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TOWARDS THE INTELLIGENT CONTROL OF RIVER FLOO0DING. HARMONIZING LONG-TERM OBJECTIVES (E.G., IRRIGATION, HYDROPOWER) WITH THE FLOODING OBJECTIVE

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Summary: This paper presents a new framework for the intelligent control of river flooding.

1 INTRODUCTION

Most dams built for flood control are operated based on rule curves, which are determined based on annual estimates of system loads, reservoir storages and resources provided by stakeholders. Rule curves neglect the flow dynamics in the entire river system, which makes this approach a "slow-response" method for flood control. This is particularly true in complex river systems when parts of the river system may have enough in-line storage capacity, while other portions of the system may be overflowing. Clearly, rule curves are insufficient for making system-wide operational decisions.

Various models for reservoir operation are available. These include optimization models, simulation models, and combined simulation-optimization models. For instance, the Hydrologic Engineering Center (HEC) supports three individual reservoir modeling tools for the simulation and optimization of reservoir system operations[1,2]. The tools include: 1) Reservoir Simulation (HEC-ResSim), 2) Multi-Objective Reservoir Optimization (Prescriptive Reservoir Model, HEC-PRM), and 3) Reservoir Flood Control Optimization (HECFloodOpt). HEC-ResSim is a reservoir simulation model that makes operation decisions following the user specified operating rules or guidelines. HEC-PRM and HEC-FloodOpt are optimization models that make operation decisions to maximize system objectives and values as defined by the user. HEC combines these three modeling tools into one package, the Reservoir Evaluation System (HEC-RES). The RIBASIM (RIver BAsin SIMulation)[3] model is another comprehensive and flexible tool which links the hydrological water inputs at various locations with specific water-users in the basin.

For achieving an optimal system-wide operational decision for flood control, it was recognized that optimization and simulation components must be combined[2]. Current frameworks that combine simulation (e.g., hydraulic routing) and optimization neglect system flow dynamics and instead simply perform mass balance in the reservoirs while assuming that reservoir's water levels are horizontal. The reasons for neglecting system flow dynamics are due to a lack of robustness and computational burden of current unsteady flow models[4].

Herein, a new coupled optimization-simulation framework for the operation of regulated river systems that accounts for system flow dynamics is proposed. This framework, that is under ongoing development, is named OSU Rivers as an acronym for Oregon State University coupled optimization-simulation model for the operation of regulated river systems. Space limitations, however, do not allow for a full description and evaluation of OSU Rivers. A manuscript by the authors with a detailed description of OSU Rivers has been submitted for review and possible publication in the Journal of Water Resources Planning and Management[4].

The work presented here is part of a long term project, the overarching goal of which is the development of a reservoir operation model that combines short-term (flooding) and long-term objectives (e.g., hydropower, irrigation). The scope of this paper is limited to the application of OSU Rivers to flood control (short-term objective). This paper is organized as follows: (1) the optimization and simulation components of OSU Rivers are briefly described; (2) a concise description of the proposed framework is presented; (3) the model is applied to the Boise River system in Idaho. Finally, the results are summarized in the conclusion.

2 COMPONENTS OF THE PROPOSED FRAMEWORK

The proposed framework is essentially a real-time operational model that accounts for system flow dynamics. It links two components: optimization and river system routing (simulation).

2.1 Optimization component: The Non-dominated Sorting Genetic Algorithm-II (NSGA-II)

The Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is a popular multi-objective evolutionary algorithm. This algorithm has been shown to be one of the most efficient algorithms for multi-objective optimization on a number of benchmark problems, including water resources engineering problems[5]. The main features of these algorithms are the implementation of a fast non-dominated sorting procedure and its ability to handle constraints without the use of penalty functions.

2.2 Simulation component

The hydraulic component of the proposed framework consists of dividing the river system into reaches and pre-computing the hydraulics for each of these reaches independently using any gradually varied flow model (one-, two- or three-dimensional). The pre-computed hydraulics for each reach is stored in matrices and is accessed as look up tables. The hydraulic routing adopted for each river reach is performed using the Hydraulic Performance Graph (HPG) and Volume Performance Graph (VPG) approach. The HPG of a channel reach graphically summarizes the dynamic relation between the flow through and the stages at the ends of the reach under gradually varied flow (GVF) conditions, while the VPG summarizes the corresponding storage. The storage volumes from VPGs are divided into left, right and main channel volumes. The left and right inundation volumes are summarized into Left Flooding Performance Graphs (LFPGs) and Right Flooding Performance Graphs (RFPGs), respectively. The LFPGs and RFPGs represent volumes of water outside of levee limits, channel banks or topographic thresholds that are used to define the limits of inundation. At the location of in-line structures (controlled and uncontrolled), the proposed framework makes use of Rating Performance Graphs (RPGs). A RPG graphically summarizes the dynamic re1ation between the flow through and the stages upstream and downstream of an in-line structure. For a detailed description of the hydraulic component of the proposed framework the reader is referred to [6].

3. DESCRIPTION OF THE PROPOSED FRAMEWORK

For facilitating the description of OSU Rivers, this model can be divided into three modules. These are:

Module I: Initial and Boundary Conditions: The initial conditions are downstream water depths and flow discharges at upstream Q_u and downstream Q_d ends of each river reach. The boundaries conditions (BCs) supported by OSU Rivers are presented below.

External Boundary Conditions (EBCs), which are prescribed at the most upstream and downstream ends of the river system. EBCs include inflow hydrographs, stage hydrographs or stage-discharge ratings.

Internal Boundary Conditions (IBCs), which are specified at internal nodes whenever two or more reaches meet. The three types of IBCs currently supported by OSU Rivers are:

- A fixed in-line structure BC (e.g., weirs or dams with fixed position of gates). A single RPG is built for this BC.
- A mobile in-line structure BC (e.g., dams with mobile sliding and radial gates). A group of HPGs is built for this BC, one for each discrete gate position (or any other mobile structure) encompassing the full range of opening/closing of gates.
- A Junction BC is defined at locations (nodes) without presence of hydraulic structures.

Module II: Optimization objective under flooding conditions: Under flooding conditions, the following optimization objective is proposed

$$\text{Minimize } f = \sum_{j=1}^{\text{RR}} (w_{L_j} FV_{L_j} + w_{R_j} FV_{R_j}) \tag{1}$$

Where w is a weight factor, j denotes a river reach, RR is the total number of river reaches, and FVL_j and FVR_j are left and right flooding volume, respectively. FVL_j and FVR_j are obtained from the corresponding LFPG and RFPG, respectively. The objective function in Eq. (1) allows controlled flooding only after the capacity of the entire river system has been exceeded. Controlled flooding is based on weight factors (w) assigned to each reach of the system depending on a hierarchy of risk to losses associated with flooding (i.e., the river reaches that are less prone to losses are assigned smaller weight factors and reaches more prone to losses are assigned larger weight factors). In practice, this hierarchy of risk to losses could be obtained based on a social and economical study of the river basin.

Module III: River system hydraulic routing

This module assembles and solves a non-linear system of equations to perform the hydraulic routing of the river system. These equations are assembled based on information summarized in the systems' HPGs, VPGs, and RPGs, the reach-wise equation of conservation of mass, continuity and compatibility conditions of water stages at the union of reaches (nodes), and the system boundary conditions. For a detailed description of this hydraulic routing, the reader is referred to [6].

4 APPLICATION OF THE PROPOSED MODEL TO THE BOISE RIVER SYSTEM

For demonstration purposes, this model was applied to the Boise River system in Idaho, the plan view of which is presented in Figure 2. Due to space limitations only key data and results are presented here. For more details of this application the reader is referred to [4]. The Boise River system was divided into twenty five river reaches, including three uncontrolled in-line structures (i.e., bridges), and one controlled in-line structure (reservoir with gates). The controlled in-line structure (Lucky peak reservoir) consists of six sluice gates that are assumed to be operated automatically to fulfill the objective of the application. The upstream end of reach R1 is located right downstream of Boise River Diversion Dam and the downstream end of reach R25 is located approximately 2600m downstream near Glenwood bridge.

For the inflow to the Boise River system, an inflow hydrograph was obtained using the Soil and Water Assessment Tool (SWAT) for a climate change scenario. For the present application, a hydrograph period of nine months (274 days) between 11/30/2041 and 08/30/2042 was selected and used in the simulations. This inflow hygrograph, which is depicted in Figure 3, corresponds to the largest volume of inflow during a period of nine months. This inflow hydrograph represents natural flows, which means that the storage capacity of the Lucky Peak Reservoir and the flow diversions are not considered.

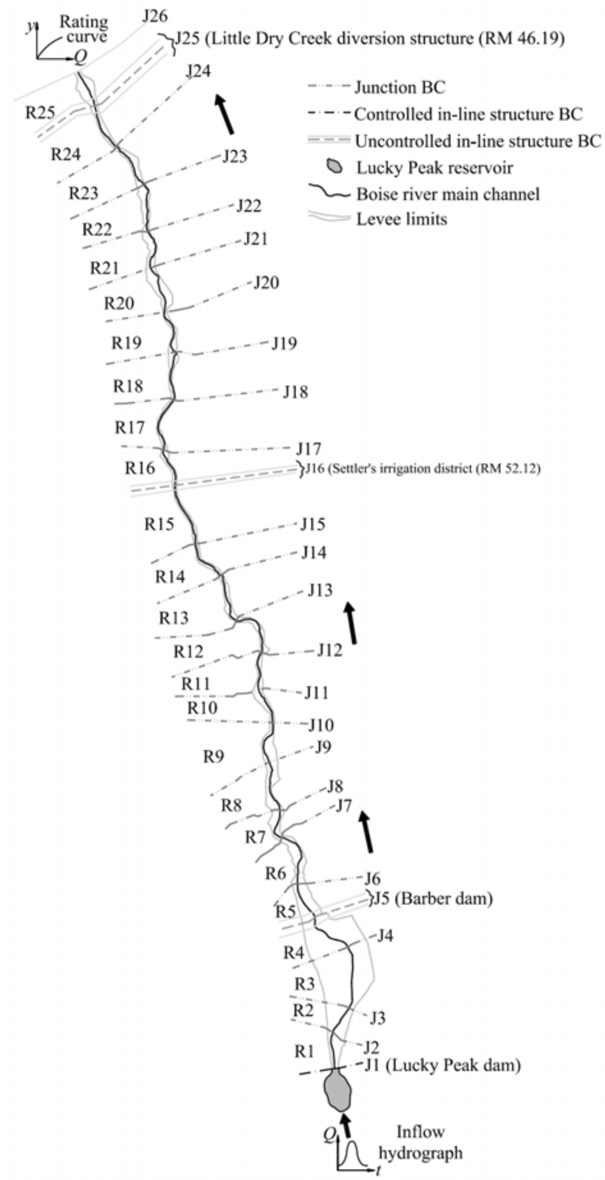

Figure 2. Rivers Schematic of the Boise River's Plan View

The optimization objective is to minimize flooding according to Eq. (1). Weight factors were assumed to be between one and three. Note that river reaches that are more prone to flood losses are assigned higher weight factors. A weight factor of one was assumed for the left and right sides of reaches R1 to R4. Reaches R1 to R4 correspond to the Barber pool conservation area (grass lands). A weight factor of two was assumed for the left side of reaches R5, R6, R16 and R17 and for the right side of reaches R6, R7, R9, R10, R11, R14, R17, R19 and R21. These regions correspond to parks and agricultural areas. Finally, a weight factor of three was assumed for the rest of the river system. These regions correspond to residential, commercial and business areas. In an actual application, weight factors should be determined from a social and economical study based on a hierarchy of losses that would be incurred as a result of flooding. The water stage in the reservoir was constrained to the minimum operating level of 874.5 m. The outflow discharge at the Lucky Peak dam was constrained to the maximum flow discharge of 184 m^3/s, which is the maximum flow that the Boise River can convey without producing flooding under normal flow conditions (no backwater effects). In unsteady flow conditions, flooding may occur at smaller or larger discharges than that corresponding to the normal flow conditions.

The outlet structure of the Lucky Peak reservoir consists of a 6.706 m diameter steel-lined pressure tunnel at the upstream end of the outlet structure and six sluice gates (1.6 m width and 3.048 m height) at the downstream end of the outlet. The hydraulic capacities of the upstream and downstream ends of the outlet structure were compared. The gate conveyance was smaller than that of the tunnel and hence it controls the flow discharge through the outlet structure. The gates were assumed to be operated identically (i.e., same gate invert elevation). The RPGs were built assuming that all gates are operated (opened or closed) using the same discrete levels. In this application 32 discrete positions (each 10 cm) for the gates have been considered (i.e., the first gate position is totally closed and the last gate position is totally open). The aerial view of Lucky Peak reservoir and the associated structures are shown in Figure 5.

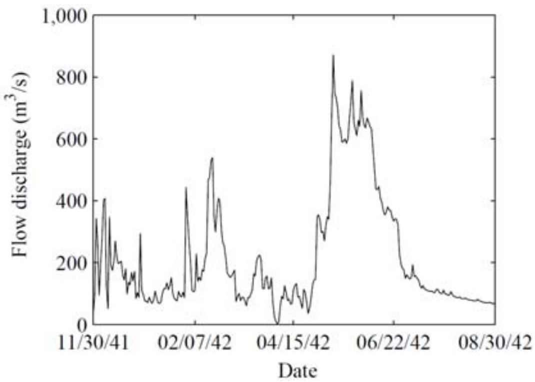

Figure 3. Inflow hydrograph at the Lucky Peak Reservoir for the period between Nov 2041 and August 2042

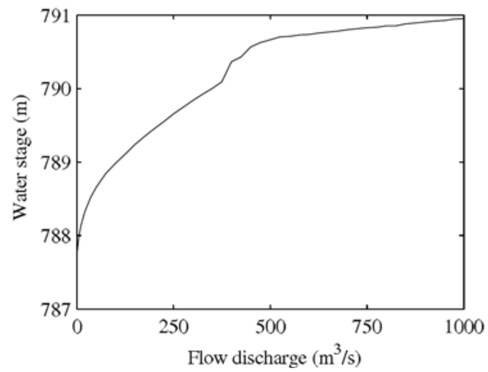

Figure 4. Rating curve at most downstream end of river system (node J26)

Figure 5. Aerial view of Lucky Peak reservoir and associated structures (source: http://commons.wikimedia.org)

The system under consideration has two external boundary conditions (EBCs): the first BC is an inflow hydrograph at the upstream end of the Lucky Peak reservoir (Figure 3) and the second BC is a flow-stage relation at the downstream end of the last river reach (Figure 4). This flow-stage relation was built assuming critical flow conditions. The initial conditions are a constant flow discharge in the system of 166.7 m^3/s and a water stage in the Lucky Peak reservoir of 879.84 m. The simulation time step and the operational decision time used were one hour.

Three scenarios were simulated. The first scenario is with no gate operation, i.e. the gates are closed. The second scenario assumes that the Lucky Peak reservoir does not exist. The third scenario operates the gates according to the results of the proposed framework (minimizing the objective function presented in Eq. 1).

The simulated results of the flooding objective (Eq. 1) are shown in Figure 6. These results show that the river starts to flood at day 16 for the first scenario, at day 2 for the second scenario and at day 165 for the third scenario. The operation of gates according to the proposed framework (third scenario) attenuates and delays the flood but does not avoid flooding due to lack of sufficient storage capacity. The storage capacity needed to avoid flooding for the inflow hydrograph under consideration is 1,323 MCM. This means that another reservoir with a capacity similar to that of Lucky peak reservoir (about 600 MCM) would be necessary to avoid flooding in this case. Results for optimized outflow discharges and water stages at the Lucky Peak reservoir according to the proposed framework (third scenario) are presented in Figure 7. Figure 8 shows the corresponding trace of gate openings.

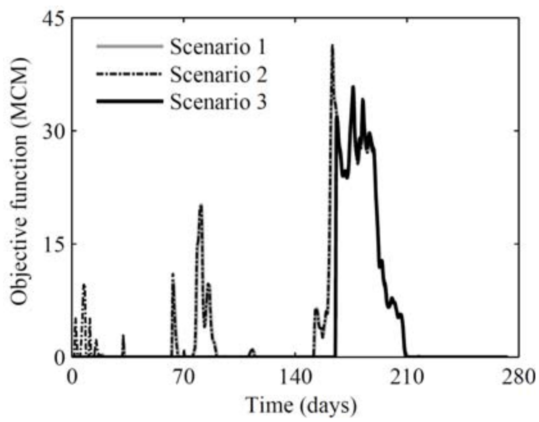

Figure 6. Flooding objective (Eq. 1) for simulated scenarios

For the third scenario, before the reservoir is full, operated gates release a flow discharge lower than 184 m^3/s, which is the maximum flow discharge without flooding under normal flow conditions. When the reservoir is full, the flow hydrograph is similar to the inflow hydrograph. The third scenario delayed and better controlled flooding; however, flooding is not entirely avoided due to storage limitations of the reservoir.

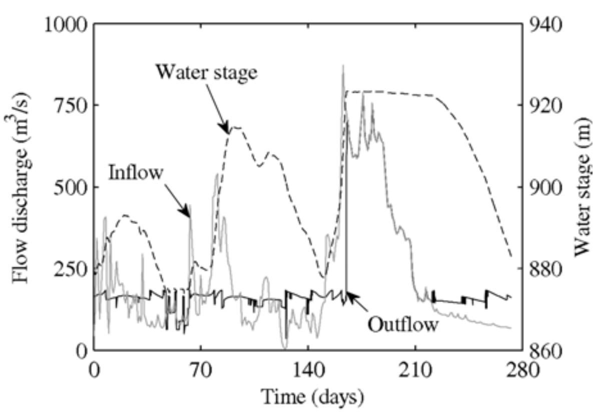

Figure 7. Inflow, outflow and water stage hydrographs at the Lucky Peak reservoir

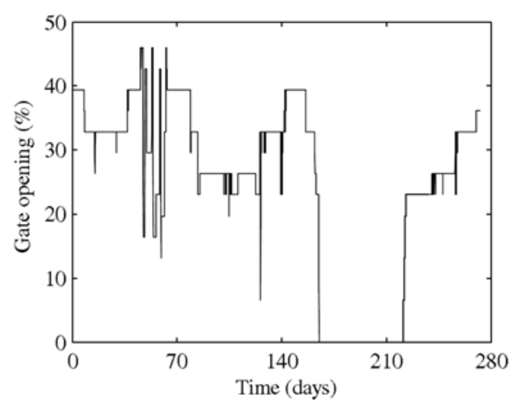

Figure 8. Gate operation traces (six gates) at the Lucky Peak reservoir according to OSU Rivers

5 CONCLUSIONS

This paper presents a new framework for the intelligent control of river flooding. The proposed approach links two components: river system routing (simulation) and optimization. The river system routing (simulation) component builds upon the application of Performance Graphs, while the optimization component uses the popular second generation multi-objective evolutionary algorithm Non-dominated Sorting Genetic Algorithm-II (NSGA-II). For illustration purposes, the proposed framework was applied to the Boise River system in Idaho. The key findings are as follows:

1. Results show that the Boise River would flood for all scenarios for the simulated inflow hydrograph under projected climate change scenario. The operation of controlled in-line structures according to the results of the proposed framework delays the occurrence of flooding, but does not avoid it due to lack of sufficient storage capacity in the Lucky Peak reservoir.
2. The use of performance graphs for river system routing results in a robust and numerically efficient model as most of the computations for the system routing only involves interpolation steps.
3. Overall, the results show a promising outcome in the application of this model for flood control.

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