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System identification and subsequent discharge estimation based on level data alone—Gradually varied flow condition

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ABSTRACT

Discharge estimation via depth/stage measurement alone in a channel reach with unknown roughness coefficient seems to be important, since it can replace the rating curve development process with all its impediments in practice. Many attempts have been made in this regard especially in the last decade which led to the development of methodologies based on hydraulic or hydrologic routing approaches. Although flow regime is considered to be transient in the literature associated to this subject, it seems that the flow under steady state condition is ignored. In this study the system identification (roughness coefficient determination) and subsequent discharge estimation is carried out for the steady state gradually varied flow condition in two cases: the first case is a wide rectangular channel with constant primarily unknown Chezy's roughness coefficient and the second one is a nonprismatic trapezoidal channel with constant primarily unknown Manning's roughness coefficient. In this regard, it was assumed that there exists a number of depth/stage observations along the reach and it was attempted to find an appropriate pair of roughness coefficient and discharge which produces a longitudinal steady state gradually varied flow profile similar to the one observed. It is shown that the problem can be treated as an optimization problem in which the sum of the squared deviations of calculated flow profile depths from the observed one is considered as the objective function. In order to choose an appropriate optimum search technique, the objective function contour map is drawn which demonstrates that the objective function surface is flat and highly near optimum in a wide range of roughness coefficient and discharge pairs. Hence, the derivative-based optimization approaches were rejected. Since the genetic algorithm is a derivative free adaptive exploratory optimum search technique parallel processing capability on a set of candidates, this method is utilized in this study to solve the corresponding optimization problem. The standard genetic algorithm is modified in order to prevent getting trapped in local optima. This modification guarantees the achievement of the global optimum solution. This GA-based optimization technique for system identification and subsequent discharge estimation in channel with depth/stage observations alone in steady state gradually varied flow condition leads to the desired performance through which the objective pair of roughness coefficient and discharge can be obtained in both wide rectangular and nonprismatic trapezoidal geometric conditions.

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1. Introduction

Flow measurement in the natural and/or artificial open channels seems to be one of the most important fields of study in hydrology during the last two centuries, as it is vitally required in various stages of any comprehensive and coordinated water resources planning and management project in a river basin. In this regard, hydrologists have conducted many studies which led to the creation of several techniques for surface flow measurement and discharge estimation [1,2]. Among these proposed methods, using stage-discharge relation or rating curve seems to be more prevalent which is nowadays widely used in practice. Nevertheless, this method suffers from several important drawbacks which persuaded the hydrologists to enhance their studies in the field of flow measurement [3].

Rating curve development at any river cross-section requires sufficient number of careful and concurrent measurement of stage and velocity in the river cross section and also it needs subsequent spatial integration for corresponding discharge computation. Hence, this method demands for velocity determination from field surveying, which is quite cumbersome and is not likely possible during severe floods and night time. Moreover, as the river bed is exposed to scouring and sedimentation as well as the growth and decay of aquatic vegetation and also accumulation of organic debris, rating curve development must be updated periodically to account for the aforementioned irregularities occurring in the

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Nomenclature

A	cross sectional area of flow
A_1	integration constant
C	Chezy's roughness coefficient
g	the acceleration of gravity
n	Manning's roughness coefficient
Q	volumetric flow rate
q	volumetric flow rate per unit width of channel
S_0	bottom slope
S_f	friction slope
T	top width of flow cross section
u	y/y_n
x	distance in the direction of flow
y	vertical depth of flow
y_c	critical depth
y_n	normal depth
α	energy correction factor
Δ	small increment
Φ	Bresse function

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flow conduit. In other words, the development step with all its impediments and difficulties must be carried out periodically. Furthermore, loop nature of the stage-discharge relationship due to the hysteresis effect of unsteady flow in the rivers with mild bed slope, and variation of the loop shape from one event to another (i.e., event-based nature of this relationship) are not entirely considered in the traditional rating curve development method which is widely used in practice.

Although many attempts have been made to use Saint–Venant equations for the achievement of a nonlinear model accounting for loop nature of rating curves [4,5], recourse to the famous Jones formula and its variants, is the most widely accepted and recommended approach in the last century's literature [6–8]. Since these methods call for accurate information about several geometric and hydraulic parameters, which are normally determined through field surveying, their application is difficult and cumbersome in practice. These limitations persuaded the hydrologists to develop discharge estimation methods indirectly with no need for velocity measurement in both development and application stages and also with less requirement for field tuned parameters.

Many studies have been conducted in the last three decades in order to estimate river flow discharge using stage or flow depth measurement alone. In this regard, two general approaches were considered. In the first approach, hydrologists use hydraulic structures such as broad or sharp crested weirs to establish control section in which a known physically-based relation between stage and discharge exists [9–11]. This physically-based relation acts as the required rating curve, and the development stage with its corresponding deficiencies is not entirely needed. Although this approach seems to be efficient, it must be considered that construction of these hydraulic structures is relatively expensive and it requires manipulating the environment which must be avoided as much as possible. Moreover, any inconsistency between ideal and constructed structure during operation, which is the rule rather than the exception, would lead to unexpected performance which somehow reduces the reliability of this approach. On the other hand, due to the requirement for a hydraulic structure, this flow measurement approach is typically a part of more comprehensive project in a region which is selected with especial considerations, and consequently cannot be implemented in an arbitrary river section.

In the second approach which was recently proposed, the hydraulic or hydrologic river flow routing is utilized to achieve river flow hydrograph from stage or depth measurement alone. Although several studies was performed in this regard [12–16], it seems that the methodology proposed in the study conducted by Perumal et al. [17] is the first recorded one which is truly independent from velocity measurement in the river reach and section. This methodology is based on the results of their earlier studies in which the concepts of hydraulic routing is employed to rationalize the parameter adaptation in Muskingum method which is the most dominant approach in hydrologic streamflow routing [18–21]. This methodology has been applied in several studies and appropriate results have been obtained and reported [22,23]. Later studies conducted by other investigators considered one dimensional unsteady flow governing equations to find the discharge values associated with the observed stages [3,24]. Diffusive model is used in recent studies to avoid the need arising from channel cross sectional geometries. Computation of the average roughness coefficient in the calibration phase was achieved via three stage measuring sections or two measuring sections combined with an assumption for a section located reasonably far downstream. Appropriate performance was reported for these developed methodologies in the discharge estimation in a channel using stage measurement alone.

Although the average roughness coefficient value is calibrated in the aforementioned studies, it seems that the unsteadiness along the river reach is an essential requirement for their calibration process. In other words, the roughness coefficient and subsequent flow computation were not considered when the flow regime was steady and non-uniform. However, what must be done if the flow was in the steady state condition? Is it possible to carry out the system identification and subsequent discharge estimation process in the steady state flow condition where stage/depth observations are available? It seems that the possibility of the roughness coefficient determination and subsequent discharge estimation in the steady state flow condition with known longitudinal water surface profile is missing from the existing literature. This study is accomplished to explore the possibility of system identification (roughness coefficient determination) and subsequent discharge estimation in the streams with stage/depth observations alone in the steady state flow condition.

This paper is organized as follows: an overview on the gradually varied flow and its solution approaches is provided in Section 2. Subsequently, in Section 3, the problem statement and appropriate optimization technique selection is discussed. An overview on genetic algorithm and the GA-based optimum search program which is developed in this study is offered in the last part of Section 3. Then, the discussion of results is presented and finally the concluding remarks are provided.

2. An overview on the gradually varied flow

2.1. Basic governing equation

Gradually varied flow governing equation for a nonprismatic channel with arbitrary cross sectional geometry, demonstrated in Fig. 1, can be written as follows [25]:

$$\frac{dy}{dx} = \frac{S_0 - S_f + \alpha Q^2/gA^3 \partial A/\partial x \mid y = cte}{1 - \alpha (Q^2 T/gA^3)} \tag{1}$$

where x is the space variable along the flow direction, y is the flow depth, S_0 and S_f are bed slope and friction slope, respectively, Q is

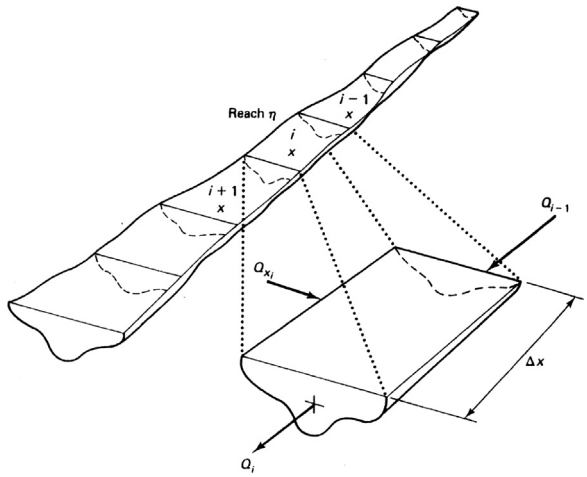

Fig. 1. A nonprismatic channel with arbitrary cross sectional geometry.

the volumetric flow rate, A is the cross sectional area of flow and T is the flow top width. It must also be mentioned that α is the kinetic energy coefficient which is assumed to be unity in practical applications and g is the acceleration due to gravity. If the channel is prismatic; the aforementioned equation can be simplified to the following equation:

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \alpha Q^2 T / g A^3} \tag{2}$$

In those situations where the streamlines are reasonably straight and parallel and the bed slope is small, the pressure distribution across the fluid flow is hydrostatic [25]. The problem can be stated as given a series of water depth measurements along the channel reach, could it be possible to compute the channel roughness and subsequent discharge uniquely?

2.2. Solution approaches

The steady state gradually varied flow problems were solved via several approaches which can broadly be classified into three different categories [26]. In the first category, analytical solution investigation was considered and many attempts have been made in this regard during the last two centuries. It seems the study conducted by Bresse (1868) cited in Ref [25], is the first recorded attempt in which the analytical solution to the gradually varied flow equation is found for the special case of wide rectangular channel with constant Chezy′s roughness coefficient in the computational reach. Several studies were performed later in order to find the analytical solutions for ordinary rectangular, trapezoidal and triangular channels based on constant or variable Chezy′s or Manning′s roughness coefficient [26–30]. These attempts led to analytical solutions for various types of cross sections. These methods normally transform the differential/integral governing equation solution into an equivalent algebraic equation solution in which the roots cannot be calculated explicitly in most of the cases. Hence, they are typically not easy to use and consequently they have limited applications.

In the second category, it was attempted to find analytical solution for the integral form of governing equation, through using an assumed relation between the conveyance factor and the flow depth [6]. There is no limitation for the channel cross sectional shape, since the relation between the conveyance factor and flow depth is approximated in these methods.

In the third category, it was tried to find the numerical solution to the ordinary differential equation which governs the steady state gradually varied flow. These methods are widespread from simple standard step method to predictor–corrector method. Due to numerical base of these methods and the requirement for numerical integration, the error embedded in numerical integration approximations is directly transferred into the solution in the water level profile computations.

As the focus of the current study is to explore the possibility of system identification and subsequent discharge estimation based on a series of water depth measurements alone, there is a vital need for choosing a reliable solution methodology which leads to relatively error-free solution. As a result, the methods which are classified in the first category were considered for the first test case. Due to its simplicity, the first numerical test in this study was conducted in the case of wide rectangular channel with constant Chezy′s roughness coefficient. In order to investigate a more general case, the second numerical test was performed in the case of nonprismatic trapezoidal channel with constant Manning′s roughness coefficient using approaches in the third category (i.e., predictor–corrector method). In the next two sections, first the wide rectangular channel and the solution found by Bresse (1868) will be reviewed and subsequently the nonprismatic trapezoidal channel and the utilized solution methodology of the aforementioned channel in the gradually varied flow condition will be briefly discussed. Needless to say, when the flow regime is steady and uniform, which is an exception rather than the rule, this system identification and subsequent discharge estimation cannot be achieved as the solution is not unique.

2.3. Wide rectangular channel and Bresse′s analytical solution

Mathematical manipulation of Eq. (2) in wide rectangular channel case with constant Chezy′s coefficient leads to [25]:

$$\frac{dy}{dx} = S_0 \frac{1 - (y_n/y)^3}{1 - (y_c/y)^3} \tag{3}$$

Integration of this equation leads to the following algebraic equation [25]:

$$S_0 x = y - y_n \left[1 - \left(\frac{y_c}{y_n} \right)^3 \right] \Phi \tag{4}$$

where

$$\Phi = \int \frac{du}{1 - u^3} = \frac{1}{6} \log \frac{u^2 + u + 1}{(u-1)^2} - \frac{1}{\sqrt{3}} \tan^{-1} \frac{\sqrt{3}}{2u+1} + A_1 \tag{5}$$

where $u = y/y_n$ and A_1 is the integration constant. It must be noted that in these equations y is the flow depth and y_n and y_c are normal and critical flow depths, respectively. Although this equation is explicit in x, it is quite implicit in water depth, y. In the latter case, the solution can be found via application of a recursive root search technique (such as fixed point method) due to the nonlinearity of the governing equation.

2.4. Nonprismatic trapezoidal channel and its numerical solution

In the case of nonprismatic channel, computation of water surface profile was achieved via a particular sort of numerical scheme so called predictor–corrector method whereby Euler method was implemented in the predictor step and modified-Euler method was utilized in the corrector step. In this method, the flow depth can be computed from the following equation [31]:

$$y_{i+1} = y_i + \tfrac{1}{2}(y'_i + y'_{i+1})\Delta x \tag{6}$$

where the subscript i refers to the quantities at section x_i and a prime on y indicates the derivative of y with respect to x. It must be noted that y'_i must be computed from Eq. (1) due to the nonprismatic geometry of the channel. Since subscript $i+1$ is

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presented in both sides of Eq. (6), y_{i+1} can be obtained through a predictor–corrector process.

Several predictor–corrector schemes have been reported in the literature. In this study, the following scheme is used in which y_i' is replaced by $f(x_i,\ y_i)$.

Initial estimation of y_{i+1} can be achieved from the following equation (predictor part):

$$y_{i+1}^0 = y_i + f(x_i,\ y_i)\,\Delta x \tag{7}$$

where the superscript indicates the number of iteration. Then the first correction to the value of y_{i+1} is carried out:

$$y_{i+1}^1 = y_i + \tfrac{1}{2}\left[f(x_i,\ y_i) + f(x_{i+1},\ y_{i+1}^0)\right]\Delta x \tag{8}$$

Subsequently, the recorrection can be done in order to obtain a better value for y_{i+1}:

$$y_{i+1}^2 = y_i + \tfrac{1}{2}\left[f(x_i,\ y_i) + f(x_{i+1},\ y_{i+1}^1)\right]\Delta x \tag{9}$$

This process will be continued until no significant change occurs in the calculated values of y_{i+1} achieved from two subsequent iterations:

$$\left|y_{i+1}^j - y_{i+1}^{j-1}\right| \le \epsilon \tag{10}$$

where ϵ is a predefined acceptable tolerance and y_{i+1}^j can be calculated from the following equation:

$$y_{i+1}^j = y_i + \tfrac{1}{2}\left[f(x_i,\ y_i) + f(x_{i+1},\ y_{i+1}^{j-1})\right]\Delta x. \tag{11}$$

3. Material and method

3.1. Problem statement

As mentioned earlier, in this study, channel flow discharge estimation using depth measurement alone is considered. In this regard, several studies have been conducted in the last two decades in which it was attempted to eliminate the velocity measurement requirement in the discharge estimation process [12–16]. In the last five years, the methodologies for river flow discharge estimation using depth/stage measurement alone were proposed, developed and applied and suitable performances have been reported [17–21]. These methods are typically based on the hydrologic or hydraulic streamflow routing concepts. The main part of these proposed methodologies is the determination of the roughness coefficient of the river reach which is attempted to be determined numerically using strictly the stage data collected from the field. In these studies, system identification (roughness coefficient determination) procedures are described for unsteady state flow condition and the flow in steady state condition is not discussed.

In the steady nonuniform flow, the flow depths are not the same in various cross sections along the channel reach. Hence, depth measurements in various cross sections contain new information about the flow and consequently can be used in system identification (roughness coefficient determination) and streamflow discharge estimation. In this study, gradually varied flow condition is considered in two test cases: in the first test case, the wide rectangular channel with constant Chezy's roughness coefficient case is utilized due to the simplicity and solution accuracy. In the second one, the nonprismatic trapezoidal channel with constant Manning's roughness coefficient case is considered in order to explore the validity of the proposed methodology for a relatively more general case.

3.1.1. Test case I: wide rectangular channel with constant Chezy's roughness coefficient

As it was mentioned before, the analytical solution to the gradually varied flow in wide rectangular channels with constant Chezy's roughness coefficient can be determined through an iterative process embedded in the methodology proposed by Bresse. The first test case in this study is performed in order to determine the constant Chezy's roughness coefficient accompanied with the flow discharge in the channel, based only on the longitudinal observations of the gradually varied flow depths along the reach. In other words, in this test case, it is tried to find out the best pair of C and q, which produces the water surface profile similar to the observed one as much as possible.

Imagine a wide rectangular channel with longitudinal bed slope equal to 0.002 for which there exists a gradually varied flow profile M1 with flow depth equal to 3.0 m in the downstream section. It is assumed that $C=50\ \mathrm{m}^{0.5}/\mathrm{s}$ and $q=2.3\ \mathrm{m}^3/\mathrm{s/m}$ are the benchmark values and based on them, the longitudinal water surface profile is calculated in a reach with 1000 m length using the methodology proposed by Bresse. Next, it is pretended that this longitudinal water surface profile is observed and the aforementioned C and q are unknown which must be estimated. This water surface profile is tabulated in Table 1.

3.1.2. Test case II: nonprismatic trapezoidal channel with constant Manning's roughness coefficient

The second test case is performed in this study, in order to discuss a more general case. It must be noted that in many practical applications such as natural streams or artificial transitions, the conduit can be treated as a nonprismatic trapezoidal channel with constant roughness coefficient. Since there is no analytical solution for this case, the water surface profile calculated by the FLDWAV model is considered as the benchmark solution which is pretended as the observed water surface profile in this scenario.

Imagine a nonprismatic transition which has trapezoidal cross sectional geometry with bottom width of 3.0 m and side slopes of 1:1 in the upstream section and rectangular cross section geometry with bottom width of 13.0 m in the downstream section. This transition has 1000 m length and the change of side slopes occurs linearly in the whole transition length. The longitudinal slope of the transition is assumed to be 0.001. It is also assumed that $n=0.014$ and $Q=28\ \mathrm{m}^3/\mathrm{s}$ are the benchmark values and 3.8 m flow depth is observed in the downstream section. The water surface profile calculated by FLDWAV model using the abovementioned information is pretended as the observed water surface profile and it is attempted in this numerical test to find out the benchmark values of Q and n based only on the observed water surface profile. This water surface profile is tabulated in Table 2. The longitudinal water surface profile and the corresponding critical water depth line (CDL) and normal water depth line (NDL) along the transition is demonstrated in Fig. 2. As it is shown in Fig. 2, a gradually varied flow M1 profile exists in the abovementioned transitional channel.

Since the flow depth in subsequent channel sections are related to each other via the common gradually varied flow ordinary

Table 1
The water surface profile obtained from the analytical solution of Bresse for a wide rectangular channel in the first numerical test based on the benchmark values of roughness coefficient and flow discharge per unit width ($C=50\ \mathrm{m}^{0.5}/\mathrm{s}$ and $q=2.3\ \mathrm{m}^3/\mathrm{s/m}$).

x (m)	0	−100	−200	−300	−400	−500	−600	−700	−800	−900	−1000
y (m)	3.0000	2.8045	2.6099	2.4168	2.2257	2.0374	1.8534	1.6727	1.5018	1.3505	1.2110

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Table 2
The water surface profile obtained from the FLDWAV model solution for a nonprismatic trapezoidal channel in the second numerical test based on the benchmark values of roughness coefficient and flow discharge (n=0.014 and Q=28 m^3/s).

x (m)	0	−100	−200	−300	−400	−500	−600	−700	−800	−900	−1000
y (m)	3.8000	3.6972	3.5966	3.4991	3.3955	3.2918	3.1882	3.0815	2.9779	2.8621	2.7402

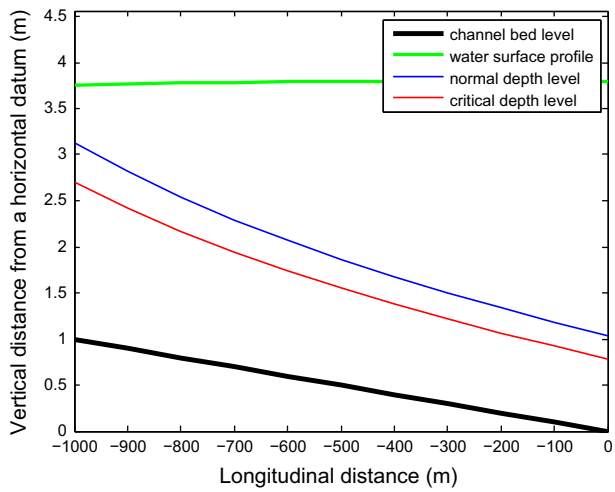

Fig. 2. Longitudinal water surface profile and corresponding critical flow depth level (CDL) and normal flow depth level (NDL) obtained as the FLDWAV model solution for the target values of roughness coefficient and flow discharge in the second numerical test.

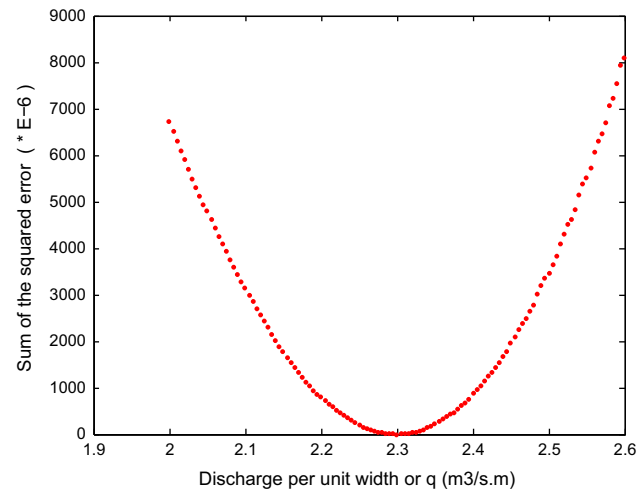

Fig. 3. Sum of the squared error related to the water surface profile calculation versus various values of q with frozen C=50 m$^{0.5}$/s in the first numerical test.

differential equation, and the flow depth in one cross section is related to roughness coefficient and discharge via the famous flow resistance equations (such as Chezy's formula or Manning's equation), the defined problem can be considered as a typical over-determined optimization problem for parameter tuning, in which the parameters roughness coefficient and flow discharge must be tuned so that the calculated water surface profile has the least deviation compared with benchmark/observed one. Hence, in this regard choosing an appropriate optimization technique is required in order to find the best pair of roughness coefficient and flow discharge, which leads to the least deviation between the calculated water surface profile and the observed one.

3.2. Selection of optimization technique

The optimization techniques are typically based on exploratory search strategies which can be classified as either derivative-based or not. The main factor which affects the selection of an appropriate optimization technique is the shape and nature of variation of the error response surface with respect to tuning parameters. In order to have a better sense of the shape and variation of response surface with calibrating parameters, the error surface is produced through utilizing various values for roughness coefficient and flow discharge and the respective water surface profile is calculated and consequently the sum of the squared error as goodness of fit criterion between the calculated longitudinal profile and the benchmark one is found. Even though the response surface behaves well when one parameter is changing while the other is fixed at its nominal value (see Figs. 3–6), a different picture emerged when both parameters are allowed to change simultaneously. As it is shown in Figs. 3–6, the response surface obtained from changing one parameter at a time is parabolic and a typical structured search such as gradient-based technique can be utilized to delineate the optimum value, such an algorithm is not efficient for the case when both parameters are changing simultaneously. Figs. 6 and 7 show the contour map of the error surface with

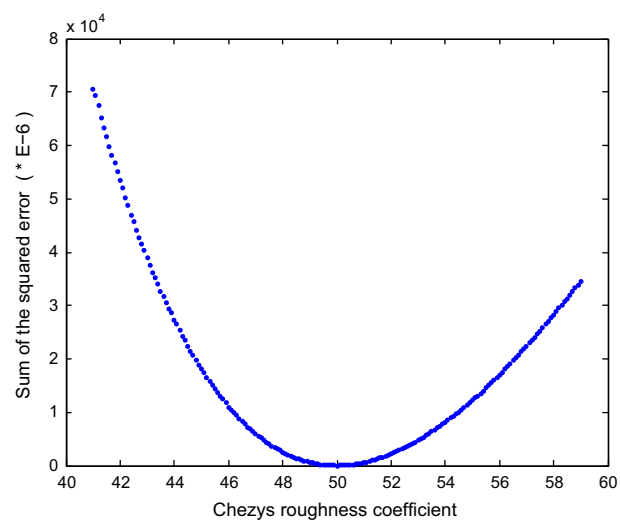

Fig. 4. Sum of the squared error related to the water surface profile calculation versus various values of C with frozen q=2.3 m^3/s/m in the first numerical test.

respect to various values of roughness coefficient and flow discharge around the benchmark values for each numerical test.

Contour lines in Figs. 7 and 8 refer to the sum of the squared error for various combinations of roughness coefficient and flow discharge. The sum of the squared error value for the water surface profile related to the benchmark values of roughness coefficient and flow discharge is equal to zero which is the global minimum (optimum) value in the whole contour map. As it can easily be seen in Figs. 7 and 8, the contour lines are not closed in the neighborhood of the optimum location and in a considerable part of the contour map (inclined relatively white band which contains the optimum pair of roughness coefficient and flow discharge), sum of the squared errors related to various combinations of roughness coefficient and flow discharge are very small and they

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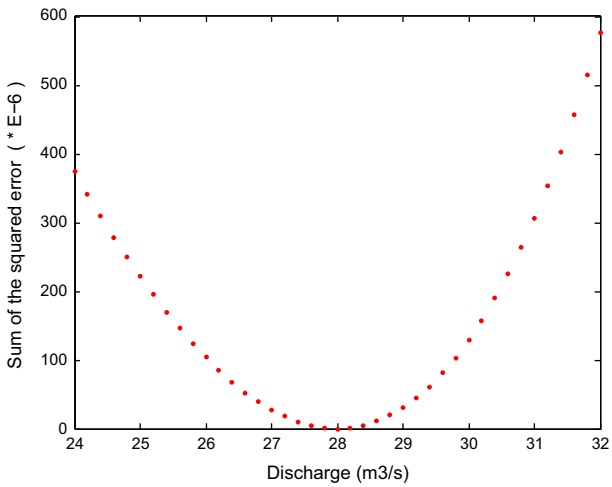

Fig. 5. Sum of the squared error related to the water surface profile calculation versus various values of Q with frozen $n=0.014$ in the second numerical test.

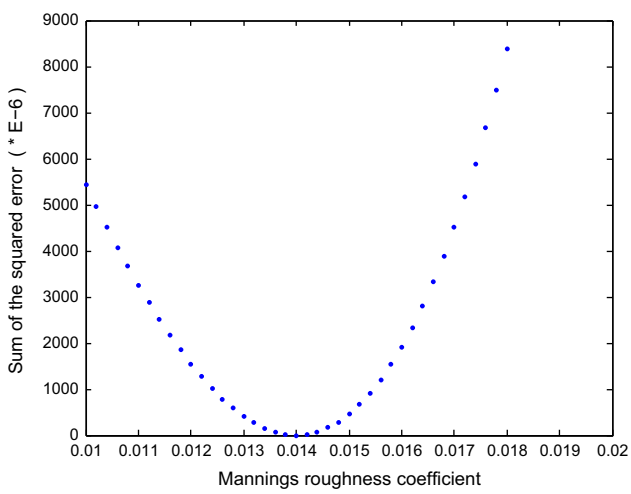

Fig. 6. Sum of the squared error related to the water surface profile calculation versus various values of n with frozen $Q=28\ m^3/s$ in the second numerical test.

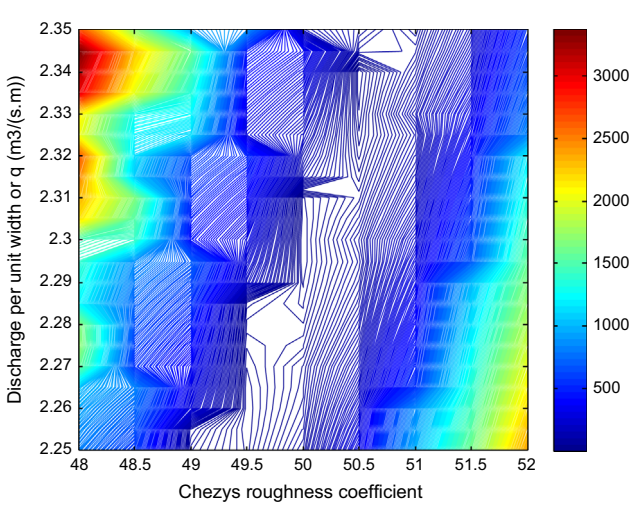

Fig. 7. Sum of the squared error contour map ($\times 10^{-6}$) for the water surface profile obtained from using various pairs of C and q in Bresse analytical solution for a wide rectangular channel in the first numerical test.

are highly near to zero. This inclined relatively white band makes it difficult to utilize a derivative-based optimization technique without trapping in local optima.

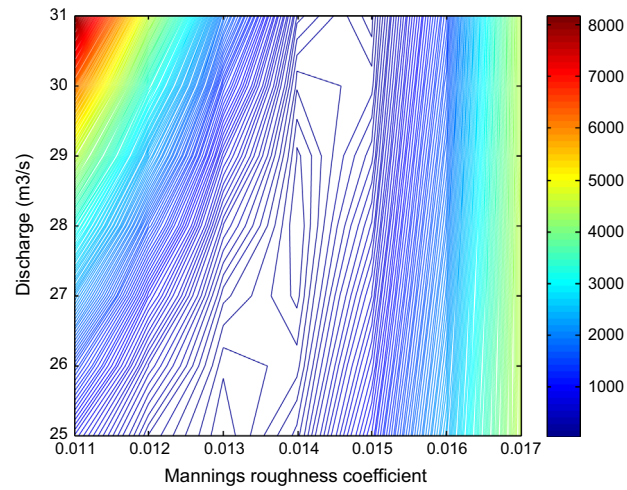

Fig. 8. Sum of the squared error contour map ($\times 10^{-6}$) for the water surface profile obtained from using various pairs of n and Q in numerical solution for a nonprismatic trapezoidal channel in the second numerical test.

As it is shown in Figs. 7 and 8, the error indicator surface would not be considered as well behaved when submitted to a derivative-based optimization algorithm. In other words, derivative-based techniques will be trapped in local minima due to their possibly inappropriate starting points or computational considerations in the pairs located on the inclined white band. Hence, a derivative free heuristic search strategy must be utilized to solve the optimization problem properly. The required optimum search technique must have two main properties. First, the calculation process must be started from a set of initial points not a single point. As the second requirement, this technique must utilize the objective function information, not its derivatives or other auxiliary knowledge. Since the genetic algorithm is a derivative free adaptive heuristic optimum search technique with parallel processing on a set of candidates, this method is used in this study to solve the above optimization problem.

3.3. Genetic algorithm (GA)

Genetic algorithm is an adaptive exploratory search algorithm based on the basic ideas of natural selection and genetics. This algorithm belongs to the larger class of evolutionary algorithms (EA), which solve the optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. In other words, genetic algorithm is a kind of stochastic optimization technique which represents an intelligent utilization of random search within a predefined search space in computational process [32].

Although no universal definition exists, genetic algorithms are composed of four principal components or steps. Initial population of potential solutions must be generated in the first step. This initial generation can be performed randomly or manually in the problem domain. The objective function must be computed for individuals or potential solutions in the second step and subsequently, these individuals must be arranged according to the essence of the optimization problem from the minimization or maximization points of view. The selection of individuals for mating pool formation and the crossover operation for new individuals′ creation is the third component of each genetic algorithm. In order to finalize the next generation population, mutation process is done in the fourth step which helps to avoid getting trapped at local optima. These steps are repeated until a suitable solution is found or the maximum number of generations

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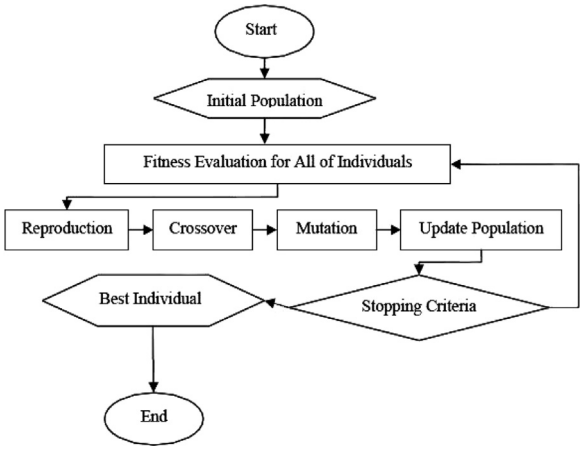

Fig. 9. Flow chart of a standard genetic algorithm after Bonakdari et al. [33].

is reached [32–34]. Fig. 9 demonstrates the flowchart of a standard genetic algorithm.

Various schemes in genetic algorithm context are obtained via the utilization of various techniques in individual selection and mating and mutation operations. Choosing appropriate techniques in selection, mating and mutation steps leads to suitable performance of genetic algorithm in solving an optimization problem. In this research, initial population is generated randomly and the roulette wheel selection approach is applied in the selection stage. Randomly one site crossover operation is used in mating stage and in order to monitor the optimization progress, the best member of each generation is transferred into the next generation with no change due to the crossover operation.

3.4. Developed GA-based optimum search program

A genetic algorithm based optimum search program is developed in Matlab. In this program, random generation of the initial population is carried out, after the computational domain was restricted and defined. Subsequently, the traits of population are encoded in the form of strings called chromosomes. Then, the objective function (which is called fitness function in genetic algorithm literature) is calculated for all chromosomes which were obtained in the last step. Since the sum of the squared errors for many combinations of roughness coefficient and flow discharge have very small values and they are highly near to zero, the following equation is employed for fitness function definition:

$$\text{fitness(sse)} = \frac{1}{1+(\text{sse}) \times 10^6} \tag{12}$$

This fitness function converts the main minimization problem to an equal maximization problem in which the fitness function value will never be zero or negative and its range is restricted between zero and one (the maximum value). Then, in order to produce the next generation, the matting pool is formed and the roulette wheel selection approach is applied to select the parents. Subsequently, randomly assigned one site crossover operation is utilized to generate the children to go into the mutation phase which create the next generation population chromosomes. It must be noted that in the developed program, the best individual(s) in the last generation will directly transfer into the next generation without disturbing with crossover operation or mutation. This is essential for monitoring the optimization progress in subsequent generations. Subsequently, the resultant chromosomes of the new generation must be interpreted or re-encoded in order to obtain the next generation population. The aforementioned flow chart is repeated until an appropriate solution is found or the maximum number of generations is reached.

Since premature convergence to local optima has been reported in the application of standard genetic algorithm, it was attempted to prevent getting trapped at local optima through overall computation renovation. In this regard, an external loop is defined in the developed program which persuades the program to start with new set of initial points, when the program reports the same optimum in 10 subsequent generations obtained from a set of initial points or the maximum number of generations is reached. In other words, the whole optimization process is repeated several times and finally the global computed optimum will be reported after the final comparison of the optima related to each overall optimization process is carried out. Hence, the maximum number of generations is limited to lower values and consequently the overall computations will be done several times with new initialization. This modification to the standard genetic algorithm leads to better performances in optimum search process, as it was used in the practical applications in this study.

4. Discussion of results

The following parameter values were used in GA-based optimum search program which was utilized in this study: C and q in the first test case and n and Q in the second one were treated as two traits of each individual in the population respectively, and based on them the string of numbers which is called chromosome in genetic algorithm context is formed. In the first test case, it is assumed that C varies between 40.0 and 60.0 with step length of 0.1 and q varies between 2.150 and 2.450 with step length equal to 0.001. In the second test case, it is assumed that n varies between 0.0010 and 0.0018 with step length of 0.0005 and Q varies between 24.0 and 32.0 with step length 0.1. The probability of crossover assumed to be 0.98 and randomly assigned one site crossover operation is utilized to make the children required for the mutation phase in both test cases. The probability of mutation is assumed to be 0.10 in both test cases which is accomplished to prevent getting trapped at local optima as much as possible.

Although the mutation phase is carried out in this study, it was detected that the solution procedure would converge to various local optima in various program runs due to the stochastic essence of the whole computations in optimum search sequences. It was also seen that increasing the number of generations cannot solve this problem and although the global optimum can be detected via using the GA-based program, it is not found and reported in several program runs. In this regard, an overall loop has been defined in the program through which the optimum search sequences are repeated several times and the best fitted individual among the final solution of each computational cycle is reported as the global optimum of the optimization problem. The computational cycle is assumed to be repeated 10 times in this study. This modification to the basic genetic algorithm based program made the program reliable in reporting the global optimum in various program runs and seems to be efficient in order to prevent getting trapped at local optima. In other words, it is recommended to renovate the program computations based on new initial population, except using a large number of generations in optimization process via a GA-based program. The number of generations can be restricted to lower values in the recommended technique due to the CPU-time considerations. It was seen that almost five out of 10 times overall computations lead to the global optimum. These successful cycles are randomly distributed in the 10 times overall computational cycles. This result demonstrates the good performance of the proposed modification to the basic genetic algorithm. In other words, since in this study the probability of the

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convergence to the global optimum is about 50%, repeating the calculation several times can guarantee the convergence to the global optimum. The global optimum was detected through using the modified GA-based program. This means that the roughness coefficient determination and corresponding flow discharge estimation can be carried out for the steady state gradually varied flow in wide rectangular or nonprismatic trapezoidal channel in which only the depth observations are accomplished.

5. Conclusions

The current study is devised to explore the possibility of obtaining channel resistance coefficient and discharge in reference to sole measurement of water surface profile. In this regard, two test cases based on the channel cross sectional geometry were considered. Wide rectangular channel cross section in the first test case and nonprismatic trapezoidal channel cross section in the second one were discussed. It was shown that these problems can be treated as equivalent optimization problems in which the parameters roughness coefficient and flow discharge must be tuned so that the minimum value of the sum of the squared error as the deviation indicator of the computed profile from the observed one is reached. In order to choose an appropriate optimization technique, a wise investigation of the deviation indicator surface behavior around the minimum value was considered. In this regard, the contour maps of the sum of the squared error (the objective function) surface were drawn for each test case, respectively. These contour maps showed that it is required to pursue the optimum search process via a method in which the calculation process is started from a set of initial points rather than a single point and also the objective function information itself is utilized instead of its derivatives. The genetic algorithm with the aforementioned requirements was selected as the suitable optimum search method. Since the basic genetic algorithm was found unreliable in converging to the global optimum (the probability of converging to the global optimum was found to be 50%), a modification was applied through which the overall calculation process was repeated several times (10 times in this study) with less maximum number of generations. This proposed modification was efficient and the global optimum was found reliably. Hence, it was demonstrated that the roughness coefficient determination and the corresponding flow rate estimation can be accomplished in both a wide rectangular and a nonprismatic trapezoidal channel with steady state gradually varied flow stage/depth observations alone. This means that, in the aforementioned situation, the flow discharge can be estimated based on the stage/depth measurement alone and the velocity measurement is not required any longer.

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