Development of A 2-D Large Basin Operational Hydrologic Model

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ABSTRACT This paper reviews recent developments in hydrologic modeling, and through development of a 2-D large basin runoff model (2-D LBRM), discusses five essential components in the development of operational hydrologic models: model input, model structure, spatial variability, model calibration, and GIS-model interface. Operational hydrologic models should utilize multiple biophysical databases to develop model input parameters over multiple temporal and spatial scales. They should be based on mass continuity equations and include land surface, soil zones, and groundwater components. Spatial heterogeneity of watersheds needs to be taken into consideration using either a hydrological response unit or grid network approach. Simulation results should be calibrated with respect to multiple-objectives for better assessment of model and data errors. GIS-model interfaces need to be developed to facilitate model implementation and applicability.
Key Words: Hydrologic modeling; Great Lakes; spatial variability; calibration; GIS interface.

INTRODUCTION

Climate change research and the increasing demand for effective water resources management, together with rapid advances in the ready availability of satellite imagery and other multiple databases and computing technology, have led to a proliferation of hydrologic models, e.g. the Stanford Watershed Model (Crawford and Linsley 1966), TOPMODEL (Beven and Kirby 1979), variable infiltration capacity models (Liang et al. 1994), and models for estimation of precipitation, soil moisture (Grimes et al. 1999), and surface temperature (Hall et al. 1992; Boni et al. 2001). Many of these models, developed for research at the microscale ($<10^2$ km^2), require multiple databases to compute spatial and temporal distributions of energy and water balances in the soil-plant-atmosphere system. Due to the nonlinearity of hydrologic responses at different scales, these microscale models cannot be directly transferred to large-scales for water resource applications.

Large-scale operational hydrologic models, unlike microscale watershed models, are defined over large areas ($>10^3$ km^2) and long time scales (typically for use over monthly and annual or longer time scales at a daily interval). To support sustainable water resources applications over large areas, large- scale models must have few parameters, use easily accessible meteorological and hydrologic databases, and be user-friendly. However, in reality, existing models are often constrained by the limited data availability, computational requirements, and model application costs over larger areas. As operational models serve as a linkage between the research community and policy/decision support institutions, it is important to identify the needs and challenges of large- scale operational models.

This paper addresses the needs and challenges of large-scale operational hydrologic models. It first reviews recent developments in hydrologic modeling and then discusses five essential components: model input, model structure, spatial variability, model calibration, and GIS-model interface, in the development of operational hydrological models. Finally, a large-scale operational hydrologic model, the two-dimensional large basin runoff model (2-D LBRM) is developed and applied to the U.S. Laurentian Great Lakes basin to demonstrate incorporation of these issues in the model development process.

RECENT DEVELOPMENTS IN OPERATIONAL HYDROLOGIC MODELING

Significant progress has been made in hydrological modeling during the past three decades. The following sections give a brief review on recent developments in model input, model structure, spatial variability, model calibration, and GIS-model interface of large operational hydrologic modeling.

Utilization of Multiple GIS and Remote Sensing Databases

Rapid advances in remote sensing, GIS, digital databases, and computing technology during the past three decades have provided enormous opportunities for the hydrologic research community. For example,

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newly launched satellites, such as the Earth Observing System (EOS) PM-1, RADARSAT (spaceborne radar), LANDSAT 7 Enhanced Thematic Mapper (TM) Plus, Space Imaging, Inc=s 1 m resolution of the IKONOS satellite, and others, enable the extraction of hydrologic parameters over multiple temporal and spatial scales. Digital Elevation Model (DEM) databases are widely used for deriving slope, aspect, drainage network, and flow direction for a watershed (Hornberger and Boyer 1995). Soil databases such as the State Soil Geographic Data Base (STATSGO) from the U.S. Department of Agriculture Natural Resource Conservation Service (NRCS) enable the incorporation of spatial variation of soil characteristics into hydrologic models (He et al. 1993; 2001). Land cover databases allow the derivation of land use/cover related parameters such as leaf area index, zero plane displacement height and Manning's coefficient (n) values to hydrologic models.

Despite the availability of a large number of digital databases, obtaining input parameters for operational hydrologic models, especially for spatially-distributed models, remains a challenge. For example, precipitation is a key parameter in rainfall-runoff modeling. Estimates of the spatial distribution of precipitation are still inadequate due to a lack of spatial and temporal coverage of satellites and rain gauge stations, particularly in rural areas. Methods for estimating precipitation rates, such as cloud indexing, thresholding, and life history methods, by satellite remote sensing (e.g. GOES and spaceborne radar) are still at an experimental stage (Engman 1995). Microwave satellites in sun-synchronous orbits, passing over any point on the earth=s surface twice daily, can only produce precipitation estimates at those two times per day. Geosynchronous orbiting satellites such as Geostationary Operational Environmental Satellite (GOES), while able to produce precipitation rates continuously for the same part of the earth in their field of observation at 30 min interval, can only provide limited types of observations (Engman and Gurney 1991; Engman 1995). Ground-based radar is currently limited to a measurement circle with a radius up to about 100 km and its distribution is mainly limited to densely populated areas (Engman and Gurney 1991; Engman 1995). Estimates of precipitation from those radar stations still need to be calibrated against measurements from nearby rain gauges. Thus, operational hydrologic models for large basins must still rely on inadequately distributed rain gauges for estimates of precipitation. Because errors in precipitation data introduce greater uncertainty into parameter estimates than errors in runoff data (Borah and Haan 1991), it is critical to expand measurements of spatial and temporal distribution of precipitation nationwide in order to improve rainfall-runoff modeling. An immediate consideration is to add more ground-based radar stations in the rural areas for a more complete coverage of the entire U.S. A long-term alternative is to develop reliable procedures for deriving precipitation estimates from a combination of visible, infrared, and microwave satellites.

Unlike precipitation networks, there are virtually no systematic measurements of solar radiation and surface temperature throughout the U.S. Although algorithms are available to derive solar radiation and surface temperature from visible and thermal bands of satellites such as GOES, LANDSAT TM, and Advanced Very High Resolution Radiometer (AVHRR) (Hall et al. 1992; Lindsey and Farnsworth 1997), application of those algorithms often requires knowledge and skills of image processing and interpretation. To overcome the challenges faced by hydrologists in use of the remote sensing data for operational purposes, a federal agency such as the U.S. Geological Survey (USGS) or National Oceanic and Atmospheric Administration (NOAA) should take a leading role in acquiring and processing satellite data, extracting hydrologic parameters such as net radiation, precipitation, surface temperature, and soil moisture, and distributing them on the World Wide Web for hydrologists to use. This would lead to wider use of remote sensing data in hydrologic modeling and save vast amounts of resources to both space institutions and management agencies in the long run.

Structure of Operational Models

The performance of hydrologic models is closely associated with their structure, the objective function in calibration, and data quality (Gan et al. 1997). Large-scale operational models should be physically based (use physics theories and principles to govern the hydrologic system) to provide a better representation of hydrologic processes. Even though being physically-based may not always guarantee the best simulation results, it ensures that the results of such models are tractable and explainable.

The model components should include land surface, soil zones, and groundwater. Variable-source- area concepts (runoff from a dynamically changing surface area) should be used in computing infiltration and saturation runoff as the variable-source models give a better representation of hydrologic processes and produce betters estimates of overland flow and are less scale dependent (Quinn et al. 1995; Abdulla et al. 1996; Koren et al. 1999; Beven 2000; Valeo and Moin 2001).

Soil layers and groundwater need to be included in the model structure as water budget is very sensitive to the number of layers in the soil profile and omission of the subsurface-groundwater component in a runoff model can lead to an increase in the model scale dependency (Koren et al. 1999; Martinez et al. 2001).

Evapotranspiration (ET, here, including evaporation) returns about 60 percent of precipitation to the atmosphere globally. Although it is one of the most important components of the hydrological cycle, ET remains probably the most poorly understood. Due to our inability to make direct measurements of ET in the natural environment and our lack of understanding of the processes and feedback mechanisms that control ET, virtually no systematic measurements of ET are available at the global scale (Morton 1994; Tateishit and Ahn 1996). Penman (1948) first developed a combination method that considers both the energy balance and the mass transfer of water vapor in determining evaporation from a wet surface (Jensen et al. 1990). Monteith (1965) introduced canopy and aerodynamic resistance terms into the Penman method for description of the ET process from vegetation (Jensen et al. 1990).The Penman-Monteith (PM) method requires determination of values of the aerodynamic resistance and canopy resistance. Errors in canopy resistance leads to larger ET errors than do errors in aerodynamic resistance, as canopy resistance is an order of magnitude larger than aerodynamic resistance for a vegetated surface (Hall et al. 1992). Since aerodynamic resistance is estimated by displacement height and roughness length, which are in turn generally estimated as a fraction of canopy height, errors in canopy height will lead to large errors in sensible heat (Hall et al. 1992). While algorithms have been developed to compute canopy resistance from leaf area index (LAI), normalized differential vegetation index (NDVI), and leaf assimilation rate (Abdulla et al.; 1996Jensen et al. 1990; Liang et al. 1994), determination of appropriate values for canopy resistance remains challenging as derivation of NDVI and LAI from satellite data requires atmospheric, topographic, and radiometric corrections of satellite imagery (Hall et al. 1992).

Another method for estimating ET is the complementary relationship (CR) concept, first proposed by Bouchet (1963). The CR concept states that under the condition of constant energy input to a land surface-atmosphere system, water availability becomes limited; then actual areal ET falls below its potential, and an excess amount of energy becomes available in the form of sensible heat and/or long-wave back radiation that increases the temperature and humidity gradients of the overpassing air and leads to an increase in potential ET (ETP) equal in magnitude to the decrease in ET. If water availability is increased, the reverse occurs, and ET increases as ETP decreases. Thus, ETP can no longer be regarded as an independent causal factor. Instead it is predicated upon the prevailing conditions of moisture availability (Hobbins et al. 2001). Morton (1983; 1994) further refined the CR concept and developed a Complementary Relationship Areal Evapotranspiration (CRAE) model. After testing the CRAE model in more than 150 watersheds in different climates, Morton (1983;1994) found that the CRAE model considers the feedback effects of vapor pressure deficit and advection. It relies solely on routine climatological observations, uses only globally-tuned coefficients, and can provide reliable, independent estimates of ET from environmentally significant areas in most parts of the world (Morton 1994; Hobbins et al. 2001). Other studies have also utilized the CR concept (Croley 2002; Hobbins et al. 2001; Kim and Entekhabi 1997; Sugital et al. 2001). An important feature of CR models is that they bypass the complex and poorly understood soil-plant processes and do not require data on soil moisture, stomata resistance of the vegetation, or any other aridity measures (Hobbins et al. 2001).

The PM method and the CR methods have both been widely used for estimating regional ET over long periods of time. The PM method assumes that actual ET does not affect potential ET (the ET and ETP are "independent"). It links the effects of vegetation to the ET process through aerodynamic and canopy resistance terms and may be more appropriate for small areas where detailed databases are available. The CR methods bypass complex and poorly understood soil-plant interactions, require fewer parameters for applications, and may be more applicable to large areas where detailed datasets are not available (Hobbins et al. 2001; Jensen et al. 1990; Liang et al. 1994; Morton 1994; Silberstein et al. 1999 ; Sugital et al. 2001; Xu and Singh 1998).

Spatial Variability of Models

Spatial variations of precipitation, soil, vegetation and topography have significant impacts on runoff modeling (Beven 2000). Available databases of digital elevation model (DEM), vegetation, climate, hydrography, and soil make development of distributed models readily feasible. Operational models should take advantage of such databases to account for spatial variations of climate, soil, topography, and land use practices. Watersheds should be discretized into either grid network or hydrological response units (HRUs), large- scale operational models applied to each cell and output from each cell routed to the watershed outlet (Becker and Braun 1999; Karvonen et al. 1999).

Accurate accounting of soil water storage has a dominant influence on watershed runoff modeling. Models employing variable source area concepts (runoff from a dynamically changing surface area) produce more accurate overland flow estimates than models using the Hortonian infiltration capacity concept (Valeo and Moin 2001). In examining the impact of soil layers on hydrologic responses, Martinez et al. (2001) state that water budget is very sensitive to the number of layers modeled in the soil profile and an insufficient number of soil layers can lead to large errors in modeled water fluxes. For modeling soil water storage, a single layer in both the upper and bottom soil zones is adequate (Martinez et al. 2001). Distributed modeling is mostly needed in such environments where vegetation cover is mixed and there is a variable rooting depth or available water capacity (Quinn et al. 1995).

The variable source area concept requires detailed information on the spatial and temporal distribution of soil moisture and properties. However, frequent spatial measurements of soil are not currently available on a routine basis (Engman and Gurney 1991). Researchers often use either soil maps or databases available such as STATSGO to extract soil moisture and characteristics for hydrologic models (Liang et al. 1994; Zhu and Mackay 2001), or estimate soil moisture storage through calibration (Croley 2002). Alternatively, microwave remote sensing is promising for higher spatial and temporal resolutions (Engman and Gurney 1991; Mattikalli et al. 1998).

Model Calibration

Hydrologic models must be calibrated (model parameters estimated) to well represent reality, i.e. to match observations with acceptable accuracy and precision (Gupta et al. 1998; Loague and Kyriakidis 1997). Traditionally, research has focused on error identification in data and model to find the Abest@ parameter set (Guptal et al. 1998). With inevitable errors in both model structure and measured data, calibration is inherently multiobjective; identification of a unique Abest@ parameter set is difficult, if not impossible (Gupta et al. 1998). Recently, a number of studies have used multiple objective functions for model calibration. Loague and Kyriakidis (1997) used five statistical criteria to evaluate the differences between observed and modeled runoff: maximum error (ME), root-mean-squared error (RMSE), coefficient of residual mass (CRM), coefficient of determination (CD), and modeling efficiency (EF). Gupta et al. (1998) suggest the use of a set of unrelated measures of differences between simulated and observed data; they use residual standard deviation, residual bias, and number of sign changes in a case study. Yan and Haan (1991) use a multiple-objective programming method to calibrate parameters for a hydrological model, the USGS Precipitation-Runoff Modeling System (PRMS), and indicate that use of multiple objectives (matching storm peak flow, storm volume, and daily runoff) yields optimized parameters that satisfy the criteria of all objectives. Therefore, a multiobjective approach should be used in model calibration for better assessment of the limitations of model structure and confidence of model predictions. In addition, with readily available satellite data and other topographic, hydrologic, land use, and soil databases, it is time now to develop areal flow observations to calibrate with for improving our understanding of spatial variations.

GIS-Model Interface

Development of operational hydrologic models, particularly distributed hydrologic models, requires integration of GIS, remote sensing and other digital bases of climate, topography, vegetation, hydrology, and soil for extracting the needed model input parameters, and for processing, analyzing, and visualizing the model results (He 2003). A number of GIS-model interfaces have been developed to assist users in data organization, parameter extraction, model execution, and output display, and to improve model applicability. Such interfaces include linkages between GRASS and AGNPS (Agricultural Nonpoint Pollution Model) (He et al. 1993), GRASS and ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), AGNPS, and SWAT (Soil and Water Assessment Tool) (Engel et al.1993), and Arc/Info and HEC-HMS (Hydrologic Modeling System) (Hellweger and Maidment 1999). He et al. (2001) developed an interface to integrate the ArcView GIS and AGNPS for modeling and analysis of agricultural watersheds. A software package, Real-time Interactive Basin Simulator (RIBS) by Garrote and Bras (1995) integrates a radar-based rainfall prediction model, a DEM-based rainfall-runoff model, and other multiple databases to forecast real-time flooding. To facilitate model implementation and applicability, operational hydrological models should incorporate linkages or interfaces to GIS for data integration, analysis and visualization.

DEVELOPMENT OF A 2-D LARGE BASIN RUNOFF MODEL

The Large Basin Runoff Model (LBRM) was developed by NOAA's Great Lakes Environmental Research Laboratory (GLERL) in the 1970s to support hydrologic simulations and water resources applications in the Great Lakes basin. It uses a serial and parallel cascade of linear reservoirs (outflows proportional to storage) to represent moisture storages within a watershed: surface, upper soil zone (USZ), lower soil zone (LSZ), and groundwater zone. The model computes potential evapotranspiration (ETP) from a heat balance, indexed by daily air temperature, and calculates actual ET as proportional to both ETP and storage. It uses variable-area infiltration (infiltration proportional to unsaturated fraction of USZ) and daily precipitation and degree-day snowmelt (Croley 2002). The model has been applied extensively to the 121 riverine watersheds draining into the Laurentian Great Lakes for use in both simulation (Croley 1990; Quinn and Croley 1999) and forecasting (Croley et al. 1993). The following sections briefly describe the structure, input, spatial variability, calibration, and GIS interface of the LBRM.

Model Structure

The tank cascade schematic of the LBRM is shown in Figure 1. Daily precipitation, temperature, and insolation (the latter available from meteorological summaries as a function of location) are used to determine snow pack accumulations and net supply, s. The net supply is divided into surface runoff, $s\frac{U}{C}$, and infiltration to the upper soil zone, $s - s\frac{U}{C}$, in relation to the upper soil zone moisture content, U, and the fraction it represents of the upper soil zone capacity, C (variable-area infiltration concept). Percolation to the lower soil zone, $\alpha_p U$, and evapotranspiration, $\beta_u e_p U$, are taken as outflows from a linear reservoir (flow is proportional to storage) (α represents linear reservoir proportionality factors, ∃ represents partial linear reservoir coefficients associated with evapotranspiration, the subscripts in ∀ and ∃ denote different storage zones, see Fig. 1 and 2). Likewise, interflow from the lower soil zone to the surface, $\alpha_i L$, evapotranspiration, $\beta_\ell e_p L$, and deep percolation to the groundwater zone, $\alpha_d L$, are linearly proportional to the lower soil zone moisture content, L. Similarly, groundwater flow, $\alpha_g G$, and evapotranspiration from the groundwater zone, $\beta_g e_p G$, are linearly proportional to the groundwater zone moisture content, G. Finally, basin outflow, $\alpha_s S$, and evaporation from the surface storage, $\beta_s e_p S$, depend on its content, S. Additionally, evaporation and evapotranspiration are also dependent on potential evapotranspiration, e_p, as determined by joint consideration of the available moisture and watershed heat balance.

Mass conservation equations of the LBRM (1-D) (Croley 2002) are described below as differential equations with respect to time t:

$$\frac{d}{dt}U = s\left(1 - \frac{U}{C}\right) - \alpha_p U - \beta_u e_p U \qquad (1)$$

$$\frac{d}{dt}L = \alpha_p U - \alpha_i L - \alpha_d L - \beta_\ell e_p L \qquad (2)$$

$$\frac{d}{dt}G = \alpha_d L - \alpha_g G - \beta_g e_p G \qquad (3)$$

$$\frac{d}{dt}S = s\frac{U}{C} + \alpha_i L + \alpha_g G - \alpha_s S - \beta_s e_p S \quad (4)$$

Croley (2002) solved the equations , yielding storages at the end of a time increment (U_t, L_t, G_t, and S_t) as functions of the inputs, parameters, and beginning-of-time-increment storages (storages at the end of the previous time increment: U_0, L_0, G_0, and S_0) by taking net supply and potential evapotranspiration as uniform over the increment. The surface storage solution is:

$$S_t = e^{-(\alpha_s + \beta_s e_p)t}\left[S_0 + \int_0^t \left(s\frac{U}{C} + \alpha_i L + \alpha_g G\right) e^{(\alpha_s + \beta_s e_p)v} dv\right] \quad (5)$$

The volume of basin outflow is

$$V_s = \left(V_r + V_i + V_g + S_0 - S_t\right)\frac{\alpha_s}{\alpha_s + \beta_s e_p} \qquad (6)$$

where V_s = basin outflow volume from surface storage, V_r = surface runoff volume, V_i = interflow volume, and V_g = groundwater volume, all into surface storage, over increment $(0,t)$.

Recently, the1-D LBRM was modified from its aggregated -parameter definition for an entire watershed to a two dimensional representation of the flow cells comprising the watershed (Croley and He 2004a, b) and was applied to the Kalamazoo River and Maumee River watersheds in the Great Lakes basin. (Croley et al. 2004). The continuity equations were modified to allow upstream surface and subsurface routing between cells of flows of the USZ, the LSZ, and the groundwater zone (Figure 2). This enables surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. Since ET and potential ET cannot be regarded as complementary when the LBRM is applied to a small cell, they are replaced with a more traditional "independent" concept (that actual ET does not affect potential ET) in the 2-D LBRM. A flow network is generated by identifying the network flow cascade of the watershed cells and arranging the cell computations accordingly (Details of the modified LBRM are described in Croley and He 2004a, b; and Croley et al. 2004).

Model Input

Input parameters to the 2-D LBRM include: daily precipitation and air temperature, solar isolation, elevation, slope, receiving cell numbers, flow direction, land use, depths (cm) of USZ and LSZ, available water capacity (%) of USZ and LSZ, soil texture, permeability (cm/hr) of USZ and LSZ, Manning's coefficient (*n*) values, and daily flows. The areally-averaged daily time series of precipitation and temperature are interpolated by weighting more than 1,800 historical climatological site records in the Great Lakes basin using one of three methods: Thiessen polygon, inverse distance, and inverse squared distance. Daily surface insolation estimates are generated by two methods: (1) from temperature databases by empirical formulae, and (2) reversed-engineered method from an available weather generation model as a function of location, day of the year, air temperature and precipitation (Croley and He 2004a). Slope, receiving cell numbers, and flow direction are extracted from digital elevation model (DEM) databases. Depths, available water capacity, and permeability of USZ and LSZ and soil texture are derived from STATSGO, a soil database. Manning's coefficient (*n*) values are derived based on the combination of land use, slope, and soil texture.

The output includes basin outflow, surface runoff, ET, infiltration, interflow, percolation, deep percolation, USZ and LSZ moisture storages, groundwater storage, lateral flows between USZ, LSZ, and groundwater. Currently, daily precipitation and air temperature and solar insolation to the 2-D LBRM still rely on measurements from ground weather stations. Once the daily, areal coverages of snowpack, rainfall, and solar radiation from remote sensing sensors such as NOAA, GOES, and other EOS satellites become available on a routine basis, the 2-D LBRM can be modified to utilize these estimates to simulate rainfall-runoff for the Great Lakes basin. Such addition will lead to better representation of the spatial distribution of net supply to the model and hence significantly improve the accuracy of the runoff simulation

Spatial Variability of the Model

The 2-D LBRM uses a serial and parallel cascade of linear reservoirs to represent moisture storages of surface, USZ, LSZ, and groundwater zone with a watershed. It discretizes a watershed into a grid network and considers surface and subsurface flow interactions both with each other and with adjacent-cell surface and subsurface storages based on spatial variability of climate, topography, land use, hydrography, and soil (Fig.2). The interactions are described by strictly continuous equations and continuous-time flow representation. Since the solutions are analytically tractable, large time steps may be employed without introducing numerical error or excessive computational requirements. These features, plus its using climatological considerations not possible for small watershed, make the 2-D LBRM particularly suitable for addressing large scale water resource questions over the long term (e.g. decades) (Croley 2002).

Model Calibration

Calibration of the 2-D LBRM is presently conducted as a systematic search of the parameter space to minimize the root-mean-squared-error (RMSE) between actual and simulated daily outflow volumes at the watershed outlet. The 2-D LBRM has been applied to the Kalamazoo River watershed (drainage area 5,612 km^2) in Michigan and the Maumee River watershed (drainage area over 17,541 km^2) in Ohio at 1 km^2 grid cell resolution. Calibrations of the model over the 1948-

1964 showed correlations between simulated and observed watershed outflows as 0.88 and 0.91, coefficient of variation of 0.24 and 0.71 for the Kalamazoo and Maumee Rivers, respectively (density of weather stations in both watersheds is approximately 600 km^2 /station). The simulations show that the Kalamazoo River has a dominant groundwater storage, allowing delayed and sustained hydrological responses to rainfall while the Maumee River lacks any significant groundwater storage, allowing a fast flashy response to rainfall. These results are characteristic of the study watersheds, indicating that the addition of surface and subsurface interactions in the model has improved watershed representation (Croley and He 2004a, b).

A new calibration procedure is to be developed to include the multiobjective approach suggested by Gupta et al. (1998) for better assessment of errors in both model structure and observed data. In addition to the daily root-mean-squared-error, bias and the number of sign changes will be added to the calibration module for assessing the systematic errors in the differences between the simulated and observed daily outflows. Future calibration will also include generating runoff surfaces for assessing spatial variations of observed and simulated runoff throughout a study watershed.

GIS Interface

The 2-D LBRM discretizes a watershed into a grid network at a resolution of 1 km^2 (to match existing areal coverage of meteorological data) or other sizes as specified by a user. It requires 13 parameters for each of the grid cells. To facilitate the implementation of the 2-D LBRM, a GIS interface, the AVNPSM (ArcView Nonpoint Source Modeling) by He et al. (2001) is modified to operationalize data processing, extraction, analysis, and visualization. The interface consists of six modules: a soil database processor, parameter generator, utility module, output visualizer, statistical analyzer, and land use simulator.

The soil database processor automatically derives spatially averaged depth, available water capacity (AWC), soil texture, soil slope (%), and permeability for the USZ (layer 1 in STATSGO) and LSZ (layers 2 to 6 in STATSGO) by soil association (soil association is a unit on which soil information is mapped and assembled) from STATSGO. The parameter generator module helps a user first set up input files of DEM, land use, soil, and hydrography, and then derives required input parameters of slope, receiving cell numbers, flow direction, depths of USZ and LSZ, available water capacity of USZ and LSZ, permeability of USZ and LSZ, soil texture, and elevation for each grid cells. As the flow net allows only one outlet, flow directions must be carefully inspected to eliminate any flow loops. A utility module in the AVNPSM is used to check such errors and allows the user to edit flow direction either by one cell at a time or several cells at a time (He et al. 2001). The verified flow net is then used to route flow (Croley and He 2004 a).

To derive appropriate Manning's coefficient (n) values for each grid cell, the interface first helps the user define the hydrologic response units (HRUs) based on combinations of land use, slope, and soil texture (i.e. dividing the watershed into different HRUs) for the entire watershed and then uses a look-up table to assign each HRU an appropriate Manning's coefficient (n) value automatically. The n values are mainly determined by land use/cover categories and then adjusted by slope and soil texture. Subsequently, the interface assigns n values from each of HRUs to each grid cells.

The output visualizer allows the user to select any variable from the output file and display it in map format in ArcView. A separate, animation program has also been developed to animate the output variables for multiple years at daily intervals, which enables examination of dynamics of hydrological variables over the long term. The statistical analyzer enables the user to conduct the analysis of variance (ANOVA) to examine the relations of land use/cover and simulated results. The land use change simulator allows the user to specify land use change scenarios in a sub-basin or specific area based on the land use/cover file and evaluate the hydrologic impact of such changes to the downstream area (He 2003). This interface has proven to be a great utility in the implementation and application of the 2-D LBRM to the watersheds in the Great Lakes basin.

SUMMARY AND CONCLUSIONS

Development of large-scale operational hydrologic models is essential for support of long-term water resource planning and management over large river basins. Through development of a 2-D LBRM in the Great Lakes basin, this paper discusses issues related to model input, model structure, spatial variability, model calibration, and GIS interface in large-scale hydrologic modeling. Operational hydrologic models should utilize multiple GIS and satellite data to develop input parameters over multiple temporal and spatial scales. The U.S. government agencies may facilitate such efforts by coordinating the processing, extracting, and distributing hydrologic parameters such as net radiation, surface temperature, and precipitation through the World Wide Web to the modeling community in the same manner as they currently distribute meteorological, streamflow, and topographic data. Measurements of precipitation should be expanded to reduce parameter uncertainty in rainfall-runoff modeling. An immediate consideration is to add more ground-based radar stations in the rural areas for a more complete coverage of the entire U.S. A long-term alternative is to develop reliable procedures for deriving precipitation rates from combination of visible, infrared, and microwave satellites.

Operational models should be based on mass continuity equations and include surface, soil zones, and groundwater components. The variable-source-area concept should be used in computing infiltration and saturation runoff. Combination methods such as the Penman-Monteith equation or complementary relationship methods should be used in estimating regional ET over long periods of time. Multiple topographic, climatic, soil, hydrologic, and vegetation databases and GIS should be integrated to discretize a study watershed into either a grid network or HRUs. Operational models should be applied to each grid cells or HRUs to take into account spatial heterogeneity of watersheds in simulating their hydrologic responses. While routing simulated flow downstream, surface and subsurface flow interactions between adjacent cells should be considered for more accurate representation of the hydrologic processes.

A multiple-objective calibration should be used for better assessment of errors in both model structure and observed data. In addition to calibrations of model flows at the outlet of a watershed to measured flows at that point, model results should also be compared to observed data across the surface of the entire watershed to provide better understanding of the spatial variation of hydrologic responses.

As operational hydrologic models require integration of multiple biophysical databases for parameter extraction, analysis, and visualization, GIS interfaces should be developed to facilitate and improve model implementation and application.

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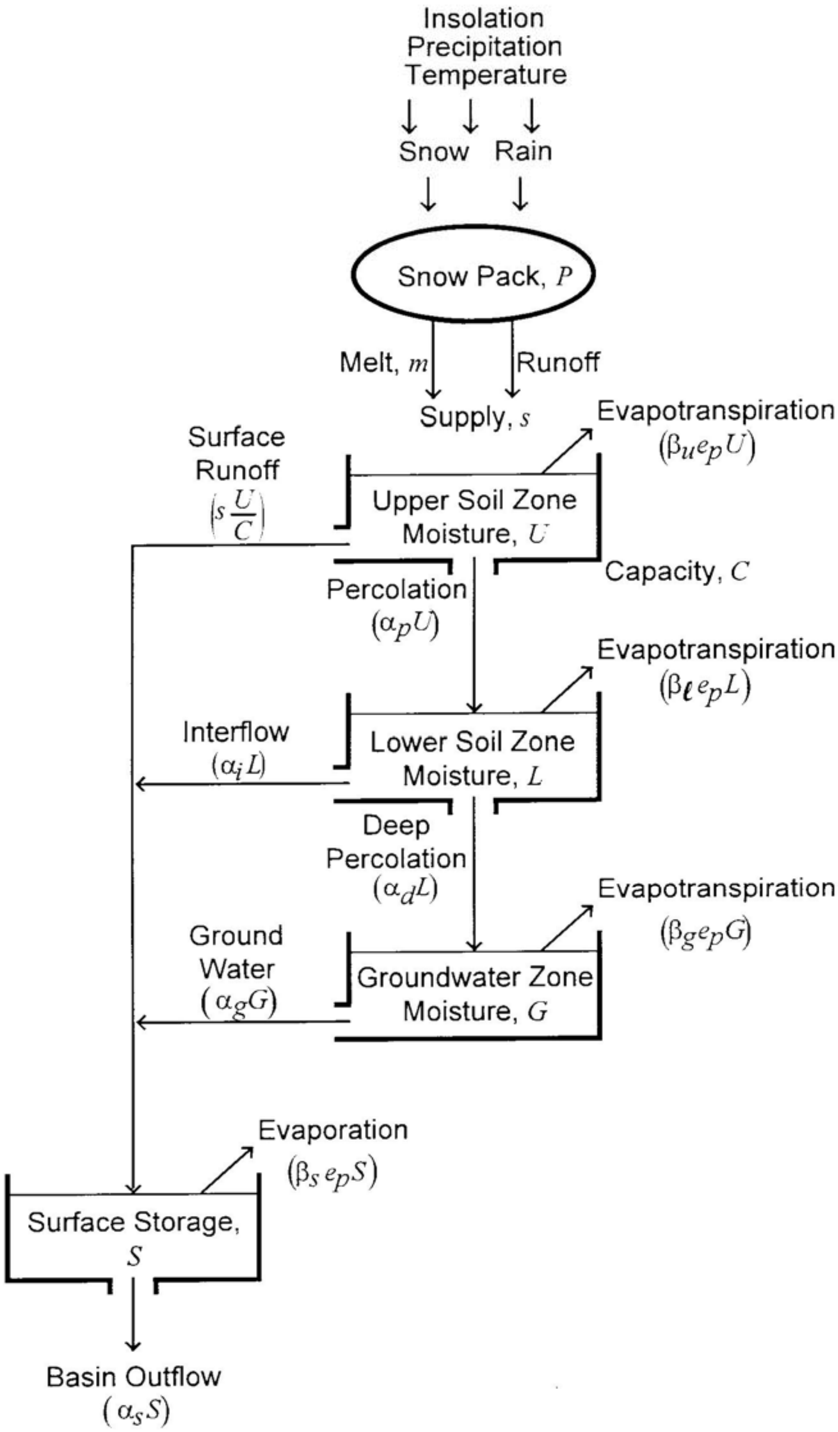

Figure 1. LBRM (1-D) tank cascade schematic

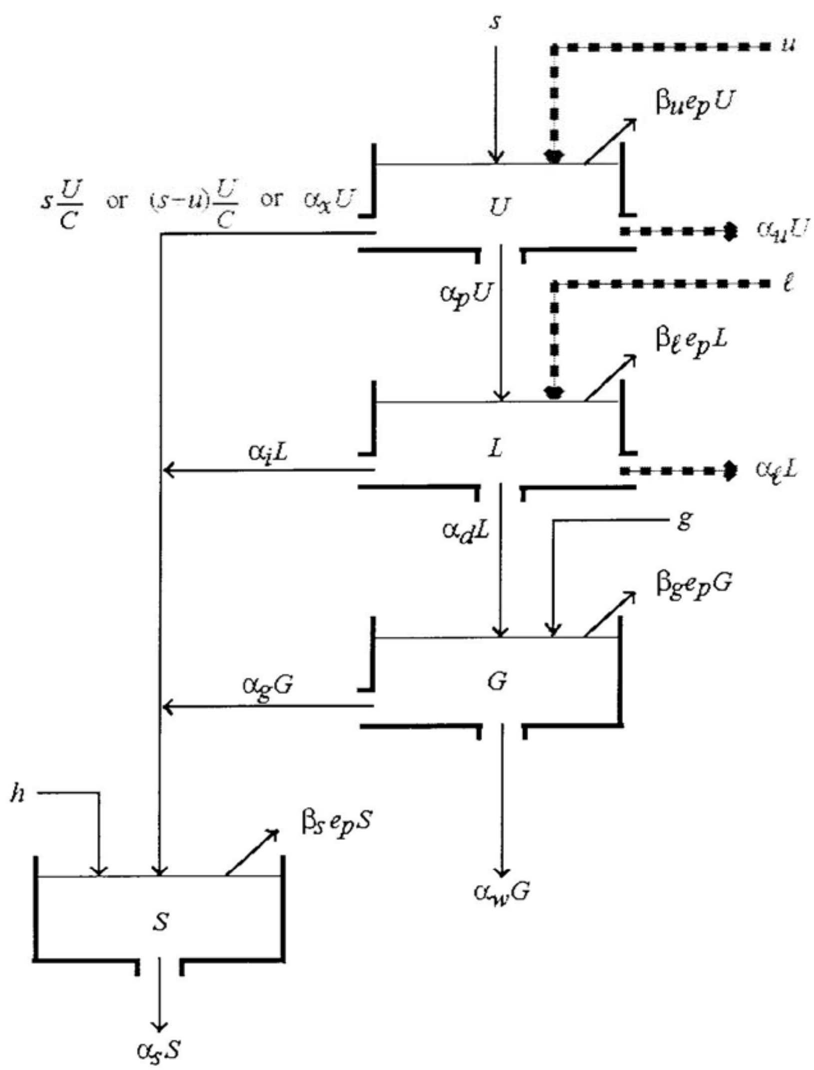

Figure 2. 2-D LBRM with surface and subsurface inflows.