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ABSTRACT

An integrated hydro-meteorological system of combining a rainfall-runoff model (kinematic wave based on geomorphologic instantaneous unit hydrograph model, KW-GIUH) with a numerical weather model (Taiwan cooperative precipitation ensemble forecast experiment, TAPEX) is proposed to perform reservoir inflow forecasting patterns in the Shihmen Reservoir, located in northern Taiwan. It found that using the average forecasting result derived by all TAPEX runs could be less uncertain than randomly choosing a run's result. Results from the study demonstrate that the proposed system could be able to substantially represent reservoir inflow forecasting in the Shihmen Reservoir and provide valuable information for operating reservoirs.

KEY WORDS: rainfall-runoff; ensemble precipitation forecast; reservoir inflow; typhoon; meteorology; TAPEX; KW-GIUH.

INTRODUCTION

Taiwan is located in the northwestern Pacific, on one of the main typhoon paths, and an average of 3.75 typhoons strike Taiwan annually. The typhoons bring heavy rains and cause damage. Typhoon-induced floods lead to serious disasters (Lin and Wu, 2011; Huang et al., 2016). However, they are also important water resources. Yang and Yang (2014) indicated a reservoir serves as an important hydraulic structure for two purposes: managing flood water release at opportune times to decrease flooding downstream and storing inflows for future uses due to limited water resources in Taiwan during a typhoon period. Brath et al. (1998) indicated that quantitative rainfall forecasting (QPF) plays an important role in extending the lead time of flow forecasting, which can improve the timeliness of flood control mechanisms. Hence, accurate reservoir inflow forecasts with enough lead time will help reservoir authorities manage reservoirs to meet the purposes listed above.

This study applies ensemble precipitation forecasts to extend the lead time and uses a rainfall-runoff model to generate hourly reservoir inflow forecasts. The reservoir operators can consider the results as a valuable reference to achieve the goal of maximizing flood protection while saving water for drier times of the year. Numerical weather predictions (NWPs) were adopted to forecast the rainfall and estimate the quantity of precipitation to extend the forecasting lead time. The ensemble technique of NWPs is widely used instead of a single deterministic model to capture rainfall forecasting uncertainties (Cloke and Pappenberger, 2009).

Taiwan cooperative precipitation ensemble forecast experiment (TAPEX) started in 2010 and was the first attempt to design a high-resolution numerical ensemble weather model in Taiwan (Hsiao et al., 2013). It aims to provide 24-, 48-, and 72-h typhoon precipitation forecasts and generates four runs a day at a 5-km spatial resolution. To date, there are over than 20 ensemble members (20 numerical weather models) for precipitation forecasts. The ensemble statistical method and probabilistic forecasting concept are used to analyze the typhoon path and precipitation distribution (Lee et al., 2013; Yang et al., 2015). This study uses TAPEX's rainfall forecasts, as well as real time rainfall gauge data as an initial condition to a rainfall-runoff model to generate reservoir inflows.

Rainfall-runoff estimation techniques can be broadly classified as non-physically based and physically based models. An artificial neural network (ANN), a kind of information processing systems with great flexibility in modeling nonlinear processes, is one of non-physically based models well-known for hydrologic forecasts, such as streamflow forecasts (Wu et al., 2014; Lin et al., 2014) and reservoir inflow forecasts (Lin et al, 2009a,b; Lin et al., 2010; Lin and Wu, 2011). However, an ANN requires a sufficient amount of hydrologic data to determine the adaptive weights, which are inadequate to be applied to data-sparse areas. There is only a limited number of studies on fully physically based reservoir inflow forecasting models with typhoon information as input. This study performs reservoir inflow simulations using a geomorphology-based and semi-distributed runoff model, named Kinematic Wave-geomorphology Instantaneous Unit Hydrograph model (KW-GIUH model) (Lee and Yen, 1997), which can account different geomorphologic and hydrological characteristics of the watersheds (Yen and Lee, 1997; Shadeed et al., 2007; Chiang et al., 2007; Kumar and Kumar, 2008; Lee et al., 2009; Ho and Lee; 2015).

The objective of this study is to provide the highly accuracy reservoir inflow forecasts during typhoon periods based on the integrated hydro-meteorological system that combines ensemble quantitative precipitation forecasts (i.e. TAPEX) with geomorphology-based runoff model (i.e. KW-GIUH model). A study area of the Shihmen Reservoir in Taiwan is conducted.

METODOLOGY

Taiwan Cooperative Precipitation Ensemble Forecast Experiment (TAPEX)

TAPEX is a collective effort among academic institutes and government agencies in Taiwan. It applied various models, including the weather research and forecasting (WRF), model, the fifth-generation Penn State/NCAR mesoscale model (MM5), and cloud-resolving storm simulator (CReSS), and initial conditions for precipitation forecast. The observed data gathered worldwide from satellites, radar, atmospheric sounding, and ground observations are used in aforementioned numerical weather models.

The experiment started in year 2010 and was the first attempt to design a high-resolution numerical ensemble weather model in Taiwan. The experiment collects worldwide observation data (e.g. temperature, wind, surface pressure, relative humidity, and etc.) from satellites, atmospheric sounding devices, buoys, aviation routine weather reports, ships, and other available sources. Numerical weather models input these collected data as boundary conditions and perform simulations on a super computer (Lee et al., 2013).

The experiment has an aim to provide typhoon precipitation forecasts and generates four runs per day at a 5-km spatial resolution. To date, 26 ensemble members (26 numerical weather models) have been established for precipitation forecasting. The ensemble statistical method and probabilistic forecast concept are used to analyze the typhoon path and precipitation distribution. One can refer to previous studies (Hsiao et al., 2013; Lee et al., 2013; Yang et al., 2015) for details about the TAPEX. This study proposes a rainfall-runoff model coupled with ensemble quantitative precipitation forecasts to assess shallow landslide potential in the next 72 hours.

Geomorphology-based Runoff Model (KW-GIUH)

A computationally efficient geomorphology-based runoff model, called KW-GIUH model (Lee and Yen, 1997) was adopted for real-time reservoir inflow forecasting in this study. KW-GIUH model is a semi-distributed runoff model based on the instantaneous unit hydrograph (IUH) theory. This model can be derived only by using watershed geomorphologic information obtained from a digital elevation model for easy usage. Hence, KW-GIUH model can operate with high efficiency to meet the requirements of real-time flow forecasting. The hydrological response function of the watershed can be expressed analytically as follows (Rodriguez-Iturbe and Valde, 1979):

$$u(t) = \sum_{w \in W} \left[f_{x_{o_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \ldots * f_{x_\Omega}(t) \right]_w \cdot P(w) \tag{1}$$

where $u(t)$ is the watershed IUH; W is the flow path space, which is expressed as $W = \langle x_{o_i}, x_i, x_j, \ldots, x_\Omega \rangle$; $f_{x_{o_i}}(t)$ denotes the travel time probability density function in state x_j with a mean value of T_{x_j}; $*$ denotes a convolution integral; and $P(w)$ represents the probability of a raindrop adopting a flow path w.

Based on the kinematic-wave approximation, the travel time equation for different orders of overland areas and streams can be derived (Henderson and Wooding, 1964; Lee and Yen, 1997)

$$T_w = T_{oc_i} + \sum_{k=i}^{\Omega} T_{cc_k} = \left(\frac{n_o \bar{L}_{o_i}}{\bar{S}_{o_i}^{1/2} i_e^{m-1}} \right)^{\frac{1}{m}} + \sum_{k=i}^{\Omega} \frac{B_i}{2 i_e \bar{L}_{o_i}} \left[\left(h_{co_k}^m + \frac{2 i_e n_c \bar{L}_{o_k} \bar{L}_{c_k}}{\bar{S}_{c_k}^{1/2} B_k} \right)^{\frac{1}{m}} - h_{co_k} \right] \tag{2}$$

where T_w is the runoff travel time for a specified flow path w; T_{oc_i} is the mean runoff travel time on the i^{th}-order overland planes; T_{cc_k} is the mean runoff travel time in the k^{th}-order channels; Ω is the order of the watershed stream network; n_o and n_c represent the overland-flow and channel roughness coefficient; $\bar{L}_{o_i}$ denotes the mean i^{th}-order overland length; $\bar{L}_{c_k}$ is the mean k^{th}-order channel length; $\bar{S}_{o_i}$ denotes the mean i^{th}-order overland slope; $\bar{S}_{c_k}$ is the mean i^{th}-order channel slope; i_e represents the effective rainfall intensity; m is an exponent recognized as 5/3 in Manning's formula. B_k is the kth-order channel width; and h_{co_k} is the inflow depth of the i^{th}-order channel caused by water transporting from upstream reaches.

Hence, the runoff travel times for different orders of overland-flow paths and channels can be estimated, and the watershed IUH can then be derived by using Eq. 1. Consequently, the watershed runoff simulated by using KW-GIUH model can be expressed as

$$Q_{sim,t} = \int_0^{\tau} i(\tau) u(t-\tau) d\tau \tag{3}$$

where $Q_{sim,t}$ is the simulated direct runoff at time t; $i(\tau)$ is the rainfall intensity; and $u(t-\tau)$ is the unit impulse response function derived from KW-GIUH model. Consequently, the runoff travel time for different orders of overland-flow paths and channels can be estimated by using Eq. 2, and then the travel time values can be substituted into Eq. 3 to obtain the watershed IUH for rainfall-runoff simulation.

Performance Indicators

Four indicators, including the percent error of peak inflow (EQ_p), the difference of time to peak inflow (ET_p), the percent error of cumulative inflow (EQ_c) and the coefficient of efficiency (CE) as defined in Eqs. 4-7, respectively, were adopted to evaluate the goodness of simulated results.

$$EQ_p(\%) = \frac{(Q_p)_{sim} - (Q_p)_{obs}}{(Q_p)_{obs}} \times 100 \tag{4}$$

$$ET_p(h) = (T_p)_{sim} - (T_p)_{obs} \tag{5}$$

$$EQ_c(\%) = \frac{\sum_{i=1}^{n} [Q_{sim}(t) - Q_{obs}(t)]}{\sum_{i=1}^{n} Q_{obs}(t)} \times 100 \tag{6}$$

$$CE = 1 - \frac{\sum_{i=1}^{n} [Q_{sim}(t) - Q_{obs}(t)]^2}{\sum_{i=1}^{n} [Q_{obs}(t) - \overline{Q_{obs}}(t)]^2} \tag{7}$$

where the subscripts of '*sim*' and '*obs*' indicate the simulated and observed inflows, respectively. Q_p is the peak inflow (m^3/s); T_p is the time to peak inflow (h). $Q_{obs}(t)$ is the observed inflow at time t (m^3/s); $Q_{sim}(t)$ is the simulated inflow at time t (m^3/s); t is time (h); $\overline{Q_{obs}}(t)$ is the average observed inflow of the total simulated time (m^3/s). The coefficient of efficiency (CE) is a suitable tool to describe the overall performance. As CE value is equal to 1, it indicates a perfect simulation overlapping exactly with the observation.

STUDY AREA

The Shihmen Reservoir, located in northern Taiwan, was selected as the study area, as shown in Fig. 1. It has a catchment area of 763.4 km^2 and an effective storage capacity of 2.33×10^8 m^3 that ranks the first and third among all reservoirs in Taiwan, respectively. Its main purposes are irrigation, water supply, flood control, hydroelectricity generation, and recreation. Water from the Shihmen Reservoir is supplied to more than two million households across 28 districts in three counties of northern Taiwan. Moreover, the reservoir has an important mission to cut peak flood flows during typhoon events due to that one-third of the total population of the Taipei metropolitan area, the largest one in Taiwan, is downstream. Therefore, to balance the goals of water supply and flood mitigation at the same time, the decision makers need to be precise when executing reservoir operation.

RESULTS AND DISCUSSION

In the study, a total of three historical typhoons, namely Morakot (2009), Fitow (2013) and Soulik (2013), were used for model calibration, validation, and further application.

Model Calibration and Validation (KW-GIUH)

As mentioned earlier, this study used KW-GIUH model to simulate reservoir inflow. In this model, only two major model parameters of n_c (to decide channel roughness) and n_o (to assign overland-flow roughness) were calibrated and validated for obtaining adequate values. For model calibration and validation, firstly, the spatial rainfall data of above three typhoon events at 10 rain gauge stations as shown in Fig. 1, located in the Shihmen reservoir catchment, were averaged using the Thiessen polygon method to provide representative rainfall data. Next, the representative rainfall data was input the model as an initial condition to simulate reservoir inflow.

Fig. 2 presents the simulations with time variations in comparison with the observations. The observed peak inflows obtained at Hsiayun flow gauge station (No. 1140H054 in Fig. 1) were 1,738 m^3/s (Morakot) and 1,429 m^3/s (Fitow). The percent errors of peak inflow (EQ_p) were -3.2 % for Morakot (model validation) and 4.8 % for Fitow (model validation), and all the relative errors can be controlled within 5%. The differences of time to peak inflow (ET_p) were 1 h for Morakot and Fitow. The percent errors of cumulative inflow (EQ_c) were -18.4 % and -2.6 %. In addition, the coefficient of efficiency (CE) were 0.85 and 0.94 in the two typhoons. Based on the above results, they confirmed that the calibrated KW-GIUH model is a reasonable representation of the actual system after the calibration and validation that minimize uncertainties originated from model parameters. Thus, it can provide predictions for the reservoir inflow with enough fidelity.

Applications (KW-GIUH+TAPEX)

After model calibration and validation, this study integrated the KW-GIUH model and TAPEX as a hydro-meteorological system to evaluate the performance of reservoir inflow forecasts. Regarding the precipitation ensemble forecasts, the ensemble-mean precipitation forecasts that averaged all the members of TAPEX were used in the present study to show reservoir inflow forecasts. Typhoon Soulik (2013) was applied and below is the detailed discussion for the simulated results.

For Typhoon Soulik, the landing warnings were issued from 20:30, July 11 to 23:30, July 13 by the Central Weather Bureau of Taiwan. This typhoon had a concentrated rainfall distribution within a day. Fig. 3 shows the rainfall hyetograph and the observed reservoir inflow of Typhoon Soulik. The total rainfall was 400 mm within the period of land warnings with the peak rainfall 66.9 mm occurred between 5:00 and 6:00, July 13. At this time, the total observed inflow was 53,296 m^3/s and the peak inflow was 5,118 m^3/s at 08:00, July 13.

The reservoir inflow forecasts and TAPEX results during Typhoon Soulik were also plotted in Fig. 3. As to the forecasting process, there were a total of seven TAPEX runs from 08:00, July 11 to 20:00, July 12, 2013. The time interval between two runs is 6 hours. Each run has its own reservoir inflow forecast. A run used the combination of 48 hours real-time rainfall records and 72 hours precipitation ensemble mean forecast provided by TAPEX as an initial condition to generate a 72 hours reservoir inflow forecast.

Fig. 4 compares the simulated reservoir inflow forecasts of seven TAPEX runs with the observed data by using the indicators of EQ_p, ET_p and EQ_c. It was found from Fig. 4(a) that the EQ_p of all runs ranged from -32.8 % (4th run) to 7.8 % (5th run) and the average EQ_p, which is the average error of all runs, was -6.2 %. Two out of seven runs had obviously less estimation than the average EQ_p. Fig. 4(b) shows that the ET_p were between -1 h and 1 h and the average ET_p was only 0.3 h. To understand reservoir inflow forecasting, not only the magnitude and timing of peak flow but also the performance of cumulative inflow needs to be considered. In Fig. 4(c), it shows a wide range of -16.4 % (4th run) to 25.8 % (5th run) in terms of the percent error of cumulative inflow, but a good average EQ_c with a value of 14.7 %. In addition, according to Fig. 5, it was found that the forecasted inflows by using 7th run were almost within the 95 % confidence interval (dash line). In general, all forecats generated a better agreement with the observations and the CE values of seven runs were more than 0.85.

CONCLUSION

The present study integrates the KW-GIUH model and TAPEX as a hydro-meteorological system to provide reliable reservoir inflow forecasts for the Shihmen Reservoir. Based on the comparative results, it showed significant variations in reservoir inflow forecasts when using different TAPEX runs. It can be attributed to that there were too many uncertainties in predicting rainfall. However, the rainfall estimation was still valuable for us to forecast reservoir inflows with enough lead time. Therefore, the study suggested that using the average forecasting result could be less uncertain than randomly choosing a run's result. Moreover, it is promising to apply the proposed system for reservoir inflow forecasts to avoid the flood disaster and keep the available water resource during typhoon events. In addition, more events and different study areas to implement the system need to be considered in the future works to ensure the findings in this study

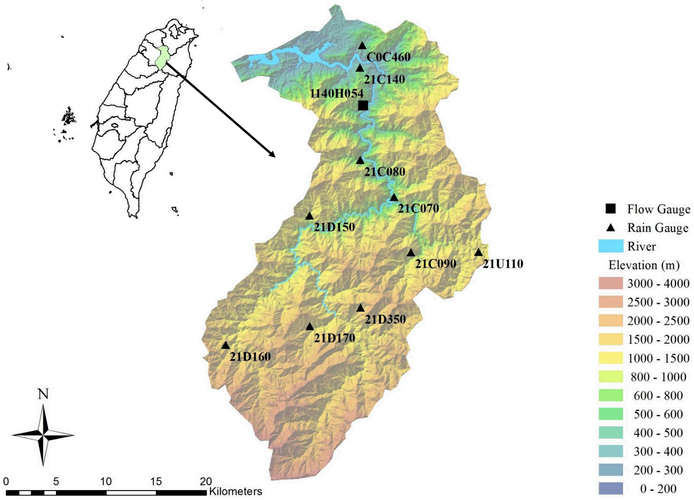
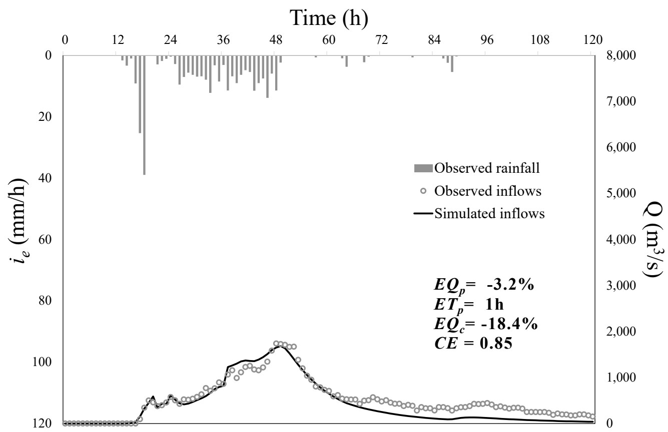
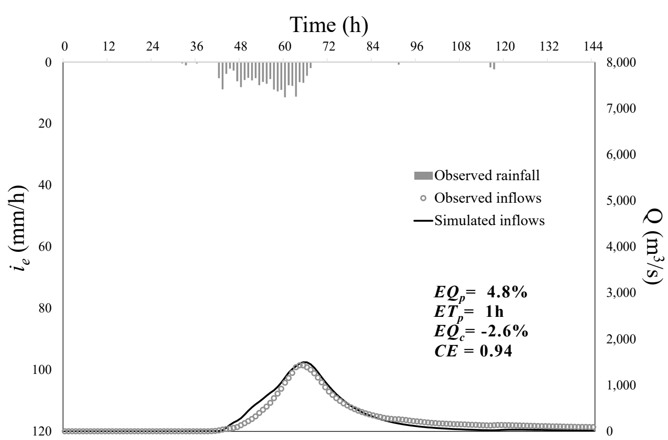


Fig. 1 Location of the study area of the Shihmen Reservoir.



(a) Typhoon Morakot (2009) (model calibration)



(b) Typhoon Fitow (2013) (model validation)

Fig. 2 Observed and simulated hydrographs of reservoir inflow.

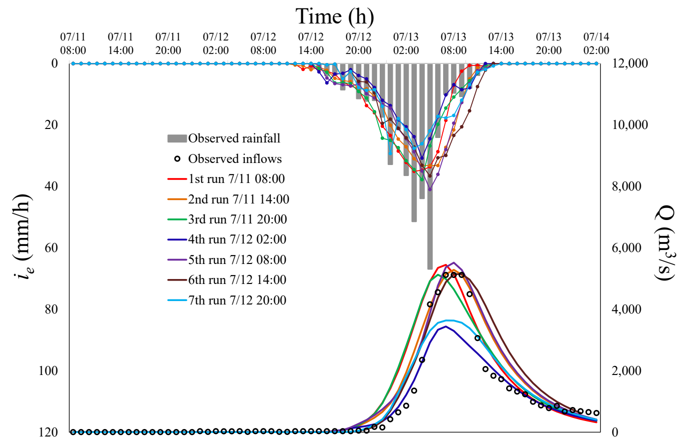


Fig. 3 Observed and simulated hydrographs of reservoir inflow forecasts during Typhoon Soulik (2013).

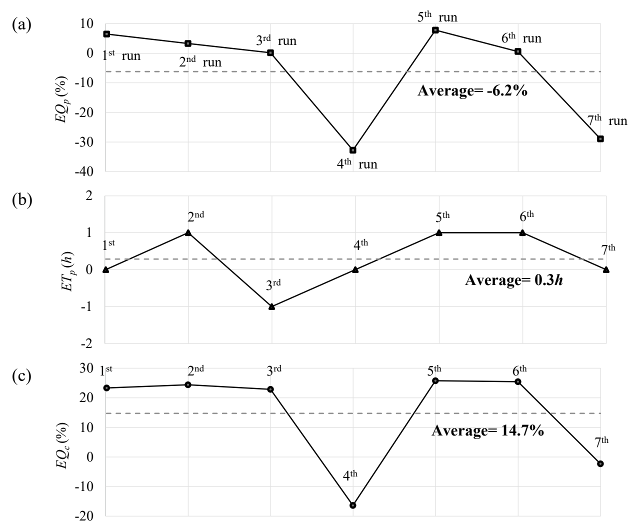


Fig. 4 Comparison with the forecasts and observations (Typhoon Soulik): (a) the percent error of peak inflow, (b) the difference of time to peak inflow, and (c) the percent error of cumulative inflow.

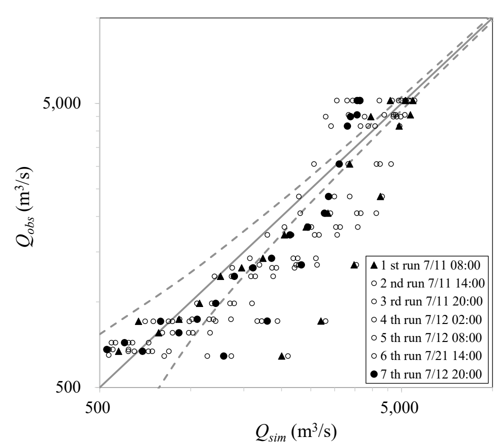


Fig. 5 The observed reservoir inflows versus the forecasts of Typhoon Soulik (2013).

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