Chapter 6
Spatial Decision Making and Analysis for Flood Forecasting

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Abstract The application of flood forecasting models requires the efficient management of large spatial and temporal datasets, involving data acquisition, storage, processing, analysis and display of model results. Difficulty in linking data, analysis tools, and models is one of the barriers to be overcome in developing an integrated flood forecasting system. The current revolution in technology and the online availability of spatial data facilitate Canadians' need for information sharing in support of decision making. This need has resulted in studies demonstrating the suitability of the web as a medium for implementation of flood forecasting. Web-based Spatial Decision Support Services (WSDSS) provides comprehensive support for information retrieval, model analysis and extensive visualization functions for decision-making support and information services. This chapter develops a prototype WSDSS that integrates models, analytical tools, databases, graphical user interfaces, and spatial decision support services to help the public and decision makers to easily access flood and flood-threatened information. Flood WSDSS helps to mitigate flood disasters through river runoff prediction, flood forecasting, and flood information (flood discharge, water level and flood frequency) dissemination. The ultimate aim of this system is to improve access to flood model results by the public and decision makers.

Keywords Flood forecasting • GIS • Web • Spatial decision support system

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6.1 Introduction

Chapters 4 and 5 have applied SCS CN model for runoff prediction, LP3, GEV, PL and GP models for flood frequency analysis and prediction, and the CA and singularity fractal model for flood threshold selection and characteristics description. However, these flood forecasting models are not accessible to the public and decision-makers. Due to the background difference, it is very difficult for the public and decision-makers to use these models directly for flood forecasting and management as they require familiarity with flood forecasting models and analysis tools. Difficulty in linking data and analysis tools and models is one of the barriers to be overcome in developing an integrated flood forecasting system. The main reason for developing a new system and tool is that the public and decision makers cannot effectively utilize available models and data unless data, analysis tools, and models are already integrated.

Meanwhile, the current revolution in technology and online availability of spatial data, such as the National Water Data Archive and National Climate Data and Information Archive, has enabled Canadians to access a wide variety of spatial data through the Internet. This has resulted in research studies demonstrating the suitability of the web as a medium for the implementation of flood forecasting.

This chapter describes the architecture and components as well as the functionality of a WFSDSS that provides a comprehensive environment for flood forecasting in the ORM area, integrating information retrieval, analysis and model analysis for information sharing and decision-making support services. It is capable of non-expert implementation and permits users for web-based river runoff prediction, water level prediction and flood frequency prediction. The ultimate aim of this system is to improve access to flood model results to the public and decision makers. This WFSDSS will improve the understanding of environmental, planning, management issues, and emergency management and response associated with the ORM's water environment, and allow development of sustainable solutions.

6.2 Problems of Real-Time Flood Forecasting

The ORM area has faced the impacts of extreme hydrological events. Water-related disasters, i.e. floods, have been more devastating as far as deaths, suffering, and economical damages are concerned, than other natural hazards (earthquakes, volcanoes, etc.). Floods not only have an impact on the ORM's economic, environmental, and social well-being, and particularly public safety, but also exacerbate major environmental problems. Despite the progress in science and technology, human settlements are still vulnerable to floods. The losses increase due to the continuing development of costly infrastructure, rise in population density, and decrease of the buffering capacities because of deforestation, urbanization, draining wetlands, etc.

The mechanism of flood forecasting is complex, involving precipitation, drainage basin characterizes, land use/cover types and runoff discharge. The application of flood forecasting models requires the efficient management of large spatial and temporal datasets, which involves data acquisition, storage, processing, 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 the combining of data from diverse and distributed data sources. The current revolution in technology and online availability of spatial data has enabled Canadians to access a wide variety of spatial data through the Internet. Internet technology has been widely used for application development because of advantages such as platform independency, reductions in distribution costs and maintenance problems, ease of use, ubiquitous access and sharing of information by the worldwide user community (Peng and Tsou 2003). This revolution has resulted in research studies demonstrating the suitability of the web as a medium for implementation of flood forecasting.

With the construction of the CGDI, much spatial data and information can be accessed from distributed sources over the Internet to facilitate Canadians' need for information sharing in support of decision-making. The CGDI can provide the user with access to integrated and timely data and services, such as Web Map Service (WMS), Web Feature Service (WFS), Filter Encoding, Geodata Discovery Service, etc for decision-making support. Using metadata services, users can know what data are available, how they have been collected, and who is responsible for managing and distributing the data. Using geodata services, users can access and query the data from distributed sources. However, WMS, WFS and Filter Encoding cannot meet the requirements for on-line flood forecasting, new application is still required to integrate WMS, WFS, statistical analysis, modeling and spatial analysis for decision making support.

Advances in flood DSS can improve flood forecasting. Flood DSS improves the decision-making process by providing data display, analytical results, and model output to summarize critical flood information. However, flood DSS are often difficult to access for non-expert public and decision-makers because they cannot effectively utilize available models and data, unless data, analysis tools and models are already integrated. There are still some challenges for the public and decision-makers to use flood DSS for flood forecasting and flood management. These challenges include (1) friendly interface development, (2) real-time data access and flood map dissemination, (3) distributed data sharing and services, (4) model sharing for decision-making support, and (5) integrating data and modeling for decision-making support.

(1) Friendly interface development

A Graphical User Interface (GUI) is the interface for WSDSS to interact with users. A GUI should be designed to be user-friendly, allow people to easy access and interact with this system and visualize flood and flood-threat information. A multiple-level web-based interface require development, through which the distributed database, the model base, and the spatial decision services can be integrated.

(2) Real-time data access and flood map dissemination

Flood forecasting and flood management require real-time data access for model input and development of decision-making services systems for real-time runoff prediction, water level prediction, and flood frequency prediction This helps to mitigate flood disasters and minimize the potential flood hazard.

(3) Distributed data sharing and services

The third challenge lies in that flood forecasting decision-making support require collaboration, because the data are distributed and managed by different organizations. For example, river runoff prediction requires diverse information that includes current and historical in-situ measurements, such as river runoff data from gauging stations and precipitation data from weather stations, which usually involves multiple organizations, so collaboration is required to facilitate an interactive decision-making process. However, it is not always possible to find all these datasets in one place or on one server. Sometimes, it is difficult to obtain the required model input data. In addition, a variety of data sources and multiple data formats of the available data present a formidable challenge to users who wish to compile information into a form that is usable for their applications. The possible usage of the available datasets remains limited primarily because of the difficulty associated with the combining of data from diverse and distributed data sources. Assuming that all the information is at the same scale and has been formatted according to the same standards, users can potentially overlay spatial information, which is originally collected and maintained by a separate organization to examine how the layers interrelate. Analyzing this layered information as an integrated whole can significantly aid decision makers in considering complex choices. The extensive data requirements have long been an obstacle to the timely and cost-effective use of a complex decision-making model, which is facilitating an increasing realism to distributed geodata sharing, supports the information exchange and knowledge sharing among different organizations through web.

(4) Model sharing for decision-making support

Flood forecasting includes rainfall-runoff model development, flood frequency prediction model development, and flood "threshold" selection to decide whether flood warnings should be issued. The complexity of flood forecasting requires decision makers to access a range of models, for example, the SCS model for river runoff prediction, LP3, GEV, PL and GP models for flood frequency prediction, CA and singularity fractal models for flood threshold selection and characteristics description. A Web-based system can be ideal for sharing these models for public information services and decision-making support.

(5) Integrating data and model for decision-making support

The last challenge is integrating data and models for decision-making support. Some hydrological models for flood forecasting have been developed and successfully applied in the ORM area. However, most of these hydrological models are inaccessible to the public and decision makers. Users need to download and install models on their local desktop computers and learn how to operate these models. Sometimes, it is difficult to obtain the required model input data. Few of these models are well integrated with GIS and are capable of non-expert implementation. Difficulty in linking data and analysis tools and models is one of the barriers to be overcome in developing integrated spatial decision-making techniques. An integrated approach is still needed to integrate models, data, decision-making support, and interface to help decision makers and the public to easily access flood and Flood-threatened information. The integrated system with a common database and a common web-based interface would make flood management easier.

Thus, further research for web-based flood forecasting is still required to integrate information retrieval, analysis, model analysis, and extensive visualization functions for information sharing and decision-making support in the ORM area. WFSDSS provides the framework within which spatially distributed data accessed remotely to prepare model input and model calculation and evaluate model results for runoff prediction, water level prediction, and flood frequency prediction.

6.3 System Overview

The chapter represents an effort to develop a spatial decision support service for flood forecasting. Obviously, flood forecasting is not a new topic, one innovation of this chapter is to develop a web-based decision support services approach, concept model, and prototype system that integrate hydrological models, analytical tools, databases, interface, and decision-making support services to help decision makers and the public to easily access flood and flood-threaten information. This system integrates information retrieval, model analysis, and extensive visualization functions for information sharing and decision-making support. The ultimate aim of this system is to improve access to flood model results to the public and decision makers.

WFSDSS is an integrated system that integrates hydrological models, analytical tools, databases, graphical user interfaces, and spatial decision-support services to help the public and decision makers for flood forecasting. WFSDSS helps to mitigate flood disasters through river runoff prediction, flood forecasting, and disaster information (flood discharge, water level and flood frequency (return period)) dissemination.

Based on the challenges in analysis of a web-based hydrological model for flood management, the key advantages of this system should be:

1. Integrated system: This system consists of different components. The runoff prediction model, water level prediction model and flood frequency prediction

model, the databases, decision support services and the user interfaces are separate components, but are integrated.
2. Web based interface, through which the distributed database, the model base and decision support services can be integrated.
3. Containing different forecasting models and decision-support services, including river runoff prediction model, water level prediction model, and flood frequency prediction model.
4. It is capable of non-expert implementation and provides flood forecasting decision support services for decision makers and the public. This system integrates information retrieval, analysis, model analysis and extensive visualization functions for information sharing and decision-making support.
5. Extensive visualization capabilities: All flood model results are visualized in maps, table or graph on the web, providing rapid dissemination of flood forecasting and flood threaten information.

6.4 Architecture of WSDSS

In this section, the architecture of flood WSDSS is proposed. This system has a multi-tier architecture consisting of presentation, business logic tier, and data tiers. Figure 6.1 provides an overview of system architecture. The presentation tier is the interface for users to interact with system, users can submit requests from the

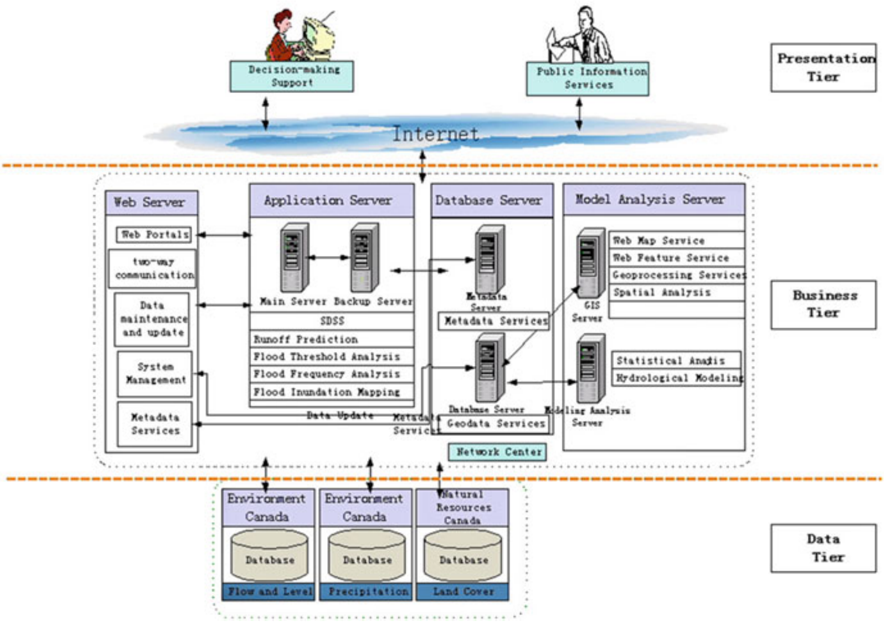


Fig. 6.1 Architecture of WSDSS

presentation tier, and it also can be used as the system client viewer for accessing geographic data and analysis results. The business tier copes with the requests from the 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. The web server is the information exchange center between users and application server, supplies two-way communication between client and application server, and is used for receiving user requests, retrieving information, transferring requests to application server, and returning the results in the proper form to the explorer at HTML/HTTP standard. The application server is the core of this system: it responds with the request from users, and transfers the requests to a database server or model analysis server according to the requirements. The metadata server supplies metadata services for users. The geodata server accesses data remotely for model analysis, statistical analysis and spatial analysis, automatically coping with problems in data heterogeneities. The spatial analysis and model analysis server supplies spatial analysis, hydrological model and statistical model analysis and geoprocessing services for river runoff prediction and flood forecasting. The data tier includes all available distributed data sources from different organizations, including river runoff, water level and precipitation data from Environment Canada, and Land Use data from Natural Resources Canada etc. The Database server is used to manage those sharing database in this system, and it also supplies data services for the application server and spatial analysis and model analysis server.

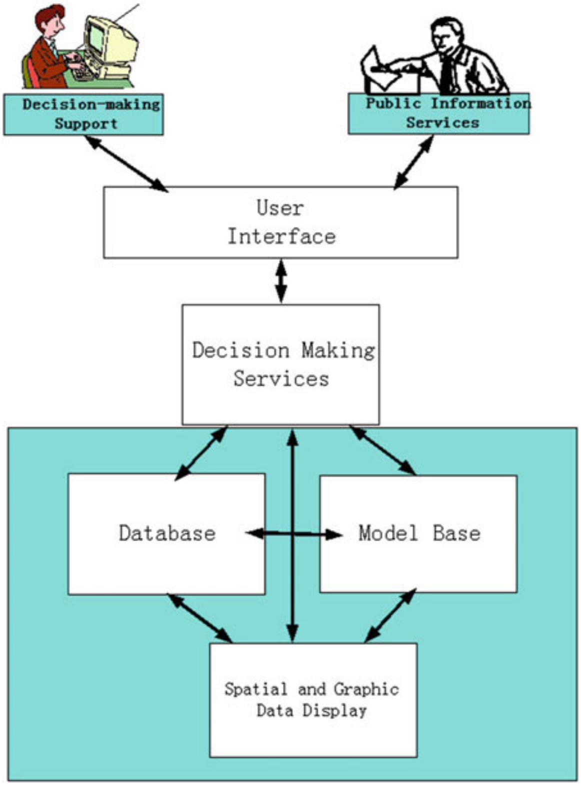
This system has two main sub-systems: a hydrological model for river runoff prediction sub-system, and hydrological models for flood frequency prediction sub-system. First, the hydrological model for river runoff prediction sub-system applies SCS CN model for river runoff prediction. Then, hydrological models for the flood frequency prediction sub-system apply LP3, GEV, PL and GP models for flood frequency prediction. Finally, river runoff, water level, and flood frequency (return period) prediction maps are published on the web for the public and decision maker to use for flood management.

6.5 Components of WSDSS

The integrated components of this system include database, model base, interface, and spatial and graphic data display system Fig. 6.2.

1. Distributed and central management database: all spatial data are stored in GIS databases and all attribute data are stored in the Relational database management system (RDBMS). There are two sets of databases in this system: distributed database for model input and central management database for model input, running and result display. The distributed database allows for data acquisition from various agencies, including river runoff, water level and precipitation data

Fig. 6.2 WSDSS components



from Environment Canada. The central management database stores data for model input, running and result display. Spatial data management is either as file based or spatial databases.

2. Model base: several models are integrated to support decision making, including hydrological models for runoff prediction, water level prediction, and flood frequency prediction.
3. Interface: a multiple-level web-based interface needs to be developed, through which the distributed database, the model base and the spatial decision services can be integrated. Users can submit their requests through this web interface and FWSDSS will publish result map to users through this interface.
4. Spatial and graphic data display system: WebGIS supplies users the functions to be able to easily visualize model output results in map such as runoff prediction, water level prediction and flood frequency prediction. The implementation of the web visualization system is supported by ESRI ArcIMS.

6.6 System Functionality

From a technical perspective, WSDSS supplies three levels of decision support and services: metadata services, geodata services, and geoprocessing services. The first level is metadata services. Metadata, which gives a detailed description of the data, provides the following information: identification information, data quality information, spatial data organization information, spatial reference information, entity and attribute information, distribution information, and metadata reference information – as well as other information. Using metadata services, users can know what data are available in this system, how the data have been collected, and who is responsible for managing and distributing the data. This system supplies metadata services for National Water Data Archive, National Climate Data and Information Archive, and National-Scale Ontario Land Cover data set. The metadata protocol used in this system is the Federal Geographic Data Committee (FGDC) metadata standard.

The second level of decision support and services is geodata services. Geodata services include Web Map Service (WMS), Web Feature Service (WFS), Web Coverage Services (WCS) and filter Encoding etc al, users are shielded from the inconvenience of worrying about a variety of data sources, multiple data formats and data maintenance and update of the available distributed data because WSDSS detects and automatically resolves data heterogeneities in the underlying datasets, supplying data services and web mapping services for the public. The decisions can be made better when the decision makers are provided with the most up-to-date and complete information. This system supplies geodata services for the National Water Data Archive and the National Climate Data and Information Archive.

The third level of decision support is geoprocessing services. Distributed geoprocessing services is very critical to help users in geodata processing, modeling and analysis. Effective sharing of methods and tools has a potentially much higher return than sharing of data. GIServices can generate new information values by sharing geographic information, spatial analysis methods, and users' experiences and knowledge. Distributed GIServices encourages sharing of analysis methods, spatial models, and geographic knowledge (Tsou 2001). In spatial decision-making, traditional SDSS and GIS software, analysis methods and models are difficult for the untrained professional to use. An easy-to-use, inexpensive set of analytical tool still need to be developed for distributed spatial decision-making support, improving accessing data, analysis tools and models. WSDSS can integrate information management, information retrieval, spatial analysis and model analysis, supporting information exchange and knowledge, analysis tools and model sharing through web. With such a system, users require only a simple web browser to access the data, the model and perform spatial analyses without the requirements or costs of installing GIS and modeling processing software packages.

6.6.1 Decision Support Services for River Rainfall-Runoff Prediction

The US SCS has developed a widely used lumped, empirical and mathematical model, SCS CN method, for estimating runoff (USDA-SCS 1968). The 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 CN. So river runoff can be predicted using the CN value and precipitation. The SCS model has been widely used for river runoff prediction and flood forecasting, but users need to be trained on how to use it. Difficulty in linking data, analysis tools and models is one of the barriers to be overcome in developing a river rainfall-runoff prediction system. Thus, WSDSS need to be developed to integrate models, data, web interface, and decision-making support to help decision makers and the public to easily access river runoff and water level prediction results. The most important benefits to users are that this system provides comprehensive support for integrating information retrieval, analysis, and model analysis for decision-making support.

First, the river runoff prediction sub-system uses the historical data for the past several decades (river gauging, precipitation, ground water, census and land use) to model the relationship among the stream runoff, precipitation and hydrological-geographical features to get the CN value for each watershed. The CN value is

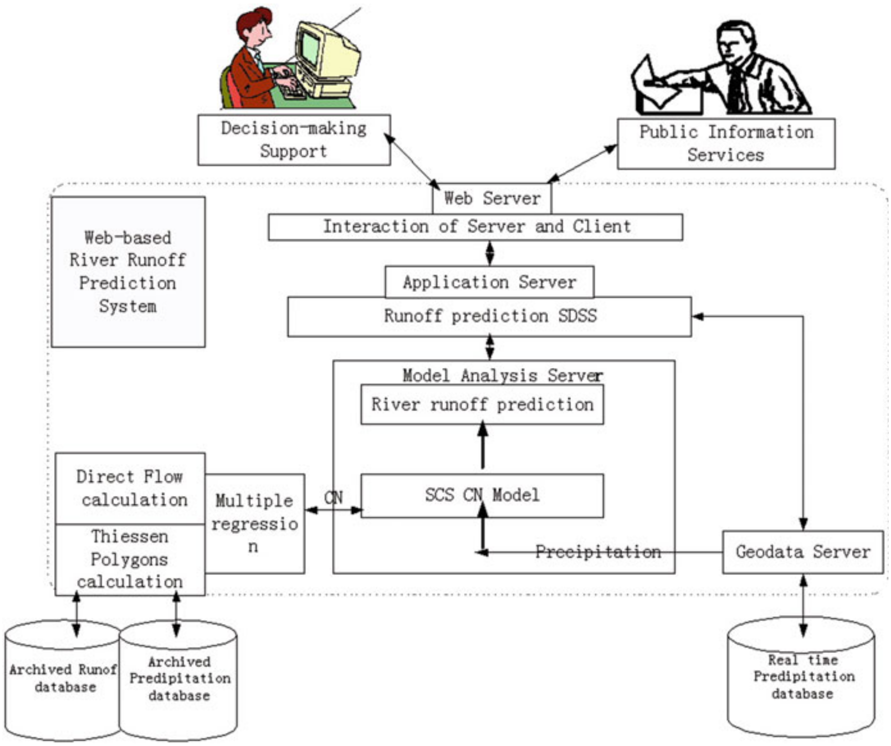


Fig. 6.3 River runoff prediction system

saved in database, and the SCS model uses this CN value and precipitation prediction results for river runoff prediction. When users submit the request from a client, the web server transfers this request to an application server. Then Geodata services access precipitation prediction data remotely from Environment Canada (precipitation prediction fall outside the scope of this study and will use the precipitation prediction result directly from Environment Canada). Next, Geoprocessing services runs the SCS model and necessary data processing for river runoff prediction and water level prediction. Web mapping services publishes the runoff prediction and water level prediction result maps on the web through ArcIMS. Figure 6.3 shows the architecture of the river runoff prediction sub-system.

6.6.2 Decision Support Services for Flood Frequency Prediction

The flood frequency prediction sub-system applies LP3, GEV, PL and GP models for flood frequency prediction.

The LP3, GEV, PL and GP models are applied for flood frequency prediction in the ORM area. The past several decades of historical data of river runoff peak discharge are used to model the relationship between flood discharge and return period by fitting theoretical statistical distributions for each gauging station. The parameters of these fitted flood frequency curves for each gauging station are saved in the database, and these fitted flood frequency curves can be used for flood frequency prediction.

The system supplies a two-way of flood frequency prediction. Users can provide flood peak discharge to predict flood frequency (return period), and the flood peak discharge is interpolated on the fitted flood frequency curve for flood frequency prediction. Or users can provide flood frequency (return period) to predict the required flood peak discharge, and the flood return period is also interpolated on the fitted flood frequency curve for required flood peak discharge prediction. The web mapping services component publishes the flood frequency prediction result maps on the web through ArcIMS. Figure 6.4 shows the architecture of flood frequency prediction sub-system.

6.7 System Development Approach: An Integrated Approach

Although many hydrological models have been developed for river runoff prediction and flood forecasting, most of these models are inaccessible to the public and decision makers, so it is very difficult for the public and decision makers to use

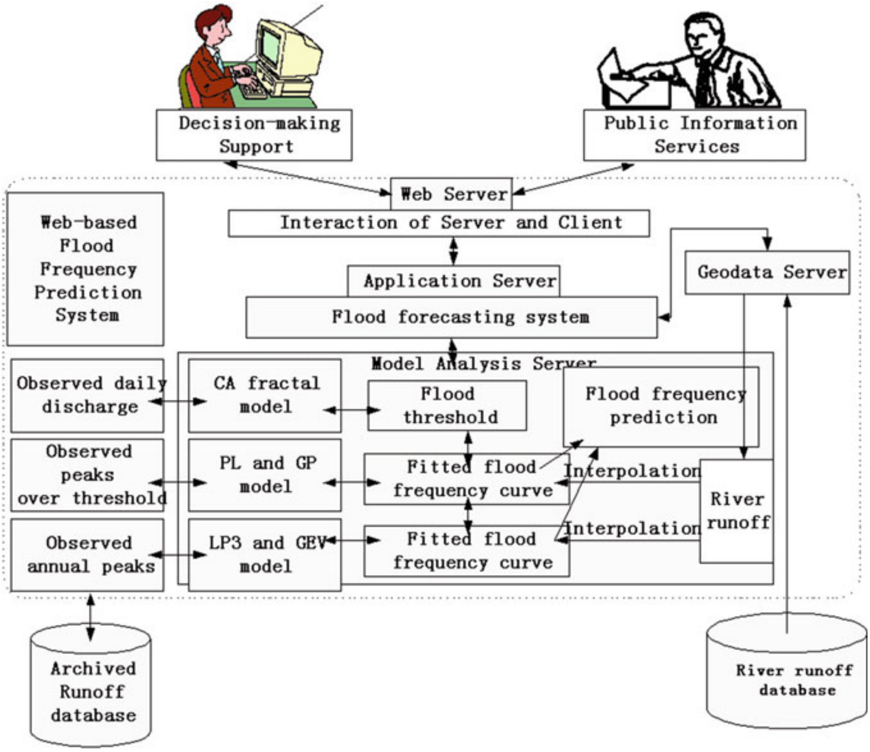


Fig. 6.4 Flood frequency prediction system

these models directly for flood forecasting and flood management. For this reason, a new system and tool are needed by the public and decision makers to enable them to utilize available models and data. An integrated approach is still needed to integrate models, data, decision making support, and interface to help decision makers and the public to easily and fast access flood and flood threaded information.

A flood WSDSS integrates models, data, interface, and decision-making support services to help decision makers and the public to easily access flood and flood-threatened information. Integrated hydrological models, statistical models and fractal models can meet model requirements for flood forecasting. The integrated system has a common database and a common web-based interface. The integration is performed using GIS as a common platform for database, model base and interface management. The SCS CN model is used for river runoff prediction, and the LP3, GEV, PL and GP models are used for flood frequency prediction. Extensive visualization capabilities are implemented, and end users can visualize the model generating results as maps on the web. The design of this system is based on database, web technology, GIS and spatial decision support services. The implementation of this system is supported by ESRI ArcIMS. The theory and knowledge required to develop this flood WSDSS include hydrology, GIS, database management system, and SDSS.

Full implementation of WSDSS is not easy. Rinner (2003) advocates for Web-based decision services as the building blocks for future WebSDSS. He believes that complex geo-processing services, such as distributed spatial decision-support services, are the highest level of SDSS. Web-based decision services can support information exchange and knowledge, and analysis tools and model sharing from different organizations through the web. The development of WSDSS is based on the concept of web services. Advanced network techniques such as Java language, ActiveX controls, Common Object Request Broker Architecture (CORBA), Distributed Component Object Model (DCOM), and Java Beans, which focus on the development of distributed component technology, have substantially enhanced the potential value of GIS because now it is possible to locate and harness data from many disparate GIS databases to develop very rich analytical information on almost any topic associated with physical locations.

Full implementation of the functionality of WSDSS requires advanced computer sciences knowledge and much programming work. In this paper, instead of developing a system to fully implement WSDSS, a prototype system is developed to demonstrate the basic functionality of flood WSDSS.

6.8 Summary

This chapter introduces the architecture, components, functionality and an integrated system development approach of flood WSDSS. This system has a multi-tier architecture consisting of presentation, business logic, and data tiers. The presentation tier allows users to interact with the system, submit requests from presentation tier, and access geographic data and analysis results. The business tier copes with the requests from the 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. The web server is the information exchange center between users and application server, supplying two-way communication between client and application server. Then the application server transfers the requests to the database server or model analysis server according to the requirements. The metadata server supplies metadata services for users. The geodata server accesses data remotely for model analysis, statistical analysis, and spatial analysis, automatically coping with problems in data heterogeneities. The spatial analysis and model analysis server supplies spatial analysis, hydrological model, and statistical model analysis and geoprocessing services for river runoff prediction and flood forecasting. The data tier includes all available distributed data sources from different organizations.

The integrated components of this system include the database, model base, interface, and spatial and graphic data display system.

This system has two main sub-systems: the hydrological model for river runoff prediction sub-system, and the hydrological model for flood frequency prediction sub-system. First, the river runoff prediction sub-system applies the SCS CN model for river runoff prediction using precipitation data and the CN value of each watershed. Then, the flood frequency prediction sub-system applies fitted flood frequency curves for flood frequency prediction.

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