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대유역의 유량예측 시스템 개발에 관한 연구
Development of Flow Forecasting System in Large Drainage Basin

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Abstract

The subject research attempts to develop a hydrologic-hydraulic forecasting system suitable for use in large river basins. A conceptual hydrologic rainfall-runoff model is used to produce streamflow from meteorological and hydrologic input data over each subbasin, while a hydraulic model is used to route the catchment outflows in the stream network. For operational flow prediction, an efficient state estimator has been designed for the real-time updating of model states from newly recorded data. The real-time application of the forecasting system indicates that this model produces reliable short-term predicted results.

요 지

본 연구는 대유역의 유량예측을 위한 수공학적 모형 시스템을 개발하는데 있다. 이 시스템은 각각의 부분유역에서의 기상학적, 수문학적 입력자료를 바탕으로 하천유량을 예측하는 개념적인 수문학적 강우유출모형과 각 부분유역의 예측유량을 입력치로 하여 하도홍수추적을 하는 수리학적 모형으로 구성되어 있다. 실시간 해석시 새로운 관측자료로부터 모형의 상태변량을 최적화 할 수 있는 효율적인 상태변량 추정자가 사용되었다. 실시간 유량예측을 위해서 본 연구에서 개발된 모형을 적용하여 본 결과, 예측가능시간이 짧은 경우 대유역의 실시간 유량예측모형으로서 타당한 것으로 판단된다.

1. Introduction

Over the last 50 years considerable research effort has been performed for the development of mathematical models for the rainfall-runoff process to obtain a better understanding of the complexity of catchment response and to reduce the magnitude of flood disasters. Perhaps, the most significant conceptual time-continuous spatially-lumped models are the Stanford Watershed Model and the National Weather Service River Forecast System. Georgakakos (1986), thereafter, proposed an Integrated Hydrometeorological Forecast System (IHFS) that a meteorologi-

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cal precipitation model was coupled to a hydrologic model. This model was designed for real-time flood and flash flood prediction. The spatial scale of its application depends on the meteorologic and hydrologic conditions on a certain basin.

The objectives of this study are to develop a flow forecasting system, hereafter referred to as University of Iowa Forecast System (UIFS), that is based on a quasi-distributed model to overcome the limit on the spatial scale of IHFS application for large drainage basins. The proposed system is unique in the formulation of its components and is particularly suited to situations with existing and maintained real-time databases.

2. Description of Large-Scale Model

The proposed model is composed of a hydrologic component for flow predictions at local subbasins and a hydraulic component for the flow connection among subbasins. The details of the model formulations and components will not be presented here for space limitations. It will be only provided the basic concept and features of the model components, the interactions within the proposed model, and the references for further details. The complete mathematical formulations are given in Bae and Georgakakos(1992).

2.1 Model Component

2.1.1 Hydrologic Component

The hydrologic component stems from the IHFS. In this study, the model further extended to allow computation of snowmelt and frozen ground. The followings are a brief description of each model.

(1) Precipitation Model: It is based on an one-dimensional conservation of mass law in a cloud column characterized by routinely available meteorological data (Georgakakos and Bras, 1982a). It performs the computation of the condensed water equivalent mass at a certain time in a unit area column that extends from the base to the top of the clouds. This condensed water produces outflow due to precipitation, while the moisture inflow to the cloud column is due to condensation and air mass ascent. Subcloud evaporation reduces the precipitation mass that reaches the ground to a value smaller than the one obtained at the cloud base level.

(2) Snowmelt Model: The model developed by Anderson (1973) was coupled to hydrologic component in this study. The basic concept of this model is that snow is regarded as a mixture of the three phases of water and air. It continuously changes its properties by meteorological and geological conditions. Based on the energy balance equation, the model computes the amounts of snowmelt during rain and no-rain periods.

(3) Surface-Runoff Model: The continuous-time state-space form of the Sacramento model (Georgakakos, 1986) is used in this study. The basic concept of this model is that it subdivides the soil layers of the drainage basin into two zones. Both zones have tension water elements and free water elements. The total channel inflow consists of direct runoff from impervious areas, surface runoff and interflow through the upper soil layers and base flow through the lower soil layers.

Frozen ground exists when temperature falls below 0℃. It will reduce the contributions of ground water to streamflow. The model developed by Anderson and Neuman (1984) was used to accomodate frozen ground effects in this study.

(4) Watershed Flow Routing Model: The conceptual, nonlinear, reservoir-type flood routing model of Georgakakos and Bras (1982a,b) was used to propagate the flood wave downstream, up to the point of interest. Their kinematic model suitable for application in upland areas is simple to implement on a digital computer.

(5) State Updating Component: It describes input and parameter uncertainty, and produces updated estimates of the model states in real-time given observations of discharge at the drainage basin outlet. The extended Kalman Filter is used to estimate the states of the model components, because the model involves nonlinear functions of the state variables.

2.1.2 Hydraulic Component

Channel routing is used to determine a downstream discharge hydrograph at a certain time from a given upstream hydrograph. This component is based on the Muskingum-Cunge method (Cunge, 1969). The reasons for the selection of this model are: (1) it can be easily converted to a state-space form for real-time operation; (2) this model possesses an inherent potential for greater accuracy as compared to simpler kinematic models. Relevant formulation of stochastic state-space form of the model has been described by Georgakakos et al.(1990). Their formulation further extended to allow natural channel irregularities for the computation of parameters in this study (Bae and Georgakakos, 1992).

2.2 Model Structure

2.2.1 State-Space Form of Hydrologic-Hydraulic Model

The proposed stochastic-dynamic model was developed to provide real-time flow predictions at several locations in a large drainage basin. The system equations and observations of the system involved both hydrologic(Eqs. 1a and 1b) and hydraulic (Eqs. 2a and 2b) components can be expressed as:

$$\frac{d\underline{x}(t)}{dt} = \underline{F}[\underline{x}(t), t] + \underline{W}(t) \tag{1a}$$

$$\underline{Z}(t_k) = \underline{G}[\underline{x}(t_k), t_k] + \underline{V}(t_k); t_k \le t \le t_{k+1}, \quad k = 1,2,\cdots \tag{1b}$$

$$\underline{Q}(t_{k+1}) = \underline{A}\ \underline{Q}(t_k) + \underline{B}\ \underline{U}(t_k) + \underline{C}\ \underline{q_l}(t_k) + \underline{W}'(t_k) \tag{2a}$$

$$\underline{Z}'(t_k) = \underline{H}^T\ \underline{Q}(t_k) + \underline{V}'(t_k) \tag{2b}$$

where $\underline{x}(t)$ is a state vector of hydrologic component represented by

$$\underline{x}(t) = [x_1(t), \cdots, x_L(t), s_1(t), \cdots, s_n(t)]^T \tag{3}$$

where $x_i(t)$ and $s_i(t)$ are the i^th^ state variables of the meteorologic and hydrologic models, respectively. The subscripts L and n denote the number of orographic zones and the number of conceptual storages over the basin, respectively. $\underline{F}[\underline{x}(t), t]$ is a nonlinear vector function that contains the dynamics of the meteorologic and stream routing models. $\underline{W}(t)$ is an additive random error vector that accounts for the model structure, input, and parameter uncertainties. $\underline{Z}(t_k)$ in Eq. 1(b) is an associated observation vector represented by

$$\underline{Z}(t_k) = [z_{p1}(t_k), \cdots, z_{pL}(t_k), z_{qn}(t_k)]^T \tag{4}$$

where $z_{pi}(t_k)$ and $z_{qi}(t_k)$ are the i^th^ elements of precipitation and discharge observations at time t_k. Vector $\underline{V}(t_k)$ represents the observation error that reflects the expected errors in measuring precipitation and discharge at time

t_k. On the other hand, $\underline{Q}(t_k)$ in Eq. 2(a) is an estimated river flow vector for the N channel reach at t_k represented by

$$\underline{Q}(t_k)=[Q_1^t,\ Q_2^t,\cdots,Q_N^t]^T \tag{5}$$

$\underline{U}(t_k)$ describes an upstream boundary condition vector obtained from the output of a hydrologic model such that

$$\underline{U}(t_k)=[Q_0^t\cdot Q_0^{t+1}]^T \tag{6}$$

The element Q_0^t represents upstream boundary condition at time t. $\underline{q}_l(t_k)$ denotes a lateral channel inflow vector represented by

$$\underline{q}_l(t_k)=[q_{l\,1}^{\,t},\ q_{l\,2}^{\,t},\ q_{l\,3}^{\,t}\cdots,\ q_{l\,N}^{\,t}] \tag{7}$$

Matrices $\underline{A}$, $\underline{B}$, and $\underline{C}$ are related to the routing coefficients and can be computed from explicit recursive forms(Georgakakos et al., 1990). $\underline{Z}'(t_k)$ in Eq. 2(b) is an associated observation vector. Again, the terms $\underline{W}'(t_k)$ and $\underline{V}'(t_k)$ represent two uncorrelated, zero mean, white noise sequences of model and observation error terms, respectively. Bae and Georgakakos (1992) provides the formulations in detail.

2.2.2 Model Configuration

The hydrologic component of the proposed system is composed of quantitative precipitation forecast (QPF) model, quantitative overland flow forecast (QFF) model, snowmelt and frozen ground models. Regarding rainfall prediction, the performance of the model is highly dependent on the availability of timely and accurate observations of the meteorologic variables that the model requires, but these situations are not existed in a certain area. For the purpose of this application the precipitation model was decoupled from the other hydrologic components. In its present form, hydrologic component of the proposed model operates on option either as a coupled or as a decoupled QPF model.

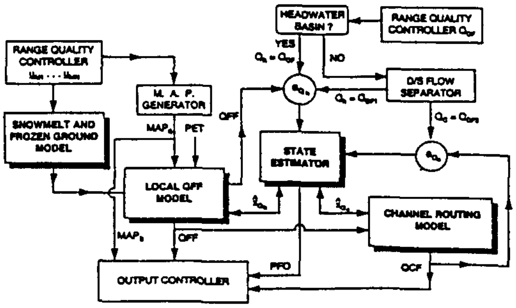


Fig. 1. Interactions of the Model Components on a Decoupled QPF Model.

Fig.1 represents the diagram of hydrologic–hydraulic components and interactions within the proposed model on a decoupled QPF model. Once the input data enter the system, consistency checks are performed in order to discard erroneous data from the range quality controller. Under the decoupled hydrometeorological system, the QPF model is inactive and the MAP is directly computed from the observational data. Snowmelt and frozen ground models are optionally operated to compute an amount of snowmelt.

The computed MAP and potential evapotranspiration are fed to a spatially–lumped QFF model. It estimates the infiltration loss to the ground and the overland flow. The estimated flow is used as an input to a kinematic watershed routing model that predicts the flow at the drainage basin outlet. Both the basin MAP and the flow forecasts are outputs of the hydrologic component. The predicted flow is used as an upstream boundary condition for the hydraulic component and as an input to the local flood warning system.

The channel routing model of hydraulic component is required for non-headwater basin to compute the attenuation of flow wave as it travels to the downstream end. Observed flow(Q_{DF}) at subbasin outlet was used only for hydrologic component(z_{qn} in $\underline{Z}$ vector, Q_h in Fig. 1) on headwater basin, while it was divided for both hydrologic(z_{qn} in $\underline{Z}$ vector, Q_h in Fig. 1) and hydraulic($\underline{Z}'(t_k)$ vector, Q_c in Fig. 1) components based on the ratio of predicted flows at previous time step on non-headwater subbasin. The predicted flow at junction or non-headwater basin outlet is the summation of predicted flow (QFF) from hydrologic component and all channel routing flows(QCFs).

The computed errors from all the observations and the predicted state variables are input to a state estimator. For headwater basin an error e_{Qh} is produced by comparison of the model-predicted QFF and observation Q_h, or for non-headwater basin the errors e_{Qh}, and e_{Qc} are produced by comparison of QFF and Q_h and by comparison of QCF and Q_c, respectively. The state estimator updates the predicted state variables and returns the updated state variables to the models so that the next forecasts will be based on updated initial conditions.

3. Case Study

3.1 Description of Study Area and Data

The study area is the 14,000km^2 Upper Des Moines River basin which is located in Minnesota and north-central Iowa, as shown in Fig. 2. The Upper Des Moines River is composed of two main tributaries: the West Fork and the East Fork Des Moines River. The elevation ranges from 290 to 518 m above mean sea level. Topological studies based on topographical map and on aerial photographs indicated that the overall channel slope is less than 0.001. The channel roughness coefficient was obtained in the range from 0.035 to 0.05 for the Upper Des Moines River channel, and from 0.04 to 0.10 for the overbank areas. The surface of the gently rolling terrain consists mainly of cultivated corn and soybean fields.

The daily data from the CD-ROM disks distributed by EarthInfo Inc. were used for the model parameter estimation because of their wide coverage in space and time (see Fig. 2). Operation of the model in real-time utilizes a prototype on-line database created by the U.S. Army Corps of Engineers, Rock Island District. The hourly data are received at the Rock Island District Office via a satellite downlink from the automated recording stations located at various points within and near the basin.

3.2 Model Organization for the Study Area

The UIFS was developed to provide real-time flow predictions at several locations in the Upper Des Moines River basin. Based on the variation of topography and the locations of interest for streamflow prediction, the area has been divided into six subbasins. Fig. 3 shows the schematic flow diagram used for

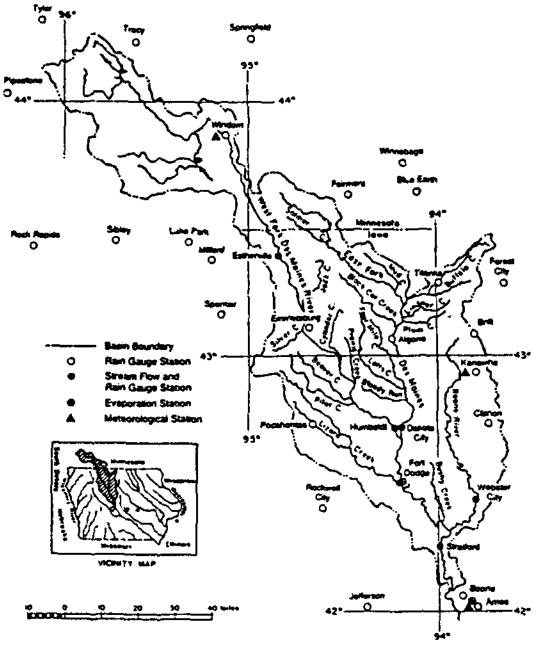


Fig. 2. The Upper Des Moines River Drainage Basin and Recording Stations.

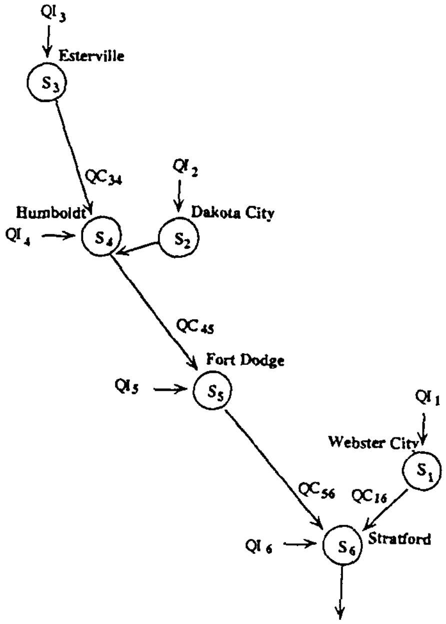


Fig. 3. Schematic Diagram for the Real-Time Application of UIFS to the Upper Des Moines River Basin.

the real-time application of UIFS on the basin. In this diagram, QI_j denotes the predicted discharge from the hydrologic component at the j^{th} subbasin outlet and QC_{ij} denotes the routed discharge within the channel network from the i^{th} subbasin to the j^{th} subbasin. First of all, UIFS predicts discharges(QI_1, QI_2, and QI_3) at the three headwater basin outlets using the hydrologic component. Then, the hydraulic component performs channel routing to determine the downstream flow(QC_{34}) at Humboldt given the upstream flow condition at Estherville(QI_3). It is noted that a model assumption is that the lateral inflow to the channel is applied at the downstream end. Therefore, the predicted flow(QS_4) at Humboldt is the summation of local predicted discharge(QI_4) from the hydrologic component and the result of channel routing(QC_{34}). This predicted discharge(QS_4) at Humboldt joins the predicted discharge(QI_2) at Dakota City. The combined discharge(QS_4+QI_2) is used as an upstream boundary condition for channel routing between Humboldt and Fort Dodge. The predicted flow(QS_5) at Fort Dodge is the summation of local predicted flow (QI_5) at Fort Dodge and the result of channel routing between Humboldt and Fort Dodge (QC_{45}). Similarly, the predicted flow (QS_6) at Stratford is composed of three parts($QC_{56}+QC_{16}+QI_6$).

3.3 Model Calibration

The components of UIFS have a number of parameters. Before this model is used for operational purposes, these parameters must be estimated from past meteorological and hydrological data, and from all available catchment information.

Parameter estimation techniques included both manual and automatic methods are used in this study. The manual estimation technique was based on guidelines given by Peck (1976), while the automatic method was based on Downhill Simplex Method (Nelder and Mead, 1965). Subsequently, sensitivity analysis of the model parameters is performed. The details of manual and automatic techniques and sensitivity analysis for all the model parameters are presented in Bae and Georgakakos (1992) and will not be presented here for space limitations.

3.4 Tests of the Model with Data from the Real-Time Database

Real-time data for the area were obtained from the Data Storage System(DSS) of the U.S. Army Corps of Engineers at Rock Island District, Illinois. The data currently available for the area consists of: hourly discharge at the six subbasin outlets; hourly station precipitation data at the six subbasin outlets and at Kanawha; and meteorological data at the Kanawha meteorological station. The real-time recording raingauges constitute only a subset of the raingauge sites shown in Fig. 2, which have historical daily data and are co-operative-observer stations. For the computation of MAP, the following raingauge stations were used for each subbasin shown in Figs. 2 and 3: 3 stations(Kanawha, Dakota City, and Webster City) for S_1; 3 stations (Estherville, Dakota City, and Kanawha) for S_2; 1 station (Estherville) for S_3; 2 stations (Estherville and Humboldt) for S_4; 3 stations (Humboldt, Dakota City, and Fort Dodge) for S_5; 3 stations (Fort Dodge, Webster City, and Stratford) for S_6. It is obvious that the network used for each subbasin does not cover the whole subbasin. For example, the suggested network for S_1 does not detect rainfall on the upper boundary of the basin (see Fig. 2), and the networks for S_4 and for S_5 can not cover the western portion of each of the two subbasins. For S_3, the single available station at Estherville is obviously not enough to cover the basin with an area of 3510km^2. Improved estimation of MAP requires at least three more real-time stations: at Slayton or some place near the upper boundary of the West Fork Des Moines River basin, at Burt downstream of Buffalo Creek, and near the headwaters of Lizard Creek. As a final comment regarding real-time input data we note that, in the absence of reporting pan-evaporation stations, long-term monthly values were used for the real-time tests.

Given the long response time of the subbasins in the study area, six-hourly accumulations of rainfall and six-hourly instantaneous discharge observations were used. The tests involved a forecast lead time of 6 hours. The data and forecasts in the operational system are given in English units and these units have been retained in this presentation(1m^3/sec$=$35.3 cfs; 1cm$=$0.394 inches). Fig. 4 shows the real-time observed hyetographs in the study area for two months starting at 12:00, on May 1, 1991. The intermittent nature of rainfall is apparent. Fig. 5 shows the resultant six-hourly observed discharges in solid line and the UIFS-predicted discharges with a six-hourly forecast lead time in dashed line for various locations on the area. The test interval was six hours and UIFS was running without state updating during this test.

The lack of reporting raingauge stations is apparent in the predictions of the second peak flow in Fig. 5(a). Simulated flows for

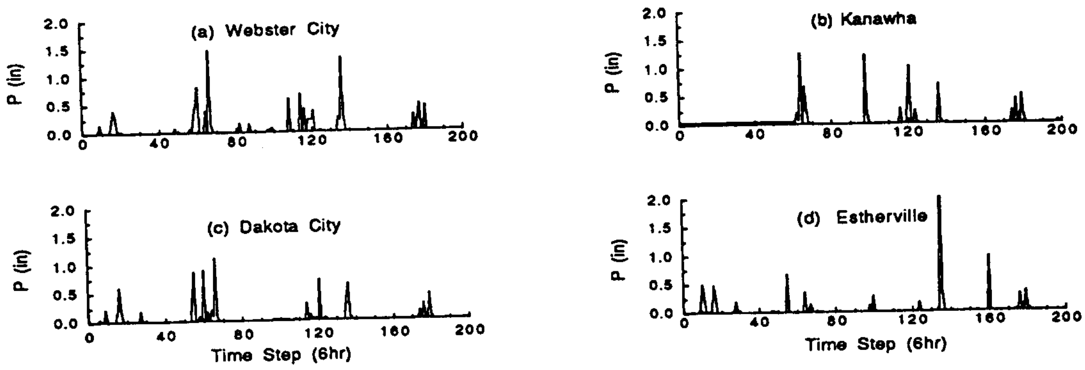
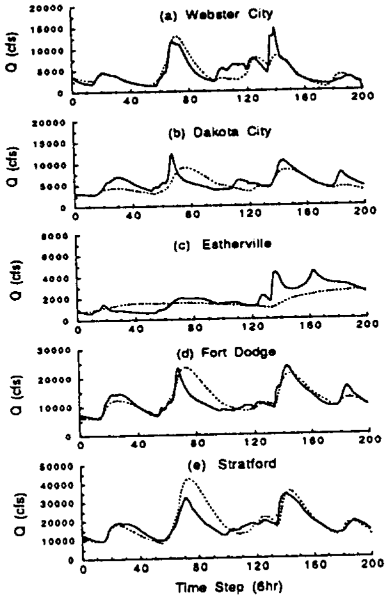


Fig. 4. Precipitation Record for the Real-Time Raingauge Sites (Six-hourly rainfall is shown for the period from 12:00 on May 1, 1991 to 12:00 on June 30, 1991).



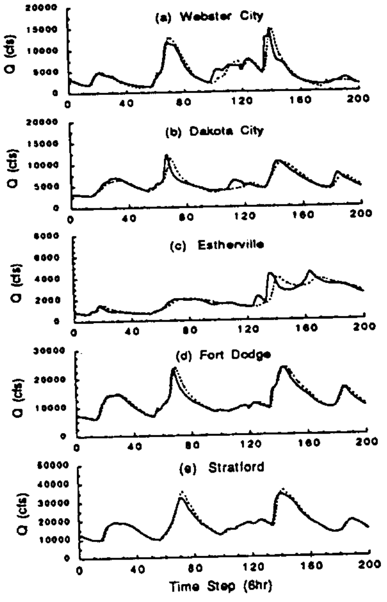


Fig. 5. Six-Hourly Instantaneous Discharge at Each Location of the Subbasin Outlet (Observed discharge is in solid line and UIFS predicted discharge is in dashed line. Period of record: 12:00, May 1, 1991 to 12:00, June 30, 1991. Updating was not used).

Fig. 6. As in Fig. 5 (but with UIFS running with a state estimator performing state updating every six hours from discharge observations).

the first peak are reasonable, but those for the second peak are underestimated. Inadequate raingauge coverage of the area near the upper boundary of the basin has caused the underestimation of the MAP input at time step 135. High rainfall in that area is inferred from the observed high rainfall at Estherville (storms usually move from west to east during this time of the year in this region). Similarly the lack of real-time recording raingauges in the area of the West Fork Des Moines River with outlet at Estherville is responsible for the results in Fig. 5(c). In this case, the existing large surface storage in that basin attenuates the rainfall signal considerably and the predictions appear reasonable. It is noteworthy that in spite of the absence of recording stations in several places within the basin, the short-term predictions of UIFS appear to capture the features of the observed hydrographs at all the streamflow gauging sites. The largest prediction error in this case is the over-prediction at Fort Dodge and Stratford of the first hydrograph peak near time step 80. Such an error was undoubtedly caused by unrecorded rainfall over the Lizard Creek basin. It is such input errors that the updating procedure was designed to accommodate.

Fig. 6 shows the model performance of UIFS running with the updating component (state estimator) active for the same test interval, time period, and 6-hr forecast lead time. Model performance is considerably improved at each location. The overestimation of the first peak predicted by the deterministic model is now considerably reduced while errors between observed and predicted peak flows are within 5 percent. Updating has successfully filtered observation errors in input data and errors in parameter estimates.

4. Conclusions

This work developed a flow forecasting model for application to large river basins. The model is a quasi-distributed model using: (a) the conceptual, spatially-lumped modified Sacramento model, a snow and frozen ground model, and a kinematic channel-storage routing model to simulate the rainfall-runoff process in local subbasins; and (b) the Muskingum-Cunge model to route the catchment outflows through the river network. Application of the proposed model without updating component showed that on-time input data availability and accurate flow forecasting in subbasins are key to good model performance, especially because predicted error accumulates in the downstream direction. The short-term predictions of the stochastic-dynamic UIFS with updating component for all forecast points were of very good quality.

It is concluded that the implementation of large-scale stochastic-dynamic model for real-time flow predictions using present-day real-time databases is feasible and produces reliable forecast systems.

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