0.25
			0.15 - 0.45
			0.05 - 0.25
			0.05 - 0.25

Industrial: Light areas Heavy areas	0.50 - 0.80 0.60 - 0.90	*Streets:* Asphaltic Concrete Brick	0.70 - 0.95 0.80 - 0.95 0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

***Note:** The designer must use judgment to select the appropriate "C" value within the ranges noted above. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lower "C" values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the higher "C" values.

For storms of 2-year to 10-year frequencies the values in Tables 1-3 are applicable. However, other studies have indicated that less frequent, higher intensity storms will require modification of the runoff because infiltration and other losses have a proportionally smaller effect on runoff. (Wright – McLaughlin, 1969). The adjustment of the formula with major storms can be made by multiplying the right side of the formula by a frequency factor C_f. The Rational formula now becomes $Q = CC_f IA$.

C_f values are listed in Table 4.

TABLE 4

Recurrence Interval (years)	C_f
25	1.1
50	1.2
100	1.25

In areas where several different values of "C" occur in subareas, a Compound value for C_c must be calculated. This is accomplished by dividing the sum of the C's for the various subareas of the drainage areas by the total drainage area. It is noteworthy that most hydrologists will select higher values of "C" to assure the peak flow contains all runoff from the drainage area and to insure there is an adequate safety factor in the event of storms larger than that selected for the analysis.

Sample Computation:

FIND C_c

In a total drainage area of 8.7 acres, 6.2 acres are forest (C = 0.25), 2.4 acres are lawn (heavy soil flat, avg; C = 0.20) and there is an asphalt paved road 24' wide by 185' long = 0.1 ac, (C = 0.90) crossing the drainage area.

C_c = (6.2 ac x 0.25) + (2.4 ac x 0.20) + (0.1 ac x 0.90) / 8.7 ac = 2.12 / 8.7=0.24

- Parameter "I"

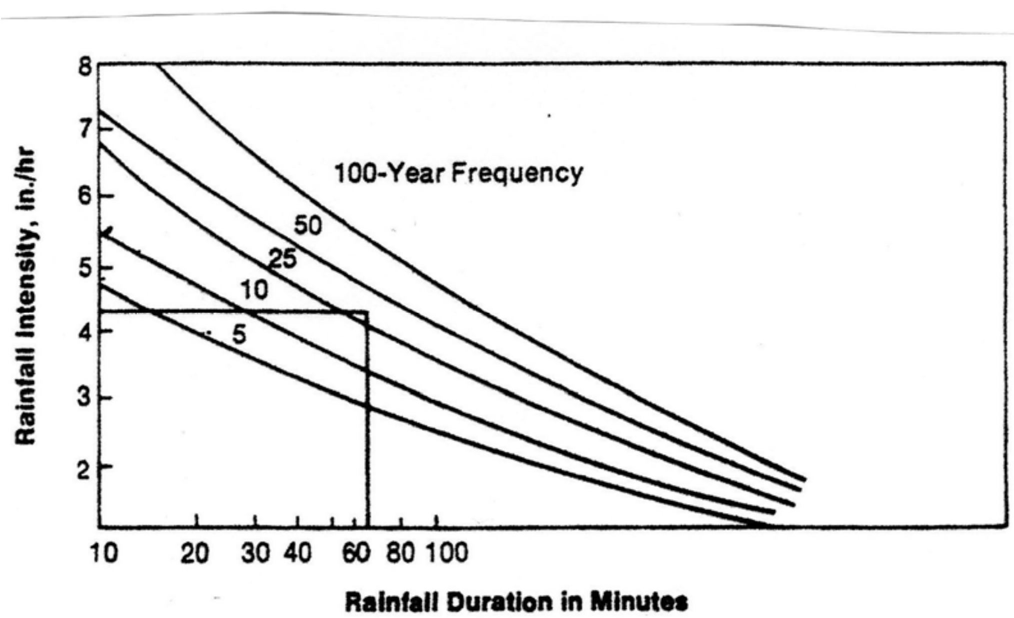
"I" is determined by rainfall Intensity-Duration Frequency (IDF) curves which are derived from the statistical analysis of rainfall records compiled over a number of years. Each curve represents the intensity-time relationship for a certain return frequency (e.g. 25 years) from a series of storms. These curves are then said to represent storms of a specific return frequency. The intensity, (i.e. the rate of rainfall), is usually expressed in depth per unit time (inches per hour) with the highest intensities occurring over short time intervals and progressively decreasing as the time intervals increase. The greater intensity of the storm, the lesser their recurrence

frequency, thus the highest intensity for a specific duration for "n" years of records, is called the "n" year storm frequency of once in "n" years.
It is important to understand that the return - recurrence of a storm (normally expressed in terms of frequency- e.g. once in "n" years), is based on a probability analysis of long term climatological data and does **NOT** indicate that a storm of say "once in ten years" will not happen again for another 10 years. In fact, storms of any selected frequency can, and often do, occur several times in a single year.

The IDF curves ***do not*** represent a rainfall pattern but are the highest distribution of the highest intensities over time durations from a storm of "n" frequency. Figure 1 is a graph giving **average** Rainfall Intensities for IDF Curves for various storm frequencies vs. rainfall durations. It is noteworthy that these average curves may not be truly representative of regional conditions and that many local agencies (e.g. Highway Departments) have developed curves for specific regions of the areas they serve.

Figure 1

Intensity-Duration Frequency Curve



- Parameter "A"

"A" is the drainage area as determined by topography and includes all land where rainfall runoff would be directed towards the selected point of analysis. This area is identified by selecting the boundary of land defined by the highest contours of the watershed to the point of analysis, and measuring the area within that boundary. "A" is expressed in acres. The determination of this watershed drainage area must be determined from an adequate topographic map. Usually a USGS Quad sheet (available in many local retail outlets) which are printed at a scale of 1 inch = 2000 feet and have contour intervals of 20 feet is adequate if no specific project topographic mapping is available.

"A" can be determined either with a computer program or manually. It is usually determined in square feet or square miles and converted to acres. Note: 43,560 sq. ft = 1 acre; 1 sq. mi = 640 acres.

SAMPLE COMPUTATION:

FIND: PEAK Q:

For a Drainage Area of 8.7 acres with, 6.2 acres are forest, 2.4 acres are lawn ((heavy soil, flat) and there is an asphalt paved road 24' wide by 185' long (= 0.1 ac) crossing the drainage area.

"C_c" = 0.24 (per sample computation above)

"I" for a 10-year storm of 20 minutes duration (per Figure 1) = 4.8 inches per hour.

"A" = 8.7 acres

$Q = C_c \times I \times A = 0.24 \times 4.8 \times 8.7 = 10.0$ cubic feet per second at the point of analysis.

Summary

This chapter provides a basic discussion of the Rational Formula and its use, and you have learned how to calculate the peak discharges from small drainage areas.

CHAPTER 2 OVERVIEW

Applying Rational Formula to Design

Standard Design Procedures for Drainage Pipes

Use of Rational Formula for Culverts

Standard Design Procedures for Ditches

Determining Ditch Configuration and Size

Ditch Protection

Need for Headwalls

Innovative System Components

Checks for Acceptability of Facility Design

Maintenance Requirements

Learning Objectives

- To understand the basics of the design of Storm Water Management Facilities
- To be introduced to a practical approach to designing Storm Water Management Facilities
- To recognize design formula's applicability and limitations
- To be able to derive appropriate parameter values
- To be aware of special considerations
- To perform calculations for use in design of Storm Water Management Facilities
- To select appropriate components of Storm Water Management Facilities
- To perform checks for acceptability and maintenance requirements

General

The derivation of peak quantity discharge (Q) of rainfall runoff from a selected drainage area by use of the Rational Formula was described in Chapter 1. The goal of Chapter 2 is to provide necessary information to lead a Design Engineer from the derivation of peak runoff to the design of a Storm Water System capable of intercepting the peak flow and delivering it to an adequate point of disposal/recycling. Design of this system should include consideration of economy (including the cost of material and delivery), environmental restraints, commercially available products, maintenance requirements and construction procedures. It also must be responsive to the requirements of any permit conditions, and recognize new and innovative features, such as those suggested by LID (Low Impact Development) and LEED (Leadership in Energy and Environmental Design) principles.

It is noteworthy that in response to Federal and State legislation, recent years have seen an explosion of new products being made available on the market to address storm water systems. The designer should conduct adequate research on available products before initiating other design actions.

To satisfactorily design the storm water drainage facilities, details of the project plan must be known including locations of buildings, pavements, utilities, retaining walls, landscaping and other facilities that will impact drainage patterns. Also the needed earthwork, grading and sediment control plans must be available.

It is not unusual for contaminants to be introduced to storm water runoff, and these contaminants must be given special consideration in the design, construction, operation and maintenance of storm water drainage systems to assure they do not adversely affect either the project or the receiving stream where the runoff will be ultimately disposed. Frequent sources of such contaminants are construction generated sediment, spills of fuel or other hazardous materials, residual grease and oil from vehicles which has washed from roadways, wash water from concrete mix trucks or from floor washing at commercial or industrial facilities. Careful attention to these matters should be made in the design process by providing plans and specifications for addressing these potential conditions via regulations of construction practices, special filters, separators, compliance with Federal, State, and local requirements for handling and reporting spills, and acquiring and complying with all required permit conditions.

Applying Rational Formula to Design

It should be recognized the there are several acceptable methods for determining peak runoff discharges. Any of these can and are routinely used to design Storm Water Management facilities. The Rational Formula, however, is simple, convenient and widely used to design systems that are consistent with the formula's applicability and limitations as learned earlier. This lesson provides standard design procedures regardless of the method used for determining "Q", and while it can use "Qs" determined by the Rational Formula, it is not specifically related singly to that Formula unless otherwise noted.

Standard Design Procedures for Drainage Pipes

Storm water drainage pipes usually depend on gravity flow since the flow is varied and spasmodic. Only in very special cases would pressure flow be required. The following discussion relates only to gravity flow.

Manning's Equation (published in 1890) is the primary Design Equation used for pipe and/or ditch/channel design. The formula solves for Velocity and (in English Units) is $V = (1.486/n)\ R^{2/3}\ S^{1/2}$. Velocity (V) is measured in "feet per second" (fps), "n" is a unitless number known as the roughness coefficient, R is the Hydraulic Radius, measured in feet as the ratio of the cross sectional Area to Wetted Perimeter (A/wp), S is slope in feet per foot.

Exhibit 1 can be used to determine “two-thirds power” for R.

A. nomograph is provided as Exhibit 2 for ease in using the Manning Formula.

The Design Engineer needs first to decide the type and pipe material based on economic and availability considerations. It should be noted that (due to market conditions) some commercial sizes and types may not always be available locally in the project area. The type of pipe material chosen will determine the “n” value. Average values of “n” have been determined by studies and are always susceptible to additions or modifications as new products are developed. Table 1 gives current “n” values for pipes of various materials as listed in leading publications, but it is a good idea to design using the manufacturer’s “n” values.

TABLE 1

Pipe Material	“n” values
Cast Iron	0.013
Smooth Steel	0.012
Corrugated Metal	0.022
Clay Tile	0.014
Concrete	0.014
Polyvinyl Chloride (PVC)	0.009 - 0.011
Polyethylene (HDPE w/ smooth inner walls)	0.009 - 0.013
Polyethylene (HDPE w/ corrugated inner walls)	0.018 - 0.025

The process for simple pipe sizing is as follows:

1. Assume a pipe size & type (flowing full) and slope
2. Use Manning’s Equation and solve for velocity (V)
3. Check your assumption using the discharge equation (Q=VA)
4. Repeat as necessary to properly size your pipe

This process is explained in further detail:

To calculate the pipe size, first assume a pipe size, then use Manning’s Formula to determine Velocity where the value of R is the Area (in feet) divided by the Wetted Perimeter (the entire surface distance touched by water, in feet). Area of a circular pipe is computed as A = (pi) x radius^2, Wetted Perimeter is the pipe’s circumference if running full (wp = 2 (pi) x radius) or the percentage of circumference if not running full (Area also would need adjusted). S is the slope of the pipe, in feet of rise per foot of run (slope = rise/run). Keep in mind the slope of the pipe can modify results, and in some cases a steeper slope can allow for a smaller pipe. Minimum pipe slopes are typically 0.004 ft/ft, but keep in mind a desirable velocity is at least 2.5 ft/sec, especially in long pipe runs.

After a velocity is calculated from the Manning's Equation, use the standard engineering formula for discharge, Q = VA to check your assumed pipe size. Q is flow rate in cubic feet per second (cfs), often calculated using the Rational Method for a particular drainage area, V is velocity (ft/sec) as calculated, and A is cross sectional area of the flow (square feet). This standard formula applies to all normal fluid flow, not just pipe flow.

The designer can now determine if the pipe size assumed will convey the required flow (Q). If not, another pipe size should be assumed and the process repeated until the assumed pipe size is found which will carry the necessary Q. This process will permit determining the proper size of pipe from those commercially available. Commercial sizes are available from the catalogues of pipe vendors. They are listed by type and pipe diameters.

Since manually calculating these equations can be cumbersome and time consuming, it is noteworthy that there are computer programs that can provide these calculations, and thus allow the Design Engineer the luxury of easier computations and also provide greater opportunities for consideration of alternative designs. A recommended free program is the FHWA Hydraulic Toolbox, found at: https://www.fhwa.dot.gov/engineering/hydraulics/software.cfm.

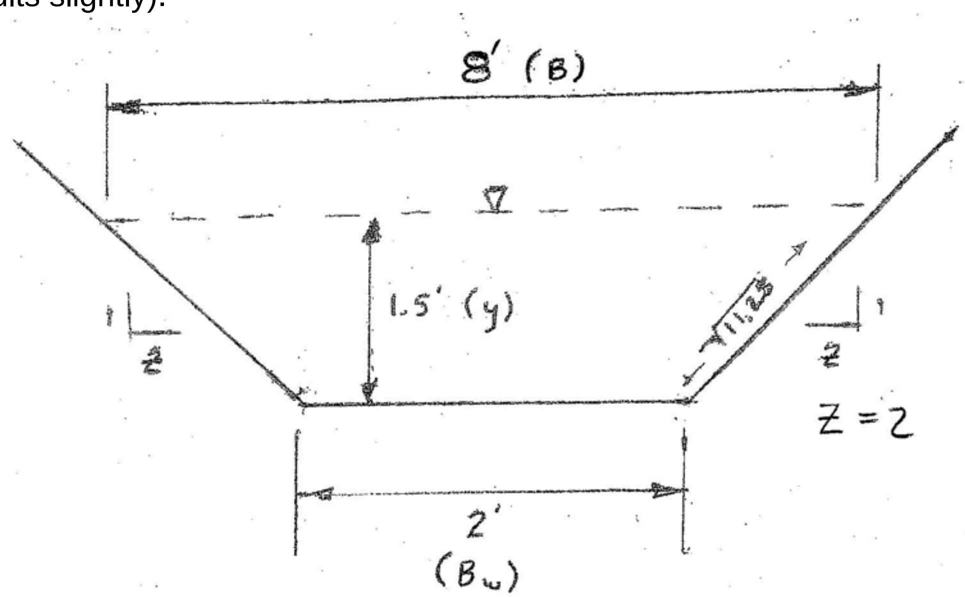
Catch Basins or drop Inlets are often necessary to accommodate changes to the topography and/or drainage patterns or to required pipe sizes. Their type, locations and sizes are optional with the Design Engineer. Standard designs and sizes of these facilities are commercially available from pipe vendors and minimum dimensions are frequently mandated by State or local regulations. Special models are available in cases where it may be necessary to accommodate foot or bicycle traffic or must be compliant with the "Americans with Disabilities Act" (ADA) i.e. (28 CFR, Part 36) requirements for handicap accessibility. Please keep in mind that the catch basin grate type may restrict flow and this lesson does not cover inlet spacing and flow through grate openings, etc.

Use of Rational Formula and Sizing of Culverts

Due to the larger size of drainage areas (> 200 acres) related to design of culverts for most major highways and road projects, the Rational Formula usually cannot be used. It is, however, quite valuable and is usually used in the design of cross culverts, channels or interceptor ditches for roads. Sizing of such culverts uses the same procedures as described above for drainage pipes. Culvert design must also always consider the weight of pavement and the traffic over the culvert, thus and the amount of earth cover required to protect the culvert's sustained capability to function properly must be addressed including consideration of future increases traffic loads. Manufacturers of culvert pipe materials specify acceptable cover depths.

Standard Design Procedures for Ditches & Channels

The Manning's Equation is also used for design of ditches. The procedure is different only in that the ditch area and wetted perimeter is often controlled by the capability and size of construction equipment. The designer therefore can start with an assumption of ditch configuration and design dimensions with a triangular or trapezoidal cross-sectional area being the most common. For example, say a trapezoidal ditch cross-section is assumed as a 2 foot deep ditch with a bottom width of 2 feet and side slopes of 2 horizontal to 1 vertical (2:1) and expected maximum water depth of 1.5 feet, as shown below, along with geometric calculations, taken from Exhibit 3 (rounding may vary results slightly).



$$\text{Area} = (B_w + zy)\,y$$

$$= (2 + 2 \times 1.5)\,1.5$$

$$= 7.5 \text{ SF}$$

$$R = A/wP$$

$$= 7.5/8.708$$

$$= 0.861'$$

$$wP = Bw + 2y\sqrt{1+z^2}$$

$$= 2 + 2 \times 1.5\sqrt{1+2^2}$$

$$= 8.708'$$

$$R^{2/3} = 0.905$$

Using the Manning's Equation with a proper "n" value (below in Table 2), hydraulic radius (R), and the ditch slope (S), the maximum velocity in the ditch can be computed and using Q = VA the maximum discharge can be calculated and compared with the discharge quantity "Q" from the Rational Formula. The ditch size adjustments can then be made as necessary to accommodate the calculated "Q".

Another option would be to plug in your calculated "Q" and solve for the required area (A) using the calculated velocity (V), to see if your assumed ditch area can handle the calculated "Q" at the given or assumed slope.

TABLE 2

Manning's "n" for Excavated Channels

A. Straight and Uniform

Clean, recently completed................................0.018
Clean, after weathering 0.022
Gravel, uniform section, clean..........................0.025
With short grass, few weeds 0.027

B. Winding and Sluggish

No vegetation 0.025
Grass, some weeds..0.030
Dense weeds, deep channels 0.035
Earth bottom and rubble sides..........................0.030
Stony bottom and weedy banks 0.035
Cobble bottom and clean sides 0.040

C. Channels (not maintained), Weeds & Brush (uncut)

Dense weeds, high as flow depth......................0.080
Clean bottom, brush on sides............................0.050
Same, highest stage of flow 0.070

D. Lined or Built-up Channels

Concrete, trowel finish......................................0.013
Concrete, float finish...0.015
Concrete, unfinished 0.017
Gunite, good section 0.019
Gravel bottom, with sides of:
formed concrete.....................................0.020
random stone in mortar...........................0.023
dry rubble or rip-rap 0.033

Often storm water from drainage systems is ultimately disposed of into a natural stream or channel for which the hydraulic capacity should be checked (unless adequate capacity is obvious. to assure there is adequate capacity for safe passage of all consequential flows (natural and those introduced from the project). Further, it is important to note that many local governments require that improved channels must be designed to preserve the existing capacity of existing flood flows (usually those with a 1% annual chance of occurrence) in addition to the proposed storm water drainage.

Average values for Manning's "n" for Natural Stream Channels are in Table 3.

TABLE 3

Manning's "n" for Natural Stream Channels

A. Fairly Regular Sections	
Some grass & weeds, little or no brush	0.030 - 0.035
Dense growth of weeds, depth of flow higher than weeds	0.035 - 0.050
Some weeds, light brush on banks	0.035 - 0.050
Some weeds, heavy brush on banks	0.050 - 0.070
Some weeds, dense willows on banks	0.060 - 0.080
With trees within channel, branches submerged at high stages:	
Increase all above values	0.010 - 0.020
B. Irregular Sections, with pools, slight channel meander	
Increase all above values	0.010 - 0.020
C. Mountain Streams, no vegetation in channel, banks usually steep, trees and brush along banks, submerged at high stages	
Bottom made of gravel, cobbles and few boulders	0.040 - 0.050
Bottom made of cobbles, with large boulders	0.050 - 0.070

Average values for Manning's "n" for Sheet Flow are in Table 4.

TABLE 4

Manning's "n" for Sheet Flow

Surface Description	n [1/]
Smooth surfaces (concrete, asphalt, gravel or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated Soils:	
Residue cover <20%	0.06
Residue cover >20%	0.17
Grass:	
Short grass prairie	0.15
Dense grass [2/]	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods: [3/]	
Light underbrush	0.40
Dense underbrush	0.80

[1/] The n values are a composite of information compiled by Engman (1968).

[2/] Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

[3/] When selecting "n", consider cover to a height of about 0.1 feet. This is the only part of plant cover that will obstruct sheet flow.

Ditch Protection

Soils by their nature will always erode when they are subjected to high velocity flows in ditches. The degree of erosion depends on the type of soil and the velocity of flow. Flowing water will pick up sediments as it moves, carry them downstream and drop them when velocity slows; thereby creating deposits, such as sand bars, which compromise the ditch's ability to dispose of storm water. Curves in ditch lines are particularly vulnerable to erosive forces. It is very important that ditches be properly protected to assure the adequate, safe passage of water during its complete life cycle.

Table 5 provides examples of **Limiting Water Velocities for Stable Ditches**.

TABLE 5

Material	Clear Water Vel. in ft/sec	Water Transporting Soil Vel. in ft/sec
Fine, sandy soil	1.50	2.50
Silt, loam	2.00	3.00
Ordinary firm loam	2.50	3.50
Clay	3.75	5.00
Cobble and Shingles	5.00	5.50
Shale & Hardpans	6.00	6.00

If the average velocity exceeds that permissible for the particular type of soil, the ditch should be protected from erosion. Grass linings are valuable where grass can be supported. Ditch bottoms may be sodded or seeded with the aid of quick growing grasses, mulches, jute bagging or fiberglass linings. Grass may also be used in combination with other, more rigid types of linings with the grass being on the upper bank.

Table 6 provides examples of **Maximum Velocities in Vegetated-lined Ditches**[1].

TABLE 6

Type of Cover	Slope Range	Maximum Velocities (ft/sec)	
(Uniform, Well Maintained)	%	Erosion Resistant Soil	Easily Eroded Soil
Bermuda Grass	0-5	8	6
	5-10	7	5
	Over 10	6	4
Kentucky Blue Grass, Buffalo Grass	0-5	7	5
	5-10	6	4
	Over 10	5	3
Grass Mixtures	0-5	5	4
	5-10	4	3
Weeping Lovegrass, Kudzu, Alfalfa, Crabgrass	0-5	3.5	2.5

[1] From Engineering Field Manual, USDA, Soil Conservation Service, 1979

NOTE: Use of Kudzu is NOT recommended due to its invasive growth characteristics.

In ditches where vegetation will not suffice, ditches must be lined with rigid material to protect their integrity.

Corrugated steel flumes and pipe spillways are favored especially in wet, unstable or frost heaving soils. Most fabricated or poured channels should be protected against buoyancy and uplift, especially when empty.

Linings may consist of stone - dumped, hand placed or grouted, preferably placed on a filter blanket, gravel or crushed stone.

Asphalt and/or concrete channels are used on many steep, erodible ditches, or high velocity flow situations.

Ditch checks are an effective means of decreasing the velocity and therefore the erodability of the soil.

High velocity at channel exits must be considered, and some provision made to dissipate the excess energy.

It is noteworthy that research is always underway to develop better means of preventing erosion, and product manufacturers are frequently publishing new products and their capabilities for erosion protection.

Need for Headwalls

For the small flows normally experienced with use of the Rational Formula, headwalls are seldom needed. For situations regarding larger culverts, the State's Department of Transportation and sometimes local agencies provide adequate information and design details for their types and requirements for Head Walls. Topography is also a factor on the choice of a headwall design.

Innovative System Components

Recent significant changes are taking place in the research, experimentation, and development of a variety of innovative system components largely related to the desire to capture and re-use storm water or for environmental preservation. New techniques and products are becoming available in quantity. The popular themes are "Rainwater Harvesting", "Pervious Pavement", "Use of Cisterns", "Bio-swales", "Creation of Wetlands", "Drip Irrigation", and "Vegetative Uptake". Even though their use is becoming more acceptable, many are not yet proven effective and are not acceptable to regulatory agencies. Also, soil type is always a prime concern for design. Some products, however, have been thoroughly tested and are approved. Designers should look carefully at available data to decide what, if any, of these devices are appropriate in their proposed system.

NOTE: The design calculations for most of these innovative systems require the determination of the runoff from the "first flush" (typically the first inch of rainfall). Also, the Rational Formula depends on the accuracy of the published IDF curves or rainfall data for the particular location (www.NOAA.gov). The Rational Formula is used for calculating a flow rate, or "Q" value, and many detention or infiltration systems require the calculation of a required volume of storm water, before the soil can accept the water. Keep this distinction in mind when designing a storm system. The NRCS Method (Formerly SCS) is an acceptable design alternative for looking at basin volume considerations, and is not covered in this lesson.

Checks for Acceptability of System Design

Following completion of a preliminary system design the Design Engineer should review the design to assure it represents an acceptable design in view of all related factors including the projected increased flows from future development, local availability of materials, conflicts with planned construction practices, stockpiles, staging areas, ease of construction, ease of maintenance and being acceptable to regulatory agencies.

Maintenance Requirements

Since future maintenance will always be required to keep storm drainage facilities fully operational, the designer should carefully consider the design to assure that maintenance can be carried on in a logical and convenient manner. Often roots or other foreign material obstructions may clog the pipes, and commercially available pipe cleaning methods will be necessary. Pipe breakage will require replacement construction. Consideration of these factors is very important to provide for easier care of the drainage facilities. Also enlarging the pipes in view of future maintenance requirements must be considered and many local ordinances now specify minimum size pipes to permit ease of cleaning.

Ditches should be monitored to locate and rapidly correct any developing problems, towards obstruction of storm water flows e.g. from debris, sand bars, roots, loss of bank protection, etc.

Following construction, the operation and maintenance of all storm water drainage system components should be subjected to vigilance and periodic routine inspections as well as to additional inspections immediately following significant storms. It is prudent in order to assist in providing a long economic life to have a prepared Maintenance Manual of all Stormwater Management System components to keep track of inspections, repairs, expected future conditions, problems, etc.

Summary

This Chapter has provided the information necessary to successfully apply the Rational Formula and its related engineering formulas and accepted parameters to the design of most simple storm water management facilities in common use today.

Table G-7 Two-thirds Powers of Numbers

No	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.000	.046	.074	.097	.117	.136	.153	.170	.186	.201
.1	.215	.229	.243	.256	.269	.282	.295	.307	.319	.331
.2	.342	.353	.364	.375	.386	.397	.407	.418	.428	.438
.3	.448	.458	.468	.477	.487	.497	.506	.515	.525	.534
.4	.543	.552	.561	.570	.578	.587	.596	.604	.613	.622
.5	.630	.638	.647	.655	.663	.671	.679	.687	.695	.703
.6	.711	.719	.727	.735	.743	.750	.758	.765	.773	.781
.7	.788	.796	.803	.811	.818	.825	.832	.840	.847	.855
.8	.862	.869	.876	.883	.890	.897	.904	.911	.918	.925
.9	.932	.939	.946	.953	.960	.966	.973	.980	.987	.993
1.0	1.000	1.007	1.013	1.020	1.027	1.033	1.040	1.046	1.053	1.059
1.1	1.065	1.072	1.078	1.085	1.091	1.097	1.104	1.110	1.117	1.123
1.2	1.129	1.136	1.142	1.148	1.154	1.160	1.167	1.173	1.179	1.185
1.3	1.191	1.197	1.203	1.209	1.215	1.221	1.227	1.233	1.239	1.245
1.4	1.251	1.257	1.263	1.269	1.275	1.281	1.287	1.293	1.299	1.305
1.5	1.310	1.316	1.322	1.328	1.334	1.339	1.345	1.351	1.357	1.362
1.6	1.368	1.374	1.379	1.385	1.391	1.396	1.402	1.408	1.413	1.419
1.7	1.424	1.430	1.436	1.441	1.447	1.452	1.458	1.463	1.469	1.474
1.8	1.480	1.485	1.491	1.496	1.502	1.507	1.513	1.518	1.523	1.529
1.9	1.534	1.539	1.545	1.550	1.556	1.561	1.566	1.571	1.577	1.582
2.0	1.587	1.593	1.598	1.603	1.608	1.613	1.619	1.624	1.629	1.634
2.1	1.639	1.645	1.650	1.655	1.660	1.665	1.671	1.676	1.681	1.686
2.2	1.691	1.697	1.702	1.707	1.712	1.717	1.722	1.727	1.732	1.737
2.3	1.742	1.747	1.752	1.757	1.762	1.767	1.772	1.777	1.782	1.787
2.4	1.792	1.797	1.802	1.807	1.812	1.817	1.822	1.827	1.832	1.837
2.5	1.842	1.847	1.852	1.857	1.862	1.867	1.871	1.876	1.881	1.886
2.6	1.891	1.896	1.900	1.905	1.910	1.915	1.920	1.925	1.929	1.934
2.7	1.939	1.944	1.949	1.953	1.958	1.963	1.968	1.972	1.977	1.982
2.8	1.987	1.992	1.996	2.001	2.006	2.010	2.015	2.020	2.024	2.029
2.9	2.034	2.038	2.043	2.048	2.052	2.057	2.062	2.066	2.071	2.075
3.0	2.080	2.085	2.089	2.094	2.099	2.103	2.108	2.112	2.117	2.122
3.1	2.126	2.131	2.135	2.140	2.144	2.149	2.153	2.158	2.163	2.167
3.2	2.172	2.176	2.180	2.185	2.190	2.194	2.199	2.203	2.208	2.212
3.3	2.217	2.221	2.226	2.230	2.234	2.239	2.243	2.248	2.252	2.257
3.4	2.261	2.265	2.270	2.274	2.279	2.283	2.288	2.292	2.296	2.301
3.5	2.305	2.310	2.314	2.318	2.323	2.327	2.331	2.336	2.340	2.345
3.6	2.349	2.353	2.358	2.362	2.366	2.371	2.375	2.379	2.384	2.388
3.7	2.392	2.397	2.401	2.405	2.409	2.414	2.418	2.422	2.427	2.431
3.8	2.435	2.439	2.444	2.448	2.452	2.457	2.461	2.465	2.469	2.474
3.9	2.478	2.482	2.486	2.490	2.495	2.499	2.503	2.507	2.511	2.516
4.0	2.520	2.524	2.528	2.532	2.537	2.541	2.545	2.549	2.553	2.558
4.1	2.562	2.566	2.570	2.574	2.579	2.583	2.587	2.591	2.595	2.599
4.2	2.603	2.607	2.611	2.616	2.620	2.624	2.628	2.632	2.636	2.640
4.3	2.644	2.648	2.653	2.657	2.661	2.665	2.669	2.673	2.677	2.681
4.4	2.685	2.689	2.693	2.698	2.702	2.706	2.710	2.714	2.718	2.722
4.5	2.726	2.730	2.734	2.738	2.742	2.746	2.750	2.754	2.758	2.762
4.6	2.766	2.770	2.774	2.778	2.782	2.786	2.790	2.794	2.798	2.802
4.7	2.806	2.810	2.814	2.818	2.822	2.826	2.830	2.834	2.838	2.842
4.8	2.846	2.850	2.854	2.858	2.862	2.865	2.869	2.873	2.877	2.881
4.9	2.885	2.889	2.893	2.897	2.901	2.904	2.908	2.912	2.916	2.920

From King's "Handbook of Hydraulics."

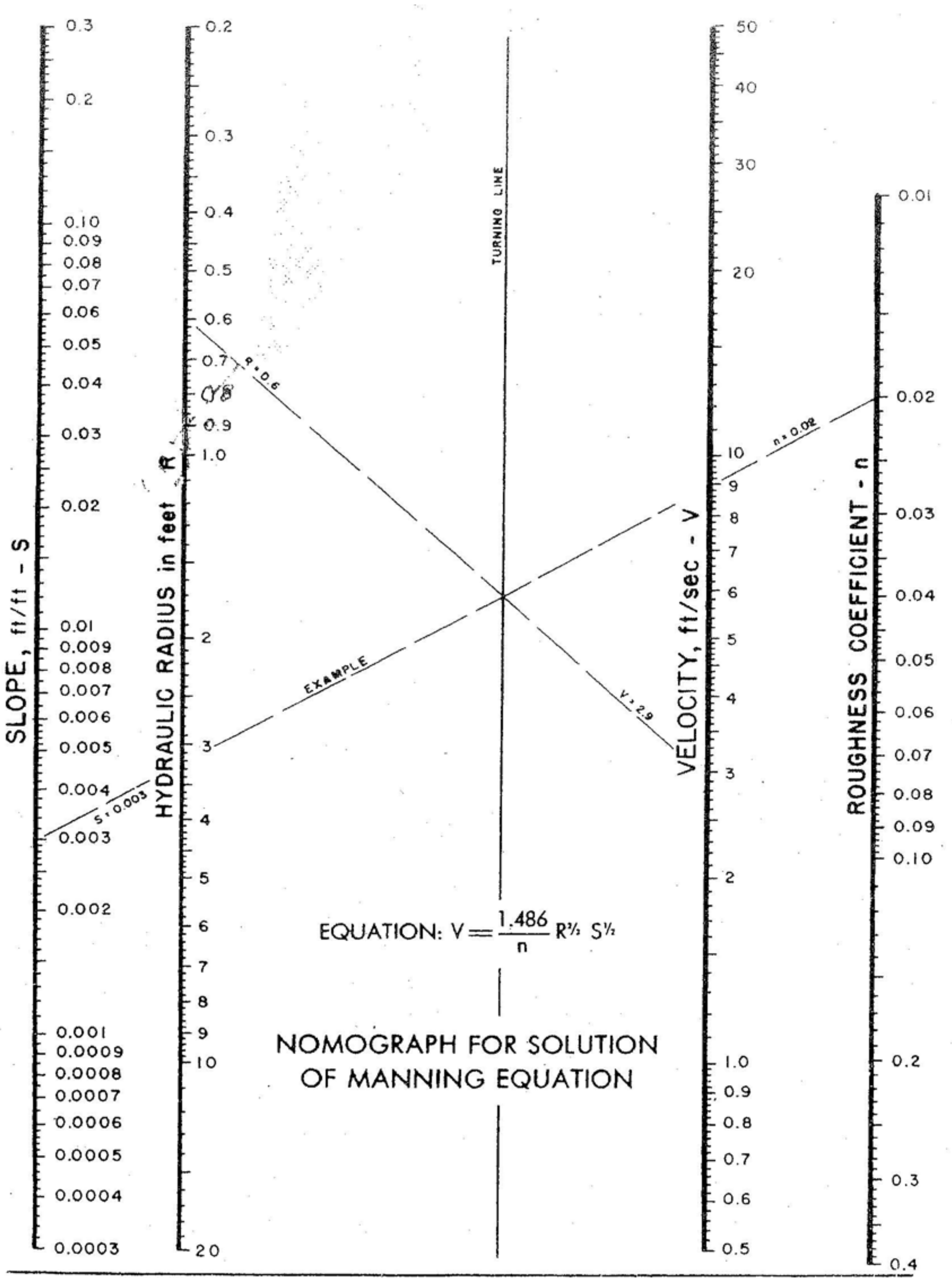
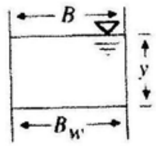
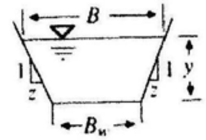
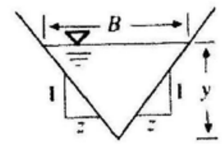
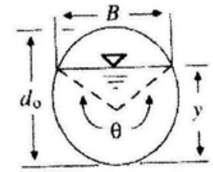

SLOPE, ft/ft - S
HYDRAULIC RADIUS in feet R
TURNING LINE
VELOCITY, ft/sec - V
ROUGHNESS COEFFICIENT - n
0.3
0.2
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2
3
4
5
6
7
8
9
10
20
50
40
30
20
10
9
8
7
6
5
4
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.2
0.3
0.4
S = 0.003
R = 0.6
EXAMPLE
V = 2.9
n = 0.02
EQUATION: $V = \frac{1.486}{n} R^{2/3} S^{1/2}$
NOMOGRAPH FOR SOLUTION
OF MANNING EQUATION

TABLE 5.6.1
Geometric functions for channel elements

Section:	Rectangle	Trapezoid	Triangle	Circle
				
Area A	$B_w y$	$(B_w + zy)y$	zy^2	$\frac{1}{8}(\theta - \sin\theta)d_o^2$
Wetted perimeter P	$B_w + 2y$	$B_w + 2y\sqrt{1+z^2}$	$2y\sqrt{1+z^2}$	$\frac{1}{2}\theta d_o$
Hydraulic radius R	$\frac{B_w y}{B_w + 2y}$	$\frac{(B_w + zy)y}{B_w + 2y\sqrt{1+z^2}}$	$\frac{zy}{2\sqrt{1+z^2}}$	$\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)d_o$
Top width B	B_w	$B_w + 2zy$	$2zy$	$\left[\sin\left(\frac{\theta}{2}\right)\right]d_o$ or $2\sqrt{y(d_o - y)}$
$\frac{2\,dR}{3R\,dy} + \frac{1}{A}\frac{dA}{dy}$	$\frac{5B_w + 6y}{3y(B_w + 2y)}$	$\frac{(B_w + 2zy)(5B_w + 6y\sqrt{1+z^2}) + 4zy^2\sqrt{1+z^2}}{3y(B_w + zy)(B_w + 2y\sqrt{1+z^2})}$	$\frac{8}{3y}$	$\frac{4(2\sin\theta + 3\theta - 5\theta\cos\theta)}{3d_o\theta(\theta - \sin\theta)\sin(\theta/2)}$ where $\theta = 2\cos^{-1}\left(1 - \frac{2y}{d_o}\right)$

Source: Chow, V. T., *Open-Channel Hydraulics*, McGraw-Hill, New York, 1959, Table 2.1, p. 21 (with additions).