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Research paper

Flood hydrograph estimation using an adjoint shallow-water model

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Abstract

This paper describes the estimation of the flood discharge hydrograph for a compound open channel floodplain using data assimilation. The hydrograph was produced iteratively using an adjoint shallow-water model with time-series data of observed water levels. Data assimilation was applied to a flood event that occurred in mid-September 1998 along a 20 km stretch of the lower Tone River in Japan. Both the estimated hydrograph and the flow field simulated using the hydrograph were verified by comparison with the results of aerial photographic analysis. Results show that the hydrograph based on the stage–discharge was overestimated, but it was reasonably corrected by the data assimilation technique used for this study. In addition, the resulting relation during the flood event exhibited a hysteresis loop characteristic, which is typical of compound open channel flows during flooding.

Keywords: Data assimilation; Discharge estimation; Adjoint model; Shallow-water equation; Compound open channel

1. Introduction

A discharge hydrograph includes crucially important data that are necessary for river engineering planning and management tasks. A hydrograph is usually obtained using the Manning formula or some sort of empirical formulas based on a single-valued stage–discharge (H–Q) relation or a rating curve. Generally, the relation is developed for a specific river location. It is uniquely determined for the entire flow range including extreme flows such as flooding. For this relation, measurements of river discharges are routinely conducted for several stages (water levels): for normal flows, direct measurements are conducted using a velocity meter such as a Price meter, but for high water flows they are typically estimated from the traveling time of a floating rod dropped from bridges between two streamwise locations. It is true that this workable engineering practice for river discharge determination enables monitoring of the current state of flow condition, and enables the prediction of subsequent hydraulic phenomena. However, it is necessary that the H–Q relation be valid only for quasi-steady flows in a stable cross-section of the river channel. Previous studies have demonstrated that the relation might change for unsteady flows because of flood wave propagation (Chow, 1959; Fread, 1975), or in compound open channels when the flood plain is inundated (Fukuoka et al., 2005). Consequently, the discharge estimated using such a simple relation might include some errors for high-water events. For instance, the practical method based on the Manning formula is reportedly difficult in the accurate estimation of river discharge because of inappropriate modelling of energy slope in the compound channel during flooding (Bousmar and Zech, 1999).

Replaced by the conventional method using the H–Q relation of limited accuracy, a new instrument using a non-intrusive sensor has been developed by several researchers for river discharge measurements. Gordon (1989) presented a new moving-boat method for the rapid measurement of a river discharge using an acoustic Doppler current profiler (ADCP). Although the entire system was not ready for easy deployment in practical measurements of river flows at early times of the

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history of ADCPs, improvements including weight reduction of instruments, simple operation, and upgraded performance have recently enabled researchers to conduct continuous measurements more accurately during flooding (Nihei and Kimizu, 2008). However, measurements using updated ADCPs still present several challenges for practical use: (1) signal decay because of high turbidity during flooding; (2) difficulty in measurements for floods with piles of drift wood and a great deal of litter in water; and (3) wash-out of equipment for measurements during severe high water events, and so on.

Fujita et al. (1998), based on the idea of PIV for laboratory flumes, developed large-scale particle image velocimetry (LSPIV) for the instantaneous measurement of surface velocity fields in rivers using a protocol for image pattern recognition (Adrian, 1991). This image velocimetry technique has been improved for practical use by several researchers including Bradley et al. (2002), Fujita and Hino (2003), and Muste et al. (2004). They used the traceless LSPIV to obtain valuable data clarifying scientific hypotheses related to river processes including flood wave propagation. Nevertheless, this technique still exhibits difficulties in continuous measurements of river discharge for some cases: (1) during normal water conditions because the free surface has a mirror-like appearance; (2) when lighting is limited, for example, at night; and (3) when strong winds blow over a targeted river reach.

Recently, flooding in small and medium-sized rivers has occurred frequently in Japan because of local intensive rainfall, which is reportedly induced by abnormal weather. As a result, tremendous damage from such flooding has increasingly occurred in many regions throughout Japan. It is acknowledged that updated observation methods offer valuable data for river engineering tasks. However, direct measurements of river flows using ADCPs and LSPIV during high water events threaten the safety of engaged personnel and engender the loss of expensive equipment and related missing data in severe natural conditions. Therefore, diversity in observation methods must be accepted for the development of a stable low-cost observation system for practical work. Flexible choices must be made among several observation methods considering strong and weak points of the methods, including total cost, robustness, user-friendliness, and accuracy might contribute to river engineering work not only in Japan but also in locations world-wide.

This paper therefore presents a new methodology of using data assimilation for improvement of the conventional $H-Q$ relation. An inverse estimation of the flood discharge hydrograph was developed for compound open channels in actual rivers using an adjoint shallow-water (backward) model. The method used here is based on a variational approach, which is a type of data assimilation technique. Previous studies (e.g., Atanov et al., 1998; Ding and Wang, 2006; Sanders and Katopodes, 1999) have used identical twin experiments to demonstrate the applicability of such an approach to hydraulic problems. The identical twin experiment is a numerical procedure by which synthetic data can be generated by the forward model to which data assimilation is applied. This numerical experiment assures us of feasibility and creditability. These studies emphasized one-dimensional solutions, which cannot be applied easily to horizontal hydraulic phenomena in natural rivers where the cross-section varies irregularly in the longitudinal direction or where the floodplains exhibit a range of bed roughness values. Additionally, it is important to use real data for data assimilation and to check the feasibility and applicability in river engineering, although such a numerical experiment is effective for designing an observation system in rivers.

This paper is organized as follows. The governing equations for both two-dimensional (2-D) shallow water-model and corresponding adjoint model are described using numerical procedures to produce a river discharge hydrograph. This study applied data assimilation methods to a flood event that occurred in mid-September 1998 along a 20 km stretch of the lower Tone River in Japan. The assimilated data comprised a time series of observed water levels. In Japan, observation data are usually difficult to obtain during flooding, except for data of water levels at established hydraulic stations. Measurements of river discharge using ADCPs and LSPIV have been conducted for experimental purposes. Practical work conducted using updated instruments is not prevalent in Japan today because of observation costs and a scarcity of sufficiently skilled engineers. Alternatively, for a flood event, aerial photographs were taken over the targeted river reach during around half an hour after the peak period of the flood wave. Therefore, the data assimilation results were verified by the surface flow field obtained from analyses of a series of aerial photographs. Consequently, discussion is conducted mainly for river discharge data and simulated data of velocity profiles of the main flow across the river during that period. Additionally, the potential of this work is presented in light of upgrading the $H-Q$ relation considering 2-D shallow-water hydrodynamics.

2. Governing equations

We used the shallow-water equations as a forward model in a boundary-fitted coordinate system as follows (Nagata et al., 2000).

$$f_h = \frac{\partial}{\partial t}\left(\frac{h}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{M}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{N}{J}\right) = 0 \tag{1}$$

$$\begin{aligned} f_M = & \frac{\partial}{\partial t}\left(\frac{M}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{M^2}{Jh}\right) + \frac{\partial}{\partial \eta}\left(\frac{MN}{Jh}\right) \\ & - \frac{m}{J}\left(\frac{\partial \xi_x}{\partial \xi}\frac{M}{h} + \frac{\partial \xi_x}{\partial \eta}\frac{N}{h}\right) - \frac{n}{J}\left(\frac{\partial \xi_y}{\partial \xi}\frac{M}{h} + \frac{\partial \xi_y}{\partial \eta}\frac{N}{h}\right) \\ & + gh\left(\frac{\xi_x^2 + \xi_y^2}{J}\frac{\partial H}{\partial \xi} + \frac{\xi_x\eta_x + \xi_y\eta_y}{J}\frac{\partial H}{\partial \eta}\right) \\ & + \frac{\tau_\xi}{\rho J} - \left(\begin{array}{l} \frac{\xi_x^2}{J}\frac{\partial \tau h}{\partial \xi} + \frac{\xi_x\eta_x}{J}\frac{\partial \tau h}{\partial \eta} + \frac{\xi_y^2}{J}\frac{\partial \psi h}{\partial \xi} \\ + \frac{\xi_y\eta_x}{J}\frac{\partial \psi h}{\partial \eta} + \frac{2\xi_x\xi_y}{J}\frac{\partial \phi h}{\partial \xi} + \frac{\xi_x\eta_y + \xi_y\eta_x}{J}\frac{\partial \phi h}{\partial \eta} \end{array}\right) = 0 \end{aligned} \tag{2}$$