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Optimal control of flood diversion in watershed using nonlinear optimization

Yan Ding *, Sam S.Y. Wang

National Center for Computational Hydroscience and Engineering, The University of Mississippi, University, MS 38677, USA

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A B S T R A C T

This study aims to develop a simulation-based optimization model applicable to mitigate hazardous floods in storm events in a watershed which consists of a complex channel network and irregular topography. A well-established model, CCHE1D, is used as the simulation model to predict water stages and discharges of unsteady flood flows in a channel network, in which irregular (i.e. non-rectangular and non-prismatic) cross-sections are taken into account. Based on the variational principle, the adjoint equations are derived from the nonlinear hydrodynamic equations of CCHE1D, which are to establish a unique relationship between flood control variables and hydrodynamic variables. The internal conditions at the confluence in channel network for solving the adjoint equations in a watershed are obtained. An implicit numerical scheme (i.e. Preissman's scheme) is implemented for discretizing and solving the adjoint equations with the derived internal conditions and boundary conditions. The applicability of this integrated optimization model is demonstrated by searching for the optimal diversion hydrographs for withdrawing flood waters through a single floodgate and multiple floodgates into detention basins. Numerical optimization results show that this integrated model is efficient and robust. It is found that the single-floodgate control leads to an unfavorable speed-up in river flow which may create extra erosions in the channel bed; and multiple-floodgates diversion control diverts less flood waters, therefore can be a cost-effective control action. This simulation-based optimization model is capable of determining the optimal schedules of diversion discharge, optimal floodgate locations, minimum capacities of flood water detention basins in rivers and watersheds.

1. Introduction

Flood control to mitigate hazardous flood waters in rivers and watershed is of vital importance for inundation prevention, flood risk management, and water resource management. By operating in-stream hydraulic structures (e.g. reservoirs, dams, floodgates, spillways, etc.), peak flood discharges and high water stages in channels during storms can be reduced so that overflow and overtopping on levees, as well as the resulting inland flooding and inundation are eventually prevented. In case of emergency when flood waters are predicted to exceed capacities of river reaches, controls of flood water diversion/withdrawal through floodgates, diversion channels, or deliberate levee breaching can quickly mitigate flood water stages over the target reaches and even the entire watershed. Among them is the optimal flood control that can give the best cost-effective flood control schedule to minimize the risk of hazardous flood waters. It also enables to find the best design of capacities and locations of flood control structures, e.g. floodgates, floodwater detention basins [5,6]. Meanwhile, optimal flood flow control methodologies can be utilized to practice best management of water resource, sediment transport (e.g. [29]), and water quality (e.g. [31]) to achieve sustainable development of economy and society that largely depend on limited water availability.

The difficulty for achieving optimal flood control in rivers and watersheds is attributed to non-uniformities of spatially-distributed flood waters, unsteadiness and nonlinearities of its dynamics. As a prerequisite, a flood simulation model must be able to predict hydrodynamic variations of nonlinear flood flows in time and space and compute efficiently and accurately flood wave propagations of in river channels. Different from man-made open channels, river cross-sections, in general, are irregular, usually, non-rectangular and/or non-prismatic. Consequently, nonlinear optimization techniques have to be developed for establishing the relationship between flood control variables/actions (i.e. lateral diversion discharge schedules in this study) and nonlinear responses of hydrodynamic variables (i.e. water stages and discharges). Among them, adjoint sensitivity analysis (ASA) based on the variational principle has been applied to find the sensitivity of hydrodynamic variables with respect to control variables in one- and two-dimensional flow models [18,33–35,5]. Through solving a set of adjoint equations of hydrodynamic equations, the solutions of adjoint variables can readily connect the control

* Corresponding author. Tel.: +1 662 915 8969; fax: +1 662 915 7796.
E-mail address: ding@ncche.olemiss.edu (Y. Ding).

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Nomenclature

A	cross-sectional area (m^2)
B^*	channel width on water surface (m)
g	the gravitational acceleration (m/s^2)
q	volumetric rate of lateral outflow (or inflow) per unit length of the channel between two adjacent cross sections (m^2/s)
Q	discharge through a cross-section (m^3/s)
J	objective function
J^*	augmented objective function
K	the conveyance K is defined as $K = AR^{2/3}/n$ (m^3/s)
L	length of river reach (m)
L_1, L_2	represent the continuity equation and the momentum equation, respectively
$\boldsymbol{M}$	coefficient matrix in the adjoint equations
n	Manning's roughness coefficient ($s/m^{1/3}$)
$\boldsymbol{N}$	coefficient matrix in the adjoint equations
$\boldsymbol{P}$	source term in the adjoint equations
R	hydraulic radius (m)
t	time (s)
T	control period (s)
u	$g - B^*\beta Q^2/A^3$ (m/s^2)
U	a vector for the adjoint variables
V	cross section averaged velocity (m/s)
W_z	weighting factor which is to adjust the scale of the objective function
x	channel length coordinate (m)
x_0	target location where the water stage is protective (m)
x_1, x_2, x_3	locations of three cross-sections in a confluence
x_c	location of flood diversion gate (m)
Z	water stage (m)
$Z^{obj}(x)$	the maximum allowable water stage (the objective water stage) (m)

Greek symbols

β	momentum correction factor
δ	Dirac delta function
Δt	time increment (s)
Δx	spatial length (m)
λ_1, λ_2	eigenvalues of the adjoint equations
λ_A, λ_Q	the Lagrangian multipliers
Λ	$2/3 - 4R/3B^*$
θ	weighting parameter of Preissmann's scheme
Ψ	weighting parameter of Preissmann's scheme

actions with nonlinear and unsteady responses of flood flows, and provide an accurate measure of sensitivity of control performance (usually defined by an objective function). Sanders and Katopodes [33] performed an ASA of flood control by operating lateral flood water outflow in a one-dimensional (1-D) straight channel. They extended to a flood control by using the nonlinear two-dimensional (2-D) shallow water equations and Hancock's predictor–corrector scheme [34]. According to these river flood control studies, ASA has shown its efficiency and effectiveness in solving optimal control problems which involve a large number of control variables, which usually are long vector variables in flow simulation model to determine the optimal diversion flow schedule over a several days long flood control period.

Meanwhile, variational data assimilation (VDA) and ASA have been used for estimating unknown bathymetries of rivers and improving flood predictions by assimilating observed flow variables from measurements and satellite images (e.g. [26,21,27]). A similar variational approach for Lagrangian data assimilation in rivers applied to identification of bottom topography and initial water depth and velocity estimation was presented in Honnorat et al. [14–16]. Elhanafy et al. [7] quantified predictive uncertainties in simulations of flood wave propagations in a prismatic channel of trapezoidal section. Gejadze et al. [10,11], Gejadze and Monnier [12], and Marin and Monnier [25] proposed a 'zoom' model to assimilate river flood observation data into a coupled open channel flow model to predict respectively a flood flow in channel network by a 1-D flow model and local overflow/innudation in a vulnerable river reach by a 2-D model. Gejadze and Copeland [9] and Gejadze et al. [10,11], developed a data assimilation method for the estimation of open boundary conditions for the vertical 2-D Navier–Stokes equations with a free surface from fixed depth and velocity measurements. Lai and Monnier [19] developed a data assimilation technique to simulate flood flows by using the 2-D shallow water equations and assimilating remote sensing observations. Hostache et al. [17] further applied this approach to predict a flood inundation in a river by using remote sensing images of the river flood. Castaings et al. [2] successfully applied adjoint sensitivity analysis and parameter estimation to a distributed hydrological model to compute flood flow in a watershed catchment. It is shown that forward and adjoint sensitivity analysis provide a local but extensive insight on the relation between the assigned model parameters and the simulated hydrological response.

This study aims to develop a simulation-based optimization model applicable to mitigate hazardous floods in storm events in channel network which covers a watershed. A well-established model, CCHE1D, is used as the simulation model to predict water stages and discharges in river reaches of the channel network, because it is computationally efficient and capable of predicting dynamic flood flow propagations in channel network with irregular cross-section shapes (i.e. non-rectangular and non-prismatic channels) [39,28]. As an extensively verified and validated numerical model, CCHE1D has become a general computational software package for simulating unsteady open channel flows, sediment transport, morphodynamic processes, and water quality in river and watershed. The optimization of flood control in the paper is based on the adjoint sensitivity approach which is the way to establish the most accurate relationship between control actions and dynamic flood flows simulated by CCHE1D. The adjoint equations are derived for the nonlinear 1-D Saint–Venant equations which are the governing equations in CCHE1D for simulating open-channel flows through non-rectangular and non-prismatic cross-sections. In order to be generally applicable to find the adjoint solutions in channel network, the internal conditions of the adjoint equations at confluences (junctions) of channel network are derived on the basis of the variational analysis. By specifying internal conditions at confluences (junctions) for both the simulation model and the adjoint model, this simulation-based optimization model becomes well-integrated to be able to automatically find the optimal solutions (i.e. lateral flow diversion hydrographs) to best control flood waters occurring in all the river reaches of the channel network. Detailed numerical solution algorithms for solving the flow governing equations and the adjoint equations are developed by using an implicit time–space discretization scheme (i.e. Preissman's scheme). For finding the optimal solutions for the best flood control, an efficient optimization procedure based on the Limited-Memory Quasi-Newton (LMQN) method [24] is used.