A Critical Review of Hydrological Modeling Practices for Flood Management

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Abstract

Hydrological modeling is the representation of real hydrological system. The real hydrological system consists of numerous components. Hence it is difficult to convert the real system on hydrological model system. In this review paper, various elements or parameters are described that involves risk during and even after completion of the project. And uncertainties which are always embedded in all the stages of reservoir operation are considered in risk management process. The risk management process considered significant in managing the floods on the watersheds. Various types of hydrological models are explained and compared thoroughly that are applied to various basins. The comparison of various hydrological models is based on different types of inputs, parameters required, output and their methods or governing equations. The application of GIS and remote sensing in hydrological modeling for flood prediction in managing the floods is considered significant. The paper discusses all significant flood management models developed during last six decades with emphasize on input parameters, data processing, outputs and real time flood forecasting capabilities.

Keywords: *Hydrological modeling, flood management, Remote sensing, GIS*

1. Introduction

The Population growth and economic growth in any area exert considerable pressure on the natural resources system. And one of the significant natural resource is water (i.e., flood) which is still quite difficult to manage. Hence the increasing population leading to Urbanization also sometimes contributes to floods and draughts in recent years. These floods are the output of the hydrological cycle. A hydrological cycle may be treated as a whole system whose components are precipitation, evaporation, runoff & other phases of the hydrologic cycle. Although the hydrological cycle is a system that is quite easy to understand but it is far from easy to quantify the processes in the system. In order to do this various types of hydrological models are developed and used. The hydrological models are models describing the hydrological cycle or its major parts. Variations in climate, topography, land types and land-use as well as various man-made interferences with the system make it very difficult to construct general models that treat the whole hydrological cycle in any given catchment in the world. Most models only treat a part of the cycle, e.g., runoff or groundwater-flow. Models developed in a certain climatic or geologic region often have difficulties when used in a different setting or different environment (parameters).

In case of hydrological model, the real system may be an entire river basin or parts of it. In hydrological modeling all the parameters have to be quantified and specified. The basic principle in hydrological modeling is that the model is used to calculate river flow based on meteorological data, which are available in basin or in its vicinity.

2. Evolution of Hydrological Modeling:

Hydrological Modeling is being introduced into the management of floods at an increasing rate. And forecast indicates that this trend will continue for the foreseeable future. Research in the area of flood management has followed several thorough studies and research. The real hydrological system consists of numerous components. Hence it is difficult to convert the real system on hydrological model system. Most hydrological model only treats a part of the cycle i.e., runoff or groundwater flow. The hydrological models can range from sand filled boxes to complicated computer program. The first type is called scale models. In these real system is reproduced on a reduced scale. The second type, where a number of equations stand for the real system, is termed mathematical (or symbolic) model. In models all parameters have to be quantified and specified. There exists a strong need to explore simulation techniques that not only represent complex dynamic systems in a realistic way but also allow users in model development to increase their confidence in the modeling processes. Numerous models have been developed by different researchers to simulate Rainfall-Runoff processes.

2.1 Modeling during 1991 to 2000:

Similar studies were done by Huang et.al. (1991), Ahmad & Simonovic (2000) and Hsu et.al. (1995) was concerned with the reservoir operations which is considered significant in flood management studies. They (Huang, Harboe, & Bogardi, 1991) presented and compared four types of stochastic dynamic programming (SDP) for on-line reservoir operation, relying on observed or forecasted inflows. The models are different because of the assumptions regarding the inflow in the next time period. According to them, in these models, if the inflow is known (either observed or forecasted with 100% reliability) than the expected present and future returns are deterministic. They studied the case study of the Feitsui Reservoir where the simulation of on-line operation of the reservoir reveals that the SDP model that relies on the observed inflows of the preceeding time step provides the best performance. Nevertheless, under different hydrological regimes this finding might be not universal, but dependent upon the characteristics of the particular water resources system.

Additionally, Daily reservoir operations rely increasingly on accurate streamflow forecasts, which today are derived from computer modeling (Hsu, KUO, ChU, & Lin, 1995). The model [called the National Taiwan University (NTU) Daily Model] closely captures the physical reality while maintaining the robustness of the statistical model, both of which must be considered in the day-to-day operations of a reservoir. Model performance was analyzed by using five statistical error measurements, including correlation coefficient, coefficient of efficiency, relative error, standard error, and volume error. The proposed model was calibrated and verified based on historical streamflow data from three gauging stations in Taiwan. The results obtained indicate that the NTU Daily Model for streamflow forecasting is satisfactory for use in daily operation of the reservoir.

On the other hand, System dynamics, a feedback-based object oriented simulation approach, is presented for modeling reservoir operations (Ahmad & Simonovic, 2000) which does not rely on inflows (i.e., rainfall data) as it is considered insignificant in the reservoir operations. The SD tool used to model reservoir operation has four basic building blocks: stocks, flow, connector and converter. Stocks are anything that accumulates e.g. stored water in reservoir (i.e., inflows). Flows are the activities that drain stocks e.g. discharge of the stored water (i.e., outflows). Connectors are to represent the relationship between various variables. They are denoted by arrows. And last one is converters they are used to convert input into output. The proposed approach is applied to the Shellmouth Reservoir, located on the Assiniboine River, close to Manitoba border in Canada. Operating rules are developed for high flood to minimize flooding. Alternative operating rules are compared by changing reservoir storage allocation and reservoir outflows. Impacts on the flood management capacity of reservoir are investigated by simulating a gated spillway in addition to an existing unregulated spillway. The system dynamic modeling process is open, interactive and transparent. The proposed SD based simulation approach is a valuable alternative to other conventional simulation techniques. Another limitation is the simplified flood routing as compared with sophisticated hydrodynamic models.

In addition, Geographic information systems (GIS) provide a digital representation of watershed characteristics used in hydrologic modeling. DeVantier & Feldman (1993) summarized past efforts and current trends in using digital terrain models and GIS to perform hydrologic analyses. Three methods of geographic information storage are discussed: raster or grid triangulated irregular network (TIN), and contour-based line networks. The computational, geographic, and hydrologic aspects of each data storage method are analyzed. The use of remotely sensed data in GIS and hydrologic modeling is reviewed. Lumped parameter, physics-based, and hybrid approaches to hydrologic modeling are discussed with respect to their geographic data inputs. Finally, several applications areas (e.g., floodplain hydrology and erosion prediction) for GIS hydrology are discussed and described thoroughly.

Table 1: Findings & results during 1991 to 2000

Authors	Study Area	Hydrological Models	Methodology	Results
Huang, Harboe, & Bogardi (1991)	Feitsui Reservoir	Stochastic Dynamic Programming Models	They presented & compared four SDP models for on-line reservoir operations, relying on observed or forecasted inflows	Results reveals that the SDP model that relies on the observed inflows provides best performance
DeVantier & Feldman (1993)	-	Digital Terrain Model	The three GIS methods are discussed. Computational, geographic & hydrologic aspect of each data storage method is analyzed.	Several applications for GIS hydrology are described.

Hsu, KUO, ChU, & Lin (1995)	Taiwan Basin	National Taiwan University (NTU) Daily Model	Model performance was analyzed by five statistical error measurements & then calibrated & verified using historical data.	Results obtained indicate that NTU Daily model for streamflow forecasting is satisfactory for use in daily operation of the reservoir.
Ahmad & Simonovic (2000)	Shellmouth Reservoir	System Dynamic Model	Operating rules are developed & compared with alternative operating rules. Impacts on flood management capacity of reservoir are investigated by simulating a gated spillway.	SD based simulation is a valuable alternative to other conventional simulation techniques.

2.2 Modeling during 2001 to 2010:

Early work by Plate (2002) was concerned with risk management process that takes place on three different levels. The first one is at an operational level, which is associated with operating system. The second one is at project planning level, which is used when a new or existing project is planned. And the third and last one is at project design level, which is embedded into the second level & describes the process of reaching an optimal solution. On 3rd level i.e., structural design level, the actual cost of a design are evaluated & compared with the benefits obtained from the planned project.

However Hall & Solomatine (2008) introduced a process of uncertainty analysis which has been designed with major flood risk management planning. They established a new framework for uncertainty analysis within flood risk management decisions. The framework consists of the following steps are (1) Establish purpose and scope of uncertainty analysis, (2) Identify and define uncertainties, (3) Assemble evidence about uncertainties, (4) Construct appropriate functions quantifying uncertainties, (5) Propagate uncertainties through to outputs of interest, (6) Store the results in a database, (7) Uncertainty- based sensitivity analysis, (8) Examine the effects of uncertainties on option choices and (9) Report and discuss results. Thus they estimate the amount of uncertainty associated with key variables, the framework supports the decision making process by identifying the most influential sources of uncertainty. Analysis is done in response to these uncertainties.

Additional work by Singh & Woolhiser (2002) deals with Mathematical modeling of watershed hydrology which is employed to address a wide spectrum of environmental and water resources problems. A historical perspective of hydrologic modeling is provided, and new developments and challenges in watershed models are discussed. These include data acquisition by remote sensing and space technology, digital terrain and elevation models, chemical tracers, geographic information and data management systems, topographic representation, upscaling of hydrologic conservation equations, spatial variability of hydraulic roughness, infiltration and precipitation, spatial and temporal scaling, model calibration, and linking with water quality models. And in this mathematical model, a great deal of attention is given to the model construction, calibration data processes, instead of validation, error propagation, and analysis of uncertainty and reliability which should be studied thoroughly.

Al-Sabhan, Mulligan, & Blackbur (2003) described the development of a web-based hydrological modeling system that permits integrated handling of real-time rainfall data from a wireless monitoring network. And it was concluded that the data can be accessed from any WWW interface, and they can be analyzed online using a number of GIS and numerical functions.

The operation of reservoirs in the Sierra Nevada Mountains of California for flood control relies on forecasts of reservoir inflows. In the past, an accurate forecast of the reservoir inflows resulting from watershed runoff have been made, but only after the water has entered the main channel. The operational National Center for Environmental Prediction Eta model provides 48-h-ahead forecasts of precipitation in 6-h intervals in a 40340 km gridded form. In this study, the mesoscale model, MM5, is used to transfer the Eta forecast data down to the appropriate space and time scales required to link the Eta model precipitation forecast results to the watershed model, HEC-HMS, for runoff prediction. An initial diagnostic study of this procedure has been performed on the Calaveras River watershed in Northern California (Anderson, Chen, Kavvas, & Feldman, 2002). Initial results indicate that: (1) model parameterization choice in MM5 is necessary to refine the precipitation forecasts; (2) the method shows promise for generating 48-h-ahead forecasts of reservoir inflows; and (3) calibration of the HEC-HMS model with distributed precipitation is necessary for this methodology.

Some hydraulic engineers or researcher had proposed the model which gives results in terms of risk to buildings; roads etc. Zerger & Stephen, (2004) are one of them. They presented a case study based in Cairns, in far north coastal Australia is presented to show that how GIS based decision support system reduces data volumes significantly, while making pre-run modeled inundation results rapidly accessible to disaster managers (Zerger & Stephen, 2004). The ability of framework is to present the results in terms of risk to buildings, roads etc. and to provide answers to relatively complex risk questions.

One-dimensional hydrodynamic modeling of a large-scale river network and floodplains is presented by Paz et al (2010). The study site comprises the Upper Paraguay River and its main tributaries a total of 4,800 km of river reaches in South American central area, including a complex river network flowing along the Pantanal wetland. The main issues are related to preparing input data for the hydraulic model in a consistent and geo-referenced database and to representing different flow regimes. Geographic information systems based automatic procedures were developed in order to produce cross-sectional profiles that encompass the large floodplains and to link hydraulic data and spatial location. The marked seasonal flow regime and relative smooth hydrographs of Paraguay River were quite well reproduced by the hydraulic model. For the tributaries, it must be mentioned the model’s ability to simulate both cases when the hydrograph does not present a marked peak flow, due to water loss for the floodplain, and when the hydrograph presents a more common shape, with recession and peak flows well defined.

Table 2: Findings & results during 2001 to 2010

Authors	Study Area	Hydrological Models	Methodology	Results
Plate (2002)	-	-	Risk management process takes place on three levels: operational, project planning & project design levels. On 3rd level, actual cost of a design are evaluated & compared with benefits from planned project.	Results show that on 3rd level the residual risk is considered, i.e., the risk which remains even after the project is completed & fully operational.
Singh & Woolhiser (2002)	-	Mathematical Model	Historical perspective of hydrology model is provided & new development & challenges in watershed models are discussed.	Model construction, calibration, data processing have received a great deal of attention, while validation, error propagation & analysis of uncertainty risk & reliability have been treated as thoroughly.
Anderson, Chen, Kavvas, & Feldman (2002)	Calveras River Watershed in Northern California	Mesoscale Model, MM5, Eta Model	MM5 model is used to transfer Eta forecast data down to appropriate space & time scales required to link Eta model to HEC-HMS for runoff prediction.	Results indicate that: (1) MM5 is necessary to refine precipitation forecasts; (2) method shows promise for generating 48 hrs ahead forecasts of reservoir inflows, (3) calibration of HEC-HMS model with distributed precipitation is necessary for this methodology.

Al-Sabhan, Mulligan, & Blackbur (2003)	-	Spatially distributed GIS based Model	They described development of a web-based hydrological model. The model is then integrated with GIS. The data can be accessed from any www interface.	Result focuses on developments in interfacing these models with end users.
Zerger & Stephen (2004)	Cairns, North Coastal Australia	Model	Case study is presented to show that how GIS based decision support system reduces data volumes significantly.	Results in terms of risks to buildings, roads, to provide answers to complex risk questions.
Hall & Solomatine (2008)	-	-	The methods of uncertainty analysis can be placed within the coherent framework. Challenges posed by severe uncertainty for flooding are discussed & robustness analyzed.	A number of challenges associated with use of uncertainty analysis is highlighted.
Paz, Bravo, Allasia, Collischonn, & Tucci (2010)	Upper Paraguay River, South America	One-dimensional hydro-dynamic Model	GIS based automatic procedures were developed in order to provide cross-section profile & to link hydraulic data & spatial locations.	Results indicate that model's ability to simulate both the cases: (1) when hydrograph does not present marked peak flow (2) when hydrograph presents recession & peak flows are well defined.

2.3 Modeling during 2011 to till date:

Best practice in river basin planning and management is characterized by use of a framework whereby all issues are addressed in an integrated fashion (Vicory & Tennat, 2012). The basic components of river basin-based planning and management are: defining the planning (i.e. the watershed) unit; investigating/understanding water quantity and quality, water uses and users and pollutant sources; setting goals and necessary regulatory regimes that represent sustainable management; establishing an institutional mechanism under whose aegis the planning and integrative management authoritatively occurs; and insuring adequate funding is available in support of the process. Advances have been made in technologies and tools to facilitate integrated approaches, but constraints remain in financial resources for appropriate levels of monitoring. A "vision" for river basin planning and management in 2050 is one where plans are in place for local watersheds and they are facilitated by well-coordinated legislative mandates and policies and take advantage of available data. The planning process insures that impacted stakeholders and citizens are equal partners.

Distributed hydrological models have been commonly used in research involving water management because of their consideration of spatial variability (Lei, Liao, Wang, Jiang, Wang, & Tian, 2014). However, practical applications still encounter technical challenges such as complicated modeling, low computational efficiency, and parameter equifinality. A user-friendly model, EasyDHM, was developed and was shown effective over the years. The essential parts of this model, namely, discretization of the spatial units, preparation and initiation of data and parameters, and the main physical processes are briefly introduced. From the application to the upstream basin of Han River in China, the simulation and parameter estimation by EasyDHM turned out to be effective and easy to operate. EasyDHM can, therefore, be widely used for practical water management applications.

The simulation models are now-a-days linked with GIS and remote sensing for better understanding and possible solution outcomes. Paz et al (2010) and Pincott- Miller et al (2012) studies various aspects of the integration of the models with GIS.

Similarly, they Pincott- Miller et al (2012) proposed a number of available spatial and meteorological datasets that open source hydrological models can utilize for the derivation of an integrated spatial hydrological framework to determine a flash flood index for a given catchment or location. The integrated spatial hydrological modeling is a method of identifying factors related with both flooding and flash flooding and their integration into a GIS. There are total three broad components which are required for integrating GIS and hydrology is: (1) pre-processing data into a suitable format for modeling (2) support for analysis and calibration and (3) post- processing to create the final products.

Dhami & Pandey (2013) and Miller, et al. (2012) compared various types of hydrological models on various criteria. They (Dhami & Pandey, 2013) focused on a comparative study of some recently developed, regularly updated and well documented hydrologic models namely: AnnAGNPS, GSSHA, HYPE, Hec-HMS, MIKE-SHE, PRMS, SWAT, WetSpa and WinSRM. In this comparative study, models are evaluated based on the followings: (1) Hydrological processed that the model can simulate, (2) Governing equations used to simulate the hydrologic processes, (3) Minimum data required to run the model and (4) Spatial and temporal scale of the model. These criteria are four common and fundamental ones that must be considered before selecting any hydrologic models. HYPE and WetSpa models are under- development and remaining models are continuously upgrading and updated. All the models are continuous parameter models but GSSHA, Hec-HMS, MIKE-SHE, PRMS and WetSpa model can stimulate storm events also. AnnAGNPS is similar to SWAT model (both have their own weather generator model) but has limited spatial scale. MIKE-SHE and GSSHA models require large input data due to which they may numerical instability problem for large basin. Hec-HMS is found to be promising model for providing multiple options for simulation processes. SWAT model is also found to be promising model for continuous simulation and also link various environmental processes. PRMS is suitable for coupling with various models but it also has instability problem due to its governing equations. This study could be helpful to potential model users to select their model based on the given problem.

Additionally, they (Zeng, Cai, Jia, & Mao, 2014) introduced a decision support system for real time flood forecasting in Yujiang River basin. This system is based on hydrological & hydraulic mathematical models. The applied case study results show the development and application of a decision support system for real-time flood forecasting and operation which is beneficial for flood control

. **Table 3: Findings & results during 2011 to till date**

Authors	Study Area	Hydrological Models	Methodology	Results
Vicory & Tennat (2012)	-	-	It is a vision where plans are in place for local watersheds & they are facilitated by legislative mandate & policies.	Results indicate that the planning process insures that impacted stakeholders & citizens are equal partners.
Lei, Liao, Wang, Jiang, Wang, & Tian (2014)	Han River, China	EasyDHM Model	Model was developed & was shown effective over the years.	Results concluded that EasyDHM can be widely used for practical water management applications.
Pincott- Miller, McGarry, Fairweather, & Srivastava (2012)	-	Spatial- hydrologic Model	They proposed a number of spatial & meteorological datasets that can be integrated in a model.	Result determines a flash flood index for a given location.

Dhami & Pandey (2013)	-	AnnAGNPS, GSSHA, HYPE, Hec-HMS, MIKE-SHE, PRMS, SWAT, WetSpa & WinSRM.	Models are compared and evaluated based on four criteria.	Results shows that study could be helpful to potential model users for selecting a model for any problem.
Zeng, Cai, Jia, & Mao (2014)	Yujiang River Basin	Hydrological & Hydraulic Mathematical Models	They introduced a decision support system for real time flood forecasting.	Results show the development & application of a decision support system for real-time flood forecasting & operation which is beneficial for flood control.
Vicory & Tennat (2012)	-	-	It is a vision where plans are in place for local watersheds & they are facilitated by legislative mandate & policies.	Results indicate that the planning process insures that impacted stakeholders & citizens are equal partners.
Lei, Liao, Wang, Jiang, Wang, & Tian (2014)	Han River, China	EasyDHM Model	Model was developed & was shown effective over the years.	Results concluded that EasyDHM can be widely used for practical water management applications.

CONCLUSIONS:

The evolution of hydrological modeling has been slow and steady over last few decades. Efficiency of various models, their capacity to simulate in real time and to mimic the various physical and climatologically changes has improved a lot during this period.

Conclusions decade wise (1991-2000): -

When observed inflows are provided, it was concluded that stochastic dynamic programming models proves best for on-line reservoir operations. System dynamic models was proved valuable alternative than other models. And NTU Daily model was satisfactory for daily use operations in reservoir.

Conclusions decade wise (2001-2010): -

It was concluded that risk management process is considered significant even after the completion and operation of the reservoir. And number of uncertainties is included in risk management process. Application of GIS and remote sensing is helpful in determination of the risks to buildings, roads, life etc.

Conclusions decade wise (2011 to till date): -

Model construction, calibration, and data processing have received a great deal of attention, while model validation, error propagation, and analyses of uncertainty, risks, and reliability have not been treated as thoroughly. It was concluded that the natural environment is always changing due to natural processes such as geo-morphological modifications of a flood plain for agricultural purposes and cutting the flood plain into different regions by building dikes. Recently hydrological models have found a new role in studies of climate change impacts on water resources.

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