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A DEVELOPMENT FRAMEWORK FOR TWO-DIMENSIONAL LARGE BASIN OPERATIONAL HYDROLOGIC MODELS

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INTRODUCTION

Large-scale operational hydrologic models are essential tools in support of multiple water resource applications such as flood control, navigation, irrigation, and habitat management, etc., at the regional or continental scales. These models, unlike micro scale 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). Often constrained by limited data availability, computational requirements, and model application costs over larger areas, large-scale models must have few parameters, use easily accessible meteorologic and hydrologic databases, and be user-friendly. Horberger and Boyer (1995) found that better representation of spatial and temporal variability and appropriate parameterization of hydrologic processes have become critical in recent years. They reviewed recent advances in watershed modeling pertinent to use of Geographic Information Systems (GIS), remotely sensed data, and environmental tracers for micro scale modeling. This paper addresses the needs and challenges of large-scale operational hydrologic models through the development of a modeling framework. It focuses on advances in parameterization of the infiltration and evapotranspiration processes and on the representation of large-scale spatial variability. It first reviews recent developments in hydrologic modeling and then proposes a developmental framework for integrating remote sensing, multiple databases, and emerging hydrologic algorithms in two-dimensional large-scale runoff modeling. Finally an application of the proposed framework is made for the Laurentian Great Lakes by spatially extending the lumped-parameter large basin runoff model (LBRM) developed at the Great Lakes Environmental Research Laboratory (GLERL).

DIGITAL DATABASES

Rapid advances in remote sensing, GIS, digital databases, and computing technology during the last two decades have provided enormous opportunities for the hydrologic research community. For example, in addition to LANDSAT, SPOT, the National Oceanic and Atmospheric Administration (NOAA) satellite series, and its Geostationary Operational Environmental Satellite (GOES), newly launched satellites, such as the Earth Observing System (EOS) PM-1, RADARSAT (space borne radar), LANDSAT 7 Enhanced Thematic Mapper 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. Such parameters include solar radiation, realtime estimates of rainfall, surface temperature, leaf area index (LAI) and vegetation indices such as the Normalized Differential Vegetation Indices (NDVI), leaf wet content index (LWCI), moisture stress index, canopy water content, and surface soil moisture (Hall et al. 1992; Engman 1995).

Digital Elevation Model (DEM) databases are widely used for deriving slope, aspect, drainage network, and flow direction for a watershed (for more information, see 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) allow use of spatial soil characteristics in hydrologic models (He et al. 2001). Land cover databases allow the derivation of related parameters such as leaf area index, zero plane displacement height and fertilizer for hydrologic models.

Despite the availability of many 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. Methods for estimating precipitation rates by satellite remote sensing (e.g. GOES and space borne radar) are still at an experimental stage. 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). 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 country. A long-term alternative is to develop reliable procedures for deriving rain rates 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 US. Although algorithms are available to derive solar radiation and surface temperature from visible and thermal bands of satellites, such as GOES, LANDSAT TM, and AVHRR, application of those algorithms often requires knowledge and skills of image processing and interpretation. For example, land cover, an important parameter in hydrologic modeling, is often derived from remotely sensed data, particularly satellite images. But accurately identifying and classifying land cover categories from remotely sensed data is still a challenging task and involves a number of processing, correction, interpretation, and verification procedures.

SOIL MOISTURE

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). Water budget is very sensitive to the number of layers modeled in the soil profile under wet conditions and an insufficient number of soil layers can lead to large errors in modeled water fluxes (Martines et al. 2001). For modeling soil water storage, a single layer in both the upper and bottom soil zones is adequate (Martines et al. 2001).

The variable source area concept, for partitioning precipitation between infiltration and runoff, requires 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 for the entire country, such as STATSGO, to extract soil moisture and characteristics for hydrologic models (Liang et al. 1994), 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).

EVAPOTRANSPIRATION

Evapotranspiration (ET, 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). Many methods and models have been developed to estimate ET, including water balance methods, radiation methods, temperature-based methods, mass transfer methods, combinations of energy balance and mass transfer methods and complementary relationship methods (Jensen et al. 1990; Morton 1994). 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. 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 has been recommended as better for estimating daily or longer periods of ET over a wide range of climate conditions (Jensen et al. 1990).

The Penman-Monteith method requires determination of values of the aerodynamic resistance and canopy resistance. Errors in canopy resistance lead 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). While algorithms have been developed to compute canopy resistance from LAI, NDVI, and leaf assimilation rate (Jensen 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. The excess is in the form of sensible heat and/or long-wave back radiation that increases the temperature and humidity gradients of the over passing 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. 2001a, 2001b). Morton (1994) further refined the CR concept and developed a Complementary Relationship Areal Evapotranspiration (CRAE) model that considers the feedback effects of vapor pressure deficit and advection. The CRAE model relies solely on routine climatological observations, uses only globally-tuned coefficients, and provides reliable, independent estimates of ET from environmentally significant areas in most parts of the world (Morton 1994; Hobbins et al. 2001a, 2001b). Brutsaert and Stricker (1979) developed an Aridity Advection (AA) model based on the CR concept. Hobbins et al. (2001a, 2001b) apply the CRAE and AA models to the conterminous US for estimating regional monthly ET. 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. 2001a, 2001b).

SCALING

Scaling (the appropriate application of information gathered at one scale to other scales) has been a very important research topic in hydrologic modeling in recent years. Studies have investigated important scaling issues related to hydrologic modeling, such as representation of spatial variability and disaggregation and aggregation. Wood and Lakshmi (1993) proposed the use of a representative elementary area (REA) for representation of the spatial variability. The REA, ranging in size from 1-2.25 km^2 to 5-10 km^2, is defined as the fundamental scale for detailed spatial modeling of hydrological processes. Beyond the REA, a statistical approach can be used to model the hydrological processes to simplify the computational burden. Others, however, conclude that REA is not a fundamental measure of the inherent spatial variability in catchment runoff modeling and cannot be used in formulating large-scale hydrology theories (Fan and Bras 1995).

Alternatively, Goodrich et al. (1997) proposed the concept of "a critical transition threshold area" of about 37-60 ha (0.37-0.6 km^2) and report that watershed runoff response becomes more nonlinear with increasing watershed scale beyond that threshold area. Other researchers have proposed the concepts of "hydrologically similar units" (HSUs) and "hydrologic response units" (HRUs) to represent the aggregate areas of similar hydrologic behavior on the basis of topography, land use, soil, and vegetation (Becker and Braun 1999). This approach, as compared to the grid approach (systematically discretizing the watershed into a grid of squares), is more efficient computationally as a specific set of model parameters is applicable to each type of HRUs or HSUs.

Although significant progress has been made in scaling, research on scaling is still evolving and many important issues, such as representation of spatial variability, are still being explored. For 2-D hydrologic modeling at large-scales, it appears that discretization, of the study watershed into either grids or hydrologic response units, is feasible to represent spatial variability of the watershed. While there is no universally uniform definition, the size of grids or HRUs should be determined in comprehensive consideration of characteristics of climate, topography, soil, land use, and vegetation in the study area.

DEVELOPMENTAL FRAMEWORK

Figure 1 summarizes our developmental framework for large-scale operational hydrologic models. These models should utilize meteorological, biophysical, and hydrological data from both remote sensing sources and ground stations for better representation of hydrologic input parameters over multiple spatial and temporal scales. A tank-cascade concept can be used to represent storage of water in upper and lower soil zones and in groundwater. Variable source area concepts should be used for partitioning precipitation into infiltration and runoff. Either the Penman-Monteith method or the Complementary Relationship method can be used in simulating water losses through ET from each storage tank. Watersheds can be discretized to either grids or HRUs. Surface runoff, interflow, and groundwater are first simulated over each grid or HRU and eventually routed accumulatively to the outlet of the watershed to produce basin outflow. A multiple objective approach should be used in model calibration for better assessment of model performance. Specific discussions on model input, model structure, spatial variability, and model calibration follow.

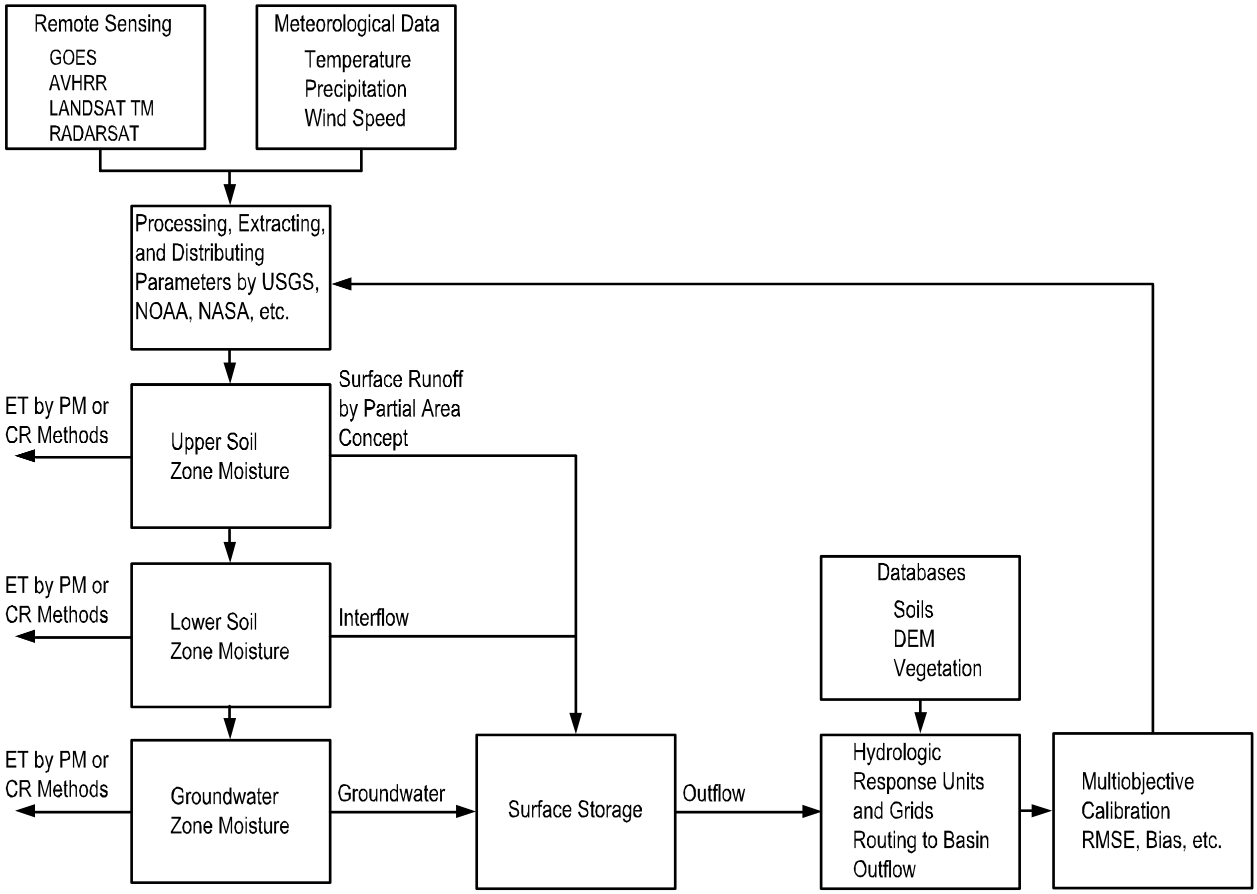

Figure 1. A developmental framework for a 2-D large-scale operational runoff model.

Utilization of Remote Sensing Databases: The increasing number of satellite sensors provides large amounts of unique, timely environmental information at the regional scale for simulation models. Yet large operational hydrologic models have not taken full advantage of such enormous opportunities. This may be due to a combination of factors such as cost of satellite data, limitations of satellite instruments to provide reliable and frequent sources of input parameters, and lack of expertise to derive accurate input parameters for the simulation models. A major reason that remote-sensing techniques have not been widely used in operational hydrologic models may be the lack of necessary expertise to process remote sensing data (e.g., atmospheric, radiometric, and topographic corrections and noise removal) to extract the needed parameters. To overcome the challenges faced by hydrologists in the use of remote sensing data for operational purposes, we propose that a federal agency such as USGS or NOAA 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 (see Figure 1). The USGS and NOAA already distribute topographic, meteorologic, and vegetation data this way. It would be cost-effective and efficient for these federal agencies to process and derive these additional parameters from their current depository of satellite images, for those agencies are well equipped to handle such tasks on a regular basis. The processed parameter data sets can then be distributed at a nominal cost to the hydrologic community through established distribution mechanisms such as the USGS Earth

Observing System Data Center or the NOAA Climate Data Center. 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 used in calibration, and data quality (Gan et al. 1997). Large-scale operational models should be physically based (use physical theory 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 allows results explainable.

The model components should include land surface, soil zones, and groundwater (see Figure 1). Variable-source-area concepts should be used in computing infiltration and saturation runoff as the variable-source models give a better representation of hydrologic processes, produce better estimates of overland flow, and are less scale-dependent (Beven 2000; Valeo and Moin 2001). Soil layers and groundwater should 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 (Martines et al. 2001).

The energy balance and mass transfer combination methods and CR methods need to be examined for estimating regional ET. Combination methods, such as Penman-Monteith, may be used in areas where datasets, related to canopy and aerodynamic resistance, are available. The CR method may be more applicable to large regions for monthly or longer periods of ET as such methods bypass the poorly understood land surface processes and have fewer coefficients (Morton 1994; Hobbins et al. 2001a, 2001b).

Spatial Variability of Models: Spatial variations of precipitation, soil, vegetation, and topography have significant impacts on runoff modeling (Beven 2000). While lumped-parameter models treat the catchment as a single unit, with state variables representing averages over the catchment area, distributed models make predictions that are distributed in space, with state variables representing local averages by discretizing the catchment into a large number of elements or grid squares and solving the equations for the state variables associated with every element grid square (Beven 2000). Compared to lumped models, distributed models (even simple 2-D ones) take into account the variation of spatial heterogeneity and help modelers and resource planners better understand the spatial response to hydrologic events.

Available topographic databases and algorithms make development of distributed models readily feasible. Operational models should take advantage of available databases in DEM, hydrography, soils, and meteorology, to account for spatial variations of climate, soil, topography, vegetation, and land use practices. Watersheds should be discretized into either grids or HRUs (see Figure 1), then large-scale operational models applied to each cell, and the output from each cell then routed to the watershed outlet. Finally, model results should be displayed in a spatially referenced format within a GIS environment to facilitate visual examination of spatial distribution of the simulation output for the entire watershed.

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). Traditionally, research has focused on error identification and minimization in data and modeling to find the "best" parameter set (Gupta et al. 1998). With inevitable errors in both model structure and measured data, calibration is inherently multiobjective; identification of a unique "best" parameter set is difficult, if not impossible. Gupta et al. (1998) suggested 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) used 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. If a single objective function is used, the optimal parameters are good only with respect to the optimized objective but poor with respect to other 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 (see Figure 1). In addition, with readily available satellite data and other GIS databases, it is time now to develop areal flow observations for calibration and for improving our understanding of spatial variations.

2-D LARGE BASIN RUNOFF MODEL DEVELOPMENT

The Large Basin Runoff Model (LBRM) of the GLERL is a lumped-parameter, interdependent tank-cascade model (Croley 2002). It uses mass continuity equations coupled with linear reservoir concepts and consists of four components: land surface, upper soil zone, lower soil zone, and groundwater zone. Snowmelt and net supply computations are based on simple degree-day empiricism. Variable source area concepts are used to determine infiltration and surface runoff. Infiltration is proportional both to the remaining capacity in the upper soil zone and to the net supply rate. Complementary relationship concepts are used in computing ET, which is taken as proportional both to the potential rate, determined from heat balance considerations over the watershed, and to available water storage (reflecting both areal coverage and extent of supply). The LBRM uses readily available daily climatological and hydrologic data, requires few parameters and data, and is applicable to other large watersheds beyond the Great Lakes basin. However, it does not take into account the effects of spatial variations of landscape. With the rapid development in computing technology and increasing availability of multiple digital databases, a new generation of the LBRM is possible to utilize available databases and new algorithms in simulating rainfall-runoff in large basins. Improvements to the current version of LBRM are based on the proposed framework.

Model Input: The current LBRM requires daily precipitation, minimum and maximum air temperature, and solar radiation. The areally averaged daily time series of precipitation and air temperature are derived by Thiessen weighting more than 1,800 historical climatological site records in the Great Lakes basin. Spatially averaged daily solar radiation estimates are generated from air temperature databases by empirical formulae. Considering the current challenges and costs in deriving daily time series of precipitation and solar radiation data sets from remote sensing sensors (both airborne and satellite sensors) for large basins on a long term basis, an immediate improvement to the model input is to estimate solar radiation from both air temperature and precipitation databases by WGEN, a weather simulation model by Richardson and Wright (1984). It generates estimates of solar radiation from precipitation and maximum and minimum air temperature data. The model has been tested and used throughout the country and satisfactory results have been produced (Richardson and Wright, 1984).

Once the daily, areal coverage of snow pack, rainfall, and solar radiation from remote sensing sensors such as NOAA, GOES, and other EOS satellites become available on a routine basis, the 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.

Model Structure: The PM method will be added to the LBRM to enable assessment of vegetation change effects on ET in the Great Lakes basin. The simulation results of the model from the PM method will be compared with those from the CR method for evaluating the applicability of both methods in modeling ET over the Great Lakes basin. As the PM method requires aerodynamic and canopy resistance coefficients, vegetation databases from the USGS will be used to infer roughness length and canopy resistance based on methods from the literature (Jensen et al. 1990; Liang et al. 1994). Wind speed data from the climatological databases will be converted to 2-m height wind speed by empirical formula (Jensen et al. 1990). Vapor pressure deficit is computed based on the minimum and maximum air temperature and dew point temperatures. Net solar radiation is estimated from the solar radiation derived by WGEN, air temperatures, and vegetation (for estimating emissivity). Soil heat flux is generated as a percentage of net radiation (Engman and Gurney 1991).

Spatial Variability of the Model: The current lumped-parameter LBRM will be expanded to two (spatial) dimensions by means of both a grid system and the definition of HRUs to discretize a study watershed (see Figure 1). The size of a grid cell will be 1 km by 1 km to match existing areal coverage of meteorological data. As the size of watersheds in the Great Lakes basin ranges from 10^3 to 10^4 km^2, it is a significant challenge to derive spatially varying input parameters for each of the 1 km^2 grid cells. To overcome this difficulty, HRUs will be developed based on a combination of slope, soil, and vegetation. STATSGO from the USDA NRCS will be used to extract soil texture, available water holding capacity, and depth of topsoil layer to the model. The land cover database from the USGS will be used to derive vegetation-related parameters such as the roughness length and zero-plane displacement height. A DEM database (at scale 1:250,000) will be used to derive slope and flow direction based on the work of He et al. (2001).

The LBRM model will then be applied to each 1 km^2 grid cell and a hydrologic routing module (the Muskingum method) will be added to the model for routing flow accumulatively downstream. Three approaches will be considered in routing simulated flow downstream. The first approach is to apply the current LBRM to each individual cell and route the total flow from each cell accumulatively down to the watershed outlet. As the current LBRM simply computes and adds interflow and groundwater flow to surface runoff at the cell outlet, this approach implies no subsurface flows between cells. However, it is simpler, computationally efficient, and relatively easier to calibrate than the following approaches. The second approach is to add interflow from the lower soil zone to groundwater, and route surface runoff and groundwater downstream separately. Surface runoff is then routed from each cell accumulatively downstream and the groundwater (including interflow from the lower soil zone) is routed from each HRU downstream. (A special case would be the entire watershed as a HRU). The third approach is to route all three separately: surface runoff and interflow from each cell and groundwater from each HRU. (Again, a special case would be the entire watershed as a HRU). The advantages of the latter two approaches are: 1) better consideration of landscape heterogeneity on subsurface hydrologic response, and 2) detailed accounting of the distribution of surface runoff, interflow, and groundwater throughout the watershed. The main challenge for these approaches is calibration of interflow and groundwater modeled components, for virtually no observed interflow and groundwater data are available over large areas of the Great Lakes basin. An imperfect but workable solution might be to use the simulated groundwater output at the outlet from the current lumped LBRM (for surface runoff at the outlet is calibrated) to approximate the groundwater from the 2-D LBRM, which will yield some insights for calibrating the 2-D LBRM at the outlet. Of course, compared to the first approach, the latter two are relatively more complex, slower, and more expensive to run. These factors must be adequately considered to determine an appropriate approach for large-scale operational hydrologic models.

Model Calibration: LBRM calibration is presently conducted as a systematic search of the parameter space to minimize the root-mean-squared-error between actual and simulated daily outflow volumes at the watershed outlet. A new holistic calibration procedure will be developed to include the multiobjective approach suggested by Gupta et a. (1998) for better assessment of errors in both model structure and observed data. In addition to the daily root-mean-squared-error, bias and 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 stream flow as these three parameters are relatively unrelated. Future calibration will also include generating runoff surfaces for assessing spatial variations of observed and simulated runoff throughout a study watershed.

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. This paper reviews recent advances and challenges in hydrologic modeling for the large-scale and proposes a developmental framework for 2-D models, which considers model input, model structure, spatial variability, and model calibration. Operational hydrologic models should utilize satellite data to develop input parameters over multiple temporal and spatial scales. The federal government may facilitate such efforts by coordinating the processing, extracting, and distributing of 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, stream flow, 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 rural areas for a more complete coverage of the entire country. A long-term alternative is to develop reliable procedures for deriving precipitation rates from a combination of visible, infrared, and microwave satellites.

Operational models should be based on mass continuity equations and include land 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, soil, climate, and vegetation databases and expanding GIS capabilities should be integrated to discretize a study watershed into either grid cells or HRUs. Operational models should be applied to each grid cell or HRU to take into account spatial heterogeneity of watersheds in simulating their hydrologic response. While routing simulated flow downstream, an integrated approach may be used to route surface runoff from each grid, and interflow and groundwater flow from each HRU, considering data availability, computational complexity, and application costs.

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. Work is underway to test the proposed framework in our development of a 2-D LBRM for the Great Lakes basin.

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