Real-Time Mobile GIS Prototype: Design, Architecture, and Usability Study

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Summary
In the past, mobile communication devices (such as cell phones) have not been utilized in flood forecasting and warning due to limitations in technology that have limited the ability of forecasters to gather and interpret geographical data in near real-time. This paper presents a prototype that integrates a GIS (geographic information system) with a hydrological model. It is a mobile mapping application for J2ME-enabled mobile communication devices that allows those in the flood forecasting, prevention, and related fields to execute programs and run mapping functions from a server using their mobile device. The proposed client-server network application uses mobile devices to connect to a server via the Internet. This study also evaluates the usability of the system using an in-lab tests. The favourable research and experimentation related to the prototype suggests that a location-based service (LBS) may also be implemented effectively on J2ME-enabled phones. Although environmental events such as floods cannot be predicted with certainty, the proposed application, if correctly implemented, may change how professionals identify and respond to flood disasters and thus greatly increase the potential for saving both life and property. Since this work lays a foundation for future mobile mapping applications, suggestions on possible design and implementation of the application are discussed.

Key words:
Real-Time, Mobile GIS

1. Introduction

Although flooding cannot be avoided completely, implementing an effective flood prevention scheme can reduce damages from severe flooding if sufficient, timely, and quality information for flood forecasting is acquired. In the past, systems for collecting information on the extent and effects of floods were not reliable. The systems depended on field information, which was often erroneous and at times could not be collected until the floodwaters had receded (EGIS, Dhaka, June 1998). Data collection methods have improved. Advanced GIS (geographic information system) combined with the use of high-resolution spatial technologies (like GPS [global positioning system] and digital orthophoto quadrangles [DOQ; corrected digital images]), provides a view of the magnitude of environmental changes over time (Skidmore, 2002).

To take advantage of improved data collection, software-modelling packages for hydrology also need improvement. Few are well integrated within spatial modelling environments and few are capable of non-expert implementation. The models require 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.

GIS technology in hydrology can provide solutions to aid both data collection and modelling. GIS supports real-time field mapping and precise positional information, tasks that are normally time-consuming and difficult through traditional methods, and which often are limited to desktop computers and hard-wired network communications. Mobile GIS services can integrate GIS, GPS, and remote sensing capabilities for accessing geospatial data sets via mobile devices, and is more cost-effective than traditional GIS and remote sensing software packages. Mobile GIS services also meet the need for devices that can be used by non-experts who lack advanced remote sensing and GIS skills or training. This study will examine the viability of a mobile GIS application in a hydrological context for increased real-time data accessibility and analysis. The study presents a prototype mobile-based model for flood warning and forecasting.

2. GIS-Based Hydrological Modelling Systems

Currently, four principle areas can be identified that impede GIS-based modelling systems: 1) complexity of use; 2) interfacing; 3) customisation, and 4) platform dependency. 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).

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There are two methods available for coupling GIS and hydrological models: loosely coupled and tightly coupled (Batty & Xie, 1994; Stuart & Stocks, 1993). In a loosely coupled models, a GIS is linked to an external model where operations are performed in languages such as FORTRAN or C. Disadvantages of this approach are that there is no common graphical interface and the data exchange and conversion between the GIS and the hydrological model are cumbersome.

In contrast to loosely coupled models, tightly coupled models are developed entirely within a GIS environment with a macro language such as AML (ESRI Arc Macro Language). This type of programming is often unable to implement complex applications and does not support the same capabilities of procedural programming languages. Tight coupling does not require file conversion or editing (Burrough, 1997), but does require a customised menu-driven user interface for display (Karimi & Houston, 1997).

GIS applications for environmental modelling are currently limited due to incompatibility between the types of models and GIS and the type of data that are associated with them, as discussed by Goodchild et al. (1993) and Burrough (1997). In 2004, Goodall and Maidment showed that storing component simulation tasks and sub-procedures in dynamic link library (DLL) files is an effective way to couple GIS geospatial data and processing routines. This method allows not only for the sharing of data but also for sharing of processing functions as long as they are created generically with universal data types. Another advantage of using DLLs is that files can be accessed through any COM language.

3. Future Needs of Hydrological Systems

Three areas have been identified as being important to the future needs of hydrological systems: real-time data, user interface, and accessibility. Real-time data refers to spatial and non-spatial data that become available to the real-time GIS, either at fixed time intervals or after the completion of certain events. GIS and hydrological models 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 of existing data difficult. Current GIS algorithms do not allow for fast responses within time constraints, therefore they cannot be used for real-time applications.

The second important area, and perhaps the most significant aspect of modelling system implementation, is an appropriate user interface, for it determines the interaction between the computer system and the user (Dodson, 1993). Researchers such as Albercht, Jung, and Mann (1997), Knill (1993), Kingston et al. (2000), and Jiang and Zipf (2004) have stressed having an easy-to-use interface that is adaptive, customizable, easily transportable, and appropriate to the user's skill level.

Consideration should be given to multi-modal, multi-user interfaces with large-screen graphical displays to improve decision-making (Rauschert et al., 2002). The authors also suggest the use of gestures for input in addition to voice.

The third important area to consider is data accessibility in the development of a successful flood forecasting system. Environmental information is usually held in government, academic, and commercial water institutions. Hydrological modelling tends to remain in the domain of the model developer to be applied within a consulting framework. The models are inaccessible to decision-makers who are not specialist modellers (Taylor el al., 1998). Yuan and Cheng (2007), however, present a system that only requires a Web browser for access to the entire system using Google Maps for vital spatial data displayed in high resolution. The system can be used by non-experts and has an interface based on the familiar Google Maps.

4. Proposed Solution

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.

4.1 Project Architecture

The data capture requirement is twofold (Worboys & Duckham, 2006). 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 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 a 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. Figure 1 illustrates the project architecture.

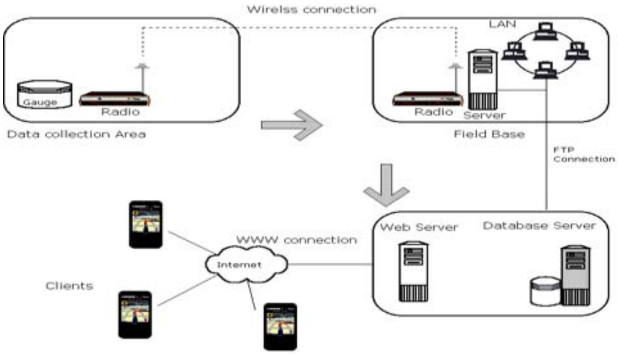

Figure 1. Project Architecture

4.2 System Architecture

As described in Figure 2, the system is divided into the following components:

- hydrological mode—a software program written in Perl
- GIS software—ArcGIS
- PHP scripts on the server side responsible for processing data sent from the mobile handset
- Java Micro Edition (J2ME) at the client side (mobile) with at least CLDC (Connected Limited Device Configuration) 1.1 and MIDB (Mobile Independent Device Profile) 2.0 with optional package location API installed; for functions such as zoom in/out, and database interaction.
- MySQL database
- graphic tool

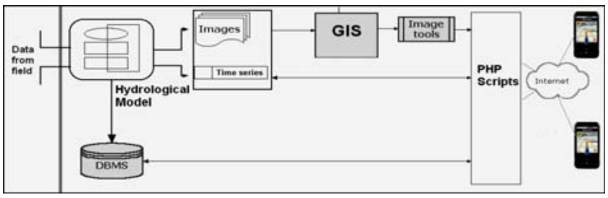

Figure 2. System Architecture

4.3 The Dynamic Model

Dynamic models are difficult to run in most GISs because they have been designed for querying and maintaining a static database with static phenomena. A standard GIS does not explicitly allow dynamic phenomena to be stored and analysed, nor do they provide efficient facilities for iteration through time (Fedra, 2005; Hongmei et al., 2008; 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 this 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, then 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 (Fig. 2).

4.4 The Map Viewer

The Map Viewer is a tool designed for map display. The first page of the model is the map, which incorporates a hybrid map-display system. Aside from displaying the two image formats most commonly supported by browsers (GIF and JPEG), non-standard data files such as large data files held on the server (digital elevation model [DEM], for example) can also be handled by the program. To load a DEM image and results obtained by applying the hydrological functions (e.g., slope, aspect, flow direction, watershed), a rendering algorithm is developed which maps between the DEM elevation data or the function results and a colour palette, then displays the image "on the fly." This J2ME-based 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; zoom-in, zoom-out, and pan are supported.

4.5 Analysis Routines

The objectives of the data analysis program are to allow the user to set queries and retrieve useful information to satisfy the specific requirements of decision-makers. 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; 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 discussing time series analysis and spatial analysis routines.

4.5.1 Time series analysis

The time series tool is a tool that interacts with non-spatial data in the database. To query the time-series database, the user first has to click the "TSS" and "Space" tabs from the main window. A display 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 indicate the highest/lowest/average level of any variable within a period of time, as well as other information.
Alternatively, 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. In addition, the system applet supports a selection mode. The form also offers options that modulate the interval and time step of data presented, enabling transmission of a more suitable representation of the time series from the server for the user's purposes. From the main applet page, the graph option can be selected to visualize 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. Figure 3 shows the rainfall time series graph interface and the result.

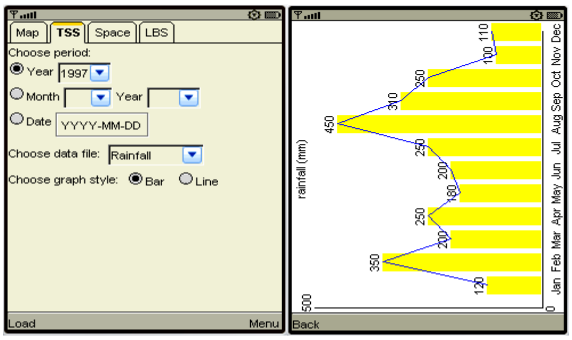

Figure 3. Rainfall Time Series Graph Interface and Result

4.6 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 that occurred between two specified time periods?
- *Which (where and when)* is the rainfall value that is less than 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. Figure 4 illustrates the spatial interface.

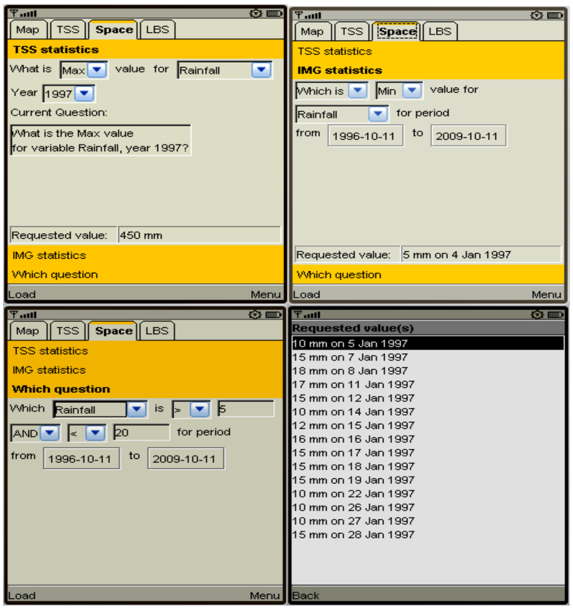

Figure 4. Spatial Interface Showing Rainfall Values using Specific Parameters

The user can choose from a variety of possible analysis methods, including terrain analysis such as slope and aspect (see Figure 5). 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. Figure 5 shows the analysis interface.

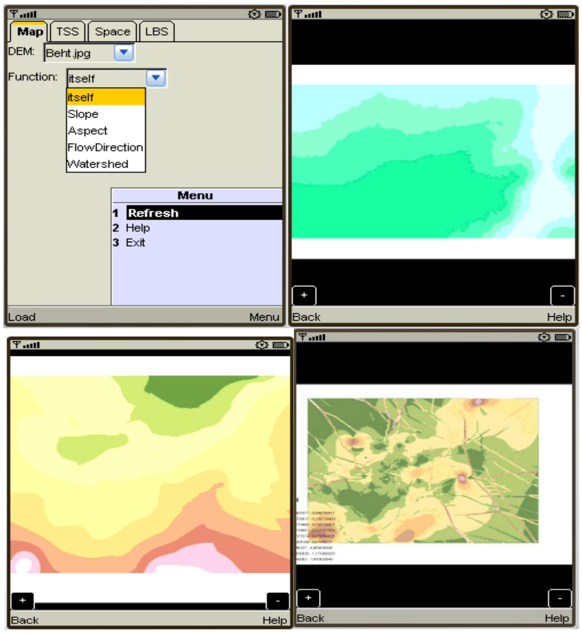

Figure 5. Analysis Interface

4.7 Location-Based Services (LBS)

The last tab in the interface is location-based services (LBS). Location-based services provide users of mobile devices personalized services tailored to their current location. The system assumes that the application relies on a GPS device attached to the user's mobile phone to determine the geographic location of the user. Currently the system only provides the user with their current location. In the next version (which we are currently working on), we will allow the user to retrieve information about a specific point of interest.

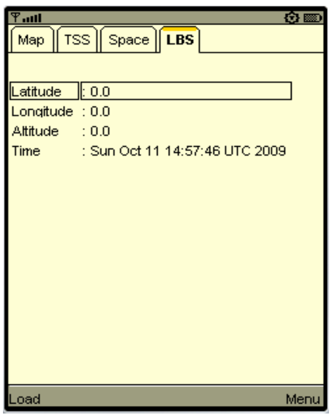

Figure 6. Location-Based Services (LBS) Display

5. Usability Study

The usability study evaluated primary tasks that a user in the field might expect to perform. A test-lab environment was chosen rather than a field study, as the test-lab environment allowed the users to work with a facilitator and to perform the tasks without interruption or distraction. Additionally, this environment allowed the facilitator optimum opportunity to observe the actions of the users as well as allowing use of a video camera to ensure that all information about how users interacted with the system was captured. Field tests will be performed at a future time.

There were 20 participants, 10 female and 10 male. Participants filled out a pre-test questionnaire that identified their knowledge and background with the mobile phones, and which asked about the users' age, experience using the mobile phones, experience with using mobile GIS, experience with the touch screen mobile phones, and their level of internet experience. Each user (participant) was given his or her own mobile phone, they were instructed first by the facilitator, and then the users performed a series of tasks using the device in front of the facilitator, who documented the users' experiences for each step of each of the tasks.

Task One: After completing the questionnaire, the users completed the first test task of using Time series files(TSS) in which he or she selected the year and the rainfall data and then set the type of graph style and pressed the load button on the bottom left corner of the screen. The users completed the task successfully but experienced problems with the radio button system and were also confused by the options names. Our experts suggested a solution to these problems, which was to automatically select the radio button on user clicks and to rename the options to be more understandable.

Task 2: The second test task asked the users to select the Spatial option and then select the TSS Statistics and to select a function (Max, Min, Avg) to find the maximum, minimum or average value for Rainfall/snowfall/etc data for a specific period of time selected by the user. The users completed this task successfully, but again, some were confused with the dropdown list, which shows the type of data (i.e., Rainfall). The solution suggested was to properly modify the text in the dropdown list or add labels to avoid user confusion.

Task Three: Another problem users experienced occurred when they performed Task Three where they were asked to select the Min value to be greater than five for the Rainfall data. In this instance, year was not required. Although this test case was very easy and users completed it successfully, some were confused by the question wording of "Which". The suggested solution for this problem was that there must be proper naming of the fields so that users do not get confused.

Task Four: The fourth test task was for users to select >, AND, < values. Although this test was not much different from tasks one through three, the users did not make any mistakes and completed the task successfully. However, during all of these task tests, users could not find any option to enter data files such as rainfall or snowfall among a set of options. Therefore, this time, the users asked the facilitator this single question. Therefore, we have noticed this, and are working to find a solution to this problem.

Task Five: This was the last test task. Users were asked to select the MAP option with DEM value to be selected and some hydrological functions. Users also performed this test accurately but once again, they could not understand the digital elevation model (DEM). This is the most serious issue raised by the users since this is a very specialized term known to GIS professionals. So surely, we will examine new naming conventions and update them in the system. In addition, we will try to provide a short description to help explain some basic terms and functions. Another issue observed during usability testing was that the functions (slope, aspect, watershed, flow direction, etc.) were difficult to understand since, and, again, these functions are special functions used by hydrologists.

After the users completed the in-lab task tests, they responded to the post-test questionnaire. The objective of this post-test questionnaire was to ask questions about whether they felt the system was useable, whether they would like to use the system again, what they perceived as the most important feature of the system, and what they felt made this system different from a desktop system. When the usability test was completed, results were analyzed and the documentation generated from the test cases were synthesized with responses to the questionnaires in order to understand limitations of the system. Additionally, the suggested improvements were further evaluated as potential corrections for improving the system.

6. Evaluation

The map loading/rendering speed is still slow, depending on the phone Internet connection speed (e.g., when the phone is connected to the Internet through WiFi (wireless fidelity) or UMTS (universal mobile telecommunications system); the map loading/rendering speed is faster than when the phone is connected to the Internet through GPRS/EDGE). This speed of map loading/showing could be improved by an image cache mechanism (both on the server side and client side) so that the client program would not need to reload the existed tile images but get it directly from a local cache on the handset, and the server would not re-render "on the fly" for existing tile images that are already rendered from the original images on the server.

The mobile program did not acknowledge the existed data time ranges on the server according to the selected data type on the client side. When the user selects a time period of the GIS data for querying the server, the program simply sends the request to the server, and the user may get the response "No data for the selected time period" from the server. This could be corrected by analysing the database on the server to return the detailed time range of the GIS data according to data types so that the user would known in advance which GIS data on any time period are available on the server. To utilize the LBS using on the handset, a mobile GIS data input module could be built into the existing program so that the program could collect the data on the go right at the current geographical location of the handset.

7. Conclusion

The increasing need for accurate real-time data collection and analysis in flood management provides a strong foundation for the integration of mobile GISs in hydrology. This integration will be more efficient and economical in providing data for hydrological prediction and management. Research shows both the viability of GIS and the increasing use and development of mobile devices. The additional constraints of a mobile GIS mapping application need to be defined before the best solution can be selected, but enough constraints are already available to conclude that a generic mobile GIS mapping application could be developed and utilized successfully. Several platforms may provide the solution to a practical integration of mobile GISs in the field; of these, a browser-based approach may be most beneficial due to cost-effectiveness, user-friendliness, popularity, and ease in coding.

We developed the system and provided minimal information for the user facility but it took us to another interface design issue that was mentioned frequently by the users. Trying to facilitate minimum information on the interface, resulted in ambiguity in the interface. So now, we are trying to adjust this issue with immediate effect. Similarly, we tried to mention all possible value range to the users to avoid incorrect input but the users demanded for that. So now we shall focus on providing more options to the users. With the exception of these issues, users seemed satisfied with the rest of the interface.

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