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A real-time hydrological model for flood prediction using GIS and the WWW

W. Al-Sabhan *, M. Mulligan, G.A. Blackburn [1]

Department of Geography, Kings College London, University of London, Strand, London, WC2R 2LS, UK

Abstract

The purpose of this paper is to examine the current status of real time hydrological models used for flood nowcasting and hazard mitigation and indicate how WWW-based systems can overcome some of the limitations of existing systems. Whilst hydrologically innovative and robust models are available, they are poorly suited to real time application, are often not well integrated with spatial datasets such as GIS. Current systems also lack flexibility, customisability and accessibility by a range of end users. We describe the development of a Web-based hydrological modelling system that permits integrated handling of real-time rainfall data from a wireless monitoring network. A spatially distributed GIS-based model is integrated on the basis of this incoming data, approximating real-time to produce data on catchment hydrology and runoff. The data can be accessed from any WWW interface, and they can be analysed online using a number of GIS and numerical functions. We discuss the potential users of such a system and the requirements for interfacing model output with these users for hydrological nowcasting and spatial real-time, emergency decision support. Rather than discuss developments in the modelling of hydrology for flood hazard mitigation, this paper focuses on developments in interfacing these models with end users.

Keywords: Geographical Information System; Web-based GIS; Real-time hydrological model; WWW GIS

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1. Introduction

Floods are major contributors to personal injury and to property damage, and can strike with little warning. Problems related to flooding have greatly increased over recent decades because of population growth and the subsequent development

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* Corresponding author. Tel.: +44-207-7848-2632; fax: +44-207-7848-2287.

E-mail address: waleed.al-sabhan@kcl.ac.uk (W. Al-Sabhan), mark.mulligan@kcl.ac.uk (M. Mulligan), alan.blackburn@lancaster.ac.uk (G.A. Blackburn).

[1] Present address: Department of Geography, Lancaster University, Lancaster LA1 4YB, UK.

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of extensive infrastructures in close proximity to rivers. Increased frequency of extreme rainfall events, characteristics of a changing climate, can also potentially contribute to this problem. An effective real-time flood modelling and prediction system could help mitigate the worst effects of flood disasters through the rapid dissemination of information regarding threatened areas, that is simple maps of potential flood water distribution. The development of such a system would be particularly important outside of urban areas where conventional hazard management systems do not operate — for example, the large expanses of agricultural land and pasture which occupy flood plains. There are, a number of legal and institutional difficulties associated with the provision of real-time flood hazard data in an automated fashion and direct to potential impactees on the ground. However, these issues fall outside the scope of this paper.

While many watershed modelling software packages are currently available, few are well integrated within spatial modelling environments (GIS) and are capable of non-expert implementation. The models require considerable expertise in hydrological data and model application and are unsuitable for real-time application because of the types of data required and the interactive nature of their application. Here we discuss models that are sufficiently simple and robust to allow automatic application and interactive interrogation by end users with little hydrological expertise.

The application of watershed models requires the efficient management of large spatial and temporal datasets, which involves data acquisition, storage, and processing of modelling inputs, as well as the manipulation, reporting, and display of results. These management requirements are usually met by integrating watershed simulation models and GISs, generating the capacity to manage large volumes of data in a common spatial structure. The integrated systems are then further developed by combining numerous software packages and mathematical programming systems, and by incorporating a database management system (DBMS) whenever necessary. For example, the EGIS project by Deckers (1993). Interaction between the user and the system relies on a graphical user interface (GUI), which may be developed by a third party such as a university, environmental agency, or commercial vendor. However, these GUIs vary in quality and sometimes contain exclusive features not found in other similar programs. Another problem is the use of temporally dynamic processes, which are considered a major obstacle when coupling a GIS with environmental modelling, (Albercht, Jung, & Mann 1997). Some of these systems are complex and sophisticated, are designed for general purposes, and cannot be customised by users for applications in specific circumstances (Bundock & Raper, 1991).

Several researchers (Bennett, 1997; Maidment, 1993; Wilson, 1996) acknowledge the lack of sophisticated analytical and hydrological modelling capabilities in existing systems. The systems also need to be adaptable for specific application and user requirements. Furthermore, existing systems, including simulation models, also lack some of the essential analysis tools such as dynamic modelling (Van Deursen, 1995), with the exception of PCRaster (Wesseling, Karssenberg, Burrough, & Van Deursen 1996), needed by watershed applications. Hydrological analysis itself is often hampered by limited data of adequate quality (Goonetilleke & Jenkins, 1999) and lacks real-time data, which are fundamental to the success of any flood forecasting system. The goal of flood forecasting is to provide a reliable prevention mechanism to eliminate disasters and reduce the negative consequences of a hazard. However, this requirement is not often met by GIS and hydrological models. The widespread and routine use of conventional GISs in important environmental applications has been hampered by numerous key obstacles (Albercht et al., 1997) such as user interfacing, data integration, presentation of dynamic processes in GIS and cartographic modelling language (Map Algebra). GIS systems are built to cover a wide range of applications and are designed to integrate a variety of environmental data, allowing them to work together in a readily accessible manner. As a result, even basic GIS functionality for modelling requires relatively complex software and hardware, resulting in substantial operating costs. Another factor to be considered is the integration of simulation models, also important tools in environmental applications of computer technology, which are capable of significantly advancing the potential of GIS for environmental simulation and understanding. However, this complex integration requires significant programming effort and data management (Burrough, 1997). Many model reviews examine the mathematical implementation of models and their applications (Beven, Kirkby, Schoffield, & Tagg, 1984; Clarke, 1973). Unfortunately, these reviews often do not acknowledge the seemingly trivial problems that are of significant concern to users and stakeholders. One such problem lies in the difficulties arising from interfacing the models and the data; simulation accessibility to interested groups and the general public is another obstacle to overcome. Rather than giving a full state-of-the-art review of watershed simulation modelling systems, impossible in only one paper, we have chosen to present highlights of some of the more recently published literature. We also review modelling programs with the principal purpose of evaluating their real-time capabilities, interfacing functionality, and public accessibility requirements.

We have two goals in this paper:

1. to review the current status of spatial hydrological models with respect to their use for (real-time) flood nowcasting; and
2. to introduce a new Web-based real-time model for interactive nowcasting.

The review provides the rationale for the development of an integrated watershed simulation model with a Web-based interface that benefits users by easing access to information and by offering technological transparency, platform independence, visual interaction with data, a multimedia environment, and cost efficiency. Implementing Web-based GISs would provide local communities with Web access to environmental databases and help them participate in the environmental decisions that directly affect them. The remainder of the paper is organised as follows: Section 2 provides an overview of spatial simulation models for flood forecasting. Section 3 presents the rationale for the development of WWW-based systems. Section 4 provides an overview of the methods used and the results obtained and Section 5 concludes the paper.

2. Review of spatial hydrological models

Hydrological models are defined as mathematical representations of the flow of water and its constituents on some parts of the land surface or subsurface environment (Maidment, 1993). Environmental modelling of this kind provides numerous benefits: (1) it explains the physical world; (2) it provides decision support to resources and hazard management (Moore, Turner, Wilson, Jenson, & Band 1993); and (3) it guides experimentation and research for presenting complex ideas in an accessible manner (Burrough, 1997). Hydrological models can be considered as stand-alone programs with data loaded via the import and export facilities within the model itself without the help of any GIS package, or as coupled to a GIS system through an interface solely designed for that purpose.

2.1. Stand-alone models

The stand-alone programs depend on a particular computing platform or hardware configuration such as the Windows-based Watershed Modelling System (WMS reference, 1999) and GIBSI (Mailhot, Roussseau, & Massicotte 1997), the UNIX-based workstations Modular Modelling System (MMS manual, 1998), or the DOS and UNIX-based PCRaster (Wesseling et al., 1996). They all run from an individual computer, or from several computers on a local area network that is not necessarily connected to a global network, and are then made accessible to the public or to managers in geographically separate locations.

One of the best known and widely used models is HEC-1, from the Hydrologic Engineering Center of the US Army Corps of Engineers, which provides a variety of options for simulating precipitation-runoff processes. A new interactive version, which replaces the command-line-oriented programs HEC-1 (flood hydrograph model) is HEC-HMS (Hydrologic Modelling System). This stand-alone rainfall-runoff modelling program has been implemented on both UNIX (Sun Solaris) and Windows NT/95/98. It has a GUI, integrated hydrological analysis components, data storage and management capabilities, and graphics and reporting facilities. Furthermore, a significant amount of data must be gathered to perform hydrological analysis using HEC-1 (Nelson, Jones, & Miller, 1994). HMS is designed to be independent of any commercial GIS, so it has no explicit ties to any of them. Another program that is well known and can be used as stand-alone is the WMS (Nelson, Jones, & Jorgeson, 1995). It is a graphically based, comprehensive hydrological modelling environment that addresses the requirements of rainfall-runoff computer simulations (DeBarry et al., 1999). If it is used as a stand-alone application, data can be imported or exported to or from a GIS package through a number of popular files formats. For example, a DEM can be imported from ARC/INFO, or GRASS and then used in WMS for further analysis. The last example is the TOPMODEL, which is classified as a distributed to semi-distributed model, and a number of papers and applications of this model have been presented (Beven, 1997; Obled, Wendling, & Beven 1994). It is not intended to be a modelling package, but rather a set of conceptual tools that can simulate the hydrological behaviour of a watershed (Beven, Lamb, Quinn, Romanowicz, & Freer 1995). Because it has been adapted and applied to suit many modellers' needs, a standard version has not been developed. Some of these various implementations are listed in the TOPMODEL manual available at http://www.es.lancs.ac.uk/hfdg/topmodel.html. Data requirements for TOPMODEL are dependant upon the version and the application used. The primary drawbacks of using this model are the lack of a standard version and the preparation of data for each application that requires a long and demanding period of data analysis (Romanowicz, Beven, & Moore, 1993).

2.2. GIS-based hydrological modelling systems

An alternative to using models as stand-alone, is to couple the model with a GIS package. There are, however, specific problems in GIS-based hydrological modelling, but before we discuss them, we briefly need to address some impediments of current GIS systems. We can identify four principal areas that impede GIS use: complexity, interfacing, customisation, and platform dependency. At the present time, GIS systems are large, complex, and difficult to use and have been severely criticised as being elitist (Pickles, 1995). The hardware, software, and data can be highly expensive for most individuals; similarly, the training required to use most GIS packages successfully is extensive. Over time, GIS software has become more versatile and general, and different user interfaces and useful models have been added, all increasing the complexity of the interface. In its early development, the GIS industry focused on system functionality and data handling. However, it soon became apparent that the evolution of GISs could not continue without developing a better user interface (Raper, 1991). Several vendors have developed new interfaces, with offerings such as ARCVIEW from ARC/INFO and others. Whilst these products represent important advances, several modellers were reluctant to use a GIS in modelling because of the complexity of developing an efficient integration technique to support the modelling effort (Stuart & Stocks, 1993).

Customisability is the term used to describe the process by which GIS software is tailored and modified to satisfy corporate, departmental, and user requirements (Bundock & Raper, 1991). Each organisation requires a system that is in many ways unique to its own structure with consideration to its specific problems, requirements, goals and objectives. At present, most GIS and simulation software customisation processes are time consuming, require technical expertise in many languages, are expensive, and very often produce poor results (Raper & Bundock, 1993). Schultz (1993) discusses the use of GISs with increasing complexity in hydrology and indicates that some necessary hydrological routines are missing from most GISs and new routines cannot be introduced directly by the user. The last point that is important to consider is that many of these hydrological models and GISs do not support multiple platforms. Most systems depend on a specific computer platform or hardware configuration. For example, WMS runs on a Windows platform (WMS reference, 1999) while MMS runs under Unix environment (MMS manual, 1998); Arc/Info, the most popular GIS software, runs on a UNIX platform and the

Windows-based version has been released recently. Thus, platform dependence is one of the issues that restrict users from data and software sharing.

The approaches for integration of environmental models with GISs have been extensively discussed and analysed by many researchers (Burrough, 1996; Goodchild, Parks, & Steyaert 1993; Karimi & Houston, 1997; Maidment, 1996; Peuquet, Davis, & Cuddy 1993). Similarly, the integration of GISs and hydrological models is well documented in the literature (Maidment, 1993; Romanowicz et al., 1993; Sui & Maggio, 1999), thus it is not our intent to discuss these in great detail in this paper. However, we will briefly discuss the two methods available for coupling GIS and hydrological models: loosely coupled and tightly coupled (Batty & Xie, 1994; Stuart & Stocks, 1993). In loosely coupled models a GIS is linked to an external model where operations are performed in languages such as C or Fortran, which are most suited to this kind of mathematical calculation. To use the external model from the GIS, a call to the model is placed to calculate certain parameter values and then store the values back in the GIS database. This method usually involves a standard GIS package and a hydrological model such as HEC-2 (Djokic, Beavers, & Deshakulakarni, 1994). It is stressed by Albrecht et al. (1997), Burrough (1997) and Frust, Gristmair, and Nachtnebel (1993) that these couplings provide access to incompatible analytical tools and "the difference in the data models and in the way relationships between variables are handled in GIS and hydrological model" (Maidment, 1993) soon becomes apparent. This mismatch also affects the quality, cost, and benefits of the modelling results (Burrough, 1997) because modellers and GIS engineers have very different conceptual views of the real world and approaches to their disciplines. This type of integration requires a number of programs that exchange data from one application to another and possibly a DBMS and/or number of transfer files. A disadvantage of this approach is that there is no common graphical interface and the data exchange and conversion between the GIS and the hydrological model can be very cumbersome. Loose coupling may also involve considerable work in changing data formats and data structure, particularly if the model has been obtained from another source (Burrough, 1997).

Tightly coupled models are developed entirely within a GIS environment through the use of a macro language such as AML (ESRI Arc Macro Language). However, this type of programming is often not able to implement complex applications and does not support the same capabilities of procedural programming languages. Unlike loose coupling, tight coupling does not require file conversion or editing; however, it is a complex process and requires a great deal of programming and data management (Burrough, 1997) plus a customised menu-driven user interface for display (Karimi & Houston, 1997). Thus, tightly coupled models require the construction of an appropriate interface that can interact with the data structures of the GIS system. Karimi and Houston (1997) stress that both the loosely and tightly coupled methods have inherent limitations for modelling.

While GISs provide powerful tools for spatial analysis, their capabilities for spatio-temporal analysis are limited (Worboys, 1995). Traditional simulation models are effective in complex and dynamic situations, but they often lack the intuitive visualisation and spatial analysis functions that a GIS offers. The increasing and ongoing literature on the integration of GISs with hydrological models confirms the recognition of these reciprocal benefits (Maidment, 1993; Moore, 1996). However, the limitations of current GIS applications for environmental modelling become apparent because of incompatibility between the types of models and GIS and the type of data that are associated with them, as discussed by Burrough (1996), Goodchild et al. (1993). When integrating the WMS with a GIS package through the use of scripts (i.e. AML and Avenue), developers are restricted to the architecture of the GIS and users, including hydrologists and engineers, are forced to learn the GIS operating environment in order to create hydrological models. Thus GIS specialists often perform the job of the hydrological engineers (DeBarry et al., 1999). Also when integrating models like MODFLOW (McDonald & Harbaugh, 1988) and the MMS with a GIS, the outcome is the development of two different processes (DeBarry et al., 1999; Karimi & Houston, 1997): the pre-processors and post-processors which are developed in order to facilitate the integration of software. The pre-processors are tools that prepare, analyse and input spatial and time series data for use in a model. The post-processors are tools that perform the analyses of the model results. These include a variety of statistical, and graphical tools, which can be used to assist in making decision, and a user-developed interface to display and analyse results. However, these processors are also designed to create the often complex and cumbersome input file requirement and to format model output (Karimi & Houston, 1997), including data preparation of spatial and time-series, analysis, and model output file for display in a particular graphic environment. Finally many hydrological processes are time-dependent, and hydrological models generally require time-series input data and generate time-series output. Current GISs are not equipped to store or manipulate time-series data; therefore, the ability to store, retrieve, and perform operations on time-series data is crucial for implementing serious hydrological modelling within a GIS (Maidment, 1993).

3. Requirements of the hydrological models of the future

3.1. Real-time

Real-time data refers to spatial and non-spatial data that becomes available to the real-time GIS, either at fixed time intervals or after the completion of certain events such as the arrival of data at a desired destination. Conventional GIS models such as data modelling, data management, and software design and engineering do not allow current GIS systems to meet the requirements of real-time applications effectively (Karimi & Chapman, 1997). The key requirement of real-time flood forecasting, however, is based on continuous in situ measurements of rainfall to improve the accuracy of model forecasts. While there have been significant advances in the accuracy of quantitative measurements and the forecasting of rainfall using weather radar and more prolific and sophisticated rain gauge networks, extensive research efforts are still required to develop systems that incorporate real-time data with a

GIS application so that real-time data can be obtained with sufficient timeliness and rapid nowcasts can be produced. Karimi and Blais (1997) provide a comparison between current and future GIS systems, arguing that interfacing of GIS with external systems for real-time processing is nearly impossible. GIS and hydrological models, however, lack a direct connection with external sensor and devices, resulting in limited access to real-time data. These deficiencies can lead to hard-coding of data directly into the system, making updating at existing data particularly difficult. Karimi and Chapman (1997) suggested that real-time GISs must contain algorithms that allow fast responses within time constraints for real-time applications. Because current GIS algorithms do not take these constraints into consideration, they cannot be used for real-time applications.

Despite advances in computing power and programming languages, FORTRAN remains the language of modellers (TOPMODEL, HSPF, HEC). Fortran and other traditional programming technologies are not suitable for the representation of dynamic geographical systems because (adapted from Bennett, 1997): (1) early or static binding inhibits the representation of processes that change through time, (i.e. where one process is replaced by another (different) process); (2) data representation and management mechanisms are not provided for the development of complex objects; (3) user defined spatial relations are difficult to capture; and (4) models developed by traditional programming languages are difficult to extend or modify. Object-oriented programming techniques provide one means to overcome these limitations. Raper and Livingstone (1995) demonstrate the use of object-oriented concepts in the representation of spatial data. Many of the hydrological models involving simulations and optimisation require significant computer resources and run for several hours (Walker, 1991), which is unacceptable in real-time applications.

Currently, there are three basic systems for providing precipitation measurements that can be used for real-time flood forecasting: first, the conventional telemetry-based rainfall gauges, the most commonly and widely used, are typically connected to a base station by telephone lines, VHF/UHF radio, metro-burst telemetry, or satellite (Latkovich & Leavesley, 1993). A second precipitation measurement system is weather radar, which provides data on spatial patterns of rainfall as opposed to point measurements indicated by rain gauges. Meteorological radar is not used as often because it is expensive and requires sophisticated technical and engineering support. A review of radar-based precipitation measurement for hydrological application can be found in James, Robinson, and Bell (1993), and Mimikou and Baltas (1996). Third measurement tool is satellite monitoring, which estimates rainfall by observing radiation signals reflected or emitted from the ground and atmosphere. Real-time estimates are possible and, once the satellite is in orbit, the process is relatively inexpensive. This method provides large area coverage, but also requires calibration with ground-measured data.

Most data acquisition systems are interfaced to a data transmission system such as telemetry or wireless radio using standard interface connections such as RS-232 ports. Data can be transmitted from a remote site to a central base station through several available communication systems. The choice of one communication system over another depends on a variety of matters: the size of the watershed, the time of data transmission, and the costs. The existing types of real-time flood forecasting systems, which generate the most reliable forecasts, are sophisticated, use very complex data input and are expensive (Feldman, 1994). For a GIS to be effectively applied in management decision-making requires reliable, up-to-date data sources be utilised in building and maintaining the system. Although, flood forecasting systems exist in many countries, deployed in many projects, real-time flood forecasting systems are still under significant research and development.

3.2. Interfacing the user

During the development of a modelling system, the most significant aspect of implementation is an appropriate user interface, for it determines the interaction between the computer system and the user (Dodson, 1993). This interface permits the application of a variety of tools regulating both the visualisation and analysis of the spatial distribution of model parameters as well as the simulated state variables set at a variety of spatial and temporal scales. The quality of the user interface connecting the GIS has become an essential contributing factor motivating people to use GIS as a means of handling spatial data and for determining policies. Frank (1993) agrees, stating that the user interface is the most important single part of the system.

In the USA, significant design initiatives have furthered GIS user interface design such as the National Center for Geographic Information and Analysis (NCGIA; Kuhn, Willauer, Mark, & Frank, 1992). Albercht et al. (1997) stated that the finished product of a modelling system must include a graphical user interface that is simple to use. Knill (1993) stresses the need for improvements in user-friendliness, including visualisation and results. Some authors focus on the need to develop an adaptive user interface, which provides multiple, customised interfaces for each class of users. For example, hydrologists can be presented with a more technical interface than casual users. Kingston, Carver, Evans, and Turton (2000) also stress the need for the development of an interface that can be modified to match the skill levels of the user.

GIS and simulation models are used most frequently in professional and academic endeavors. Therefore, the developments in watershed model integration with GISs are actually the result of the development of interfaces that facilitate the creation of watershed model input data sets (DeBarry et al., 1999). Models such as HEC-1, TR-20, SWMM, and others which lack good interface design require intensive data development for input which is often very labour intensive and time consuming (DeBarry et al., 1999). Even programs such as HEC-HMS, which are designed with an interactive GUI to provide a convenient means for entering data and displaying results, the use of the GUI is cumbersome when it is desired to execute a series of model applications with alternative sets of parameters (HEC, 1996). Because interfacing is the most important part of hydrological model development, the need for improvement in user-friendliness, and flexibility is definitely needed in order to facilitate the use of such systems.

3.3. Accessibility

Environmental information is usually held in government, academic, and commercial water institutions. Hydrological modelling tends to remain in the domain of the model developer and to be applied within a consulting framework. The models are inaccessible to decision makers who are not specialist modellers (Taylor, Cameron, & Haines, 1998) and appear to be designed for experts and professionals for use as in-house tools. While data are currently available for public use through the Internet by some institutions and governmental agencies, many of these institutions, however, provide the data in varying formats and use complicated relational databases (Dai, Evans, & Shank, 1997). However, some, like the United States Environmental Protection Agency (USEPA) and United States Geological Survey (USGS), have made significant progress toward providing public access, in the form of real-time data (Stewart, 1999), to various environmental databases. Unfortunately, effective use of these data requires specialised software not available to every user. Thus, providing public access and analysis to various environmental databases could help local communities and researchers to participate effectively in environmental decisions that directly affect people's lives.

Public participation and involvement are important components in the implementation of a water resources project. Wood, Gooch, Pronovost, and Noonan (1985) stress the importance of public consultation and participation in flood management planning. Recently, geographers have begun to consider the practical and societal impacts of using GISs to support public participation (NCGIA, 1995, 1996). In addition, it has long been recognized that GISs provide the user with a flexible framework for the development of GIS-based Spatial Decision Support Systems (SDSSs; Clarke, 1990). A GIS is often designed for spatial decision support, lacking the capacity for collaborative spatial decision-making (Jankowski, Nyerges, Smith, Moore, & Horvath, 1997). However, in the future, a GIS must support SDSSs in collaborative environments (Karimi & Blais, 1997) designed for sharing, executing, and comparing model results, especially when the decision makers and/or stakeholders are from geographically separate locations (Carver, Frysinger, & Reitsma, 1996).

Despite the progress in flood forecasting systems, some researchers in the UK (Parker, Fordham, Tunstall, & Ketteridge, 1995) have been critical of the Environmental Agency for not giving more attention to warning and dissemination processes. More work is needed on increasing community involvement in establishing local flood warning schemes (Haggett, 1998; Parker et al., 1995).

Finally, data analysis is not only useful for professionals and decision makers but also for a public that demands openness, as is reflected in legislation such as the Council of European Communities Directive (1990) and the US Freedom of Information Act (1965), which specify that all information must be available to anyone who wants it. Data accessibility and participation are one of the issues that need to be considered in the development of a successful flood forecasting systems. Therefore more consideration needs to be undertaken in order to provide a better simulation and warning system not only for flood forecasting but various environmental management systems.

Eight key conclusions can be drawn from this review of current hydrological modelling. These key points include:

1. *Interfacing is difficult.* It requires tedious, and complex development and typically presents the user with difficult to use and limited visualisation of complex information.
2. *Knowledge of GIS is required.* GIS and simulation systems are complex, difficult to use and expensive computer programs, which limit the number of users. A detailed knowledge of the underlying GIS architecture is required.
3. *Platform dependency.* Conventional hydrological modelling systems are platform-dependent because every program runs on a specific platform. This results in limiting the number of targeted users that can access the system.
4. *Computer and programming knowledge is necessary.* Technical expertise in multiple languages and subsystems are required (e.g. Databases definition language, macro language, C and Fortran, operating system commands).
5. *Customisation of models is very difficult.* The customisation required to implement a GIS can run many times the cost of the hardware and software. With each upgrade, the custom software must be updated, recompiled and sometimes rewritten from the ground up.
6. *Limited accessibility for data and analysis must be rectified.* Models are still mostly confined to research laboratories, water and academic institutions and not widely used in the public at large.
7. *Limited collaboration.* There is a growing need towards consortium-based projects, in which projects are, performed by teams of collaborating modellers from different geographical locations.
8. *Real-time data acquisition and communication are costly.* The methods and equipment of data acquisition and communications used are costly.

4. Aims for developing a novel web-based GIS hydrological model

The Internet and the Web are exceptionally important tools, which can potentially contribute to the achievement of the goals of watershed analysis. The benefits and the advantages that the Internet and the Web offer to watershed analysis are openness, a user-friendly interface, interactivity, flexibility, and fast communication. It is relatively cheap and therefore gives the general public access to a variety of both GIS systems and data of varying degrees of sophistication. This direct access, as a means of allowing wider involvement and participation in environmental decision-making, is an important prerequisite of watershed management. This accessibility occurred because of user interface familiarity, portability across many computer platforms and capability to display different multimedia and hypermedia formats. Additional benefit that is offered by Java programming language is the development of a sophisticated user-friendly interface, which can interact with data meaningfully and efficiently. Users can easily interact with the contents of the database or run simulation models, thus creating their own analysis results. These results being spatial or non-spatial data, hydrographs, still or animated images are processed in a Web server and then displayed immediately in the client machine from any computer in the world. This fast communication via the Internet is probably the fastest and the most economic media. Therefore, by integrating a Web-based system with wireless monitoring network, real-time data can be obtained and disseminated instantly. These important features and tools that enhance and improve watershed analysis are available and therefore it becomes a question of using them efficiently and professionally.

The promising step in the development of Web-based GIS systems has been the implementation of the Java programming language (Arnold & Gosling, 1996). Java provides tools for creating graphic, networked, and database applications that are essential for building watershed management. Java features like object-orientation, GUI, platform neutrality, security, image processing, and multi-threading are useful for building such applications (Alsabhan, Mulligan, & Blackburn, 1999). The proposed system was conceived through a general need for real-time data acquisition, data management, a user-friendly-interface, and accessibility of the data and applications. The primary aim was to develop an integrated system that would overcome problems related to the above requirements. The system was designed to act as a means of archiving and for updating hydrological data as well as for using data in a rapid decision support system. The system has been developed with the recognition that several user requirements are currently implemented within watershed simulation models. Therefore, the aims of the project are:

1. *Real-time data access and analysis*. One of the aims is to provide data accessibility and analysis by permitting access to real-time data through the Web.
2. *On-line watershed simulation and analysis*. A detailed implementation of hydrological analysis should be undertaken in order to provide a decision support system.
3. *Development of a user-friendly interface*. A well-designed interface should be implemented to facilitate the use of the system so that users can focus on the data, not the interface.
4. *Platform-independence*. An additional aim is to provide data accessibility and analysis regardless of the computing platform so that whoever has access to the Internet can run the programs.
5. *Inter-departmental collaboration*. A system should be published on a project Web site, which allows users and stakeholders to share data, as well as software as means for coordinating activities between users from different geographic locations.
6. *Cost-effectiveness*. One of the aims is to use cost-effective software development and inexpensive equipments.

5. Methodology and results

The approach taken by the authors has been to develop a system that is practical and can be applied to a wide variety of watershed scenarios where rainfall data input is relayed to the system in real-time. This paper is not concerned with the hydrological model used, but rather with the provision of a methodology for a rapid, easy-to-use, and cost-effective means for implementing watershed simulation models.

5.1. Data and DBMSs

The data capture requirement is two-fold (Worboys, 1995). First, it must provide the physical devices, such as automatic loggers (e.g. climatic and hydrological data) and field computers for capturing data external to the system and for writing to the database. Second, software must be provided for converting data to structures compatible with the data model of the database, and for checking the validity and integrity of data before entry into the system. The physical devices used for capturing data in this particular project are automatic loggers, wireless modems, and NT servers. The data input procedures in this project use rain gauges to measure rainfall. Using a wireless modem, input data are transmitted from the field to a second wireless modem connected to an NT server that stores the data. These data are then downloaded in near real-time by File Transfer Protocol (FTP) and stored in a database, which is immediately accessible to the GIS model for further analysis. Fig. 1 illustrates the project architecture.

A Java-based model is then used to process the data. The primary advantage of this approach is that it provides the end user with real-time data. During the planning phase of this project, we began our first version with a database connectivity

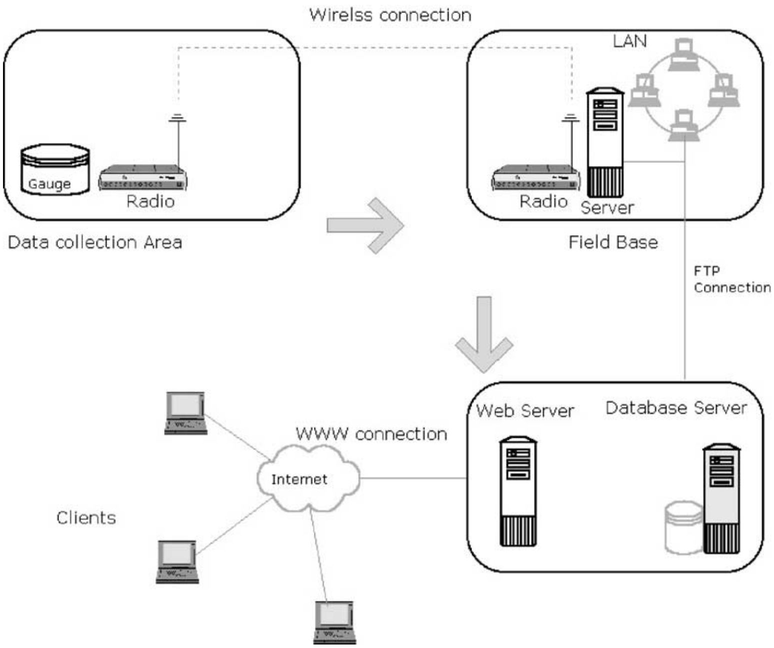


Fig. 1. Project architecture.

that uses the JDBC approach (Alsabhan, Mulligan, & Blackburn, 2000). However, the JDBC has a number of shortcomings, the most significant being slow performance. Therefore, we upgraded the system using a server-side Java application (servlet). When the Web page is accessed by a user, the *servlet* is executed on the Web server. Unlike applets, *servlets* run on the server, so they can be large and can perform a variety of tasks without taxing machine resources or network performance. Database connectivity using this approach provides a tool that is powerful, flexible, and easy to use. Java provides many more capabilities and enhances the functionality of Web-based data access. A Web data access application, however, interacts with a database and uses the Web as a means of connection with a Web browser or Java client on the front-end as a common Web server interface. With associated libraries such as the Abstract Window Toolkit (AWT; Geary & McClellan, 1997), Swing, which is a subset of the Java Foundation Classes (Gutz, 1998) and threading (Oaks & Wang, 1999), Java provides the developer with all the necessary assistance for the development of user- friendly and cross-platform GIS which lead to performance optimisation.

6. The dynamic model

Dynamic models are difficult to run in most GIS because GIS have been designed for querying and maintaining a static database with static phenomena. Standard GIS do not explicitly allow dynamic phenomena to be stored and analysed nor do they provide efficient facilities for iteration through time (Wesseling et al., 1996).

We have developed our own hydrological model that provides a quantitative description and understanding of hydrological processes. The details and operation of this model will be provided in future publications as this is not within the scope of the present paper. The dynamic modelling unit is a batch program that runs continuously in the system background. The main purpose of this unit is to process the incoming data by applying hydrological analysis and then to produce the desired results. The results of this modelling unit are non-spatial (time series) and spatial (raster images) of different variables (rainfall, soil moisture, etc.). The program was designed to store the results in specific directories so that the data loader program can determine when the program was executed. After the data have been processed by the modelling unit and the results have been stored in their specified locations, the database loader program uploads the file automatically to the database. Fig. 2 illustrates the system architecture.

6.1. The map viewer

The map viewer is a Java applet designed for map display. The first page of the model is the map viewer, which incorporates a hybrid map-display system. Aside from displaying the two image formats most commonly supported by Java and browsers, GIF and JPEG, non-standard data files such as large data files held on the server (the DEM for example) can also be handled by Java. To load a DEM image

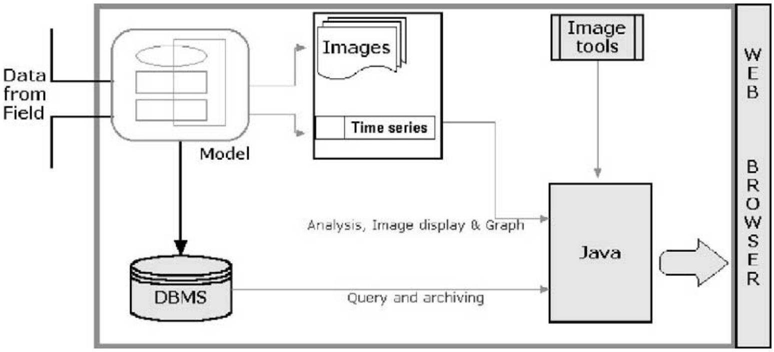


Fig. 2. System architecture.

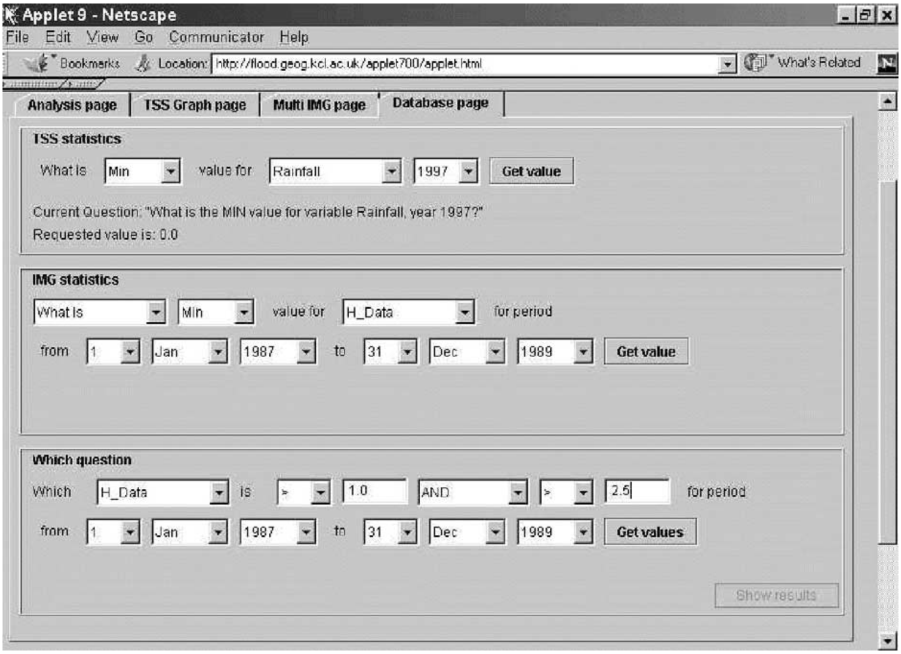
and the results obtained by applying the hydrological functions (e.g. slope, aspect, etc.), a rendering algorithm is developed which maps between the DEM elevation data or the function results and a colour palette and then displays the image 'on the fly'. This client-side program is designed in order to reduce network traffic and processing burden on the server when displaying large files such as DEMs. Once the DEM is displayed, users can select from the different buttons allowing them to adjust the map view. To adjust the map view, zoom-in, zoom-out, and pan are supported. The system is also capable of performing animation, permitting users to see more than one image at a time in the same applet frame, thereby allowing a view of the changes of a set of images selected by the user. Before the animation applet can run, a Java application was designed that run at fixed-time intervals and walks through specific directories (rainfall, soil moisture, etc.) to convert the specific file formats to GIF. This application then stores each GIF in its predefined directory so the animation applet can process when it is called. Additionally, the applet generates a legend for a selected map. It also allows users to obtain some analytical statistics on maps to obtain minimum, maximum, and average selected cell values within user-specified windows, or the whole image can also be chosen to refine the analytical process. The mechanics of the access and the analytical process are available to anyone on the Web who has authorization.

6.2. Analysis routines

The objectives of the data analysis program are to allow the user to set queries and to retrieve useful information to satisfy the specific requirements of decision-makers, and an important function of the analysis is the ability to predict what will occur at a location, at another point in time, and under certain conditions. The most important analytical process of the GIS is the provision of capabilities for spatial analysis functions that are responsible for the manipulation and analysis of the spatial data. Currently, the analytical capabilities of GISs related to the structure of the database (raster or vector) are used, and the proposed prototype uses the raster GIS structure because that raster family is determined to have greater analytical power. This system provides the user with two kinds of analytical capabilities as introduced in the following sections: time series analysis and spatial analysis routines.

6.3. *Time series analysis*

The time series tool is a Java applet that interacts with non-spatial data in the database. To query the time-series database, the user first has to click the database option from the main applet page. An easy-to-use form is presented that is designed to be user-friendly. Then, the user can query the database by specifying the time period and the function (Max, Min, Ave) in order to find, for example, the average rainfall within a specified period of time. The resulting data indicates the highest/lowest/average level of any variable within a period of time, and some other information. Or the user can specify several variables and produce a list that includes the date(s), time(s), and value(s) of the time-series data in question. Additionally, the applet supports a selection mode. The form also offers options that modulate the interval and time step of data presented, enabling transmission from the server of a more suitable representation of the time series for the user's purposes. From the main applet page, the graph option can be selected to visualise the time-series data. Depending on user-selected parameters, the graph applet viewer shows changes in rainfall, temperature, and other variables over daily, monthly, and yearly periods as they occur. The applet provides the user with the option to view any of these changes as either line or bar graphs. Fig. 3 shows rainfall time series graph.



Location: http://flood.geog.kcl.ac.uk/applet700/applet.html

TSS statistics

What is Min value for Rainfall 1997

Current Question: "What is the MIN value for variable Rainfall, year 1997?"

Requested value is: 0.0

IMG statistics

What is Min value for H_Data for period

from 1 Jan 1987 to 31 Dec 1989

Which question

Which H_Data is > 1.0 AND > 2.5 for period

from 1 Jan 1987 to 31 Dec 1989

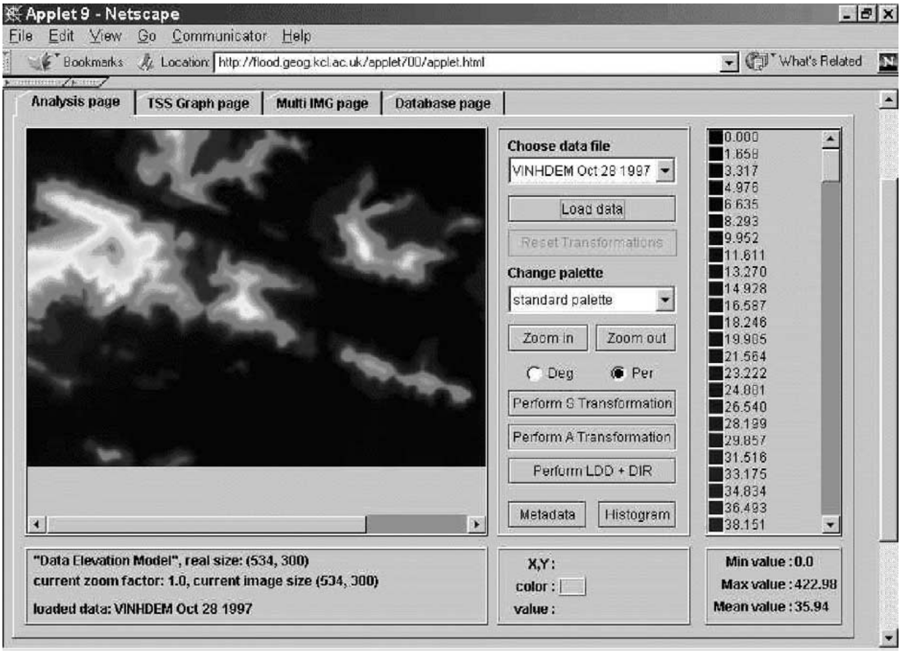
Fig. 3. Time series graph page.

6.3.1. Spatial analysis routines

The spatial database interface offers the user more flexibility by providing a series of drop-down lists to choose from. The user has to select a query (What, When, Where is, or Which), a function (Min or Max), and variable (Rainfall, Precipitation, Soil Moisture, Runoff, Recharge), and the system searches the corresponding table to produce results according to the query type. To provide the most flexible and easy-to-use query interface possible, we have built in a series of questions. The user can select from a drop-down list for the query type, function, variable, and various additional parameters. From these variables, a query can be constructed to satisfy given predicates or conditions, that is, to define what return row of the database should be projected by specifying conditional Boolean operators that search expressions identifying the tuples to be retrieved by the query. For example:

What is the lowest soil moisture value that occurs in a specified period of time?
When is the highest rainfall value that occurred between two specified periods of times?
Where in the catchment is the lowest rainfall value that occurred between two specified periods of times?
Which (where and when) is the rainfall value that is less than a specific value AND greater than a specific value?

Typical queries specifying a number of variables can thus be accommodated, and the data is presented in a result frame. Fig. 4 shows the spatial interface.



Location: http://flood.geog.kcl.ac.uk/applet700/applet.html

Choose data file: VINHDEM Oct 28 1997

Change palette: standard palette

○ Deg ● Per

0.000
1.658
3.317
4.976
6.635
8.293
9.952
11.611
13.270
14.928
16.587
18.246
19.905
21.564
23.222
24.881
26.540
28.199
29.857
31.516
33.175
34.834
36.493
38.151

"Data Elevation Model", real size: (534, 300)
current zoom factor: 1.0, current image size (534, 300)
loaded data: VINHDEM Oct 28 1997

X,Y:
color:
value:

Min value : 0.0
Max value : 422.98
Mean value : 35.94

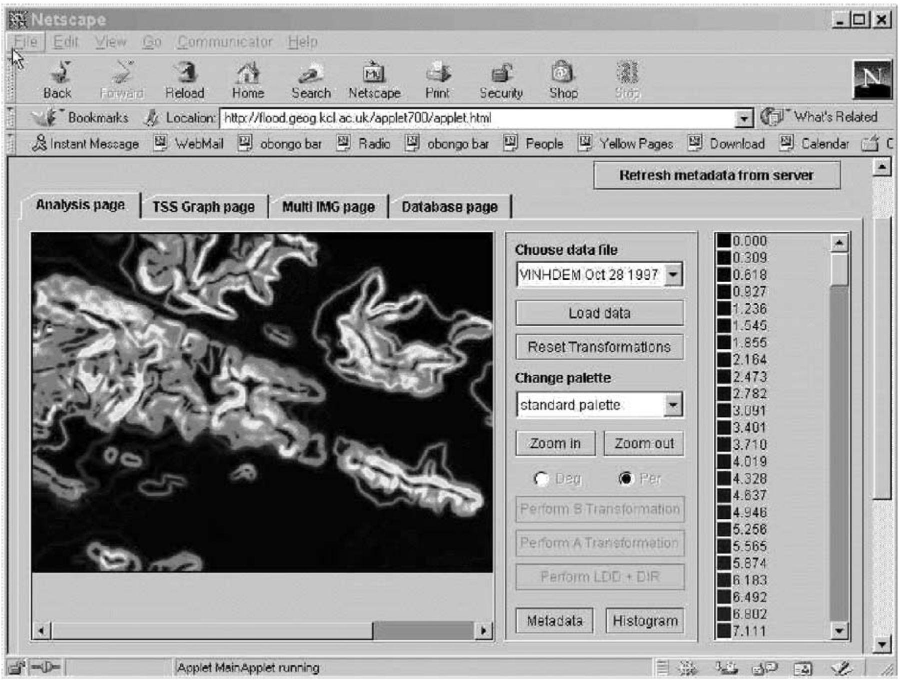
Fig. 4. Database interface.

The user can choose from a variety of possible analysis methods, including terrain analysis such as slope (Fig. 5) and aspect. More complex analyses are also provided, such as accumulated flux, the process of calculating the accumulated amount of water and material that flows over a topological network operating over local drain direction (LDD) maps. Accumulated flux analysis produces a map displaying grid cells indicating the amount of water or materials that traversed the cells on their way to the outlet (Fig. 6). Fig. 7 shows the analysis interface.

7. Conclusion

The availability of GISs via the Web is becoming a reality in many fields (Doyle, Dodge, & Smith, 1998). Therefore, the intriguing question of "Web GIS: Toy vs. Tool?" (Thoen, 1995) has been, in just a few years, answered by the GIS community loud and clear. Many non-GIS specialists are beginning to use Web GIS and many major institutions are moving GIS products and data to the Web.

Real-time data acquisition is increasingly important in many fields, particularly in hydrology. The acquisition of data is becoming more necessary each day, but retrieval of that data can be quite expensive. This paper discusses the development of a real-time Web-based data access system for watershed analysis using cost-effective tools. A Web-based interface surpasses the limitation of a traditional decision



Location: http://flood.geog.kcl.ac.uk/applet700/applet.html

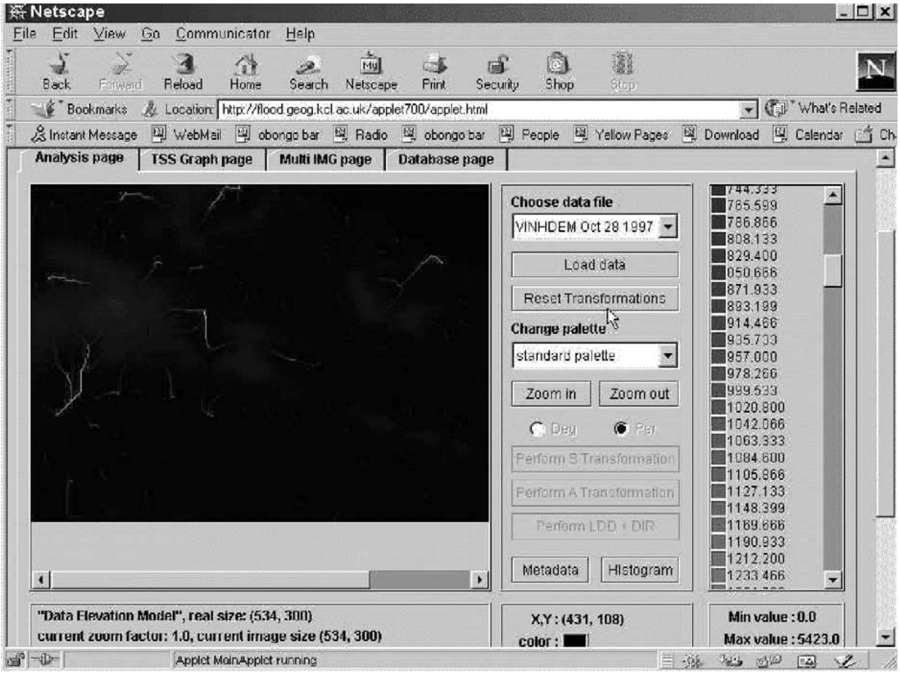
Choose data file: VINHDEM Oct 28 1997

Change palette: standard palette

○ Deg ● Per

Applet MainApplet running

Fig. 5. Slope result of the DEM in Fig. 4.



Location: http://flood.geog.kcl.ac.uk/applet700/applet.html

Choose data file: VINHDEM Oct 28 1997

Change palette: standard palette

"Data Elevation Model", real size: (534, 300)
current zoom factor: 1.0, current image size (534, 300)

X,Y : (431, 108)
color : ■

Min value : 0.0
Max value : 5423.0

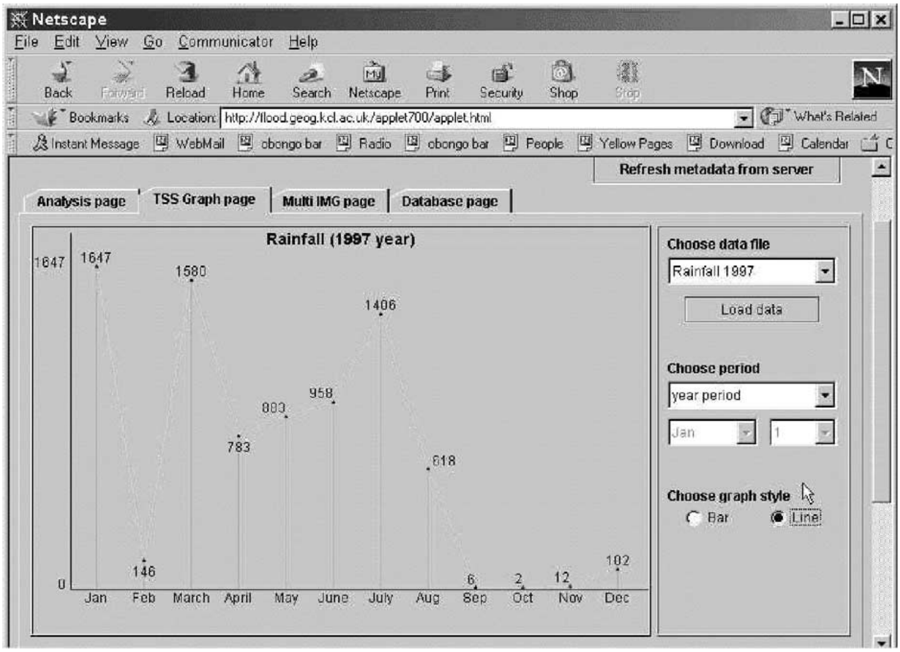
Applet MainApplet running

Fig. 6. Flow accumulation map.

support system that stores data, model, and user interface on a single computer (Bhargava & Tettlebach, 1997). It is a convenient system and can be applied to a wide variety of vital applications necessary for the public good.

One of the advantages of the Web is that it generates information presentation on demand (Kutschera, Schimak, & Humer 1996). With the inclusion of Java for spatial data navigation and temporal data visualisation, a system can achieve flexible user interaction without sacrificing efficiency (Taylor, Ackland, Walker, & Jackson 1997). Another significant advantage of the Web is that access to it is relatively inexpensive and stakeholders can form collaborative contacts. A range of innovative technologies are being developed that offer different ways of modelling over the Internet. Pieplow (1998) has demonstrated that several other geographical information technologies are capable of delivering visual, audio, and multimedia presentations in support of traditional public participation. Doyle et al. (1998) has shown the potential use of Web-based mapping and virtual reality technologies for environmental modelling.

Our project exploits recent networking technology to permit Internet users to obtain delivery of the desired flood-prediction and management data in real-time and provides the tools to analyse these data. Using the Web to develop data access and projected analysis for real-time watershed analysis offers tremendous potential. Not only to the benefit of environmental users, but also for other disciplines who need to locate and analyse data. We believe that a Web-to-hydrological model



Choose data file: Rainfall 1997

Choose period: year period

Choose graph style: ○ Bar ● Line

Fig. 7. System analysis interface (DEM displayed).

interface can play a beneficial role in real-time watershed modelling, as a valuable research and educational medium (Parson, 1999) and as a link bringing stakeholders together for collective decisions.

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