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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.

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

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