Web-based hydrological modeling system for flood forecasting and risk mapping

Lei Wang∗a, Qiuming Cheng a,b,c

a Department of Geography, York University, 4700 Keele Street, Toronto, Canada, M3J 1P3;
b Department of Earth and Space Science and Engineering, York University, 4700 Keele Street, Toronto, Canada, M3J 1P3;
c State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China

ABSTRACT

Mechanism of flood forecasting is a complex system, which involves precipitation, drainage characteristics, land use/cover types, ground water and runoff discharge. The application of flood forecasting model require the efficient management of large spatial and temporal datasets, which involves data acquisition, storage, pre-processing and manipulation, analysis and display of model results. The extensive datasets usually involve multiple organizations, but no single organization can collect and maintain all the multidisciplinary data. The possible usage of the available datasets remains limited primarily because of the difficulty associated with combining data from diverse and distributed data sources. Difficulty in linking data, analysis tools and model is one of the barriers to be overcome in developing real-time flood forecasting and risk prediction system. The current revolution in technology and online availability of spatial data, particularly, with the construction of Canadian Geospatial Data Infrastructure (CGDI), a lot of spatial data and information can be accessed in real-time from distributed sources over the Internet to facilitate Canadians' need for information sharing in support of decision-making. This has resulted in research studies demonstrating the suitability of the web as a medium for implementation of flood forecasting and flood risk prediction. Web-based hydrological modeling system can provide the framework within which spatially distributed real-time data accessed remotely to prepare model input files, model calculation and evaluate model results for flood forecasting and flood risk prediction.

This paper will develop a prototype web-base hydrological modeling system for on-line flood forecasting and risk mapping in the Oak Ridges Moraine (ORM) area, southern Ontario, Canada, integrating information retrieval, analysis and model analysis for near real time river runoff prediction, flood frequency prediction, flood risk and flood inundation area prediction.

Keywords: Web-based Decision Support System, hydrological model, river runoff prediction, food forecasting

1. INTRODUCTION

The Oak Ridges Moraine (ORM) is a major aquifer complex and major source of drinking water for southern Ontario, Canada. It is also a geologically and hydrogeologically unique and one of the most environmentally sensitive areas in Canada. The ORM area has always faced the impacts of extreme hydrological events. Water-related disasters, such as flood, not only have impacts on the ORM’s economic and social well-being, but also exacerbate major environmental problems. The impacts continue to increase due to rise in population density, and decrease of the buffering capacities because of deforestation, urbanization, draining wetlands, etc. To understand the mechanism of flood forecasting and flood risk prediction may provide scientific evidences for decision makers in assessment of water resources and development planning.

∗ E-mail: leiw@yorku.ca
Mechanism of flood forecasting is a complex system, which involves precipitation, drainage characteristics, land use/cover types, ground water and runoff discharge. The application of flood forecasting model require the efficient management of large spatial and temporal datasets, which involves data acquisition, storage, pre-processing and manipulation, analysis and display of model results. The extensive datasets usually involve multiple organizations, but no single organization can collect and maintain all the multidisciplinary data. The possible usage of the available datasets remains limited primarily because of the difficulty associated with combining data from diverse and distributed data sources. Difficulty in linking data and analysis tools and model is one of the barriers to be overcome in developing real-time flood forecasting and flood risk prediction system. The current revolution in technology and online availability of spatial data, particularly, with the construction of Canadian Geospatial Data Infrastructure (CGDI), a lot of spatial data and information can be accessed in real-time from distributed sources over the Internet to facilitate Canadians' need for information sharing in support of decision-making. This has resulted in research studies demonstrating the suitability of the web as a medium for implementation of flood forecasting and flood risk prediction. Web-based hydrological modeling system can provide the framework within which spatially distributed real-time data accessed remotely to prepare model input files, model calculation and evaluate model results for flood forecasting and flood risk prediction.

2. HYDROLOGICAL MODEL AND GIS

Hydrological model is the basic approach to study hydrological process. Hydrological modeling technology has been developed for more than a few decades. It is widely used in the river rainfall-runoff prediction and flood forecasting. Hydrological models can be empirical or theoretical, lumped or distributed, physical or mathematical, stochastic or deterministic, depending on the discretization scheme of the basin characteristics, the assumption of physical relation or the applied sciences [1].

The progress in GIS technology and Spatial Decision Support System (SDSS) has led to significant advances on hydrological models. However, most of these watershed analysis models are not directly implemented into the GIS technology, and only few models have a well-developed capability to analyze and display information [2]. Clearly water resources model applications could benefit from spatial analysis and display capabilities of GIS, and GIS could benefit from the modeling capability of water resource models. Integrating these two systems will result in more powerful tools to aid the planning and management of water resource problems [2] [3]. Goodchild (1993 in Clark, 1998 p. 825) summarizes the three broad approaches for integrating GIS and hydrology as: 1. Preprocessing data into a format suitable for analysis (scale, coordinate system, data structure, data model etc). 2. Direct support for modelling so that the GIS carry out tasks such as analysis, calibration and prediction itself. 3. Post processing data through reformatting, tabulation, mapping and report generation. Sui et al [4] and Al-sabham et al [5] reviews the practices, the problems, and the prospects of hydrological modeling based on GIS. While many watershed modelling software packages are currently available, few are well integrated within GIS and are capable of non-expert implementation [5].

The development and use of web-enabled tools for hydrological modeling and decision-making have gained popularity lately with the increase in Internet speed and accessibility. Al-sabham et al [5] examine the current status of real time hydrological models used for flood forecasting and hazard mitigation and indicate how web-based systems can overcome some of the limitations of existing systems. He thinks that the requirements of the hydrological models of the future including real-time, interfacing the user and accessibility are the motive for web-based hydrological modelling systems. And based on this analysis, he proposed a novel web-based hydrological model. But the models he discussed “are sufficiently simple and robust to allow automatic application and interactive interrogation by end users with little hydrological expertise.” Li et al [6] introduce a Web-based flood forecasting system for Shuangpai region. This system includes five main modules: real-time rainfall data conversion, model-driven hydrologic forecasting, model calibration, precipitation forecasting, and flood analysis. He think that this system“ brings significant convenience to personnel engaged in flood forecasting and control and allows real time contribution of a wide range of experts at other spatial locations in times of emergency”. Prastacos et al [7] report their progress about ANFAS: a Decision Support System for Flood Risk Assessment. This system can be used by decision makers and stakeholders to simulate river floods and estimate the potential impacts. Key characteristics of the integrated system include web-based integrated system with a
distributed architecture, extensive visualization capabilities and generic. This system integrates in a transparent way for
the user different modules: GIS data bases, hydraulic models, and impact assessment procedures.

3. WEB-BASED HYDROLOGICAL MODELING SYSTEM FOR FLOOD FORECASTING
AND RISK MAPPING

3.1 System Architecture
This system has a multitier architecture consisting of presentation, business logic, and data tiers. Figure 1 below provides
an overview of the system architecture. The presentation tier is the interface for users to interact with system, users can
submit request for information services and decision-making support from presentation tier, and it also can be used as the
system client viewers for accessing geographic data and analysis results. Business tier will cope with the requests from
presentation tier. The components in the business tier, including web server, application server, metadata server, geodata
server and spatial analysis and model analysis server, are used for handling requests and modelling analysis. Web server
will transfer the requests to application server. Geodata services will access real time data remotely, automatically cope
with data heterogeneities problems for model analysis, statistical analysis and spatial analysis. Geoprocessing services
will run hydrological model analysis (such as SCS model) and statistical model for river runoff and flood risk prediction.
The data tier includes all available distributed data sources from different organizations.

3.2 System Development Approach: An integrated approach
A web-based system integrates multiple models will be more effective than separate applications for each model. This
web-based hydrological model system will integrate hydrological model, statistical model, web technology, GIS, web
services technology and decision support system together. The integration is performed using GIS as a common platform
for database management, model base and interface management. A user accesses the system over the web and chooses
watershed and date to create a “what if” scenario. This system integrate hydrologic model for runoff prediction, flood
forecasting and flood risk prediction, statistical model, and HEC-RAS model within its model-base. The integrated

Fig. 1. System architecture
system has a common database and a common web based interface. The models can communicate with each other transparently.

The integrated components of this system include Database, Model base, Interface, Spatial and Graphic Data Display and Analysis and Decision support systems. 1. Distributed database, one of the main advantages of this system is to ensure that all data (topographic, land use, hydrologic, hydraulic, census) are accessible to all users in order to provide support for flood management activities. The system includes a distributed database allowing data acquisition from various agencies such as Environment Canada, Statistical Canada and Natural Resources Canada. 2. Model base, several hydrological models are integrated to support decision-making, including Hydrological model for runoff prediction, hydrological model for flood frequency assessment, model fro flood risk mapping and hydraulic models for flood area mapping. 3. Interface, a multiple-level web-based interface has been developed, through which the distributed database, the modelbase and the information sources will be accessed, client request will be received and model analysis results will be sent to client by interface. 4. Spatial and Graphic Data Display and Analysis, GIS plays a very significant role in the system since it manages the databases, handles the two-way data flow between databases and models and provides the needed visualization once a model run has been completed. This will supply end users the functions to be able to easily visualize model outputs and most importantly visualize the results in map. Two types of visualization capabilities are provided. The first one is embedded in the web system and permits end users to display maps on the web that show the flood extent. The second type is handled on the desktop using ArcGIS and HEC-RAS. 5. Decision support systems, several decision making support are supplied in this system including online river runoff prediction, online flood forecasting, online flood risk mapping and flood inundation simulation.

This system is implemented by ARCIMS. It has two main parts: Integrated hydrological model for flood forecasting and integrated hydrological model for flood risk and flood area mapping. First, precipitation will be accessed from Environment Canada website, then SCS model will be applied to predict river runoff based on the precipitation data. Meanwhile, Pearson III model will be used for flood frequency analysis. If flood are identified, river runoff and high-resolution DEM data, land use data, statistical data are used to analyze the flood vulnerable areas and develop the flood risk mapping methods to predict flood risk. Finally, the flood risk map and flood area map will be published for public and decision maker use. Figure 2 below illustrated in detail the how the integrated system works.
3.3 Integrated hydrological model for flood forecasting

Although a lot of hydrological models have been developed by the researches around world. However, few are well integrated with GIS and are capable of non-expert implementation [5]. Some models are unsuitable for real-time application because of the types of data required and the interactive nature of their application. Difficulty in linking data and analysis tools and model is one of the barriers to be overcome in developing integrated spatial decision-making techniques. The Soil Conservation Service (SCS) has developed a widely used lumped, empirical and mathematical model, curve number method, for estimating runoff [8]. Underlying theory of the SCS-CN procedure is that runoff can be related to soil cover complexes and rainfall through a parameter known as a Curve Number (CN). So river runoff can be predicted using CN value and precipitation. Ko [9] investigated the influence of topographical and geomorphologic attributes of drainage basins on spatial–temporal distribution of river flows and their responses to the precipitation events, the SCS model was applied to estimate annual storm runoff volume. Further study has demonstrated that the SCS curve number method has 70% accuracy for the prediction of river runoff volume [10]. Since the SCS model has only one parameter (CN), the model calculation is not very complex, so it is easy to use and particularly useful for hazard emergency management, such as flood emergency management. However, users need to be trained to learn how to use this model. Sometimes, it is difficult to obtain the required model input data. Thus, Web-based hydrological model system is needed to integrate data and modeling for decision-making support. The most important benefits to users are that this system provides comprehensive support for integrating information retrieval, analysis and model analysis for decision-making and information services.

First, this system will use the historical data for the past several decades (river gauging, precipitation, ground water, census, land use change detected from remote sensing images) to model the relations among the stream runoff, precipitation and hydrological-geographical features to get the CN value for each basin. The CN value will then be saved in database and river runoff will be calculated by using SCS model based on precipitation data. This system will access real time precipitation data remotely from Environment Canada website and SCS model will be applied for river runoff prediction using CN value and precipitation data. Runoff prediction results map will be published using ArcIMS. Figure3 illustrate in detail how flood forecasting system works.

![Fig. 3. Flood forecasting system](image-url)
Meanwhile, Pearson III model will be used for flood frequency analysis. As we know, many standard theoretical probability distribution functions have been used to describe hydrological process. Normal, Log-Normal and Pearson III, are commonly used in the literature. The Pearson III distribution has been widely adopted as the standard method for flood frequency analysis in a form known as the Log-Pearson III in which the transform y=log (x) is used to reduce skewness. The Pearson III has been applied to a number of variables such as precipitation and watershed runoff during a given storm event. The transformed log-Pearson III is mostly used to approximate the CDF for annual flood peaks. After fitted the designated distribution, we can calculate the return period of a given value. Given a discharge value, one obtains the return period by interpolating on the fitted Pearson Type III curve. In the system, first, the past several decades historical gauge station discharge data and frequency factor analysis method will be used to model the relations between discharge and return period for each basin. Then the Pearson Type III curve will be established for each basin. When SCS model have the river runoff prediction results and this prediction result will be interpolating on the fitted Pearson Type III curve to get the flood frequency prediction. This system will automatically publish flood frequency map on the web.

### 3.4 Integrated hydrological model for flood risk and flood area mapping

Risk is defined as the possibility of harmful consequence of expected losses due to exposure to hazards. Risk assessment is based on flood hazard and vulnerability. The product of hazard factor and vulnerability factor determines the risk factor (Risk= Hazards * Vulnerability). Flood hazard assessment is the estimation of overall adverse effect of hazard parameters such as depth of flooding, duration of flooding, flood discharge and rate of rise of water level. Vulnerability is a measure of the intrinsic susceptibility of an element at risk exposed to potentially damaging natural phenomena. It depends on many parameters including population, dwelling, average income and basin descriptor such as average slope, urbanized area ratio and basin area. The intensity of flood hazard and vulnerability is called as hazard factor and vulnerability factor, which are always expressed on a scale from 0 to 1.

Hazard factor calculation is based on river runoff prediction results. When the web-based hydrological system gets the river runoff prediction results, the hazard factor and vulnerability factor will be calculated to predict flood risk. At first, regression will be applied to get the Stage–Discharge curves to model the relationship between stage and discharge according to historical flow discharge and water level data in each basin. Then using Stage–Discharge Curves, runoff (Q) will be used to predict water level. The depth of flood will be calculated by using basin water level plus gauge station elevation and then subtract the flood plain elevation. And multifractal model like singularity will be used to predict flood duration. Other parameters such as rate of rise of water level can also be calculated accordingly. Each of these four parameters will be classified into five hazard categories based on different criteria. And furthermore different weights will be applied to combine these four parameters into hazard factor.

The calculation of vulnerability factor need calculate six parameters, including population, dwelling, average income and basin descriptor such as average slope, urbanized area ratio and basin area. Population, dwelling and average income are calculated based on Census Subdivision (CSD) from Statistics Canada (2001). Census subdivision (CSD) is the general term for municipalities or areas treated as municipal equivalents for statistical purposes (Statistics Canada, 2001). Geoprocessing(such as Intersect) will be applied to intersect the basin map with CSD base map and get the basin based population, dwelling and average income. Spatial analysis is applied on DEM data to calculate average slope. And the urbanized area ratio in basin is calculated using Ontario Land Cover Data Base (1999) from Ontario Ministry of Natural Resources. The basin area can be accessed directly from Environment Canada website. Each of these six parameters will be classified into five vulnerability categories based on different criteria. And furthermore different weights will be applied to combine these eight parameters into vulnerability factor. Risk factor will be calculated as the product of hazard factor and vulnerability factor. Based on this result, basin based flood risk map will show the high-risk area and low-risk area. Then web mapping services will show the real-time flood risk map on-line. Figure3 illustrate in detail how flood forecasting system works. Figure4 illustrate in detail how flood risk prediction system works.

Furthermore, this system will use the high resolution DEM data, land use data to analyze the flood vulnerable areas and develop the flood inundation mapping methods. HEC-RAS is a computer program that models the hydraulics of water flow through natural rivers and other channels. Using GIS for hydrologic/hydraulic modeling usually involves three...
steps: 1) pre-processing of data, 2) model execution, and 3) post-processing/visualization of result. Similarly, The general procedures for HEC-RAS model has three steps, first create geometry database in HEC-GeoRAS, including river centerline, river banks, flowpaths, cross-sections, hydraulic structures and other physical attributes of river channels. Then the geometry database will be imported into HEC-RAS, and flow data and boundary conditions will be entered. For flood simulation, steady flow data (peak flow) will be entered and the steady flow will be calculated. Last, the HEC-RAS calculation results will be exported into ArcGIS again and flood inundation mapping result will be shown in ArcGIS. This will create a surface with water surface elevation and floodplain inundation delineation mapping.

Based on DEM (10m) and topographic database, HEC-RAS model will be applied to model flood area in ORM area. First, DEM data and topographic database will be used for the geometry database creating by using HEC-Georas, topographic database will be used to create river center line, DEM and contour (2m) will be used to create river band, flow path and cross sections. After that, the geometry database will be imported into HEC-RAS and flow discharge and boundary condition will be entered for each reach and tributary. After the model running, floodplain map and flood depth can be visualized in ArcGIS and published to public by using ArcIMS for public information services and decision making support.

4. CONCLUSION

This paper develop a web-based hydrological model system for flood forecasting and risk prediction in the ORM Area, integrating information retrieval, analysis and model analysis for information sharing and decision-making support. Several decision making support are supplied in this system including online river runoff prediction, online flood forecasting, online flood risk mapping and flood inundation simulation. Using precipitation as input from Environment Canada website, this system will use SCS model for river runoff prediction and use Pearson III model for flood frequency prediction. And high-resolution DEM data, land use data, statistical data will be used to develop flood risk
mapping methods and flood inundation simulation. Such a system will improve understanding of the environmental planning and management issues and emergency management and response associated with the ORM’s water environment. This system can be used to provide a reliable prevention mechanism to eliminate disasters and reduce the negative consequences of hazards, and it also can be used to help decision makers in assessment of water resource management and develop sustainable development planning in the ORM area.

REFERENCES