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Multi-phase intelligent decision model for reservoir real-time flood control during typhoons

Nien-Sheng Hsu [a,*], Chien-Lin Huang [a], Chih-Chiang Wei [b]

[a] Department of Civil Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
[b] Department of Digital Content Designs and Management, Toko University, No. 51, Sec. 2, University Road, Pu-Tzu City, Chia-Yi County 61363, Taiwan

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SUMMARY

This study applies an Adaptive Network-based Fuzzy Inference System (ANFIS) and a Real-Time Recurrent Learning Neural Network (RTRLNN) with an optimized reservoir release hydrograph using Mixed Integer Linear Programming (MILP) from historical typhoon events to develop a multi-phase intelligent real-time reservoir operation model for flood control. The flood control process is divided into three stages: (1) before flood (Stage I); (2) before peak flow (Stage II); and (3) after peak flow (Stage III). The models are then constructed with either three phase modules (ANFIS-3P and RTRLNN-3P) or two phase (Stage I + II and Stage III) modules (ANFIS-2P and RTRLNN-2P). The multi-phase modules are developed with consideration of the difference in operational decision mechanisms, decision information, release functions, and targets between each flood control stage to solve the problem of time-consuming computation and difficult system integration of MILP. In addition, the model inputs include the coupled short lead time and total reservoir inflow forecast information that are developed using radar- and satellite-based meteorological monitoring techniques, forecasted typhoon tracks, meteorological image similarity analysis, ANFIS and RTRLNN. This study uses the Tseng-Wen Reservoir basin as the study area, and the model results showed that RTRLNN outperformed ANFIS in the simulated outcomes from the optimized hydrographs. This study also applies the models to Typhoons Kalmaegi and Morakot to compare the simulations to historical operations. From the operation results, the RTRLNN-3P model is better than RTRLNN-2P and historical operations. Further, because the RTRLNN-3P model combines the innovative multi-phase module with monitored and forecasted decision information, the operation can simultaneously, effectively and automatically achieve the dual goals of flood detention at peak flow periods and water supply at the end of a typhoon event.

1. Introduction

The topography of Taiwan is influenced by complex convergent geology, resulting in steep basins and rapid runoff after storms. Taiwan is frequently in the path of typhoons that carry heavy precipitation, resulting in flooding during the rainy season. However, precipitation varies widely between the wet and dry seasons. To control flooding during the wet season and store water for the dry season, the government of Taiwan has constructed reservoirs along flood-prone channels. During typhoons, rains fall with high intensity over long durations; thus, reservoir inflow is considerably high. During these times, reservoir operations involve important decisions about real-time releases to mitigate flood disturbances such as dam breaches, while holding back enough water to avoid downstream flooding and future water shortages. At present, reservoir operations in Taiwan mainly rely on human experience, public safety considerations, and government guidance. But all of these considerations must be made while making real-time operational decisions during typhoons.

Research in real-time reservoir flood control operations has received much attention in recent years. The frequency of typhoons that bring heavy rain has been growing due to climate change (Kelly and Adger, 2000; Hughes et al., 2003; Webster et al., 2005; Wu et al., 2005a, 2005b; Oouchi et al., 2006; Knutson et al., 2010), and inflows are more frequently surpassing original design and construction standards. Managing the releases from these multi-purpose reservoir systems is both a critical and complex problem. However, previous studies have mainly focused on the methodology establishment including model construction (Windsor, 1973; Needham et al., 2000; Shim et al., 2002; Hsu and Wei, 2007; Chang et al., 2010) and formulation of operational

* Corresponding author. Tel.: +886 2 33662640; fax: +886 2 33665866.
E-mail address: nsshue@ntu.edu.tw (N.-S. Hsu).

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rules (Schultz and Plate, 1976; Chang and Chen, 1998; Bagis and Karaboga, 2004; Chang, 2008), and the application of models (Unver and Mays, 1990; Niewiadomska-Szynkiewicz et al., 1996) and operational rules (Wei and Hsu, 2009; Huang and Hsieh, 2010) in real-time operations is relatively rare.

Studies about real-time flood control operations can be divided into deterministic, fuzzy and stochastic methodologies. In general, deterministic and fuzzy approaches are easier to be connected with practice and be understood by operator. In an early deterministic model, Windsor (1973) employed recursive linear programming as an optimization tool for analysis of multi-reservoir flood control systems. Later, Unver and Mays (1990) developed a nonlinear programming (NLP) model to address the real-time hourly flood control problem. Niewiadomska-Szynkiewicz et al. (1996) used predictive methods for real-time hourly flood operations. The objective in this case was to minimize the overflow for each section of the river downstream of the reservoir. Needham et al. (2000) developed a reservoir flood control decision model (HEC-FCLP) based on Mixed Integer Linear Programming. In their study, a weighted penalty function that considered reservoir storage, release, and downstream channel flow, was constrained by reservoir storage and release limitations, the continuity equation, and the channel routing equation. Shim et al. (2002) presented a prototype spatial decision support system (SDSS) for integrated real-time river basin flood control in a multipurpose multi-reservoir system. The SDSS integrated a geographic information system with a database management subsystem, a real-time meteorological and hydrological data monitoring system, a model-based subsystem for operation simulation and optimization, and a graphical dialog interface allowing effective use by system operators. Hsu and Wei (2007) developed a multipurpose reservoir real-time optimal operation model for flood control (RES-RTFC). This model was developed for real-time release decisions by coupling precipitation forecasts, reservoir inflow forecasts and an optimization model which solved by Mixed Integer Linear Programming (MILP). Wei and Hsu (2009) established a series of optimal tree-based release rules for real-time flood control operations in a multipurpose multi-reservoir system. The rules could be used to decide the optimal reservoir release during typhoons. From these previous studies, we found that the deterministic real-time model (e.g. MILP) potentially made operational decision-making easier, when combined with operation guidance and expert knowledge. Although this type of decision mechanism can search and provide an optimal numerical solution, the disadvantages include time-consuming computation and difficult system integration that would be the gap for practical real-time operation use.

Fuzzy models provide a potential alternative. Bagis and Karaboga (2004) proposed a new and efficient control method based on fuzzy logic for real-time operation of reservoir spillway gates during floods of variable sizes. In their study, artificial neural networks were used to model the non-linear relationship among the main variables of the reservoir under consideration. Huang and Hsieh (2010) developed an early warning model for real-time reservoir flood control operation during typhoons. The model contained three main parts: (a) "flood watch" to monitor the current flood situation; (b) "flood release" to estimate probable reservoir releases in the near future; and (c) "decision analysis" to determine an appropriate release policy. A new flood alert index based on fuzzy logic was also defined to account for risk and augment reservoir flood operation, and a genetic algorithm (GA) was presented to specify suitable releases in response to the nature of flood inflows and reservoir water levels. Chang et al. (2010) constructed an intelligent real-time fuzzy reservoir flood control operation model (IFF-CM). IFFCM was constructed by the optimized best operation hydrograph from historical typhoon events using a GA, and the real-time release could be immediately evaluated by an Adaptive Network-based Fuzzy Inference System (ANFIS). Results showed that the model could be used to decrease downstream peak water levels and store enough water for future use effectively, and the model outperformed historical operation. From the above studies, we conclude that applying fuzzy logic-based approach could save time in real-time routing decisions.

The flood control process can be divided into three stages: (1) before flood (Stage I); (2) before peak flow (Stage II); and (3) after peak flow (Stage III). The operation goals in each flood control stage are different: during Stage I, the goal is to release in advance to increase reservoir storage space; during Stage II, release as little as possible for flood detention; and during Stage III, retain close to full storage capacity. However, in most previous studies, model development and applications did not completely consider the reservoir release and decision mechanisms between each flood control stage. Li et al. (2010) proposed a well model which consists of three modules: (1) pre-release module; (2) refill operation module; and (3) risk analysis module for reservoir operation. However, considering the challenge of real-time operation under tremendous typhoon-flood and extreme rainfall posture within a reservoir of narrow storage in Taiwan, the multi-phase intelligent decision model need to be specially developed to deal with.

Labadie (2004) indicated that artificial neural networks (ANN) may be useful as an alternative to multiple regression analysis for determining optimal rules. Raman and Chandramouli (1996) claimed that simulation of rules obtained from the trained ANN outperforms rules produced by linear regression analysis, as well as optimal feedback laws obtained from optimization of historical operations. Other uses of different kinds of ANN may be in representing the deterministic programming model with fewer sampling points. Besides, reservoir operation system during typhoons belongs to small-scale time-varying decision systems. Among various ANN models, Haykin (1999) and Chang et al. (2002) indicated that Real-Time Recurrent Learning Neural Networks (RTRLNN) possesses dynamic real-time recurrent routing mechanisms that can simulate time-varying systems effectively. The routing mechanism is similar to the decision mechanism of deterministic models, but this tool has not been researched to the evaluation of real-time reservoir flood control operation. Hence, this study attempts to construct a multi-phase real-time reservoir operation model using the RTRLNN with optimal releasing operation hydrographs obtained from a deterministic optimization model to solve the time-consuming problem of deterministic model.

The purpose of this study is to combine short lead time reservoir inflow forecasts, total inflow forecasts, and the distinct differentiating decision mechanisms and operation rules of each flood control stage to develop various multi-phase intelligent decision models for real-time reservoir flood control operations during typhoons. The developed deterministic-fuzzy approach would be applied to practical use to solve the previous time-consuming problem, achieve optimal real-time operation, and deal with tremendous typhoon-flood and extreme rainfall posture within a reservoir of narrow storage.

2. Development of methodology

2.1. Procedures

This research can be divided into three steps (Fig. 1):

Step 1: Develop an integrated forecast from reservoir hydrologic and operation information. The integrated forecast models include an ANFIS or RTRLNN-based short lead time reservoir inflow forecast model, Real-Time Revised Quantitative Precipitation Forecast model based on Typhoon Central Location (RTR-TCL-QPF), and total reservoir inflow forecast model.