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Research papers

Physically based coefficient for streamflow estimation in ice-covered channels

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ABSTRACT

Measuremental and methodological problems arising from the presence of ice cover on waterways have seriously hindered the progress in predicting timely and accurate streamflow, which is a prerequisite for the effective management of ice-covered waterways (e.g. streams, rivers, channels, and canals). Among various methods in the attempt to address this issue, the most attractive is the physically-based method, which does not require abundant, and often unobtainable, data. This paper develops a physically based *K*-factor method, in the form of a generalized Manning equation, for discharge estimations in ice-covered channels. The main advantage of this method is that it enables the prediction of streamflow in ice-affected seasons by a *K*-factor adjustment of the stage-discharge relationship developed in the open-water seasons. The results of parameter estimation show that the *K*-factor is only related to the boundary resistance ratio, which is parameterized by two exponents of the two-power law for describing the vertical streamwise velocity profile. Experimental measurements collected from the literature were used to test the applicability of the proposed formula, and to compare its relative accuracy with the Sabaneev and Larsen formulae. The comparative results indicate that the proposed method is more accurate in estimating streamflow of ice-covered channels than these two widely-used formulae based on traditional two-layer hypothesis.

1. Introduction

In cold regions, timely and reliable estimates of streamflow throughout the year, especially in the ice-affected season, are essential for supporting the appropriate management of ice-infested waterways (e.g. streams, rivers, channels, and canals). This includes the control of ice-related floods (Ambtman and Hicks, 2012), design and operation of water transfer canals (Altunin et al., 1981; Guo et al., 2017), assessment of river water quality (Healy and Hicks, 2004), and aquatic habitat maintenance (Lind et al., 2014). During ice-free periods, discharge estimates are usually made by continuously monitoring water levels at gauging stations and then converting these data to discharge using established stage-discharge rating curves (Morse and Hicks, 2005; Chokmani et al., 2008). However, when channels are covered with ice in winter, flow under ice is retarded by an additional boundary, which halves hydraulic radius, increases flow resistance, and thence reduces channel conveyance capacity (Davar and Elhadi, 1981; Chokmani et al., 2008; Ghareh Aghaji Zare et al., 2016). Consequently, the rating curve derived for the open-water periods is not applicable during ice-affected periods (Teal et al., 1994; Chen et al., 2016). Moreover, because of spatial and temporal variations in ice roughness, it may be impossible to establish a unique rating curve for the ice-affected season (Morse and Hicks, 2005). The determination of ice-affected streamflow entails direct measurements using the velocity-area method (Teal et al., 1994; Attar and Li, 2012) or alternative methods, such as the one-point method, two-point method, and complete-profile method (Walker, 1991). Operationally, direct measurements are labor-intensive and place hydrometric agencies at personal risk (Healy and Hicks, 2004). The development of an analytical method capable of simply and accurately estimating discharge during the ice-affected period is urgently needed.

Since the 1920s, numerous studies have been devoted to ice-affected discharge assessment of ice-covered channels. Notable work has been periodically reviewed by Uzuner (1975), Walker (1991), Chokmani et al. (2008), and Ghareh Aghaji Zare et al. (2016). The methods reviewed could be mainly classified into hydrologic, hydraulic, statistical, and artificial intelligence. The hydrologic method (including the hydrographic method), summarized by Walker (1991), such as base-flow

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Nomenclature

The following symbols are used in this paper:

A	cross section area (m^2)
B	width of a rectangular channel (m)
B_1, B_2	widths of channel bottom and the underside of ice cover in a trapezoidal channel, respectively (m)
E	relative error (dimensionless)
E_Q	relative error of flow discharge (dimensionless)
f_1, f_2	Darcy-Weisbach resistance coefficients (dimensionless)
g	gravitational acceleration (m/s^2)
H	total flow depth (m)
h_1	elevation of zero shear stress (m)
K, K_L, K_S	K-factors in the proposed formula, the Larsen and Sabaneev formulae, respectively (dimensionless)
M	number of the test runs (dimensionless)
m_1, m_2	exponents in the two-power law (dimensionless)
n	Manning resistance coefficient ($s/m^{1/3}$)
n_{0S}, n_{0L}	composite Manning coefficients estimated by the Sabaneev and Larsen formulae, respectively ($s/m^{1/3}$)
P	wetted perimeter (m)
Q	flow discharge (m^3/s)
R	hydraulic radius (m)
R_e	Reynolds number (dimensionless)
r_m	ratio of the two exponents in two-power law (dimensionless)
r_n	ratio of the Manning coefficients in two-flow layers (dimensionless)
r_Y, r_h	flow depth ratios for the traditional and modified two-layer hypothesis, respectively (dimensionless)
S_0	energy slope (dimensionless)
s	channel sidewall lateral slope (dimensionless)
u	streamwise velocity (m/s)
$u_{\max}$	maximum streamwise velocity (m/s)
V	cross-sectional mean velocity (m/s)
Y_1	elevation of the maximum velocity (m)
α, β	regression coefficients (dimensionless)
δ	aspect ratio (dimensionless)
δ_*	critical aspect ratio for distinguishing wide channel form narrow channel (dimensionless)
ε_V, ε_n	acceptable iteration accuracies for the bulk velocity and the Manning coefficient, respectively
η	constant related to flow rate in the two-power law (m/s)
θ	angle of side-wall with horizontal direction (rad)
κ	von Karman constant (dimensionless)
λ_1, λ_2	correction factors (dimensionless)
ρ	mass density of water (kg/m^3)
τ	boundary shear stresses acting on the fixed boundaries (N/m^2)
τ_{zx}	shear stresses along the x-axis in the z-x plane (N/m^2)
ψ_1, ψ_2	constants (dimensionless).

Subscripts

i	subscript denoting parameter for arbitrary subsection numbered i
0	subscript denoting composite values for the entire flow section.

Superscripts

k	iteration times.

recession, K-factor determination, interpolated discharge, and backwater shift, is generally unsuitable for timely estimates of winter discharge because of its irreproducibility, excessive time-consumption, and relatively low precision of predictions (Hamilton et al., 2000; Chokmani et al., 2008). The statistical method uses, for example, conductance correlation and multiple regression to establish an empirical relationship for discharge prediction (Walker, 1991). The artificial intelligence technique, such as artificial neural networks, is an alternative predictor for winter discharge using historical data (Chokmani et al., 2008). The statistical and artificial intelligence methods are data-driven procedures that require abundant historical meteorological and hydrometric data. Hence, these two methods are difficult to apply to discharge predictions for ungauged streams and rivers, and for designs of planed channels and canals. The limitations of poor in-situ databases on method selection and the requirements of reliable discharge estimates for river management result in the widespread use of the hydraulic method in estimating winter discharge under ice-affected conditions.

Of the hydraulic methods available for calculating winter discharge, the Manning equation has advantages because it does not require flow velocities, which are difficult to obtain during ice-affected periods. Ice-covered channels are typically composite channels with varying degrees of roughness along their wetted perimeters (Sukhodolov et al., 1999). Pioneering work on ice-covered channel hydraulics was thus mainly centered on the derivation of the composite roughness coefficient that incorporates the frictional effect of fixed boundaries (Nezhikhovskiy, 1964; Larsen, 1973; Uzuner, 1975). Various formulae have been suggested for estimating the composite roughness for ice-covered channels with parabolic sections (Larsen, 1969; Uzuner, 1975; Ghareh Aghaji Zare et al., 2016), but few have considered the rectangular or trapezoidal sections that are widely used in the design of water delivery channels (Chow, 1959). Moreover, if using these existing methods, we need to develop separate stage-discharge relationships for ice-free and ice-affected periods in cold region rivers. Given the easiness in collecting data during ice-free periods, there is a potential alternative method to streamflow estimation during ice-affected periods by using the well-established stage-discharge relationships developed during ice-free periods. The objective of this paper was, therefore, to develop a physically-based formula for estimating the discharge capacity during ice-free and ice-affected periods.

The paper is organized as follows. A new analytical predictor is derived for streamflow estimation in ice-covered channels in Section 2. Section 3 discusses the methods for estimating the parameters in the proposed formula. In Section 4.1, field observations and laboratory measurements are documented to verify performance of the proposed formula. Section 4.2 compares the relative accuracy with two other frequently-used formulae, discusses the delimitations of the two-layer flow, and pinpoints the scope of applicability of the proposed formula. Finally, the main conclusions are presented in Section 5.

2. Theoretical analysis

Although the presence of ice cover alters the structure of the underlying flow, quasi-uniform conditions also prevail in cold region waterways during winter (Beltaos, 2011). Therefore, the flow velocity may be related to the resistance coefficient using a conventional friction formula, e.g. the Manning equation (Chow, 1959; Yen, 1992):

$$V_0 = \frac{1}{n_0} R_0^{2/3} S_0^{1/2} \tag{1}$$

where V is the sectional average velocity, R is the hydraulic radius, n is the Manning resistance coefficient, S is the energy slope, and the