Hydrologic Calculator: an educational interface for hydrological processes analysis

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Abstract: Hydrology, which deals with the study of water, is one of the fundamental courses to the undergraduate program of many disciplines: civil engineering, agricultural engineering, earth sciences, environmental sciences, geography, etc. This course covers various events of the hydrological cycle, namely, rainfall, runoff, hydrograph, infiltration, evapotranspiration, and flood routing. These events involve a large number of techniques and methods for the analysis, which are time-consuming. To enhance the learning, this study presents a tool called 'Hydrologic Calculator', an educational interface with eight modules for analyzing the various hydrological related events. In addition, 'Help' module in 'Hydrologic Calculator' provides a thorough understanding of the theory and methodology adopted for solving the different hydrological problems. Hydrologic Calculator includes a graphical user interface, which helps in input data preparation and output display in both graphical and tabular forms. Besides, it also provides detailed results in log (.txt) format. All the eight modules of the software were tested using the available published data. The validation results obtained using Hydrologic Calculator were in good agreement with the respective results given in the source. Thus, Hydrologic Calculator can be used as a professional computer tool for teaching and analyzing different hydrological processes.

Keywords: Hydrologic Calculator, Visual Basic 6, hydrograph, runoff, rainfall, infiltration, evapotranspiration

1 Introduction

The hydrologic cycle deals with many processes, e.g., rainfall, condensation, evaporation, transpiration, and runoff. All these processes play a vital role in the protection and management of not only water resources but also several environmental resources. As a result, hydrology these day forms a part of educational curricula of diverse engineering and science disciplines: agricultural, civil, environmental, geography, geology,

forestry, and water, etc. The first course or undergraduate level in hydrology basically covers various engineering aspects of the hydrologic cycle and introduces students to different techniques/methods for hydrological data analysis. Hence, there is an increasing interest in hydrology education at the university level and in the continuous development of water professionals (Seibert et al., 2013). On one side, most of the engineering hydrology courses focus mainly on mathematical/ empirical approaches and lack necessary emphasis on understanding of basic hydrologic processes. On the other side, hydrology curriculum lack in exposure to real world problems, modeling activities, and learning from field data, specifically at the undergraduate and lower division level (ASCE, 1990; MacDonald, 1993; Nash et al., 1990; Ruddell and Wagener, 2015; and Wagener et

al., 2007, 2012). Therefore, a specific type of education with the introduction of computer simulation modules is needed during under graduation level such that they cover not only the basic hydrological concepts but also to deal with the real world problems. These computerized techniques afford instructors the opportunity to have their students engage in realistic and authentic problem based on activities without the need to manage other logistical constraints often encountered with field research (i.e., transportation, materials, etc.).

As such, the hydrologic research community has expressed the need for fundamental improvements in current practices of hydrologic education, especially at the undergraduate level (Bourget, 2006; Wagener et al., 2007; Howe, 2008; Loucks, 2008; Ledley et al., 2008; CUAHSI, 2010; Ngambeki et al., 2012; Pathirana et al., 2012; Uhlenbrook and de Jong 2012). In recent years, a series of publications has recognized and reviewed the challenges in emphasizing the introduction of new computer based on pedagogies in hydrology education.

Sanchez et al. (2015) demonstrated that the computerized learning in hydrology context can effectively bring the "real world" into the classroom and make it accessible, especially in the case of undergraduate students. Merwade and Rudell (2012) stated that traditional classroom with lecture-format pedagogy plays a critical role in delivering hydrology concepts to students, but there is a need to explore how these traditional approaches can be augmented with new pedagogies that include the use of digital data, simulation and visualization tools to enhance students' learning. Ruddell and Wagener (2015) reviewed how hydrology education has evolved over the decades, where the community (especially United States and European) appears to be headed, and grand challenges in the 21st century. The challenges include development of formal pedagogies, new technologies, and a broadening and globalization of hydrology education. Habib et al. (2012) designed and evaluated a web-based educational tool called 'HydroViz' to support active learning in hydrology education. This tool basically simulates the real-world natural hydrologic systems by learning model either with filed data or with stored random computer data.

The findings of the above papers strengthen the fact that it is possible to introduce or improve the undergraduate hydrological curriculum with a small effort in the way of computer modeling and programming. Further, hydrological processes analysis is time consuming and often requires the standard text to perform the analysis. Therefore, there is a need to develop a tool for performing hydrological processes analysis. In the past, a number of graphical user interface (GUI) based computer software has been developed for analyzing the different hydrological variables. Some of the early developed software in the field of hydrology include: RRL (Perraud et al., 2003) for rainfall-runoff analysis; WHAT (Lim et al., 2005), WBNM (Boyd et al., 1996), and IHACRES (Allen and Liu, 2011) for hydrograph analysis; RAINBOW (Raes et al., 2006) for hydro-meteorological frequency analysis; HEC-SSP (Harris et al., 2010) for rating curve analysis; SIDES (Adamala et al., 2014a) for surface irrigation design; and DSS_ET (Bandyopadhyay et al., 2012) for evapotranspiration estimation.

All the above software have been developed only to analyze any one of the various hydrological processes. These softwares do not have a single platform based comprehensive module for all hydrological processes/events. Further, these softwares are good for research and design but lack in the stepwise design process, which is essential for undergraduate student learning. Therefore, the present study is carried out an aim to develop a user-friendly software package for analyzing and solving different hydrologic processes and yield a step-wide design procedures for thorough understanding. Use of this software is encouraged to reduce the time required to reach a solution.

2   Theoretical background

The Hydrologic Calculator has provision to analyze various problems related to different hydrological processes. Since the detailed description of all hydrological processes is beyond the subject of this paper, interested personnel are directed to refer to references in Table 1. Figure 1 shows various methods used in the software. However, detailed description of analysis techniques, which are not available in standard textbooks, is presented herein.

Table 1   Analysis of various hydrological processes

|	Hydrologic processes/analysis	Source
Rainfall analysis	Test of consistency of rainfall records Missing data estimation methods Mean rainfall estimation methods Presentation of data (Hyetograph/mass curve) Adequacy of raingauge stations	Subramanya, 2013
Runoff analysis	Estimation ϕ -Index Rational method Velocity-area method SCS-CN method	Subramanya, 2013 Subramanya, 2013 Subramanya, 2013 Suresh, 2013
Hydrograph analysis	Conversion of FH to DRH/UH Conversion of UH to DRH/FH Change of duration of UH Construction of Synthetic UH	Subramanya, 2013
Flood routing	Channel routing by Muskingum method Determination of K and x Reservoir routing by modified Puls method Channel routing by kinematic wave method	Subramanya, 2013 Subramanya, 2013 Subramanya, 2013 Chow et al., 1988
Statistical analysis	Test of adequacy of length of records Randomness test	Hypothetical data
Frequency analysis	Frequency factor method	Subramanya, 2013
Evapotranspiration analysis	Thornthwaite method Pan evaporation Christiansen pan evaporation Penman-Monteith	Michael, 2009
Infiltration analysis	Kostiakov model Green-Ampt model Philip Two-term model Horton model	Singh, 1994 Singh, 1994 Singh, 1994 Singh, 1994
Stage-discharge analysis	Rating curve method	Subramanya, 2013
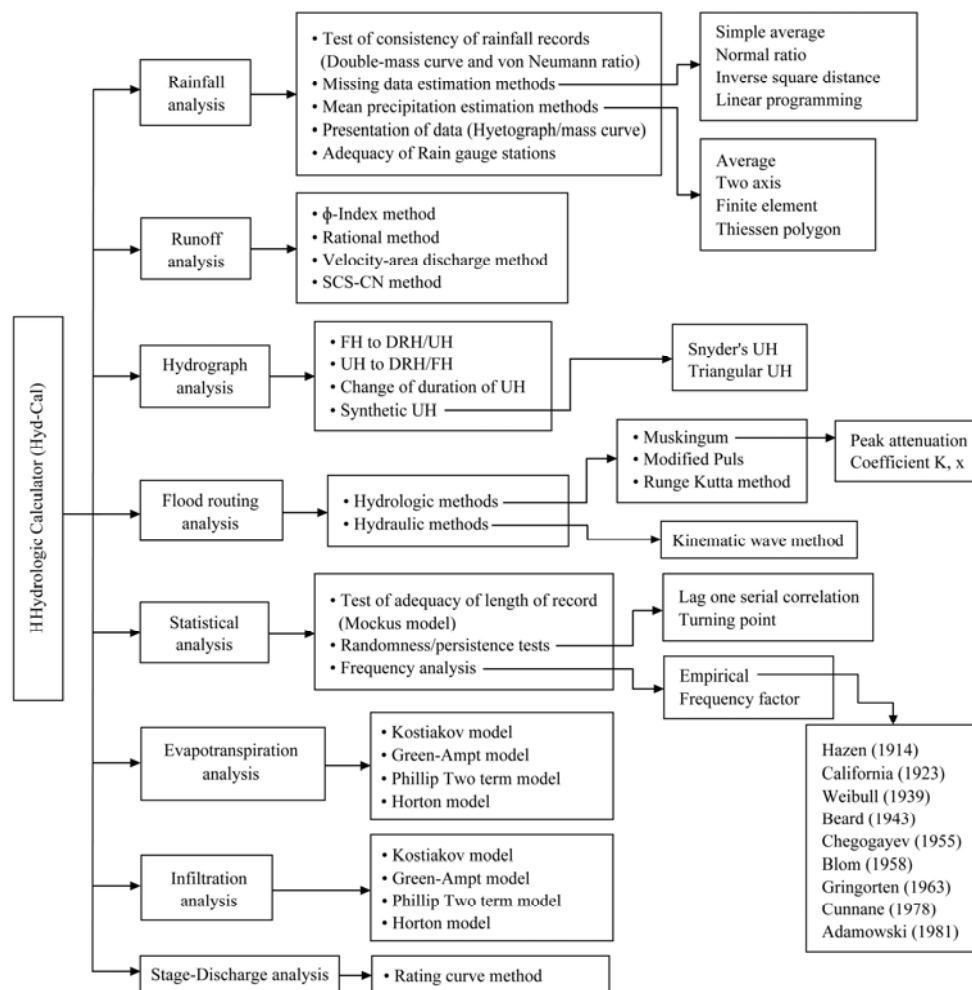
Figure 1   Schematic diagram of Hydrologic Calculator (Hyd-Cal)

2.1   Rainfall analysis

Rainfall analysis includes test of consistency of rainfall records (double mass curve, Von Neuman Ratio method), missing data estimation (simple average, normal ratio, inverse square distance and linear programming method), mean areal rainfall estimation (simple average, two-axis, finite element, and Theissen polygon method), representation of rainfall using hyetograph and mass curve, and raingauge networks analysis (Table 1).

2.1.1   Von Neuman Ratio (VNR) test for consistency of rainfall records

Many hydrological studies require long-term rainfall data; therefore, a test must be conducted to check self-consistency of the rainfall records. The consistency of rainfall records can be checked using VNR test. The VNR test is basically based on statistics and is also called as a 'statistical test'. Let P_i ($i=12,3,…,n$), denotes the departures from some average of rainfall value, whose consistency is to be tested. The test can be expressed as:

$$V = \frac{\sum_{i=1}^{n+1}(P_i - P_{i+1})^2}{\sum_{i=1}^{n}(P_i - \overline{P})^2} \qquad (1)$$

where, P and $\overline{P}$ = rainfall and mean rainfall values; n = number of data points in rainfall series. For a non-homogeneous record, the value of V should be less than 2 or vice-versa.

2.1.2   Estimation of missing rainfall data

The point observation from a rainfall gauge may have a short break in the records due to instrument failure or absence of the observer. Therefore, it is often necessary to estimate the missing records using data from the neighboring stations. The inverse square distance (ISD) method is the most suitable method to estimate the missing rainfall data (P_x) at station 'x', which connects it to nearest raingauge (of known rainfall data) stations and measures the distances x_1, x_2, x_3,..., x_n. Therefore, the weight of each station ($W_i = 1/x_i^2$) with respect to station 'x' can be used to calculate the missing rainfall (P_x) as follows:

$$P_x = \frac{\sum_{i=1}^{n}P_i W_i}{\sum_{i=1}^{n}W_i} \qquad (2)$$

Unlike the other methods, the linear programming (LP) method does not determine the weighting factors beforehand (Singh, 1994). It selects the base station and several surrounding index stations and determines optimal weighting factors, by minimizing the deviations between observed and computed rainfall at a base station for a number of rainfall events.

Suppose the weight assigned to the each index stations is W_1, W_2, W_3, …W_n and rainfall is P_{1j}, P_{2j}, P_{3j}, …P_{nj} and rainfall at the base station is P_{bj} for j^{th} event. The deviation is a difference between the computed ($\sum_{i=1}^{n}W_i P_{ij}$) and observed rainfall (P_{bj}), and it is unrestricted in sign if both the quantities are positive. Hence, it is replaced by the difference of two positive quantities (u_j, v_j). Therefore, the objective is to minimize the sum of these two positive quantities as follows:

Minimization: $Z = \sum_{j=1}^{k}(u_j + v_j)$, k = Number of events

$$\qquad (3)$$

Subjected to the constraints:

$$\sum_{i=1}^{n}W_i P_{ij} - u_j + v_j = P_{bj} \quad \text{for } j = 1, 2, 3, ……, k \qquad (4)$$

$$W_i \geq 0 \quad \text{for } i = 1, 2, 3, ……, k \qquad (5)$$

$$u_j \geq 0, v_j \geq 0 \quad \text{for } j = 1, 2, 3, …., k \qquad (6)$$

After finding weight at each station, the value of rainfall at missing raingauge station can be found as follows:

$$P_b = \sum_{i=1}^{n}W_i P_i \qquad (7)$$

2.1.3   Conversion of point rainfall to areal rainfall

Mean areal rainfall is required for many engineering applications, which can be estimated from the group of point rainfall events in a watershed of n number of raingauge stations. It is most commonly estimated using the simple average, Theissen polygon, and Isohyetal methods. The alternative methods are Two-Axis (Bethlahmy, 1976) and Finite Element (Akin, 1971) methods.

2.1.3.1   Two-Axis method

Based on the nearness of each gage to the center, draw the longest straight line that can be drawn on a map of watershed (major axis) and draw a perpendicular

bisector (minor axis). Further, draw two lines from each of the gages, one line to farther end of the major axis, the other to the farther end of the minor axis. Define the coordinates of the gauging stations in terms of x and y coordinates, i.e. for an ith gauge, the coordinates are (x, y) and the rainfall measured is donated by P_i. The acute angle between these two lines θ is measured and subsequently the areal rainfall over a given area can be determined as follows:

$$\overline{P} = \frac{\sum_{i=1}^{n} \theta_i P_i}{\sum_{i=1}^{n} \theta_i} \qquad (8)$$

2.1.3.2   Finite Element method

Connect the number of gauging stations in a watershed arbitrarily to form m triangular sub-areas. Assign an identification number to each gauging station, beginning with one. Assume the rainfall over the sub-area varies linearly between the three gauging points. Therefore, for an ith gauge interior to the nth sub-area, the rainfall can be expressed as:

$$p_{ni}(x, y) = a_{n1} + a_{n2}x_i + a_{n3}y_i \qquad (9)$$

$$p_{nj}(x, y) = a_{n1} + a_{n2}x_j + a_{n3}y_j \qquad (10)$$

$$p_{nk}(x, y) = a_{n1} + a_{n2}x_k + a_{n3}y_k \qquad (11)$$

where, a_{ni} = constant related to the rainfall measurements at the corners. The above equation is also valid for the corners of the sub-areas.

Solve the above simultaneous equations for a_{n1}, a_{n2} and a_{n3}, and calculate volume of rainfall at any point within the subarea (V_n) as:

$$V_n = A_n \left[a_{n1} + a_{n2}(x_i + x_j + x_k)\frac{1}{3} + a_{n3}(y_i + y_j + y_k)\frac{1}{3} \right] (12)$$

where, A_n = area of sub triangle.

Compute the total volume (V) and area (A) of rainfall over the triangular mesh as:

$$V = \sum_{i=1}^{m} V_i \qquad (13)$$

$$A = \sum_{i=1}^{m} A_i \qquad (14)$$

Compute the mean areal rainfall $(\overline{P})$ as:

$$\overline{P} = \frac{V}{A} \qquad (15)$$

2.2   Flood routing

Flood routing deals with determination of time and magnitude of a flood wave at a section of a river (i. e. Flood hydrograph at the section) by utilizing the data of flow at one or more upstream section. There are several methods available for flood routing and they can be further classified into two groups:

i. Hydrologic routing: methods under this category employ equation of continuity.

ii. Hydraulic routing: methods under this category employ equation of continuity and equation of motion for unsteady flow.

Hydrologic routing can be further classified into reservoir routing and channel routing. In Hydrology calculator, the Modified Puls method is used for reservoir routing and Muskingum routing method and Runge-Kutta method are used for channel routing. Under hydraulic routing category, kinematic wave method of channel routing is used and is briefly described below.

2.2.1   Kinematic wave method (channel routing)

The kinematic wave model consists of continuity equation and a simplified form of the momentum equation, based on the assumption that the energy grade line is parallel to the channel bottom slope, i.e., the acceleration and pressure terms in the momentum equation are negligible. The kinematic wave model is defined by the following equations:

Continuity equation, $\dfrac{\partial Q}{\partial x} + \dfrac{\partial A}{\partial t} = q \qquad (16)$

Momentum equation, $S_o = S_f$ (or) $A = \left(\dfrac{nP^{2/3}}{1.49\sqrt{S_o}} \right)^{3/5} Q^{3/5}$
$$(17)$$

Equations (16) and (17) can be combined for kinematic wave approximation with only Q as dependent variable as follows:

Equation of continuity becomes, $\dfrac{\partial Q}{\partial x} + \alpha\beta Q^{\beta-1}\left(\dfrac{\partial Q}{\partial t} \right) = q$
$$(18)$$

where, Q = flow along the length (x) of channel; S_o = channel bed slope; S_f = slope of the energy line; n = manning's roughness coefficient; q = lateral inflow into the channel; y = depth of flow; B = width of the channel; A = area of cross-section of the channel $(B \times y)$; P = wetted

perimeter ($B+2y$, for $B>>y$); α and β = parameters.

Equation (18) is solved by the backward-difference (finite difference) method to determine the outflow hydrograph from inflow hydrograph for given value of channel parameters α and β, the lateral inflow $q(t)$ and initial and boundary conditions. The finite difference form of the space derivative is found by substituting the value of Q on the $(j+1)^{th}$ time as:

$$\frac{\partial Q}{\partial x} = \frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} \qquad (19)$$

where, Δx = length along the channel between two segments; i and j denotes the distance along the channel length and time, respectively.

The finite difference form of the time derivative is found likewise by substituting the value of Q on the $(i+1)^{th}$ distance as:

$$\frac{\partial Q}{\partial t} = \frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t} \qquad (20)$$

where, Δt = time interval.

If the value of Q were used in '$\alpha\beta Q^{\beta-1}$' term,

$$Q = \frac{Q_{i+1}^{j} + Q_i^{j+1}}{2} \qquad (21)$$

The value of lateral inflow q is found by averaging the value of the $(i+1)^{th}$ distance (these are assumed to be given in the problem)

$$q = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \qquad (22)$$

By substituting Equations (19) to (22), Equation (18) becomes:

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} + \alpha\beta\left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1}\left(\frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t}\right)$$
$$= \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \qquad (23)$$

This equation is solved for the unknown Q_{i+1}^{j+1} as follows:

$$Q_{i+1}^{j+1} =$$
$$\frac{\left[\frac{\Delta t}{\Delta x}Q_i^{j+1} + \alpha\beta Q_{i+1}^{j}\left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1} + \Delta t\left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2}\right)\right]}{\left[\frac{\Delta t}{\Delta x} + \alpha\beta\left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2}\right)^{\beta-1}\right]}$$
$$(24)$$

By using above equation Q_{i+1}^{j+1} can be found out for given value of Δt, Δx, α, β, q_{i+1}^{j}, q_{i+1}^{j+1}, Q_{i+1}^{j}, Q_i^{j+1}.

2.3 Frequency analysis

Frequency analysis deals with the chance of occurrence of an event over a specified period of time. Suppose, P is the probability of occurrence of an event (rainfall) whose magnitude is equal to or in excess of a specified magnitude X. The recurrence interval (return period) is related to P as follows:

$$T = \frac{1}{P} \qquad (25)$$

Before performing frequency analysis data should be checked for adequacy of the length of the record and randomness.

2.3.1 Test of adequacy of length of record

To check the adequacy of the length of record, Mockus (1960) developed the following equation:

$$Y_{min} = (4.3t_{10}\log Q_2)^2 + 6 \qquad (26)$$

where, Y_{min} = minimum acceptable years of record; t_{10} = Student "t" value at 10% significance level, and Q_2 = ratio of 100 year maximum rainfall to two year maximum rainfall and is defined as below:

$$Q_2 = \frac{Z_{T=100}}{Z_{T=2}} \qquad (27)$$

$$Z_T = \bar{Z}(1 + C_V C_T) \qquad (28)$$

where, Z_T = annual rainfall for T years recurrence interval; $\bar{Z}$ = mean annual rainfall of the sample; C_V = coefficient of variation of the sample; and C_T = frequency factor, and is determined as follows:

$$C_T = \frac{-2.45}{3.1416}\left[0.577 + \ln\left\{\ln T - \ln(T-1)\right\}\right] \qquad (29)$$

2.3.2 Test for randomness or persistence test

Hydrologic data must be checked for independence. The independence means that the outcome of the hydrologic variable (rainfall amount) at a given time does not depend on the value of the variable at a previous time. The Lag one serial correlation and Turning point tests can be used for checking the independence of the hydrologic data.

The lag one serial correlation can be determined using the following equation:

$$r_1 = \frac{\frac{1}{(N-1)}\sum_{i=1}^{N-1}(X_i - \bar{X})(X_{i+1} - \bar{X})}{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^2} \qquad (30)$$

where, N = number of data points, and X = hydrologic variable. For data to be random lag one serial correlation should be within:

$$-\frac{1}{N-1} \pm 1.96\frac{(N-2)}{(N-1)^{3/2}} \qquad (31)$$

In Turning point test, the variable X_i is assigned a score of 1 in case it meets either of the two conditions ($X_{i-1} < X_i > X_{i+1}$ or $X_{i-1} > X_i < X_{i+1}$), otherwise 0. The Normal standard deviate, u is calculated as follows:

$$u = \left[\frac{SN - \frac{2}{3}(N-2)}{\sqrt{\frac{(16N-29)}{90}}}\right] \qquad (32)$$

where, SN = score number; N = number of data points. If u lies within ± 1.96 - series is random.

2.4 Evapotranspiration estimation

Evapotranspiration is one of the most basic components of the hydrologic cycle. It denotes the quantity of water transpired by plants plus the moisture evaporated from the surface of the soil and the vegetation (Adamala et al., 2014b,c). Table 2 shows the different evapotranspiration estimation methods that were included in the Hydrologic Calculator software.

Table 2   Evapotranspiration estimation methods

Method	Model
Pan evaporation	$ET_o = K_p \times E_p$
Christiansen (1968)	$ET_o = 0.755 \times E_p \times C_{T2} \times C_{W2} \times C_{H2} \times C_{S2}$
Penman-Monteith Combination	$ET_o = \dfrac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{T_{avg}+273}W_s(e_s - e_a)}{\Delta + \gamma(1 + 0.34W_s)}$
Thornthwaite (1948)	$e = 1.6\,(10t/I)^a$

Note: ET_o = reference crop evapotranspiration (mm); K_p = pan coefficient; E_p = pan evaporation (mm day^{-1}); e = unadjusted potential evapotranspiration, cm per month; t = mean air temperature (ºC); I = annual or seasonal heat index, the summation of 12 values of monthly heat indices (i) when, $i = (t/5)1.514$, a = an empirical exponent; C_{T2}, C_{W2}, C_{H2}, C_{S2} = empirical constants; R_n = daily net solar radiation (MJ m^{-2} day^{-1}); G = soil heat flux (MJ m^{-2} day^{-1}); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); Δ = slope of saturation vapor pressure versus air temperature curve (kPa ºC^{-1}); T_{avg} = average daily air temperature at 2 m height (ºC); W_s = wind speed at 2 m height (m s^{-1}); γ = psychrometric constant (kPa ºC^{-1}).

2.5 Infiltration models

Infiltration is the process of the entry of water into a soil through the soil surface in a vertically downward direction. Infiltration rate (f) is the rate at which water enters the soil surface. Table 3 shows the different infiltration models that were included in the Hydrologic Calculator software.

Table 3   Infiltration estimation methods

Method	Model
Kostiakov	$f = (ab)\,t^{b-1}$
Green-Ampt (GA)	$f = K + \dfrac{aK}{F}$
Phillip Two-Term	$f = (a/2)^{0.5}t^{-0.5} + f_c$
Horton	$f = f_c + (f_0 - f_c)\exp(-at)$

Note: K = Darcy's hydraulic conductivity; F = cumulative infiltration capacity; f = infiltration rate at any time t from the start of the rainfall; f_0 = initial infiltration rate at $t = 0$; f_c = final steady state infiltration rate occurring at $t = t_c$; a and b = local parameters with $a > 0$ and $0 < b < 1$.

3   Hydrologic Calculator software interface

The Visual Basic 6.0 programming language is used to develop the software, called Hydrologic Calculator. The Hydrologic Calculator interface was developed with a total of eight modules. Figure 1 and Figure 2 show the block diagram and main menu window of the developed software, respectively with different modules and sub-modules. Module-I was designed for analyzing rainfall records with sub-modules to test the consistency of rainfall records, to estimate missing data (using simple average, normal ratio, inverse square distance, and linear programming methods), to estimate mean rainfall (using average, two-axis, finite element, and Thiessen polygon), representation of rainfall data (mass curve and hyetograph), and to test the adequacy of raingauge stations. Module-II facilitates the analysis of runoff using ϕ-index, rational, velocity-area, and SCS-CN methods. Module-III includes four sub-modules for estimation of unit hydrograph (UH) from direct runoff hydrograph (DRH) and flood hydrograph (FH), construction of FH from DRH and UH, deriving UH of different durations (method of superposition and S-curve), construction of Synthetic UH (Snyder's method and Triangular hydrograph).

Module-IV deals with flood routing analysis using the hydrologic (Muskingum, modified Pulse, and Runge-Kutta) and hydraulic (kinematic wave) methods, whereas Module-V consists of statistical analysis to test adequacy of length of records, randomness tests (Lag one

serial correlation and turning point test), and frequency analysis (empirical and frequency factor methods). Module VI and VII facilitate evapotranspiration (Pan evaporation, Christiansen pan evaporation, Penman-Monteith, and Thornthwaite methods) and infiltration (Kostiakov, Green-Ampt, Philip Two-term, and Horton

models) analysis, respectively. Module VIII analyzes the stage-discharge relationships using the rating curve method. To facilitate classroom usage, a comprehensive 'Help' module is also provided in the Hydrologic Calculator with a set of basic theory and methodologies of different hydrological processes.
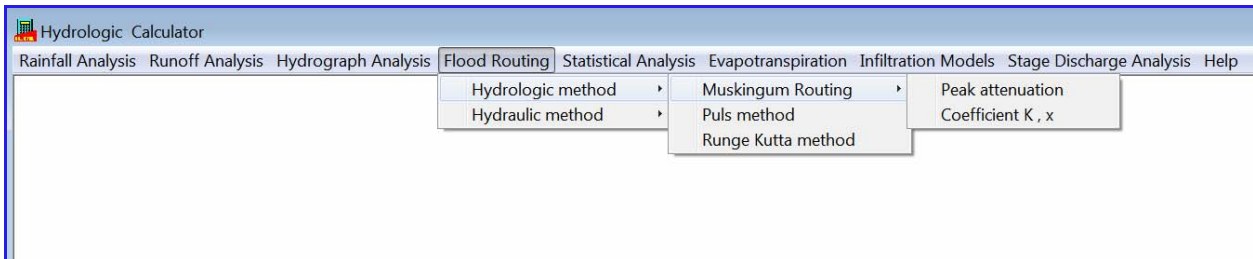

Figure 2   Main menu window of the developed software

4   Validation of Hydrologic Calculator

The Hydrologic Calculator software includes a graphical user interface (GUI) that allows the user to select and edit data, save and retrieve input and output data files, and to view the output both in graphical (line and bar) and tabular forms. The Hydrologic Calculator was tested against the solved numerical solutions from different published books (Table 1). Wherever, solved numerical were not available, the software was tested against the hand calculations. One of the very important aspects of Hydrologic Calculator is logging of the stepwise calculations for all designed modules. The user can save step wise calculations in to a log file (.txt).

4.1   Rainfall analysis

The point rainfall can be converted to areal rainfall using methods described in the 'rainfall analysis' module of Figure 1. Figure 3a shows the data input window as well as results for the Finite Element method. In the case of Finite Element method, the user has to enter point rainfall values for all the stations in the spreadsheet of the active window along with the (x,y) coordinates of raingauge stations as well as coordinates for the watershed boundary. The (x,y) coordinates of raingauge stations and watershed boundary are also displayed in a graphical form (Figure 3a). The 'Do calculation' command performs the analysis and displays mean areal rainfall. To save the step wise calculations in a log file (.txt), the user has to click Log Calculations button (Figure 3b).

Similar type of windows were developed for checking the consistency of rainfall records (double mass curve and VNR methods), to estimate missing data (using simple average, normal ratio, inverse square distance, and linear programming methods), to estimate mean areal rainfall (using average, two-axis, and Thiessen polygon), interpretation of rainfall data (mass curve and hyetograph), and to test the adequacy of raingauge stations. The results pertaining to above analysis are not shown and discussed due to space limitations.
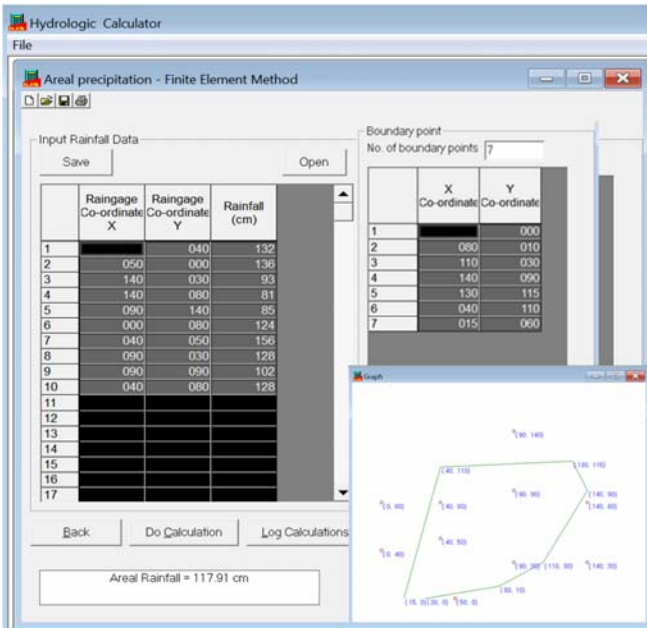
4.2   Runoff analysis

In order to calculate the ϕ-index, the analysis window (Figure 4) can be assessed by clicking on the Runoff analysis module (Figure 2). The active window contains a spreadsheet for entering information on rainfall intensity at different time scale. Further, the user also has to specify the total runoff depth (cm). After entering the required data, select the number of rows to be considered for calculation and press on the 'Do Calculation' button to obtain the ϕ-index (cm h^{-1}) value and effective rainfall duration (h). The model also provides a graphical display of effective rainfall hyetograph (ERH) and rainfall hyetograph. The stepwise procedure for calculating ϕ-index is shown in Appendix A1 as log file (.txt).

### 4.3   Hydrograph analysis

To change the duration of UH, the analysis window can be assessed by clicking on the 'Hydrograph Analysis' module (Figure 5). The user has to enter the data

(discharge and time) for a given UH as well as the duration of old and new UHs. The 'Do Calculation' command displays the results both in graphical and Tabular form in detail (Appendix A2).

(a) Rainfall analysis
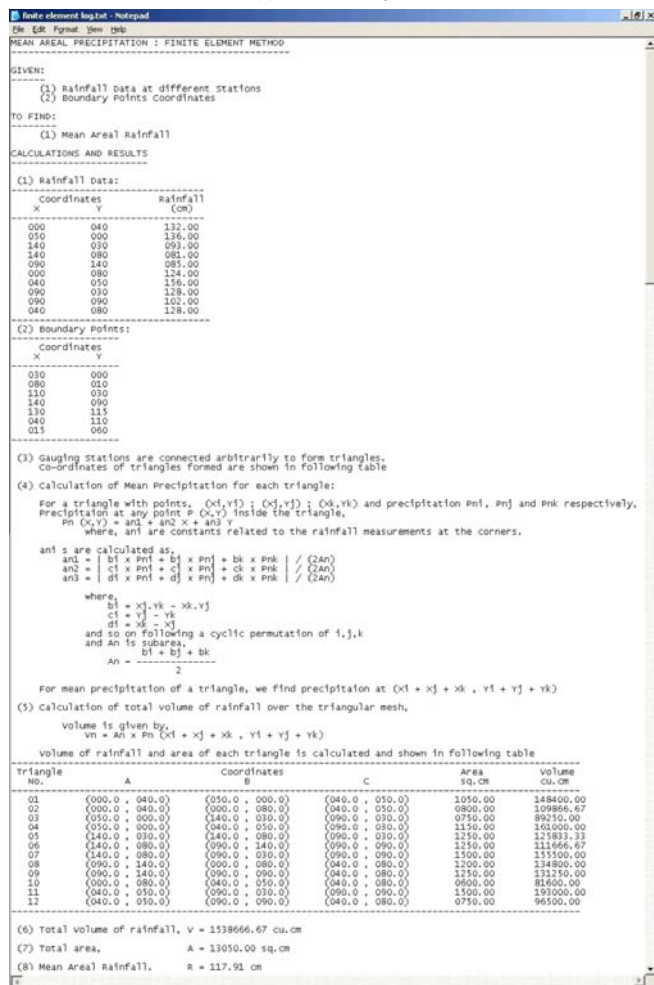
(b) Generated step wise rainfall analysis (log file)

Figure 3   Rainfall analysis and generated step wise rainfall analysis using Finite Element method
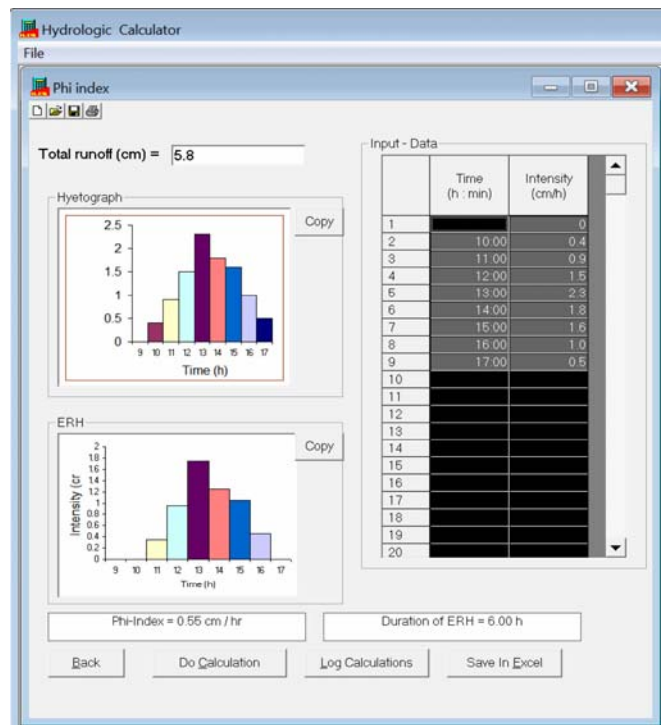
Figure 4 ϕ-index calculation in runoff analysis
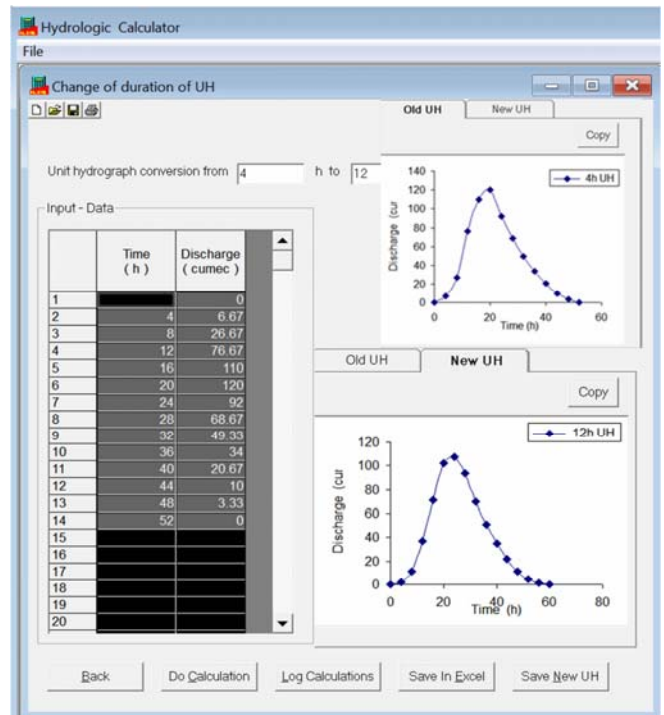
Figure 5   Change of duration of unit hydrograph in hydrograph analysis

4.4   Flood routing analysis

Muskingum routing method is a channel routing method, which comes under a hydrologic routing group. This method can be used either to determine the Muskingum routing constants or outflow hydrograph along with the attenuation in peak flow rate and time lag. In order to determine routing coefficients (k and x), the analysis window can be assessed by clicking on 'Flood

routing' module (Figure 6). In this method, the user has to enter information on inflow hydrograph (time and inflow discharge) along with the outflow discharge. Appendix A3 shows a detailed stepwise analysis window for the estimation of coefficient k and x in Muskingum equation.

Figure 6   Determination of constants in hydrological Muskingum routing method

4.5   Frequency analysis

The frequency analysis can be done either using the empirical methods or frequency factor methods. However, prior to applying any of these methods, the data should be tested for adequacy of the length of record and randomness. To test the adequacy of the length of record, the analysis window can be assessed by clicking on 'Statistical Analysis' module (Figure 7). In this method, the user has to enter the values of the hydrologic variable in the spreadsheet. The model te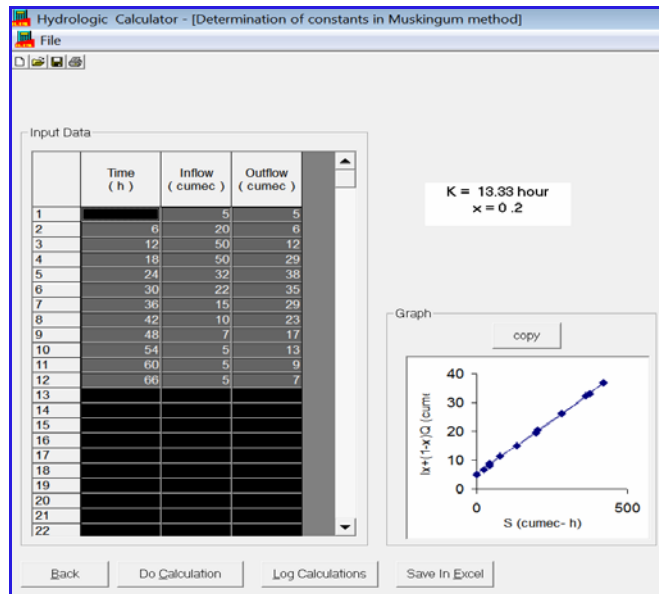sts the input data series for adequacy of the length of the record using the Mockus model and displays the results in developed module.

4.6   Evapotranspiration estimation

To estimate the evapotranspiration using the Thornthwaite method, the input window can be opened by clicking on the 'evapotranspiration analysis' module (Figure 8). In the input window, a spreadsheet is displayed to enter the mean monthly temperature and mean sunshine hours for each month. Potential evapotranspiration (PET) values can be obtained by clicking on the 'Do Calculation' button. Stepwise calculations can be saved in a log file (.txt) by clicking on the Log Calculations button (Appendix A4).

Figure 7   Testing adequacy of length of records using Mockus model
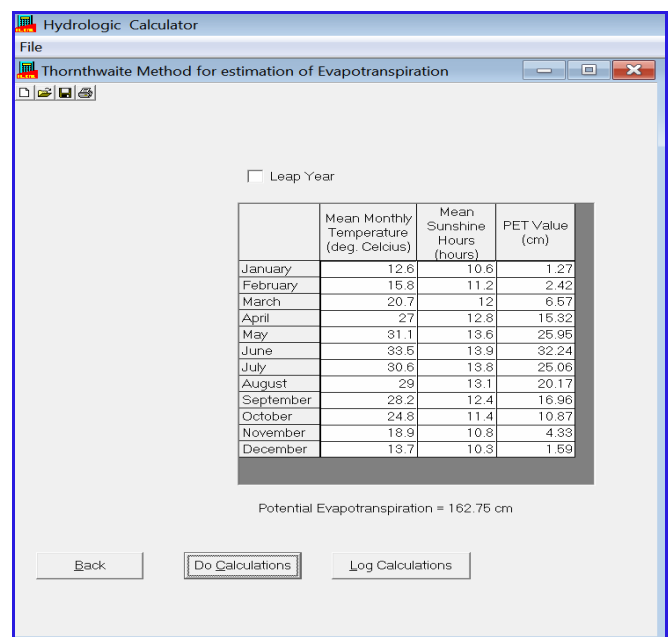
Figure 8   Evapotranspiration estimation using Thornthwaite method

4.7   Infiltration estimation

The analysis window for calculating Green-Ampt infiltration parameters is accessed through the Infiltration analysis module (Figure 9). The cumulative infiltration data (cm) with respect to time (s) can be entered in the spreadsheet and the model parameters a and k can be calculated by clicking on the 'Do Calculation' command. The graphical comparison of actual and model values along with the Green-Ampt fitted equation are also

displayed (Figure 9). Stepwise calculations can be saved in a log file (.txt) by clicking on the 'log calculations' button (Appendix A5).
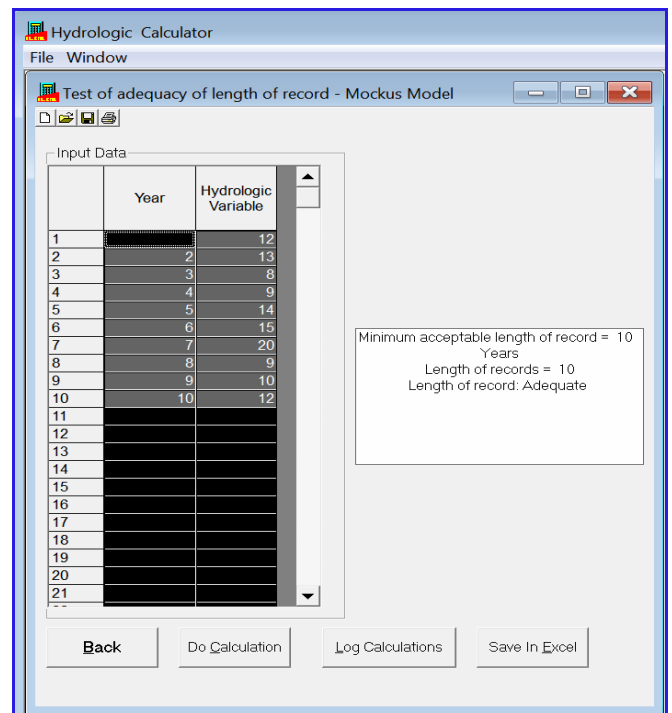

Figure 9   Estimation of Green-Ampt parameters

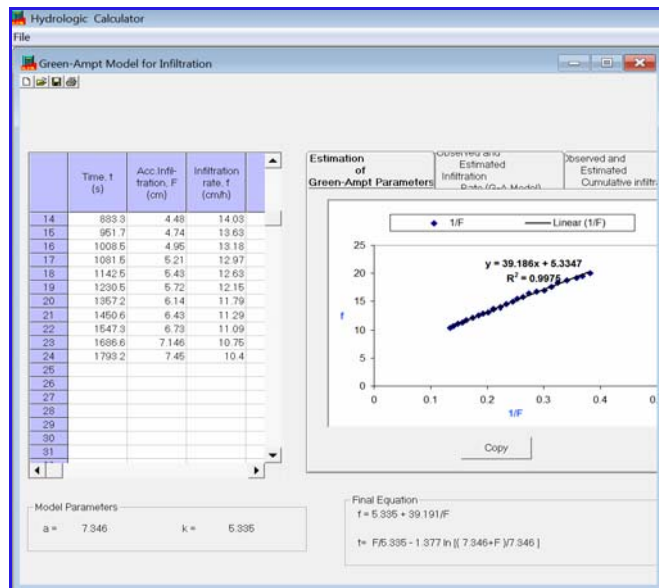## 4.8   Stage-discharge analysis

Rating curve is a relationship between the gauge height and discharge, and is used for estimating the discharge corresponding to known gauge height. To calculate discharge at particular gauge height, the analysis window can be assessed by clicking on the 'stage-discharge analysis' module. Figure 10 shows the results related to rating curve analysis. The detailed generated stepwise procedure for analyzing the rating curve is shown in Appendix A6. Inside the active window, input data frame contains a spreadsheet for entering the data related to gauge height and discharge. The user has to specify the value of gauge height at zero discharge. The output contains information on the coefficient of correlation and graphical representation of rating curve. In case the user does not know the gauge height at zero discharge, the model asks for a permission to calculate it. Once the calculation is over, the user is able to calculate discharge for different gauge heights.

Similar types of windows were developed for different sub-modules of runoff, hydrograph, flood routing, frequency analysis, evapotranspiration and infiltration estimation, and stage-discharge relationships. Due to the similarity in analyzing these hydrological processes, the developed windows are not shown here. Further, the software is equipped with a help file for

user's reference. The help file contains the detailed information on the step by step procedure of working of software.

A pilot validation study was conducted from under graduation and research students of various institutes in India and one institute in Nepal to determine the effectiveness of the Hydrologic Calculator tool in solving and simulating hydrological processes. Several suggestions were welcomed from the participants during this validation and efforts are always made to improve this tool. Hydrologic Calculator was effective in facilitating students' learning and understanding of hydrologic concepts. Thus, the software is validated successfully and can be used as a professional tool to teach and analyze various hydrological processes.
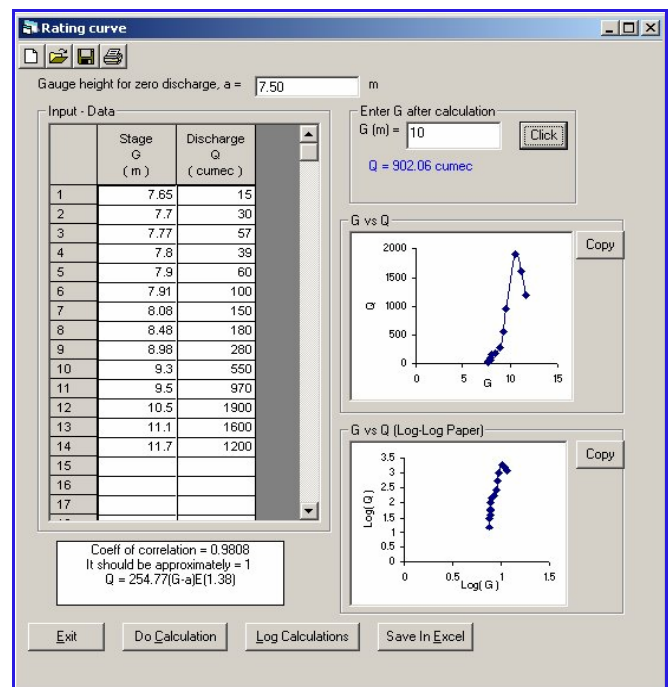
Figure 10   Stage-discharge analysis using Rating curve method

5   Conclusions

Teaching undergraduate level hydrology has always been a longstanding challenge for students (Nash et al., 1990; Ruddell and Wagener, 2015) due to diversity from both the engineering and science backgrounds with very different educational foci. Further, the students have to understand both the general model concepts and be able to use particular computer programs, when learning to apply models. In this study, a user-friendly windows based comprehensive software package (Hydrologic Calculator) is presented for the analysis of hydrological

data. The model covers different techniques for analysis of hydrologic data dealing with rainfall, runoff, hydrograph, flood routing, frequency analysis, evapotranspiration estimation, infiltration models, and stage-discharge analysis. For each analysis, the model provides several options to the user. Furthermore, the model includes GUI and a system to store the result in a local file system. The important property of the GUI is that it allows user to select a particular method among various available methods for a given analysis, edit, and retrieve input data, and display of results both in table or graphical forms. It also allows the user to save the step wise calculations in a log file (.txt format). The "Hydrologic Calculator" also saves the step-wise calculation of the problems and thus the print of the file can be taken and used as a guideline. The graphs, etc. can be copied and can be saved in bmp/gif/jpg format.

The completed methods of "Hydrologic Calculator" model were validated or tested with the help of standard examples from different textbooks. The results obtained using the Hydrologic Calculator matched exactly with the respective results given in the source. Thus, it can be concluded that the "Hydrologic Calculator" model is validated successfully and can be used to perform rainfall, runoff, hydrograph, flood routing, statistical analysis, evapotranspiration estimation, infiltration models analysis, and rating curve analysis. The adaptability of this software will make teaching and learning of basic hydrology more interesting and stimulating. Further, it will prove a good analytical tool for field engineers. The software will have a wide application in both teaching and research in the several disciplines related to water and the environment.

Abbreviations

Abbreviation	Full title
WHAT	Web GIS based Hydrograph Analysis Tool
WBNM	Watershed Bounded Network Model
IHACRES	Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Stream-flow data
HEC-SSP	Hydrologic Engineering Center-Statistical Software Package
RRL	Rainfall Runoff Library
UH	Unit Hydrograph
DRH	Direct Runoff Hydrograph
FH	Flood Hydrograph
ISD	Inverse Square Distance

Appendix

A1: Calculation of Phi-index and effective rainfall hyetograph

GIVEN:

------

(1) Total Runoff,

R (cm)

(2) Rainfall Intensity vs Time data,

Intensity in cm h^{-1} and time in (hh:mm)

TO FIND:

----

(1) Phi-Index (cm h^{-1})

(2) Effective Rainfall Hyetograph,

ERH (Intensity vs Time)

CALCULATIONS AND RESULTS:

----

(1) Total Runoff = 5.8 cm

(2) Time distribution of the storm:

Time (h)	Incremental Rainfall (cm)
09.00	00.00
10.00	00.40
11.00	00.90
12.00	01.50
13.00	02.30
14.00	01.80
15.00	01.60
16.00	01.00
17.00	00.50

Time Interval (h)	Rainfall (cm)
01.00	00.00
01.00	00.40
01.00	00.90
01.00	01.50
01.00	02.30
01.00	01.80
01.00	01.60
01.00	01.00

(3) Total Infiltration = 9.5 − 5.8 = 3.7

(4) Assume te = time of rainfall excess = 8 hr for the first trial

Hence,

$$\text{Phi} = \frac{3.7}{8} = 0.4625$$

But this value of Phi makes few rainfall(s) ineffective where,

Time = 9 hr and Magnitude = 0 cm

Time = 10 hr and Magnitude = 0.4 cm

(5) Subtracting above rainfall(s) and modifying the value of te

Now te = 6 hr

Therefore,

$$Phi = \frac{3.3}{6} = 0.55$$

Hence, Phi-Index = 0.55 cm h^{-1}

Rainfall Excess Duration = 6 hr

A2: Changing the duration of a unit hydrograph

GIVEN:

------

(1) Duration of the original UH (D hr)

(2) Duration of the required UH (t hr)

(3) Ordinates of the original UH

CALCULATIONS AND RESULTS:

S Curve Method

Steps:

(1) D = 4 hr

(2) t = 12 hr

(3) Develop D hr (4 hr) S-Curve using standard technique (col.4)

(4) Develop another D-hr (4 hr) S-Curve lagged by t hr (12 hr) from the first one (col.5)

(5) Ordinate (Sa - Sb) represents a DRH by t hr (12 hr) effective rainfall and t/D (3)magnitude (col.6)

(6) t hr (12 hr) UH = ((Sa - Sb) × D)/t (col.7)

Time (hr)	4 hr UH ordinates (cumec)	S-Curve addition (cumec)	S-Curve ordinate (cumec) (2) + (3)	S-Curve lagged by 12 hr (cumec)	Sa - Sb (4) - (5)	12 hr UH ordinates (cumec) (6)/(t/D)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
000	000.00	000.00	000.00	000.00	000.00	000.00
004	020.00	000.00	020.00	000.00	020.00	006.67
008	060.00	020.00	080.00	000.00	080.00	026.67
012	150.00	060.00	230.00	000.00	230.00	076.67
016	120.00	150.00	350.00	020.00	330.00	110.00
020	090.00	120.00	440.00	080.00	360.00	120.00
024	066.00	090.00	506.00	230.00	276.00	092.00
028	050.00	066.00	556.00	350.00	206.00	068.67
032	032.00	050.00	588.00	440.00	148.00	049.33
036	020.00	032.00	608.00	506.00	102.00	034.00
040	010.00	020.00	618.00	556.00	062.00	020.67
044	000.00	010.00	618.00	588.00	030.00	010.00
048	000.00	000.00	618.00	608.00	010.00	003.33
052	000.00	000.00	618.00	618.00	000.00	000.00

A3: Hydrologic flood routing: determination of Muskingum coefficients k and x

GIVEN:

------

(1) Inflow Hydrograph

(2) Outflow Hydrograph

TO FIND:

Muskinghum Equation Coefficients:

(1) K

(2) x

CALCULATIONS AND RESULTS:

Time (hr)	Inflow I (cumec)	Outflow Q (cumec)	I-Q (cumec)	Average I-Q (cumec)	delta S (5) × delta t (cumec hour)	Storage S Cumulative (6) (cumec hour)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
00	05.00	05.00	000.00	000.00	000.00	000.00
06	20.00	06.00	014.00	007.00	042.00	042.00
12	50.00	12.00	038.00	026.00	156.00	198.00
18	50.00	29.00	021.00	029.50	177.00	375.00
24	32.00	38.00	−006.00	007.50	045.00	420.00
30	22.00	35.00	−013.00	−009.50	−057.00	363.00
36	15.00	29.00	−014.00	−013.50	−081.00	282.00
42	10.00	23.00	−013.00	−013.50	−081.00	201.00
48	07.00	17.00	−010.00	−011.50	−069.00	132.00
54	05.00	13.00	−008.00	−009.00	−054.00	078.00
60	05.00	09.00	−004.00	−006.00	−036.00	042.00
66	05.00	07.00	−002.00	−003.00	−018.00	024.00

							[x.I + (1–x).Q] (cumec)							
x=0.00	x=0.02	x=0.04	x=0.06	x=0.08	x=0.10	x=0.12	x=0.14	x=0.16	x=0.18	x=0.20	x=0.22	x=0.24	x=0.26	x=0.28	x=0.30
05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0	05.0
06.0	06.3	06.6	06.8	07.1	07.4	07.7	08.0	08.2	08.5	08.8	09.1	09.4	09.6	09.9	10.2
12.0	12.8	13.5	14.3	15.0	15.8	16.6	17.3	18.1	18.8	19.6	20.4	21.1	21.9	22.6	23.4
29.0	29.4	29.8	30.3	30.7	31.1	31.5	31.9	32.4	32.8	33.2	33.6	34.0	34.5	34.9	35.3
38.0	37.9	37.8	37.6	37.5	37.4	37.3	37.2	37.0	36.9	36.8	36.7	36.6	36.4	36.3	36.2
35.0	34.7	34.5	34.2	34.0	33.7	33.4	33.2	32.9	32.7	32.4	32.1	31.9	31.6	31.4	31.1
29.0	28.7	28.4	28.2	27.9	27.6	27.3	27.0	26.8	26.5	26.2	25.9	25.6	25.4	25.1	24.8
23.0	22.7	22.5	22.2	22.0	21.7	21.4	21.2	20.9	20.7	20.4	20.1	19.9	19.6	19.4	19.1
17.0	16.8	16.6	16.4	16.2	16.0	15.8	15.6	15.4	15.2	15.0	14.8	14.6	14.4	14.2	14.0
13.0	12.8	12.7	12.5	12.4	12.2	12.0	11.9	11.7	11.6	11.4	11.2	11.1	10.9	10.8	10.6
09.0	08.9	08.8	08.8	08.7	08.6	08.5	08.4	08.4	08.3	08.2	08.1	08.0	08.0	07.9	07.8
07.0	07.0	06.9	06.9	06.8	06.8	06.8	06.7	06.7	06.6	06.6	06.6	06.5	06.5	06.4	06.4

Plot [x.I + (1–x).Q] vs Storage, S for all values of x

Choose that value of x which gives the thinnest loop i.e close to a straight line

Fit a straight line through points for above value of x

Inverse slope of the straight line will give the value of K

Here,

$x = 0.2$

$K = 13.3$ hours

A4: Thornthwaite evapotranspiration calculation

Given: (1) Mean monthly Temperatures in degree Celsius. (t)

(2) Mean monthly Sunshine Hours. (h)

Formulae Used:

(1) Monthly Heat Index,

$$i = (t/5)^{1.514}$$

(2) Annual or Seasonal heat index,

$I = $ sum of all i's

(3) An empirical exponent,

$a = 0.000000675 \times I^3 - 0.0000771 \times I^2 + 0.01792 \times I + 0.49239$

(4) Unadjusted Potential Evapotranspiration (in cm),

$$e = 1.6(10\, t/I)^a$$

(5) Correction Factor,

$c = $ (sunshine hours x no. of days in month) / (12×30)

(6) Corrected Potential Evapotranspiration (in cm),

$$pet = e \times c$$

(7) Total Potential Evapotranspiration (in cm),

$PET = $ sum of all pet's

Mean Monthly Temperature (deg. C) (t)	Mean Monthly Sunshine Hours (hours) (h)	Monthly Heat Index (i) $(t/5)^{1.514}$	Unadjusted PET (cm) (e) $1.6(10t/I)^a$	Correction (c) (h*days)/(12*30)	CorrectedValues of PET (cm) (e*c)
12.60	10.60	4.052	1.387	0.913	1.266
15.80	11.20	5.709	2.777	0.871	2.419
20.70	12.00	8.593	6.359	1.033	6.571
27.00	12.80	12.848	14.364	1.067	15.322
31.10	13.60	15.915	22.161	1.171	25.953
33.50	13.90	17.811	27.835	1.158	32.243
30.60	13.80	15.529	21.086	1.188	25.057
29.00	13.10	14.316	17.884	1.128	20.174
28.20	12.40	13.723	16.414	1.033	16.961
24.80	11.40	11.297	11.068	0.982	10.865
18.90	10.80	7.487	4.811	0.900	4.330
13.70	10.30	4.600	1.793	0.887	1.591
		I = 132			PET = 162.752

a = 3.066918

A5: Infiltration model: Green-Ampt model

GIVEN:

------

(1) Infiltration Measurements (Infiltration depth and rate vs time)

TO FIND:

----

(1) Green-Ampt Model Parameters K and a

(2) Green-Ampt Model Equation for Infiltration

CALCULATIONS AND RESULTS

----

(1) Green-Ampt Model is expressed as

$$f = K + K - \frac{a}{F}$$

$$t = \frac{F}{K} \ln\left(\frac{a+f}{a}\right) + C$$

where, K and a are model parameters; F is infiltration depth; f is infiltration rate; C is constant of integration.

(2) Relationship between f and F is:

$$f = K + K - \frac{a}{F}$$

(3) Plotting graph of f vs F and fitting a straight line,

K is given by the y intercept and K.a is given by the slope

(4) Calculations:

Time t (min)	Accumulated Infiltration F (cm)	Infiltration Rate f (cm h^{-1})	1/F	F (Model) (cm)	f (Model) (cm h^{-1})
0472.2	02.62	20.02	00.38	02.52	20.29
0489.7	02.72	19.54	00.37	02.62	19.74
0507.5	02.80	19.21	00.36	02.72	19.33
0531.5	02.94	18.75	00.34	02.85	18.66
0559.8	03.08	18.32	00.32	03.00	18.06
0582.3	03.19	17.60	00.31	03.11	17.62
0609.4	03.32	17.00	00.30	03.25	17.14
0644.1	03.48	16.70	00.29	03.41	16.60
0682.9	03.66	16.42	00.27	03.59	16.04
0714.7	03.80	15.74	00.26	03.73	15.65
0751.1	03.95	15.43	00.25	03.89	15.26
0783.9	04.09	14.93	00.24	04.03	14.92
0831.2	04.28	14.46	00.23	04.22	14.49
0883.3	04.48	14.03	00.22	04.43	14.08
0951.7	04.74	13.63	00.21	04.70	13.60
1008.5	04.95	13.18	00.20	04.91	13.25
1081.5	05.21	12.97	00.19	05.17	12.86
1142.5	05.43	12.63	00.18	05.39	12.55
1230.5	05.72	12.15	00.17	05.69	12.19
1357.2	06.14	11.79	00.16	06.12	11.72
1450.6	06.43	11.29	00.16	06.42	11.43
1547.3	06.73	11.09	00.15	06.72	11.16
1686.6	07.15	10.75	00.14	07.15	10.82
1793.2	07.45	10.40	00.13	07.46	10.59

(5) From step 3, we get,

    K = 5.33473

    K.a = 39.186

or,   a = 7.346

(6) Green-Ampt Model Parameters:

    K = 5.335

    a = 7.346

(7) Green-Ampt Model Equation:

    f = 5.335 + 39.191/F

    t = F/5.335 − 1.377 ln [(7.346+F)/7.346]

A6: Stage-discharge relationship: Rating curve method

GIVEN:

------

(1) Gauge Height for zero discharge, a (m) [optional]

(2) Gauge Reading (Stage) vs Discharge data

    Stage in m and Discharge in cumec

(3) Gauge Reading at which discharge to be calculated, G (m) [optional]

TO FIND:

----

(1) Stage - Discharge Relationship

(2) Coefficient of Correlation

(3) Gauge Height for zero discharge, a (m) [if required]

CALCULATIONS AND RESULTS

----

(1) Gauge Height for zero discharge, a = 7.50 m

(2) Input: First two columns of the table.

(3) The gauge - discharge equation is:

$$Q = Cr.(G − a)\text{^}beta \qquad (1)$$

where, Q is stream discharge; G is gauge height (stage); a is gauge Height for zero discharge; Cr and beta are rating curve constants.

By taking logarithms of eqn (1)

    log Q = beta . log (G−a) + log Cr

or   Y = beta . X + b

where, Y = log Q and X = log(G−a).

Values of X, Y and XY are calculated for all data as shown:

Gauge G (m)	Discharge Q (cumec)	(G-a)	X = log(G-a)	Y = log Q	(XY) (cumec)
07.65	0015.00	00.15	−0.824	1.176	−0.969
07.70	0030.00	00.20	−0.699	1.477	−1.032
07.77	0057.00	00.27	−0.569	1.756	−0.998
07.80	0039.00	00.30	−0.523	1.591	−0.832
07.90	0060.00	00.40	−0.398	1.778	−0.708
07.91	0100.00	00.41	−0.387	2.000	−0.774
08.08	0150.00	00.58	−0.237	2.176	−0.515
08.48	0180.00	00.98	−0.009	2.255	−0.020
08.98	0280.00	01.48	0.170	2.447	0.417
09.30	0550.00	01.80	0.255	2.740	0.700
09.50	0970.00	02.00	0.301	2.987	0.899
10.50	1900.00	03.00	0.477	3.279	1.564
11.10	1600.00	03.60	0.556	3.204	1.782
11.70	1200.00	04.20	0.623	3.079	1.919

(4) From the above table,

$$sum\ (X) = -1.2611 \qquad sum\ (Y) = 31.9460$$

$$sum\ (XY) = 1.4337$$

$$sum\ (X^2) = 3.2382 \qquad sum\ (Y^2) = 79.0801$$

$$(sum\ (X))^2 = 1.5903 \qquad (sum\ (Y))^2 = 1020.5478$$

(5) Now, from regression line,

$$beta = \frac{N.sum(XY) - sum(X).Sum(Y)}{N.sum(X^2) - (Sum(X))^2}$$

$$= \frac{(14 \times 1.434) - (-1.261)(31.946)}{(14 \times 3.238) - 1.590} = 1.380$$

$$sum(Y) - beta.sum(X)$$

$$b = \frac{sum(Y) - beta.sum(X)}{N}$$

$$= \frac{(31.9460142757761) - 1.380(-1.261)}{14} = 2.406$$

Hence,

$$Cr = 254.769$$

(6) The required gauge-discharge relationship is therefore

$$Q = 254.8(G-a)^{1.380}$$

(7) Coefficient of correlation,

$$r = \frac{N.sum(XY) - (sum(X))(sum(Y))}{\sqrt{[N.sum(X^2) - (sum(X))^2][N.sum(Y^2) - (sum(Y))^2]}}$$

$$= 0.981$$

The value of r is be close to 1.

References

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