A Computer Program for Open Channel Design

M.Sc. Thesis
in
Civil Engineering
University of Gaziantep

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by

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September 2005

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ABSTRACT

A COMPUTER PROGRAM FOR OPEN CHANNEL DESIGN.

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September 2005, 67 pages

In this thesis a computer program (ChannelProfiler) is developed in Visual Basic for calculating some parameters of steady-uniform flow in open channels. This program is able to calculate the parameters such as flow area, wetted perimeter, critical depth, critical slope, top width, velocity, velocity head, specific energy, Froude number, Reynolds number and friction factor for three types of open channel cross-sections. These sections are rectangular, trapezoidal and triangular.

The program is able to calculate the above mentioned parameters by solving three different formulas. These are Manning, Darcy Weisbach and Hazen Williams formulas.

Another future of this program is to calculate the water surface profile in the open channel for the given discharge and slope. The longitudinal distance that the water surface profile will be plotted, is determined by the user.

The program which is developed in this thesis can be used to help engineers who deal with open channel design such as irrigation and drainage channels.

Key Words: Open channel, steady flow, uniform flow, open channel design and water surface profile.

ÖZET

AÇIK KANAL DİZAYNI İÇİN BİR BİLGİSAYAR PROGRAMI

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Yüksek Lisans Tezi, İnş. Müh. Bölümü
Tez Yöneticisi: Yrd. Doç. Dr. Mustafa GÜNAL
Eylül 2005, 67 sayfa

Bu tezde, açık kanallarda ki düzgün-kararlı akımlar için bazı parametrelerin hesaplanmasını sağlayan Visual Basic dilinde bir bilgisayar programı (ChannelProfiler) geliştirildi. Bu program üç çeşit kanal kesiti için kesit alanı, ıslak çevre, kritik derinlik, kritik eğim, üst genişlik, hız, hız yükü, spesifik enerji, Froude sayısı, Reynolds sayısı, sürtünme katsayısı gibi parametreleri hesaplayabilir. Bu kanal kesitleri dikdörtgen, üçgen veya yamuk olabilir.

Program aynı zamanda yukarıda bahsedilen parametrelerin üç farklı formülle hesaplayabilir. Bunlar Manning, Darcy-Weisbach, Hazen-Williams formülüdür.

Bu programın bir başka amacıda açık kanallardaki su yüzey profilini verilen debi ve eğim için hesaplamaktır. Su yüzey profilinin çizileceği kanalın boyuna mesafesi kullanıcı tarafından hesaplanır.

Bu tezde geliştirilen program, sulama ve drenaj kanalları gibi açık kanalların tasarımı ile ilgilenen mühendislere yardım için kullanılabilir.

Anahtar Kelimeler : Açık kanal, kararlı akım, düzgün akım, açık kanal tasarımı ve su yüzey profili.

ACKNOWLEDGEMENTS

I really thanks to my supervisor Asst. Prof. Dr. Mustafa GÜNAL for his guidance, helps, and sharing knowledge.

I want to thanks deeply to Asst. Prof. Dr. Mazen KAVVAS for his helps during writing text of thesis.

I want to thanks deeply to my older brother Mehmet ÖZCAN (İnönü University) for technical support. And also I would like to thank Battal GÖLDAĞ (İnönü University) and Sait VURAL (Mersin University) for their guidance and powerful helps during writing code of program in Visual Basic.

Finally, I would like to thank to my family for their continuous encouragement and stimulation during the period of this study.

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LIST OF SYMBOLS

A	flow area;
C	Chezy coefficient;
F	Froude number;
g	gravitational acceleration;
P	wetted perimeter;
Q	discharge;
Sc	critical slope;
Sf	friction slope;
So	bed slope;
Sy	flow-depth gradient;
T	top width;
x	distance along the channel; and
y	flow depth.
V	the mean velocity in m
R	the hydraulic radius in m
S	the energy slope
dy/dx	flow-depth gradient,
He	Energy head, in meters
E	Maximum height of water surface in meters above "d"
b	Width or bottom width of channel in meters.
r	Radius of channel centreline in meters.
K	Cotangent of bank slope.
d	Depth of flow in meters
Ø	Central angle of curve from B.C. to point of beginning of zone of maximum depth in degrees.
B	Wave angle in degrees
Yc	Critical Depth
p	Pressure

γ	Specific Weight
ν	Kinematic Viscosity
Re	Reynolds Number
z	Elevation above datum
n	Manning's coefficient,
k	the coefficient of units. It is 1.00 for SI units.
f	Friction Coefficient

CHAPTER 1

INTRODUCTION

1.1 GENERAL INFORMATION

It is very important for students or engineers to full understand the methodologies behind hydraulic computations. Once these concepts are learned however, the solution process can become repetitive and tedious-the type of procedure that is well suited to computer analysis.

There are several advantages of using computerized solutions for common hydraulic problems:

1 - The amount of time to perform an analysis can be greatly reduced.

2 - Computer solutions can be more detailed than hand calculations. Performing a solution manually often requires many simplifying assumptions.

3 - The solution process may be less error-prone. Unit conversion and the rewriting of equations to solve for any variable are just two examples of where hand calculations tend to have mistakes, while well-stated computer program avoids these algebraic and numerical errors.

4 - The solution is easily documented and reproducible.

5 - Because of the speed and accuracy of a computer model, more comparisons and design trials can be performed in less time than single computation, would take by hand. This results in the exploration of more design options, which eventually leads to better more efficient designs.(www.haestad.com)

The flow of water in a conduit may be either open channel flow or pipe flow. The two kinds of flow are similar in many ways but differ in one important respect. Open channel flow must have a free surface. A free surface is subject to atmospheric pressure. Flow conditions in open channels are complicated by the fact that the position of the free surface is likely to change with respect to time and space and also by the fact that the depth of flow, the discharges, and the slopes of the channel bottom and of the free surfaces are independent.

Water surface profiles are required for most reservoir projects, both upstream and downstream from the project.

Open channel flow can be classified into many types and described in various ways. We can classify it as steady flow and unsteady flow. Here, time is the criterion. Flow in an open channel is said to be steady if the depth of flow does not change or if it can be assumed to be constant during the time interval under consideration. And the flow is unsteady if the depth changes with time.

Steady flow can be divided into two groups.

1 – Uniform Flow.
2 – Varied Flow.

It was interested with uniform flow. So it was used Steady-Uniform flow for solving open channel design problems by computer program.

1.2 PRINCIPAL OBJECTIVES

In this thesis, a computer program in Visual Basic was developed for a steady flow in open channels. Name of the program developed in this thesis is ChannelProfiler.

The developed program ChannelProfiler allows us to solve open channel problems for the following cross-sections.

1 – Rectangular.
2 – Triangular.
3 – Trapezoidal.

And following formulas can be used to solve problems.

A – Manning’s Formula.
B – Darcy-Weisbach Formula.
C – Hazen-Williams Formula.

ChannelProfiler also draws water surface profile of open channels for gradually varied flow.

1.3 LAYOUT OF THESIS

Text of thesis deals with study on writing a computer program for open channel design and drawing water surface profile. The contents of each chapter can be described as follows.

- Literature survey about open channel design, gradually varied flow and water surface profile are given in chapter 2.
- In chapter 3, general information about open channels, types of open channels and development of uniform flow and its formulas are analysed.
- Chapter 4 deal with gradually varied flow, water surface profiles and its classification.
- In chapter 5, description of ChannelProfiler, used formulas and terms in the program, water surface profile calculation and using of ChannelProfiler are given.
- An example for water surface profile was solved by both hand and ChannelProfiler in chapter 6.
- And chapter 7 interested with discussion of outputs of ChannelProfiler and graphs in research articles.
- In chapter 8, conclusions are outlined about ChannelProfiler and suggestions for future work are discussed.
- In appendix, roughness coefficient values for Manning’s Formula, Hazen-William’s Formula and Darcy-Weisbach Formula are given.

CHAPTER 2

LITERATURE SURVEY

2.1 COMPUTERIZED SOLUTIONS FOR OPEN CHANNELS

Past of the computerized solution is not so far. So in the past engineers designed the open channels by hand with classical formulas. But now we can design open channels easily by using computers.

The program developed in this thesis, can be used to design open channels with steady-uniform flow.

2.1.1 Computer Programs:

The choice of an appropriate method for computing profiles depends upon the following characteristics: the river reach, the type of flow hydrograph, and the study objectives. The gradually varied, steady flow profile computation is used for many studies. However, the selection of the appropriate method is part of the engineering analysis. This section provides information on formulating a hydraulic study and a discussion of the analytical methods in general use. The following sections provide general guidance on the methods and the potential application in reservoir related studies.

The analysis of water surface profile problems is best performed by computer. The basic computational procedure is based on the solution of the energy equation. The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e. hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions). The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be considered in the computations. The steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also, capabilities are available for assessing the change in water surface profiles due to channel improvements, and levees. Special features of the steady flow component include: multiple plan analyses; multiple profile computations; scour computations; and multiple bridge and/or culvert opening analysis (Miyamoto, 2003).

2.2 STEADY FLOW ANALYSIS:

2.2.1 Method Assumptions:

A primary consideration in one-dimensional, gradually varied, steady flow analysis is that flow is assumed to be constant, in time, for the profile computation. Additionally, all the one-dimensional methods require the modeller to define the flow path when defining the cross-sectional data perpendicular to the flow. The basic assumptions of the method are as follows:

(1) Steady flow - depth and velocity at a given location do not vary with time.

(2) Gradually varied flow - depth and velocity change gradually along the length of the water course.

(3) One-dimensional flow - variation of flow characteristics, other than in the direction of the main axis of flow may be neglected, and a single elevation represents the water surface of a cross section perpendicular to the flow.

(4) Channel slope less than 0.1 m/m - because the hydrostatic pressure distribution is computed from the depth of water measure vertically.

(5) Averaged friction slope - the friction loss between cross sections can be estimated by the product of the representative slope and reach length.

(6) Rigid boundary - the flow cross section does not change shape during the flood.

2.2.2 Gradually Varied Steady Flow:

The assumption of gradually varied steady flow for general rainfall and snowmelt floods is generally acceptable. Discharge changes slowly with time and the use of the peak discharge for the steady flow computations can provide a reasonable estimate for the flood profile. Backwater profiles, upstream from a reservoir, are routinely modelled using steady flow profile calculations. However, inflow hydrographs from short duration, high intensity storms, e.g., thunderstorms, may not be adequately modelled assuming steady flow.

2.2.3 Downstream Profile:

Obviously, the downstream profile for a constant reservoir release meets the steady flow condition. Again, the consideration is how rapidly flow changes with time. Hydropower releases for a peaking operation may not be reasonably modelled using steady flow because releases can change from near zero to turbine capacity, and back, in a short time (e.g., minutes) relative to the travel time of the resulting disturbances. Dam-break flood routing is another example of rapidly changing flow which is better modelled with an unsteady flow method.

2.2.4 Flat Stream Profiles:

Another consideration is calculating profiles for very flat streams. When the stream slope is less than 0.0004 m/m, there can be a significant loop in the downstream stage-discharge relationship. Also, the backwater effects from downstream tributaries, or storage, or flow dynamics may strongly attenuate flow. For slopes greater than 0.0009 m/m, steady flow analysis is usually adequate.

2.3 UNSTEADY FLOW ANALYSIS:

2.3.1 Unsteady Flow Methods:

One-dimensional unsteady flow methods require the same assumptions with steady flow, herein, except flow, depth, and velocity can vary with time. Therefore, the primary reason for using unsteady flow methods is to consider the time varying nature of the problem. Examples of previously mentioned rapidly changing flow are thunderstorm floods, hydroelectric peaking operations, and dam-break floods. The second application of unsteady flow analysis consideration, mentioned above, is streams with very flat slopes.

2.3.2 Predicting Downstream Stages:

Another application of unsteady flow is in the prediction of downstream. Reservoirs disrupt the flow of sedistages in river-reservoir systems with tributaries, or lock-ment when they store or slow down water. At the upper and-dam operations where the downstream operations limit of the reservoir, the velocity of inflowing water affects the upstream stage. Flow may not be changing rap- decreases and the ability to transport sediment decreases idly with time, but the downstream changes cause a time and deposition occurs. Herein presents reservoir varying downstream boundary condition that can affect the sediment analysis. Reservoir releases may be sediment upstream stage. Steady flow assumes a unique stage- deficient, which can lead to channel degradation discharge boundary condition that is stable in time.

2.4 MULTIDIMENSIONAL ANALYSIS:

Multidimensional analysis includes both two- and three-dimensional modelling. In river applications, two-dimensional modelling is usually depth-averaged. That is, variables like velocity do not vary with depth, so an average value is computed. For deep reservoirs, the variation of parameters with depth is often important. Two-dimensional models, for deep reservoirs, are usually laterally-averaged. Three-dimensional models are available; however, their applications have mostly been in estuaries where both the lateral and vertical variation is important.

Two-dimensional, depth-averaged analysis is usually performed in limited portions of a study area at the design stage of a project. The typical river-reservoir application requires both the direction and magnitude of velocities. Potential model applications include areas upstream and downstream from reservoir outlets. Additionally, flow around islands, and other obstructions, may require two-dimensional modelling for more detailed design data.

2.5 OTHER WORKS

In a study by LMNO Engineering, Research, and Software, Ltd. fundamental flow equations are first presented, followed by equations for computing the critical depth Y_c and normal depth Y_n. Then, using the input value of Y_s, the GVF profile type is determined and the GVF profile is computed using the Improved Euler method. References for the equations are shown alongside the equations. Manning's equation for Y_n and the equation for the friction slope S_f are empirical; they are shown in the form that uses meters and seconds for units. Units for all other equations can be from any consistent set of units (www.lmnoeng.com).

Richard L. Schaefer writes a computer program which is name BAKWATR. This computer program computes profiles of gradually varied flow in open channels of irregular shape using a microcomputer. Channel cross sections are defined by a series of points outlining the channel boundaries, each having a horizontal and vertical coordinate. The program generates tables of area, hydraulic radius and surface width as functions of flow depth. These tables are then used to determine the depth of flow at each defined cross-section by a standard step method. Results are printed in tabular form and include water surface elevation, depth of flow, cross-sectional area, hydraulic radius, velocity and velocity head at each section, and friction and eddy losses in the reach of channel downstream of each section. Application of the BAKWATR program is limited to steady gradually varied flow behaviour in subcritical flow regimes. Options are provided for establishing the depth of flow at the control section, as BAKWATR can compute the steady flow depth through rectangular weirs and submerged or unsubmerged circular culverts, or the user may input a known depth at the control section for the given flow rate (Schaefer, 1985).

The study by Hitoshi Miyamoto and Kenji Shimoyama concerned behaviour of free surface in turbulent open channel flows. In this study Laboratory experiments were conducted to investigate characteristics of the free surface behaviour and its influences on turbulence structures in an open-channel shear flow.

The main conclusions obtained in this study are as follows.

1. There is a layer near the water surface where the turbulence is strongly affected by the water surface fluctuations. In the surface influence layer, the turbulent flow seems to become parallel to the wavy surface.
2. There is a specific interaction between the surface fluctuation and the large-scale turbulence structure having the same stream wise scale.
3. The stream wise spectrum of water surface fluctuations follows the –10/3 power low.
4. The surface influence layer is approximately less than 20 percent of the mean water depth and its thickness became large as the wavelength of the surface fluctuation increases but small as the Froude number increases (Miyamoto, 2003).

Nabil A. Zaghloul indicates gradually varied flow profile in a study. The Gradually Varied Flow profile in a circular channel section is computed using the Direct Step

Method and the Integration Method. The effect of variable pipe roughness on the length of the profile is investigated. The variation in the profile length ranged from 0.53 to 4.73 depending on the type of the Gradually Varied Flow profile. A computer model is developed to calculate the length of the Gradually Varied Flow profile using the Step and Integration Methods. Variable pipe roughness is used with downward (positive), horizontal and/or adverse bed slopes. The computer model can provide total Gradually Varied Flow length or a detailed x-y calculation. Lotus 1-2-3 print graph, Energraphic and Free Lance graphics capabilities are used to plot the Gradually Varied Flow profiles (Zaghloul, 1992).

In another study a computer model is developed to calculate the gradually varied flow profiles based on the Keifer and Chu approach. Numerical integration using Simpson's rule is adopted. The model can handle positive, horizontal and adverse pipe slopes. The computer model can provide total G.V.F. length or a detailed x-y calculation. Lotus 1-2-3 print-graph capabilities are used to plot the G.V.F. profiles (Zaghloul, 1990).

In a study, most wastewater flow and storm drainage transportation systems consist largely of circular pipes. Gradually varied flow (GVF) conditions predominate in such systems. This article presents a software package based on Lotus 1-2-3 to solve for GVF problems in circular pipes using the direct step method. The results are presented in tabular form. In addition, the Lotus print graph capabilities are used to delineate the GVF profiles (Zaghloul and Marwan, 1993).

World Meteorological Organization developed a program called as WSPRO. The program WSPRO computes water-surface profiles for subcritical, critical, or supercritical flow as long as the flow can be reasonably classified as one-dimensional, gradually-varied, steady flow. WSPRO can be used to analyse open-channel flow, flow through bridges (single or multiple openings), flow through culverts, embankment overflow floodway analysis and bridge scour. The program was developed primarily for evaluating the effects of backwater from existing stream crossings or evaluating alternative bridge openings and/or embankment configurations. The program is applicable to water-surface profile analysis for highway design as well as problems related to floodplain mapping and developing stage-discharge relations. The data input scheme is generally designed for unformatted, order-independent data with the provision of propagation of constant data and limited capabilities for synthesising cross sections. Open-channel computations use standard step-backwater computational techniques. Input data consists of coordinate data defining the cross-sectional shape of the channel, roughness coefficients, flow lengths, discharges, starting water-surface elevations, sub area breakpoints, bridge and culvert geometry and program-control parameters. The initial boundary condition is either the water-surface elevation or energy gradient at either end (downstream for subcritical flow, upstream for supercritical flow) of the study reach for the specified discharge. If it is not specified, WSPRO defaults to the water-surface elevation for critical flow. WSPRO generates output describing the processing of the input data and the results of all profile computations. Tables of cross-sectional properties and/or velocity and conveyance distributions are available except for embankments and culverts. Cross-sectional plots can be produced in digital and line-printer formats. Tables of selected parameters can be defined by the user to produce a specific output format. WSPRO is written in Fortran and has been used on a wide variety of personal computers, workstations, minicomputers, and mainframe computers (Shearman, 1990).

In a study, a new perspective on water-surface profiles is made possible by expressing the gradually varied flow equation in terms of the critical slope S_c. In this way, the flow-depth gradient (dy/dx) is shown to be strictly limited to values *outside* the range encompassed by S_c and S_o, in which S_o is the bed slope. This new perspective improves and completes the definition of flow-depth-gradient ranges in the analysis of water surface profiles. In this article, the GVF equation is alternately expressed in terms of bed slope S_o, critical slope S_c, and Froude number F. Analysis of this equation reveals that the flow-depth gradient dy/dx is strictly limited to values outside the range encompassed by S_c and S_o. This improves and completes the definition of flow-depth-gradient ranges in the analysis of water surface profiles. As a summary the gradually varied flow equation is alternatively expressed in terms of the critical slope S_c. In this way, the flow dept gradient (dy/dx) is shown to be strictly limited to values outside the range encompassed by S_c and S_o. This new perspective completes the definition of depth-gradient ranges for all water surface profiles. For instance, the flow depth gradient for the S_3 profile decreases from S_c (a finite positive value) to 0 (asymptotic to normal depth). Likewise, the flow depth gradient for the C_1 and C_3 profiles is constant and equal to $S_o = S_c$ (Ponce et al., 2002).

In a article indicated that computation of surface profiles for steady gradually varied flow can be accomplished by use of Newton's iteration technique. The magnitude of error is controlled and the profile depth can be conveniently calculated at selected distances upstream or downstream from a control point. A Fortran IV program is provided for utilizing the technique in a trapezoidal channel. Newton Iteration Technique has an advantage over the trapezoidal method by being a more straightforward solution to the integration of the gradually varied flow equation and being computationally more efficient (Fread and Harbaugh, 1971).

In another article the hydraulic design of peripheral channels for circular tanks is based on a solution of the gradually varied flow equation for spatially varied flow. The results are presented in graphical and tabular form with the maximum depth of flow given for the complete range of tank diameters, surface loadings, channel widths and slopes. In addition, typical flow profiles are obtained which show that the maximum depth reduces with increasing bed slope of channel and the position of maximum depth moves downstream towards the outfall as the gradient increases from zero up to 0,5%. By increasing the channel slope zero to 0,5% the maximum depth of flow is typically reduced by approximately 25 to 30 %. The positions of maximum depth of flow for slopes of zero, 0,2% and 0,5% are the upstream end, approximately half way down and approximately three-quarters way down the channel respectively. From the tabulated results, it is possible to obtain the maximum depth of flow in a peripheral channel for a wide range of surface loadings and tank diameters. The peripheral channels are of various slopes and widths, and it is assumed that the discharge from the channel is free flow and not subject to backwater at any time (Anderson, 1996).

In another article mathematical expressions are derived for the hydraulic exponents as functions of the gradually varied flow (GVF) depth using a trapezoidal channel cross-section. An approach is developed utilizing the continuously varying exponents to calculate the GVF length based on several numerical integration approaches, namely four and five points Gaussian quadratures and adaptive Simpson quadrature.

Several applications for various channel bed slopes and GVF depths are presented. An integrated computer program is developed using four and/or five points Gaussian and adaptive Simpson quadratures for the numerical integration. In this article general expressions for varied hydraulic exponents are derived for a trapezoidal channel section. Numerical integration techniques are used to compute the GVF length, namely four and/or five points Gaussian quadratures and adaptive Simpson formula (Zaghloul and Anwar, 1991).

In a study a software package based on the Lotus 1-2-3 is developed to solve the Gradually Varied Flow problem using the direct step method. The information needed (e.g. normal depth, critical depth and G.V.F. depths) is determined first. Flow profile classification is subsequently checked to identify the type of profile. Finally, the profile length is computed and tabulated. In addition, the Lotus printgraph capabilities are used to provide a graphical representation of the G.V.F. profile, the bed slope and the normal and critical depths (Zaghloul and Darwish, 1987).

In a article an idea of using a human-computer interactive program for an engineering design dealing with a nonlinear multisolution problem is introduced. The example shown is a program for a design of a drainage open channel. The hydraulics and geometry equations for triangular or trapezoidal ditches are to be satisfied by the ditch parameters, which are the side slopes SL and SR, the depth d and the width of the bottom Wb. The data are the flow rate Q and the maximum allowable flow velocity. After Wb and one of the slopes for a nonsymmetrical ditch SL are chosen by the designer, the other slope and d may be found as a solution of two nonlinear algebraic equations.

Design procedure: After user types in the data input (Q,S,n and Vmax), the program computes A and WP considering the permissible velocity equal to Vmax. Then, the ditch geometry curves are drawn on the screen after the keys indicating user’s choice of symmetrical or nonsymmetrical ditch are pressed. The coordinates for the curves are calculated only for the following range of ditch parameters: $0 \leq s \leq 5$; $0 < Wb \leq 5$ ft. The range can be changed if necessary. The program assumes a triangular ditch Wb=0 for the flow rate below 60 fps, and a trapezoidal ditch otherwise. At any time the designer may input new data for SL for a nonsymmetrical ditch of any shape or introduce a new value for a trapezoidal ditch, otherwise the program assumes Wb=2 ft, SL = 1 (Kuznetsov, 1988).

CHAPTER 3

OPEN CHANNEL FLOW

3.1 DESCRIPTION

The flow of water in a conduit may be either open channel flow or pipe flow. The two kinds of flow are similar in many ways but differ in one important respect. Open-channel flow must have a free surface, whereas pipe flow has none, since the water must fill the whole conduit. A free surface is subject to atmospheric pressure. Pipe flow, being confined in a closed conduit, exerts no direct atmospheric pressure but hydraulic pressure only. The flow in a closed conduit is not necessarily pipe flow. It must be classified as open-channel flow if it has a free surface. The storm sewer, for example, which is a closed conduit, is generally designed for open-channel flow because the flow in the sewer is expected to maintain a free surface most of the time.(Chow, 1959)

Flow conditions in open channels are complicated by the fact that the position of the free surface is likely to change with respect to time and space and also by the fact that the depth of flow, the discharge, and the slopes of the channel bottom and of the free surface are interdependent.

Reliable experimental data on flow in open channels are usually difficult to obtain. Furthermore, the physical condition of open channels varies much more widely than that of pipes. In pipes the cross section of flow is fixed, since it is completely defined by the geometry of the conduit.

In open channels the surface varies from that of the polished metal used in testing flumes to that of rough irregular riverbeds. Moreover, the roughness in an open channel varies with the position of the free surface. Therefore, the selection of friction coefficients is attended by greater uncertainty for open channels than for pipes. In general, the treatment of open-channel flow is somewhat more empirical than that of pipe flow. The empirical method is the best available at present and, if cautiously applied, can yield results of practical value.

3.2 TYPES OF FLOW:

Open-channel flow can be classified into many types and described in various ways. The following classification is made according to the change in flow depth with respect to time and space.

Steady Flow and Unsteady Flow: Time as the Criterion. Flow in an open channel is said to be steady if the depth of flow does not change or if it can be assumed to be constant during the time interval under consideration. The flow is unsteady if the depth changes with time. In most open-channel problems it is necessary to study flow behaviour only under steady conditions. If, however, the change in flow condition with respect to time is of major concern, the flow should be treated as unsteady. In floods and surges, for instance, which are typical examples of unsteady flow, the stage of flow changes instantaneously as the waves pass by, and the time element becomes vitally important in the design of control structures.

For any flow, the discharge Q at a channel section is expressed by

$$Q = VA \tag{3.1}$$

In which V is the mean velocity and A is the flow cross-sectional area normal to the direction of the flow, since the mean velocity is defined as the discharge divided by the cross-sectional area.

In most problems of steady flow the discharge is constant throughout the reach of the channel under consideration; in other words, the flow is continuous. Thus, using

$$Q = V_1 A_1 = V_2 A_2 = \ldots \tag{3.2}$$

In which the subscripts designate different channel section. This is the continuity equation for a continuous steady flow.

Eq. (3.2) is obviously invalid, however, where the discharge of a steady flow is no uniform along the channel, that is, where water runs in or out along the course of flow. This type of flow, known as spatially varied or discontinuous flow, is found in roadside gutters, side-channel spillways, and the wash water troughs in filters, the effluent channels around sewage-treatment tanks, and the main drainage channels and feeding channels in irrigation systems.

Uniform Flow and Varied Flow: Space as the Criterion. Open-channel flow is said to be uniform if the depth of flow is the same at every section of the channel. A uniform flow may be steady or unsteady, depending on whether or not the depth changes with time.

Steady uniform flow is the fundamental type of flow treated in open-channel hydraulics. The depth of the flow does not change during the time interval under consideration. Flow is varied if the depth of flow changes along the length of the channel. Varied flow may be either steady or unsteady. Since unsteady uniform flow is rare, the term “unsteady flow” is used hereafter to designate unsteady varied flow exclusively. Varied flow may be further classified as either rapidly or gradually varied. The flow is rapidly varied if the depth changes abruptly over a comparatively short distance; otherwise, it is gradually varied. A rapidly varied flow is also known as a local phenomenon; examples are the hydraulic jump and hydraulic drop.

For clarity, the classification of open-channel flow is summarized as follows:

A. Steady flow
   1. Uniform flow
   2. Varied flow
      a. Gradually varied flow
      b. Rapidly varied flow
B. Unsteady flow
   1. Unsteady uniform flow (rare)
   2. Unsteady flow (i.e., unsteady flow)
      a. Gradually varied unsteady flow
      b. Rapidly varied unsteady flow

3.3 KINDS OF OPEN CHANNEL

An open channel is a conduit in which water flows with a free surface. Classified according to its origin a channel may be either natural or artificial. Natural channels include all watercourses that exist naturally on the earth, varying in size from tiny hillside rivulets, through brooks, streams, small and large rivers, to tidal estuaries. Underground streams carrying water with a free surface are also considered natural open channels.

The hydraulic properties of natural channels are generally very irregular. In some cases empirical assumptions reasonably consistent with actual observations and experience may be made such that the conditions of flow in these channels become amenable to the analytical treatment of theoretical hydraulics. Artificial channels are those constructed or developed by human effort: navigation channels, power canals, irrigation canals and flumes, drainage ditches, trough spillways, flood ways, log chutes, roadside gutters, etc., as well as model channels that are built in the laboratory for testing purposes.

The hydraulic properties of such channels can be either controlled to the extent desired or designed to meet given requirements. The applications of hydraulic theories to artificial channels will, therefore, produce results fairly close to actual conditions and, hence, are reasonably accurate for practical design purposes.

3.3.1 Channel Geometry:

Artificial channels are usually designed with sections of regular geometric shapes. The trapezoid is the commonest shapes for channels with unlined earth banks, for it provides side slopes for stability. The rectangle and triangle are special cases of the trapezoid. Since the rectangle has vertical sides, it is commonly used for channels built of stable materials, such as lined masonry, rocks, metal, or timber. The triangular section is used only for small ditches, roadside gutters, and laboratory works.

3.4 SPECIFIC ENERGY:

Specific energy in a channel section is defined as the energy per pound of water at any section of a channel measured with respect to the channel bottom. Thus, the specific energy becomes

$$E = d\cos\theta + \frac{\alpha V^2}{2g} \qquad (3.3)$$

Or, for a channel of small slope and $\alpha = 1$,

$$E = y + \frac{V^2}{2g} \qquad (3.4)$$

This indicates that the specific energy is equal to the sum of the depth of water and the velocity head. For simplicity, the following discussion will be based on Eq. (3.4) for a channel of small slope. Since V=Q / A. Eq. (3.4) may be written as;

$$E = y + \frac{Q^2}{2gA^2} \qquad (3.5)$$

It can be seen that, for a given channel section and discharge Q, the specific energy in a channel section is a function of the depth of flow only.

When the depth of flow is plotted against the specific energy for a given channel section and discharge, a specific-energy curve (Figure 3.1) is obtained.

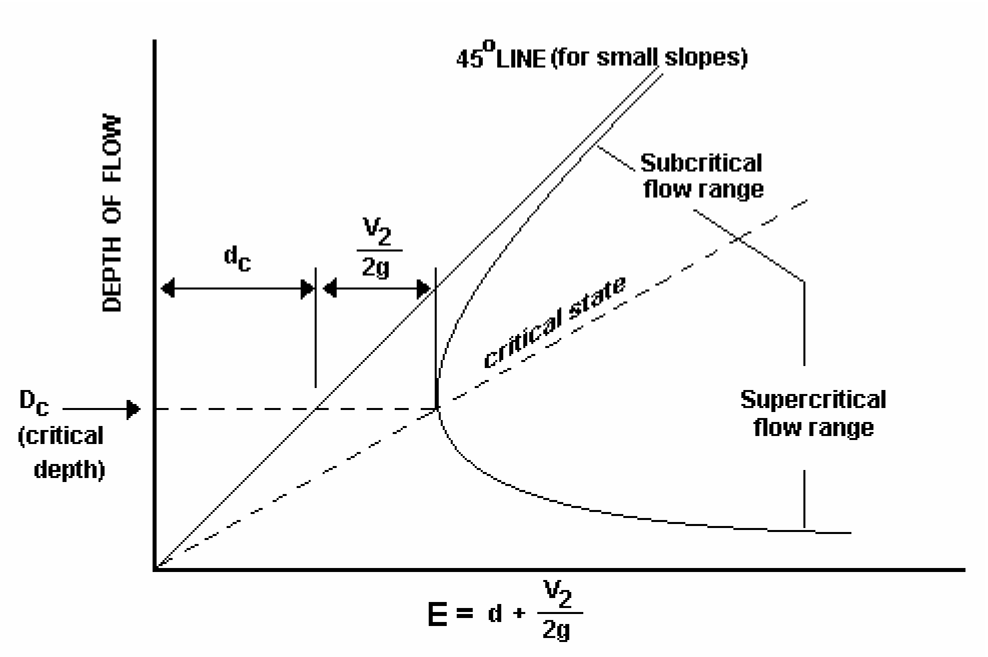


Figure 3.1 Specific-Energy Curve

The curve shows that for a given specific energy there are two possible depths, a high stage and a low stage. These flow depths are called alternate depths. Starting at the upper right of the curve with a large depth and small velocity, the specific energy decreases with a decrease in depth, reaching minimum energy content at a depth of flow known as critical depth. Thus, at the critical state the two alternate depths apparently become one, which is known as the critical depth y_c. When the depth of flow is greater than the critical depth, the velocity of flow is less than the critical velocity for the given discharge, and, hence, the flow is sub critical. When the depth of flow is less than the critical depth, the flow is supercritical. A further decrease in flow depth results in a rapid increase in specific energy.(Highway Design Manual, 2001)

If the discharge changes the specific energy will be changed accordingly. The two curves in Figure 3.1 represent positions of the specific-energy curve when the discharge is less and greater, respectively, than the discharge used for the construction of the curve AB.

3.5 CRITICAL FLOW:

The critical state of flow through a channel section is characterized by several important conditions. Recapitulating, they are:

1 - The specific energy is a minimum for a given discharge.

2 - The discharge is a maximum for a given specific energy.

3 - The specific force is a minimum for a given discharge.

4 -The velocity head is equal to half the hydraulic depth in a channel of small slope.

5 - The Froude number is equal to unity.

6 - The velocity of flow in a channel of small slope with uniform velocity distribution is equal to the celerity of small gravity waves in shallow water caused by local disturbances.

The slope of the channel that sustains a given discharge at a uniform and critical depth is called the critical slope S_c. A slope of the channel less than the critical slope will cause a slower flow of sub critical state for the given discharge, as will be shown later, and, hence, is called a steep or supercritical slope.

A flow at or near the critical state is unstable. This is because a minor change in specific energy at or close to critical state will cause a major change in depth.

If the channel has a supercritical slope, the flow is initially subcritical. If the channel has a supercritical slope, the flow is initially supercritical. When the channel is on a sub critical slope a control section at the downstream and may be a critical section, such as that created on the top of an overflow spillway. On a supercritical slope, the control section at the upstream end may also be a critical section. It should be noted that whether the channel slope is critical, sub critical or supercritical will depend not only on the measure of the actual slope but also on the discharge or the depth of flow.

3.6 DEVELOPMENT OF UNIFORM FLOW AND ITS FORMULAS:

The uniform flow to be considered has the following main features:

1 – The depth, water area, velocity, and discharge at every section of the channel reach are constant

2 - The energy line, water surface, and channel bottom are all parallel; that is, their slopes are all equal, or $S_f = S_w = S_0 = S$. For practical purposes, the requirement of constant velocity may be liberally interpreted as the requirement that the flow possess a constant mean velocity.

Uniform flow is considered to be steady only, since unsteady uniform flow is practically nonexistent. In natural streams, even steady uniform flow is rare, for rivers and streams in natural states scarcely ever experience a strict uniform-flow condition. Despite this deviation from the truth, the uniform-flow condition is frequently assumed in the computation of flow in natural streams. The results obtained from this assumption are understood to be approximate and general, but they offer a relatively simple and satisfactory solution to many practical problems.

It should be noted that uniform flow cannot occur at very high velocities, usually described as ultra rapid. This is because, when uniform flow reaches a certain high velocity, it becomes very unstable. At higher velocities the flow will eventually entrain air and become unsteady.

For purposes of explanation, a long channel is shown with three different slopes: sub critical, critical, and supercritical. At the sub critical slope the water surface in the transitory zone appears undulatory. The flow is uniform in the middle reach of the channel but varied at the two ends. At the critical slope the water surface of the critical flow is unstable.

Expressing the velocity of a uniform flow; for hydraulic computations the mean velocity of a turbulent uniform flow in open channels is usually expressed approximately by a so-called uniform-flow formula.

Most practical uniform-flow formulas can be expressed in the following general form:

$$V = C R^{x} S^{y} \tag{3.6}$$

where;

V : the mean velocity in m

R : the hydraulic radius in m

S : the energy slope

x and y : exponents

C : a factor of flow resistance, varying with the mean velocity, hydraulic radius, channel roughness, viscosity, and many other factors.

For practical purposes, the flow in a natural channel may be assumed uniform under normal conditions, that is, if there are no flood flows or markedly varied flows caused by channel irregularities. In applying the uniform-flow formula to a natural stream, it is understood that the result is very approximate since the flow condition is subject to more uncertain factors than would be involved in a regular artificial channel.

CHAPTER 4

GRADUALLY VARIED FLOW

Gradually varied flow (GVF) is described as a steady state flow condition where the depth of water varies gradually over the length of the channel. Under this condition, the streamlines of flow are practically parallel and therefore, the assumption of hydrostatic pressure distribution is valid and uniform flow principles can be used to analyze the flow conditions.

4.1 GRADUALLY VARIED FLOW EQUATION:

The GVF equation is (Chow 1959-Henderson 1966)

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \left[\frac{\left(Q^2 T\right)}{\left(g A^3\right)} \right]} \tag{4.1}$$

where;

y = flow depth,

x = distance along the channel,

dy/dx = flow-depth gradient,

Q = discharge,

T = top width,

A = flow area, and

g = gravitational acceleration. This equation is valid for small bed slopes, which is usually the case.

S_0= bed slope

S_f= friction slope

The friction slope in terms of the Chezy coefficient *C* is (Chow 1959):

$$S_f = \frac{Q^2}{C^2 A^2 R} \tag{4.2}$$

in which R = A/P means hydraulic radius, and P means wetted perimeter.

The Froude number in terms of discharge is (Chow 1959):

$$F^2 = \frac{Q^2 T}{g A^3} \tag{4.3}$$

Combining Eq (4.2) and (4.3) leads to:

$$S_f = \left(\frac{P}{T}\right)\left(\frac{g}{C^2}\right)F^2 \tag{4.4}$$

At normal critical flow, F = 1, and the critical slope S_c is, from Eq. (4.4),

$$S_c = \left(\frac{P_c}{T_c}\right)\left(\frac{g}{C^2}\right) \tag{4.5}$$

Combining Eq (4.1) – (4.4) – (4.5) :

$$\frac{dy}{dx} = \frac{S_0 - S_c F^2}{1 - F^2} \tag{4.6}$$

Which is strictly valid only as P approaches T, i.e., for a hydraulically wide channel. Then, Eq. (4.6) is an asymptotic solution of steady-gradually-varied flow for hydraulically wide channels.

For ease of expression, the flow-depth gradient $S_y = dy/dx$ is renamed, and solved for Froude number from Eq. (4.6):

$$F^2 = \frac{S_0 - S_y}{S_c - S_y} \tag{4.7}$$

Since $F^2 \geq 0$, the flow-depth gradient *must* satisfy the following inequalities:

$$S_0 \geq S_y \leq S_c$$

$$S_0 \leq S_y \geq S_c$$

This effectively limits the flow-depth gradient to values outside the range encompassed

by S_o and S_c.

Furthermore, Eq. (4.6) can be alternately expressed as follows:

$$\frac{S_y}{S_c} = \frac{(S_0 / S_c) - F^2}{1 - F^2} \tag{4.8}$$

Eq. (4.8) is the GVF equation in terms of bed slope S_o, critical slope S_c, and Froude number **F**. The bed slope could be positive (steep, critical, or mild), zero (horizontal), or negative (adverse). The critical slope (Eq. (4.5)) and Froude number squared (Eq. (4.3)) are always positive. (http://www.Imnoeng.com)

4.2 WATER SURFACE PROFILE

Water surface profiles are required for most reservoir projects, both upstream and downstream from the project. Profile computations upstream from the project define the “backwater” effect due to high reservoir pool levels. The determination of real estate requirements are based on these backwater profiles. Water surface profiles are required downstream to determine channel capacity, flow depths and velocities, and other hydraulic information for evaluation of pre- and post-project conditions.

For the gradually varied flow condition, the depth of flow must be established through a water surface profile analysis. The basic principles in water surface profile analysis are where:

(a) Water surface approaches the uniform depth line asymptotically,

(b) Water surface approaches the critical depth line at a finite angle,

(c) Subcritical flow is controlled from a downstream location, and

(d) Supercritical flow is controlled from an upstream location.

Putting in the dam created a backwater, and it is easy to see why the dam is called a *control section*. Since we know that the depth will be the critical depth (at least somewhere in the vicinity) we can calculate the critical depth from the discharge Q, and the height of the energy line is determined at that point. Nothing we do to the grade line upstream will make the slightest difference to this. Raising the dam will push the backwater upstream, and lowering it will bring the backwater downstream. Also note that we can find the discharge by simply measuring the height of the water on the spillway. This is the principle of using weirs to measure flow quantity.

If, instead of a dam, we simply made a free outfall at the end of the channel, we would again get critical depth in the vicinity. Because of the curvature of the streamlines at the lip of the outfall, the point of critical depth is moved upstream by 3 to 10 times y_c. The actual depth at the lip is about 0.72 y_c. Now the depths are less than the normal depth, and the depth approaches the normal depth from below as we move upstream, instead of from above, as in a backwater. The water surface is now called a *drop-down* curve, and can be calculated in exactly the same way as a backwater curve.

The backwater curve and the drop-down curve on a mild slope are the most commonly observed water profiles. The flow is tranquil or upper-stage. The water level rises when the velocity is retarded, and falls when the velocity is increased. If the initial flow is rapid or lower-stage, then the water level is certainly less than the normal level, as well as the critical depth, and the velocity much greater. The velocity must decrease, since it cannot be supported by the mild slope, and the water level must rise. In this case, however, the water does not placidly go through the critical depth, but before this happens a hydraulic jump occurs that makes a turbulent transition to mild flow at a higher level.

Water profiles can be classified by the relative values of the depth, the normal depth and the critical depth, and whether the slope is mild, steep, critical, horizontal or adverse. There are 12 possibilities, of which we have mentioned the 3 occurring on a mild slope, which are by far the most common. There are 3 kinds of water profile on a steep slope, all of which involve a hydraulic jump here or there. There are only 2 kinds of profiles for the special cases of the slope, which do not differ greatly from those on mild or steep slopes. For example, the drop-down curve for a horizontal grade is just like the one for a mild slope. (http://www.du.edu)

4.2.1 Methods of Analysis:

Two methods of performing a water surface profile analysis are: 1. The Direct Step method 2. The Standard Step method both methods make use of the energy equation to compute the water surface profile. The direct step method can be used to analyze straight prismatic channel sections only. The standard step method is applicable to nonprismatic and non-straight channel alignments.

4.3 CLASSIFICATION OF WATER SURFACE PROFILES:

We use Eq. (4.8) to develop a classification of water surface profiles based solely on the three dimensionless parameters: S_y / S_c , S_o/S_c , and F. For the sake of completeness, subcritical flow is defined as that for which the flow depth is greater than the critical depth ($F^2 < 1$) (Chow 1959; Henderson 1966). Paralleling this widely accepted definition, *subnormal* flow is defined as that for which the flow depth is *greater* than the normal depth [$F^2 < S_o/S_c$]. *Supernormal* flow is defined as that for which the flow depth is *smaller* than the normal depth [$F^2 > S_o/S_c$] (USDA SCS 1971).

Using Eq. (4.8), the following combinations of GVF profiles are possible:

Table 4.1. Type of water surface profiles

	Type 1 Subcritical / Subnormal	Type 2A Supercritical / subnormal	Type 2B Subcritical /Supernormal	Type 3 Supercritical /Supernormal
Steep	S_1	S_2		S_3
Critical	C_1			C_3
Mild	M_1		M_2	M_3
Horizontal			H_2	H_3
Adverse			A_2	A_3

A summary of the twelve possible water surfaces profiles is shown in Table 4.1 The classification follows directly from the Eq. (4.8) shown at the top of the table. It is seen that the general type of profile (Type 1, 2, or 3) determines the sign of S_y / S_c (Column 2) and thus, the classification of either backwater or drawdown (Column 3). Also, the general type of profile determines the feasible range of S_o/S_c (Column 4) and thus, the existence of specific profiles types (Steep, Critical, Mild, Horizontal, or Adverse) within each general type. Note that not all combinations of S_y / S_c and S_o/S_c are feasible.

Unlike the description available in standard references (Chow 1959; Henderson 1966), the flow-depth-gradient ranges (Table 4.1) are now complete for all twelve water surfaces profiles. Significantly, the flow depth gradient S_y is shown to be outside the range encompassed by S_c and S_o. Figure 4.1 shows a graphical representation of flow-depth-gradient ranges in the water surface profiles. The arrow shows the direction of computation. For instance, the depth gradient for the S_3 profile (supercritical/supernormal) decreases from S_c (a finite positive value) to 0 (asymptotic to normal flow). Likewise, the depth gradient for the C_1 (subcritical/subnormal) and C_3 (supercritical/supernormal) profiles is constant and equal to $S_o = S_c$.

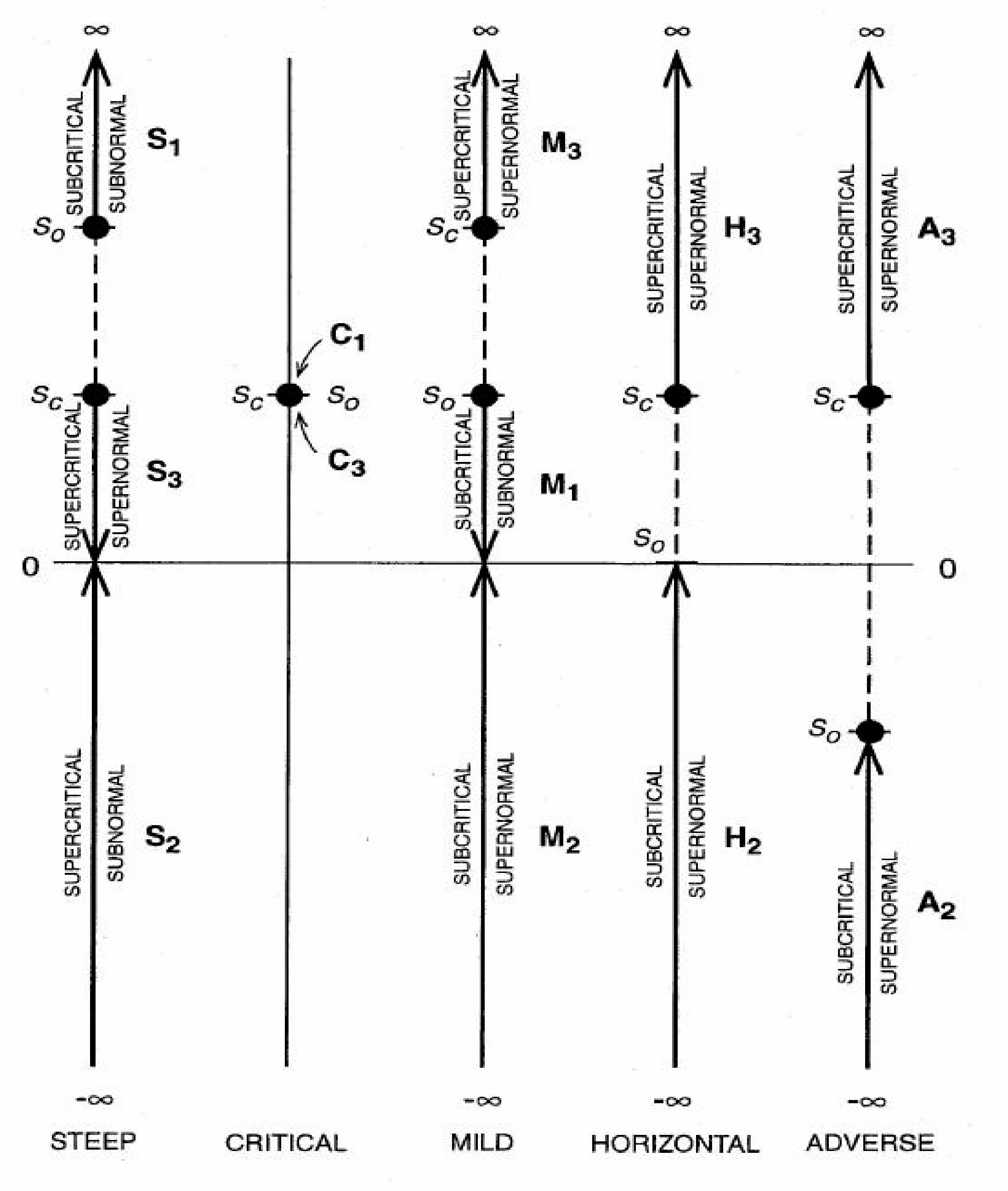


Figure 4.1 Graphic of Flow-Depth-Gradient Ranges in Water Surface Profiles.
(Victor M. Ponce, Anil Lohani, Ampar V. Shetty, 2002)

This thesis deals with steep, critical and mild slopes for open channels. Horizontal and adverse slope are not studied.

4.4 FREEBOARD CONSIDERATIONS:

Freeboard is the extra height of lining above the design depth where overflow is predicted to cause damage. Freeboard allowances will vary with each situation. When the possibility of damage is slight or nonexistent, or where the type of facility is minor, freeboard need not be provided.

4.4.1 Height of Freeboard:

In channels where overflow may cause substantial damage, a guide for freeboard height, for channels on a straight alignment, is provided in Table 4.3.

Table 4.2. Guide to Freeboard Height

Shape of Channel	Subcritical Flow	Supercritical Flow
Rectangular	**0,1 He**	**0,20 d**
Trapezoidal	**0,2 He**	**0,25 d**

Where;

He = Energy head, in meters

d = Depth of flow, in meters for a straight alignment

An unstable zone of flow occurs where the flow is near critical state. This is characterized by random waves. An allowance for waves should be added to the normal depth when the slope of the channel is between 0.7 Sc and 1.3 Sc. Hw = 0.25 dc(1 - 11.1 (S/Sc - 1)2) where Hw = height of wave, in meters dc = critical depth, in meters S = slope of channel, in meter per meters Sc = critical slope, in meter per meters

The height of freeboard discussed above does not provide for superelevation of the water surface on curved alignments. Flow around a curve will result in a rise of the water surface on the outside of the curve and extra lining is necessary to guard against overtopping. Supercritical flow around a curve will cause the water to rise alternately on the outside and inside of the curves due to cross waves. This cross wave pattern may persist for a considerable distance downstream. Extra height of lining must be provided on both sides of the channel. The heights required by this superelevation of the water surface can be computed by the following Soil Conservation Service (SCS) formulas:

- Rectangular Channels.

Subcritical flow $$E = \frac{3V^2 b}{4gr} \tag{4.9}$$

Supercritical flow $$E = \frac{1{,}2V^2 b}{gr} \tag{4.10}$$

$$\phi = \cos^{-1}\left(\frac{r - \frac{b}{2}}{r + \frac{b}{2}} \cos B\right) - B \tag{4.11}$$

- Trapezoidal Channel.

Subcritical flow $$E = \frac{V^2 (b + 2Kd)}{2(gr - 2KV^2)} \tag{4.12}$$

Supercritical flow $$E = \frac{V^2 (b + 2Kd)}{(gr - 2KV^2)} \tag{4.13}$$

Where;

E = Maximum height of water surface in meters above depth "d".

V = Average velocity for the flow cross section in m/s at entrance to curve.

b = Width of rectangular channel or bottom width of trapezoidal channel in meters.

g = Acceleration of gravity = 9.81 m/s^2.

r = Radius of channel centreline in meters.

K = Cotangent of bank slope.

d = Depth of flow in meters for straight alignment at entrance to curve.

Ø = Central angle of curve from B.C. to point of beginning of zone of maximum depth in degrees.

B = Wave angle in degrees, defined as:

$$\sin B = \frac{(gd)^{1/2}}{V} \tag{4.14}$$

Height of freeboard was not calculated in this study.

CHAPTER 5

COMPUTER PROGRAM FOR GRADUALLY VARIED FLOW

ChannelProfiler was established by using Visual Basic Program. The program approximately allocates 3 MB memory in computer. And it works on Windows operating system.

ChannelProfiler is an easy-to-use program that helps civil engineers to design and hydraulic analysis of open channels. To do this, program computes flows and some parameters that are used for open channel design. Program use some well-known equations such as Darcy-Weisbach, Hazen-Williams, Manning’s to compute parameters. The program works when user entering parameters such as roughness coefficient, bed slope, depth, cross-section dimensions, discharge.

In this program, worksheets are created for different shapes such as rectangular, triangular or trapezoidal cross-sections.

User can easily access to the internet and the calculator from the toolbar of the program at any stage of design procedure.

5.1 USED FORMULAS IN THE PROGRAM

5.1.1 The Manning's Formula:

In 1889, the Irish engineer Robert Manning presented a formula, which was later modified to its present well - known form of following equation.

$$V = \frac{k}{n} R^{\left(2/3\right)} S^{\left(1/2\right)} \tag{5.1}$$

Where;
V : the mean velocity in m/s,
R : the hydraulic radius in m,
S : the slope of energy line,
n : the coefficient of roughness, specifically known as Manning's n,
k : the coefficient of units. It is 1.00 for SI units.

The formula was developed from seven different formulas, based on Bazin’s experimental data, and further verified by 170 observations. Owing to its simplicity of form and to the satisfactory results it lends to practical applications, the Manning formula has become the most widely used of all uniform-flow formulas for open channel flow computations.

The custom values for roughness coefficient of Manning’s formula n are listed in Appendix A.

5.1.2 Hazen-Williams Formula:

The Hazen-Williams Formula relates velocity to a C coefficient, hydraulic radius, and friction slope. This formula has been used extensively for flow in water distribution piping (Zipparro, 1993) as;

$$V = 1{,}318\, C R^{0.63} S^{0.54} \qquad (5.2)$$

Where;
C : Hazen-Williams Coefficient
R : Hydraulic Radius (m)
S : Channel Slope (H:V)
V : Velocity (m/s)

The custom values for roughness coefficient C of Hazen-Williams formula are listed in Appendix B.

5.1.3 Darcy-Weisbach Formula:

The Darcy-Weisbach Formula is derived from the Colebrook-White Formula, which computes a friction coefficient based on velocity, kinematic viscosity, hydraulic radius, and absolute roughness or roughness thickness. The Darcy-Weisbach Formula relates velocity to a friction factor, hydraulic radius, and friction slope as follows.

$$V = \left[\sqrt{\frac{8g}{f}} \right] \sqrt{(R\,S)} \qquad (5.3)$$

$$\frac{1}{\sqrt{f}} = 2\log\left(\frac{k}{C_1}\right) R + \frac{2.51}{Re}\sqrt{f} \qquad (5.4)$$

Where;

C_1 : Constant equal to 14.8 for full flow and 12 for open channel flow

f : Friction Coefficient

g : Acceleration due to gravity (m/s^2)

k : Absolute Roughness (m)

R : Hydraulic Radius (m)

Re : Reynolds Number

S : Channel Slope (H:V)

V : Velocity by iterative use of Darcy-Weisbach Formula (m/s)

The custom values for roughness coefficient *k* of Darcy-Weisbach formula are listed in Appendix C.

5.2 WATER SURFACE PROFILE CALCULATION

To compute the water surface profile, the improved Euler method (Chaudhry, 1993) is used. At control section, $i=1$ and $Y_i=Y_s$. Repeat for $i=2$ to n in increments of distance dX . Compute T_i, A_i, and P_i using the fundamental equations using $Y=Y_i$. Compute the friction slope, depth increment, and intermediate depth as

$$S_{f1} = \frac{(n\,Q)^2\, P_i^{4/3}}{A_i^{10/3}} \tag{5.5}$$

$$\left(\frac{dY}{dX}\right)_1 = \frac{S_0 - S_{f1}}{\cos\theta - \frac{T_i\, Q^2}{g\, A_i^3}} \tag{5.6}$$

$$Y_2 = Y_i + \left(\frac{dY}{dX}\right)_1 dX \tag{5.7}$$

Compute T_2, A_2, and P_2 using the fundamental equations with $Y=Y_2$. Then, compute the friction slope based on T_2, A_2, and P_2 followed by computation of a second depth increment. Finally, compute the water depth, Y_{i+1} by using the average of the two differential depth increments (this is the basis of the Improved Euler method).

$$S_{f2} = \frac{(nQ)^2\, P_2^{4/3}}{A_2^{10/3}} \tag{5.8}$$

$$\left(\frac{dY}{dX}\right)_2 = \frac{S_0 - S_{f2}}{\cos\theta - \frac{T_2\, Q^2}{g\, A_2^3}} \tag{5.9}$$

$$Y_{i+1} = Y_i + \frac{\left(\frac{dY}{dX}\right)_1 + \left(\frac{dY}{dX}\right)_2}{2} dX \tag{5.10}$$

Then repeat the loop by incrementing *i*.

5.3 PROGRAM RUNNING

The ChannelProfiler is very easy to use. When the ChannelProfiler executed, a beginning form appears on the screen as;

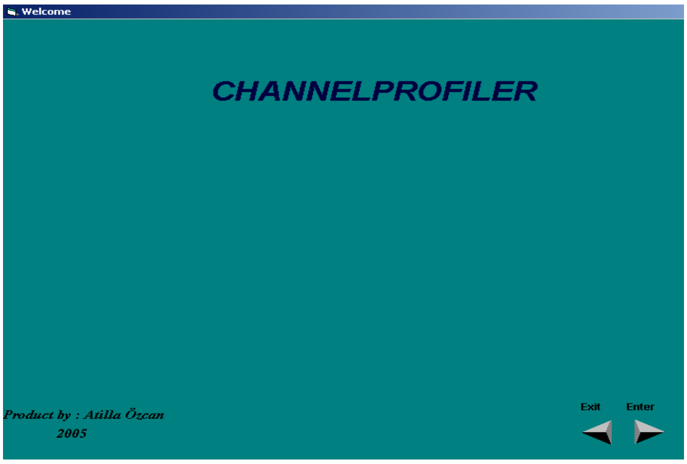


Figure 5.1 Beginning Form.

From this screen, the program can be executed or ended via clicking enter and exit buttons, respectively. If enter button is clicked, basic background form and options form appears on the screen as;

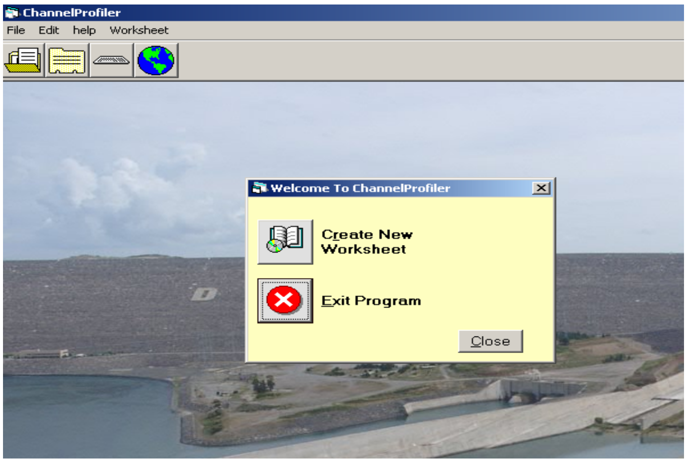


Figure 5.2 Background and Options Forms.

If user wants to open a new project, user can click on *Create New Worksheet button*. Option form can be closed by clicking *Close* button. Also the program can be ended directly by clicking *Exit Program* button.

Steps to solve an open channel problem are described as;

- Click *Worksheet* on menu bar. Then choose *Create* option on worksheet menu, as;

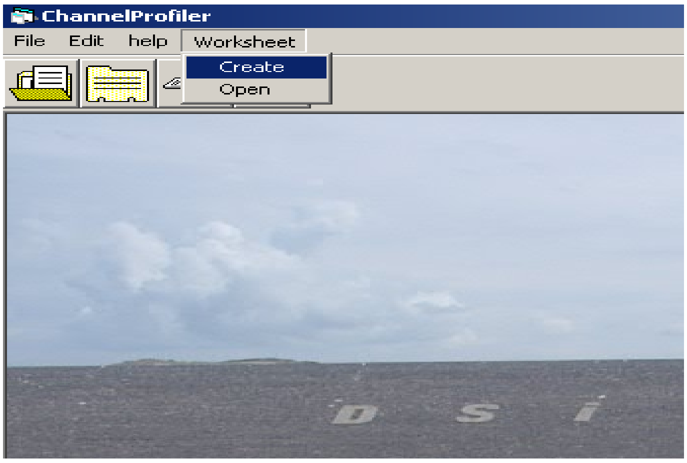
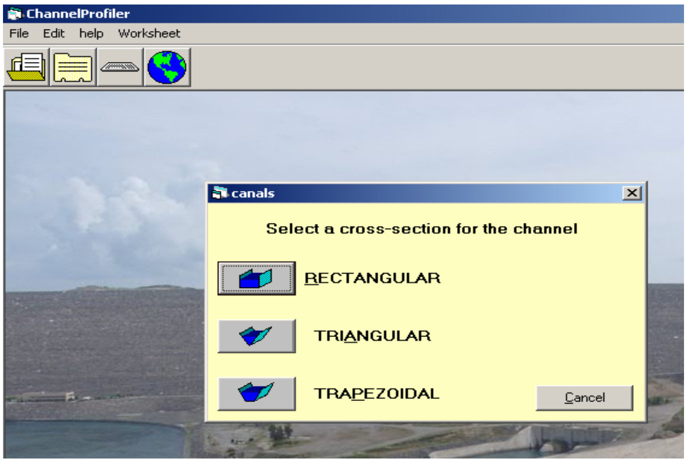


Figure 5.3 Worksheet Menu.

- Then canal cross-section form including rectangular, triangular, or trapezoidal cross-section choices appears on the screen. One of them should be selected to solve the problem, as;



Select a cross-section for the channel

Figure 5.4 Sections of Channels.

- After selection of cross-section another form which allows selecting formula to solve problem appears on the screen.

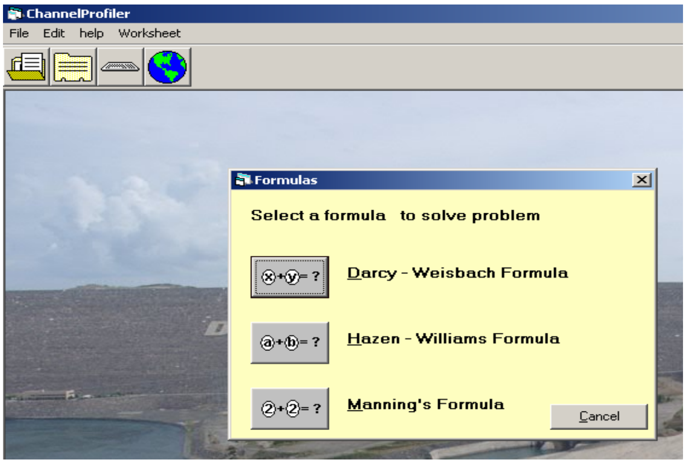
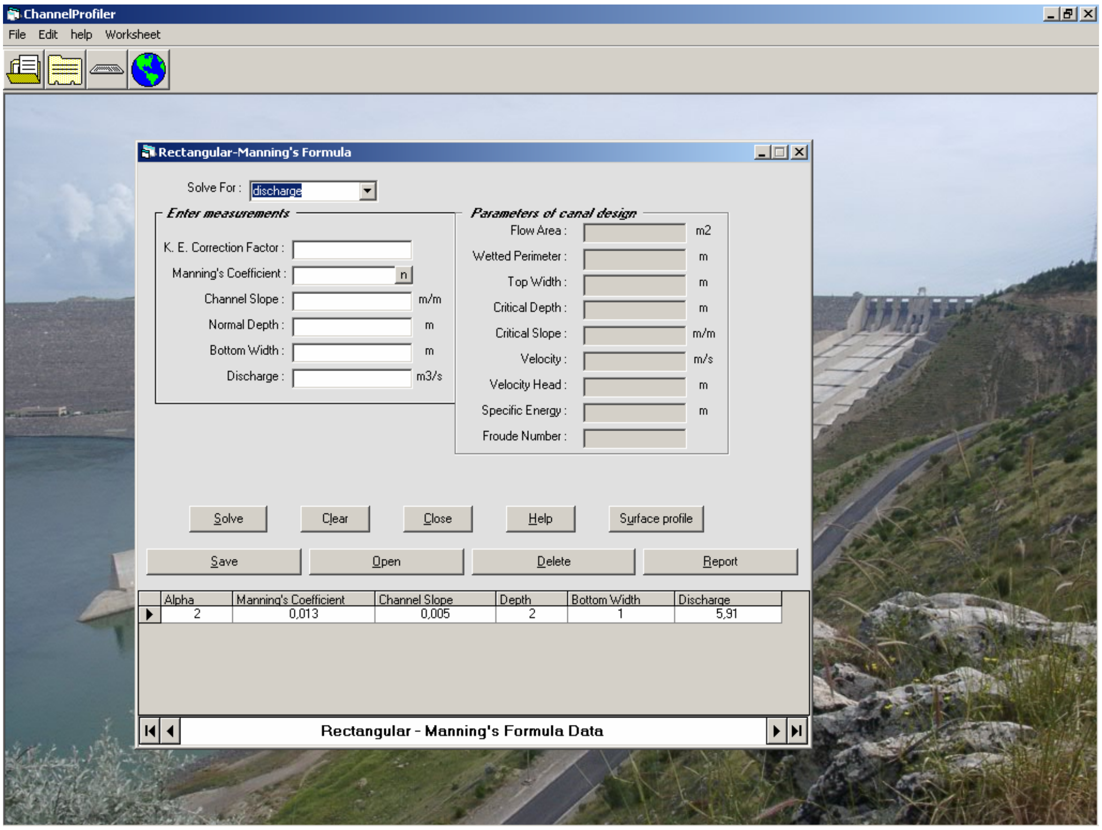


Figure 5.5 Formulas to Solve Problem.

- In this form there are three choices to select a formula to solve your open channel problem. User can choose one of the formulas that are Manning’s Formula, Darcy-Weisbach Formula, Hazen-Williams Formula.
- Then, main input form to solve the problem appears on the screen depends on your section and formula selection. For example, if user selected rectangular section and Manning’s Formula, *Rectangular – Manning’s* form appears on the screen as follows.



Solve For : discharge

	Alpha	Manning's Coefficient	Channel Slope	Depth	Bottom Width	Discharge
▶	2	0,013	0,005	2	1	5,91

Figure 5.6 Rectangular-Manning’s Formula.

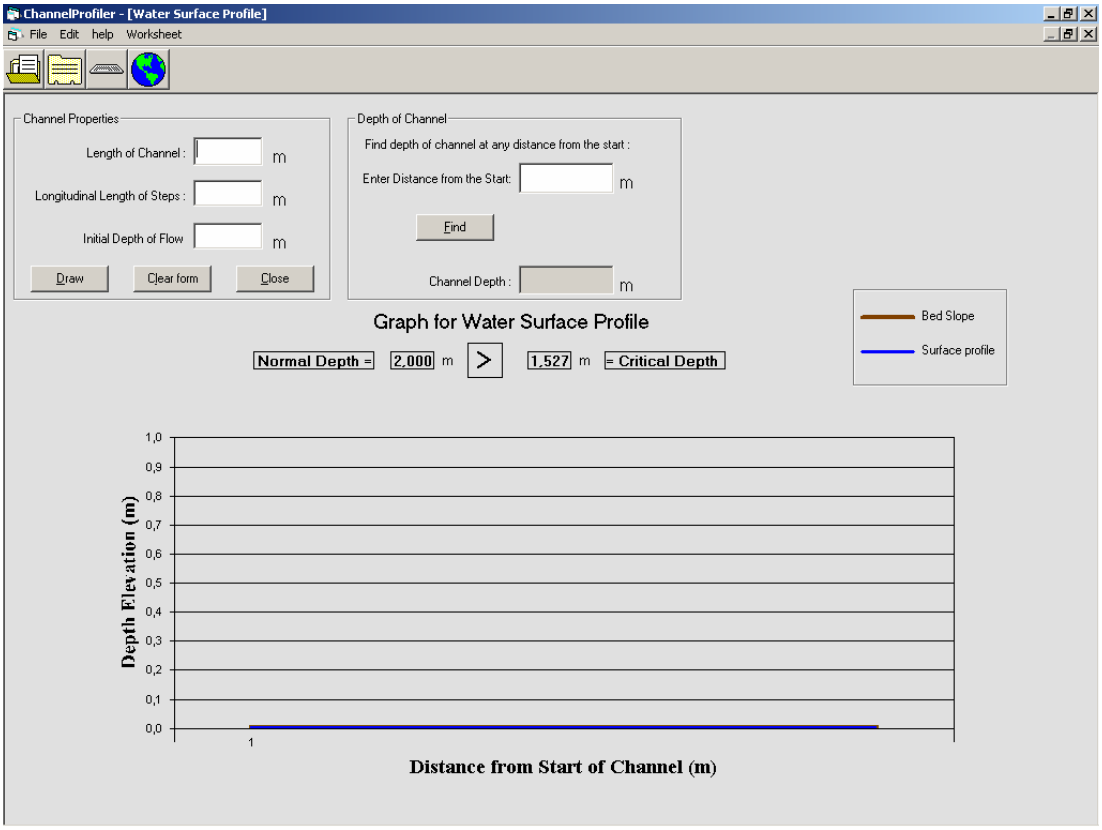
On this form, input parameters are Manning’s coefficient, channel slope, depth, bottom width, discharge and alpha. When user enters known parameters of problem, program will solve some characteristic parameters of open channel. Output parameters of problem are flow area, wetted perimeter, top width, critical depth, critical slope, velocity, velocity head, specific energy, froude number.

When *Clear* button clicked all input and output textboxes cleared. Then another open channel problem can be solved. *Close* button can be used to back basic form of the program. *Help* button open a form including some information about program. *Surface profile* button allows drawing water surface profile for open channel. If inputs want to be recorded *Save* button can be used. And if old saved records can be opened on textboxes by using *Open* button. Also stored records can be deleted by *Delete* button and can be reported by *Report* button.

5.3.1 Water Surface Profile:

The program developed in this thesis can draw water surface profile for given discharge and slope. After solving open channel's parameters such as flow area, wetted perimeter, top width, critical depth, critical slope, velocity, velocity head, specific energy and froude number step by step explained in section 5.4, the water surface profile form can be opened by clicking *surface profile* button to draw water surface profile for the problem. On this form input parameters for problem are Length of channel and Distance for depth calculation.

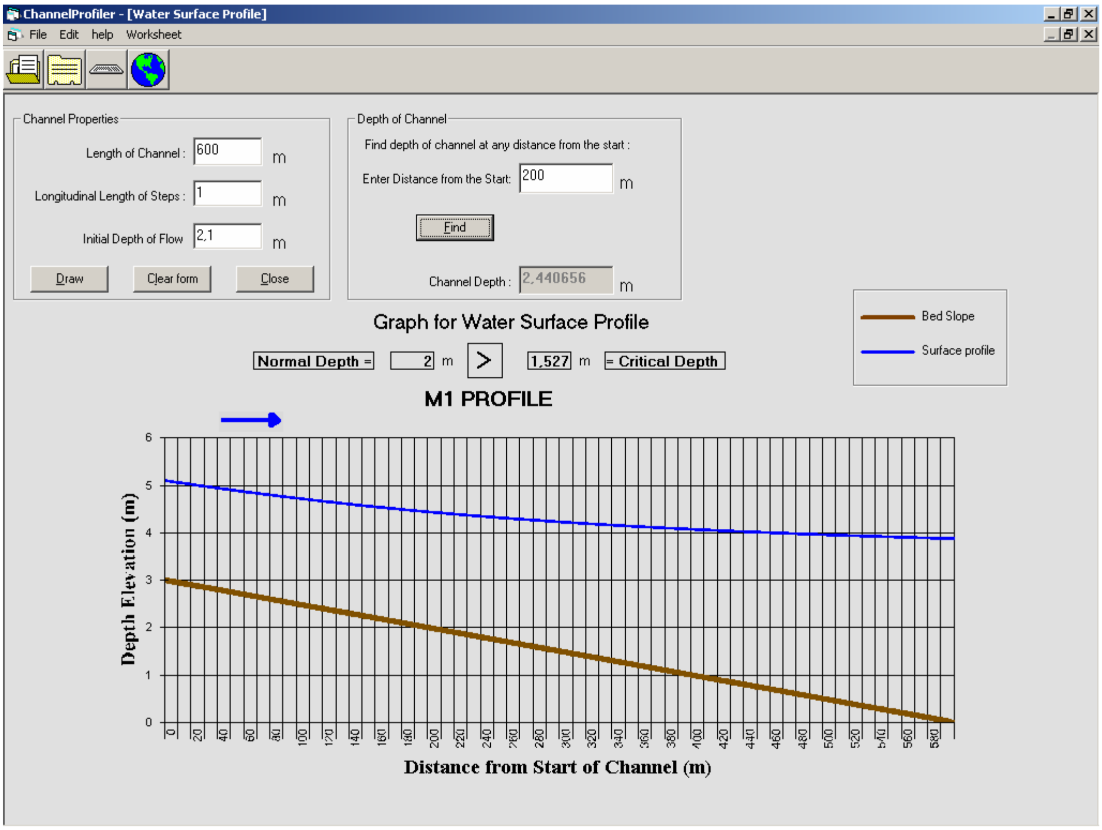
Limits for this program depend on computer hardware. If length of the open channel is so high, the calculation of depth and drawing of graph can take a long time.



Normal Depth = 2,000 m > 1,527 m = Critical Depth

Figure 5.7 Water Surface Profile Drawing Form Before Edit

After entering input parameters that are *length of channel* and *longitudinal length of steps*, and *initial depth for flow*, the graph can be drown by clicking *Draw* button. *Clear* button can be used to clear inputs and drawn graph. And *Close* button can be used to back calculation form for open channel parameters. Another profit of the program is finding water depth through longitudinal length of the channel. To find water depth at any point on channel, *distance from the start* would be entered into the input box and *Find* button would be clicked on *depth of channel* frame.



Length of Channel : 600 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 2,1 m

Find depth of channel at any distance from the start :

Enter Distance from the Start: 200 m

Channel Depth : 2,440656 m

Normal Depth = 2 m > 1,527 m = Critical Depth

M1 PROFILE

Figure 5.8 Water Surface Profile Drawing Form After Edit

CHAPTER 6
DESIGN EXAMPLE

6.1 EXAMPLE 1

An open channel has a cross-section in the form of a trapezium with a bottom width B of 6.1 m and side slopes lss and rss of 1 vertical to 2 horizontal. Assuming that the roughness coefficient n is 0.025, and kinetic energy correction coefficient alpha is 1.

a) Find the volume rate of flow Q using the Manning formula and characteristic parameters of the channel such as flow area, wetted perimeter, top width, critical depth, critical slope, velocity, velocity head, specific energy, Froude number.

b) Draw water surface profile of open channel according to following table.

Table 6.1. Values for Runs

RUN	Slope	Normal Depth y_n	Critical Depth y_c	Limits for Initial Depth y_i	Flow Condition	Profile Classification
I	0.0016	1.024	0.655	$y_i \geq 1.024$ $1.024 > y_i \geq 0.655$ $0.655 > y_i$	$y_i \geq y_n > y_c$ $y_n > y_i \geq y_c$ $y_n > y_c > y_i$	M_1 M_2 M_3
II	0.0078	0.655	0.655	$y_i > 0.655$ $0.655 \geq y_i$	$y_i > y_n = y_c$ $y_n = y_c \geq y_i$	C_1 C_3
III	0.02	0.50	0.655	$y_i \geq 0.655$ $0.655 > y_i > 0.5$ $0.5 \geq y_i$	$y_i \geq y_c > y_n$ $y_c > y_i > y_n$ $y_c > y_n \geq y_i$	S_1 S_2 S_3

6.1.1 Solution by Hand Calculation

a) Width of water surface $= B + (\text{lss} \times D) + (\text{rss} \times D)$

$$= 6.1 + (2 \times 1.024) + (2 \times 1.024) = 10.196 \text{ m}$$

Area of cross-section, $A = B \times D + \left[\text{lss} \times \left(D^2 / 2\right)\right] + \left[\text{rss} \times \left(D^2 / 2\right)\right]$

$$= 6.1 \times 1.024 + \left[2 \times \left(1.024^2/2\right)\right] + \left[2 \times \left(1.024^2/2\right)\right]$$

$$= 8.34 \text{ m}^2$$

Wetted perimeter, $P = B + \left[D \times \left(\sqrt{\text{lss}^2 + 1}\right)\right] + \left[D \times \left(\sqrt{\text{rss}^2 + 1}\right)\right]$

$$= 6.1 + \left[1.024 \times \left(\sqrt{2^2 + 1}\right)\right] + \left[1.024 \times \left(\sqrt{2^2 + 1}\right)\right]$$

$$= 10.68 \text{ m}$$

Volume rate of flow, $Q = A \times \left(\frac{1}{n}\right) \times \left(\frac{A}{P}\right)^{2/3} \times s^{1/2}$

$$= 8.34 \times \frac{1}{0.025} \times \left(\frac{8.34}{10.68}\right)^{2/3} \times (0.0016)^{1/2}$$

$$= 11.32 \text{ m}^3/\text{s}$$

Velocity of water, $V = \frac{Q}{A}$

$$V = \frac{11.32}{8.34}$$

$$V = 1.36 \text{ m/s}$$

Flow area $A = B \times D + \left[\text{lss} \times \left(D^2 / 2\right)\right] + \left[\text{rss} \times \left(D^2 / 2\right)\right]$

$$= 6.1 \times 1.024 + \left[2 \times \left(1.024^2/2\right)\right] + \left[2 \times \left(1.024^2/2\right)\right]$$

$$= 8.34 \text{ m}^2$$

Wetted perimeter $P = B + \left[D \times \left(\sqrt{\text{lss}^2 + 1}\right)\right] + \left[D \times \left(\sqrt{\text{rss}^2 + 1}\right)\right]$

$$= 6.1 + \left[1.024 \times \left(\sqrt{2^2 + 1}\right)\right] + \left[1.024 \times \left(\sqrt{2^2 + 1}\right)\right]$$

$= 10.68\ \mathrm{m}$

Top width $\quad TW = B + (lss \times D) + (rss \times D)$

$= 6.1 + (2 \times 1.024) + (2 \times 1.024) = 10.196\ \mathrm{m}$

Critical depth $\quad D_c = g \times A^3 - Q^2 \times TW$

Implicit solution, solving for D_c

= 0.66 m

Critical slope $\quad A_c = B \times D_c + \left\lfloor lss \times \left(D_c{}^2 / 2\right) \right\rfloor + \left\lfloor rss \times \left(D_c{}^2 / 2\right) \right\rfloor$

= 4.8972 m^3/s

$$V_c = \frac{Q}{A_c}$$

= 2.31 m/s

$$P_c = B + \left\lfloor D_c \times \left(\sqrt{lss^2 + 1}\right) \right\rfloor + \left\lfloor D_c \times \left(\sqrt{rss^2 + 1}\right) \right\rfloor$$

= 8.39 m

$$R_c = \frac{A_c}{P_c} = 0.58$$

$$S_c = \left[\frac{V_c \times n}{R_c^{2/3}} \right]^2$$

$$S_c = \left[\frac{2.31 \times 0.025}{0.58^{2/3}} \right]^2 = 0.10015$$

Velocity $\quad V = \dfrac{Q}{A} = 1.36$ m/s

Velocity head $\quad V_h = \mathrm{alpha} \times \dfrac{V^2}{2 \times g}$

$$V_h = 1 \times \frac{1.36^2}{2 \times 9.81} = 0.094\ \mathrm{m}$$

Specific energy $\quad E_s = \left(\frac{V^2}{2 \times g} \right) + D$ = 1.12 m

Froude number $\quad F = \frac{V}{\sqrt{9.81 \times D}}$ = 0.429

b) To compute the water surface profile, the improved Euler method (Chaudhry, 1993) is used. At control section, $i=1$ and $Y_i=Y_s$. Repeat for $i=2$ to n in increments of distance dX. Compute T_i, A_i, and P_i using the fundamental equations using $Y=Y_i$. Compute the friction slope, depth increment, and intermediate depth as

Initial Depth D = 1.036 m
Longitudinal length of steps dx = 1 m
For i = 1

$$TW_1 = B + (lss \times D) + (rss \times D) = 6.1 + (2 \times 1.036) + (2 \times 1.036) = \underline{10.244}\ \text{m}$$

$$A_1 = B \times D + \left[lss \times \left(D^2 / 2 \right) \right] + \left[rss \times \left(D^2 / 2 \right) \right]$$
$$= 6.1 \times 1.036 + \left[2 \times \left(1.036^2 / 2 \right) \right] + \left[2 \times \left(1.036^2 / 2 \right) \right] = \underline{8.466}\ \text{m}^2$$

$$P_1 = B + \left[D \times \left(\sqrt{lss^2 + 1} \right) \right] + \left[D \times \left(\sqrt{rss^2 + 1} \right) \right]$$
$$= 6.1 + \left[1.036 \times \left(\sqrt{2^2 + 1} \right) \right] + \left[1.036 \times \left(\sqrt{2^2 + 1} \right) \right] = \underline{10.733}\ \text{m}$$

$$S_{f1} = \frac{(n \times Q)^2 \times P_i^{4/3}}{A_i^{10/3}} = \frac{(0.025 \times 11.32)^2 \times (10.733)^{4/3}}{(8.466)^{10/3}} = \underline{0.00153323}$$

$$\theta = \frac{(180 \times s)}{\pi} = \frac{(180 \times 0.0016)}{3.1415927} = \underline{0.091673}$$

$$\left(\frac{D_Y}{D_X} \right)_1 = \frac{S_0 - S_{f1}}{\cos\theta - \frac{T_1 \times Q^2}{g \times A_1^3}} = \frac{0.0016 - 0.00153323}{\cos(0.091673) - \frac{10.244 \times (11.32)^2}{9.81 \times (8.466)^3}} = \underline{8.5660405 \ .\ 10^{-5}}$$

$$D_2 = D + \left[\left(\frac{D_Y}{D_X} \right)_1 \times dx \right] = 1{,}036 + \left(8.5660405 \times 10^{-5} \times 1\right) = \underline{1.036086}\ \text{m}$$

Again compute TW, A, P using same formulas including D_2:

$$TW_2 = 6.1 + (2 \times 1.036086) + (2 \times 1.036086) = \underline{10.244344}\ \text{m}$$

$$A_2 = 6.1 \times 1.036086 + \left[2 \times \left(1.036086^2/2\right)\right] + \left[2 \times \left(1.036086^2/2\right)\right] = \underline{8.46707}\ \text{m}^2$$

$$P_2 = 6.1 + \left[1.036086 \times \left(\sqrt{2^2 + 1}\right)\right] + \left[1.036086 \times \left(\sqrt{2^2 + 1}\right)\right] = \underline{10.733517}\ \text{m}$$

$$S_{f2} = \frac{(0.025 \times 11.32)^2 \times (10.733517)^{4/3}}{(8.46707)^{10/3}} = \underline{0.00153268}$$

$$\theta = \frac{(180 \times s)}{\pi} = \frac{(180 \times 0.0016)}{3.1415927} = \underline{0.091673}$$

$$\left(\frac{D_Y}{D_X} \right)_2 = \frac{S_0 - S_{f2}}{\cos\theta - \dfrac{T_2 \times Q^2}{g \times A_2{}^3}} = \frac{0.0016 - 0.00153268}{\cos(0.091673) - \dfrac{10.244344 \times (11.32)^2}{9.81 \times (8.46707)^3}}$$

$$= \underline{8.635756835 \times 10^{-5}}$$

$$D_3 = D_2 + \left[\frac{\left[\left(\frac{D_Y}{D_X} \right)_1 + \left(\frac{D_Y}{D_X} \right)_2 \right]}{2} \times dx \right]$$

$$= 1.036086 + \left[\frac{8.5660405 \times 10^{-5} + 8.635756835 \times 10^{-5}}{2} \times 1 \right] = \underline{1.0361720}\ \text{m}$$

where ;

TW : top width,

D : depth of water,

$\frac{D_y}{D_x}$: depth increment,

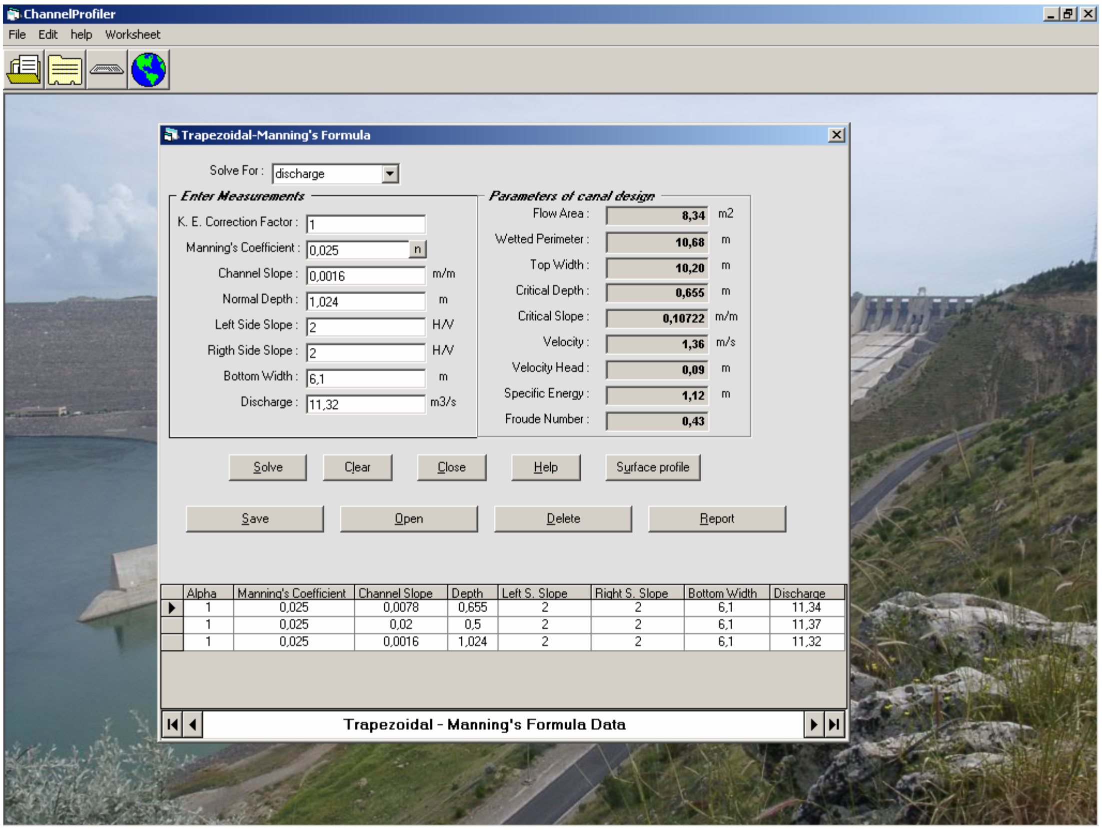
S_f : friction slope,

By increment *i* computation can be repeated. It can be seen during computations depth of water is increased. After sufficient iteration the values for depth of water to draw surface profile can be obtained.

6.1.2 Solution by ChannelProfiler

a) To solve this example Trapezoidal-Manning's form can be used.

Solution for RUN I:



Solve For : discharge

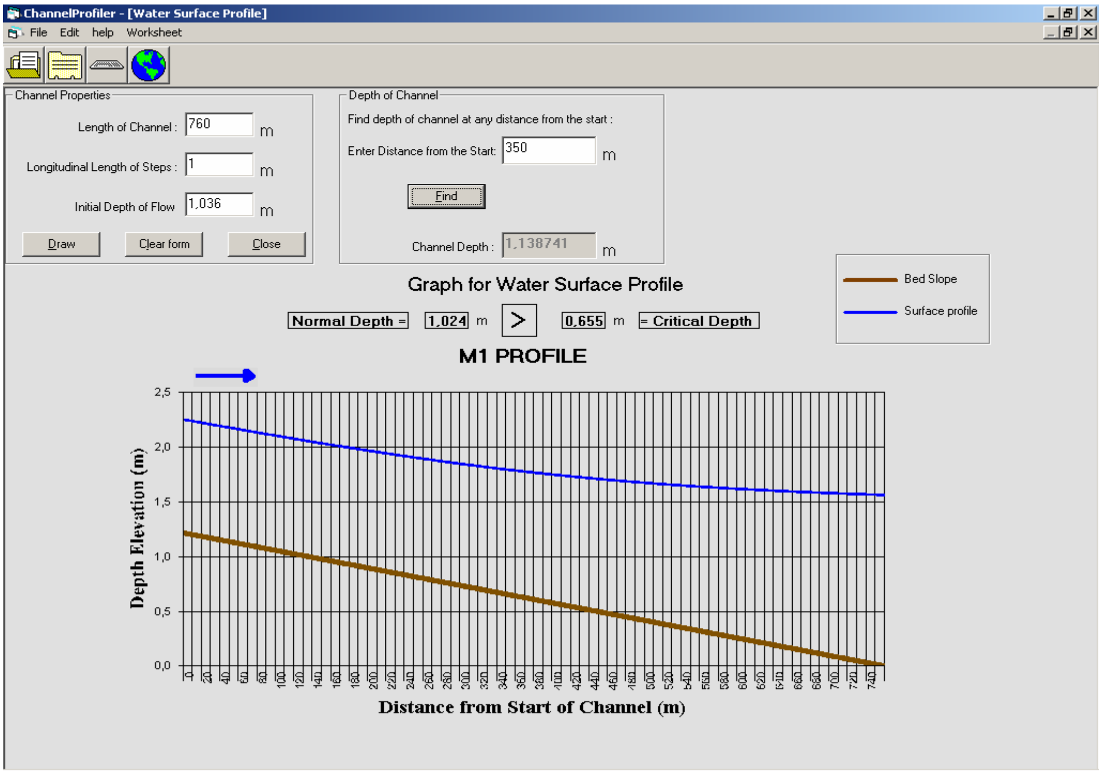
K. E. Correction Factor : 1
Manning's Coefficient : 0,025
Channel Slope : 0,0016 m/m
Normal Depth : 1,024 m
Left Side Slope : 2 H/V
Rigth Side Slope : 2 H/V
Bottom Width : 6,1 m
Discharge : 11,32 m3/s

Flow Area : 8,34 m2
Wetted Perimeter : 10,68 m
Top Width : 10,20 m
Critical Depth : 0,655 m
Critical Slope : 0,10722 m/m
Velocity : 1,36 m/s
Velocity Head : 0,09 m
Specific Energy : 1,12 m
Froude Number : 0,43

Alpha	Manning's Coefficient	Channel Slope	Depth	Left S. Slope	Right S. Slope	Bottom Width	Discharge
1	0,025	0,0078	0,655	2	2	6,1	11,34
1	0,025	0,02	0,5	2	2	6,1	11,37
1	0,025	0,0016	1,024	2	2	6,1	11,32

Figure 6.1 Trapezoidal Manning's Formula Form for RUN I

To draw water surface profiles for RUN I *Surface Profile* button can be clicked. According to initial depth of water that should be input by user following curves may be obtained.



Channel Properties

Length of Channel : 760 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 1,036 m

Depth of Channel

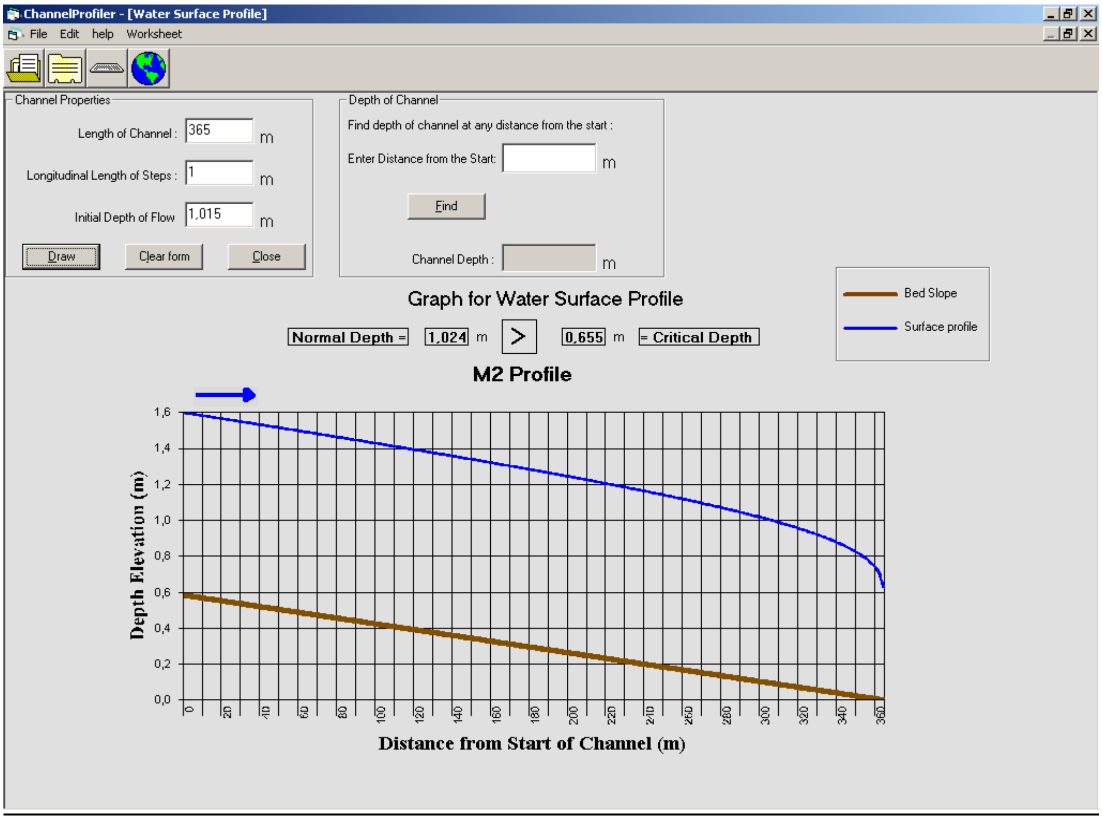
Find depth of channel at any distance from the start :

Enter Distance from the Start: 350 m

Channel Depth : 1,138741 m

Normal Depth = 1,024 m > 0,655 m = Critical Depth

Figure 6.2 Graph for M1 Profile



Channel Properties

Length of Channel : 365 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 1,015 m

Depth of Channel

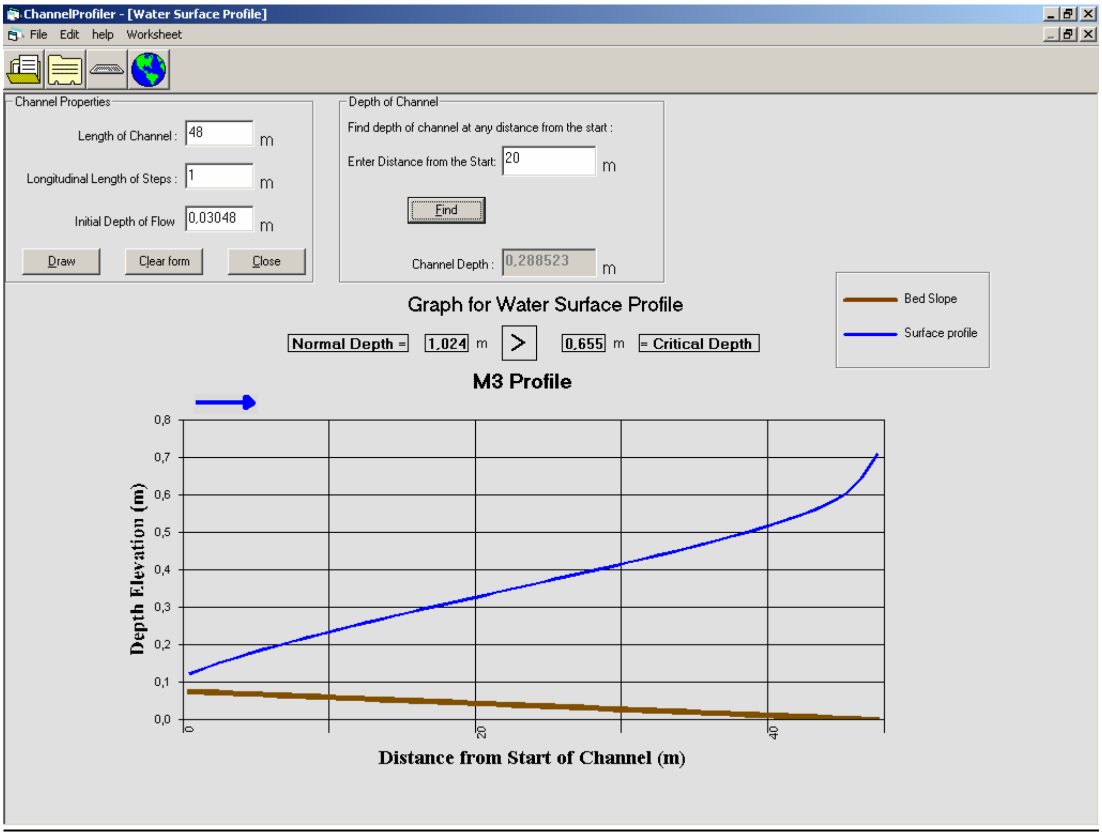
Find depth of channel at any distance from the start :

Enter Distance from the Start: m

Channel Depth : m

Normal Depth = 1,024 m > 0,655 m = Critical Depth

Figure 6.3 Graph for M2 Profile



Length of Channel : 48 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 0,03048 m

Find depth of channel at any distance from the start :

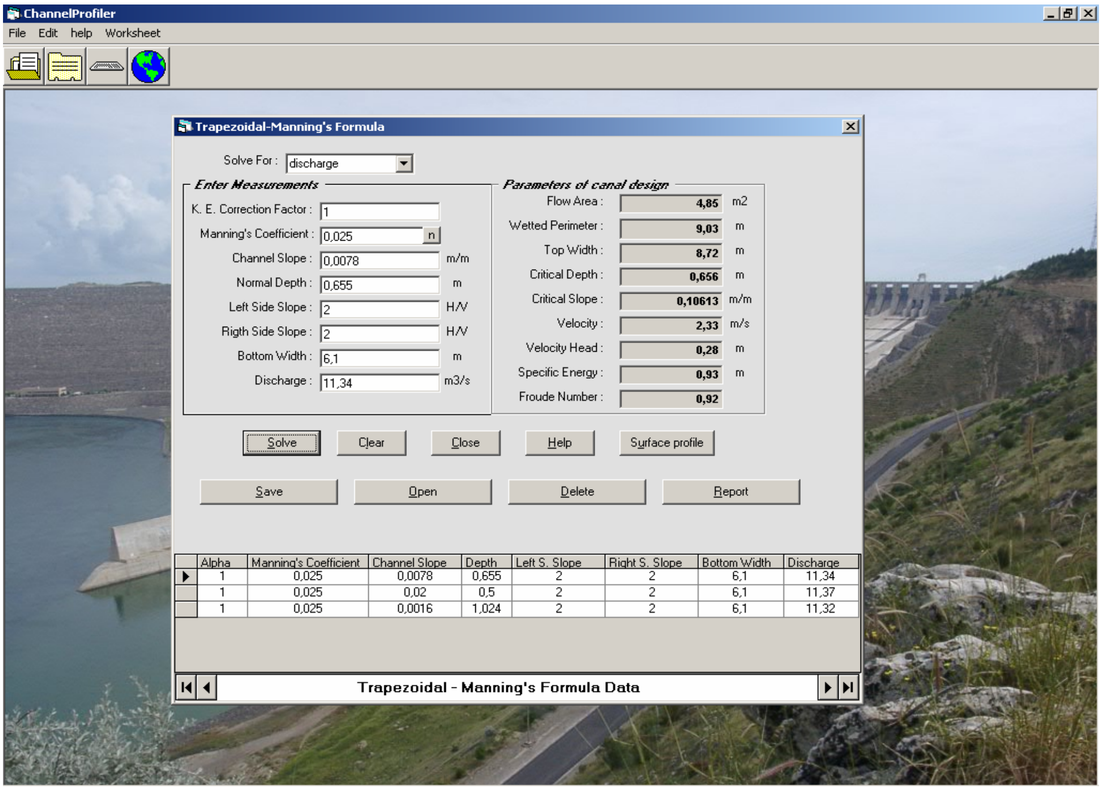
Enter Distance from the Start: 20 m

Channel Depth : 0,288523 m

Normal Depth = 1,024 m > 0,655 m = Critical Depth

Figure 6.4 Graph for M3 Profile

Solution for RUN II:



Solve For : discharge

K. E. Correction Factor : 1

Manning's Coefficient : 0,025

Channel Slope : 0,0078 m/m

Normal Depth : 0,655 m

Left Side Slope : 2 H/V

Rigth Side Slope : 2 H/V

Bottom Width : 6,1 m

Discharge : 11,34 m3/s

Flow Area : 4,85 m2

Wetted Perimeter : 9,03 m

Top Width : 8,72 m

Critical Depth : 0,656 m

Critical Slope : 0,10613 m/m

Velocity : 2,33 m/s

Velocity Head : 0,28 m

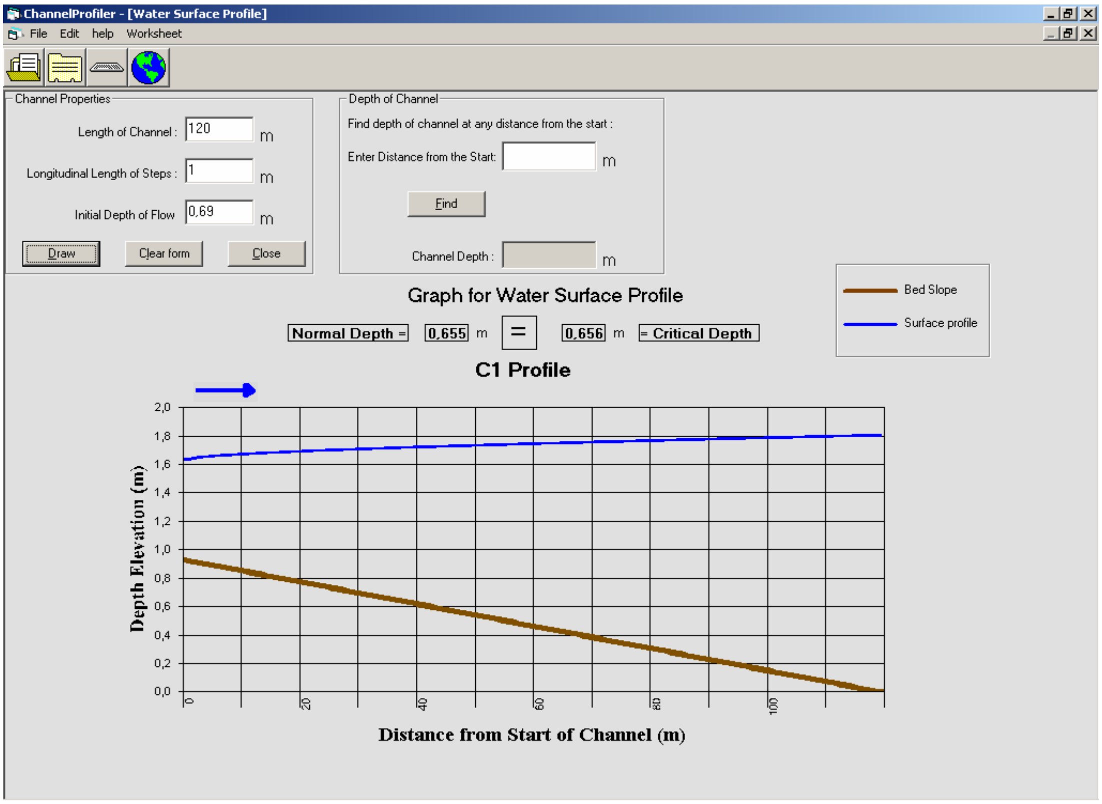
Specific Energy : 0,93 m

Froude Number : 0,92

Alpha	Manning's Coefficient	Channel Slope	Depth	Left S. Slope	Right S. Slope	Bottom Width	Discharge
1	0,025	0,0078	0,655	2	2	6,1	11,34
1	0,025	0,02	0,5	2	2	6,1	11,37
1	0,025	0,0016	1,024	2	2	6,1	11,32

Figure 6.5 Trapezoidal Manning's Formula Form for RUN II

To draw water surface profiles for RUN II *Surface Profile* button can be clicked again. Water surface profiles occur such as:



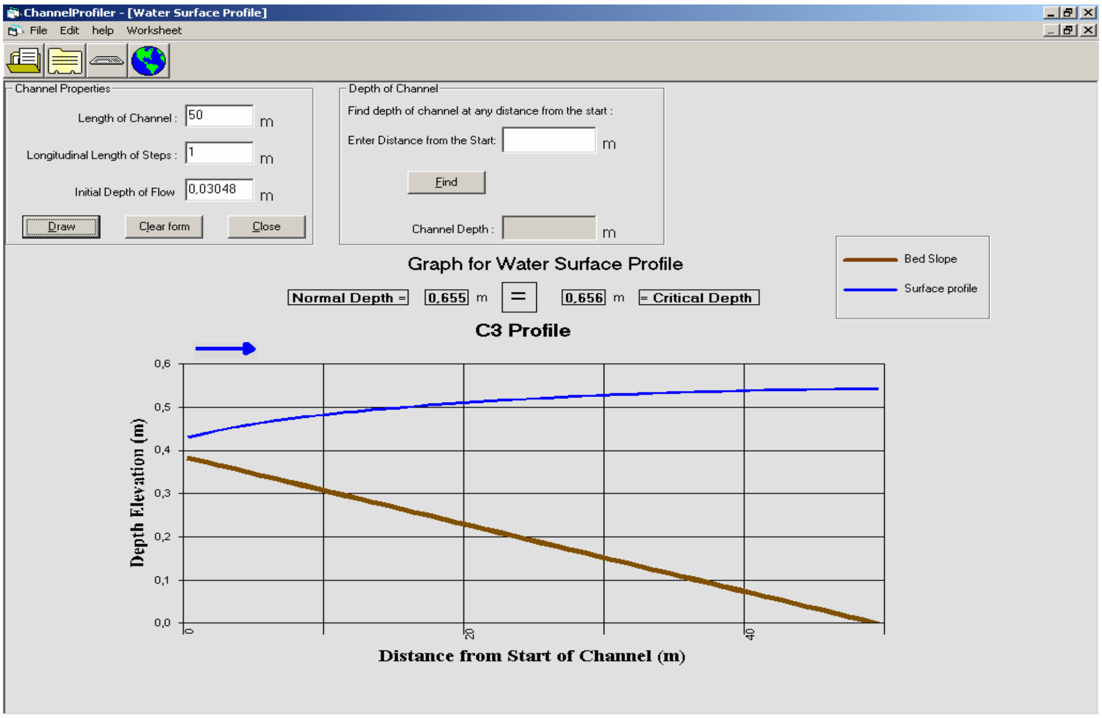
Length of Channel : 120 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 0,69 m

Normal Depth = 0,655 m = 0,656 m = Critical Depth

Figure 6.6 Graph for C1 Profile



Length of Channel : 50 m

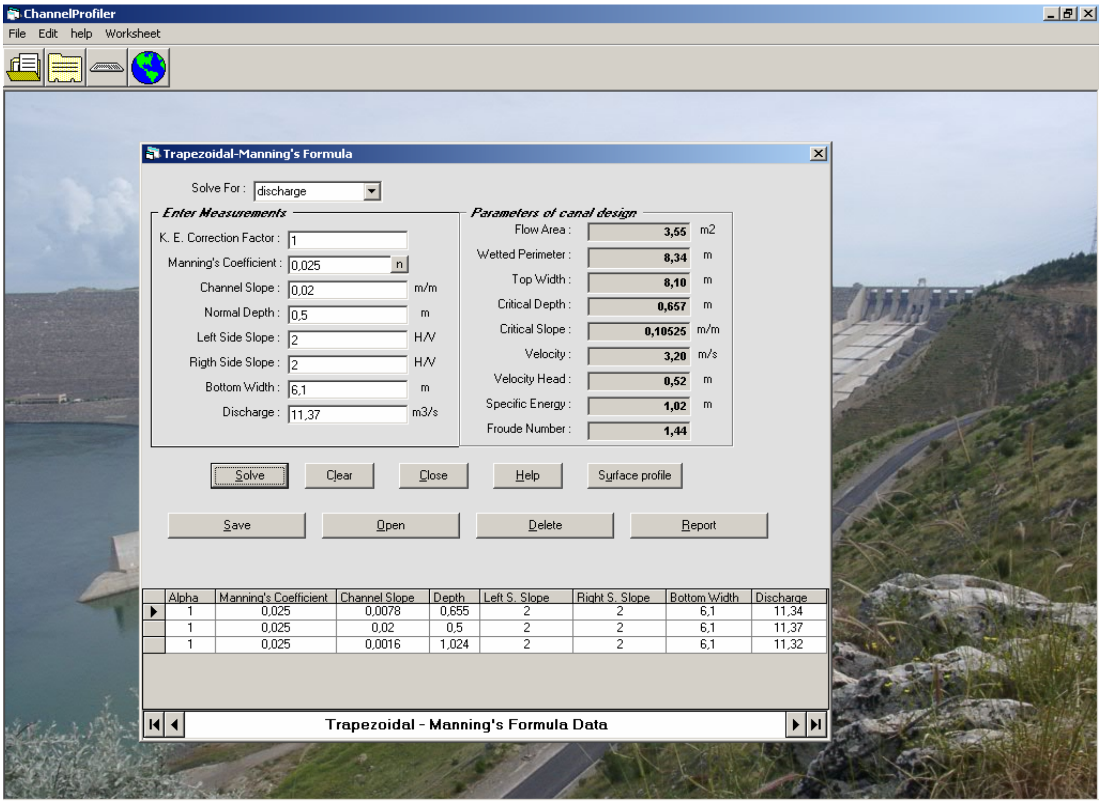
Longitudinal Length of Steps : 1 m

Initial Depth of Flow 0,03048 m

Normal Depth = 0,655 m = 0,656 m = Critical Depth

Figure 6.7 Graph for C3 Profile

Solution for RUN III:



Solve For : discharge

Enter Measurements

K. E. Correction Factor : 1
Manning's Coefficient : 0,025
Channel Slope : 0,02 m/m
Normal Depth : 0,5 m
Left Side Slope : 2 H/V
Rigth Side Slope : 2 H/V
Bottom Width : 6,1 m
Discharge : 11,37 m3/s

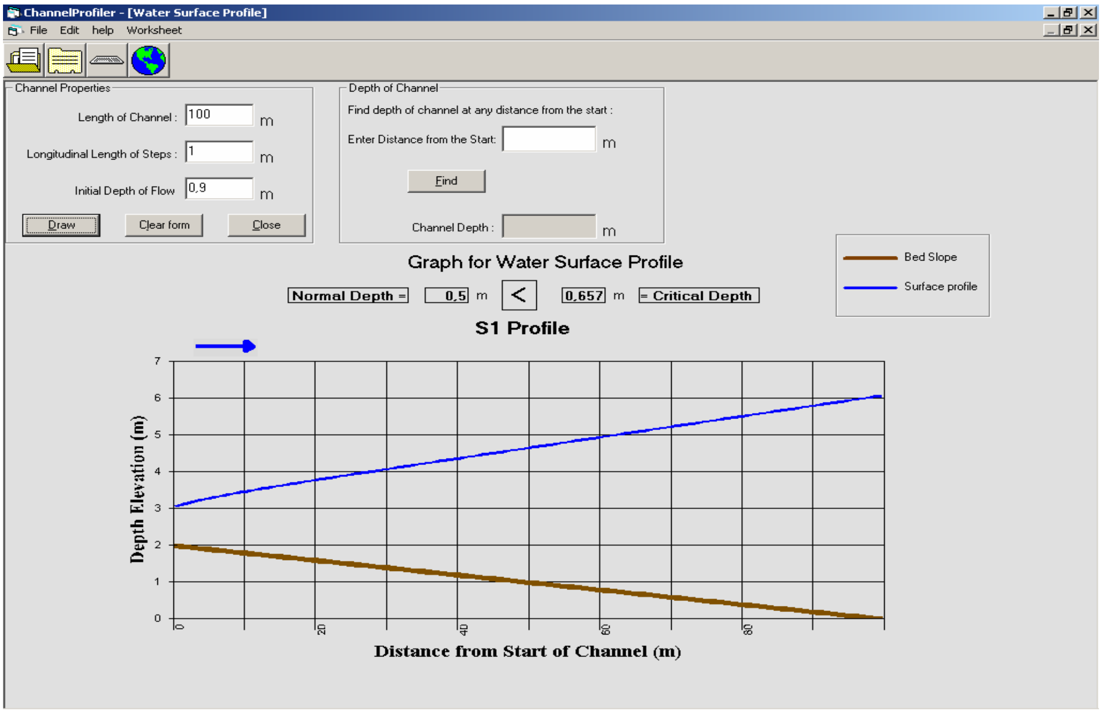
Parameters of canal design

Flow Area : **3,55** m2
Wetted Perimeter : **8,34** m
Top Width : **8,10** m
Critical Depth : **0,657** m
Critical Slope : **0,10525** m/m
Velocity : **3,20** m/s
Velocity Head : **0,52** m
Specific Energy : **1,02** m
Froude Number : **1,44**

	Alpha	Manning's Coefficient	Channel Slope	Depth	Left S. Slope	Right S. Slope	Bottom Width	Discharge
▶	1	0,025	0,0078	0,655	2	2	6,1	11,34
	1	0,025	0,02	0,5	2	2	6,1	11,37
	1	0,025	0,0016	1,024	2	2	6,1	11,32

Figure 6.8 Trapezoidal Manning’s Formula Form for RUN III

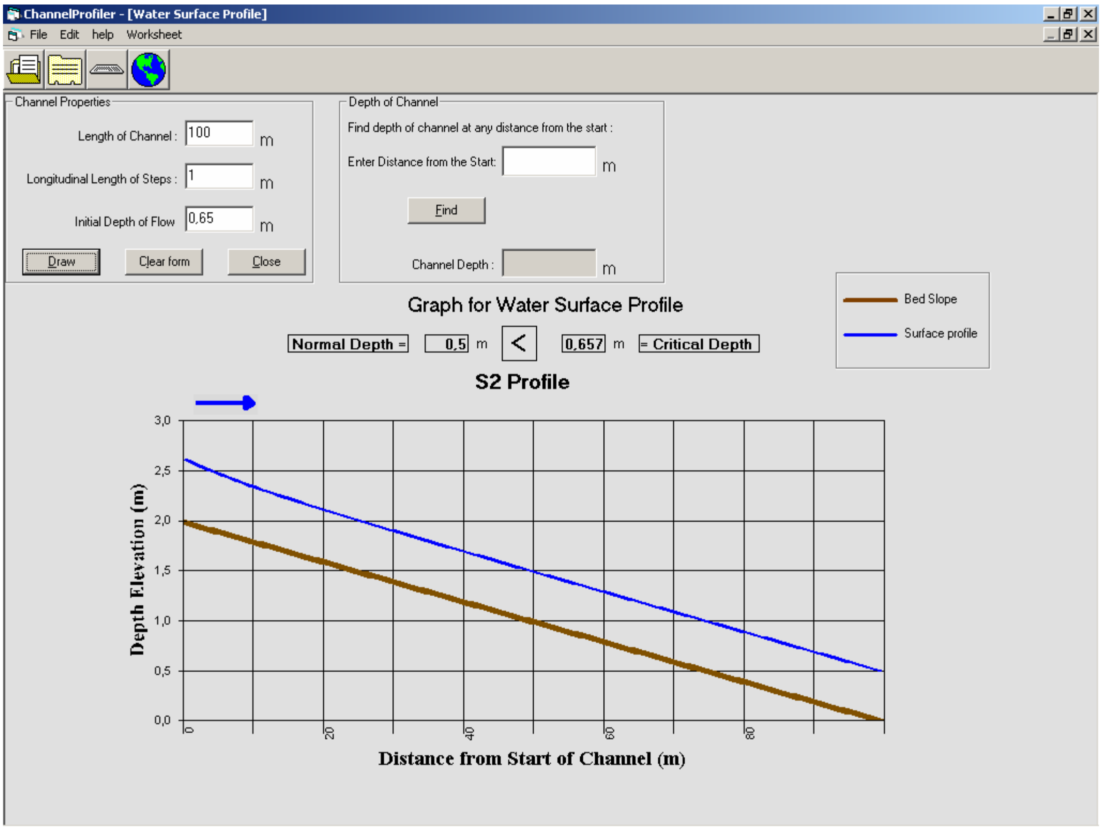
Water surface profiles for RUN III drawn by the ChannelProfiler as following.



Length of Channel : 100 m
Longitudinal Length of Steps : 1 m
Initial Depth of Flow 0,9 m

Normal Depth = **0,5** m < **0,657** m **= Critical Depth**

Figure 6.9 Graph for S1 Profile



Channel Properties

Length of Channel : 100 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 0,65 m

Depth of Channel

Find depth of channel at any distance from the start :

Enter Distance from the Start: m

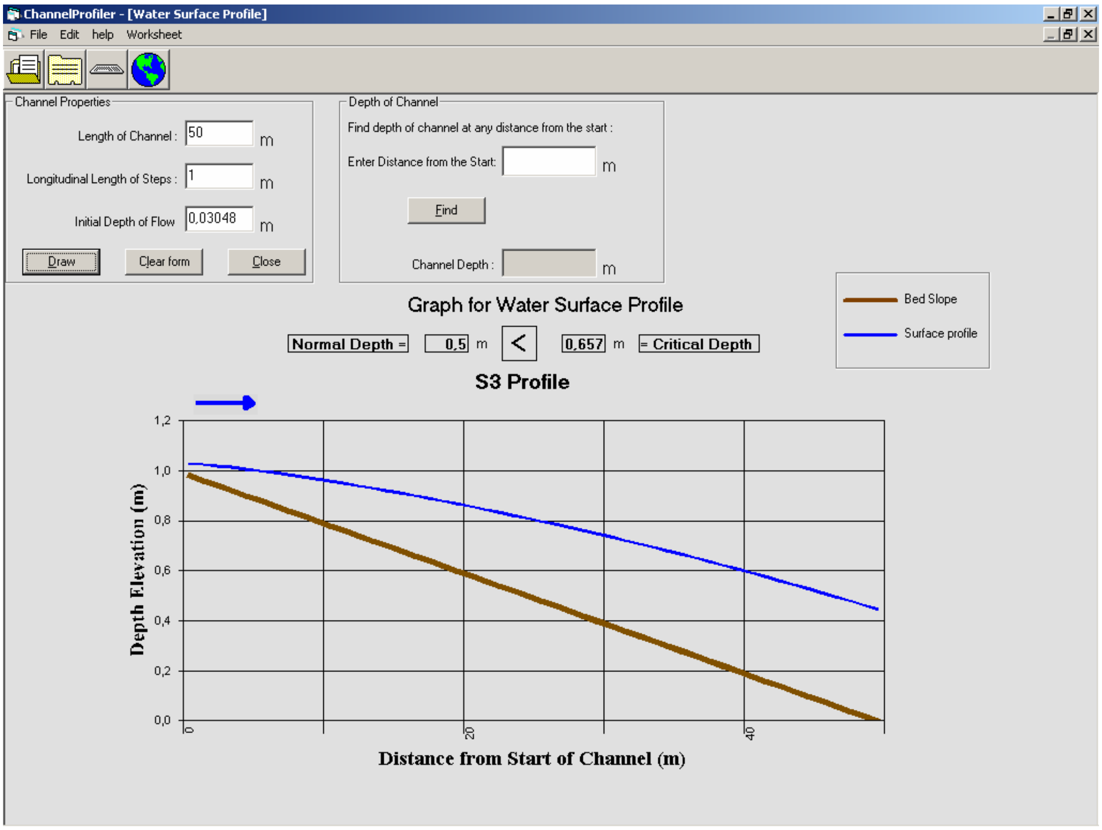
Channel Depth : m

Graph for Water Surface Profile

Normal Depth = 0,5 m < 0,657 m = Critical Depth

S2 Profile

Figure 6.10 Graph for S2 Profile



Channel Properties

Length of Channel : 50 m

Longitudinal Length of Steps : 1 m

Initial Depth of Flow 0,03048 m

Depth of Channel

Find depth of channel at any distance from the start :

Enter Distance from the Start: m

Channel Depth : m

Graph for Water Surface Profile

Normal Depth = 0,5 m < 0,657 m = Critical Depth

S3 Profile

Figure 6.11 Graph for S3 Profile

CHAPTER 7

DISCUSSION

7.1 DISCUSSION OF CHANNEL PROFILER

1. An engineer can evaluate the characteristic parameters (critical slope, critical depth, froude number etc.) of an open channel easily by using ChannelProfiler. Computer calculations are more fast and easy to solve than hand calculations.

2. ChannelProfiler is a user-friendly program. It has a visual and useful interface for users. Input parameters can be entered or changed easily during solution process of an open channel problem.

3. Main input parameters are kinetic energy correction factor, absolute roughness, bed slope, normal depth, side slopes, bottom width and discharge. Here bed slope, normal depth, bottom width and discharge are optional to calculate by ChannelProfiler. One of these inputs is calculated by ChannelProfiler automatically due to other inputs. The parameter which is calculated automatically is chosen by user before entering all inputs. User can select anyone of these optional inputs. For instance discharge was selected; ChannelProfiler calculates discharge of open channel automatically after entering main input parameters except discharge.

4. Absolute roughness values have been previously entered to program. These values are needed during the solution process. User either select this value from the given list by clicking related button next to the input box or enter own value for absolute roughness.

5. ChannelProfiler draws water surface profile for gradually varied flow only. According to initial input parameters the flow of open channel may change from gradually varied flow to other flow type such as rapidly varied flow. On this condition ChannelProfiler can not draw water surface profile of the open channel.

6. User can also reach internet provider or calculator by clicking at any time during the solution process.

7. One example has been solved by both hand and ChannelProfiler, and given in chapter 6. This example which shows that the outputs which are carried out in the ChannelProfiler, are compatible results by hand calculation.

8. ChannelProfiler can be used to help engineers who deal with open channel design such as irrigation and drainage channels.

7.1.1 Comparisons of ChannelProfiler Results with Others

A software package based on the Lotus 1-2-3 is developed to solve the gradually varied flow problem using direct step method by Nabil A. Zaghloul and Adnan Y. Darwish (1987). This software provides a graphical presentation of water surface profile.

Zaghloul and Mohamed N. Anwar (1991) derived mathematical expressions for the hydraulic exponents as functions of the gradually varied flow depth using a trapezoidal channel cross-section. And an integrated computer program is developed using four and/or five points Gaussian and adaptive Simpson quadratures for the numerical integration.

In this section, some excel graphs have been formed to compare outputs of study in above articles and outputs obtained from the ChannelProfiler. To do this, water depths of channel has been read from graphs of articles and graphs from ChannelProfiler.

In the following figures, the blue line illustrates the depth of water obtained from articles, while the pink one refers to water depth obtained from the ChannelProfiler.

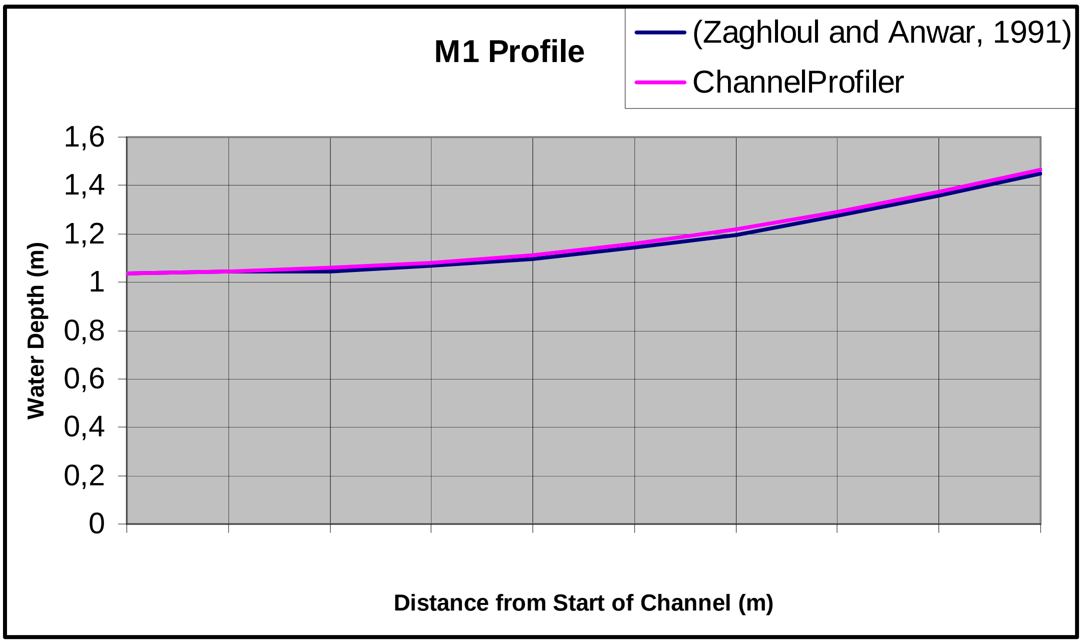


Figure 7.1 Comparison Graph for M1 Profile

Figure 7.1 illustrates the comparison of water depth values obtained from Zaghloul and Mohamed N. Anwar (1991) and ChannelProfiler for an open channel with mild slope. Here initial depth of water in open channel is greater than normal depth and also normal depth is grater than critical depth for the channel. It can be observed from this graph that the depth of water increases along the channel length.

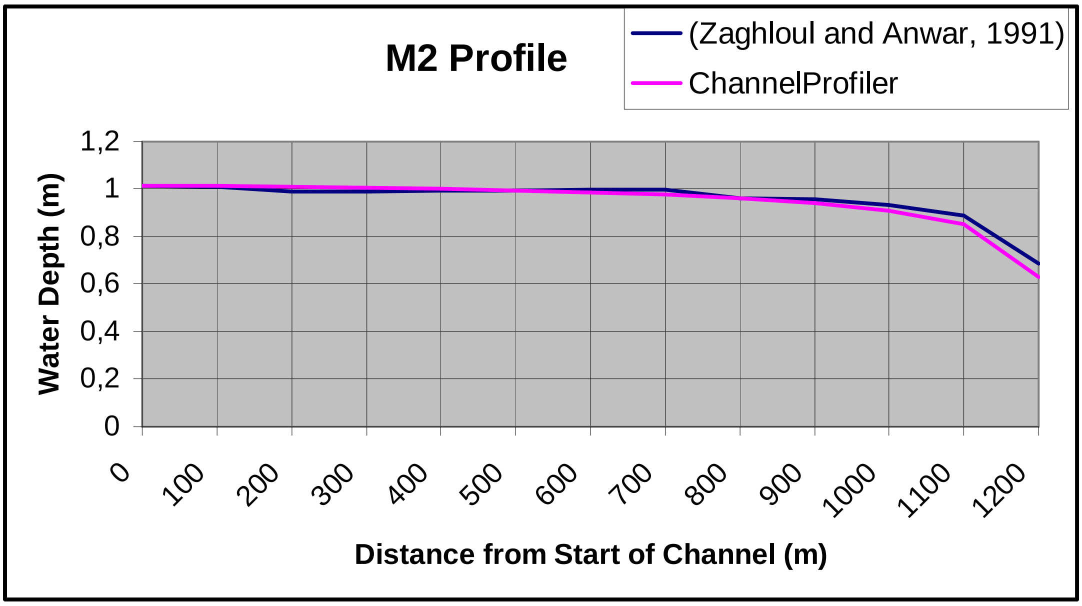


Figure 7.2 Comparison Graph for M2 Profile

Figure 7.2 also shows water depth for mild slope but here initial depth is between normal depth and critical depth. According to this condition the depth of water decreases along the channel length for specific distance. In this graph, when the longitudinal distance reaches the1100 meters, water depth decreases incredibly and flow type changes to a rapidly varied flow.

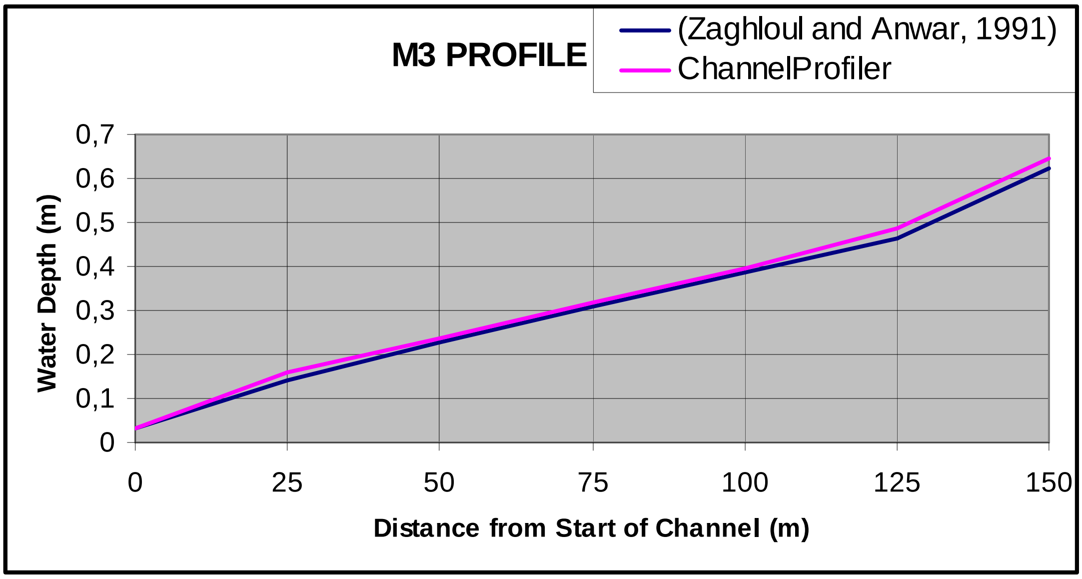


Figure 7.3 Comparison Graph for M3 Profile

Figure 7.3 illustrates water depth values along the channel with mild slope and an initial depth value is smaller than both normal depth and critical depth. Initial depth is taken as 0.03 depth changes incredible along the channel length from 0.03 to 0.65.

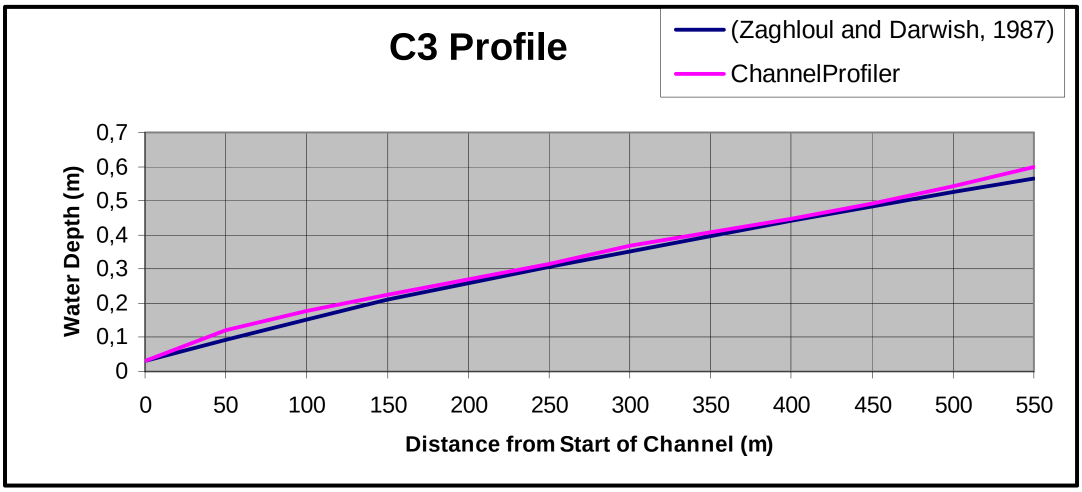


Figure 7.4 Comparison Graph for C3 Profile

Figure 7.4 shows the comparison of S2 profile of Zaghloul and Darwish (1987) with the ChannelProfiler. In critical bed slopes, normal depth is equal to the critical depth for open channels. And here initial water depth is smaller then both of critical and normal depth.

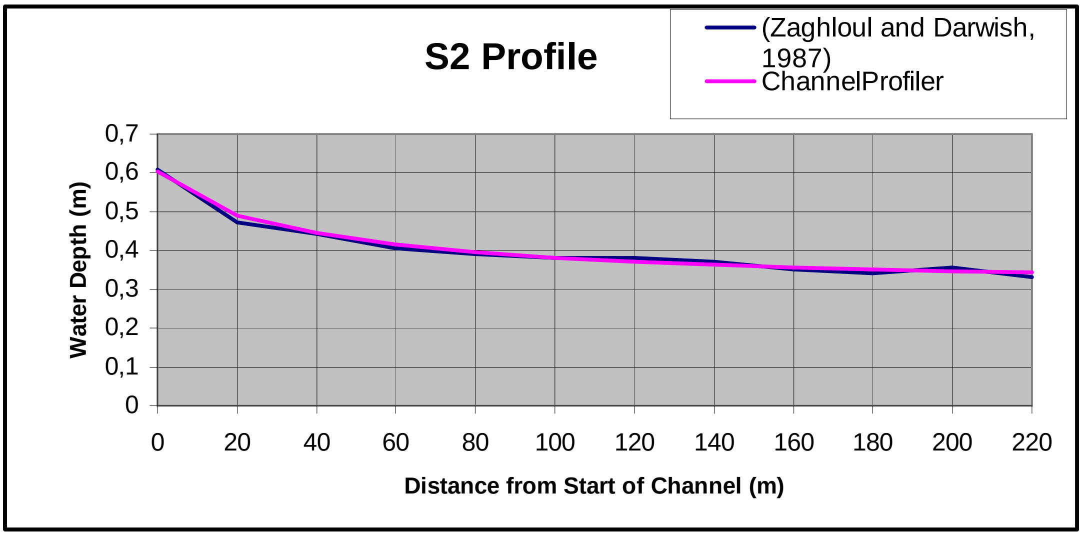


Figure 7.5 Comparison Graph for S2 Profile

Finally, Figure 7.5 shows the results of water depth for an open channel with steep bed slope of Zaghloul and Darwish (1987) with the ChannelProfiler. Here critical depth is greater than normal depth and initial depth is between them. In this condition, water depth decreases gently along the longitudinal length of the open channel.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 CONCLUSION

1. In this thesis, a computer program is developed in Visual Basic to calculate flow area, wetted perimeter, critical depth, critical slope, top width, velocity, velocity head, specific energy, Froude number, Reynolds number and friction factor which are used to design of open channels.

2. ChannelProfiler is also able to draw water surface profile for given discharge and slope. After calculating the open channel's parameters, ChannelProfiler draws water surface profile for gradually varied flow. After entering input parameters that are *length of channel* and *longitudinal length of steps*, and *initial depth for flow*, ChannelProfiler will draw a graph of surface profile along the longitudinal length of channel.

3. Another advantage of the program is finding depth of water through longitudinal length of the channel. To find the depth of water at any point in the channel, *distance from the start* would be entered then ChannelProfiler will illustrate the depth of water at that point in the channel.

4. ChannelProfiler uses Manning's, Hazen-Williams and Darcy-Weisbach Formulas to calculate cross-sectional characteristic parameters of open channels.

8.2 SUGGESTION FOR FUTURE WORK

1. In this thesis, open channel design parameters were estimated for only gradually varied flow. So ChannelProfiler may be developed for other open channel flow type such as rapidly varied flow.

2. ChannelProfiler may be developed for channels which have other geometric or non-geometric cross-sections for example circular sections and natural channels.

3. ChannelProfiler can only be run for open channels. It may be developed for pipe networks. Notches and weir with variable cross-sections or geometries.

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APPENDIX

A. ROUGHNESS VALUES FOR MANNING'S FORMULA

Commonly used roughness values (n) for different materials

Channel Type and Description		Minimum	Normal	Maximum
A.	Closed Conduits Flowing Partly Full			
A-1.	Metal			
a.	**Brass, smooth**	0.009	0.010	0.013
b.	**Steel**			
1.	Lockbar and welded	0.010	0.012	0.014
2.	Riveted and spiral	0.013	0.016	0.017
c.	**Cast iron**			
1.	Coated	0.010	0.013	0.014
2.	Uncoated	0.011	0.014	0.016
d.	**Wrought iron**			
1.	Black	0.012	0.014	0.015
2.	Galvanized	0.013	0.016	0.017
e.	**Corrugated metal**			
1.	Subdrain	0.017	0.019	0.021
2.	Storm drain	0.021	0.024	0.030
A-2.	**Nonmetal**			
a.	**Lucite**	0.008	0.009	0.010
b.	**Glass**	0.009	0.010	0.013
c.	**Cement**			
1.	Neat, surface	0.010	0.011	0.013
2.	Mortar	0.011	0.013	0.015
d.	**Concrete**			
1.	Culvert, straight and free of debris	0.010	0.011	0.013
2.	Culvert with bends, connections, and some debris			

		0.011	0.013	0.014
3.	Finished	0.011	0.012	0.014
4.	Sewer with manholes	0.013	0.015	0.017
5.	Unfinished, steel form	0.012	0.013	0.014
6.	Unfinished, smooth wood	0.012	0.014	0.016
7.	Unfinished, rough wood	0.015	0.017	0.020
e.	**Wood**			
1.	Stave	0.010	0.012	0.014
2.	Laminated, treated	0.015	0.017	0.020
f.	**Clay**			
1.	Common drainage tile	0.011	0.013	0.017
2.	Vitrified sewer	0.011	0.014	0.017
3.	Vitrified sewer with inlet	0.013	0.015	0.017
4.	Vitrified subdrain	0.014	0.016	0.018
g.	**Brickwork**			
1.	Glazed	0.011	0.013	0.015
2.	Lined with cement mortar	0.012	0.015	0.017
	Sanitary sewers	0.012	0.013	0.016
i.	**Paved invert, sewer**	0.016	0.019	0.020
j.	**Rubble masonry, cemented**	0.018	0.025	0.030
k.	**PVC**	0.007	0.009	0.011
B.	Lined or Built-up Channels			
B-1.	Metal			
a.	**Smooth steel surface**			
1.	Unpainted	0.011	0.012	0.014
2.	Painted	0.012	0.013	0.017
b.	**Corrugated**	0.021	0.025	0.030
B-2.	Nonmetal			
a.	**Cement**			
1.	Neat, surface	0.010	0.011	0.013
2.	Mortar	0.011	0.013	0.015
b.	**Wood**			
1.	Planed, untreated	0.010	0.012	0.014

2.	Planed, creosoted	0.011	0.012	0.015
3.	Unplaned	0.011	0.013	0.015
4.	Plank with battens	0.012	0.015	0.018
5.	Lined with roofing paper	0.010	0.014	0.017
c.	**Concrete**			
1.	Trowel finish	0.011	0.013	0.015
2.	Float finish	0.013	0.015	0.016
3.	Finished, with gravel	0.015	0.017	0.020
4.	Unfinished	0.014	0.017	0.020
5.	Gunite, good section	0.016	0.019	0.023
6.	Gunite, wavy section	0.018	0.022	0.025
7.	On good excavated rock	0.017	0.020	
8.	On excavated rock	0.022	0.027	
d.	**Concrete bottom float finished with sides of**			
1.	Dressed stone in mortar	0.015	0.017	0.020
2.	Random stone in mortar	0.017	0.020	0.024
3.	Cement rubble masonry	0.016	0.020	0.024
4.	Cement rubble masonry	0.020	0.025	0.030
5.	Dry rubble or riprap	0.020	0.030	0.035
e.	**Gravel bottom with sides of**			
1.	Formed concrete	0.017	0.020	0.025
2.	Random stone in mortar	0.020	0.023	0.026
3.	Dry rubble or riprap	0.023	0.033	0.036
f.	**Brick**			
1.	Glazed	0.011	0.013	0.015
2.	In cement mortar	0.012	0.015	0.018
g.	**Masonry**			
1.	Cemented rubble	0.017	0.025	0.030
2.	Dry rubble	0.023	0.032	0.035
h.	**Dressed ashlar**	0.013	0.015	0.017
i.	**Asphalt**			
1.	Smooth	0.013	0.013	
2.	Rough	0.016	0.016	
j.	**Vegetal lining**	0.030	.....	0.500

C.	Excavated Or Dredged			
a.	**Earth, straight and uniform**			
1.	Clean, recently completed	0.016	0.018	0.020
2.	Clean, after weathering	0.018	0.022	0.025
3.	Gravel, uniform section	0.022	0.025	0.030
4.	With short grass	0.022	0.027	0.033
b.	**Earth, winding and sluggish**			
1.	No vegetation	0.023	0.025	0.030
2.	Grass, some weeds	0.025	0.030	0.033
3.	Dense weeds	0.030	0.035	0.040
4.	Earth bottom	0.028	0.030	0.035
5.	Stony bottom	0.025	0.035	0.040
6.	Cobble bottom	0.030	0.040	0.050
c.	**Dragline-excavated or dredged**			
1.	No vegetation	0.025	0.028	0.033
2.	Light brush on banks	0.035	0.050	0.060
d.	**Rock cuts**			
1.	Smooth and uniform	0.025	0.035	0.040
2.	Jagged and irregular	0.035	0.040	0.050
e.	**Channels not maintained, weeds and brush uncut**			
1.	Dense weeds	0.050	0.080	0.120
2.	Clean bottom	0.040	0.050	0.080
3.	highest stage of flow	0.045	0.070	0.110
4.	Dense brush, high stage	0.080	0.100	0.140
D.	Natural Streams			
D-1.	Minor streams (top width at flood stage < 100 ft)			
a.	**Streams on plain**			
1.	Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2.	Same as above, but more stones and weeds	0.030	0.035	0.040
3.	Clean, winding, some pools and shoals			

		0.033	0.040	0.045
4.	Same as above, but some weeds and stones	0.035	0.045	0.050
5.	Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6.	Same as 4, but more stones	0.045	0.050	0.060
7.	Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
b.	**Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages**			
1.	Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2.	Bottom: cobbles with large boulders	0.040	0.050	0.070
D-2.	Flood plains			
a.	**Pasture, no brush**			
1.	Short grass	0.025	0.030	0.035
2.	High grass	0.030	0.035	0.050
b.	**Cultivated areas**			
1.	No crop	0.020	0.030	0.040
2.	Mature row crops	0.025	0.035	0.045
3.	Mature field crops	0.030	0.040	0.050
c.	**Brush**			
1.	Scattered brush	0.035	0.050	0.070
2.	Light brush and trees, in winter	0.035	0.050	0.060
3.	Light brush and trees, in summer	0.040	0.060	0.080

B. ROUGHNESS VALUES FOR HAZEN FORMULA

Commonly used roughness values for different materials

Pipe Materials	**CHW**
Asbestos Cement	140
Brass	130-140
Brick sewer	100
Cast-iron	
New, unlined	130
10 yr. old	107-113
20 yr. old	89-100
30 yr. old	75-90
40 yr. old	64-83
Concrete or concrete lined	
Steel forms	140
Wooden forms	120
Centrifugally spun	135
Copper	130-140
Galvanized iron	120
Glass	140
Lead	130-140
PVC	150
Steel	
Coal-tar enamel, lined	145-150
New unlined	140-150
Riveted	110
Tin	130
Vitrified clay (good condition)	110-140
Wood stave (average condition)	120

C. ROUGHNESS VALUES FOR DARCY FORMULA

Commonly used roughness values for different materials

Pipe Materials	**e (mm)**	**e (ft)**
PVC	0.0015	0.000005
Glass, drawn brass, copper (new)	0.0015	0.000005
Seamless commercial steel (new)	0.004	0.000013
Commercial steel (enamel coated)	0.0048	0.000016
Commercial steel (new)	0.045	0.00015
Wrought iron (new)	0.045	0.00015
Asphalted cast iron (new)	0.12	0.0004
Galvanized iron	0.15	0.0005
Cast iron (new)	0.26	0.00085
Wood Stave (new)	0.18~0.9	0.0006~0.003
Concrete (steel forms, smooth)	0.18	0.0006
Concrete (good joints, average)	0.36	0.0012
Concrete (rough, visible, form marks)	0.60	0.002
Riveted steel (new)	0.9~9.0	0.003-0.03
Corrugated metal	45	0.15