Designing a Human-Centred, Mobile Interface to Support Real-time Flood Forecasting and Warning System

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By

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Abstract

There is a demand for human-centred technology which improves the management of flood events. This thesis describes the development, design and evaluation of a mobile GIS-based hydrological model. The application provides hydrological forecasts and issues flood warnings. The thesis reports on the usability and practicality of the application.

The application, a mobile-based hydrological modelling system, permits the integrated handling of real-time rainfall data from a wireless monitoring network. A spatially distributed GIS-based model integrates this incoming data, approximating real-time, to generate data on catchment hydrology and runoff. The data can be accessed from any android-based mobile computer or mobile phone. It may be further analysed online using several GIS and numerical functions.

A human-centred approach to design was taken. Design guidelines for a user-centric application were developed and deployed in the first prototype. There was intensive consultation with potential users. Particular attention was paid to the ease of use of the mobile interface. Users' needs and attitudes were relevant in the achievement of a highly functional but intuitive interface.

The first prototype underwent intensive testing with users. After the initial testing of the first prototype an interactive approach was taken to development. This generated a high-fidelity prototype which was matched to the taxonomy from a user's mental model. Users were interrogated under controlled laboratory conditions as they performed predefined tasks which were selected to generate data across all aspects of the system and to identify weaknesses.

Subsequent to this work there was a major prototype re-design. User test data, identified issues and an improved mental taxonomy closer were used to further refine the application. Of particular note was new functionality which aligned with user expectations and enhanced the applications credibility.

The final evaluation of the system was undertaken with diverse subjects. Overall, the subjects considered the system efficient and effective. Users said the system was easy to learn and integrate into their work. Task completion rates were satisfactory. The final interviews with users confirmed that the application was ready to proceed to the implementation phase.

Dedications

I would like to dedicate this thesis to my parents. They have taught me how to be goal-oriented and patient to achieve what I am aiming for. Their encouragement and inspiration had a great impact on the successful completion of this thesis. Special thanks go to my beloved wife, Fahda, who has been a source of encouragement and has put up with me being 'lost in thought' sometimes for weeks. Thanks also to my two beloved sons, Khalid and Mamdouh who were very patient and supportive. Without their love and help, I would never have been able to complete this work. I also express my gratitude to my brothers, sisters and friends. I am very appreciative of all their great support during all the stages of my PhD.

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Abbreviations

AML	Arc Macro Language
AMSR	Advanced Scanning Microradiometer
API	Application Programming Interface
AVM	Automatic Voice Messaging
CAD	Computer Aided Design
CEAM	Centre for Exposure Assessment Modelling
CPU	Central Processing Unit
CSDMS	Community Surface Dynamic Modelling System
DB	Database
DBMS	Database Management System
DP	Design Principle
DR	Design Requirement
DEM	Digital Elevation Model
DGI	Distributed Geographic Information
DTS	Data Transmission System
EA	Environment Agency
EEA	European Environment Agency
EGIS	Environmental Graphical Information System
EIS	Environmental Information Systems
EPA	Environmental Protection Agency
EPS	Ensemble Prediction System
FTP	File Transfer Protocol
FWD	Floodline Warnings Direct
GIR	Geographical Information Retrieval

GPRS	General Packet Radio Service
GPS	Global Positioning System
GUI	Graphical User Interface
HCD	Human-Centred Design
HCI	Human-Computer Interaction
HEC	Hydrological Engineering Centre
HSP	Hydrological Simulation Programme
HP	Hewlett-Packard
ICT	Information and Communication Technology
IDC	International Data Corporation
IDE	Integrated Development Environment
IR	Information Retrieval
JAR	Java Archive
LBS	Location-Based Service
LDD	Local Drain Direction
MBPS	Megabits per second
MIDAS	Mapping Display and Analysis System
MIDP	Mobile Information Device Profile
MMS	Modular Modelling System
NRCS	Natural Resources Conservation Service
NCGIA	National Center for Geographic Information and Analysis
OS	Operating System
PDA	Personal Digital Assistant
RDBMS	Relational Database Management System
RTS	Regional Telemetry System
SBE	Simple Back End

SDK	Software Development Kit
SDSS	Spatial Decision Support System
SPSS	Statistical Package for the Social Sciences
SWAT	Soil & Water Assessment Tool
UK	United Kingdom
US	United States
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WMS	Watershed Modelling System
WORA	“write once, run anywhere”

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Chapter 1 Introduction

1.1 Overview

The key objective of the present study is to develop a prototype of a fully integrated, real-time, mobile, GIS (geographic information system)-based hydrological system. The design, development and evaluation of this study are motivated by the need to understand the capabilities of this system. After providing an overview of GISs and hydrological modelling, this introductory chapter discusses the subject, goals and methodology of the present research, describes its contributions and outlines the remainder of the thesis.

1.2 Geographic information systems

The last few decades have witnessed increasing interest in GISs and their application to everyday problems. Researchers have developed GIS applications for use in fields as diverse as geography, technology and the environmental sciences. The use of GISs has caused a paradigm shift in how geography is viewed in the age of the Internet and World Wide Web. Since the mid-1990s, internet usage has grown phenomenally. The Web, which began as a service to access interlinked hypertext documents, has grown into the world's largest and most accessible information source. Complex information, including formatted sound, video and spatial information, can be shared, accessed and used through the Web. As laptops, tablets and smartphones have become commonplace, the Internet and Web have permeated the very fabric of our lives. Given these developments, the role of GIS applications has become ever more relevant.

1.2.1 GIS: A historical perspective and modern-day view

Systems for analysing spatial information existed as early as the 19th century. Along with the accelerated development of computers in the 1960s, an increasing number of computer applications was created to fulfil different purposes. The term "geographical information system" was first coined in 1968 by Roger Tomlinson, who also developed the world's first true GIS, the Canada Geographical Information System for the Canada Land Inventory.

Following the development of the first desktop GIS product in 1986, the Mapping Display and Analysis System (MIDAS), GIS systems began to be utilised for business purposes rather than just for research. By the start of the new millennium, Internet usage had become mainstream, and diverse users began exploring GIS applications over the Internet. Today, GIS applications are in widespread use by enterprises, governments and educational and research organisations for a variety of functions.

Over the years, different definitions of GIS have been proposed. Worboys and Duckham (2004) provided the following widely-accepted definition of a GIS:

> A GIS is a computer-based information system that enables capture, modelling, storage, retrieval, sharing, manipulation, analysis and presentation of geographically referenced data.

However, researchers and experts who view GIS from the perspective of computer science propose a different definition. According to the *Dictionary of Information Technology* (Bangia, 2010):

> A GIS is an application or suite of applications for viewing and creating maps. Generally, geographic information systems contain a viewing system (sometimes allowing users to view maps with a Web browser), an environment for creating maps and a server for managing maps and data for real-time on-line viewing.

This definition portrays GIS as an application utilising client–server architecture to deliver geographical maps over the Internet, and supports the assertion that the focus of GIS research has shifted from applications as tools providing spatial analysis to information retrieval (IR). Due to this shift in focus, there exists a dichotomy between the old concept of a desktop GIS and the modern Web-based GIS. The combination of the Web and GIS technology has created a promising and rapidly expanding area of research and applications referred to as “Web-based GISs” (also “Internet GISs” and “On-line GISs”).

According to Savvaidis and Stergioudis (2012), until the early 2000s, GIS systems had two basic characteristics in common:

- they were designed to operate in high-performance desktop computer systems;
- only trained specialists in GIS technology could make use of them.

With the rapid development of hardware and Internet technology, these characteristics gradually disappeared. As a consequence, a GIS is no longer an office-based tool, and cloud and mobile devices have made the technology accessible to users anywhere in the world. Web-based GIS applications can now be used on site just as easily as in the office. Moreover, with cloud computing, downtime is a thing of the past; GISs and data are accessible at all times. Finally, applications are no longer built to be used on one device only. With HTML5/JavaScript, GIS web apps can run on any device (smartphone, phablet or tablet) and across platforms (e.g., iOS, Android and Windows).

1.2.2 Challenges in GIS development

A variety of issues pose challenges in the development of a GIS. In general, these can be divided into four categories: complexity, interfacing, accessibility, and customisation and platform dependency. Each of these are addressed below.

1.2.1.1 Complexity

Complexity is a major issue for GIS applications (Rumi et al., 2013), whose size and complexity have led some to describe them as elitist (Pickles, 1995). Raper and Green (1992) and Butler and Fitzgerald (2006) stated that the “technical complexity of GIS principles and their sophisticated implementation in a computing environment” make GIS implementation and operations quite difficult to understand. Since GIS applications are not generally intuitive, their effective use requires a great familiarity with computer applications. As a consequence, in workplaces where GISs are used, a single user can become the resident specialist and act as a surrogate for other, less experienced, users lacking the technical expertise needed to operate the system or the resources to acquire it (Timmermans, 2003). Surveys conducted by Joậo and Fonseca (1996) and Gemelli et al. (2009) indicated that complexity is a primary factor contributing to failure to adopt GISs as well as their underuse.

1.2.1.2 GIS interfaces

Over time, as GIS software began to cater to a wider array of needs and became more versatile, different user interfaces and models were added to it (Mark & Frank, 1992; Schee & Jense, 1995; Longley, 2005; Katz, 2013). These additions served to increase the complexity of the interface, adding more and more options that might be relevant to only a single user’s work.

In the early stages of development, the GIS industry concentrated its efforts on improving the system’s functionality and its data-handling capability. However, it soon became clear that the continued development of GIS applications and their evolution depended on developing a better user interface (Aoidh et al., 2008).

It is now recognised that the user interface of any computer application is as a crucial factor in its success. The technical and economic importance of this interface is due to the fact that, for many users, the interface *is* the system and their choice of system depends on its ease of use (Oliveira & Medeiros, 1996; Campagna, 2005).

Although several vendors have worked on developing new interfaces, practitioners within modelling have been reluctant to employ a GIS for their work because of the difficulty of developing a viable integration technique to support the modelling effort (Stuart & Stocks, 1993; Kemp, 2003). This finding supports Dodson's view that an appropriate user interface is the most significant aspect of implementation because it determines the interaction between the computer system and the user (Dodson, 1993).

Improvements in the quality of the GIS user interface have become a critical contributing factor motivating people to use GIS as a means of handling spatial data and related decision-making. Frank (1993) and Doyle et al. (2008) agree, stating that the user interface is probably the most important factor in system design as it is usually the only part of the system with which the user has direct contact.

In the United States (US), initiatives have sought to further the development of GIS user interface design. The establishment of the National Center for Geographic Information and Analysis (NCGIA) is one such initiative (Kuhn et al., 1992; Raper, 2003). Albrecht et al. (1997) stated that the final product of a modelling system must include an intuitive graphical user interface (GUI). Montoya and Masser (2005) emphasised the need for user-friendliness, including visualisation and results.

Some researchers focus on the need for development of a user interface that is adaptive within the nature of the user's work, providing different customisable interfaces for each type of user. For example, experts within hydrological modelling and forecasting could be offered a more sophisticated technical interface than that used by casual users. Kingston et al. (2000) also emphasised the value of a self-adaptable interface which is customisable with respect to user proficiency and capabilities.

GIS and simulation models are most often employed within expert and educational endeavours. Therefore, advancements in watershed model integration with GISs have, in fact, resulted from the development of interfaces that facilitate creation of watershed-model input data sets

(DeBarry et al., 1999; Singh & Frevert, 2005). Models such as HEC-1,[1] TR-20,[2] SWMM[3] and others lack an interface design that is easy to comprehend and so require intensive input data development, which is often a laborious and time-consuming task (Singh & Frevert, 2005).

Even programmes such as HEC-HMS, which has an interactive GUI to provide an easily understandable interface for data input and viewing results, are cumbersome when required to execute a series of model applications with alternative sets of parameters (Al-Sabhan, 2004). Interfacing is an integral part of hydrological model development, and increasing convenience and flexibility remains a priority for such systems.

1.2.1.3 Accessibility

Hydrological modelling tends to be the domain of the model developer and so is usually applied within a consulting environment. These models are inaccessible to actual decision-makers, who typically lack specialist modelling experience and technical expertise (Taylor et al., 1998; DeMers, 2002). Government, academics and commercial water institutions are the usual custodians of environmental information. While data are currently made available for public perusal through the Internet by some institutions and governmental agencies, much of this information was and still is published only using proprietary formats or in ways that create barriers of use for various interested parties. Examples include device incompatibilities for users of mobile devices, and older hardware or computers without the required proprietary software, about which information is unavailable.

However, some information providers, such as the United States Environmental Protection Agency (USEPA) and the United States Geological Survey (USGS), have made significant progress toward

[1] US Army Corps of Engineers Flood Hydrograph Package for rainfall-runoff simulations from Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers.

[2] TR-20 is a computer programme for the generation and routing of runoff hydrographs from Natural Resources Conservation Service (NRCS).

[3] Storm Water Management Model for water quantity and quality simulation model developed by the Centre for Exposure Assessment Modelling (CEAM) of the USEPA.

providing unrestricted access to various environmental databases (Faundeen and Johnson, 2001) in the form of real-time data (Stewart, 1999a). Unfortunately, effective use of these data requires specialised software not available to every user. Indeed, the USEPA reports that various user groups have expressed interest in processed information, including the output of environmental models (e.g., flood plain models), and that there is far less interest in accessing “raw data” (Haklay, 2003).

Public participation and involvement are important components in the implementation of a water resources project and in flood management planning (Manuta et al., 2006; Goodspeed, 2008; EEA Report, 2014). Recently, researchers and geographers in particular have begun to consider the practical and societal impacts of using GISs to support public participation (Seiber, 2006). Thus, the growth in demand for public access to environmental information, as well as the need for publicly-accessible environmental information systems (EISs), have long been recognised (Haklay, 2002, 2003).

In addition, the need for GISs to provide a flexible framework for the development of GIS-based Spatial Decision Support Systems (SDSSs)[4] (Clarke, 1990; Manos, 2010) has also been acknowledged. Therefore, GISs are often designed for spatial decision support, although they lack the capacity for collaborative spatial decision-making (Jankowski et al., 1997; Skider and Aryya, 2004). Research into collaborative SDSSs (Harris, 1995; Horita, 2000; Northridge & Freeman, 2011; Rydin et al., 2012) and into the related area of technical aspects of Public Participation GIS (PPGIS) (Kingston et al., 2000; Laurini, 2001; Sieber, 2006; Drummond and French, 2008; Thomas and Sappington, 2009) has been extensively pursued. In the future, a GIS must support SDSSs in collaborative environments (Karimi & Blais, 1997; MacEachren & Brewer 2004; Cai 2005) designed for sharing, executing and comparing model

[4] SDSS is an interactive, computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision-making while solving a semi-structured spatial decision problem.

results, especially with decision-makers and/or stakeholders physically distanced from one another (Carver et al., 1997).

1.2.1.4 Customisability and platform independence

Customisability describes the process by which GIS software is tailored and modified to satisfy corporate, departmental or user requirements (Bundock & Raper, 1991; Longley et al., 2010). Each organisation requires a system that is versatile and customisable so that it can be moulded to meet the requirements unique to its particular structure and to its specific strategic objectives. Customising or embedding a technique focuses on combining GISs and model components, thereby eliminating the need for intermediate transfer software. Customisation requires complex programming and specific data-management approaches to ensure full integration (Martin et al., 2005) and sometimes produces poor results (Raper and Bundock, 1993); this has remained the case in spite of several developments.

Schultz (1993) and Bhatt et al. (2009) discussed the use of GISs' increased intricacy with respect to hydrology, indicating that some necessary hydrological routines are missing from most GISs and that new routines cannot be introduced directly by the user. Furthermore, many hydrological models and GISs do not support multiple platforms. In the past, most systems depended on a specific computer platform or hardware configuration. For example, Watershed Modeling System (WMS)[5] runs on a Windows platform (WMS reference, 2015), while Modular Modelling System (MMS) and PRMS[6] used to operate within the UNIX environment (*MMS Manual*, 1998). Thus, platform dependence is one of the issues that restrict users in data and software sharing.

[5] WMS has graphical interfaces to HEC-1, TR-20, NFF, Rational Method and HSPF from Scientific Software Group (http://www.scisoftware.com/index.html).

[6] Precipitation-Runoff Modelling System. From the USGS.

1.3 Modelling and GIS

Modelling, according to a very simple definition, is the representation and simulation of real-world processes on computer systems, based on actual input. In a model constructed with a GIS, the multi-stage operation of the GIS is utilised to create complex indicators or to recreate the distinct steps of a dynamic process using temporal data (Goodchild, 2005).

The importance of integrating simulation models with GIS technology is well-recognised and -documented (Burrough et al., 1988; Goodchild, 1992; Van Deursen & Kwadijk, 1993; Raper & Livingstone, 1993; Wang, 2005; Daniel et al., 2010). Modelling has proven its usefulness in the context of analysing data gathered from different sources in comprehensive flood management (Correia et al., 1997; Chen, 2004). Strategies for integrating GISs with simulation programmes, a subject of continuous and considerable debate, range from loosely-coupled to fully-integrated systems (Nyerges, 1993; Sui & Maggio, 1999; Wang, 2008).

While GISs provide extensive tools for analysis of spatial data, their capabilities for spatio-temporal modelling, and hence the handling of temporal data, have been cited as limited (Worboys & Duckham, 2004).

In the past, GISs were viewed as poor handlers of time or dynamic variations in a process (Langran, 1993; Roddick et al., 2001). According to Karssenberg and De Jong (2007), the set of functionalities available in proprietary GIS for modelling, planning and decision-making is still quite limited. Many functions, such as statistical, optimisation, simulation and decision analysis, need to be added through specifically designed software add-ins.

GISs do not provide interfaces specially developed for dynamic model construction, and they lack good tools for database management and visualisation of temporal data, such as that pertaining to rain or vegetation-pattern time series (Karssenberg & De Jong, 2007). Adhering to this view, Wesseling et al. (1996a) and Malczewski (2004) stated that

GISs in general, with their standard functionality, do not explicitly allow dynamic processes to be captured and analysed. GISs have traditionally been associated with maps, and the capabilities of contemporary GISs represent map-related ideas of layers, projections and generalisations (Goodchild, 2005).

However, in the last decade, GISs have been used additionally for spatio-temporal modelling. A GIS is a viable environment to represent spatial variation and incorporates the tools required to acquire, process and transform data for modelling (Goodchild, 2005). Further, object-oriented models have paved the way for GISs to move from cartographic representation to a more general modelling environment (Zeiler, 1999) where representing time data and the variations in dynamic processes is possible.

1.3.1 The characteristics of GISs

The important difference between the definition of a GIS and the definitions of other information systems used for cartography—computer-aided design (CAD) systems, remote sensing systems and Database Management Systems (DBMSs)—is the ability of a GIS to manipulate and analyse spatial information. Manipulation and analysis of geographic data can be used to mimic certain aspects of the real world in order to answer questions about what exists now or what existed at some point in the past. Most importantly, it can be used to predict what will happen or has happened in another location or at another point in time. The ability to analyse and then to model what may occur provides an opportunity to consider alternatives, leading to more informed choices and decisions. The types of questions to be answered can be categorised as follows:

Location: What is at…?

The simplest of these question types seeks to discover what exists at a particular location. For example, a user might wish to find place name, latitude, longitude or elevation data.

Condition: Where is it?

This query type requires answers that meet certain conditions or are the intersection of multiple conditions. For example, a user may wish to find the value of an area's rainfall that is greater than a specific value and between two different periods.

Trends: What has changed since…?

This question type seeks to find the differences of an area over a period of time, for example of a county that identifies wetland areas that have decreased in size over the past 10 years. In another example of this type, the spread of HIV was examined through the use of animated mapping techniques, where a series of maps from the same area but for different periods was ordered chronologically. When displayed in sequence as a computer animation, the movement of the HIV virus across the study area was quite evident and provided a more complete conceptual model of this temporal geographic data.

Patterns: What spatial patterns exist?

This type of question ascertains whether or not events exhibit a systematic pattern – some form of regularity or clustering that can be used to estimate the intensity of events over a study region for which data are not available. Such patterns are relevant to the study of disease incidence and spread, commissions of certain types of crimes, distribution of precipitation and many similar subjects.

Modelling: What if…?

This question is posed to determine what happens, for example, if a toxic substance seeps into the local groundwater supply or if the sea level rises as a result of global atmospheric warming. The model may, for example, estimate future sea levels and determine which areas would be flooded.

1.3.2 Utilisation of GIS for hydrological modelling

In the last decade, there has been a concerted effort to couple hydrological modelling with GIS, and so GIS has become a powerful tool for supporting hydrological modelling requirements. A GIS has the capability of capturing, storing, retrieving, analysing and presenting large amounts of data. Because hydrological models generate large amounts of spatial and temporal data, the potential application of GIS functionality to this data type makes integrating the two models an attractive proposition (Bakir & Xingnan, 2008).

1.3.3 Hydrological modelling with GIS – considerations

With respect to adapting GIS technology to capture the essentials of hydrological modelling (e.g., effective flood forecasting or watershed management), it would have to support real-time modelling, model interfacing and model accessibility. The following subsections discuss these three considerations in turn.

1.3.3.1 Real-time modelling

A hydrological model that can provide accurate, timely and comprehensive real-time and long-term hydrologic forecasts is essential in the implementation of integrated water resources management programmes as well as for environmental disaster mitigation efforts for such events as floods and droughts. A key requirement of flood forecasting is near-to-real-time data acquisition and analysis. Any forecasting organisation using a flood-forecasting model needs to be able to rely on sufficient warning time and accuracy within a reasonable degree, taking into consideration the limitations of the real-time data available as well as the resources (World Meteorological Organization (WMO), 2009).

With respect to forecasters' reliance on hydrological modelling to provide reliable and intelligible forecasts of flood flows with a long lead-time, there is a need for up-to-date data of adequate quality (Karimi & Chapman, 1997; Soria et al., 2008). The lack of such data has been identified as an issue in the analysis of most water resource systems. For instance, in some modelling systems used in real-time flood forecasting (NOAA, 1994; Vehviläinen & Huttunen, 2001), delays of one month or more in reporting and verifying data such as precipitation measurements have been observed. Such delays are not acceptable in a flood-forecasting system where successful delivery of a viable forecast is essential (WMO, 2009).

1.3.3.2 Model interfacing

Hydrological models are used primarily in the research stage of environmental projects, providing information for the development of new hydrological designs or the evaluation of existing designs (Todini & Di Bacco, 1995; Haggett, 1998; Soria et al., 2008). Models often supplement on-site monitoring because of the expensive and time-consuming nature of monitoring. Hydrological model users become skilled at overcoming the three big challenges of traditional hydrological modelling (Parson 1999; Seibert & Vis, 2012): compiling the proper input files, running the model to create output files and evaluating the output files.

From a practical standpoint, two of the major criteria that a successful hydrological forecast model should satisfy are an easy-to-use functionality and operability by staff with moderate technical training (WMO, 2009). These considerations are important because the commercial success or popularity of any system is dependent on usability by target users.

1.3.3.3 Model accessibility

The need to improve access to both spatial information (Feeney and Williamson, 2003; Williamson et al., 2003; Masser, 2005) and the analytical tools of watershed management is widely recognised. Williamson et al. (2003) and many other studies reported therein have explained the manifold benefits offered by improved access to spatial data for the public sector, private sector and individual citizens. As per the status quo, the population that would be most affected by the results of watershed management, or indeed by any hydrological forecasting modelling systems, has little or no access to them. This group—which includes rural populations, urban dwellers, watershed residents, environmental experts, business persons and others directly affected by any forecasting system—needs direct access to spatial data used for flood management and needs to be involved in the mitigation measures that are decided upon as a result of the forecasts.

Singh and Woolhiser (2002) and Singh and Frevert (2010) stated, “There is a need for watershed models to interface with economic, social, political, administrative and legal models. Thus, watershed models will become a component of the larger management modelling strategy.”

However, at present, the effective use of GIS technologies for flood monitoring and prediction systems requires specialised computer hardware and software that typically are not available to the groups that are most affected. For example, in some communities, the powerful computer equipment/software/tools required are not available; in others, even a reliable source of power cannot be found due to electrical power outages (WMO, 2009). Consequently, communities currently lacking the ability to access GIS systems do not significantly benefit from access to valuable data collected and maintained by government agencies, universities and private organisations around the world.

1.4 Research problems

Information retrieval (IR) is essentially the practice of storing, recovering and disseminating data through a computerised system (Merriam Webster, 2015). Geographical information retrieval (GIR) is, hence, a subset of IR with an emphasis on “geographically-oriented indexing and retrieval” (Larson, 1996). All sources with geo-referenced information are provided access through GIR. Plewe (1997) introduced Distributed Geographic Information (DGI) in an attempt to boost public access to GIS technology. DGI is used to disseminate geographic information to a large user-base.

Using the mobile system/web with GISs, geographers and hydrologists can provide access to GIS databases and simulation models to people who otherwise would not have access to these technologies but who would find the information useful in their decision-making activities. As mentioned above, in the past high hardware and software costs prohibited individuals from having their own GISs. Access was also limited by steep learning curves surrounding their use. Web- or mobile-based GISs eliminate these barriers.

However, problems persist in web-based GIS technology produced by commercial developers. Price remains an issue, coupled with steep programming knowledge prerequisites, making such GISs unsuitable for inexperienced users. In addition, GIS packages categorised as general purpose may not work for all applications. Purpose-built, customised, web-based GIS and simulation models developed from scratch could serve as alternatives to commercially developed GISs, as they would not only be cheaper but would also provide relevant, tailored solutions.

Flood forecasting remains a challenging area that could benefit from the support of web/mobile-based GIS technology. Currently, efficient management of extensive, multidisciplinary data from diverse and distributed sources remains a potent hurdle in providing real-time prediction systems (Wang & Cheng, 2008). Enhanced data retrieval and improved on-line analysis with mobile and web-based spatio-temporal models can make way for hydrological modelling. Progress in GIS technology over the years has led to significant advances in hydrological models (Malleswara & Umamahesh, 2003).

Greater public access to integrated environmental databases and spatio-temporal models via GIS integration with the Web and mobile technology could improve flood forecasting models, thereby reducing the threat to life and property. The ability of the Web and mobile devices to provide real-time access to information for relevant stakeholders can significantly enhance forecasting power. According to Vehviläinen (1999), reliable hydrological forecasts and watershed modelling on the Internet are available for nearly all possible users. In addition, according to Zhang et al. (2015), quasi-real-time decision-making is obtained by utilising cloud computing technology, for which an intuitive and user-friendly GUI is provided, which largely enhances the user experience while maintaining high cost efficiency.

Several programming languages, including HTML5, Java and JavaScript, are inherently platform-independent, allowing seamless GIS integration with the Web and mobile devices and so permitting user access without platform limitations.

Interaction between the public and spatial decision-makers can be achieved through a Web-based approach. The benefits include more opportunities for public feedback and increased involvement of potential audiences in the decision-making process (Carver et al., 1997).

Government mandates also support the use of GISs on the Web. The US government and others are required to make certain types of information available to everyone (Dai et al., 1997). This principle is encoded in US law, which places all information produced by the federal government, except that impinging on personal privacy or national security, in the public domain (Freedom of Information Act, 1965). Therefore, the Web can be (and is) used to great advantage for the enhancement of participatory democracy in local environmental decision-making (Kingston et al., 2000). As Carver et al. (2001), Simao and Densham (2004), and Allen et al. (2009) argued, the Web and mobile technology “generate a new public sphere supporting interaction, debate, new forms of democracy and ‘cyber cultures’ which feed back to support a renaissance in social and cultural life of cities.”

To summarise, the specific research problems identified above and addressed in the research reported here are as follows:

- A lack of real-time hydrological hazard assessment and warning capabilities.

- Difficulty in linking GIS to environmental simulation models.
- Restricted access to data, tools, and results.
- Difficulty of interacting with hydrological models.
- Modelling requirements related to GIS technology: GISs and simulation systems are complex, difficult to use and expensive computer programmes, thus limiting the number of their users.
- Modelling requirements related to computer and programming knowledge: technical expertise in multiple languages and subsystems is required.
- Difficult customisation of models*:* the customisation required to implement a GIS can run to many times the cost of the hardware and software.
- The lack of a user-friendly interface that would allow non-expert users such as farmers, students etc. to interact with a flood-prediction system.

1.5 Research motivation

This research was conducted to address the issues discussed above and will define problem objectives and develop solution methodologies.

The impact of most natural disasters, particularly floods, can be controlled and minimised by development of a better communication system. Thus, GIS-based flood-forecasting and warning capabilities are necessary elements in a sustainable flood management strategy and can be considered a complement to preventative or defensive measures designed to protect the public and property.

However, for regular users, standard GIS and hydrological models are difficult and expensive to use and are often limited to desktop computers and hard-wired network communication. Moreover, they are often perceived as complicated by users who lack GIS skills and training (Tsou, 2004). Traditional GISs require multiple programming language prerequisites and steep learning curves, as well as complicated modelling knowledge of GIS, rendering them unsuitable for inexperienced users.

Therefore, an affordable and easy-to-use mobile-based forecasting and warning system is needed. However, a warning system that is effective in minimising the devastation caused by flooding must be widely accepted and so requires an intuitive user interface that meets user needs but avoids complicated technology that makes the system unworkable for the inexperienced user.

Creating an intuitive system with an appropriate fit for potential users' mental models requires a clear understanding of who the users will be, as well as of their needs and expectations. A study of those aspects of the issue is the next best step for successfully developing practical and effective user-friendly warning systems.

In recent years, considerable improvement has occurred in GIS technologies, mobile computing, processing power and mobile telecommunications networks, and sensor networks and internet connectivity have increased dramatically. These improvements have made feasible the deployment of a system for the frequent delivery of relevant forecasting and warning information to civilians’ mobile devices. Moreover, delivery of this information has no geographical restrictions and can be offered at a relatively low cost. GIS and its application in flood forecasting and warning is considered an important advancement in minimising the impact of floods.

Furthermore, flood management, which entails the interaction of many natural and human-caused parameters, is becoming an increasingly complex problem due to human intervention in the natural environment, which influences the morphology and hydrological characteristics of the land. The complexity of flood forecasting and warning lies in its dependency on the availability of accurate data and the interaction of numerous spatial, geological, meteorological, hydrological and temporal parameters. Real-time flood-forecasting systems that link weather forecasts, state-of-river catchment, water-levels and river discharges can be used to respond to floods as they occur and to reduce flood impact in terms of lives lost, property destroyed and breakdown in infrastructure.

In these instances, the availability and application of new technology is imperative. The transition to mobile-GIS flood forecasting and monitoring implies the emergence of many opportunities for the development of location-based forecasts and warning services. Most notable are the client–server and distributed system characteristics that have emerged as a consequence of mobile technologies. These provide the capabilities for flexible systems that utilise up-to-date information collected through sensors and through the manual submission of data by mobile users, delivering location-specific predictions and notifications to virtually anyone in the world.

Mobile computing, in its turn, is powered by the Internet, and web technologies have allowed the introduction of distributed GIS-based flood-forecasting and warning systems. Public awareness of flood risk is increasing due to the greater accessibility and availability of detailed flood data on mobile phones, although screen size and processing power set limitations for some users.

Availability of open source development frameworks has produced the potential for the adoption of browser-based applications in such instances. While all of these create opportunities for new developments, the cost factor of mobile communications services may be considered an important barrier to deploying a comprehensive mobile-GIS flood warning and forecasting system, particularly in rural areas where people may be more vulnerable to the effects of flooding.

1.6 Aim and objectives

The aim of this thesis is to use human computer interaction techniques to produce interface guidelines for mobile, real-time flood-forecasting and warning systems and to create and test a prototype that uses these guidelines. This aim was achieved by accomplishing the following specific objectives:

- reviewing the Activity Theory and the potential of its use in HCI;
- applying participatory design in order to understand the users and the complexity of their potential interactions with mobile real-time flood-forecasting and warning systems;
- producing interface guidelines for mobile real-time flood forecasting and warning systems, as well as specific system requirements for different user roles;
- creating a prototype that uses the identified guidelines and requirements;
- testing the prototype twice with real users in order to understand whether the requirements and guidelines have been identified correctly and whether there is a need for interface refinement;
- refining the prototype based on user feedback (iterative design approach);
- reflecting on the methodology and approach used, as well as on the outcomes;
- developing a mobile-based interface that interacts with a GIS-based hydrological model for a real-time flood-forecasting and warning system.

1.7 Methods and goals

The key objective is to develop a fully-integrated, real-time, mobile, GIS-based hydrological model. A range of innovative technologies is investigated and used to develop a prototype that incorporates the most recent technologies. These technologies offer different approaches to performing computer modelling on mobile devices such as smartphones and tablet computers. This mobile-based hydrological model with a backend web-based GIS is intended to provide real-time accessibility and watershed management analysis for improved forecasting.

The prototype must support the integration of multiple geographical data structures into a single conceptual framework capable of dealing with different data models. It must provide a sufficiently low turnover time for field-monitoring data and the real-time integration of this data with the GIS. It must provide rapid postdictive validation of environmental simulation models and enhanced prediction through real-time processing of hydrological fluxes and events. Finally, it must support validation of the concepts and capabilities investigated, in terms of realism and interactivity available to the end user.

More specifically, the prototype should incorporate the following elements:

- Data Transmission System (DTS): for real-time data acquisition by a GIS server from distant data-stations;
- Model Interface: for the integration of a test model for flood hydrology with the DTS and a web-based GIS;
- Web-enabled DBMS: for establishing a hydrological database coupled with data processing facilities;
- mobile application that accesses the Web server and displays data to the mobile user;
- flexible mobile UI to facilitate a seamless experience for the end-user.

1.8 Thesis contributions

The contribution of this project is two-fold: firstly, this work aims to integrate the relevant background, theory and models to develop a framework for a real-time forecasting and warning system through a mobile device. More specifically, the author will investigate and develop an effective spatio-temporal hydrological analysis tool to perform mobile watershed simulation and analysis that can support understanding and decision-making. The proposed results of this research are a usable mobile interface and server-side GIS system coupled with a real-time dynamic hydrological model. The prototype developed is the first GIS to be coupled with real-time dynamic hydrological modelling.

Secondly, and more importantly, this work aims to extend the knowledge of the field of human-computer interactions (HCIs). In particular, the primary contributions this project seeks to make are as follows:

- proposing conceptual tools to be used in designing, developing, evaluating and reflecting on mobile technology for interacting with real-time dynamic hydrological modelling;
- researching and understanding the complexity of user interaction with mobile GIS-based hydrological models for flood prediction and warning systems;
- producing concrete interface guidelines for interactive user interface designs for mobile GIS-based hydrological models. These can then serve as a flood prediction and warning system. They are intended to be concrete enough to be useful for selecting a suitable design;
- creating a prototype that uses the identified guidelines and the requirements on the above-mentioned GIS-based hydrological model;
- evaluating the prototype and the guidelines using testing methodology in order to understand whether the guidelines have been identified correctly and whether there is a need for interface refinement;
- developing and improving understanding of mobile context and mobile usage, important steps in improving the future design of mobile interaction.

Overall, the final evaluated conceptual framework should provide a mobile-based system in general, as well as mobile GIS and hydrological developers. In particular, there should be an understanding of mobile users alongside significant improvement of interaction with mobile devices in the context of environmental modelling.

1.9 Thesis organisation

The remainder of the thesis is organised as follows.

Chapter 2 gives an overview of the development of GIS over the years and a literature review of mobile GISs and their application in flood-forecasting and warning systems.

Chapter 3 describes the evolution and history of mobile technology. The chapter also gives a review of mobile operating systems (OSs) and their programming languages.

Chapter 4 gives an overview of hydrological modelling tools. The chapter presents an overview of the historical events in the development of GISs with a critical review of hydrological modelling and forecasting.

Chapter 5 introduces a detailed description of an application that integrates mobile-based GIS with hydrological modelling. The chapter describes the architecture and implementation of a prototype mobile-based GIS modelling tool for hydrological nowcasting application.

Chapter 6 describes the user-centred design and development of the prototype. A human-centred design (HCD) process means users' needs are taken into consideration in all processes throughout the system lifecycle.

Chapter 7 describes prototype design and development. This chapter includes the design and implementation of the first prototype of the system, which was tested by real users and refined based on the user testing results, following the iterative design approach.

Chapter 8 is the evaluation chapter. In this chapter, the author presents the last part of the HCD approach: the second round of user testing conducted on the final prototype.

Chapter 9 summarises this research, presents the limitations of the proposed system and offers direction for future research in this area.

1.10 Conclusion

The purpose of this thesis is to record the development of an integrated, real-time, mobile, GIS-based hydrological model with a user-friendly interface. It sets out how the hydrological application of GIS technology is an extension of its use in other disciplines, beginning with Tomlinson's 1968 Canada Land Inventory.

Consideration is given to the definitions of GIS that Worboys and Duckham proposed in 2004, as well as the more computer science-oriented definition given by Bangia in 2010. Initially, GIS systems were designed for use by trained specialists using high-performance desktop computers. Innovations in mobile technology and cloud servers helped to spread the technology. This has produced the challenges of complexity, interfacing, accessibility, customisation and platform dependence.

Increased complexity, both of principles and implementation, has resulted in reduced uptake of the software due to training challenges, leading to an emphasis on the human interface of the technology, including graphical interfaces which may be adaptable to the expertise of the user.

Hydrological models still remain the domain of model developers; thus, they are often not accessible to industry decision-makers. Two American government agencies (USEPA & USGS) have developed public access to real-time environmental databases; however, these require specialised software that is not readily available to everyone. Public participation in the implementation of water resource management and flood management planning has become a current issue.

This chapter introduces the research objectives for the thesis. The broad goals are as follows:

1. to design an inexpensive and user-friendly, mobile-based, hydrological GIS-based model;
2. to develop spatio-temporal hydrological analysis tools that subsequently assist online watershed simulations;
3. to thus improve hydrologists' decision-making.

In this work, the thesis investigates current accessibility and usability issues, with a particular focus on HCI for mobile GIS. The chapter introduces a review of innovative technologies and the production of prototypes for evaluation.

Chapter 2 Literature Review

2.1 Introduction

The introduction of mobile GISs and their application in flood forecasting and warning is considered an important advancement in minimising the impact of floods. In recent years, improvements in GIS technologies, mobile computing, processing power and mobile telecommunications networks, and the proliferation of sensor networks and Internet connectivity, have made it feasible to deploy a system for the frequent delivery of useful and relevant forecasting and warning to one's mobile device without any geographical restrictions and relatively inexpensively.

GIS-based flood-forecasting and warning capabilities are necessary elements in a sustainable flood management strategy and can be considered to complement preventative or defence measures for the protection of civilians and property. Flood-forecasting systems deliver forecast data on possible flood events (channel flows, river levels, etc.) across time and locations. Flood warning systems utilise the forecasts to make decisions on disseminating flood warnings to various user groups, such as civilians and flood management staff.

The transition to mobile-GIS flood forecasting and monitoring implies the emergence of many opportunities for the development of location-based forecasts and warnings services. Most notably, the client–server and distributed system characteristics that have emerged as a consequence of mobile technologies, applied to flood forecasting and warning, provide the capabilities for flexible systems that utilise up-to-date data, collected through sensors and manual data submission of mobile users, to deliver location-specific predictions and notifications to virtually anyone in the world.

The aim of this chapter is to provide an overview of the literature related to research conducted in the area of mobile-GISs for flood management. This will focus on the themes specific to the application of mobile-GISs for flood forecasting and warning. Section 2.2 provides a brief overview of the impact of floods worldwide. In section 2.3, flood forecasting and warning challenges are outlined, and a brief explanation of how mobile-GISs can address these challenges is given. Section 2.4 outlines the major modelling difficulties in using GISs and 2.5 addresses some of the benefits these can bring to flood management. Section 2.6 covers the major challenges in flood-forecasting and warning systems. Section 2.7 describes the increasing use of mobile-GISs for flood forecasting and warning, and the main factors contributing to the proliferation of mobile-GIS.

The sections that follow provide an overview of the integration of mobile-GISs in a comprehensive flood management strategy. Section 2.8 offers a description of mobile-GIS characteristics and the mobile-GIS architectural model. Sections 2.9 and 2.10 review specific mobile-GIS related themes with regard to flood forecasting and warning respectively. Section 2.11 discusses some limitations to mobile-GIS technology. Section 2.12 discusses mobile-GIS flood forecasting and warning in a modern flood management strategy, followed by a discussion of mobile-GIS technology in section 2.13 and a general conclusion in 2.14.

2.2 Floods and their impact

Floods can be considered as among the major natural hazards impacting both developed and developing countries. The literature review has provided well-documented information that floods affect a significant portion of the world population. According to the WMO (2009), floods account for 15 per cent of all deaths related to natural disasters. In Europe, between 5 and 10 per cent of the population is now estimated to live or work in floodplains; recent demographic data for Europe provided by the European Environment Agency (EEA) (2003) indicate that the areas with the greatest population growth (such as the Mediterranean coast and River Rhine catchment) are also more prone to floods.

From a human perspective, flood-related loss of life and property damage has continued to rise steadily during recent years (Karmakar et al., 2010). The financial and societal impact of floods in both urban and agricultural areas is potentially devastating to local communities. Floods account for 31 per cent of economic losses resulting from natural hazards (Lawal et al., 2011). According to a recent study (Jongman, Ward & Aerts, 2012), the total potential loss from river flooding in 2010 was estimated at US $46 trillion based on the estimated proportion of the population exposed to river and coastal flooding.

Furthermore, floods are becoming more complex due to human intervention in the natural environment, influencing land morphology and hydrological characteristics. Dramatic changes in land use due to urbanisation and industrialisation create an ever-changing, vulnerable and unstable environment in which flood forecasting and warning become a challenging task, since the parameters dictating flood-forecasting models are in constant flux and can only be monitored through continuous updating of relevant data. In addition, significant reduction of forests in some regions over a relatively short time change land characteristics and pose an unknown flood risk. This is largely because, in many cases, local authorities have not managed to take the necessary precautions and actions, or make the necessary changes to their infrastructure (e.g., drainage systems) and flood management strategy.

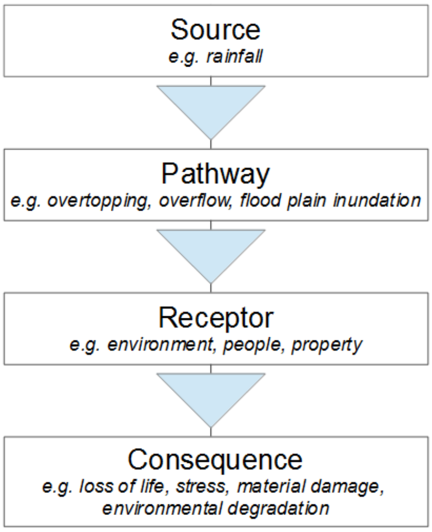

Figure 2.1 Source-Pathway-Receptor-Consequence model (source: Sayers et al., 2002)

Sayers (2002) presents a simple diagram depicting the relationship between the occurrence and consequences of floods (Figure 2.1).

From the above diagram, it is evident that the effort to effectively quantify and systematise the multitude of sources, pathways and receptor types at play during a flood event and parameterise their interaction and interdependencies is a challenging task. All this information needs to be continuously updated and combined to produce flood models that provide reliable flood forecasts and warnings.

2.3 GIS technology

GIS is the critical underlying technology used in mobile-GISs for flood forecasting and warning. Thorat et al. (2012) describe a GIS as a computer-assisted system for the acquisition, storage, analysis and display of geographic data. According to researchers (Thorat et al., 2012), “Geographic” indicates that data items are expressed in terms of geographic coordinates; “Information” implies that the data in the GIS are processed to yield useful analysis; and “System” implies that a GIS is made up of several interdependent components.

Numerous natural phenomena, including floods, can be articulated through the definition of spatial parameters. The relationship of different types of spatial information can be depicted on one digital map through the overlay of layers (streets, buildings, rivers, etc). The information to construct such maps is usually provided through GIS technology.

GIS can be viewed as technology that helps people to understand and visualise data to make decisions based on the best information and analysis. A GIS stores all vital data (maps, land, surface and soil characteristics) and is naturally viewed as a core element of any mobile-GIS flood-forecasting and warning system. GIS systems are built to cover a wide range of applications and are designed to integrate a vast variety of environmental data, allowing them to be used together in a readily accessible way (Al-Sabhan et al., 2003).

GIS technology has enabled the development of more accurate models at shorter times. Kang and Merwade (2011) summarise these improvements in forecasting accuracy by stating that the use of spatially-distributed topographic, soils, land use, land cover and precipitation data in a GIS-ready format provides the framework for the development, verification and eventual acceptance of new hydrological models. These models are capable of taking full advantage of these new data, while acknowledging the uncertainty inherent in them.

GISs have been widely used for determining the spatial distribution of flood risk and vulnerability to flooding and can be integrated as a major component of warning, evacuation and emergency response systems. According to Zipf and Leiner (2004), natural disasters such as floods can be viewed as spatio-temporal events for which only a GIS can fulfil the needs of the disaster recovery authorities (e.g., provision of timely updates and predictions to civilians and authorities of the spatial extent of a disaster). GIS-based systems enable the generation of flood hazard maps which can help the authorities responsible to quickly assess the potential impact of the flood disaster and take appropriate control measures to mitigate predicted flood impacts by delivering flood warnings. The technology provides a broad range of tools for determining areas affected by floods or predicting areas that are likely to be inundated by significant flooding, which can aid the planning authorities and the floodplain managers in detecting and delineating flood-prone areas in a given community. It also facilitates geographical information storage in a database that can be queried and displayed graphically for analysis. Exposures of soil and geology to flood, urban infrastructure and socioeconomic data can be input and stored in a GIS and then analysed to identify areas prone to flood, identify vulnerable populations, forecast flood events and aid in land-use zoning decisions to improve flood mitigation and management (Karmakar et al., 2010). Flood-prone zones can be detected and alleviation measures or stringent floodplain management practices aimed at through the overlay or intersection methods of various geographical layers (Lawal et al., 2011). Therefore, GIS-based software systems are used to store, input, analyse, manage, integrate and output spatial data that can aid with real-time decision-making and strategic planning for effective risk management and hazard preparedness (Smith, 2001).

Currently, GISs are widely used for historical data management because they allow the storage of geographical as well as textual information (Audisio, Nigrelli & Lollino, 2009). GIS-based systems are built to store and manipulate historical data, which is a major input to forecasting models. Mishra and Bhatnagar (2012) provide an overview of the type of data stored and shared through a GIS-based flood management system. In all cases, a base map and a satellite image of the area under consideration constitute the fundamental data. Typically, information stored in a GIS-based system to support forecasting and warning includes (Mishra & Bhatnagar, 2012):

- a building-level base map providing information on present and projected land use (i.e., information on rail and road networks, landmark buildings, government offices, law and order agencies, schools, colleges, etc.);
- a general geology and soil map displaying potential seepage patterns over the area under consideration;
- an urban census map displaying demographic data across the map;
- a plan of the electricity and water distribution network;
- a digital elevation model displaying the morphology of the area under consideration;
- a plan of the drainage network displaying artificial drainage systems that include attribute data about dimensions, slope and so on.

GIS technology is a major component in flood-forecasting and warning systems, having the capacity to assimilate and present data in a spatial context. The ability to map and display information quickly enables a more effective understanding to take place. Spatial data useful in a flood-forecasting and warning system include maps of monitoring units, Digital Elevation Models (DEMs), isohyets of rainfall, alarm signals and flooded areas (WMO, 2011). For example, digital maps can be created for coverage of rainfall data, most effectively from radar output, but also from point-source rain gauge data (WMO, 2011).

A GIS provides data on the topography (e.g., elevation data) and soil types of the area under study, which are required for accurate flood simulation. In addition, flood-forecasting and warning GIS-based systems utilise land-use data (e.g., urban, crops, forest, grass, marsh, shrubs). However, high-resolution elevation data are costly and commonly unavailable; hence, only publicly available data sources (e.g., USGS, DEMs and contour maps) are typically relied on (Chen et al., 2009).

A GIS supports real-time field-mapping and precise positional information, tasks that are time-consuming and difficult using traditional methods and which were often limited to desktop computers and hard-wired network communications (Tsou, 2004).

2.4 Classical hydrological modelling difficulties

Hydrological modelling is one of the major challenges in using a GIS. It requires knowledge of several specific tools such as GISs, computer programming and mathematical modelling, as well as hydrology expertise. The hydrologist's personal perception of a given hydrological system can itself strongly influence the level of conceptualisation and the complexity of the model structure (Wagner et al., 2001).

A hydrological model is a mathematical representation of a basin. The main objective of the modelling process is to understand how precipitation falls into the basin and flows through it. What are the effects of the flows (runoff) on the area? How do they affect the main canals and which areas of the modulated territory can be flooded (Kraijenhoff van de Leur, 1973)?

In order to create a hydrological model, it is necessary to deal with a large component of GIS processing and data manipulation (Karamouz et al., 2012). The elements of the model are mainly grid representation of the geographical properties of the basin, such as a terrain description using a DEM; maps of soil classification that characterise the topological properties of the soil; hydro-meteorological data such as rainfall data (gauges); or radar or satellite images and discharge data (level observations and discharge curve).

It is important to note that all these data have different sources, formats, resolution, codification and errors. That is why all the information needs to be processed from raw data to depurated data, in order to provide the hydrological model with information that it can process. This is the key step in a successful modelling exercise because all the following steps depend on it. It can take a long time to process data and several unexpected problems can occur (Larson & Peck, 1974).

The initial step is the delimitation of the basin to define the catchment area (Lambert, 2006) so the model can take the exact rainfall input. Sometimes problems in the DEM can lead to erroneous basin delimitations so it is necessary to perform DEM correction. It is also necessary to implement corrections of the flow direction in the DEM in order to guarantee that the drainage network is coherent (Oki & Sud, 1998).

Typically, all hydrological information contains some noise due to instrumental measurement errors (Gupta et al., 1998). A consistency process is necessary to overcome this problem. The process itself consists of verification of gauges' time series, radar or satellite data where the incoherent or missing values are corrected (Hadjimitsis et al., 2010; Seo et al., 2003).

The main input of the hydrological models is the representation of the precipitation in the basin. For most of the models it is necessary to provide a field that can be constructed with the gauges' stations and can be mixed with satellite and radar data (Rodell et al., 2004; Xie & Arkin, 1997).

In the specification and implementation stage, a deep understanding of the mathematics of the given hydrological model and a technical expertise in multiple programming languages are crucial skills. Models are usually implemented in several different languages and use a diverse variety of libraries and software (CSDMS, 2016). These tools are often complex and difficult to master and require a long learning time before the user is able to use them properly.

The hardware where the software is running has to be powerful enough to meet the requirements to run the models. The RAM has to be big enough to store all the variables of the model and a powerful CPU is needed to run the model in an acceptable time. At this point the user has to define the configurations to guarantee that the model will be able to fulfil its purpose. This is one of the most time-consuming stages but has to be carried out carefully and properly because a small error in the programing code can lead to unwanted behaviour or an erroneous forecast that can be very difficult to track down later on.

Whichever model is chosen, there are always some constants (parameters) used to represent the physical process in the basin. These so-called parameters must be assigned fixed numerical values before the model may be used to predict the runoff; in other words, one needs to estimate these parameters such that the best agreement between modelled and observed runoff can be obtained. The process by which the parameters are selected is called model calibration.

In order to evaluate the performance of the model it is necessary to define a fitness function that estimates numerically how accurate the model is to represent a set of patterns (Sorooshian et al., 2008). To guarantee the universality of the model, a training set and a validation set are usually chosen. The parameters can be chosen manually or with automatic techniques in order to minimise error produced by the model. Any of these methods requires parameter specification, in which we use prior knowledge of the system's behaviour to specify initial estimates and an initial range for the parameters. A manual calibration can then be performed, in which the user carries out a trial-and-error process of parameter adjustment; after each parameter adjustment is made, the simulated and observed outputs are compared to see if the match is improved.

With the help of training and a good deal of experience, it is possible to obtain very good calibration using the manual approach. However, for the inexperienced and untrained person, manual calibration can be a rather frustrating and time-consuming exercise. This is mainly because the logic by which the parameters should be adjusted to improve the match is difficult to determine.

For this reason, it is necessary to use different methods for automatic calibration, such as the Monte Carlo simulation (Robert & Casella, 2013), gradient optimisation (Braak & Prentice, 1988) and genetic algorithms (Wang, 1997) among others. This allows the user to explore a wider range of parameter configuration without knowing the exact dynamics of the fitness function.

It is important to point out that hydrological models can be computationally expensive and can take from minutes to hours to run. If the parameter search is large, it can result in a very long calibration time (days to weeks) depending on the hardware on which the model is running. Most of the users do not have access to servers or clusters of computers to run the models.

After the calibration is completed, it is necessary to test the model with different sets of data that were not used in the calibration process, which enables the accuracy of the model to be estimated.

Hydrological modelling requires a vast knowledge of GISs and data manipulation and processing, a deep understanding of the mathematics and a technical expertise in multiple programming languages, libraries and software. It requires a long learning time for the user to able to use them properly and several unexpected problems can occur. Furthermore, hydrological models can be computational and time-expensive, require specialised hardware and need several tools and methods to calibrate them.

As we can see, implementing a hydrological model requires a skilful user who is able to overcome all the difficulties in the construction of the model, which is something most normal users are unable to do.

2.5 Mobile-GIS for flood management

Prior to the mid-1990s, a GIS was considered a tool for experts, running on expensive machines and requiring many special skills. Reichenbacher (2001) rightly predicted that the success of the Internet and cellular technology would lead to their convergence with GISs. In fact, advancements in information technology, the Internet, GIS-based specialised software, flood models and mobile devices have created the ideal conditions to make mobile-GIS for flood forecasting and warning reliable and widely available. A rapidly increasing number of mobile GIS applications are currently being developed and used by private companies, government agencies and academic research institutes (Tsou, 2004). It is believed that mobile GISs will become a very effective tool to integrate multiple geospatial technologies for researchers, educators and non-expert GIS users.

Mobile-GISs are bringing fundamental changes to the way geographical data is being managed, analysed and collected in mobile environments. A mobile-GIS is characterised by the ability of the mobile device to display spatial data and receive, process and retrieve the GIS requests of mobile user; the most common framework for a mobile-GIS is to be considered as an extension to Web-GIS, where the GIS requests of the mobile user are processed via an Internet web browser (Hussein et al., 2011). On the other hand, Hussein et al. (2011) showed that providing a single definition for mobile-GISs is challenging as there are many disciplines and technologies related to mobile-GISs.

Accounts of Web-GISs in the recent available literature are often linked to mobile-GISs. Mobile devices are considered a means of both consuming and submitting data. In various web-GIS flood management projects, mobile devices play an important role in data collection. For example, Aronica et al. (2009) present a web-GIS employing a global positioning system (GPS) and mobile devices for the collection of accurate territorial data that handles information and transmits it to the server. Holz et al. (2006) clearly identify mobile devices as an integral part of their proposed concept of a web-based flood management information system and conclude that the PC has turned from a ‘‘computation’’ into a ‘‘communication’’ engine as a consequence of hand-held devices and Internet-enabled cell phones representing an environment for working and communicating at “any place” and “any time”.

The development of mobile GIS applications in general, as introduced by Tomko (2003), requires attention concerning: (a) storage and data query in a spatial database; (b) the provision of a mechanism for querying and accessing remotely located data; and (c) the most effective use of technology. Regarding the database, (a) one must use a DBMS that is capable of storing and managing geo-spatial data. Some DBMSs available today, such as Oracle and SQL-Server among others, provide this functionality through an extension for spatial data. To deal with remote access to information (b), a frequently adopted solution is the use of web services that can be dynamically accessed by a network. Finally, with respect to the adopted technologies (c), it is important to choose a tool capable of manipulating and displaying geo-spatial data, both in its graphic and descriptive form, in mobile devices.

Tsou (2004), Zipf and Jöst (2006) and Alsabhan and Love (2011) expand the idea of a mobile-GIS solution by using the terms “Mobile GI Services” and “Mobile GIS Services” to refer to a comprehensive solution that provides a service to the public. According to Tsou (2004), mobile-GISs and mobile Geographic Information Services (mobile GI Services) extend the capability of a traditional GIS to a higher level of portability, usability and flexibility. “Mobile GI Services,” refers to a framework to utilise mobile-GIS devices to access network-based geospatial information services (Tsou & Sun, 2006).

Much of the literature has focused on describing the findings and conclusions of real cases in which a mobile-GIS technology set up for flood forecasting and warning is applied to a specific case and geography, or proposing specific models and architectures (Nyamugama et al., 2007; Chu et al., 2011).

Alsabhan and Love (2011) conclude that the increased need for accurate real-time data collection and analysis in flood management provides a strong foundation for the integration of mobile-GISs in hydrology and that the integration will make data collection for hydrological prediction and management more economical and efficient. Furthermore, they state that a browser-based approach may be most beneficial due to its cost-effectiveness, user-friendliness, popularity and ease of coding.

According to Tsou (2004), there are two major application areas of mobile-GIS: field-based GIS and location-based services (LBSs). A field-based GIS focuses on GIS data collection, data validation and updates in the field, such as adding new point data or changing the attribute tables of an existing GIS dataset. A LBS focuses on business-oriented location management functions, such as navigation, street routing, finding a specific location or tracking a vehicle (Shekhar et al., 2002).

Mobile-GISs with field-based functionality in the context of flood forecasting and warning are aimed at enabling field workers to collect up-to date data and update datasets for the geographical area under consideration. As a result, forecast models are fed with the most accurate data. In some cases, civilians may also act as field workers with the ability to record and submit non-critical data. Thorat et al. (2012) looked into the use of the technology for collecting socio-economic and water resource management, while Bronder and Person (2013) analysed use of mobile-GISs in implementing a land registration system in Africa. In the context of disaster management, Lwin and Murayama (2011) introduced a web-based GIS system to collect field data from personal mobile phones.

On the other hand, LBSs focus on providing the user with information concerning a specific location (e.g., provision of flood data or delivery of warning based on the user's location). In this mode, civilians could receive flood warnings and forecasts in real time according to their actual location. The integration of GPSs in mobile devices has enabled the emergence of research in the area of LBSs. Under mobile-GISs, GIS, GPS and sensor data are combined to provide up-to-date location-based forecasting and warnings. Mobile-GIS systems have the capability to combine GIS, global positioning system and remote sensing abilities to retrieve geospatial data sets at a relatively low cost when compared with traditional GISs and remote sensing software packages (Alsabhan & Love, 2011). Location-specific flood forecasts and warnings can also be provided at a lower cost through the extensive use of open source software in the development of applications, the Internet and the integration of GPS-enabled devices.

Both mobile-GIS modes (field-based and location-based) should be used in a comprehensive flood-forecasting and warning platform, providing agencies with the ability to perform flood forecasting, and members of the public to receive flood risk warnings.

Mobile-GIS technology extends the portability, usability and flexibility of traditional GISs (Billen et al., 2006). Larger displays and the ability to access applications from a variety of devices (e.g., a flood forecast or a warning can be viewed on a mobile phone or tablet browser) have improved both flexibility and usability. Portability is achieved through the broader use of mobile devices ranging from mobile phones to tablets. Mobile-GIS services come with user interfaces adapted to the needs of non-experts, such as civilians receiving forecasts or warnings, which leads to an improved user experience.

As anticipated by earlier publications, mobile-GISs are not limited to flood management applications. In a significant proportion of cases, the research has focused on mobile-GIS case studies in which the technology is applied to different fields in innovative ways (Feng & Liu, 2012; Ismaeel & Jabar, 2013; Ismaeel, 2012; Noguera et al., 2012).

2.6 Flood forecasting and warning challenges

It is evident that flood forecasting is a challenging field since floods are complex phenomena that depend on the interaction of many natural and human-caused parameters. Forecasting and warning are not limited to the processing of meteorological data. Meteorological information regarding rain, snowfall and snow-melt is not sufficient to predict floods. Other factors to be taken into consideration for flood forecasting include previous rainfalls and water-levels of lakes and rivers, terrain morphology and surface run-off. In addition, complexity in forecasting floods is further increased by the interaction of natural and human factors, such as land use, urbanisation, transport and hydraulic infrastructures. The complexity of flood forecasting and warning lies in its dependency on the availability of accurate data on numerous spatial, geological, meteorological, hydrological and time parameters that all interact.

Consequently, the availability of accurate and real-time data is an important factor in determining the quality of forecasting and warnings. Reliable forecasts can only be provided from up-to-date geological and hydrological data that can be stored in a GIS-based application. Real-time flood-forecasting systems that link weather forecasts, state of river catchment, water-levels and river discharges can be used to respond to floods as they occur and to reduce flood impact in terms of lives, property and break-down in infrastructure (Butts et al., 2006).

Timing of flood warnings, especially during a flash flood, is crucial to the effectiveness of a warning system designed to protect the public. The term “flash flood” refers to the phenomenon of a rapid increase of water levels in a drainage network that reaches a crest within minutes to a few hours after the onset of the rain event, leaving extremely short lead-times for warning. Flash flooding is thus a major challenge as inundation occurs over normally dry land from within minutes to a few hours of the causative rainfall and can have devastating impacts on lives and infrastructure (Hong et al., 2012). According to Younis and Thielen (2008), accurate monitoring and prediction of local severe storms that cause flash floods continues to be a major challenge due to the strong interaction of different physical and micro-physical processes across different scales. As presented in later sections, the challenge of disseminating customised flood warnings on time can be met by the implementation of a mobile-GIS forecasting and warning system. Internet technology and the GPS-enabled mobile devices can be used as the basis for the delivery of timely geo-targeted warnings.

Traditionally, flood forecasting has been a discipline that few engage in, and user-friendliness has been a challenge for flood-forecasting and warning systems, as these were designed for use by flood experts and a restricted user base. Mobile-GIS services meet the need for devices that can be used by non-experts who lack advanced remote sensing and GIS skills or training (Tsou, 2004; Alsabhan & Love, 2011). Mobile-GIS applications deliver a user-friendly interface and the widespread use of mobile devices provides opportunities for improving data quality. By becoming accessible to more users, mobile-GIS is providing affordable supplementary data in hydrology and leading to easier interpretation and understanding of flood phenomena and characteristics (Wagtendonk & De Jeu, 2005).

Unlike traditional desktop-bound flood-forecasting systems and models that were available to a limited number of specialists, mobile-GIS applications for flood forecasting and warning allow for information to be disseminated to larger audiences. A comprehensive mobile flood-management system is available at any time and can be potentially used by flood management staff conducting field surveys and capturing data. In addition, workers in the field can provide valuable inputs to the system by submitting readings while outdoors, such as an updated water-level recording or even a flood warning. Moreover, flood management staff can use flood risk information for formulating and executing their flood-management strategy.

2.7 Driving forces behind the proliferation of Mobile-GISs

Mobile computing powered by the Internet and web technologies has paved the way for the introduction of distributed GIS-based flood-forecasting and warning systems. As the result, the availability of detailed flood data on one's mobile phone is raising public awareness of flood risk. According to Lawal et al. (2011), for the very first time the public can now observe similar information regarding their environment as policy-makers. Factors that are contributing to the proliferation of mobile-GISs have been well documented in the available literature.

The move to mobile-GISs has been possible due to improvements in technology achieved in recent decades. Mobile-GIS flood-forecasting and warning applications have become a reality due to the advances in wireless networks and mobile devices. Reliable broadband networks provide the basis for data exchanges between devices and GIS flood-forecasting and warning applications. Screen size and processing power limitations previously identified as barriers to the advancement of mobile-GISs are gradually becoming less of a constraint as mobile devices are becoming more powerful, with larger screens and greater battery life. Most importantly, mobile phones have become an integral part of everyday life, making every mobile phone owner a potential consumer of mobile-GIS flood-forecasting and warning information.

Most importantly, the increase in the use of mobile-GISs can be considered a consequence of bringing together various technologies and systems to deliver a distributed system. Montoya (2003) comments that mobile-GIS is a growing technology that makes use of existing off-the-shelf techniques and equipment, and mainly focuses on the linking of various existing resources and data rather than on the development of new stand-alone devices. Maguire (2001) states that the development of mobile-GIS has been stimulated by the increasing demand for up-to-date geospatial information along with improvements in mobile hardware performance and wireless network bandwidth.

The Internet and web technologies have played an important part in the advancement of mobile-GISs. The impact of mobile-GISs has been addressed by a range of researchers. Niu et al. (2004) comment that the latest advances in mobile-GISs have come most notably with the support of the Internet, providing access to spatial data and delivering web-based GISs. In addition, the availability of web-browsers on mobile phones is making all previously desktop-bound flood-forecasting and warning systems available on the go and to a wide audience. For example, Sunkpho and Ootomakron (2011) present a case of a real-time flood monitoring and warning system available to users, authorities, stakeholders and experts, which can be accessed from a web browser in the office or through mobile devices.

Open source development frameworks used for browser-based applications have reduced the barriers of development in terms of cost and time. Pulsifer et al. (2008) claim that currently, open source software has become increasingly prominent in the Web mapping domain. Today, the most common framework for a mobile-GIS is to be considered as an extension to a Web-GIS, where the GIS requests of the mobile user are processed via an Internet web browser (Hussein et al., 2011). One of the advantages of the web-based GIS is that flood forecasts and warning are potentially accessible by a large proportion of the population. Moreover, the availability of a range of web-mapping applications and freely available geographic data are facilitating the development of web-mapping applications (e.g., Google Maps), such as flood management systems.

As mobile computing and the use of mobile devices (phones, tablets and laptops) becomes commonplace across the world, the lines between mobile and non-mobile applications are becoming blurred. Nowadays, all web-based flood-forecasting and warning systems can be accessed by powerful mobile devices. Popular examples of flood-warning and forecasting services available to the public include the websites of the NOAA National Weather Service in the US, the Bangladesh Water Development Board, the Bureau of Meteorology in Australia and the Environment Agency (EA) in the UK.

All these changes in technology are enabling communities to become more engaged with issues such as flood protection. Tran et al. (2008) observe that advances in computer and GIS technology have increased the accessibility and mobility of GIS tools such that communities can use GISs to manage their local knowledge and community data collections using mobile-GISs and GPS technologies.

To sum up, all these technological improvements have undoubtedly led to the proliferation of mobile-GIS devices, deploying one of the most vital technologies for the future development of disaster management systems (Tsou & Sun, 2006).

2.8 The Mobile-GIS model

Nearly all the available literature posits or studies a mobile-GIS system based on the idea of a client-server GIS framework (Alsabhan & Love, 2011; Nyamugama et al., 2007; Billen et al., 2006; Zipft & Leiner, 2004). In summary, the client side consists of mobile-GIS software, local or global positioning devices and a mobile-GIS receiver. Server-side components include geospatial data in a variety of formats provided by a GIS content and data server. Communication takes place through a wireless communication network.

Billen et al. (2006) identify four elements comprising a mobile-GIS platform: the data server, application server, wireless network and hand-held mobile device. To this concept, one can also add the sensor element (discussed in numerous academic papers), which enables the collection of field data and feeds real-time monitoring, forecasting and warning.

Mobile devices representing the client-side can include mobile phones, PDAs, tablets or laptops. Devices with GPS capabilities enable the application to serve location-specific data to the user. Mobile devices may incorporate a lightweight client-side application or use a web browser to deliver the appropriate user interface for consuming, analysing, visualising (map display), processing or even collecting and submitting data. Most commonly, users will be able to view flood data and warnings using any available web-browser.

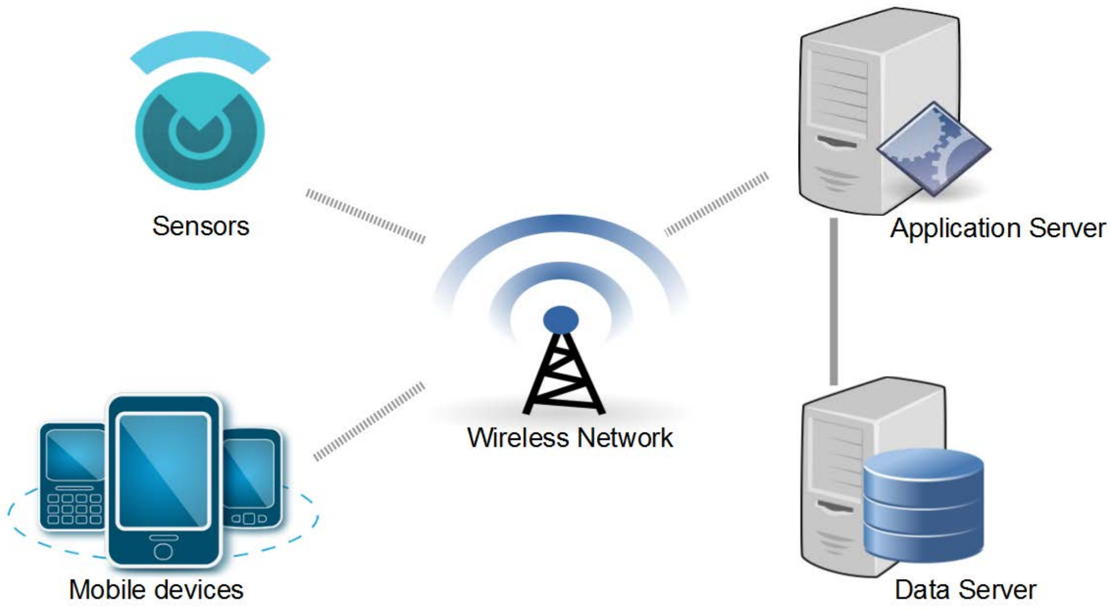

Figure 2.2 A mobile-GIS platform (adapted from Billen et al., 2006)

Sensors are a major element of a comprehensive, accurate and real-time mobile-GIS set-up for distributed flood forecasting and warning. Much research has focused on incorporating sensors for the reliable measurement of rainfall and flow and water levels across a geographical area. In their review, Lawal et al. (2011) conclude that remote sensing, together with GIS applications, is the most efficient and cost-effective technique for curtailing flood disastrous effects. Marin-Perez et al. (2012) demonstrate an autonomous and robust monitoring system for long-term collection of water level data in many sparse locations during flood events. Sensors may also be seen as an element for realising the delivery of location-based flood forecasts and warnings.

Marin-Perez et al. (2012) define a sensor network used in a flood-forecasting and warning system as a network comprising a set of nodes, where each node includes a processor, a wireless radio module and a power supply, and is equipped with sensor hardware to capture environmental data. Mishra and Bathnagar (2012) identify rainfall gauges, water level meters, flow meters and weather stations as the four main types of sensors used in a comprehensive flood-forecasting and warning system. Each node performs the tasks of data gathering, physical parameter processing and wireless data transmission to the application server. In a comprehensive flood-forecasting and warning system based on a wireless network, data capture can be realised through a set of wireless sensors (i.e., measuring water-levels, flows, etc.) that log data and transfer them to a web-based information centre to build a real-time Internet–based flood management system (Sunkpho & Ootomakron, 2011). For example, Smith et al. (2009), present a methodology for providing automated, detailed and location-specific warnings that are computed on-site, using sensors.

Zhang et al., (2002) and Sapphaisal (2007) have recognised that the integrated use of wireless sensors and web-based decision support systems has played an important role in monitoring, controlling, relieving and assessing natural disasters such as flood events.

Sensors can automatically collect, process and transmit environmental data to the application and data servers. Sensors that are connected to a wireless network collect continuous and real-time information used for the release of flood warnings. Actual and real-time monitored data of precipitation level, water level and flow are supplied to the system's server and serve as a major input in deciding to publish a flood warning: such data are essential in order to make a reasonable decision as to the actions necessary to reduce the impacts of flooding.

In examining the degree of accuracy of flood warning, Smith et al. (2009) found that many currently issued warnings can be assessed as inaccurate, and suggest that data provided by a sensor grid can improve the accuracy of flood warning by delivering location-specific, real-time data.

In the mobile-GIS model, sensors extend to remote sensing systems. Remote sensing satellites now provide a continuous stream of data. They are capable of rapid and effective detection of hazards, such as changes in water levels. As an example, floods are monitored worldwide from the Dartmouth flood observatory, which provides public access to major flood information, satellite images and estimated discharge. Currently, orbital remote sensing (Advanced Scanning Microradiometer, AMSR-E and QuickScat) is used to detect and map major floods worldwide (United Nations Environment Program, 2012).

Between clients and server, there are various types of communication networks to facilitate the exchanges of geodata and services (Tsou & Sun, 2006). Wireless communication in the mobile-GIS architecture is supported by high-speed mobile networks (3G or 4G) and WIFI networks. The use of the Internet under a mobile-GIS model enables data access to potentially all Internet users across the world.

The data server stores data used or submitted (i.e., GIS data or data gathered in the field) and serves data requested by the application users. GIS data servers may be stand-alone GIS workstations or web-based servers providing geospatial data or map services to mobile-GIS receivers (Tsou & Sun, 2006). A single GIS data server can also provide data and services to multiple mobile-GIS receivers simultaneously. The data server may extend beyond GIS data to include environmental data (Zipf & Leiner, 2004).

The application server serves the data requests of the users using the application through their Internet-enabled mobile devices; in addition, it may deliver the functionality of generating digital maps by reading the data stored in the data server. Moreover, the application server entails the forecast models and the algorithms used to generate location-specific forecasts and warnings. A management and communication system could also be part of the application server. The management system supports decision-making, information analysis and report-generation. The communication module is responsible for enabling the sharing of data, forecasts and warnings.

Sunkpho and Ootamakorn (2011) provide an example of the building blocks comprising the application and data server sides (Figure 2.3) of a mobile flood-forecasting and warning system. According to the researchers, the modules include real-time data reporting from sensors, forecasting, statistical and historical information and warnings. The real-time reporting module collects the data from the database, which interfaces with the GPRS Gateway server, and displays it to users. The latest data from sensors are collected through a set of Application Programming Interfaces (APIs) and stored in the database.

The forecasting module delivers forecasts using available data stored in the relational database. It may allow the key users to set the spatial parameters (such as the required location and the time frame) of the forecast to be generated. In conjunction with the warning module, the application can alert flood management staff or civilians if specific thresholds are reached.

The historical data module uses information stored in the database to deliver graphs and tables depicting GIS data (e.g., water-level data). The warning module uses the data output from the forecasting module and dispatches warnings based on specific criteria. It can also provide the user with an interface to allow the set-up of warning thresholds and methods of dispatch per user or user group.

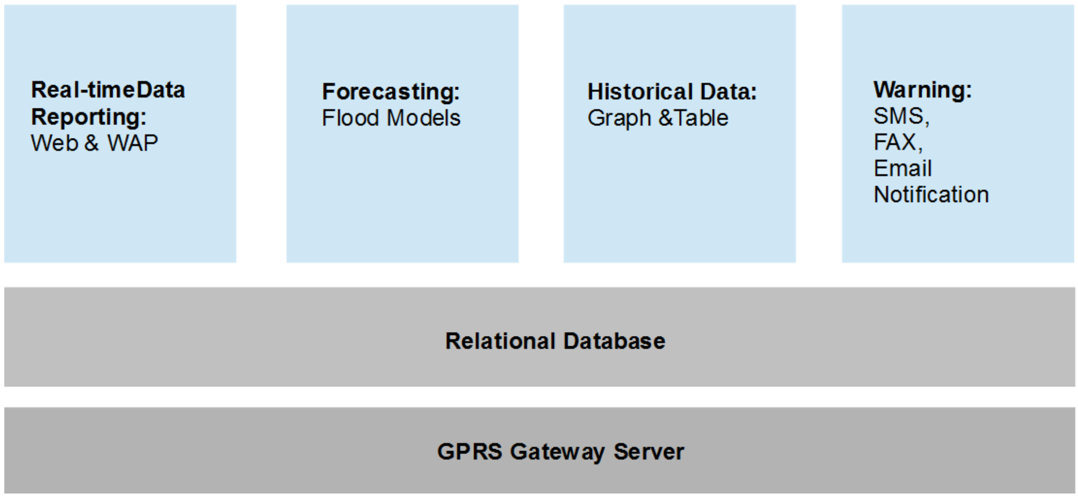

Figure 2.3 System architecture of the database and application server (adapted from Sunkpho & Ootamakorn, 2011)

Zipf and Leiner (2004) identify that a mobile-GIS disaster management system based on a distributed and component-based architecture should satisfy the prerequisites of maximum robustness and high scalability; decentralised architecture and open standards; handling of geo-data on mobile client; integration of external data and simulation models; and support of heterogeneous terminals. In the client–server environment, all the above prerequisites are met. Separate application and data servers, distributed devices consuming, analysing and collecting data, and the use of open source internet technologies satisfy the prerequisites of robustness, scalability and open standards. The prerequisites of geo-data handling on heterogeneous mobile devices and the generation of simulation models based on external data are also met. In a generic mobile-GIS platform, mobile devices with client applications or Internet browsers are able to view, manage and retrieve data, request forecasts from the application server or collect data.

Lwin et al. (2014) combine the use of a smartphone and a web-based GIS in a system that gathers, integrates, analyses and visualises the collected spatial data in real time. These researchers point out that integration of web GISs, wireless networks and web services allows users of mobile GISs to gather huge amounts of geospatial information in the form of a base map. These researchers' findings are similar to those of Alsabhan and Love (2011), showing that the addition of mobile GISs significantly reduces both time for data-processing and cost. The addition of location-based services improves the accuracy of field data gathering and makes it easier to determine field locations.

Chu et al. (2011) developed a tour-guiding system for a mobile GIS in the Yehliu GeoPark. The system offers contents that change with the location of the moving tourist spatially and temporally. The system is implemented by integrating GPS and GIS techniques using hand-held mobile devices. The aim is to improve guide services in an outdoor environment. The advantages, as indicated by many researchers mentioned above, are its low cost and the fact that extra guiding facilities are not needed. Moreover, detailed information about scenic spots can be helpful to educate visitors and protect the valuable and rare geological landscape of the Yehliu GeoPark.

2.9 Flood forecasting and mobile-GISs

As implied above, forecasting requires a range of geospatial data that are stored within the GIS database; GIS applications running flood forecast models use GIS data to generate location-specific forecasts. Flood forecasting provides information of expected channel flows or river levels at various moments across a given period and at given locations. Therefore, a mobile-GIS application is the best way to depict changing flood risk areas across time relevant to the users' location and provide authorities assigned with issuing flood warnings with the flexibility they need. The value or benefit of a flood forecast depends on its accuracy and timeliness (Butts et al., 2006).

Arduino et al. (2005) state that flood forecasting has evolved from a purely hydraulic and hydrological discipline into a cross-cutting multidisciplinary research field ranging from meteorology, via statistics, hydraulics and hydrology, all the way to communications science.

Flood forecasting is complicated due to the nonlinear, time-dependent and spatially variable nature of the rainfall and runoff mechanism. Luckily, advances in information technology and the availability of abundant computational power are enabling the emergence of ever-improving models for flood forecasting and warning.

The literature review has revealed a range of flood models used within flood management applications to provide insights into different types of flood scenarios (Cheng et al., 2006; Smith et al., 2009; Chen et al., 2009; Adamowski & Chan, 2011; Paiva et al., 2011). Flood models usually involve approximate descriptions of the rainfall-runoff transformation processes, based on empirical, theoretical or combined descriptions of the physical processes involved (Dawod & Koshak, 2011).

Lecca et al. (2011) portray flood forecasting as a sequence of dependent models, starting from meteorological simulations that deliver precipitation forecasts; hydrological models that use precipitation forecasts as an input to determine discharge from the area under consideration; and, finally, hydraulic models that utilise hydrographs and field data to generate flood forecasts and scenarios (Figure 2.4).

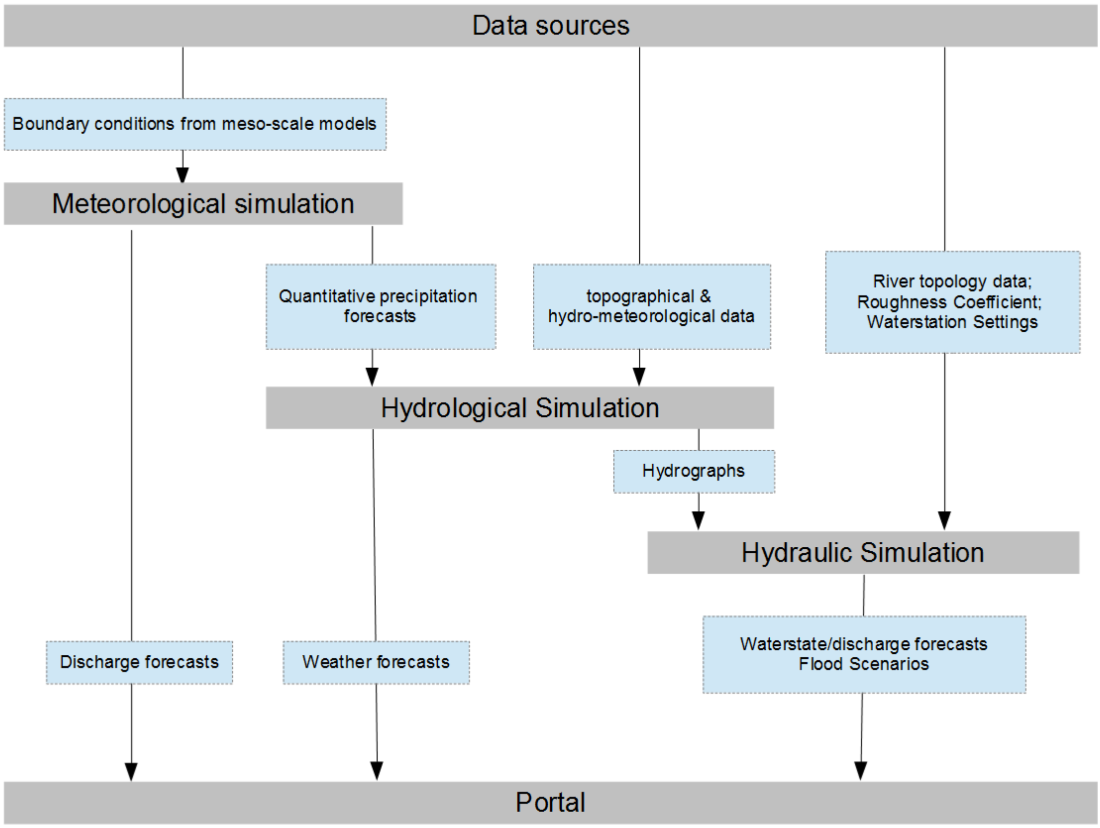

Figure 2.4 Workflow of the cascade of simulations for flood forecasting (source: Lecca et al., 2011)

Typically, the results of the simulations depicted in Figure 2.4 are subsequently imported into GIS software for analysis to be integrated into maps for impact assessment and to display data in maps.

2.10 Flood warning and mobile-GISs

Flood warnings are directly dependent on flood forecasts; flood forecasts have no value by themselves unless they reach the affected population. Flood warnings involve the activity of reading flood forecasts and making decisions on issuing flood warnings to the public, or retracting or changing previous warnings. These warnings are usually delivered by the flood-management authorities in charge of the administration of the distributed flood-management system. The accuracy of flood warnings will depend on the quality of the field data available and flood models.

The WMO (2011) outlines the following as the main objectives of flood warnings:

- to bring operational teams and emergency personnel to a state of readiness;
- to warn the public of the timing and location of the event;
- to warn as to the likely impacts on, for example, roads, dwellings and flood defence structures;
- to give individuals and organisations time to take preparatory action;
- in extreme cases, to give warning to prepare for evacuation and emergency procedures.

Also, the WMO (2011) provides the following list of the information that a flood warning should contain

- the location of the flood;
- the timing of the flood;
- the size and impact of the flood;
- the duration of the flood.

Flood warnings are an essential part of a strategy aimed at protecting populations from flood hazards. The purpose of a flood warning is to provide advice on impending or occurring floods so people can take action to minimise their negative impacts (Australian Government, Attorney General's Department, 2009). The vast majority of researched and quantified benefits of flood warnings arise from reducing the scale of flood damages to property (Parker et al., 2005). In most cases, flood warnings will result in individuals taking action on their own behalf and others doing so as part of agency responsibilities.

Information and communication technology (ICT) is a key element in early warning. ICT plays an important role in disaster communication, and the dissemination of information to organisations in charge of responding to warnings and to the public during and after a disaster (Tubtiang, 2005). As mobile devices are owned by a significant proportion of the population in both developed and developing countries and are an integral part of the everyday life experience, they form the ideal method for the effective and timely dissemination of flood warnings. Using a mobile device infrastructure as a flood warning network to alert people of the risk of flood is a good means of real-time information dissemination and an effective approach to help people evacuate from a flood area (Keoduangsine & Goodwin, 2012). All this means mobile-GIS offers great potential, as it can work on smart-phones and tablets and allow flood warnings to be disseminated instantly to a large population.

Mobile-GISs have the capability to deliver both flood and flash flood warnings. Flood warnings are usually delivered using mid-term forecasts, while flash flood warnings rely on real-time information as they are relatively short-duration, unpredictable natural phenomena that carry high risk. As weather changes can be abrupt and unpredictable, flood warnings will continue to play an important role in protecting civilians from the hazards of floods and flash floods.

Mobile-GISs for flood warnings can accommodate the spatial variability of both the flood and civilians. As a flash flood advances, it may affect new areas. Similarly, civilians may move in or out of a flood area.

GIS warning systems rely heavily on the use of sensors. Tsou and Sun (2006) observed that mobile-GISs can be used to create various early warning systems by combining wireless remote sensors with GPS and mobile devices. Sensor integration can play a vital role in generating early warning systems, monitoring the extent of disaster and predicting the near future forecast scenario (Mishra & Bhatnagar, 2012). With sensor networks, environmental data can be observed and collected in real time and used for forecasting upcoming phenomena and sending prompt warnings if required (Marin-Perez et al., 2012).

Thielen et al. (2009) found that (unlike temperature forecasts, which have a high degree of accuracy spanning 5-6 days) precipitation levels, which are a major input in flood forecasting models, cannot be accurately forecast more than 2–3 days in advance. This can result in false flood alarms. However, this lead-time for skilled precipitation forecasting can be extended by exploring ensemble prediction systems (EPS) (e.g., Tracton & Kalnay, 1993; Molteni et al., 1996). Applying these systems during the floods in 2005 and 2006 proved that it was possible to forecast the floods well in advance and report them with lead-times longer than 2 days.

Therefore, Theilen et al. (2009) report that after their partners incorporated the forecast into regular procedures it was concluded that false alarms from the system were less critical to users than missed events. Consequently, they agreed that alarms would be activated for lower flood probabilities, which could result in more frequent alarms, even if higher false alarm rates were also to be expected. Since the events can be monitored online through the interface, whether or not the event is confirmed as the forecast date approaches can be directly checked, and a false alarm can be less harmful for flood preparedness. For this reason, increased flood warnings can be used as a counter measure to lack of accuracy in relying on precipitation levels.

The crucial element in effective disaster notification management, also applicable in the case of flood warnings, is the on-time delivery of the warning. Warning lead-time is the time between the issuing of a message containing a prediction and the time when the predicted height is reached (or when the stream peaks below that height). The value of flood prediction is determined by both the accuracy of the prediction itself (where optimal performance represents the predicted level actually being reached at the expected time) and the warning lead-time (Australian Government, Attorney General's Department, 2009).

A reliable warning system can be created by developing a mobile-GIS integrated to a hydrological model capable of handling all the GIS hydrometeorological information and producing a coherent estimation that can be delivered as a real-time flood warning. The accuracy of the prediction is undoubtedly important; however, ensuring accuracy is not among the aims of the present research and it is beyond the scope of this research. Rather, testing and ensuring accuracy can be dealt with at a later stage of the investigation, in future work, because providing a warning lead-time will reduce the uncertainty of the behaviour of the basin and can therefore be used as an early warning diffusion tool (Sene, 2012). This will consequently increase awareness of flooding hazards, providing the necessary lead-time for communities to respond if a flood and flash flood event occurs.

2.11 Mobile-GIS limitations

The literature review has indicated various limitations on the use of mobile-GIS as applicable to flood forecasting and warning. In many cases, the degree to which the documented limitations applies depends on the mobile device under consideration. Limitations are more apparent in highly mobile devices, such as smartphones, and non-existent on portable devices with low mobility, such as laptops. The need for portability is likely to keep display sizes small, so constraints with navigating around images, showing large amounts of information and so on will remain issues (Drummond et al., 2006).

Processing performance, memory, display area and storage capacity are considered to be the main limitations (Qiang et al., 2012; Tsou, 2004). Pooroazizi et al. (2008) identify the same limiting factors but also identify the range of available mobile platforms as a factor limiting the widespread use of mobile-GIS applications. Shi et al. (2009) identify the existing large databases and limited wireless communication bandwidth as the main factors negatively affecting the achievement of the objectives of fast response times and accurate information delivery within mobile-GISs. The limitations provide strong motivation for research into technologies to improve both response time and the provision of the desired accurate information concerning spatial, temporal and attribute domains (Shi et al., 2009). Hussein et al. (2011) attempted to overcome the relatively small storage and processing capabilities of highly mobile devices by implementing an application that requests all data and processing from the central server. The limitations of mobile hand-held devices also include the network data transfer speeds and bandwidth (Drummond et al., 2006). In this area, the available literature proposes various technical and architectural models to minimise processing time and maximise reliability (Elariss & Khaddaj, 2013; Chi et al., 2009).

The cost of mobile communications services may be considered as an important barrier to deploying a comprehensive mobile-GIS flood-warning and forecasting system (Drummond et al., 2006), especially in rural areas in which incomes may be lower. In addition, a mobile-GIS for flood forecasting is dependent on the service levels provided by the mobile carrier (Nyamugama, 2007), which is prone to service interruptions.

Steiniger and Hunter (2013) provide an insight into the functional limitations of mobile-GIS software in comparison with other types of GIS. The table below provides an overview of the features available in mobile-GISs in comparison with other GIS software.

Table 2.1 Typical tasks accomplished using different GIS software (source: Steiniger & Hunter, 2013)

GIS task vs. GIS Software	Query	Select	Storage	Exploration	Create maps	Editing	Analysis	Transformation	Creation	Coflation
Desktop GIS										
- Viewer	●	●	●	○						
- Editor	●	●	●	●	●			○	●	
- Analyst / pro	●	●	●	●	●	●	●	●	●	●
Remote sensing software		●	●	○	●		●			
Explorative data analysis tools	●	●	●	●	○	●	●			
Spatial DBMS	●	●					○	●		
Web Map Server	●		●	●		○			○	
Server GIS / WPS Server	●	●	●		●		●	●		●
Web GIS Client										
- Thin client	●			●						
- Thick client	●	●	●	●	●	●				
Mobile GIS	●	●	●			●			●	
GIS Library			●		●		●	●		●

● Standard Functionality ○ Optional Functionality

Apart from the technical limitations, the literature has revealed some practical limitations and barriers to the use of mobile-GISs. The difficulties with moving to a mobile-GIS flood-management system could include the learning curve required, the resistance to change (especially for field workers), harsh weather environments and the inability to easily use mobile devices under direct sunlight (Thorat et al., 2012). The WMO (2013) also identifies large numbers of people unable to access the Internet, especially in communities in remote areas or developing countries, who may not be able to receive warnings. Keoduangsine and Goodwin (2012) refer to the "digital divide" between countries, identifying the lack of technology, infrastructure and expert knowledge as major impediments.

2.12 Mobile-GIS flood forecasting and warning in a modern flood-management strategy

Having a comprehensive mobile flood-forecasting and warning system can deliver a range of significant social and economic benefits; however, it is not enough to focus on tangible flood protection infrastructure: the whole system needs to be considered.

Butts et al. (2006) state that a flood prediction decision support system encompasses the processes of flood monitoring, flood forecasting, flood warning and real-time decision-making. At the same time, flood forecasts and warnings need to reach large audiences in a cost-efficient and timely manner.

Parker, Tunstall and Wilson (2005) identify three elements at play in reducing the adverse impact of floods: the nature of the flood event; the development and effectiveness of the flood forecasting, warning and response systems; and the characteristics of the flood-affected population and their response. Under this perspective, a mobile-GIS system can be implemented to provide a reliable forecasting and warning platform.

GIS and mobile-GIS flood-forecasting and warning systems should be considered as vital elements in a flood management strategy, because GIS-based solutions for forecasting and warning are detailed and comprehensive decision-making tools that can contribute to reducing the loss of life and the economic impact caused by floods.

Local authorities responsible for flood management cannot ignore mobile-GISs. Mobile-GIS technology is considered as one of the most promising for the future development of disaster management systems because it improves the capability of traditional GIS technology in terms of portability, usability and flexibility. Alsabhan and Love (2011) claim that GIS technology in hydrology offers solutions to aid data collection as well as modelling by helping to provide real-time field mapping and accurate positional information, tasks that are notoriously inefficient and time-consuming when using traditional methods. Mobile-GIS services can integrate GPS, GISs and remote sensing capabilities for accessing geospatial data sets via mobile devices and are more cost-effective than traditional GISs and remote sensing software packages. Moreover, mobile-GISs can promote the creation of environmental collaborative monitoring networks by enabling citizen participation and utilising data collected by volunteers.

Flood management professionals should also focus on the provision of quality data. Reducing the impact of flooding requires the availability of sufficient and on-time quality data for the delivery of reliable flood forecasts. The WMO (2011) identifies the basic elements of a real-time flood forecasting as:

- the provision of specific forecasts relating to rainfall, detailing both quantity and timing, for which numerical weather-prediction models are necessary;
- the establishment of a network of manual or automatic hydrometric stations, linked to a central control via some form of telemetry;
- the flood-forecasting model software being linked to the observing network and operating in real time.

Current technology allows for the deployment of distributed flood-forecasting and warning systems. Advances in mobile computing and mobile devices, coupled with the increased availability of computational power and reliable broadband wireless connections, provide the ideal ground for deploying a distributed mobile-GIS flood-forecasting and warning system.

Web technologies should be considered as central to deploying an effective, distributed and open flood-forecasting and warning system. Access to spatial data (e.g., topographic, geological, socioeconomic, rainfall and meteorological) over the Internet is becoming more popular, and web-based

GIS systems are increasingly prevalent. Authorities can take advantage of the technology to make critical flood-related information available to any user in timely fashion and irrespective of location. As early as 2002, Chang and Chang (2002) recognised that, in most attempts to provide real-time flood condition information and timely and accurate flood warnings to stakeholders, a web-based decision support system for flood management was often used. Operations such as querying spatial data, performing spatial analysis or modelling have become possible on the go (Nyamugama et al., 2007). Mobile-GIS systems allow for the extraction of particular sets of information and offer users greater flexibility, allowing them to quickly produce results that are tailored to their needs and location.

Response times of a few seconds in a mobile-GIS environment can be supported by reliable wireless networks and Internet technologies. Map types become more pragmatic as the mobile-GIS architecture allows for updated data to be received from sensors and users. Moreover, GPS-enabled systems and devices provide users with location-specific data. As the nature of mobile-GISs is for flood-forecasting and warning information to be shared with potentially anyone, such systems are open and rely on Internet technologies and web servers to handle the user base.

Mobile-GISs improve responsiveness of flood management staff and civilians to abrupt changes and is better suited to process real-time data and deliver updated forecasts and subsequent warnings. Tsou and Sun (2006) support the idea that mobile-GIS services are ideal for real-time disaster management and responsiveness to constantly changing conditions, in contrast to traditional GIS models that are more suitable for long-term forecasting, planning and flood management tasks (Table 2.2).

Table 2.2 Differences between real-time systems and long-term planning processes (Adapted from Tsou & Sun, 2006)

	Long-term planning tasks (GIS modelling)	Real-time disaster management (Mobile GI Services)
Response Time	Flexible (1-10 days) (long-term tasks)	Immediate (1-10 seconds) (time-sensitive tasks)
Map Types	Thematic maps (land use, census data, administration boundary, soil, etc.)	Pragmatic maps (water levels, roads and traffic updates, event locations, evacuation maps, GPS integration)
Number of Users	Small number (at administration level)	Large number (general public, rescue teams, etc.)

2.13 Discussion

As can be seen from the overview of literature above, mobile-GIS technology has great potential in the area of flood forecasting and flood warning, and thus to reduce the impact of floods. Various improvements in technology have made it feasible to deploy mobile-GISs in creating forecasting and warning systems. Mobile-GISs can reduce the complexity in forecasting and thus make it more accessible to a wide range of people; moreover, since it runs on devices possessed by an ever-increasing number of people, such as smartphones, many technical limitations that previously enabled only a small group of professionals to use GISs disappear. This inclusiveness opens the door to a higher number of people participating in flood forecasting and warning, either by supplying various data to the system or warning neighbours; however, it poses some challenges. It is much harder to design a system that is sufficiently user-friendly to be used by the general population than it is to design a system to be used by professionals, who are likely to receive some training or simply be more motivated to learn when needed. The technical potential of mobile-GISs is not enough; in order to be accepted and widely used, any system has to match users' needs, as well as be easy to use and perceived as useful (Davis, 1993). The simplicity provided by a mobile GIS should be utilised; however, user needs and expectations should be understood in order to develop a system that is accepted.

Although mobile-GISs can significantly reduce the level of complexity of standard GISs by allowing users to access and analyse geospatial data through a mobile interface, that interface has to be easy to use in order to enable users to take an advantage of the simplicity achieved. It is important to understand the mental models and level of knowledge of various user roles and types in order to ensure that the system is intuitive to each of them: for example, it is likely that non-expert users would prefer it without any technical terminology whereas expert users might not appreciate that. Therefore, the user interface needs to match the level of knowledge and expectations of all users.

To enable non-experts to use the system effectively, as much technical complexity as possible needs to be hidden. A mobile-GIS allows that, by allowing GIS and environmental model coupling to take place behind the scenes. (Without these operations, it is complex since integrating hydrological models with a GIS does not have an interface and requires users to do pre-processing and post-processing as well as learning both the systems). Moreover, it requires no integration of hardware and software components. Therefore, there is a potential for users to be able to carry out data collection, analysis and forecasting without understanding the technical complexity behind these operations. Adding an intuitive user interface has a high potential for developing a tool that is used by many and can make a difference to the community.

Using a mobile-GIS does not require the computer and programming knowledge in several languages and sub-systems needed for a standard GIS, which is a considerable benefit since non-expert and less highly-motivated users will not have these skills. It can overcome the limitation of steep learning curves associated with a GIS. However, it is important to ensure that the system does not use any technical or programming terms that are relevant, but only understood by expert users. One of Nielsen's 10 usability heuristics (Nielsen, 1995), which are the most widely-accepted for developing user-friendly systems, requires a system to “speak” users' language rather than technical terms. It is important to understand users in order to discover the terminology they use and understand what they call various things and how they understand various relevant terms and concepts, etc. If this is not done, there is a risk that designers and developers assume that everybody uses the terminology they use and design a system understandable to themselves, but not the actual users. Achieving this requires studying users and understanding how to deal with various weather-related data from their perspective.

In order to address the issue of learning curves and people's natural adverseness to changes, it is important to take into account the possibility that users will already be using some forecasting or warning system. Any new system should not require them to 'unlearn' what they know and learn again but, rather, should build on their existing knowledge and understanding. Therefore, it is important to use user-centred methodology to understand what they know and what mental models they have.

One important issue that needs addressing in creating a useful and usable mobile-GIS based system is customisation. In general, customisation of models is difficult and general-purpose GIS packages do not allow working on specific applications since they do not provide all the functions needed for every single application. Since there is a need for a flood-warning application that is simple to use, it should only contain the functionality needed for that purpose and nothing else. Therefore, there is a need to understand and clearly define the functionality required by users. Overall, further study must be made into what combination of information a system needs in order to be useful to users, and how it should appear (i.e., the user interface) so that non-experts do not experience barriers to gathering the knowledge required to create useful and usable early warning systems.

2.14 Conclusions

The literature review has revealed that, although continuous advancements in meteorology have allowed the public and authorities to obtain reliable data on weather conditions, the same is not true for rainfall and storm paths regarding accessibility to reliable spatial precipitation and water level data (flood-related data). A mobile-GIS for flood forecasting and warning based on a client–server architecture supported by wireless Internet connections is the perfect candidate for effectively sharing vital flood-related information that can potentially save lives. The mobility factor creates immense opportunities for raising flood awareness among civilians.

The introduction of mobile-GISs comes with some limitations, which are mostly related to technological limitations such as processing power, technology infrastructure and the possible digital divide between populations. Considering the proliferation of mobile computing and smartphones, and the expansion of mobile networks, these barriers are expected to recede in the coming years.

Besides limitations, there are some user experience challenges. One must not ignore the fact that a flood-forecasting system based on a mobile-GIS is potentially available to all owners of mobile devices, which means a wide range of degrees of familiarity with GIS and mobile applications, as well as a wide range of mental models and expectations, need to be taken into account in order to develop a warning system that could be used by everyone. The technological potential of mobile-GISs must be coupled with understanding user needs and expectations in order to create an effective warning system. Focusing on meeting user needs and ensuring user-friendliness would address challenges such as steep learning curves and resistance to change. User-centred methodology needs to be used in order to understand the needs, knowledge, mental models and the complexity of the context of use; otherwise, there is a risk of developing a system whose complexity stems not from the complexity of the GIS itself, but from an unnecessarily complex and hard-to-predict user interface which is understandable to designers, developers and experts, but not to actual users.

Therefore, in our project of creating a prediction and early warning system, a great deal of knowledge needs to be obtained about users. It is difficult, in fact nearly impossible, to collect information about user needs, the relationships between different user groups and the contexts of usage without using any user-centred methods: nobody can better state what users need and how they perceive a particular digital product than users themselves. As a result, the project will involve both technical prototyping and user-centred research and development.

First, the functional requirements for a real-time, mobile-based GIS modelling tool, as well as various hardware requirements and other technical aspects for such an application, will be defined and discussed and a technical prototype will be developed and tested.

User-centred research will ensue in order to understand the exact user needs and their contexts. Activity theory will be used as a design framework, since it focuses beyond individual users and considers the entire system, accounting for environment, culture, tools and motivations which are important to understand in order to develop a system that is accepted by users. Potential users will be invited to brainstorm, discuss and analyse ideas, the outcome of which will later be transformed into a clear set of DPs and DRs for the system. These outcomes will be used to design a prototype of the user interface of the system. The DPs and DRs will be likely to be reusable: the main principles are highly likely to be applicable to other similar situations and systems and thus contribute to the development of useful and usable early warning systems.

However, having a list of DPs and DRs is not enough, since it is possible that brainstorming session participants might miss something or that researchers might make some wrong assumptions. Thus, more research will be needed to validate ideas and ensure the development of a useful and user-friendly final prototype. Therefore, user testing will follow. First, a first version of the prototype (functional, high-fidelity) will be developed based on the defined principles and requirements, and users will be recruited to test it; the prototype will be adjusted according to users' feedback. Initially, qualitative feedback will be collected, in order to see whether users are able to achieve a set of predefined tasks using the prototype and what the pain points and the areas of uncertainty are. The focus will be on observing users and understanding their mental models, expectations, etc. The outcome will be a refined prototype.

Afterwards, a second round of user testing will follow in order to collect a combination of qualitative and quantitative data. Since some understanding of user mental models will be obtained during the previous step, more focus will be given to measuring the performance and usability of the system; however, some qualitative insights will be obtained as well. The outcome will be a further refined prototype ready for development.

Chapter 3 Hydrological Modelling Tools

3.1 Introduction

This chapter presents a critical review of hydrological modelling and forecasting. It includes a brief overview of the historical development of GISs. This critique of modelling programmes has as its focus attempts to appraise their interfacing capabilities, real-time capabilities and public accessibility requirements.

The review offers a basis for the development of an integrated watershed simulation model with a web-based interface. This benefits users by improving access to information and by providing platform independence, technological transparency and visual interaction with data, a multimedia environment and greater cost efficiency. Implementing mobile-based GISs provides human communities with online access to environmental databases. This helps the public participate in the environmental decisions that pertain to them and their families. The chapter develops some of the methods this involves.

In summary, the chapter provides a brief contextual outline which stresses the links between hydrology forecasting, GISs, the Internet and mobile technology.

3.2 Background: hydrology and GISs

Floods may strike with little warning and are major contributors to property damage and personal injury. As discussed in Chapter 1, the recent development of extensive infrastructures in close proximity to rivers – as a direct consequence of population growth – has further increased the problems related to flooding. In addition, increased occurrences of extreme rainfall events, possibly owing to climate change, may be factors that have aggravated the situation.

A real-time flood-modelling prediction system with accurate prediction and rapid information dissemination capabilities could at least help alleviate the most disastrous effects of flood. Simple means, such as animated maps of potential floodwater distribution, can be employed for this. The progress of these systems would be mainly significant outside urban provinces that have hardly any operational conventional hazard-management systems in place, for example, the large expanses of pasture and agricultural land that occupy flood plains. Nevertheless, a number of institutional and legal hurdles need to be addressed before real-time flood-hazard data could be directly accessed by the people at ground level who could be most vulnerable to the effects of flooding. Though vital, these issues are beyond the scope of this thesis, as its main focus is enabling technologies rather than their institutional uptake and implementation.

Many watershed-modelling software packages are currently available, with only a few effectively incorporated within GISs. These software packages commonly require a high level of expertise for installation and operation. The models also need proficiency in hydrological data and modelling applications, making them mostly unsuitable for real-time application as the interpretation of data could be time-intensive. The current research is conducted with the aim of addressing this issue and presenting models that are significantly simpler, to allow automation, while being sufficiently robust to achieve interactive interrogation, even by end-users with little expertise in hydrology.

Practical application of watershed models requires efficient management of huge temporal and spatial datasets. This can be achieved only through proper data acquisition, storage and processing of modelling inputs, along with features to manipulate and report the data. These management requirements are achieved by integrating GISs and watershed simulation models, which helps in the management of large volumes of data in a common spatial structure. These integrated systems are further developed by combining several software packages and mathematical programming systems, along with a DBMS if required. The Evaluation of Groundwater Resources Information System (EGIS) project by Deckers (1993; Bhargava & Downs, 1996; González, 2012) is an example of such a system.

The Graphical User Interface (GUI) allows interaction between the system and the user and can be developed by an independent third party, such as a university research team, environmental agency or commercial vendor. However, the quality and features of GUIs vary with the programmers, some of their features being exclusive to some developers. Further problems could arise owing to the use of temporally dynamic processes that are known to cause major obstacles when coupling environmental modelling with GISs (Albrecht et al., 1997; Goodchild, 2005). Some of these systems are complex and sophisticated, are designed for general purposes and cannot be customised by users for applications in specific circumstances. This limits the possibility of users' customising the systems to meet their unique requirements (Bundock & Raper, 1991; Malczewski, 2004; Dye & Shaw, 2007).

Lack of sophisticated analytical and hydrological modelling capabilities in existing systems is acknowledged by several researchers (Wilson, 1996; Bennett, 1997; Camara, 1999; Bhatt et al., 2009). Bhatt et al. (2009) suggest that the data structure of the existing hydrologic models is still not developed to the extent necessary to facilitate close linkage to decision support systems (DSSs) and GISs. The systems also need to be adaptable to user requirements and specific applications. Furthermore, the majority of the existing systems, including simulation models, lack various essential analytical tools, such as dynamic modelling, which are required for watershed applications (Van Deursen, 1995; Karssenberg & De Jong, 2005a, 2005b).

Hydrological analysis itself is often hampered by two problems that are absolutely essential for the success of any flood-forecasting system: adequate data quality and its real-time availability (Goonetilleke & Jenkins, 1999; Al-Sabhan et al., 2003). While the fundamental goal of flood forecasting is to mitigate the disastrous and hazardous effects of flooding, this requirement is not often met by GISs and hydrological models (Karimi & Blais, 1997; Karimi & Chapman, 1997; Al-Sabhan et al., 2003).

The routine and extensive use of established GISs in imperative environmental applications has been hindered by several fundamental obstacles (Albrecht et al., 1997; Pullar, 2003), such as data integration, user interfacing, cartographic modelling language (Map Algebra[7]) and the presentation of dynamic processes in GISs. GISs are designed to integrate a variety of environmental data through different modules so that a wide range of applications can be implemented. This substantially increases operational costs, as relatively complex hardware and software are required to obtain even a basic GIS functionality. Additional considerations need to be given to the integration of simulation models capable of significantly advancing the potential of GISs for environmental simulation and understanding.

It is obvious that the need for complex integration is essential for the environmental application of computer technology; however, it must be noted that the required intricacy necessitates significant data management and programming efforts (Burrough, 1997; Brimicombe, 2010).

Numerous models have been reviewed for applications and mathematical implementations (Clarke, 1973; Beven et al., 1984; Argent, 2004). However, these reviews frequently fail to acknowledge the seemingly trivial problems that are of considerable importance to end-users and stakeholders. Haklay’s (2001) suggestion reinforces this idea. “As any research in a library catalogue or scientific journal index will reveal, a very limited amount of literature deals with EIS[8] directly. Most of it focuses on implementation issues and an extensive body of research on environmental modelling and analysis techniques.” The data and interfacing of the models top the list of overlooked concerns. Furthermore, the problem of making the simulation model accessible to all the relevant stakeholders is also grossly ignored in the literature.

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[7] Map Algebra is a language developed by Tomlin for the manipulation of map data. It includes a large number of functions for performing common operations on a single map layer or on multiple map layers.

[8] Environmental Information Systems.

3.3 Hydrological modelling

Hydrological models are based upon our understanding and interpretation of hydrological processes, and are aimed at depicting these processes in simplified versions. These models function through various mathematical equations containing parameters and variables depicting hydrologic processes. These variables represent characteristics of a system that varies temporally or spatially in numeric value (Singh, 1988; Singh, 2006). Some of the most common hydrologic variables are evaporation, temperature and precipitation (Singh, 1988).

Hydrological modelling is one of the most important forms of modelling and employs the principles of geographical data analysis and manipulation. Modelling is one of the most important stages in the development of an information system (Worboys & Duckham, 2004). The hydrological and other dynamic processes of rainfall and rivers are mathematically simulated to forecast future levels and flow based on currently available information. Based on the requirements, these models could be simple empirical equations or sets of complex differential equations based on fundamentals of physics. They serve a variety of purposes and have been commonly employed to study and examine:

- groundwater movement;
- watershed hydrological processes;
- water-quality dynamics;
- atmospheric processes;
- the behaviour of rivers and reservoirs;
- combinations of sub-component models.

Nowcasts, or short-term predictions based on real-time data inputs, are used for decision-making, hazard assessment and disaster prevention.

A modelling system fundamentally consists of two key components:

a) a modelling tool for performing the numerical analyses; and
b) an interface for user interaction (that allows input of parameters, execution of functions and display of results) with the modelling tool.

Furthermore, other assessments, such as the impact of rainfall and subsequent river discharge due to climate change (Brilly et al., 2014) or model uncertainty in natural resources (Davis & Keller, 1997; Chacon et al., 2006), can also be undertaken using simulation models. These analyses are helpful in providing insights and answers for decision-makers.

In summary, the mathematical models have numerous advantages (DeCoursey, 1991; Singh & Woolhiser, 2002): they provide quantified description and a clearer understanding of chemical, biological and hydrological processes; assist in devising a conceptual framework and identifying the different knowledge gaps; help stimulate new ideas and approaches; facilitate the availability of knowledge in user-friendly formats; enable the adoption of better methods, as alternative methods and models can be easily compared through research; reduce ad-hoc experimentation as models simplify the design of focused experiments; provide a coherent view of the behaviour of the whole system by amalgamating the knowledge of different parts when several components are involved; provide strategic and tactical support to research programmes, thereby increasing motivation and collaboration amongst scientists; are a powerful means of summarising and integrating data, interpolation and cautious extrapolation; are economically justified, as they use the given data efficiently and effectively, reducing the need to obtain additional costly data; can be used in research and development, management and planning owing to their prediction capabilities; and provide a mechanism to transfer data to required places, especially when models validated by data from experimental watersheds are used.

Essentially, hydrological models are mathematical depictions of flow of water and its constituents on the surface of the land or subsurface environment (Maidment, 1993; Mujumdar & Kumar, 2002). Environmental modelling offers various benefits, such as:

a) explaining the nature of the physical world;
b) providing results that support decision-making for resource and hazard management (Grayson et al., 1992; Moore et al., 1993; Singh & Woolhiser, 2002); and

c) guiding in the presentation of complex ideas in an accessible manner (Burrough, 1997; Brimicombe, 2010).

Hydrological models can function in two ways. They can either work as independent stand-alone systems, which receive data through inbuilt import/export facilities, or can be coupled with an external GIS system through a dedicated interface. These are discussed in the next two subsections.

3.3.1 Stand-alone models

A stand-alone programme is based on a specific hardware configuration and a particular computing platform, such as the Windows-based WMS[9] (Erturk et al., 2006); Gestion Intégrée des Bassins versants à l'aide d'un Système Informatisé [GIBSI][10] (Mailhot et al., 1997); the Windows and UNIX-based PCRaster[11] (Wesseling et al., 1996b; Karssenberg et al., 2001); or the UNIX-based workstation MMS (MMS manual, 1998). These programmes function either on a single computer or on multiple computers connected through a local area network that may or may not be connected to a global network. The outcomes are then made accessible to the managers or general public across geographically separate locations.

The Hydrological Engineering Center (HEC), located at the United States Army Corps of Engineers (USACE), has developed one of the most popular flood hydrograph models, named HEC-1 which provides numerous options for simulating precipitation-runoff processes. This command-line-oriented programme has now been replaced by a newer interactive stand-alone-rainfall-runoff modelling version, the HEC-Hydrological Modelling System

[9] Watershed Modelling System. developed by the Brigham Young University and US Army Corps of Engineers.

[10] A software system that allows water resource management decision-makers to explore different options for modelling watersheds. Developed at INRS-Eau, Quebec, Canada.

[11] A spatio-temporal environmental modelling language developed at the University of Utrecht, the Netherlands (http://www.geog.uu.nl/pcraster/).

(HEC-HMS). This model has been implemented on both Windows and UNIX. The programme boasts the following impressive features:

- GUI;
- integrated hydrological analysis components;
- data storage and management capabilities;
- graphics and reporting facilities.

The HEC-HMS requires fewer data to perform hydrological analysis than its predecessor versions (Nelson et al., 1994; Chu & Steinman, 2009). Moreover, HMS[12] can function independently of any commercial GIS.

The WMS, a graphically-based, comprehensive hydrological modelling environment that addresses the requirements of rainfall-runoff computer simulations (DeBarry et al., 1999; Erturk et al., 2006; Beven, 2012), is another well-known stand-alone programme (Nelson et al., 1995; Goodall et al., 2011). It supports the exchange of data files with GIS packages in many of the popular formats. For instance, WMS can import a DEM from GRASS or ArcInfo that can be subjected to further analysis directly.

Other popular hydrological models include SHE[13], TOPMODEL and SWAT[14] (Reed et al. 2004). The first can be used only in small watersheds, and the latter two can be applied in large or semi-large basins (Deng et al., 2008). TOPMODEL,[15] which is available as either a semi-distributed or distributed model, has been reported by numerous papers for various applications

[12] The HEC-HMS (Hydrologic Engineering Center-Hydrologic Modelling System) programme supersedes HEC-1 and provides a similar variety of options for simulating precipitation-runoff processes.

[13] SHE is a physically-based, distributed, catchment modelling system produced jointly by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France) with the financial support of the Commission of the European Communities.

[14] SWAT (Soil & Water Assessment Tool) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds.

[15] A rainfall-runoff model developed at the University of Lancaster.

(Beven, 1997; Obled et al., 1994; Reed et al., 2004; Niu et al., 2005). However, this is not intended to be a modelling package, but aims to serve as a set of conceptual tools for simulation of the hydrological behavior of a watershed (Beven et al., 1995; Niu et al., 2005). Since TOPMODEL has been adapted and applied to appeal to a broad range of modellers, a standard version has not been developed. Data requirements for TOPMODEL are dependent upon the version and the application used. The main drawbacks of using this model are the lack of a standard version and the likelihood of a long and demanding period of data preparation for each application (Romanowicz et al., 1994). The old version of the model, which is based on the 1995 FORTRAN version, is not supported today because it will not run on modern 64 bit machines. There are now R versions of both TOPMODEL and Dynamic TOPMODEL that can be downloaded with manuals and example data sets from any of the R CRAN Servers. TOPMODEL is an open source version developed in the R environment. It incorporates handling of geo-referenced spatial data that allows it to integrate with a modern GIS (Metcalfe et al., 2015).

The effort and degree of specialism needed to create powerful environmental models has led to model-building being seen as a scientific activity in the field. Despite the work that goes into these products, many may not be able to understand the models as well as the creators do, and thus disregard the technology as black boxes in an information-processing system. Often these models are linked to GISs as sources of data, and as a means of displaying the results or for linking with other spatial information.

3.3.2 GIS-based flood-forecasting tools

The GIS packages can be coupled with models as an alternative to using these stand-alone programmes. Many researchers have extensively discussed the approaches for integration of environmental models with GISs (Maidment, 1996; Karimi & Houston, 1997; Sui & Maggio, 1999; Brimicombe, 2003; Bhatt et al., 2008) and they have been well documented in the literature (Correia et al., 1998; Sui & Maggio, 1999; Bhatt et al., 2014). Hence, these will not be discussed in great detail here. However, we will briefly discuss the two methods for coupling GISs and hydrological models: loose coupling and tight coupling methods (Stuart & Stocks, 1993; Batty & Xie, 1994; Liu & Weller, 2008; Castronova & Goodall, 2009).

In loose coupling, an external model that could be based on languages such as C or FORTRAN for performing operations is linked to a GIS. The external model is operated through a call from the GIS to calculate parameters and values that are subsequently incorporated into the GIS database. It commonly involves a hydrological model such as HEC-1 or HEC-2[16] (Djokic et al., 1994; Brown et al., 2005), a standard GIS package (e.g., ArcGIS or GeoMedia) or a statistical package (e.g., SAS[17] or SPSS[18]). Loose couplings can help in accessing the analytical tools that are, as such, incompatible with the system. This helps in deriving the required end-points in the GIS and hydrological models, even when these models lack such data-handling and analytical capabilities (Frust et al., 1993; Albrecht et al., 1997; Burrough, 1997; Maidment, 1993; Brown et al., 2005).

The mismatch is also likely to affect the quality, cost and benefits of the modelling results as GIS engineers and modellers might have diverse conceptual views of the real world (Burrough, 1997; Brown et al., 2005). The loose coupling requires a number of additional programmes, such as DBMSs that can handle data exchange functions. On the other hand, the data exchange between a GIS and a hydrological model can be quite cumbersome (Karimi & Houston, 1997; Brown et al., 2005). Furthermore, the integration fails to provide a consistent user interface (Bennett, 1997; Correia et al., 1998; Brown et al., 2005) and requires operational efforts and time in exchanging

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[16] HEC-2 is for Water Surface Profiles and was released by the Hydrologic Engineering Centre (HEC), US Army Corps of Engineers, in 1966.

[17] SAS is an advanced statistical software system for data analysis, statistical computation and report writing (http://www.sas.com).

[18] SPSS (Statistical Package for the Social Sciences) is one of the most widely available and powerful statistical software packages (http://www.spss.com).

data structures and changing data (Burrough, 1997; Brown et al., 2005). These shortcomings will be further exacerbated if the models are provided by different developers.

In tight coupling, using a macro language such as the ESRI Arc Macro Language (AML),[19] the model is developed entirely within a GIS environment. This type of programming, though convenient, may often fail to support the same capabilities of procedural programming languages, as it may not support sophisticated applications. Though editing and file conversion are not required, tight coupling still requires substantial data management and programming in addition to a customised, menu-driven user interface (Burrough, 1997; Karimi & Houston, 1997; Brown et al., 2005). Given the dearth of GIS macro-enabled programmers able to construct an interface facilitating interaction with the GIS data structures, the task is particularly challenging. Karimi and Houston (1997) acknowledge that loosely and tightly coupled methods each have their own advantages as well limitations for modelling.

Although GISs are excellent for spatial analysis, their lack of important sophisticated analytical and modelling capabilities has been recognised by GIS researchers and hydrologists alike as one of the foremost drawbacks of GIS technology (Maidment, 1993; Sui & Maggio, 1999; Zhang et al., 2012). GISs also have limited spatio-temporal analysis capabilities (Worboys & Duckham, 2004). Traditional simulation models work effectively under dynamic and complex situations but mostly lack the spatial analysis and intuitive visualisation functions offered by GISs.

The rapidly accumulating literature on the integration of hydrological models with GISs supports the recognition of their reciprocal benefits (Maidment, 1993; Moore, 1996; Al-Sabhan et al., 2003). Nonetheless, the shortcomings become apparent as the incompatibility between model types, GISs and data

[19] Arc Macro Language is a procedural scripting language used with ArcInfo and ArcGIS.

types surfaces (Burrough, 1996; Goodchild et al., 1993; Al-Sabhan et al., 2003). During the integration of GIS script packages (e.g., AML[20], Avenue[21], VBA[22] and Python[23]) with WMS, developers are mostly restricted to the architecture of the GIS. On the other hand, in order to create hydrological models, the users, including engineers and hydrologists, need to learn the GIS operating environment. Hence, GIS experts are required to have an in-depth understanding of the job of hydrological engineers (DeBarry et al., 1999; Al-Sabhan et al., 2003).

The integration of GISs with models like MMSs and MODFLOW[24] (McDonald & Harbaugh, 1988; Martin et al., 2005) could yield two processor outcomes (DeBarry et al., 1999; Karimi & Houston, 1997; Martin et al., 2005), namely pre-processors and post-processors, both of which facilitate software integration. The data preparation, analysis and input of spatial and temporal data is handled by pre-processor tools, whereas the subsequent analysis of model results is conducted by post-processor tools (De Roo et al., 1989; De Roo, 1996; Kite et al., 1996; Martin et al., 2005). These include numerous geographical and statistical tools that can assist in decision-making, along with a user-developed interface to visualise and evaluate results. However, these processors require complex input files and formatting of the model output, including the preparation of time-series and spatial analysis for display in the desired graphic environment (Karimi & Houston, 1997; Martin et al., 2005). Finally, hydrological models generally require time-series input and

[20] *ARC Macro Language (AML)* is the native programming language of the ArcInfo *and ArcGIS.*

[21] Avenue is Arc View's object-oriented application development environment, which enables users to customise the Arc View interface and to create custom applications.

[22] Microsoft's Visual Basic for Applications, the built-in development environment for ArcGIS.

[23] Very popular with Geospatial professionals working in the ESRI environment and considered the primary scripting language for ArcGIS.

[24] A Three-Dimensional Finite-Difference Ground-water Flow Model, developed by the US Geological Survey. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions.

output data, even though most hydrological processes are time-dependent. The ability to store, retrieve and perform operations on time-series data is critical for implementing hydrological modelling within a GIS, as existing GISs are not equipped to store or manipulate time-series data (Maidment, 1993; Martin et al., 2005).

3.4 The need for real-time analytics

Real-time data reflect collected information without any lag period. It is instantaneous. The GIS receives real-time spatial and non-spatial data either at predetermined time intervals or on the completion of certain events, such as the influx of data at a desired destination. Some researchers assert that existing data modelling and management technologies, and software designs, are not capable of supporting the current GIS systems sufficiently to effectively meet the requirements of real-time applications (Karimi & Chapman, 1997; Noel et al., 2004; Gong et al., 2015). As mentioned in Chapter 1, however, Goodchild (2011) states that newer tools that treat information as a changing variable are required, as GISs will involve much more real-time situation monitoring and assessment applications. This would enhance the precision of decision-making based on the real-time data, as well as improving rational decision-making with respect to future predictions (Van der Walle et al., 2009). Continuous remotely sensed measurements of rainfall to improve the accuracy of model forecasts will determine the key requirements in real-time flood forecasting. Even though accurate quantitative estimations are now possible, attention is still required for the development of more prolific and sophisticated rain-gauge networks that could forecast the rainfall using weather radar. Development of nowcasting systems that acquire real-time data also needs extensive research. Comparing current and future GIS systems, Karimi and Blais (1997) argue that interfacing external systems for real-time processing with GISs is currently extremely complicated. Hydrological models and GISs lack a direct connection with external sensors and devices, which limits the access to real-time data. These shortcomings can result in hard-coding of data directly into the system, which further complicates the possibility of updating the data. To be able to provide results that can have real-time applications, real-time GISs must also contain algorithms that drastically minimise response times (Karimi & Chapman, 1997; Zerger & Smith, 2003).

FORTRAN and C remain the languages of choice for modellers (Westervelt, 2012), despite advances in computing power and programming languages (TOPMODEL, HSPF-FORTRAN[25] and HEC-1). However, traditional programming technologies, including FORTRAN, are unsuitable for dynamic geographical system representation for the following reasons (Unland & Schlageter, 1989; Herring, 1992; Bennett, 1997; Bonham-Carter, 2014):

1. static or early binding[26] inhibits the representation of processes that change through time (i.e., where one process is replaced by another, different process);
2. data management and representation mechanisms are unavailable for the development of complex objects;
3. it is difficult to capture user-defined spatial relations (e.g., queries such as 'retrieve all upstream channel segments' are not well supported); and
4. modification or extension of models is difficult.

It is possible to overcome these limitations by employing object-oriented programming techniques, as demonstrated by their utility in the representation of spatial data (Raper & Livingstone, 1995; Bonham-Carter, 2014). Most of the hydrological models that involve optimisation and simulations need significant computer resources and run for several hours (Walker, 1991; Rani & Moreira, 2009), which automatically renders them incompatible with real-time applications.

[25] Hydrological Simulation Program—FORTRAN, developed by the Research Lab of EPA in the late 1970s.

[26] Static (or early) binding is the concept of resolving a function/method call at compile time as opposed to dynamic (or late) binding where a function/method call is resolved at runtime.

At present, three basic systems are available for providing precipitation measurements that can be used for real-time flood forecasting. The first are traditional systems, which are typically connected to a base station by VHF/UHF radio, telephone lines, metro-burst telemetry or satellite (Latkovich & Leavesley, 1993; Al-Sabhan et al., 2003). The second is weather radar, which collects data on rainfall spatial patterns, as opposed to the rain gauge, which collects point measurements. These radars are not commonly used as they require sophisticated engineering and technical support in addition to being expensive. Some of the reviews have evaluated hydrological applications of radar-based precipitation measurement (James et al., 1993; Mimikou & Baltas, 1996; Al-Sabhan et al., 2003). The third measurement system, also involving satellite monitoring, estimates rainfall through observation of cloud-radiative temperature and provides real-time estimates. Once the satellite is in orbit, the process is relatively inexpensive. This method covers large areas and provides a huge amount of data, but requires extensive calibration with ground-measured data.

The majority of the data collection systems are interfaced through standard connections such as RS-232 ports, with data transmission systems such as wireless radio or telemetry, which enables data transmission from a remote site to a central base station through several available communication systems. A variety of factors, such as the size of watershed, the cost and the data transmission time, play a role in determining the best communication system.

Currently available real-time forecasting systems are expensive but sophisticated; they use complex data inputs and provide the most reliable forecasts (Feldman, 1994; Al-Sabhan et al., 2003). Up-to-date and reliable data sources are necessary to enable effective application of a GIS to management decision-making. Thus, although flood-forecasting systems exist in many countries and are deployed in numerous projects, there is still a definite need for significant research and development for real-time flood-forecasting systems (Todini, 1998; Al-Sabhan et al., 2003).

3.5 Public access to hydrological information

In spite of the developments in flood-forecasting systems, a few researchers in the UK (Parker et al., 1995; Harvatt et al., 2011; Harries & Penning-Rowsell, 2011) were critical of the EA, and the UK Flood Warning System, for not giving due consideration to flood warning and dissemination processes. Further work is required to understand possible ways to increase community participation in setting up local flood-warning strategies (Parke et al., 1995; Haggett, 1998; Charnley & Engelbert, 2005; Johnson et al., 2007).

In addition to fulfilling the requirements of the decision-makers and professionals, data analysis can also be useful for a general public that demands openness. This is reflected in legislation such as the Council of European Communities Directive (1990), and the US National Environment Policy Act-NEPA (1969). The latter includes the following statement:

> "All agencies of federal government shall make available to States, counties, municipalities, institutions, and individuals, advice and information useful in restoring, maintaining, and enhancing the quality of the environment"
> (Haklay, 2002, 2003).

To achieve heightened public awareness of environmental issues and foster participation in decision-making, public access to environmental information is vital. Conventions that promulgate public access to environmental information have been developed and signed, including the Freedom of Access to Information on the Environment (Hallo, 1997) and the Arahus convention (UN/ECE, 1998). The Arahus convention states:

> "Improved access to information and public participation in decision-making enhance the quality and implementation of decisions, contribute to public awareness of environmental issues, give the public opportunity to express its concerns, and enable public authorities to take due account of such concerns."

Reacting to public pressure owing to public debates on environmental awareness during the late 1960s (Haklay, 2002), UK policymakers created the Royal Commission on Environmental Pollution (1969) and the Department of the Environment (1970) (McCormick, 1995).

As discussed in Chapter 1, the results of the modelling are much more useful to the public than unprocessed or raw data. Hence, researchers and professionals, in addition to those in academic and scientific roles, bear the additional responsibility of providing the results in a form that can be easily interpreted by the public (Haklay, 2002, 2003).

Patel and White (2005) and Poblet (2011) studied the possibility of using mobile devices to achieve increased public participation in environmental decision-making. The widespread use of mobile phones (Trimi & Sheng, 2008) has already been exploited by different sectors for numerous applications such as crime-fighting, supply of information, banking, voting, surveys and many other areas.

Mobile phone users have already been engaged extensively in contests and competitions, reporting traffic congestion, photography and dissemination of pictures, or spreading news and sharing views (Vincent & Harris, 2008). In addition, mobile phones effectively facilitate information sharing between "a large number of similarly minded people within a short period of time and at short notice" (Hermanns, 2008), leading to greater interest and awareness in politics, including in the planning system. Web-based GISs have also seen an enormous increase in the number of users during recent times (Froese, 2007; Adnan et al., 2010). These systems are available at all levels of complexity, ranging from simple global maps to front-ending complex spatial analyses of processes. Furthermore, GIS-enabled web applications can utilise any of the numerous database platforms and technologies, the choice of which can impact the performance of these applications.

As with any other system, participation and data accessibility are critical and need due consideration during the development of successful flood-forecasting systems. Accordingly, detailed attention to these considerations is required to devise better warning and simulation systems for flood forecasting, as well as various environmental management systems.

3.6 The UK flood warning system

Prior to 1996, telemetry was employed by the predecessors to the EA to monitor river levels. Local police and councils were responsible for warning the public, with the EA's predecessor involved in some aspects, such as providing informal advice on timing of evacuation. The responsibility for both flood monitoring and public warning was transferred to the EA by a 1996 parliamentary decision (EA, 1999).

Currently, an Automatic Voice Messaging (AVM) system is used by the EA for public warning. The messages are sent through fax, telephone or pager to the public contacts of the concerned area in the database. A pre-recorded message is broadcast via the telephone network once a decision is taken to warn the public. A successful contact is registered by the computer when the contacts press a particular button on the telephone as per the instruction that is either pre-informed or delivered during the broadcast. Simultaneously, a message is sent to professional partners of the EA, such as the emergency services and communications media (EA, 1999, 2009).

The regions of Britain that are likely to be at the risk of flooding are identified and updated through annual mapping carried out by the EA. The mapping programme combines photographical contouring and modelling and involves a variety of other geographical data. The results also strongly emphasise possible worst-case scenarios. The property owners within the high-risk areas are informed about the situation immediately by the EA by telephone, fax, pager, mobile, e-mail or SMS text message. As of April 2009, over 430,000 people in England and Wales were registered on Floodline Warnings Direct (FWD), and numbers have increased every year since the service was introduced in 2004. In February 2009, they warned over 50,000 people in 24 hours, providing information about the developing flood risk across southern and eastern England.

Improving real-time capabilities is the first priority of the EA, which relies mostly on information obtained by the Meteorological Office for weather monitoring. Radar-data capture occurs four times every hour using the Hyrad satellite. These data are instantly made available for viewing and undergo analysis within the Met Office by the Nimrod forecasting and modelling system. Although the EA has direct access to the data in the Meteorological Office, complete access is limited to certain domains. The EA's use of the information is further limited by Nimrod's inability to detect thunderstorms perfectly.

Immediately after rain stops, the EA undertakes water-level monitoring across Britain using its own Regional Telemetry System (RTS). The recorders and gauges, through data loggers at each site, subsequently link to EA's eight regional offices by telephone lines. The gauges, flow and level recorders of waterways are automatically scanned every morning, while manual updating is carried out every 15 minutes in highly vulnerable areas during potential emergencies. This is followed by graphical analysis of the data at regional offices of the EA.

On-site batteries power scanning-data loggers. This limited resource can create a problem during periods of emergency when continuous monitoring may drain the batteries. Hence, a large operational risk may be posed to RTS by battery failure.

The data-loggers send an alarm message to regional offices on recording a value that exceeds programmed limits. Reliable warnings are sent only when telemetry information is considered along with Hyrad radar images. The stages of warning set by the EA are “Flood Watch”, followed by “Flood Warning”, “Severe Flood Warning” and “All Clear”.

Currently relying on RTS monitoring, the EA warning system does not utilise GIS modelling. The next update has been planned to include the introduction of a GIS. This lack of flexibility has hindered it from incorporating other factors such as rainfall intensity. A provision that could allow EA officers to customise the system to input conditions that they deem important could significantly improve the predictive capabilities of the model. Furthermore, a GIS can help in incorporating additional factors and producing three-dimensional models. In addition to enhancing the predictive power, this would allow instant warnings to be sent to densely-populated areas that require instant attention. However, densely-populated areas may also pose a risk of large-scale unnecessary evacuation if warnings happen to be false. A GIS that provides high accuracy could help overcome such problems.

A website was launched by the EA in 2001 that gives the local government, public and emergency services the ability to monitor announced warnings. Public users can access static maps of their locality by providing an area post code. Accuracy of these maps has been limited by concerns over data protection. The EA has repeatedly stressed that its information is designed only for the use of flood warning, and not as a resource for home-buyers in determining which properties are within flood plains. However, such concerns still limit the amount of information the EA can post on the Internet.

3.7 Conclusion

This chapter provides important links between the technology of hydrology and the human problems that hydrology attempts to address, in particular, flooding. Flooding is a global, national, local, institutional and personal challenge. The amelioration of floods depends on our understanding of hydrology and the advancement of technology to address new (and apparently) more devastating situations. More recent work has made greater use of the Internet, GISs and advanced techniques of communication. Thus, use may be made of flood-modelling predictions in real time. It may not be possible to stop floods, but accurate predictions of the spread of floods through both urban and rural land have the potential to minimise damage to property (including that which is necessary for the production of food) and save human lives.

A little over a decade ago, the UK began to implement a comprehensive system of flood prediction and amelioration. This followed a period when many researchers drew attention to the unsophisticated nature of modelling and prediction services. Hydrological models improved from about this time onwards. The chapter draws attention to the work of Wilson, Bennett, Camara and Bhatt. Today, serious modelling always involves numerical analysis and a graphic interface for user interaction with the data. Stand-alone models predominate, and examples include SHE, TOPMODEL and SWAT. These differ in the size of the watersheds they address, but they are current applications ideal for particular circumstances.

The desirability of real-time analysis has become clear. Today this capability is available and real-time data can be hard-wired into the predictive system. FORTRAN and C remain the choice of programmers who work on projects of this kind.

To conclude, the UK flood-warning system is still a work in progress. Some regions of Britain that are particularly at risk of flooding are identified and data are updated annually by the EA. There is still a dependence on automated voice systems, pre-recorded messages and telephone networks. Much of this is vulnerable to severe, unexpected weather events. Email and social media registration are now complementary systems of public notification, but again they depend on infrastructure which might be at risk. Precipitation recorders throughout the country depend on telephone lines to report their data. It was only in 2002 that the EA began a comprehensive website to provide data which, they stress, is still only to be used for flood warnings and not for other purposes such as deciding where to live.

Chapter 4 Review of mobile technology

4.1 History of mobile operating systems

Cellular technology has evolved rapidly over about the last 20 years, preceded by wire line telegraphy, telephony and wireless radio. A radio wave fills empty space through diffraction and reflection, allowing the information carried on the wave to be available throughout a large coverage range. This property of radio waves makes it possible for millions of individuals to share a common broadcast at very low cost. This same characteristic of radio waves, filling empty space, contributes to mobile communication, allowing us to reach another person, anywhere and anytime.

Marconi introduced useful radiotelegraph signals between ship and harbour in 1899, and the Detroit police force was using small, multi-channel radios in cars by 1928. In 1947, researchers from Bell Laboratories proposed the idea that by using small cells (i.e., each cell uses a different set of frequencies from neighbouring cells, to avoid interference and provide guaranteed bandwidth within each cell), people could reuse channels to maximise the number of calls per channel. The development of the transistor by William Shockley, Walter Brattain and John Bardeen, combined with the invention of the integrated circuit by Jack Kilby in 1958, finally made it practical and affordable to manufacture and use small, portable radios (Rutgers, The State University of New Jersey, n.d.; Farley, 2005). As of today, there are 5 generations of mobile OSs. In the next section, we will discuss the generation of OS 4G, which is used in this research. 4G is also called Native IP.

4.1.1 Native IP or "4G"

With Nokia helping to bringing 3G to full maturity, developers were anxious to meet new user demands. They defined fourth-generation, or 4G, technology as the switch that is connected to native IP networks, and is designed to incorporate mobile Internet service and wired home Internet connections (Evans & Baughan, 2000). The ITU then created a specification called IMT-Advanced (after IMT-2000), which states that 4G technologies deliver download speeds of 1Gbps when not mobile and 100 Mbps when mobile. This guideline demonstrates a speed potential of up to 10 times that of 3G.

Despite the ITU specifications, other technologies, such as North America’s LTE, have claimed to have formulated 4G. Some of these technologies also label themselves as 4G even though their speeds do not meet IMT-Advanced requirements. Subsequently, it is not always clear what comprises a 4G device and what does not. The technology is still very much evolving and is not by any means standardised in practical use, having wide variations in metrics such as coverage.

4.2 OSs and platforms

Before examining each of the OSs and platforms for mobile phones, a review of the respective market shares of each OS is helpful. The open source Android OS holds the majority of the market, though it is expected that Apple’s IOS will gain as users begin to upgrade to iPhone 6. The data shown in Figure 4.1 is as reported by the International Data Corporation (IDC) and represents Q3 of 2014. Android held 84.4% of market share, followed by IOS at 11.7%, Windows Phone at 2.9%, Blackberry at .5%, and all others at .6%. Clearly, users are driven by value for money (IDC, 2014).

In the following sub-sections, we will discuss all major OSs. Apart from the important ones, there exist other OSs such as Symbian, Meego and Palm which are almost obsolete or replaced by other OSs.

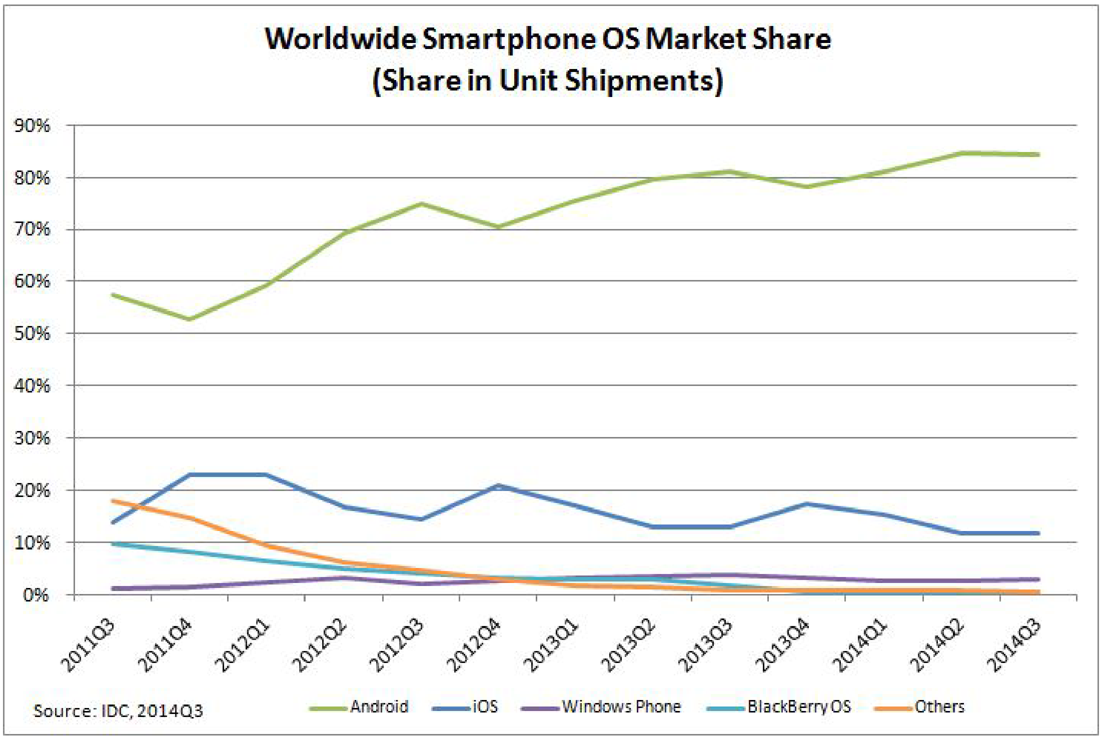

Figure 4.1 Worldwide smartphone OS market share (based on units shipped) (IDC, 2014)

4.2.1 Blackberry

Introduced into the market in 1999, Blackberry devices are highly multifunctional, providing Internet, camera, media and many more features (Renner, 2014). Blackberry has achieved much of its success with email, instant messaging and its other services thanks to their smartphones' proprietary mobile OS, Blackberry OS. This very reliable and robust OS is capable of supporting corporate mail via Mobile Information Device Profile (MIDP), thereby allowing users to sync wirelessly to Microsoft Exchange, calendar and other services when utilising a Blackberry Enterprise Server. The ability to access Blackberry's substantial library sets, along with the ability to write applications in Java and take advantage of a protected run time environment, makes the OS especially attractive to developers (Oliver, 2008).

4.2.2 iPhone iOS

iOS is a mobile OS from Apple, Inc. A Unix-based platform, it bears similarities to Mac OS X, sharing technologies such as the Mash kernel and BSD interfaces (Lettner et al., 2011). iOS is exclusive to Apple hardware

(Gartner, 2010). Nevertheless, newer versions are providing additional services that meet increased user demands, such as storage in the cloud (iCloud), support for Airdrop and instant messaging (Anderson, 2007). Apple has also developed the Apple Store. This service, which is well-known, gives developers a platform through which to publish their iPhone or iPod touch applications.

4.2.3 Android

Android is a set of programmes from Google first released in 2008. The OS, middleware and key applications run together as a software stack, creating a complete platform (Gandhewar & Sheikh, 2010). Now used in over a billion tablets, phones and other mobile devices around the world, it is one of the most popular systems among general users, businesses and developers. The primary competitor for Apple's iOS, it has advanced considerably through continual changes to both supported hardware and features. For its many advantages and wide user base, Android is used for this research and mobile development.

Here is a list of advantages and disadvantages of Android OS.

Table 4.1: Android OS Advantages and Disadvantages

Advantage	Disadvantage
Allows app installation from outside vendors	Too much advertising with free apps
Apps are cheaper than on Apple or Windows apps	Needs constant Internet connection
Customisable Widgets	Greater frequency of phone hanging, particularly when playing games requiring fast movement or when downloading large files
Near field communication to check social media feeds or to use as payment	Battery drains quickly

processor	
Open source development	Peripherals not compatible with all devices due to third party development & multiple device manufacturers
Wide variety of devices & prices available	
Rapid release of new versions	

4.2.4 WebOS

WebOS, also known as Palm WebOS, is a mobile OS originally designed by Palm Inc. for smartphones. Developers have since expanded its functionality to host other hardware platforms that may or may not incorporate keyboards or touch panels, such as smart TVs and watches. Hewlett-Packard (HP) has acquired Palm OS. Since the acquisition, the company has promoted the OS heavily within large businesses, ramping up management and security in WebOS 3.x to meet the tougher demands of the corporate environment. HP currently incorporates the OS into several of its products, such as the HP Touchpad, as well.

4.2.5 Windows Phone 7.8, 8 and 8.1

Windows Phone is a mobile OS for smartphones and other mobile devices. Developers created it in 2010 as a successor to Microsoft's Windows Mobile, which was facing tough competition from other OSs such as Android. The first major release of the OS, Windows Phone 7.8, is notable for its new "Metro" user interface system, which is a significant departure from the original appearance and experience of Windows Mobile.

Released in 2012, Windows Phone 8 is available across several different platforms, such as desktop and tablets. It is in use by manufacturers such as Samsung, Nokia Huawei and HTC, as the design and hardware offer substantial capacity (Rubino, 2012). Since its acquisition of Nokia in 2014, Microsoft has been revamping Nokia's product portfolio with Microsoft-branded Lumia devices.

4.3 Languages

One of the initial steps in the process of app development is to choose which programming language is suitable for use in a particular app. There is a wide variety of choices to suit a wide variety of apps. Every programming language has its own advantages and limitations and it is important to identify the language that fits the application.

After analysing some of the major programming languages such as Javascript, C#, C, C++, Visual Basic, Objective-C and some cross-platform tools such as Titanium[27], Rhodes[28], PhoneGap[29], Unity[30] and Xamarin[31], It is observed that the programming language Java best fits the requirements of this research, so Java is used as the programming language for this Mobile GIS app development. More details on Java are given in the next sub-section.

4.3.1 Java

Java is an object-oriented programming language from Sun Microsystems. Class-based and suitable for creating applications within a huge range of domains, it is considered a general-purpose language.

[27] Titanium is a free Apache 2-licensed, cross-platform toolkit that lets web developers use JavaScript, CSS, HTML and scripting languages like Ruby or Python to build native apps for the iPhone, Android and the iPad.

[28] Rhodes is a platform for building locally executing, device-optimised mobile applications for all major smartphone devices. http://www.rhomobile.com.

[29] PhoneGap is an HTML5 app platform that lets developers build native apps using HTML5, CSS3 and JavaScript.

[30] http://unity3d.com/

[31] http://xamarin.com/

Developers turn to Java on a widespread basis, in part because it is not necessary to recompile code from one platform to another. As a result, developers can create their software on one device and expect the applications to run on other Java-enabled devices. This capability is becoming increasingly important as users want a higher degree of flexibility between the devices they have, and as more mobile, Internet- and wireless-enabled products hit the market (Riggs et al., 2001). The platform-to-platform concept, embodied by Sun Microsystems' slogan "write once, run anywhere" (WORA), has led to the use of Java on billions of mobile devices and turned it into "the most ubiquitous application platform for mobile devices" (Sun, 2008).

Java ME, also known as Java Platform, Java 2 Platform or Micro Edition, is designed specifically for embedded systems such as mobile phones, printers and micro-controllers. Nevertheless, it maintains the key elements of the standard Java language, leaving the potential for developers to create software that is graphically rich, strong, interactive and easy on available bandwidth (Gupta & Srivastava, 2001). Developers typically distribute their Java ME programmes, or MIDlets, in Java Archive (JAR) files. Users download the applications via web servers. Once downloaded, the programmes can usually run offline on their own (Kenteris et al., 2006).

4.4 Viability for building large applications

Dedicated developers are capable of creating large-scale programmes designed specifically for the mobile environment. Nevertheless, the job is a challenge, and to be successful, developers must overcome some basic problems that stem from the three main properties of mobile computing (communication, portability and mobility) (Forman & Zahorjan, 1994; O'Grady & O'Hare, 2005).

When compared to their desktop counterparts, mobile devices tend to be lacking in terms of how long their power source functions on a single charge. Processing power is not as good, and smaller screen sizes can make viewing and interacting with an application more difficult. Network capability is an additional area in need of improvement. Notably, these gaps between desktops and mobiles are not as large as they used to be (O'Grady & O'Hare, 2005) but improvements in these areas might expand what developers are capable of writing and distributing. According to Islam and Mazumder (2010), mobile applications also stand to become more advanced if additional technical features such as high-performance digital cameras or GPS move forward.

4.4.1 Android OS

With Android dominating the mobile market, it is imperative that developers understand the direction in which the OS is headed. In November 2014, Google released Android 5.0 Lollipop. One of the biggest releases in Android history, it is notable for its considerable differences with Android 4.0 Ice Cream Sandwich. Lollipop offers users extended battery life and a new runtime. Each application is also redesigned. Additionally, through the WebView feature, Google is able to release new updates to users through the Google Play store very quickly, with updates for the WebView browser happening with at least the same frequency as those for Chrome. Users also can check for updates every time they get online via Lollipop's updatable setup process. Finally, Android 5.0 features Play Auto Install, which stores new applications on a temporary basis. Users can use Play Auto Install to download applications whenever it is convenient for them (DotComInfoWay, n.d.). The Nexus 6 phablet, Nexus 9 tablet and the Nexus Player (the first Android TV device) serve as Lollipop's flagships and were the first products designed for the OS. The release of Google Inbox and related software tools also corresponds with the launch of Lollipop onto the market.

4.5 Mobile GIS or devices used for GIS application

The Mobile GIS application will be developed using the Android OS combined with the Java programming language. To get online data access for field work, there is a specific need for handheld devices such as laptops, Personal Digital Assistants (PDAs) and smartphones; the Android OS can be run on tablets, phones and even smart TVs. It therefore becomes crucial to select a device that makes use of Android OS (Lu et al., 2013).

For this Mobile GIS application, the smartphone can be an optimal choice due to a large number of users. Other devices such as PDAs, smart TV's and tablets may have limited users. A laptop could be the better option but still, the issue of large time-consumption and challenges due to larger size are associated with the use of laptops; therefore, the smartphone is the best option (Yi, Jia & Saniie, 2012). Hence, Mobile GIS using smartphones is going to be chosen as a platform for GIS application because it is widely adopted by utilities and enterprises in field work.

4.5.1 Android smartphone and GIS application

In recent years, an incredible development of the mobile industry has been evident which has further facilitated the use of smartphones. Today, smartphones are not only used for calling and messaging but contain numerous functions such as MP3, Wi-Fi-connection, GPS, etc. In previous years, the smartphone was designed with 8 to 32 gigabytes of memory; this, however, has now been increased. Smartphone devices can now connect to the Internet (Fu and Sun, 2010).

Like personal computers, smartphones can work with different OSs, such as iOS, Android, Symbian, Windows and Blackberry. Each OS also has its own GUI. The foremost task for application developers is to develop a mobile GIS application while choosing an optimal OS that may cater the needs of a large number of target users (Fu and Sun, 2010).

The Android OS is the most popular mobile phone OS, and was acquired by Google in 2005. In the secondary investigation, it has been found that the Android smartphone offers a free Software Development Kit (SDK) that can be used by application developers (Kristian, Armanto & Frans, 2012). Furthermore, it has been evident that the Android system is less costly and user-friendly; therefore, numbers of software developers prefer to design Android applications.

In order to gather and update data via mobile GIS, it is important to have wireless communication, as most of the applications need an online connection. Along with this, wireless communication technologies may have different speed, range and setup costs. Some typical technologies can support to Android devices, e.g., Bluetooth, Wi-Fi and cellular networks. Nonetheless, a cellular network is needed to be there; therefore, 4G connection is required as it is the most used network. In the modern technological scenario, 4G technology can support mobile GIS functionalities with its approximate speed of 100 megabits per second (Mbps) (Fu and Sun, 2010).

The GPS function is as important as a wireless communication for a mobile GIS application. Smartphone Android devices have such functions, which are also useful in passive real-time 2D or 3D positioning as well as supportive for navigating and velocity data. A GPS system includes various components such as space, control and user segments (Awange & Kiema, 2013). These components are used for the purpose of monitoring the information on speed, time, bearing, tracking and trip distance. Beyond these features, a GPS system can work with different weather conditions and can even be used 24 hours a day without any payment for the service; nonetheless, Internet connectivity is a must (Qinghua et al., 2010).

A LBS is also required for GIS applications. LBSs are very common on the web, as nearly 20% of web-based search engines provide such services while focusing on places or regions (Liu, Rau & Gao, 2010). LBSs are going to be developed based on the Android platform in the near future; such a development is already underway (Shu, Du & Chen 2009). For many management fields, such as of power grids and traffic, LBSs can act as an emergency support and will also be helpful in speeding up the response time.

4.6 Key characteristics of application development and functionality

To design an effective GIS application, developers need wireless communications, a GPS and a LBS, as the use of all these will boost the speed of information transmission. The inclusion of these will lower the cost. Hence, it can be said that all these features in an application will make an Android-based GIS application more attractive. An investigation into the available literature revealed that a GIS application development must have several key characteristics, such as programming language, system architectures, database systems, an API and an Integrated Development Environment (IDE). The programming language used in Android systems is Java, and this language has been tested, extended and refined by developers.

Furthermore, it has been evident that Android is associated with the Linux platform, which is also denoted as a host middleware, and instructs Java to run the applications. This programming language, Java, is helpful in analysing cloud services that are based on an Android application (Bläsing et al., 2010). In similar fashion, Java is compared with C project and has been found as more advantageous in spatial extensions that are associated with GIS Relational Database Management Systems (RDBMSs) (Martinez-Llario & Gonzalez-Alcaide, 2011). The GIS application designed for the Android Software will be based on modern DBMSs; the database is a major characteristic for storing data. Among the major characteristics of GIS application development, the availability of an IDE is important as this is used for assisting programmers in developing software. Along with this, IDE is helpful for programmers to test the application. In order to develop an Android application, an ordinary IDE named Eclipse can be used (Fu & Sun, 2010).

4.7 Conclusion

Around the world, Android is a heavyweight, controlling about 80% of the mobile market. It is attractive to both developers and users as it is capable of running on a plethora of products and is open source. The number of apps available is also considerable. Nevertheless, these benefits come with some costs—namely, poor security and fragmentation.

This literature review demonstrates that consumers have plenty of choices when it comes to mobile phones. The four major OSs currently in use differ significantly when it comes to elements such as security and functionality. None of these systems necessarily wins over the others. The market has produced multiple high-quality choices capable of meeting different consumer needs, just as it should, with the industry growing naturally to the advantage of manufacturers and consumers alike.

After reviewing multiple OSs, we decided to use the Android OS, for its wide user base, to build the Mobile GIS application. The Java programming language has a clear edge over the other programming languages which were listed in section 3.3, so we used Java for the research and development of this GIS app.

Chapter 5 An application that integrates Mobile-based GIS modelling and hydrological nowcasting: architecture and implementation

5.1 Introduction

This chapter describes the architecture and implementation of a prototype real-time, mobile-based GIS modelling tool for hydrological nowcasting applications. First, functional requirements are given regarding data acquisition and analysis, user-side operation and performance. The upper Wye catchment in Central Wales is discussed as the problem domain. Then the integration of the test model for flood hydrology with the data transmission system and mobile-based GIS technologies is discussed. Next, the data collection hardware is described: the devices used in the prototype are automatic loggers, wireless modems and Windows servers. This is followed by a description of the computer hardware and software used in the prototype. Online watershed simulation and analysis is discussed, along with the support of spatio-temporal hydrological analysis tools in understanding and decision-making. Platform heterogeneity within and across cooperating enterprises, and with legacy applications and data, is also considered. Multiple geographical data structures are integrated into a single conceptual framework to deal with different data models, which are discussed in turn. Java, PHP, Perl and Android provide the support needed to develop the GIS within the mobile paradigm. Then, the user interface flow is described, including LBSs, time-series analysis, query and map tabs, and the map viewer. Finally, the system testing process is described, followed by a summary of the modelling tool architecture and use.

5.2 Requirements

Functional requirements for a mobile-based GIS include the ability to invoke remote services, share information and execute functions across heterogeneous computing environments. Specific requirements include real-time data acquisition and analysis, user-side operation with a Web browser only, speedy performance, preferably under a few seconds per request, and low cost, particularly for the user.

Technical support requirements include software, hardware, an Internet connection and specific development tools. The Internet connection should have a high bandwidth; if the system connects to the Internet through a local area network with a firewall, placing it outside the firewall will ease the programming. (For the prototype, the system site connects to the Internet through the network, which has no firewall).

The problem domain choice determines the requirements for the database, the system functions and the system results.

5.3 Problem domain

The area chosen for field data collection is the upper Wye catchment in Central Wales. Data for the project was obtained from the Institute of Hydrology. The Institute's Plynlimon catchments are found in the centre of the Cambrian Mountains in Central Wales. To give a situational framework and backdrop, they are placed at the headwaters of the Rivers Wye and Severn. The 870-hectare Severn experimental catchment is largely forested with spruce, while the 1005-hectare Wye experimental catchment is mostly pasture grassland. The basic instrumental network, with 40 storage rain gauges, nine river-gauging stations and four automatic weather stations, is supplemented by recording facilities, a manual weather station and soil-moisture access tubes. The original Plynlimon experiment was a water-budget investigation designed to resolve the controversy over the water yield of forested and moorland catchments but the facility soon became an outdoor laboratory used for investigations of flood generation, modelling of hydrological systems and the study of upland water quality.

The upper Wye catchment, the focus of this research, is much smaller, comprising an upland research basin that has been used previously for hydrological modelling (Bathurst, 1986a; Bathurst, 1986b; Quinn & Beven, 1993; Kirchner, 2009). The basin covers 10.55 km^2; elevations range from 350–700 m above sea level; and average annual rainfall is approximately 2,500 mm (See et al., 1998). Ground cover is grass or moorland, and soil profiles are thin, mostly peat overlying a podzol or similar soil (Knapp, 1970; Newson, 1976a).

This area has been the focus of intensive hydrological modelling and research for 30 years. For example, in TOPMODEL (Beven and Kirkby, 1979; Neal, 2004), forecasts were acquired for the upper River Wye. This physically-based process model, first developed in the late 1970s, was calibrated on 1985 data with additional predictions computed for 1984 and 1986 (See & Abrahart, 1999) using the reported parameterisations of Quinn and Beven (1993). For other investigations and information on this area, refer to Rodda (1971), Kirby et al. (1991), Rowan and Walling (1992), Edmondson (1995), Pilling et al. (1998) and Pilling and Jones (2002).

The choice of the Plynlimon catchments for the prototype was motivated by the importance of the area, as indicated by the number of research studies performed there, and the amount of available data.

5.4 Data-collection hardware

Data capture and input, generally the most time-consuming task in building any GIS, have two main requirements (Worboys and Duckham 2004). First, one must provide both the physical devices for capturing data external to the system and a method for inputting the captured data into a database. Windows servers, automatic loggers and wireless modems are the devices used in the prototype. The field data is collected automatically in real time by rainfall-measuring gauges and transmitted via a wireless modem to a Windows server for storage. It is 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. Second, one must provide software for converting the field data into structures compatible with the database and for checking the data integrity. A Java-based subsystem is used in the prototype. The data-collection configuration is shown in Figure 5.1.

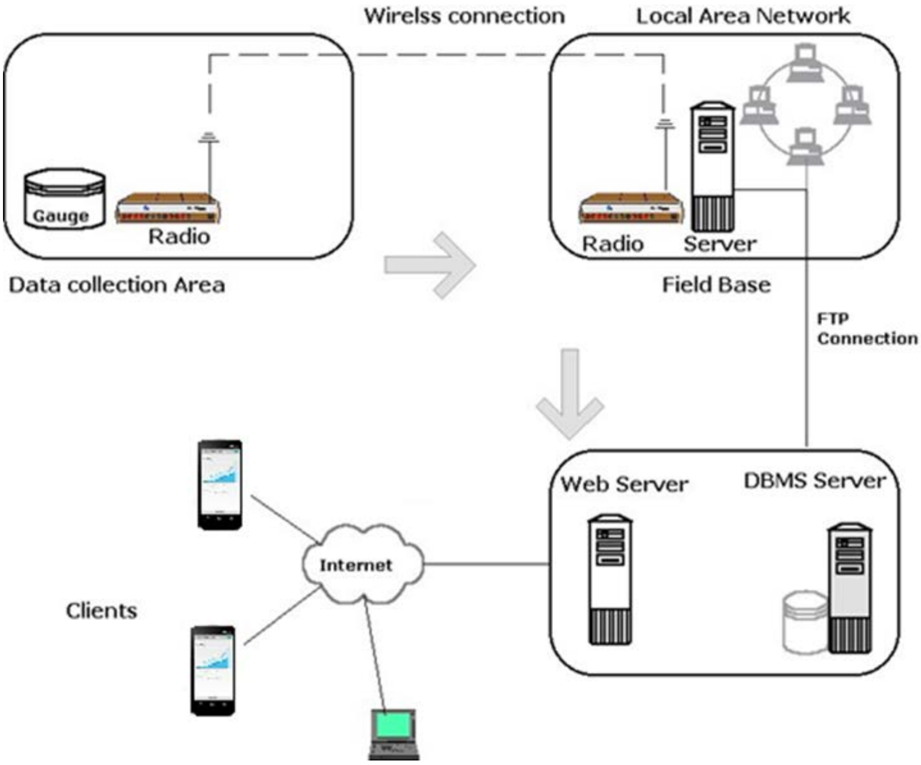

Figure 5.1 Connection Model

5.4.1 Rainfall measurement

A *rain gauge* is a device used to measure rainfall over a specified period. Some also measure frozen precipitation. Precipitation is measured as the vertical depth of water that would accumulate on a flat level surface. Rainfall is measured in inches or millimetres by means of a simple receptacle-and-gauge apparatus or by more complex electrical or weighing devices placed where eddies of air will not interfere with the normal fall of raindrops. In addition to daily, monthly and annual totals, the depth of individual rainfalls and their intensity—the amount of rain falling during a specific time period—and other pertinent facts are recorded. In the prototype, two tipping-bucket rain gauges—Aerodynamic rain gauge arg100/LX fitted with plug to suit data logger—were used in Plynlimon catchments.

5.4.2 Spread-spectrum radio modems

A 2.4-GHz frequency-hopping spread-spectrum radio modem with an RS-232 serial interface was chosen. It operates licence-free with world-wide compliance at full-duplex speeds up to 115.2 Kbps asynchronously or 64 Kbps synchronously. The radio has an over-the-air data rate of 250 Kbps. The basic modem has 80mW of output power and a range of over 300 metres with a small whip antenna attached to the jack on the rear panel. Ranges of up to 30 miles line-of-sight are possible with high-gain directional antennae. Installation is simple and inexpensive. With such wireless technology, one can forgo wire or fibre cable, which is more expensive and difficult to install.

5.5 Computer hardware

5.5.1 Web-server computer

For the Web server, we selected a Dell PowerEdge computer, with Intel® Xeon® E5-2403 v2 1.80GHz, 4GB memory and a 500-GB hard disk.

5.5.2 Database server

The database server is similar to that of the Web server. A database server allows clients to send Structured Query Language (SQL) request messages to the database and the database returns results to the users.

5.5.3 Design guidelines

This section describes the software design of the Rainfall Analysis System, a client–server software solution for flood prevention. Users are able to browse statistical data about precipitations that are crossed with terrain elevation models to highlight the areas where water is likely to flow more intensively, thus risking generating flood events.

The system offers the system administrator the capacity to manage the data on which the system operates (i.e., pluviometric data and DEMs of the monitored areas). Weather stations can also push data directly to the system via a web interface, or these data can be manually uploaded by the system administrator. Meanwhile, end users can query the pluviometric data stored in the database and get results in the form of tables or graphs as well as browse landscape maps generated by the system, merging the digital elevation models provided by the system administrator with the statistical pluviometric data.

5.6 Software

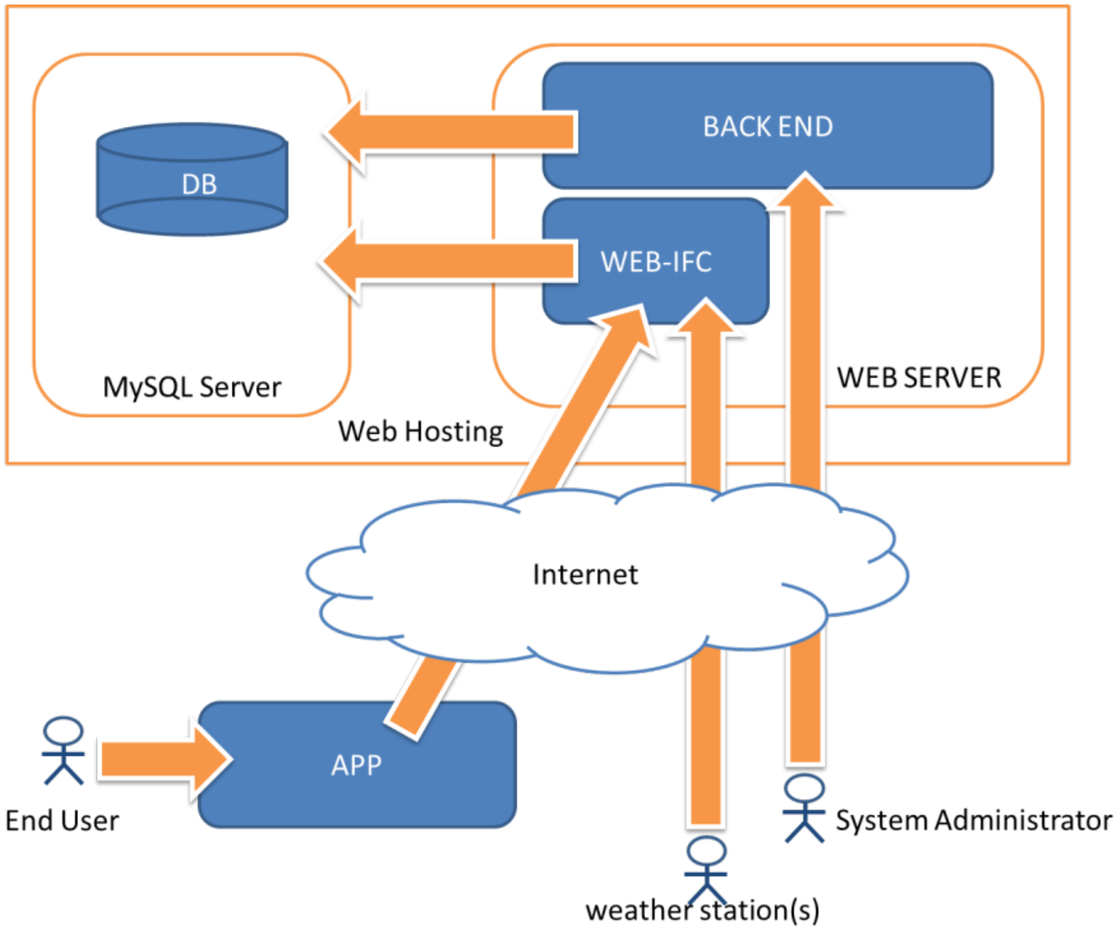

Figure 5.2 System diagram

The system is composed of the following high-level software components (or macro-blocks):

1) **Database (DB)**. The DB is a database in MySQL format, which stores the pluviometric data as well as the existing DEMs; this should be in a format that is suitable not only for querying but also for processing.

2) **BACK-END**. A back-end is a web application that is used by system administrators, which allows them to manage the entry of data and promotes efficient data browsing.
3) **WEB-IFC**. A web interface that executes the data retrieval functions that are needed in the application-level (e.g., the performance of high-level queries on the database; the retrieving of a map tile, etc.)
4) **APP**. A mobile application that implements the user interface being used by the users to identify and make queries. It retrieves data from the DB through WEB-IFC and displays them in an easy-to-understand format.

The diagram above depicts graphically how these four components work together.

In the following sections, the architecture and behaviour of the various macro-blocks will be described in detail.

5.6.1 The database (DB)

The DB is a relational MySQL database capable of storing atmospheric data as well as DEMs in a format that is easy to use for queries and process-based requests. There are two options for the choices of a MySQL client for DB design: PHPMyAdmin (web tool), an interface (web-based) that can be installed and is available through various hosting platforms on the Web; and MySQL Workbench, a PC client that is used to connect local and remote MySQL databases. Among its capabilities and operations are the reverse engineering of existing databases, generating a graphical diagram of tables.

For this project, DB design is critical. This means that the design for the DB should allow users to spend as little time, through the most efficient means, possible. Because of this, we expect large amounts of data used in the DB.

With one operating weather station capable of reading data from five required atmospheric parameters hourly, which includes the sending of data every hour to the server, each year there will be at least 8,760 samples generated. In a small area, for example, there are already 100 weather stations being used, which translates to 876,000 samples every year.

DEM storage alone requires huge amounts of data. The manipulation of that much data would need not only a solid back-end system, but also powerful hardware.

5.7 Development

Project implementation may be divided into two major aspects: server-side (back-end) and client-side (mobile application). These are discussed in turn in the following two subsections.

5.7.1 The server-side (back-end)

The back-end is a software or dashboard that system administrators may use to manipulate (i.e., edit and upload) data. Functions for the back-end include the creation and editing of locations, uploading of location atmospheric data and uploading of DEMs. Aside from this, the back-end enables auto-generation of random locations and data. The developer needs a text editor for this task.

This component is inspired by a closed-source application called the **0xFF-SBE**[32] (SBE stands for "Simple Back End"). The 0xFF-SBE is capable of the creation of a password-protected area on the web server. This part of the server may only be accessed by users who are logged in. However, registration is not among the user's options. To register, users may manipulate the database through the PHPMyAdmin. The 0xFF-SBE is also able to expose APIs so that the MySQL may conveniently be accessed. It also allows for a public area ("front-end") which allows database access as well as some aspects of the "back-end" so that the data may be displayed to users. Ours does not include the public area. Meanwhile, the 0xFF-SBE also executes permissions for plug-ins that have several functionalities. We have

[32] The 0xFF-SBE is a plug-in that operates as a self-contained module.

developed a customised plug-in that is called the ‘GIS’. All the logic of the Rainfall Analysis System back-end component resides in this plug-in. The Rainfall Analysis System’s back-end component’s logic is located here. Other capabilities of the 0xFF-SBE are the redirection of users who are not logged in and the sharing of a format that is common, including headers, content areas and footers.

A thorough exposition of the 0xFF-SBE’s design is beyond the scope of our document, which only refers to the Rainfall Analysis System’s design. Our document will only describe the 0xFF-SBE plug-in’s generic structure, and the Rainfall Analysis System plug-in (GIS) for 0xFF-SBE’s detailed design.

Below, we see a screenshot of the website’s main page.

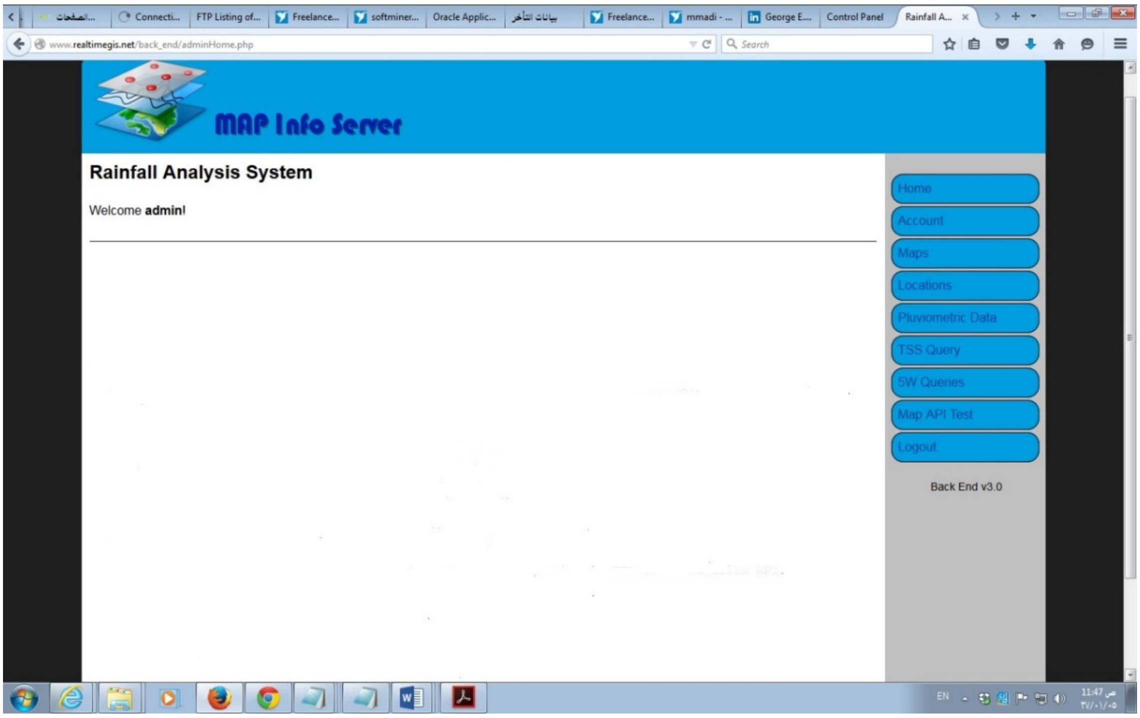

Figure 5.3: A screenshot of the website’s main page

The following are the functions that are performed at the server-side:

5.7.2 The dynamic model

A hydrologic model, a computerised representation of a natural system, embodies mathematical equations depicting the processes of water flux and storage within the earth–atmosphere system. Such models are used for: (a) a better understanding of the hydrological system; (b) prediction of flood events and their area of influence; and (c) impact assessment for land surface, climate change or river engineering scenarios. Prediction and impact assessment help to manage river systems and flood hazards.

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

The prototype's dynamic and spatial model, designed to meet the four essential requirements (real-time data analysis, data accessibility, visualisation and public involvement), provides a quantitative description and understanding of hydrological processes. It is only one of many potential applications that could have been developed; the purpose of its incorporation in the prototype is not to demonstrate the model itself but rather to develop a means of implementation that can readily be applied to other models and other applications.

The model, approximately 1150 lines of Perl, was previously developed and used within an offline spatial decision-support system for the MODULUS project (Engelen, 2000; Oxley et al., 2002). It was chosen because it is a simple data-lean system, which had already been applied within the context of decision support for hydrological purposes at the regional scale. Many better hydrological models were available, but none had the advantages of simplicity and previous application, as well as being in-house and thus available freely for this project.

5.7.3 Dynamic-modelling functions

Using a regularly gridded DEM, the model programme calculates the *accumulated water* flowing out of a cell into its neighbouring downstream cell. Accumulated water is that in the cell plus that transported from upstream cells. In addition, the movement of water downstream over a local drainage network is calculated. Based on the transport capacity of a cell, only a transport of water less than or equal to that capacity is modelled; remaining water is assumed to be stored.

Cell properties are table-driven. For example, *infiltration capacity*, the maximum amount of water that can infiltrate during one time-step, different for each soil type, is given by a lookup table similar to that in Table 5.1. Given an infiltration soil map showing soil type and the infiltration capacity table, an infiltration capacity map can be generated.

Table 5.1: Infiltration Capacity

Key	Capacity mm/2 hrs
1 (clay)	2.1
2 (loam)	8.3
3 (sand)	19.0

For each time-step, cell values are assigned based on a time-series linked to a soil map. Values for each cell or cells are written to a time-series file. The result, after a model run, is a time-series containing a list of cell values per time-step for each identified cell.

5.7.4 GIS functions

A local drain-direction map is created using the 8-points-pour algorithm with flow directions from each cell to its steepest downslope neighbour. The algorithm used is one of several widely-accepted and used algorithms which were utilised in this project in order to build on existing knowledge. Aspect and slope are calculated using elevation data from a digital elevation model. Comparison, Boolean, arithmetic, trigonometric, exponential and logarithmic functions are performed on a cell-by-cell basis. For example, with the constant definition moist_critical=20, the programme can compare moisture map values with the moist_critical constant to do further analysis, such as reporting the result to a time-series file. For another example, to convert a runoff map from mm/2 hrs to m^3/sec at each time-step and to transform to an approximately normal distribution with the log10 operator, the programme computes LogRunOff = log10 (Runoff/ConvConst + 0.0001), where ConvConst=720000 is a constant definition in the programme for the conversion of mm/2 hrs to m^3/sec.

The programme specifies maximum and minimum cell values. Commands are available for operations such as summing all cell values and calculating the total area represented by non-missing-value cell values. One non-spatial value, as a function of cell values associated with a map, can be computed. For example, the programme can compute the maximum value of moisture content of two or more soil moisture maps and write the result to a time-series file showing soil-moisture-content variation over time.

5.7.5 Programme operation

The dynamic modelling programme runs continuously in the background, processing incoming rainfall data through hydrological analysis. At each time-step (of one hour), the maps and data tables from the previous time-step are used to calculate new maps and data tables. For each time-step, a time series containing a set of map cell values is input or output. Figure 5.4 illustrates the dynamic model.

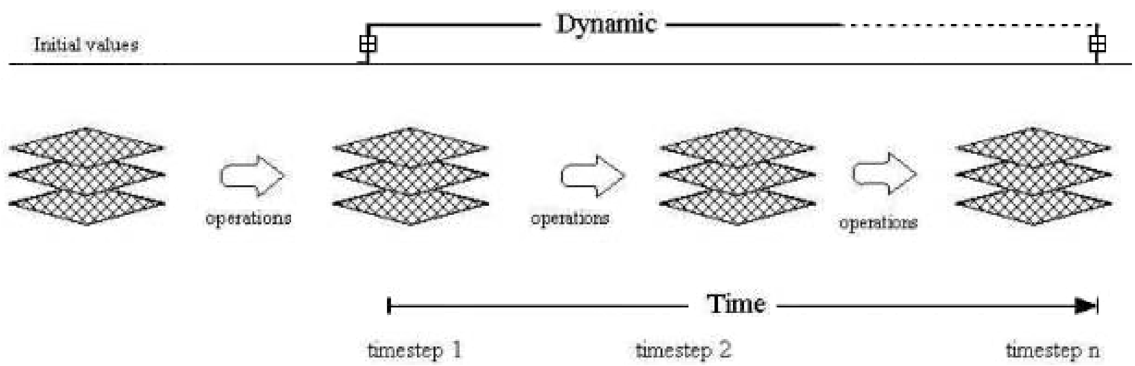

Figure 5.4: Dynamic Model

For each time-step, non-spatial time-series and spatial raster-image data on variables such as rainfall and soil moisture are stored as a set of maps, one for each time-step, or as a time-series file. A database loading programme uploads these files automatically to the database. Figure 5.5 illustrates the interactions between the model, the loading programme and the database.

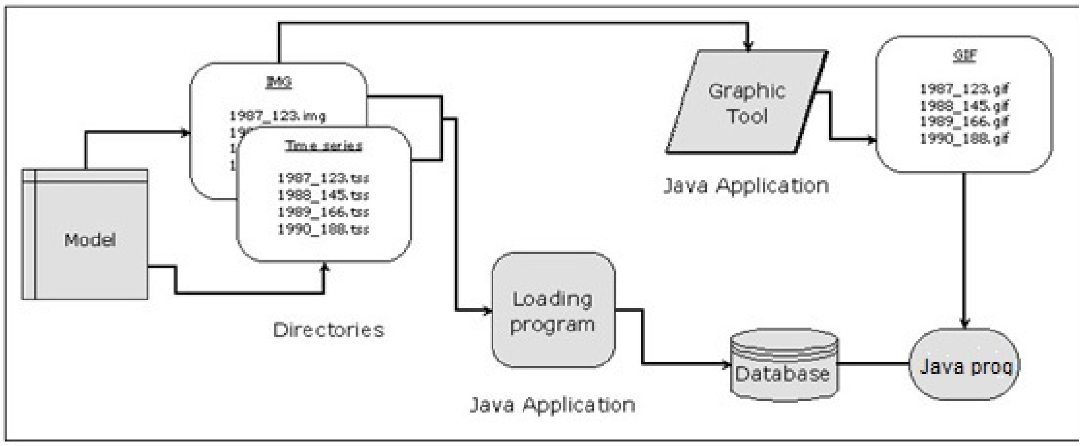

Figure 5.5: Interactions within the modelling programme

5.7.6 Image rendering and map generation

To display a DEM image along with the results obtained by applying a hydrological function, such as aspect or slope, a rendering algorithm maps between the DEM data, or the function results, and a colour palette. The image is displayed dynamically.

Elevation is the simplest possible transformation. It relies on the Elevation() function, which reads the elevation value from the DEM data given its latitude and longitude. The Elevation() function's task here is simply to decide what colour to assign to the pixel at these coordinates, given its elevation. To do that, the map API supports two different colour schemes.

5.7.7 Colour schemes for elevation transformation

For elevation transformation, two colour schemes can be used: greyscale and multi-colour. In the greyscale colour scheme, the colour of a pixel is directly proportional to its elevation. An RGB colour where the red, green and blue components are the same is a shade of grey, with RGB (0,0,0) being black and RGB (255,255,255) being white. Therefore, if we assign MAX_ELEVATION to the value of the maximum possible elevation (on Earth, this is the 8611 meters of Mount Everest, but in the UK/Ireland the 1344 meters of Ben Nevis suffice), then we can calculate the colour of any pixel with a simple division:

Colour (LAT, LON) = **RGB**(V, V, V),

Where V = **Elevation**(LAT, LON) x 255 / MAX_ELEVATION

So, for example, if at the latitude (0, 0) we read elevation = 15 m above sea level, the colour assigned to its pixel (or area, if the map magnification is very high) will be RGB (3, 3, 3), so almost black. The summit of Ben Nevis will instead appear white.

In multi-colour scheme, instead, the colour is assigned according to the following legend (the same as usually found on geographic maps).

Elevation	Approximate pixel colour with multi-colour scheme
Depression (< 0 m)	
0–200 m	
200–500 m	
500–1000 m	
1000–2000 m	
2000–3000 m	
> 3000 m	

Figure 5.6: Multi-colour scheme legend

Once a DEM is displayed, a user can adjust the map view with zoom-in, zoom-out and pan. After calculating colour for each data value, the programme generates a visual image for an arbitrary zoom factor. For zoom factor 1, each data value is represented by a single pixel, for which colour is easily calculated. For zoom factor 2, each data value is represented by four pixels, all with the same value. For zoom factor 0.5, only even values are displayed.

Panning is the process of moving the map in a specified direction; the cursor is positioned and the mouse clicked and dragged. Since panning is performed in Java, there is no need to send the coordinates of the map to the server and wait for a result, as it is done in a server-side application. The generated image is shifted and the programme renders only the visible part. The relevant events are mouse-Down to set the anchor points for the image, mouseUp, and mouse-Drag to move the image. The new image moves from the anchor point to the mouse position.

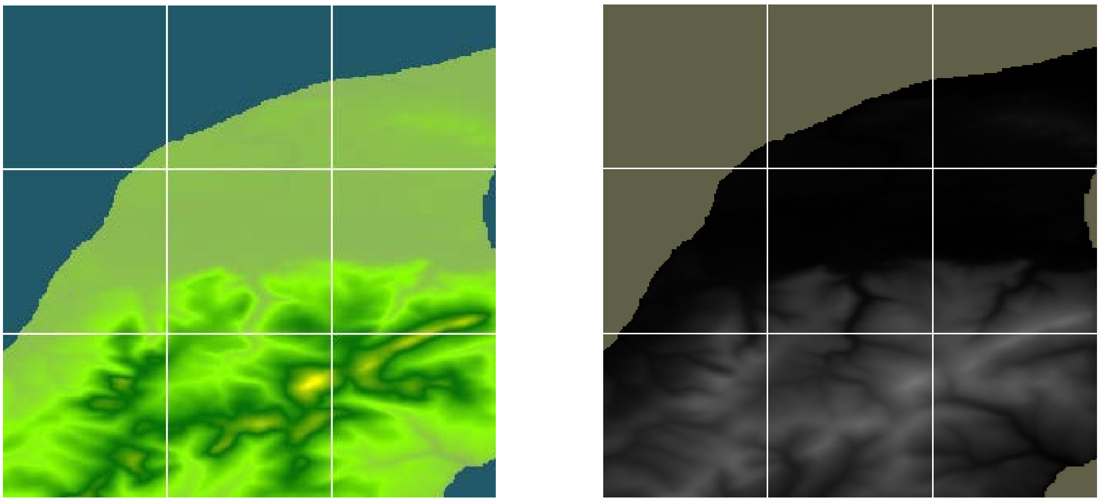

Figure 5.7: An elevation map in which upper left corner is (latitude: 54.435; longitude -4.60315), rendered in multi-colour (left) and greyscale (right)

5.7.8 Analysis functions

The analysis used provides a variety of methods such as slope and aspect terrain analyses. The slope function works as follows. For each cell, the programme calculates the slope of the cell based on the elevation of its eight neighbours in a 3x3-cell window. The maximum-drop method of Horn (1981) and Skidmore (1989) is used. The slope result is given as *dz/dx*, the change in vertical distance per change in horizontal distance.

5.7.9 Slope transformation

Slope is defined as the change in elevation over a certain distance. In this case, the certain distance is the pixel size. Slope is most often expressed as a percentage, but it can also be calculated in degrees. We calculate the slope for a point by using the elevation of the nearest available points on a 3 x 3 window. To calculate the slope for the following 3 x 3 window, we follow the algorithm used by ERDAS IMAGINE. This algorithm is described below.

A	B	C
D	E	F
G	H	I

Figure 5.8: 3×3 window to calculate slope

$\Delta x1 = C - A$ $\Delta y1 = A - G$

$\Delta x2 = F - D$ $\Delta y2 = B - H$

$\Delta x3 = I - G$ $\Delta y3 = C - I$

$$\Delta X = (\Delta x1 + \Delta x2 + \Delta x3)/\ 3 * x \text{ pixel size in metres}$$

$$\Delta Y = (\Delta y1 + \Delta y2 + \Delta y3)/\ 3 * y \text{ pixel size in metres}$$

The slope (in percentage) at pixel x, y is then calculated as:

$$\text{Slope (in percentage)} = SQRT(\Delta X\text{^}2 + \Delta Y\text{^}2)/2$$

To convert slope percent to degrees (0°=flat, 90°=vertical) we use the arctan() function like this:

Slope (in degrees) = arctan (slope in percentage)

where slope percentage is entered as a ratio; thus 63% is entered as 0.63.

Example

Consider the following matrix, assuming that the cell size is 10×10 metres:

A 42	B 45	C 47
D 40	E 44	F 49
G 44	H 48	I 52

Figure 5.9: Example of 3X3 Window to calculate slope

$\Delta x1 = C – A = 5$ $\Delta y1 = A – G = -2$

$\Delta x2 = F – D = 9$ $\Delta y2 = B – H = -3$

$\Delta x3 = I – G = 8$ $\Delta y3 = C – I = -5$

$$\Delta X = (\Delta x1 + \Delta x2 + \Delta x3)/ 3 * x \text{ pixel size} = 22/(3 * 10) = 22/30 = 0,7333$$

$$\Delta Y = (\Delta y1 + \Delta y2 + \Delta y3)/ 3 * y \text{ pixel size} -10/(3 *10) = - 10/30 = - 0,3333$$

$$\Delta Z = SQRT(\Delta X\text{^}2 + \Delta Y\text{^}2)/2 = SQRT(0,5377+0,1111)/2 = SQRT(0,6488)/2 = 0,8055/2 = 0,4027$$

$$\text{SINCE } \Delta Z < 1$$

$$slope\_pct = \Delta Z * 100 = 0,4027 * 100 = 40,27\%$$

$$slope\_deg = \arctan(slope\_pct) = \arctan(0,4027) = 21,9o$$

5.7.10 Colour schemes for slope transformation

For slope calculation, two colour schemes can be used: greyscale and multi-colour.

In greyscale, the colour of a pixel is directly proportional to its slope value (in percentage). The logic is exactly the same as seen in the previous paragraph, except that now our maximum value, MAX_SLOPE, is 100, and the Slope() function is the algorithm just described. Thus, the colour of a pixel can be obtained as follows:

Colour (LAT, LON) = **RGB**(V, V, V)

Where V = **Slope**(LAT, LON) x 255 / MAX_SLOPE

In the multi-colour scheme, the colour is assigned according to the following legend (we use the 7 colours of the light spectrum, with lower frequencies to represent lower slopes and higher frequencies to represent higher slopes).

Slope (percentage)	Approximate pixel colour with multi-colour scheme
0–15 %	
15–30 %	
30–45 %	

45–60 %	
60–75 %	
75–90 %	
>90 %	

Figure 5.10: Multi-colour scheme legends

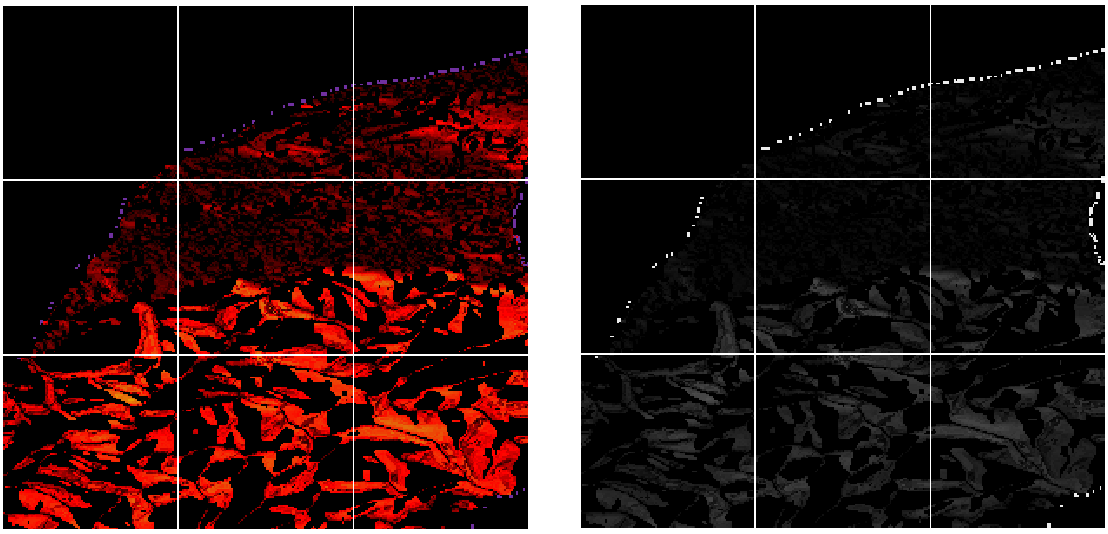

Figure 5.11: The same map as in the previous example, where the slope transformation has been applied, rendered in multi-colour (left) and greyscale (right)

To test the slope function, the slope-function result was compared to that of Idrisi software run on the same DEM. Then the image produced by Idrisi was overlaid with our image and the Idrisi pixels subtracted from the pixels of our system. Figures 5.12, 5.13 and 5.14 show the image generated by the proposed system, the Idrisi image and the combined image, respectively. The overlay operation was performed using Idrisi's overlay function.

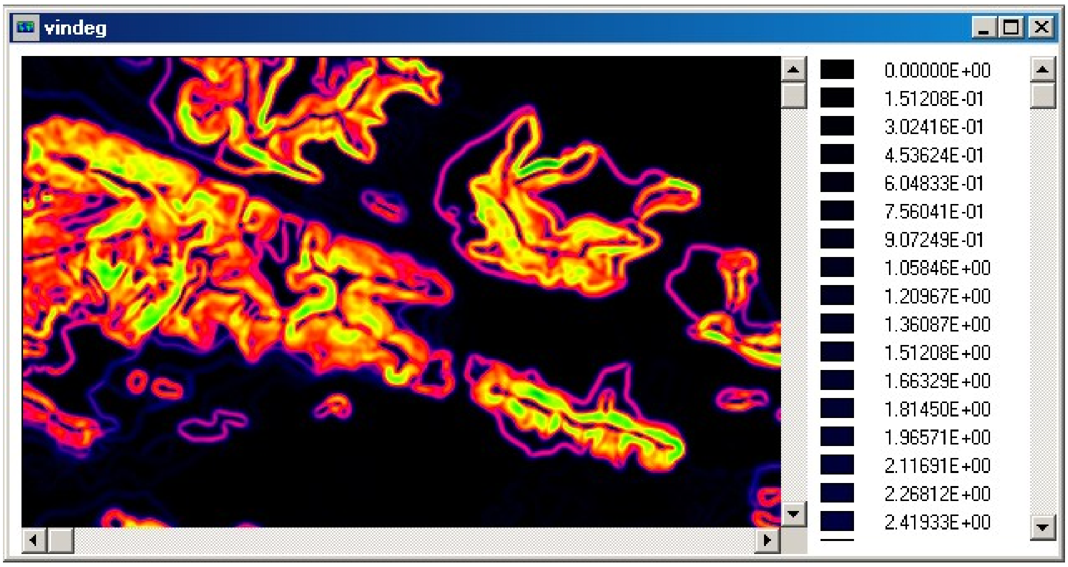

Figure 5.12: Slope generated by the proposed system

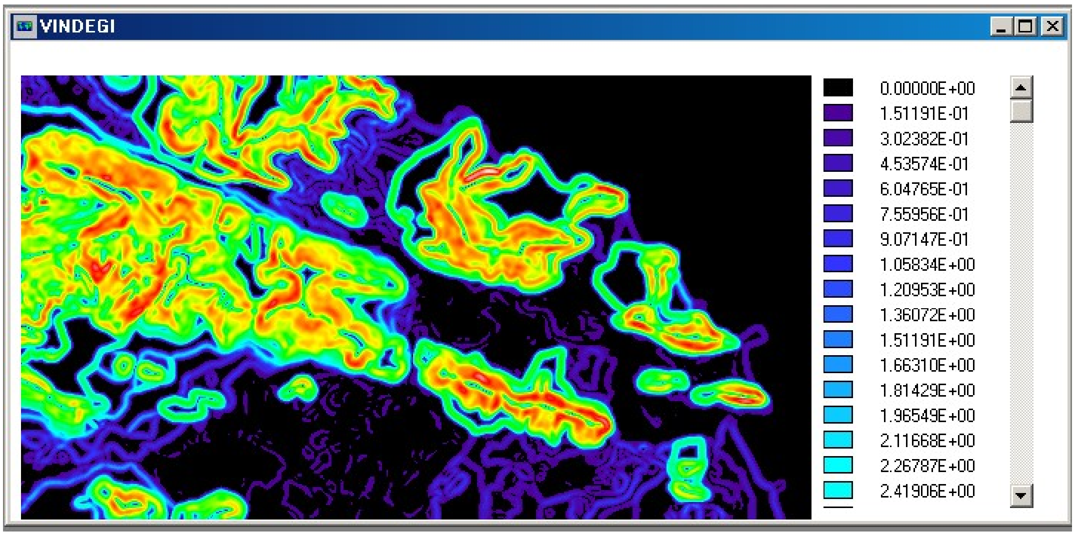

Figure 5.13: Slope generated by Idrisi

A histogram of the overlay results shows that the difference between the proposed system and Idrisi methods ranges from –1.04 to –1.2 degrees. Although the calculated slopes differ, because different algorithms are used, the variation is very small.

Figure 5.14: Overlay result

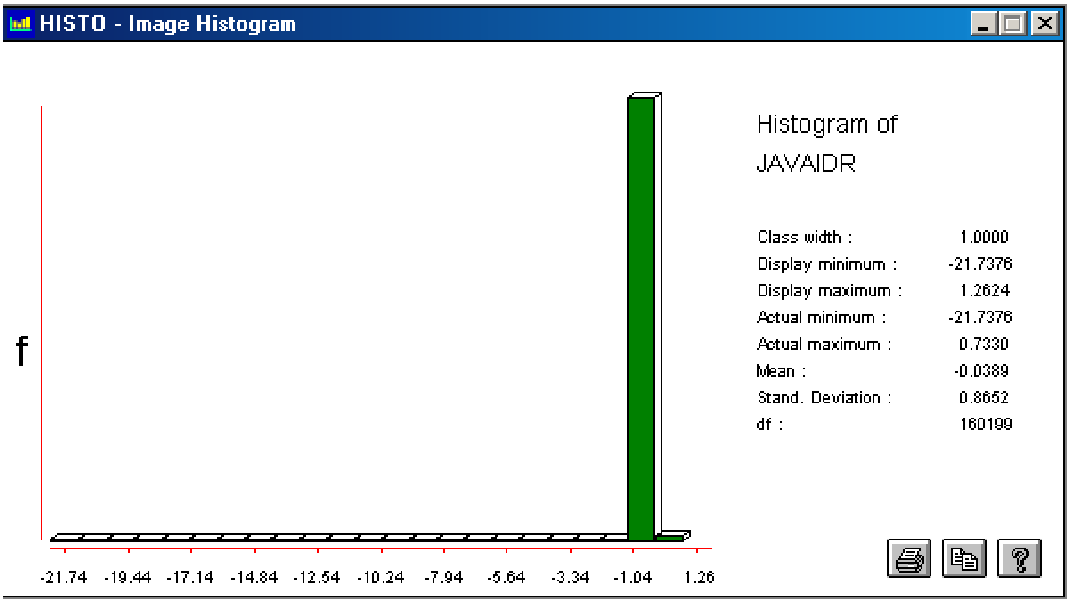

Figure 5.15: Histogram of Overlay Operation

This histogram clearly demonstrates the accuracy of the result; however, it is important to note that showing accuracy is not the objective of this project. If it were, many more slope comparisons for different images would be needed, and it is beyond the scope of this research to provide such data.

5.7.11 Aspect transformation

Aspect is defined as the prevailing direction that the slope faces at each pixel. It is calculated from 0° to 360°, with 0° being true north and 180° being true south. Similarly to the slope, the aspect of a given point is calculated using the elevation of its neighbouring points on a 3 x 3 window. The algorithm that followed also comes from ERDAS IMAGINE, and is described below.

A	B	C
D	E	F
G	H	I

Figure 5.16: 3×3 window to calculate aspect

$\Delta x1 = C - A$ $\Delta y1 = A - G$

$\Delta x2 = F - D$ $\Delta y2 = B - H$

$\Delta x3 = I - G$ $\Delta y3 = C - I$

$$\Delta X = (\Delta x1 + \Delta x2 + \Delta x3)/ 3$$

$$\Delta Y = (\Delta y1 + \Delta y2 + \Delta y3)/ 3$$

If $\Delta X = 0$ and $\Delta Y = 0$, then aspect is flat (coded 361°). Otherwise, given θ:

$$\theta = \arctan (\Delta X / \Delta Y)$$

the aspect is:

$$\textit{aspect in degrees} = 180 + \theta.$$

Example

Considering the same matrix as before:

A	B	C

42	45	47
D 40	E 44	F 49
G 44	H 48	I 52

Figure 5.17: Example of 3×3 window to calculate aspect

$\Delta x1 = C - A = 5$ $\Delta y1 = A - G = -2$

$\Delta x2 = F - D = 9$ $\Delta y2 = B - H = -3$

$\Delta x3 = I - G = 8$ $\Delta y3 = C - I = -5$

$$\Delta X = (\Delta x1 + \Delta x2 + \Delta x3)/\ 3 = 22/3 = 7.3$$

$$\Delta Y = (\Delta y1 + \Delta y2 + \Delta y3)/\ 3 = -10/3 = -3.3$$

$$\theta = \arctan\ (\Delta X\ /\ \Delta Y) = \arctan\ (-2.21) = 65.65$$

aspect in degrees = 180 + 65.65 = **245.65°**

5.7.12 Colour schemes for aspect transformation

For aspect calculation, only a multi-colour scheme is used. Each colour represents a prevailing different orientation.

Aspect (degrees)	Approximate pixel colour
North (337.5°–22.5°)	Blue
North–East (22.5°–67.5°)	Purple

East (67.5°–112.5°)	Yellow
South–East (112.5°–157.5°)	Orange
South (157.5°–202.5°)	Red
South–West (202.5°–247.5°)	Brown
West (247.5°–292.5°)	Green
North–West (292.5°–337.5°)	Bright Blue
Flat (361°)	White

Figure 5.18: Aspect transformation colour schemes

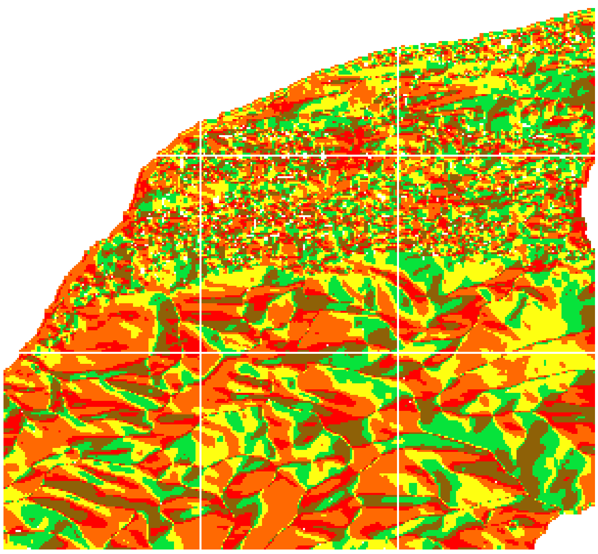

Figure 5.19: The same map as in the previous example where the aspect transformation has been applied, rendered in multi-colour

5.7.13 Accumulated flux transformation

Accumulated-flux (**accuflux**) analysis calculates accumulated water and water flow over a topological network on a *local-drain-direction* (LDD) map. It produces a map of grid cells giving the total amount of water that has traversed each cell.

For each cell in the map, the accumulated amount of water that flows out of the cell and into its neighbouring downstream cell is calculated. This accumulated amount is the amount of water in the cell itself plus the amount of water in upstream cells. An LDD map is first determined, using the eight-points-pour algorithm with flow directions from each cell to its steepest downslope neighbor. From an analysis of a DEM, a grid of flow directions is created, which assigns to each cell an LDD code directed to the neighbour with the lowest value.

An LDD map is a network of cells, with each cell assigned an integer from one to nine to identify the neighbour to which water flows, as in the figure below:

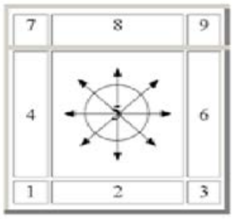

Figure 5.20: LDD map cells indexing

The value five represents a pit, a cell without drainage to a neighbour. Therefore, an LDD map shows the direction of the steepest descent for each cell in the DEM, as in this example of a 5x5 grid:

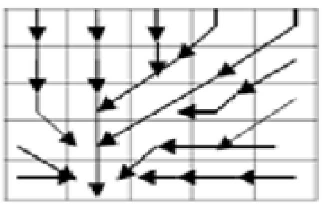

Figure 5.21: An LDD map shows the direction in which the water is likely to flow in each cell

Connecting the individual LDD values yields stream lines for water flow and the drainage pattern of the landscape. After creating the LDD map, if we are given a water map for the grid stating the amount of water initially present in each grid cell, as in Figure 5.21, this can be used as an input for the accuflux calculation.

6	0.5	2	2	2
0.5	0.5	2	2	2
0.5	0.5	2	2	0
0.5	0.5	6	0	0
0.5	6	6	6	6

Figure 5.22 A water map contains the amount of water that each cell lets run off

The accumulated flux map is obtained by calculating the amount of water that flows out of the cell into its neighbouring downstream cell. This accumulated amount is the amount of water in the cell itself plus the amount of water in upstream cells. The procedure and resulting map are shown below.

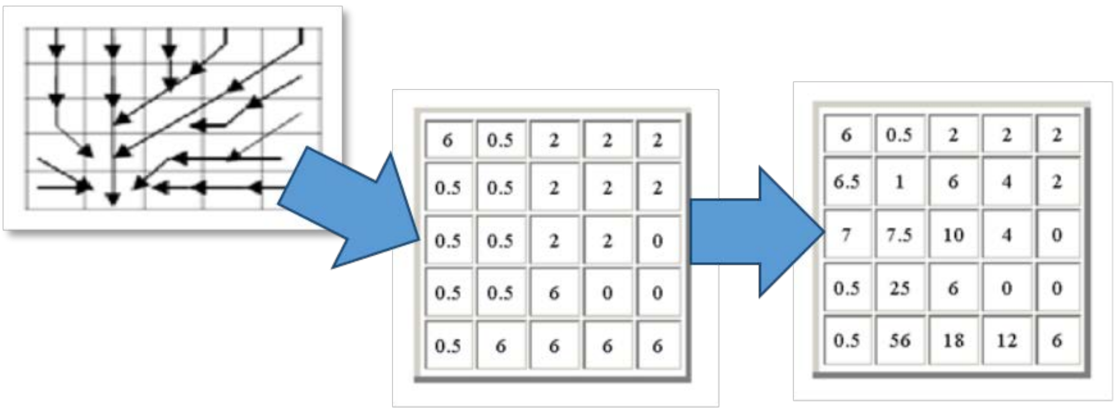

Figure 5.23: Applying the LDD map to a water map generates the accuflux map transformation

5.7.14 Calculating the LDD from DEM data

For the sake of speed and simplicity, the LDD map is generated from the DEM data using the popular D8 algorithm. The D8 algorithm is based on the quite strict assumption that, within a window of 9 cells, water always flows in the direction of the steepest slope. That is, the slope to each of the eight individual neighbors of a central source cell has to be calculated using the following formula:

$$slope = \arctan\left(\frac{\Delta z}{d}\right),$$

where d is the distance and Δz is the elevation difference between two grid points. In a raster, where the cell width is 1, we have to distinguish between two situations:

- If we compute the slope in cardinal directions (north, east, south or west), the distance, d, between the grid points is 1.
- If we want to compute the slope in diagonal directions (northeast, southeast, southwest and northwest), the distance, d, between the grid points is $\sqrt{2}$.

Thus, once again, we use a moving window of 3x3 cells and, given a cell, we calculate the slopes of the neighbouring cells. The water will flow from the cell under consideration to the neighbouring cell that has the highest slope. We can say, therefore, that the cell in consideration points to a target cell. We tag our cell with a numeric id that represents the direction to the target cell. Doing this for all the cells in the tile (a cell corresponds to a pixel) produces the LDD map.

Example:

27	26	22
15	33	13
22	32	32

Figure 5.24: 3×3 window to calculate LDD

$$Slope = arctan(\frac{biggestvalue - value}{pixeles \times d})$$

arctan[(33-27)/(3*sqrt(2))]= 0.955 rad	arctan[(33-26)/(3*1)]= 1.165 rad	arctan[(33-22)/(3*sqrt(2))]= 1.202 rad
arctan[(33-15)/(3*1)]= 1.405 rad		arctan[(33-13)/(3*1)]= 1.421 rad
arctan[(33-22)/(3*sqrt(2))]= 1.202 rad	arctan[(33-32)/(3*1)]= 0.321 rad	arctan[(33-32)/(3*sqrt(2))]= 0.231 rad

Figure 5.25: Step 2 in calculating LDD

If we calculate the slopes, we see that the steepest slope is the one towards the yellow cell. We can then assume that the water will flow from the red cell under observation to the yellow cell on the right.

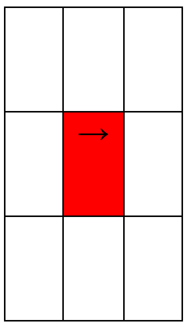

Figure 5.26: Step 3 in calculating LDD

Therefore, we tag the red cell with a “right arrow” that corresponds to the value “6”.

Moving the window over the DEM for the number of pixels needed produces the LDD map, which may look like this:

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	↖	↖	↖
0	0	↖	↖	↖	↖	↖	↖	↑	←
↖	↖	↖	↑	←	←	←	←	↖	↘
↖	↑	←	↖	←	←	↖	↓	↓	↘
←	↖	↖	↙	←	↙	←	↙	←	↓
←	←	←	←	↖	←	↙	↙	←	↓
↘	→	→	↘	↘	→	→	→	↗	↓
↘	→	→	↗	→	→	→	↗	→	↙
↓	→	↗	↘	→	→	↘	→	→	↗

Figure 5.27: LDD Map

The value 0 is assigned for cells whose neighbours all have the same slope (i.e., cells in a plane). The water flow direction for cells in a plane is undefined. In this example, the zeroes represent the sea, while the arrows represent the local drain direction (LDD) of cells on the land.

The arrows to numbers used in the code are the following:

↖	↑	↗
←	·	→
↙	↓	↘

Figure 5.28: Example of LDD map

1	2	3
4	5	6
7	8	9

Figure 5.29: The coding of arrows

5.7.15 Calculating accumulated flux transformation given the LDD map, and colouring it

After having calculated the LDD map, we can calculate flux accumulation by applying the LDD map to a water map that states the initial conditions (i.e., the amount of water initially available in each cell of the map). As explained before, this operation modifies the water map and results in a map where each cell contains the accumulated amount of water that flows out of the cell and into its neighbouring downstream cell.

For the sake of simplicity and given the scope of this project, we will assume that the amount of water initially present in each cell is constant. Therefore, our water map is a grid that has the same width and height in the cells as the LDD and contains in each cell a value representing the amount of precipitated water that each piece of terrain (measuring *pixel_width x pixel_height* square metres) lets run off, and in reality depends on factors such as the nature and composition of the soil. For the time being, we do not have any information about this but if this information becomes available in the future, the algorithm can easily be modified to populate the water map properly rather than one that assumes a constant value for each point: the implementation uses a function called *waterMapGet (Lat, Lon, Width, Height)* that returns the water amount from the water map for a terrain block centred in <*Lat,Lon*> and *Width* metres wide by *Height* metres tall. For now, this function simply returns the value of the *WATERLEVEL* constant (1) but in future it may be extended to read from a water map in a similar way as the osola.co.uk DEM APIs do.

To apply the LDD to the water map and thus generate the accuflux map, we use the following algorithm.

Step 1. For this part, the user assigns the values of the water map to the accuflux map. In the figure below, given the LDD on the left as well as the water map on the opposite side, the accuflux map is the same as the water map:

8	8	8	7	7
8	8	8	7	7
9	8	7	4	7
9	8	7	4	4
6	8	4	4	4

Figure 5.30: LDD map

6	0.5	2	2	2
0.5	0.5	2	2	2
0.5	0.5	2	2	0
0.5	0.5	6	0	0
0.5	6	6	6	6

Figure 5.31: Water map

6	0.5	2	2	2
0.5	0.5	2	2	2
0.5	0.5	2	2	0
0.5	0.5	6	0	0
0.5	6	6	6	6

Figure 5.32: Initial accuflux map

Step 2. The accuflux map value of any neighbouring cell that points to it is added to each cell. In the figure, the cell contribution out of the map equals zero. Cursor movement on the accuflux map may appear, for example, with the pattern below:

START	→	→	→	↓
→	→	→	↓	↓
→	→	↓	↓	↓
→	↓	↓	↓	↓
↓	↓	↓	↓	↓

Figure 5.33: Frequencies representing lower and higher water levels

Example:

In the first iteration we touch the cells in red. In this example, the corresponding cells of the LDD do not have any other cell pointing to them, so their value is unchanged and remains solely the amount of water from the Water Map. The accuflux map after the first iteration is:

6	0.5	2	2	2
0.5	0.5	2	2	2
0.5	0.5	2	2	0
0.5	0.5	6	0	0
0.5	6	6	6	6

Figure 5.34: Accuflux map after the first iteration

In the second iteration, we touch the cells in yellow. The LDD map says that the first cell considered in this iteration (0,1) has one cell pointing to it: (0,0). The value of cell (0,1) is then modified by summing up the value of cell (0,0); its new value becomes 0.5+6 = 6.5. The same happens for cell (1,1): its new value becomes 0.5+0.5 = 1. Cell (2,1) has two cells pointing to it, (2,0) and (3,0), so its new value becomes 2+2+2 = 6, and so forth.

At the end of the second iteration, the accuflux map looks like this:

6	0.5	2	2	2
6.5	1	6	4	2
0.5	0.5	2	4	0
0.5	0.5	6	0	0
0.5	6	6	12	6

Figure 5.35: Accuflux map after the second iteration

In the third iteration, we touch the cells in green. The accuflux map is modified like this:

6	0.5	2	2	2
6.5	1	6	4	2
7	7.5	10	4	0

0.5	0.5	6	0	0
0.5	6	18	12	6

Figure 5.36: Accuflux map after the third iteration

In the fourth iteration, we touch the cells in bright blue. The accuflux map is modified like this:

6	0.5	2	2	2
6.5	1	6	4	2
7	7.5	10	4	0
0.5	25	6	0	0
0.5	56	18	12	6

Figure 5.37: Accuflux map after the fourth iteration

Finally, in the last iteration, we touch the cell in dark blue. The accuflux map is unmodified, since the corresponding cell in the LDD has no neighbour pointing to it. The resulting accuflux map is thus exactly as illustrated in Figure 5.38.

6	0.5	2	2	2
6.5	1	6	4	2
7	7.5	10	4	0
0.5	25	6	0	0
0.5	56	18	12	6

Figure 5.38: The final accuflux map

Once the accuflux map has been calculated, the data are ready to be displayed. We can use either the greyscale or multi-colour colour schemes, as follows.

5.7.16 Colour schemes for accuflux transformation

For accuflux calculation, two colour schemes can be used: greyscale and multi-colour. In the greyscale colour scheme, the colour of a pixel is directly proportional to the accumulated flux value in its underlying cell. Our maximum value, MAX_WATER, is the maximum value of accumulated flux detected in the map tile, and the Accuflux() function is the procedure described above. Thus, the colour of a pixel can be obtained like this:

Colour (LAT, LON) = **RGB**(V, V, V),

where V = **Accuflux**(LAT, LON) x 255 / MAX_WATER

This means that, for this particular transformation only, the greyscale intensity is relative to the tile and not an absolute reference. If we place two tiles side by side, what is displayed as “almost white” in the one in the left may be significantly lower (or higher) than what is displayed with the same colour in the one in the right. However, this is probably not an issue if maps are rendered using a few tiles per map view (i.e., 3x3 or 5x5).

In the multi-colour scheme, instead, the colour is assigned according to the following legend (we use the 7 colours of the light spectrum plus white, with lower frequencies representing lower water levels and higher frequencies representing higher water levels). Unlike greyscale, this colour scheme for accuflux transformation uses an absolute scale, because the maximum level used (640) is a constant and not calculated dynamically tile-by-tile.

Accumulated flux	Approximate pixel colour with ‘multi-colour’ colour scheme
0	
0–10	
10–20	
20–40	
40–80	

80–160	
160–320	
302–640	
More than 640	

Figure 5.39: Multi-colour scheme

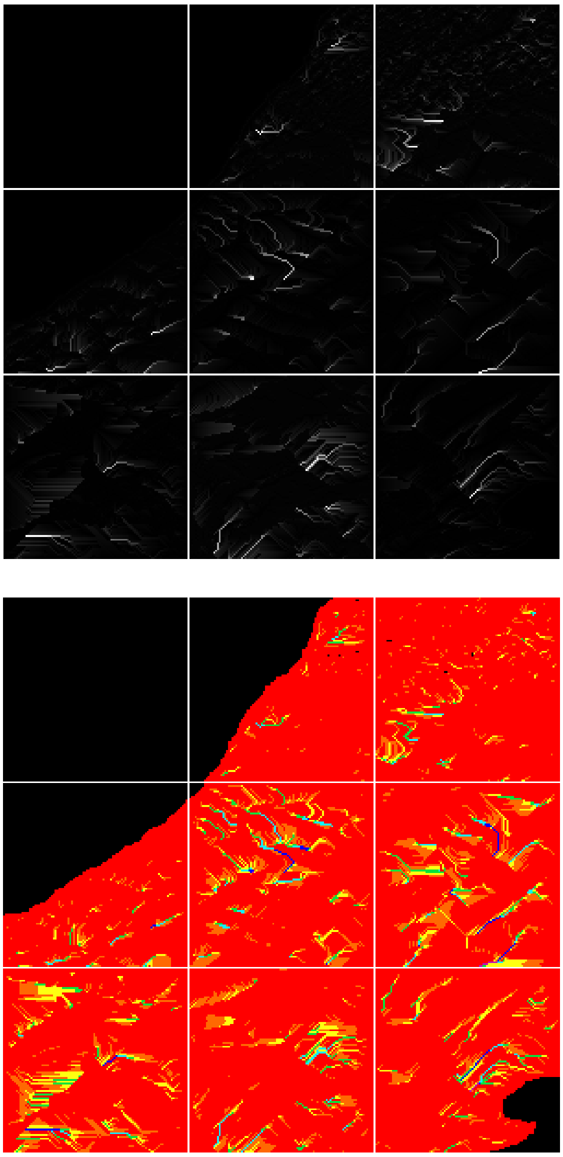

Figure 5.40: The same map as in the previous examples where the accuflux transformation has been applied, rendered in greyscale (top) and multi-colour (bottom)

5.8 Testing

The programmes in the prototype were carefully tested, first separately and then together. Testing of Internet applications was the most difficult because of the Internet being highly heterogeneous with different OSs, browsers and languages.

Traditional testing is the process of executing a programme with various inputs to discover errors. However, it also includes evaluations performed by humans or by machine to assess other aspects of the software. *Requirement testing* reviews a programme's requirements to ensure that the description of the problem to be solved is appropriate for the application. *Specification testing* reviews a programme's specifications to ensure that they correctly capture the intent of the requirements. Such evaluations should occur before coding begins.

One evaluation technique that can be used both before and after coding is the software *walkthrough*, usually carried out at a meeting in which people carefully review a requirements document, a design specification document or a section of code. The goal of a walkthrough is to identify problems, not to solve them. It can evaluate software quality as well as correctness. A walkthrough can examine whether or not requirements are appropriate, whether or not the system is decomposed appropriately and correctly, or whether or not the code faithfully represents the design. For the prototype, numerous meetings, e-mails and feedback during consultations with advisors constituted the walkthrough process.

As regards testing the user interface, the approach chosen was user testing. The next three chapters will be devoted to the user interface and user testing, which are two fundamentally important aspects of the project. Chapters 6 and 7 will explore user-centred design, and prototype design and development; and Chapter 8 will present an evaluation of the interface.

5.9 Summary

The chapter has discussed the components of, and their integration within, a customised GIS system prototype that was created using existing and widely used algorithms (such as slop, aspect and accumulated flux) and a customised hardware and software set-up. The prototype mobile-based GIS modelling tool provides an affordable, efficient and distributed real-time flood-forecasting tool. However, limited hardware and software resources have made it difficult to provide advanced GIS functions. Although the complexity of the proposed system is moderate, it incorporates frequently-used GIS techniques for hydrological modelling. It is a raster-based system that permits the integration of environmental modelling functions with classical GIS functions such as database maintenance and screen display. The modules for dynamic modelling are integrated with the GIS at a high level.

In the proposed modelling tool, main-gauge data covering daily, monthly and annual totals, as well as individual rainfalls and their intensity, are sent in near-real-time to a central database via wireless modem. They are checked for integrity, entered into the database and stored along with historical rainfall data and other contextual data.

Another important component of the prototype, which will have a significant impact on its potential success, is the user interface. It is not enough for a system to be robust and well-implemented from a technological point of view; it should also be useful to, and usable by, its potential users. Usefulness and usability are the key goals in user interface design, the process of which is discussed in the following chapters. In order to achieve these goals, various HCI research methods and principles will be used. The aim will be to focus on users and their tasks as early as possible in order to understand users' needs (thus making the system useful), as well as their expectations and mental models (thus making the system usable).

To this end, one of the HCI theoretical frameworks will be employed, namely, the Activity theory. This will serve as a design framework since it allows us to focus on the full context of the interactions between users and the proposed system. Another HCI design methodology – user-centred design - will also be adopted in order to maintain the focus on users throughout the process of designing a user interface. In particular, potential users will be involved in stages ranging from requirement-gathering to testing of the prototype’s user interface. Furthermore, in order to ensure the user interface is of high quality, iterative design will be employed: the prototype will be tested with potential users and refined twice, based on the outcomes of that testing. This is to ensure that it truly meets users' expectations and allows them to achieve their goals efficiently.

As the first stage, potential users will be invited to a brainstorming session whose goal will be to discuss and analyse how, and for what goals, the system could be used. The resulting scenarios will be analysed according to the Activity theory and transformed into a list of DPs and DRs for the system. These DPs and DRs will then be transformed into a prototype of the user interface, developed in collaboration between UX researchers and designers. The prototype will later be tested to validate the assumptions on which it was built and to ensure its usability.

At first, qualitative user testing will be used in order to identify the main points and areas of uncertainty, as well as to get a deeper understanding of users’ overall experience of the system. Subsequently, the prototype will be refined bearing in mind the outcomes of the user testing, and the refined prototype will be tested again. This time, a combination of qualitative and quantitative methodology will be used in order to obtain qualitative insights as well measure the system’s usability. The prototype will be further refined as required by the outcomes.

Chapter 6 Human Centred Design and Development

6.1 Designing the Interface

6.1.1 Introduction

In interactive system design, the HCD process means users' needs are taken into consideration in all processes throughout the system lifecycle. This enables the designed system to inherently serve the users by requiring the minimum mental effort to use it.

In this project, an HCD approach was used in order to create a user-friendly and intuitive interface that enables users to complete their tasks efficiently and effectively. At a very early stage of the design, the appropriate field research process was selected to create the basis of the application's interface. To do this, we used participatory design, which enabled us to understand the users by involving them in the design process. We agreed on the design framework that would be used, and then conducted a carefully designed workshop, bringing together members of our team and real users to brainstorm and, after analysing the results, to create a set of design guidelines (comprised of design principles (DPs) and design requirements (DRs) that would serve as a basis for designing the prototype of our system.

In this chapter, the underlying design framework is discussed first. The methodology of the main design phase is then explained in detail. The chapter continues with the analysis of our results and the design guidelines along with a critical discussion of our approach and the results.

6.2 Design Framework – Activity Theory

In the project at hand, activity theory was used as a design framework in the design phase in order to provide a more elaborated concept of activity. Activity is an integral part of everyday life, and a foundational concept in Human Computer Interaction and Interactive Design (Moran, 2003); as such, it is considered a vital component of the design process. However, everyone has an intuitive understanding of what activity is, making its use in design both an advantage and disadvantage.

Activity theory allows a deeper understanding of the tasks that people are engaged with as part of an activity, their goals and how they achieve them, the reasons behind specific tasks and the meaning of the tasks for them. In addition, it allows designers to explore how people interact with others in order to complete their tasks, the roles of society and people's immediate environment in their performance and, finally, what tools or instruments people use in order to attain their goals. By applying activity theory, all of the aforementioned aspects can be addressed in great detail.

The application of activity theory enables designers to classify procedures as activities or non-activities, break the former into smaller sub-activities, examine the impact of technology on human activity and analyse each activity in depth to achieve a comprehensive and refined understanding (Kaptelinin & Nardi, 2012).

6.2.1 Overview of Activity Theory

Activity theory has its origins in the Soviet psychology developed in the early decades of the 20th century. In particular, the primary driver of its development was the work of Lev Vygotsky, a Soviet psychologist much influenced by Marxist theory, which led to the development of cultural-historical psychology.

One of the most interesting characteristics of cultural-historical psychology is the role, in higher forms of human behaviour, of cultural mediation. Vygotsky introduced a mediating artifact between a stimulus (subject) and its response (object), which is related to the cultural and social context. For example, let's say that a child is asked to match given words with pictures. At first, the child does not know how to interrelate them; the mediating artifact is simply the way the child learns how to do so. Then, after sufficient practice and repetitions, the response can be instantaneous, without the need of the mediator (Vygotsky et al., 1929; Vygotsky, 1978; Vygotsky, 1979). Figure 6.1 illustrates the stimulus-response triangle of Vygotsky's theory.

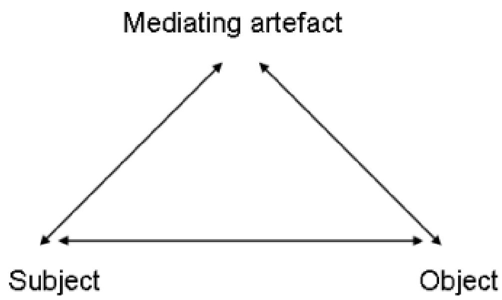

Figure 6.1: The stimulus-response triangle of Vygotsky's theory

Aleksei Leontiev extended Vygotsky's work, with human activity as the core concept of his extended framework. By "activity," Leontiev was referring to every non-additive, molar entity for a physical subject (i.e., that entity of life that is "mediated by mental reflection"). Furthermore, he describes activity as a "system with its own structure, its own internal transformations and its own development" (Leontiev, 1974). Leontiev focused on the general flows of human activities, and identified three distinct levels of human processes. The highest level is the activity itself, which is driven by its motive, which differentiates it from other activities. The intermediate level is the action required for an activity, which is associated with a goal. Finally, the lowest level is composed of the actual operations and conditions required to achieve a specific goal (Leontiev, 1977; Kuutti, 1996). In Figure 6.2, we see the described hierarchical model of an activity.

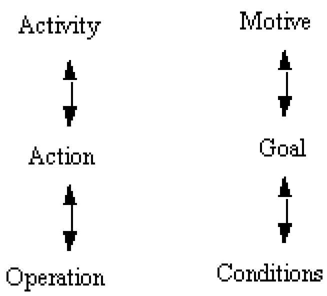

Figure 6.2: Hierarchical levels of an activity

Activity theory was further developed by Scandinavian researchers, especially Yrjö Engeström (1987), who identified some problems and weaknesses with the Soviet approach. In order to overcome the limitations he observed, he expanded the activity model (Figure 6.3). In his model, three new categories are introduced: community, division of labour and rules. Community includes all the actors except the main subject(s) involved in an activity, and the social environment created and developed by them. Division of labour includes compartmentalisation based on disciplines, structure of the activity and so on. Finally, the rules can be both explicit and implicit, and include guidelines, conventions and norms applied during an activity. When an activity takes place, relationships are formed and developed between all these categories.

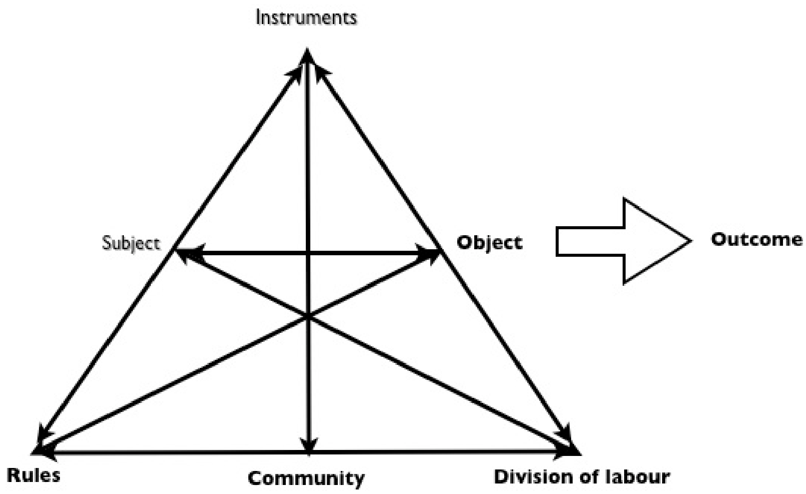

Figure 6.3: Engeström's expanded model of an activity system

6.2.2 Activity Theory in System Design

The work of Nardi (1996) and Kuutti (1996) introduced activity theory as a methodology of system design. In order to apply this framework for the present project, the scenario-based design (SBD) approach was used as a tool. Designers use scenarios in the very early stages of system design; the purpose of this is to describe the future or anticipated use of the system. This, in turn, allows designers to understand the user interactions and needs, which will lead the design (Carroll, 1995). Scenarios describe a sequence of events leading to a specific outcome. They have a plot and include actors, objectives and actions in addition to the context in which the scenario applies. Possibilities and concerns are expressed through different scenarios; when these are combined, an ecosystem map is created, allowing for a more holistic understanding of the system. The scenarios are analysed and the extended activity theory diagram is filled, using the information which resulted from the scenario analysis.

Brainstorming is a very common method for generating scenarios and has been adopted by many researchers in the information design field (Tognazzini, 1996, Weidenhaupt et al., 1998; Khakee et al., 2002; Sears & Kacko, 2009) and beyond. It was introduced by Osborn (1962) as an individual or group idea-generation method for use in problem solving. According to Wilson (2013), the fundamental principles of brainstorming are:

- Quantity of ideas: aim for the maximum possible number
- No judgment: the quality of any given idea should not be criticised in any way (facial or verbal expressions)
- New and wild ideas: encourage synthesising ideas, improving existing ideas and so on

The main advantage of brainstorming is that it allows for quick idea generation, encourages creativity and gives valuable insights into the problem at hand. It is a relatively cheap design method and a democratic tool providing social interaction to people.

Brainstorming sessions can be unstructured, in which case a group of people gathers to generate ideas without a facilitator or rules. The risk of unstructured brainstorming is that loud and dominant individuals will overshadow the quiet participants. In order to mitigate this risk, structured brainstorming sessions can be used, in which there are clear rules and procedures (and, usually, a facilitator).

Research has proved that individual brainstorming generates more ideas than group brainstorming (Dunnette et al., 1963). Since this realisation, various techniques have been used in order to get the maximum possible number of generated ideas. For example, Delbecq and Van de Ven (1971) proposed the nominal group, which encourages passive group members to participate. Sample (1984), described the procedure as follows: large groups are divided into groups of 5-6 people, each of whom is asked to spend some time brainstorming individually. Then, the group’s ideas are collected and shared in a round robin approach, without any criticisms being made. Subsequently, the group members vote anonymously for the best ideas, and then the outcome is revealed to the group. The resulting ranked list can then be discussed among the participants, and the results presented to the large group.

The aforementioned approach was used as part of the early design process in the present project in order to identify the design guidelines to be used at a later stage to create a prototype.

6.3 Methodology

The system to be designed should provide flooding data and analysis to end users through a mobile application, and should include an administration panel that enables the administrator to manage the system and analyse data. The goal is to create a system that ensures that the users achieve their goals.

In order to create the set of DPs of the interactive system, an empirical and evaluation study was carried out. Utilising the methods and tools discussed in section 6.2, the study was divided into four discrete stages. In the first stage, the participants were asked to brainstorm in nominal groups, and produce scenarios about the main use and expansion of the current system. Next, the facilitator collected the scenarios and the ideas produced during the first stage, and the participants were asked to evaluate them and vote for the best ones, reflecting Sample's (1984) procedure. During the third stage, the facilitator, with the help of participants, divided the top-rated scenarios into instruments, subjects, objects, rules, community and division of labour, and built the extended activity theory diagram on that basis. Next, the results of the study were analysed and the findings were discussed in order to extract the DPs of the system. In the following two subsections, the empirical and evaluation studies are detailed in turn.

6.3.1 Environment

The study was divided in four separate stages, three of which required the participation of external users. Hence, the participants were required to visit our meeting room at a given time. The meeting room was designed in such a way as to meet all the requirements of the study, which are discussed later in this chapter. In order to help participants feel more comfortable and encourage socialising, they were provided with food and drinks. One facilitator was present to help the participants engage with the required activities. In addition, an assistant was used to help the participants with their tasks and make them feel more comfortable. The different stages required different timeframes: ten minutes for a brief description of the study, thirty minutes for the first stage, thirty minutes for the first break, forty-five minutes for the second stage, fifteen minutes for the second break and thirty minutes for the third stage. The fourth stage did not require the participation of external users; thus, the research team took as much time as needed to provide the findings and the results of the study.

6.3.2. Participants

The selection of the study participants was based on homogeneity but with plentiful variation among the group members, taking into account characteristics like occupation, age, gender, experience with mobile applications and so on.

To recruit the users, a recruitment screener and script (Appendix A) were created and used during the recruitment. The participants were recruited through a recruitment agency, which was responsible for finding study-users of the required target groups.

The optimal group size is typically between five and ten participants, depending on their experience of and interest in the topic (Tynan & Drayton, 1988; Stewart & Shamdasani, 2014). The less experience they have, the more participants are required. In this study, diversity of participants' roles, experience and interest is desired; hence, ten participants took part in the study. The participants were next divided randomly into two sub-groups of five, in order to have a more productive nominal group technique (Boddy, 2012).

To decide on the participant backgrounds and types that should be included to the study, an in-house brainstorming session was conducted, in which all the members of the team participated (user experience researchers and designers, software developers, test engineers, etc.). This was unofficial in form, all members expressed their opinion in regards to the system's users and the breakdown of the participants was decided.

It was decided to recruit a group with multidisciplinary characteristics and a range of roles and levels of experience with mobile applications and weather-oriented systems. Participants who were not familiar with mobile applications and/or weather systems were not recruited.

The following user types were recruited:

- 5 representative users (i.e., users with different levels of experience with mobile applications, different levels of experience with GIS systems and different levels of experience with weather systems, combined with different ages and genders that could possibly be users of the final system);
- 1 software developer (selected for insights regarding software development issues, as well as to ensure that there was at least one participant with strong analytical skills to ensure the variability of participants);
- 1 software designer (selected for their potential to provide some design-related insights. Even though no design work would be done during the workshop, it was possible that some insights might be provided during the discussion session. Also, by having a designer, it was ensured that at least one participant would have a creative mindset, which contributes to the variability of participants);
- 1 business analyst (who had the potential to provide some business-related insights. Even though that was not the main goal of the

workshop, it would be a useful contribution; also, having somebody business-minded contributes to the variability of participants);

- 2 GIS experts (people who specialise in the GIS field, i.e., a geospatial intelligence analyst and a GIS engineer, who had been working in the field for at least 5 years. Since they are highly knowledgeable in the area, they would be likely to create some useful scenarios that non-experts would not be able to create; also, they would be very valuable in providing their opinions regarding the technical viability of other users' scenarios – non-expert users might provide some scenarios that cannot be implemented in real life due to some technical or other limitations).

The representative users were three females and two males, aged from 20 to 41, with a mean age of 31 years.

During the recruitment screening process, participants were asked to rate their experience in using mobile applications on a five-point Likert-type scale, with 1 being not experienced and 5 being very experienced. They were also asked to rate their familiarity with GISs, again on a five-point scale, with 1 being not familiar and 5 being very familiar; they had to rate their familiarity with weather systems in the same way. The aim was to ensure that there was some variability, that is, that not only expert users or total novices participated. Users who were completely unfamiliar with mobile applications or weather systems (1 in Likert scale) were not recruited, since their lack of familiarity with the subject and interest in it might have biased the results.

Table 6.1: Brainstorming session participants

Participant	Role	Gender	Age	Education Level	Mobile app expertise	Weather expertise	GIS expertise	Group
Part 1	GIS	M	32	MSc	4/5	5/5	5/5	G 1
Part 2	Software Designer	F	30	MSc	5/5	3/5	2/5	G 1
Part 3	Repr. user	M	31	Graduate	5/5	4/5	4/5	G 1
Part 4	Repr. user	F	20	Undergrad	4/5	4/5	3/5	G 1

Part 5	Repr. user	F	28	Postgrad	5/5	4/5	3/5	G 1
Part 6	GIS	F	34	MSc	5/5	5/5	5/5	G 2
Part 7	Business Analyst	M	43	Graduate	3/5	3/5	3/5	G 2
Part 8	Software Developer	M	28	Graduate	5/5	4/5	2/5	G 2
Part 9	Repr. user	M	34	Graduate	5/5	3/5	3/5	G 2
Part 10	Repr. user	F	41	PhD	4/5	4/5	4/5	G 2

Table 6.2: Brainstorming session participants by group

Category	**Users**	**Gender**	**Age**	**Education**	**Mobile app experience**	**Weather experience**	**GIS experience**
Group 1	1 GIS / 1 SwDesigner / 3 rep.	2M / 3F	28.2 +- 4.8	2MSc / 1 G / 1 UG / 1 PhD	4.6 +- 0.5	4.0 +- 0.6	3.4 +- 1.0
Group 2	1 GIS / 1 Business / 1 Sw Developer / 2 rep	3M / 2F	36.0 +- 6.1	1 MSc / 3 G / 1 PhD	4.4 +- 0.9	3.8 +- 0.7	3.4 +- 1.0
All		5M / 5F	32.1 +- 6.6	3 MSc / 4 G / 1 UG / 2 PhD	4.5 +- 0.7	3.9 +- 0.7	3.4 + - 1.0

6.3.3 Preparation

In order to carry out a smooth and productive study, participants should be prepared effectively and efficiently. To this end, the participants were all provided with a detailed set of instructions several days before the study (Appendix B). The instructions were repeated just before the study, so the participants had a clear picture of what they would do during it.

6.3.4 Ethics

People were involved in the study; thus, research ethics had to be considered. Each individual involved was required to have an understanding of what they were asked to do; to know that they were permitted to do it; and to know why they were doing it. During the project, personal data (although anonymised) was used throughout the evaluation process and the interaction between the users and the system. Therefore, each individual taking part in the project was informed as to what information was held about them, and given access to that information. The project was in compliance with the Data Protection Act (1998) and the users signed a consent form before taking part in the project (part of Appendix B). Ethical approval for the study has been obtained from Brunel university.

6.3.5 Pilot study

A pilot study is a small trial study carried out before the main study; in the present study, this was done in order for the research team to test the environmental components, the study instruments and flow and the participants' behaviour. Thereby, information is gathered in order to modify or refine the research methodology that was decided based on the study design. Any issues raised were intended to be addressed before the main study. The pilot study raised a few issues about the time needed between stage one and two; thus, this parameter was modified as appropriate. The participants were encouraged to use this additional time to have a coffee break and socialise, participating in the study implicitly during the break, as they had time to discuss the study so far, and the derived scenarios.

6.3.6 Main Study

The procedure of the main study is summarised in Figure 6.4 and discussed in detail in the following sub-sections.

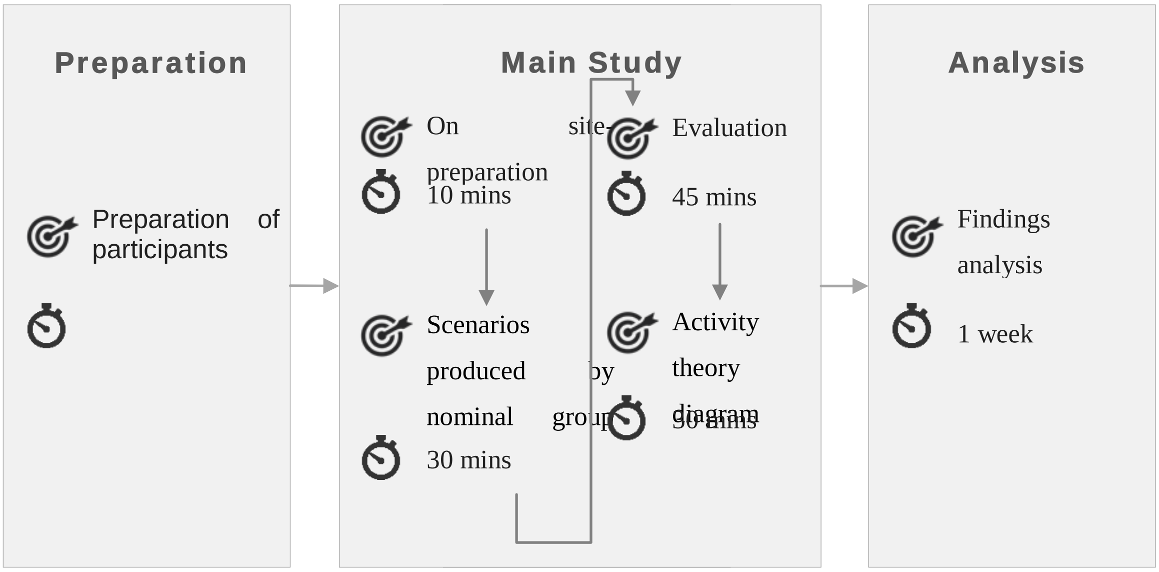

Figure 6.4: Study diagram

6.3.6 Preparation

The preparation of the study participants was divided into two stages: remote preparation and on-site preparation. The first one was discussed in the previous sub-section. The second one involved a brief explanation of the study, the procedure of the study and its impact on the project. It was performed in the meeting room, where all participants were present, and they were encouraged to ask any questions needed to clarify anything related to the study. It lasted less than ten minutes, and the participants had enough time to be introduced to each other.

First Stage: Scenarios produced by Nominal Group Technique

During the first stage, the participants were divided into two groups of five. The participants of each group were seated around a table. The facilitator was responsible for encouraging the participation of each individual. Each participant spent several minutes in silence, individually brainstorming and writing on cards all the scenarios of possible uses of the system. Next, each group collected the scenarios by sharing them round robin-fashion (i.e., one scenario per person each time), while all scenarios were recorded on a board. During that task, no criticism was allowed, but the group members were allowed to ask for clarifications, which in turn encouraged discussion and enrichment of the produced scenarios, as well as the production of new ones.

Second Stage: Evaluation of Scenarios

After the first stage finished, the researchers collected all the scenarios written on the cards and the board, from both groups, and recorded them on a whiteboard which was visible to every participant, merging any duplicated scenarios. The total number of the discrete scenarios was sixty-three (63). The derived scenarios were evaluated by the stakeholders of the system (i.e., the system providers and the technical project committee), who eliminated twenty-two (22) scenarios as they were beyond the scope of the project. Therefore, forty-one (41) scenarios were finally carried forward to the evaluation stages.

The two groups were merged into one group of ten participants. Along with the two user experience researchers, they composed a group of twelve people who would evaluate each scenario. Each person was asked to individually evaluate the scenarios and anonymously vote for those that, in their opinion and from their experience, or their needs and expectations in case of users, should be addressed by the system. In particular, they were asked to rate each scenario on a 10-point based scale, as several studies suggest that ten is an optimal number of response categories in rating scales, regarding reliability, validity, discriminating power and respondent preferences (Preston & Colman, 2000; Ganzfried, 2016). Each participant rated each of the forty-one scenarios with the rate scale from one (1) to ten (10), where 1 means that the participant disagrees with having this scenario supported by the system, and 10 means that the scenario should definitely be supported by the system. The votes were then collected and tabulated, showing the scenarios which received the most points. A detailed view of the scoring procedure is presented in Appendix C. Next, a brief group discussion of them was held, in order to also understand why some scenarios were preferred to others.

Third Stage: Activity Theory Diagram

During the third stage, the participants, with the researchers, broke the top-rated scenarios into instruments, subjects, objects, rules, community and division of labour, and built the extended activity theory diagram. This was drawn on a whiteboard and was visible and accessible to everyone in the meeting room. The participatory nature of this stage made the participants more active, engaged and influential regarding the study, leading to qualitative conceptualisation of the components of the activity theory diagram and their interrelationships. The results of this analysis are detailed in section 6.4.

Fourth Stage: Results

Based on stages one to three, the research team analysed the data and derived the results and the findings (discussed in the next section), along with the derived DPs.

6.4 Results

In this section, the findings of the study are discussed. It is organised in two sub-sections: first, the produced scenarios are discussed, and then an analysis of the activity theory model is performed.

6.4.1 Produced Scenarios

As was discussed previously, sixty-three (63) scenarios were identified by the two groups, and written on cards (Figure 6.5). However, only forty-one (41) of them were evaluated, as twelve were excluded by the system stakeholders as beyond the scope of the project. The full list of scenarios is presented in Appendix C, along with the points of each user on each of them and the reasons why they were included or excluded. The next graph (Figure 6.6.) displays the votes for each scenario. As it shows, only twelve scenarios were rated above 60 points out of a maximum of 120 points (12 participants x 10 points), which is the middle of the scale. Therefore, the participants were positive only that twelve scenarios should be supported by the system. The decision to choose only the scenarios that got at least 50% of the maximum number of points (60 points) was made beforehand by the team, since there was a need to have a clear cut-off point. However, the team looked at the numbers critically: the team members and stakeholders also looked at scenarios that got fewer points, and insights from the brief discussion at the end of the second stage were used to understand why some scenarios got fewer points and whether it was really worth excluding them. No scenarios that got fewer than 60 points were selected for inclusion, since the reasons users did not vote for them were clear. However, if there had been an underrated scenario which stakeholders believed was underrated because participants did not understand its importance, it would have been included.

Special focus was given to scenarios that lacked only a few points to be selected. For example, scenario 14 (checking rainfall probability) got 59 points; however, many participants mentioned that they already had similar applications on their smartphones, which are very easy to use and would not need anything else. Thus, it was safe to exclude this scenario. With scenario 22 (finding the location of the weather station), similarly, some participants suggested that although it sounds like a good feature, they could not imagine a situation where it would be useful; a similar functionality could be added to the application later, if users decide it is necessary.

Some scenarios indirectly overlapped, for example scenarios 14 and 18; however, 18 was selected by users because it provides a higher range of weather information, which many other applications do not. Besides, the functionality of scenario 14 is covered by scenario 18.

Overall, the decision as to which scenarios should be included was made by participants; however, the team had the authority to alter this decision if they saw a real need.

In theory, more scenarios could have been chosen to be implemented; however, it was decided to focus at the beginning of the project only on the features that users really need. Generally, the more features the application has, the harder it is to use it. Thus, it was decided to have limited functionality at the beginning and add more features later, when existing users would be more familiar with the application (and thus would not have a steep learning curve), and new users would see the application as a popular, well-established application, and thus be more willing to put some effort into learning it.

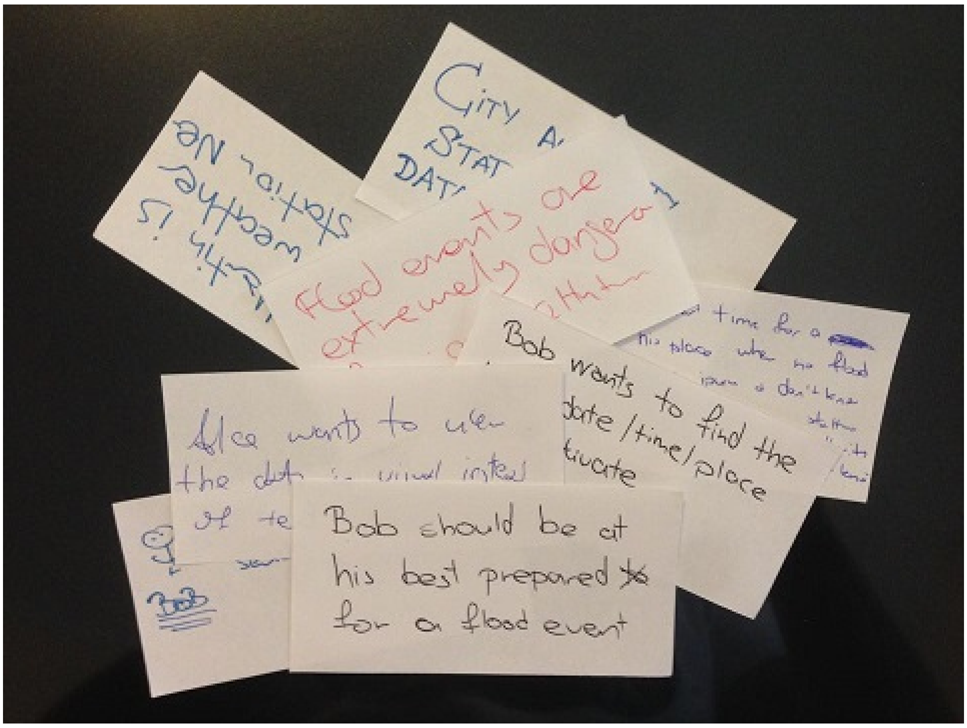

Figure 6.5: Scenarios written on cards (group B)

Figure 6.6: Votes chart of the qualified scenarios

The twelve top-rated scenarios as they resulted after the second stage of the study are listed in Table 6.3:

Table 6.3: Selected scenarios

Rank	Scenario	Points
1	The city authority is notified by the local weather station that there is an increased likelihood of flood in the next two days. Combining statistical data about precipitation and terrain elevation models, the system informs the weather station and the local authority about the risk of a likely upcoming flood.	105
2	Martin is one of the officers in weather station X, which is connected with the system infrastructure; he noticed a change in the precipitation and moisture levels, so he uses the system to update the current values.	98
3	Alice has just moved to a town, and she is quite curious to find out what the weather conditions (e.g., rainfall) are in it so she uses the system to view historical data of such characteristics.	94
4	Bob wants to travel to London this weekend. However, he doesn't know the weather, the likelihood of rainfall and other weather parameters, so he uses the application to get the desired information.	93
5	Since the system provides information about rainfall, precipitation, moisture and so on, it would be extremely helpful for Bob, a farmer, in order to help him pick the best dates to plant his vegetables.	87
6	Bob uses the application in order to be notified when the likelihood of flooding in the various places he has entered is high, in order to take the actions required to address the threat and safeguard his properties. A quick guide on how to address the threat of flooding would be extremely beneficial.	78
7	The stored data has been lost or is inaccurate, hence the system administrator enters the system to manage, check and restore the data, (e.g., pluviometric data and DEMs of the monitored areas).	73
8	Alice uses the user-friendly web interface of the application to upload some data about the location where she currently lives, and keep the community aware of the new facts. However, Martin, the weather station officer, should first check and then activate the given data.	69
9	The system has been out of service, but the administration team works on the network, database and security of the system to put it back online in a few minutes, ensuring the proper functionality of the system.	68
10	The local authority and the local weather stations record the floods of the previous years and evaluate the risky periods and locations. They produce a guide informing citizens about the threat of flooding and what they should do to be better prepared.	64
11	In order to find the best place and date frame to cultivate his favourite fruit, Bob uses the application to compare different locations at different periods of time.	64
12	The textual information is too chaotic/confusing for Alice. She would definitely prefer to view the data visualised in charts or graphs.	61

In the aforementioned scenarios, different personas were used, such as Bob and Martin, representing real users but different roles. Some of the scenarios recorded on the board, along with their points, are displayed in Figure 6.7.

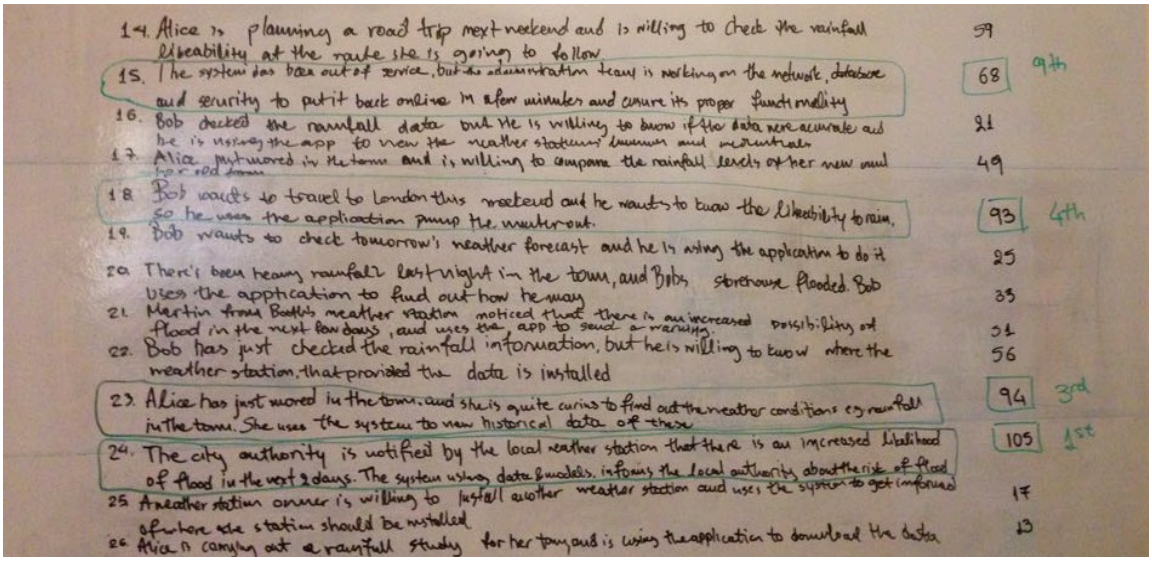

Figure 6.7 Board with the scenarios and their points

6.4.2 Activity Theory Application

As was discussed earlier, the model of activity theory that will be used is the one proposed by Engeström (1987, 1999), since it is well-established and allows the research team to analyse the various aspects of the activity system. Therefore, the system is analysed on six axes: subject(s) and object(s) of these activities; the instruments the subjects are going to use in order to complete their tasks; the social environment in which they are involved; the division of the activities among other actors in the system; and the rules regulating activities in the system.

In order to fill the activity theory triangle using the scenarios, the group analysed each scenario one after the other. They discussed the six different aspects of the triangle, starting with finding the possible subjects of the scenario at hand, then finding the instruments, the objects and so on, as these were described on the scenario. Any information that was not included in the initial scenario was discussed, and the group added the supplementary information to the triangle. For example, the participants with prior experience of GISs provided a lot of useful insights into what else the system needs to do in order to serve the scenarios, even though such functionality was not covered by the scenarios. After analysing all the scenarios, the group reviewed all the information added to the triangle, and members were encouraged to add any additional information that might be missing (in their opinion). The activity theory triangle as supplemented during this phase is displayed in Figure 6.8.

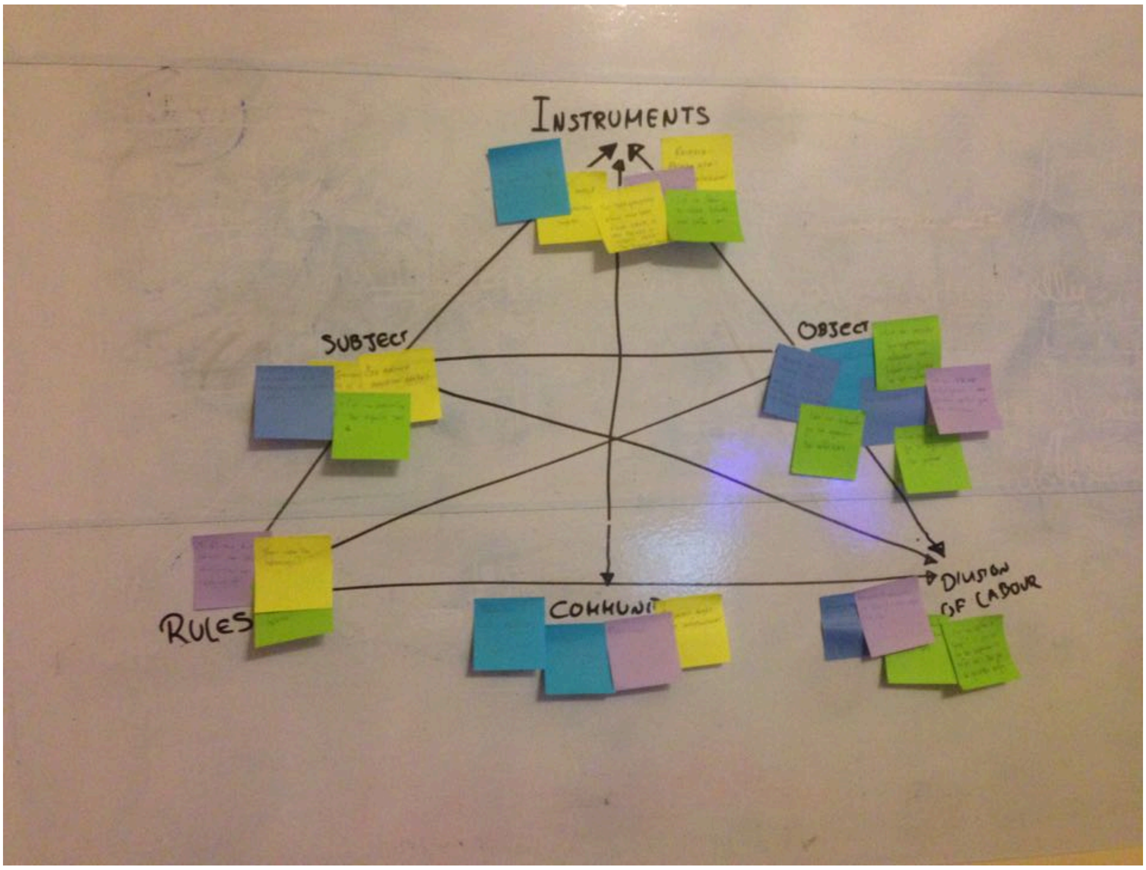

Figure 6.8: Activity theory triangle

Subsequently, the team analysed the activity theory diagram, and discussed the typical tasks and objectives for the scenarios and the corresponding technical requirements. During these discussions, DPs and DRs were created. In the following sections, the scenario analysis is presented, based on the six edges of the activity theory diagram along with the DPs and DRs that derive from each section.

Subject

It is clearly implied by the research context that the main actors in the aforementioned activities and scenarios are people who want to view data regarding weather, flood events and so on, and who contribute to the community: people on weather stations who update the data, and administrators who are responsible for the overall performance of the system.

Therefore, the system should be governed by the following DPs and DRs:

Table 6.4: Design Principles

DP1	The users should be divided into groups with discrete rights and responsibilities, depending on their roles. The three main user groups are the front-end users, the weather stations and the administrators.

Table 6.5: Design Requirements

DR1	The system supports three user roles: front-end users, weather-station users and administrators.
DR2	Each role has discrete access/view/write rights in the system.
DR3	For different roles, different user-interface layouts are supported.
DR4	A log-in and log-out mechanism should be supported.

Object

The main objective of the administrator is to maintain the system and ensure the integrity of the data, and the efficiency and performance of the system. Regarding the weather-station users, their objective is to update the data of the system responsibly and accurately, as well as to inform authorities when a severe weather event is expected. The front-end users use the system in order to get information about pluviometric data and flooding conditions.

The main activities identified for each user type can easily be broken into smaller units, creating smaller activities that must be completed for users to achieve the main objectives. For example, the front-end users should be able to view historic data, have the system perform a rainfall prediction, view flood likelihood on a specific location and so on. In all cases, the user gets information about the various pluviometric data, and the different paths that could be created during the analysis are so many in number and type that a full review would be beyond the scope of this project proposal. However, some of the most common sub-activities, and therefore secondary objectives, are going to be studied in this analysis.

The DPs and DRs that derive from the aforementioned analysis are:

Table 6.6: Design Principles

DP2	The system should provide information about pluviometric data and DEMs of the various monitored areas.
DP3	The weather-station users should be able to manage data periodically and effortlessly, either automatically or manually, over their network channel. They should also be able to communicate with local authorities easily and quickly.
DP4	Administrators should be able to maintain the system, and ensure the integrity of the data and the efficiency and performance of the system.
DP5	The front-end users should be able to provide and get information about pluviometric data through sophisticated filtering mechanisms.

Table 6.7: Design Requirements

DR5	The system should answer questions related to pluviometric data and DEMs of each monitored area.

DR6	The weather-station users should be able to update data periodically, either automatically or manually, over their network channel.
DR7	The weather-station users should be able to update data either automatically or manually, over their network channel.
DR8	The system should provide communication mechanisms (e.g., text-based, messaging, quick-call actions) to support the communication between weather-station users and local authorities.
DR9	Administrators should be able to have full access to the system.
DR10	Administrators should be able to maintain and modify the system functions, users and roles.
DR11	Administrators should ensure the integrity and security of the data provided in the system.
DR12	Administrators should keep the performance, efficiency and reliability of the system at the highest level.
DR13	Front-end users should be able to provide pluviometric information to the system, which should be moderated first.
DR14	Front-end users should be able to view historical pluviometric data.
DR15	Front-end users should be able to search for pluviometric data using filtering mechanisms of various conditions.
DR16	Front-end users should be able to get information about available samples.

Community

The social relationships created and developed between the subjects of an ecosystem and their social environments are parameters to which great consideration must be given in the activity theory framework. In the proposed system, the users, despite their roles, rights and system access levels, are members of a community, which helps the ecosystem to grow and better serve the needs of its users.

The administrators are members of the administrative team, which typically communicates and cooperates with the weather-station users. Each user of a local weather station is a member of the local station community and of the national station community, which supports all the local weather stations. They often cooperate with both the administrators and the front-end users. The front-end users, who are the majority of the system's users, share information and experience with each other, with the weather-station users, with people who do not currently use the system and so on. They may ask for help in order to complete a desired task, share information in order to notify other users about a flood event update the system with new data and notify the system moderators about an error state, among other activities which may be required.

Therefore, the system community could be described as three circles, reflecting the three main user types, which are interacting with each other. However, there is a fourth circle, which represents the people who are not yet members of the system, and which interacts with the three others. Figure 6.9 illustrates the system community.

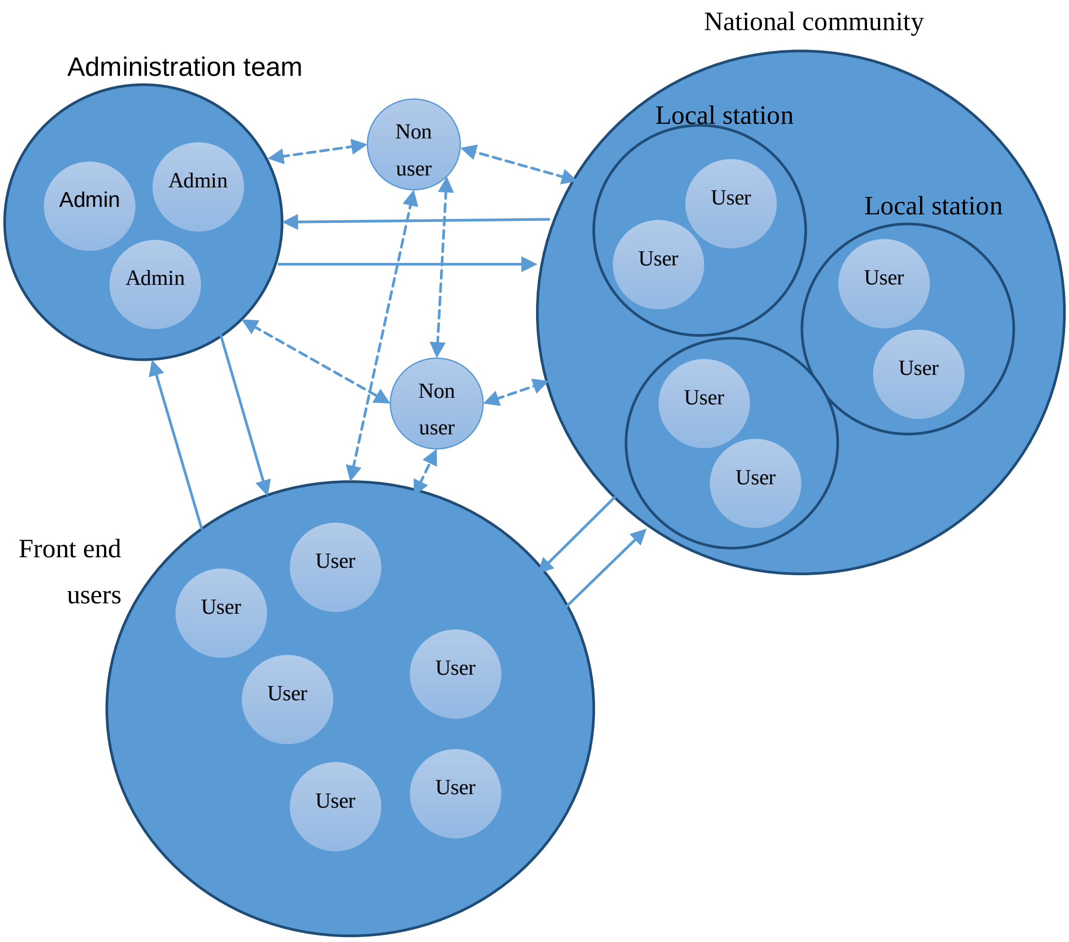

Figure 6.9: System community

The DPs and DRs that derive from the aforementioned analysis are:

Table 6.8: Design Principles

DP6	The system should provide mechanisms to support the communication between the different user groups and collaboration within these groups.

Table 6.9: Design Requirements

DR17	The system should support a communication channel among all user types.
DR18	Weather-station users should be notified when a change is made regarding the data they manage.
DR19	Weather-station users should be able to approve or reject system states regarding pluviometric data (e.g., verify data received from front-end users).
DR20	Weather-station users should be able to add users and assign them local weather-station rights.
DR21	Weather-station users should be able to collaborate in order to manage pluviometric data of common interest.
DR22	Administrators should be notified when new users or data have been added into the system.
DR23	Administrators should be able to manage users’ rights and roles.
DR24	Administrators should be able to communicate with weather-station

	users regarding the management of system functions.
DR25	Front-end users should be able to share information with the community.
DR26	Front-end users should be able to notify administrators of system errors.

Instruments

The subjects will need various resources and tools in order to accomplish their objectives. Depending on their experience, the procedure followed for each activity might differ and, thus, new paths and patterns are created. However, the main instruments used to accomplish their goals are the same, and are detailed in the next five subsections.

User Panel

The user panel is actually a metaphor to provide the user with control of the system software and hardware features, depending on their rights and permission levels. Multiple settings and configuration tools are available to the users, forming sub-instruments that are utilised by the users to accomplish their objectives. These tools could refer to global settings, such as display and network settings, or be more specialised to the user role.

In particular, the weather-station users should be able to update the system with new data related to their local 163uthorized area. They should also be able to review the incoming information by the front-end users, and update the system accordingly. In addition, data-handling tools should be available to them.

Through the admin panel, the administrators should have a superior level of access rights. That is, they should be able not only to manage the data that is critical in order to for the system to operate, such as pluviometric data and

DEMs of the monitored areas, but they should also be able to manage the users of the system, and set their access rights and permission levels.

The front-end users, who are the majority of the system's users, should use more tools in order to accomplish their objectives. These tools are not exclusively provided through a user panel; an intuitive and user-friendly web interface is required. The sub-components of this interface form a group of instruments, and are detailed in the next sections.

Based on the aforementioned analysis of the system instruments, the following DPs and DRs were derived:

Table 6.10 Design Principles

DP7	The user panel should be used to facilitate user objectives, supporting different levels of abstraction and taking into consideration the different user roles and rights.

Table 6.11 Design Requirements

DR27	All functions supported for each user type should be provided via the user panel tool.
DR28	The functions provided by the user panel should be implemented through a web interface.
DR29	The users should be able to manage their profile through the user panel.
DR30	The user panel should allow the weather-station users to upload weather data related to their authorised areas.
DR31	The user panel should provide notification messages to weather-

	station users when weather data is uploaded by the front-end users or other weather-station users.
DR32	The user panel should provide weather-station users with weather data management tools.
DR33	An API should be provided to the weather-station users.
DR34	Through the API, the weather-station users should be able to push and pull information regarding date, map, location (of the weather station), time range, time series analysis and sophisticated queries regarding a list of events.
DR35	The user panel should provide the administrators with tools to check and fix issues critical to system performance, security and operation.
DR36	The user panel should provide accounts settings configuration tools to administrators , providing rich information for each system user (e.g., username, telephone and email address).
DR37	The user panel should provide the administrators with tools regarding the back-end functions of the system, such as maps management tools, and supporting functions for inserting, modifying and deleting system elements.
DR38	The user panel should provide the front-end users with functions to upload weather data of their area.
DR39	The user panel should provide the front-end users with search tools, including advanced search features.
DR40	The user panel should notify the front-end users regarding their requests status (e.g., uploading new weather data or setting a new

	query).

Pluviometric Queries

In order to get information about the desired pluviometric data, the front-end user should interact with the system, and request it. Therefore, the system should provide the front-end users with a customisable mechanism that can answer queries such as:

- What are the highest rainfall values during the month of January in London?
- When was the last flood event in Bristol?
- How many days was the longest period of rainfall in the United Kingdom (UK)?

The range of the supported pluviometric data should be large enough to support the most common user queries, including rainfall, temperature, moisture and so forth. The users should be able to set their queries by selecting one or more pluviometric characteristics, one or more time periods and one or more locations. Extra filtering should also be supported by the system, so the user can limit the query results with higher detail and accuracy.

Based on the aforementioned analysis of the system, the following DPs and DRs are derived:

Table 6.12: Design Principles

DP8	The system should provide its users with meaningful pluviometric data of high detail, after a request is performed, which should support sophisticated filtering and advanced search features.

Table 6.13: Design Requirements

DR41	The users should be able to set requests to system regarding pluviometric data.
DR42	The system should support different types of pluviometric data, e.g., rainfall level, temperature and moisture.
DR43	The system should perform the temporal/spatial analysis based on various parameters, such as the pluviometric data variable and geolocation information.
DR44	The users should be able to refine their search by applying filters regarding the type of the requested pluviometric data, time period and location.
DR45	The users should be able to combine different types of queries to produce a sophisticated mixed query, such as pluviometric variable, location and date, e.g., what is the *maximum level of rainfall* for *November 2015*.
DR46	The users with higher access/write rights (i.e., administrators and weather-station users) should be able to modify (e.g., edit or delete) pluviometric data, applying the aforementioned filters.
DR47	The users with higher access/write rights (i.e., administrators and weather-station users) should be able to modify (e.g., add, edit or delete) pluviometric data types and characteristics.
DR48	The users should be able to import and export pluviometric data in a common format (e.g., CSV format).
DR49	The system should automatically scan for errors on data import action, and notify the users accordingly.

DR50	The system should keep a history of the pluviometric data requests.

Spatial Data

The system should provide the users not only with pluviometric data but also with data analysis of the corresponding area. Hence, spatial data should be supported—that is, geographic characteristics and features of the selected location, including coordinates and topology data. The front-end users should be able to view spatial data in a meaningful way (e.g., through a map). They should be able to view and access different areas and spatial data, though only the administrators have the right to add and manipulate new data. The system should also automatically get the current location of each user, and update the main interface at regular time periods (e.g., every 60 seconds), assuming the user has permitted such an action.

Based on the aforementioned analysis of the system, the following DPs and DRs were derived:

Table 6.14: Design Principles

DP9	The system should provide spatial and non-spatial data with statistical pluviometric data.

Table 6.15: Design Requirements

DR51	The system users should be able to set temporal/spatial analysis queries.
DR52	The system should provide statistical analysis of pluviometric data for both spatial and non-spatial input.

DR53	The administrators and weather-station users should be able to manage the supported locations, including the functions of adding, deleting or updating a location.
DR54	The administrators and weather-station users should be able to test and validate the locations on the map and their proper visualisation.
DR55	The system should be able to interpret the longitude and latitude data into map locations (and vice versa).
DR56	The users should be able to view weather information about any given location (along with any changes made).

Historical Data

The study revealed that the users would like to view historical data of pluviometric information, so they can compare various characteristics using a filtering mechanism, such as selecting an area or a specific time period. They would also be able to estimate a future condition more accurately, such as foreseeing a flood event. However, this is a feature that should also be implemented in the system, which should be able to analyse historical statistical data, merge spatial and non-spatial characteristics and inform the front-end users and weather-station users about likely events of high risk.

Furthermore, the historical data could be used for a regression analysis based on independent and dependent variables in order to build a stronger and more reliable predictive tool for forecasting purposes. However, the use of historical data and regression analysis has its limitations in hazardous events forecasting. For example, a hazardous event, such as a flood, could be due to a sequence of events, some of which are beyond the scope of the proposed system. Therefore, a more sophisticated mechanism is required in order to help the system increase accuracy in determining the likelihood of hazardous events.

Based on the aforementioned analysis of the system, the following DPs and DRs were derived:

Table 6.16: Design Principles

DP10	The users should be able to view historical data and filter it under various conditions, also getting information about the available samples.

Table 6.17: Design Requirements

DR57	The users should be able to provide and view information about past time periods.
DR58	The system should provide the users with historical information about any requested pluviometric data type or request.
DR59	Time-series analysis-report tools should be used for non-spatial data, providing meaningful historical information to the system users.
DR60	Administrators and weather-station users should be able to modify historical data.

Data Visualisation

Every information system should display meaningful concepts to human viewers; hence, the core principles of the visual representation theory should be followed. The information provided by the current system is typically represented as text, diagram or icon.

The textual information helps human readers to understand it, since they are used to reading text information. However, the font type and size plays a great role in improving reading efficiency, reading time and attractiveness. Indeed, several studies have been conducted (Bernard et al., 2001; Bernard et al., 2002; Beymer et al., 2008; Sanocki & Dyson, 2012) comparing different styles of fonts in terms of their influence on reading performance. Moreover, the position of the text on the page or screen, the margins, line length and space, and the use of typographic grids have a great impact on the information visualisation (Chaparro et al., 2004; Hillesund, 2012; Van Overschelde & Healy, 2005).

Diagrammatic conventions, like maps and graphs, comprise one of the most common and efficient ways of visualising abstract information, such as statistical information (Burkhard, 2004; Card et al., 1999; Ware, 2012). However, human perception should be considered when designing diagrammatic concepts, as these have an impact on the selected type of diagram (e.g., pie chart or bar graphs). Regarding human perception, the findings of the present study did not differ from the Gestalt[33] principles (Kohler, 1966). Therefore, according to the study findings, the data should be visualised to ensure:

- Similarity
- Proximity
- Enclosure
- Continuity, and
- Connection

The use of icons and symbols is required in order to design a more intuitive and user-friendly interface (Blackler et al., 2014; Islam & Bouwman, 2016). These should be designed carefully in order to create meaningful, self-explanatory and memorable concepts, based on the experience and cultural background of the users, in order for them to be used effectively and efficiently.

[33] Gestalt is a psychology term which means "unified whole". It refers to theories of visual perception developed by German psychologists in the 1920s. These theories attempt to describe how people tend to organise visual elements into groups or unified wholes when certain principles are applied.

Based on the aforementioned analysis of the system, the following DPs and DRs were derived:

Table 6.18: Design Principles

DP11	Data should be properly displayed and visualised when needed with the use of diagrammatic conventions and icons, along with textual information, ensuring usability and accessibility.

Table 6.19: Design Requirements

DR61	The system should provide a detailed view of each location to the users, including information about their types, insert/update date, coordinates and so on.
DR62	The system should provide a detailed view of each map to the users, including information about their types, insert/update date, boundaries, covered areas and so on.
DR63	The users should be able to view information related to variables such as rainfall, precipitation, moisture, runoff and recharge in a specified timeframe.
DR64	The system users should define the time period (e.g., day, month and year) of any request in a graphical way[34].
DR65	The system should provide the users with a graphical options set regarding the values of the requested pluviometric data (e.g., average, minimum and maximum values).

[34] 'Graphical way' refers to the visualisation of information using graphics, icons, etc., often combined with text labels and prompts.

DR66	Various graphical types should be used to visualise the obtained information in the most appropriate way each time (e.g., bar chart and time series lines).
DR67	Interactive markers on the maps should be used to create an enhanced and more efficient interaction experience between the user and the system.
DR68	Colour schemes should be supported to visualise the different states of the elevation, slope, aspect and accuflux parameters on each map.
DR69	Warning message and notifications should be displayed in a meaningful graphical way.
DR70	The system should follow a minimal and aesthetic design approach.
DR71	Icons (along with textual information) should be used across the system layout to accelerate users' visual perception.
DR72	Usability heuristics should be applied across the system layout.
DR73	The system information architecture and layout should be adaptive, providing assistive functions attuned to accessibility standards.

Division of Labour

There is an underlying division of labour behind achieving the objectives described previously. For the administrators to achieve their objectives, the maintenance and the physical and digital security personnel of the server where the system and the data are stored, the audit experts, the system logs analysts, the network administrator and the database administrator constitute vital parts of the activity system.

For the weather-station users to achieve their objectives, the supported data must be delivered to them accurately. Accordingly, the responsible staff must install and maintain correctly the data-collecting devices. In addition, manual observations must be made daily, and imported into the system by data entry personnel.

For the end-users to be able to achieve their objectives, the weather stations must provide accurate data, the administrator must ensure the integrity of the system and the data must be represented in a comprehensive way on the screen. The device used must have internet access; therefore, the service provider plays an important role in the activity system. In addition, the energy level of the device must allow the running of the application; therefore, the energy supplier could also affect the system use. Finally, in order for the users to be able to understand some of the complex pluviometric data analysis, they must have previous knowledge of hydrology and GISs.

This knowledge can be acquired in the help section of the system, which introduces hydrology and GIS experts to the division of labour map. Based on the aforementioned analysis of the system, the following DPs and DRs were derived:

Table 6.20: Design Principles

DP12	The system data should be stored and transmitted accurately and with integrity among the system users, implementing supportive mechanisms.

Table 6.21: Design Requirements

DR74	The system should support maintenance and security actions by all authorised administration personnel.
DR75	The system should provide access to auto-sized system users only to critical system files, such as error logs, security information and

	storage mechanisms.
DR76	The system should deliver the supported weather data to the weather-station users with high accuracy.
DR77	The maintenance and installation of data-collection devices should be performed by authorised personnel only.
DR78	The weather stations should provide the front-end users with accurate data of high integrity.
DR79	The system should support low-energy consumption schemes.
DR80	The system should be flexible and lightweight in order to be easily accessed by various devices with poor internet connection.
DR81	The system should support the creation of new user types and roles.
DR82	The system should provide supportive tools (e.g., a thorough and user-friendly documentation manual) to help its users to overcome problematic situations.

Rules

The interrelationships between the subjects and the rest of the system during an activity are mediated by rules, which can be implicit or explicit norms, conventions, guidelines or even social relations within the community.

Regarding the information collection/search, the users do not follow specific rules to complete their tasks, as their actions and patterns are driven by their motives and their experience. However, some conventions are followed, according to individual experience. For example, a user can look up a specific thing by name, coordinates, postal/zip code or something else.

The users of the weather stations, who are mainly responsible for managing the data collection devices, follow specific rules and procedures to keep the system up-to-date, and notify the administrator of the application about the changes. Typically, the instructions of the procedure are in written form, but the system should also help users to complete their tasks and prevent them from effecting errors.

Like the users of the weather stations, the administrators should also follow specific rules and procedures in order to maintain the system and ensure the integrity of the data and the efficiency and performance of the system. However, some of the met conditions might be emergent, unexpected or not supported in documentation; thus, the administrators are required to perform an action based on their experience and their evaluation of a given situation. In any case, the performed actions should be documented in order to help other users to familiarise themselves with the issues, evaluate the actions required and enrich the documentation with more situations and their required actions.

Finally, some social and other types of norms should be followed when the users seek additional information or help, contacting other people or even web services.

Based on the aforementioned analysis of the system, the following DPs and DRs were derived:

Table 6.22: Design Principles

DP13	A set of rules and relegations should be applied to the system, in order to ensure its usability, functionality, operability, accessibility and security. This set is defined by technological and user-experience factors.

Table 6.23: Design Requirements

DR83	The defined set of rules and regulations should be thoroughly described in a technical report document, providing information about the system functionality and extensibility.
DR84	The system should provide testing and validation functions to the administrators, regarding navigation on the maps and the various transformation effects that are applied to them.
DR85	The system should provide the system administrators with tools to define the rules by which a search is performed (e.g., search variables).
DR86	The rules applied for each search should be tested, validated and modified by users with high access/write rights (e.g., administrators and weather-station users).
DR87	The information architecture of the system should follow common approaches and widely-accepted conventions, regarding the digital content, metaphors used and information flow.

6.5 Design Principles and Requirements

In the previous section, the findings of the study were analysed and the main functions of flood prevention systems were discussed. At the end of each section, the derived DPs and DRs were provided. In this section, the sets of DPs and DRs, as derived from the analysis, are combined. This will be used to design a system covering the main objectives regarding flood prevention. Each DR is referenced to a design decision section we made based on the resulting scenarios. The numbering of both the DPs and DRs are the same as the one used in the previous section.

Design Principles

Based on the aforementioned activity theory analysis, as well as team members' and GIS experts' expertise, the DPs are specified as:

Table 6.24: Design Principles

DP1	The users should be divided into groups with discrete rights and responsibilities, depending on their roles. The three main user groups are the front-end users, the weather-station users and the administrators.
DP2	The system should provide information about pluviometric data and DEMs of the various monitored areas.
DP3	The weather-station users should be able to manage data periodically and effortlessly, either automatically or manually, over their network channel. They should also be able to communicate with local authorities easily and quickly.
DP4	Administrators should be able to maintain the system, and ensure the integrity of the data and the efficiency and performance of the system.
DP5	The front-end users should be able to provide and get information about pluviometric data through sophisticated filtering mechanisms.
DP6	The system should provide mechanisms to support the communication between the different user groups and collaboration within these groups.
DP7	A user panel should be used to facilitate user objectives, supporting different levels of abstraction and taking into consideration the different user roles and rights.

DP8	The system should provide its users with meaningful pluviometric data of high detail after a request is performed, which should support sophisticated filtering and advanced search features.
DP9	The system should provide spatial and non-spatial data with statistical pluviometric data.
DP10	The users should be able to view historical data and filter it under various conditions, also getting information about the available samples.
DP11	Data should be properly displayed and visualised, when needed, with the use of diagrammatic conventions and icons, along with textual information, ensuring usability and accessibility.
DP12	The system data should be stored and transmitted accurately and with integrity among the system users, implementing supportive mechanisms.
DP13	A set of rules and relegations should be applied to the system, in order to ensure its usability, functionality, operability, accessibility and security. This set is defined by technological and user-experience factors.

Design Requirements

Based on the aforementioned activity theory analysis, as well as team members' and GIS experts' expertise the DRs are specified as:

Table 6.25 Design Requirements

#	Description	Source Design Principle	User Type
DR1	The system supports three user roles: front-end users, weather-station users and administrators.	DP1	All users
DR2	Each role has discrete access/view/write rights in the system.	DP1	All users
DR3	For different roles, different user-interface layouts are supported.	DP1	All users
DR4	A log-in and log-out mechanism should be supported.	DP1	All users
DR5	The system should answer questions related to pluviometric data and DEMs of each monitored area.	DP2	All users
DR6	The weather-station users should be able to update data periodically, either automatically or manually, over their network channel.	DP3	Weather-station users
DR7	The weather-station users should be able to update data, either automatically or manually, over their network channel.	DP3	Weather-station users
DR8	The system should provide communication mechanisms (e.g., text-	DP3	Weather-station users

	based, messaging, quick-call actions) to support the communication between weather-station users and local authorities.		
DR9	Administrators should be able to have full access to the system.	DP4	Administrators
DR10	Administrators should be able to maintain and modify the system functions, users and roles.	DP4	Administrators
DR11	Administrators should ensure the integrity and security of the data provided in the system.	DP4	Administrators
DR12	Administrators should keep the performance, efficiency and reliability of the system at the highest level.	DP4	Administrators
DR13	Front-end users should be able to provide pluviometric information to the system, which should be moderated first.	DP5	Front-end users
DR14	Front-end users should be able to view historical pluviometric data.	DP5	Front-end users
DR15	Front-end users should be able to search for pluviometric data using filtering mechanisms of various conditions.	DP5	Front-end users
DR16	Front-end users should be able to get information about available samples.	DP5	Front-end users

DR17	The system should support a communication channel among all user types.	DP6	All users
DR18	Weather-station users should be notified when a change is made regarding the data they manage.	DP6	Weather-station users
DR19	Weather-station users should be able to approve or reject system states regarding pluviometric data (e.g., verify data received from front-end users).	DP6	Weather-station users
DR20	Weather-station users should be able to add users and assign them local weather-station rights.	DP6	Weather-station users
DR21	Weather-station users should be able to collaborate in order to manage pluviometric data of common interest.	DP6	Weather-station users
DR22	Administrators should be notified when new users or data have been added into the system.	DP6	Administrators
DR23	Administrators should be able to manage users' rights and roles.	DP6	Administrators
DR24	Administrators should be able to communicate with weather-station users regarding the management of system functions.	DP6	Administrators

DR25	Front-end users should be able to share information with the community.	DP6	Front-end users
DR26	Front-end users should be able to notify administrators of system errors.	DP6	Front-end users
DR27	All functions supported for each user type should be provided via the user panel tool.	DP7	All users
DR28	The functions provided by the user panel should be implemented through a web interface.	DP7	All users
DR29	The users should be able to manage their profile through the user panel.	DP7	All users
DR30	The user panel should allow the weather-station users to upload weather data related to their authorised areas.	DP7	Weather-station users
DR31	The user panel should provide notification messages to weather-station users when weather data is uploaded by front-end users or other weather-station users.	DP7	Weather-station users
DR32	The user panel should provide weather-station users with weather data management tools.	DP7	Weather-station users
DR33	An API should be provided to the weather-station users.	DP7	Weather-station users

DR34	Through the API, the weather-station users should be able to push and pull information regarding the date, the map, the location (of the weather station), time range, time series analysis and sophisticated queries regarding a list of events	DP7	Weather-station users
DR35	The user panel should provide the administrators with tools to check and fix issues critical to system performance, security and operation.	DP7	Administrators
DR36	The user panel should provide accounts settings configuration tools to administrators, providing rich information for each system user (e.g., username, telephone and email address).	DP7	Administrators
DR37	The user panel should provide the administrators with tools regarding the back-end functions of the system, such as maps and management tools, and supporting functions for inserting, modifying and deleting system elements.	DP7	Administrators
DR38	The user panel should provide the front-end users with functions to upload weather data from their area.	DP7	Front-end users
DR39	The user panel should provide the front-end users with search tools, including advanced search features.	DP7	Front-end users

DR40	The user panel should notify the front-end users regarding their requests status (e.g., upload new weather data or set a new query).	DP7	Front-end users
DR41	The users should be able to set requests to the system regarding pluviometric data.	DP8	
DR42	The system should support different types of pluviometric data, e.g., rainfall level, temperature and moisture.	DP8	
DR43	The system should perform the temporal/spatial analysis based on various parameters, such as the pluviometric data variable and geolocation information.	DP8	
DR44	The users should be able to refine their search, by applying filters regarding the type of the requested pluviometric data, the requested time period and location.	DP8	All users
DR45	The users should be able to combine different types of queries to produce a sophisticated mixed query, such as pluviometric variable, location and date, e.g., what is the *maximum level of rainfall* for *November 2015*;	DP8	All users
DR46	The users with higher access/write rights (i.e., administrators and weather-station users) should be able to modify (e.g.,	DP8	Admin/Weather

	edit or delete) pluviometric data, applying the aforementioned filters.		
DR47	The users with higher access/write rights (i.e., administrators and weather-station users) should be able to modify (e.g., add, edit or delete) pluviometric data types and characteristics.	DP8	Admin/Weather
DR48	The users should be able to import and export pluviometric data in a common format (e.g., CSV format).	DP8	All users
DR49	The system should automatically scan for errors on data import action, and notify the users accordingly.	DP8	
DR50	The system should keep a history of the pluviometric data requests.	DP8	
DR51	The system users should be able to set temporal/spatial analysis queries.	DP9	
DR52	The system should provide statistical analysis of pluviometric data for both spatial and non-spatial input.	DP9	
DR53	The administrators and weather-station users should be able to manage the supported locations, including the functions of adding, deleting or updating a location.	DP9	Admin/Weather

DR54	The administrators and weather-station users should be able to test and validate the locations on the map and their proper visualisation.	DP9	Admin/Weather
DR55	The system should be able to interpret the longitude and latitude data into map locations (and vice versa).	DP9	
DR56	The users should be able to view weather information about any given location (along with any changes made).	DP9	All users
DR57	The users should be able to provide and view information about past time periods.	DP10	All users
DR58	The system should provide the users with historical information about any requested pluviometric data type or request.	DP10	All users
DR59	Time-series analysis-report tools should be used for non-spatial data, providing meaningful historical information to the system users.	DP10	All users
DR60	Administrators and weather-station users should be able to modify historical data.	DP10	Admin/Weather
DR61	The system should provide a detailed view of each location to the users, including information about their types, insert/update date, coordinates and so	DP11	

	on.		
DR62	The system should provide a detailed view of each map to the users, including information about their types, insert/update date, boundaries, covered areas and so on.	DP11	
DR63	The users should be able to view information related to variables such as rainfall, precipitation, moisture, runoff and recharge in a specified timeframe.	DP11	All users
DR64	The system users should define the time period (e.g., day, month and year) of any request in a graphical way.	DP11	All users
DR65	The system should provide the users with a graphical options set regarding the values of the requested pluviometric data (e.g., average, minimum and maximum values).	DP11	All users
DR66	Various graphical types should be used to visualise the obtained information in the most appropriate way each time (e.g., bar chart and time series lines).	DP11	
DR67	Interactive markers on the maps should be used to create an enhanced and more efficient interaction experience between the user and the system.	DP11	

DR68	Colour schemes should be supported to visualise the different states of the elevation, slope, aspect and accuflux parameters on each map.	DP11	
DR69	Warning message and notifications should be displayed in a meaningful graphical way.	DP11	All users
DR70	The system should follow a minimal and aesthetic design approach.	DP11	
DR71	Icons (along with textual information) should be used across the system layout to accelerate users' visual perception.	DP11	
DR72	Usability heuristics should be applied across the system layout.	DP11	
DR73	The system information architecture and layout should be adaptive, providing assistive functions attuned to accessibility standards.	DP11	
DR74	The system should support maintenance and security actions by all authorised administration personnel.	DP12	
DR75	The system should provide access to authorised system users only to critical system files, such as error logs, security information and storage mechanisms.	DP12	Admin/Weather

DR76	The system should deliver the supported weather data to the weather-station users with high accuracy.	DP12	Weather-station users
DR77	The maintenance and installation of data-collection devices should be performed by authorised personnel only.	DP12	Admin/Weather
DR78	The weather stations should provide the front-end users with accurate data of high integrity.	DP12	Weather-station users
DR79	The system should support low-energy consumption schemes.	DP12	
DR80	The system should be flexible and lightweight in order to be easily accessed by various devices with poor internet connection.	DP12	
DR81	The system should support the creation of new user types and roles.	DP12	Administrators
DR82	The system should provide supportive tools (e.g., a thorough and user-friendly documentation manual) to help its users to overcome problematic situations.	DP12	All users
DR83	The defined set of rules and regulations should be thoroughly described in a technical report document, providing information about the system functionality and extensibility.	DP13	Admin/Weather

DR84	The system should provide testing and validation functions to the administrators regarding the navigation on the maps and the various transformation effects that are applied to them.	DP13	Administrators
DR85	The system should provide the administrators with tools to define the rules by which a search is performed (e.g., search variables).	DP13	Administrators
DR86	The rules applied for each search should be tested, validated and modified by users with high access/write rights (i.e., administrators and weather-station users).	DP13	Admin/Weather
DR87	The information architecture of the system should follow common approaches and widely-accepted conventions regarding the digital content, metaphors used and information flow.	DP13	All users

The user interface should be intuitive and aesthetic and have adaptive behaviour. It should be designed in such a way as to attract new users, and ensure they quickly acquire a certain level of familiarity with it, demanding the least possible effort to learn how to use it.

6.6 Conclusion

The set of design guidelines (comprised of DPs and DRs) created in this phase of the project provides a starting-point for creating an early prototype of the system to be designed. Our intention was to involve users as early as possible, thereby avoiding design errors that would be too costly to fix in later phases of the system's lifecycle. Combining the team's expertise with the users' point of view allowed us to dig into the problem, understand the users' attitudes and needs and ensure that the system would be designed by the users, and would, therefore, be intuitive and include all the required functionality. Our team members were there to guide the users and trigger possible pain points or other issues that had to be identified before beginning work on the prototype.

The activity theory framework allowed our team to form a holistic view of the problem and better understand how the system fits into the environment. It provided great insight into how the system could be expanded and ensured that an appropriate design and implementation strategy would be adopted allowing for future expansion.

Chapter 7 Prototype Design and Development

7.1 Introduction

The design guidelines discussed in the previous section were used in order to design the early prototype of the system. In this second phase of the design, an iterative design process was adopted. The designers, starting from the design guidelines of the first phase, used low-fidelity sketching to conceptualise the structure of the system and then transformed this to high-fidelity interactive wireframes. The interactive prototype was then used under controlled conditions by real users, who were asked to carry out a set of predefined tasks and think aloud as they were completing them. As per the iterative design process, the feedback provided by the testing sessions was analysed and the results were used to refine certain aspects of the prototype.

7.2 Prototype Design Approach

7.2.1 Theoretical Framework

The iterative design process was introduced by Buxton and Sniderman (1980) and refers to a cyclic design approach of consecutive rounds of prototyping, testing and refining of the system, as shown in Figure 7.1.

This process enables the design to be refined according to user needs and behaviours that could not have been predicted during the requirement-gathering phase. It also ensures that old design decisions can be abandoned in favour of new ideas that are more appropriate for satisfying user needs early enough to avoid any unpredicted design flaws that would be too expensive, in terms of time and money, to overcome at later stages (Landay & Myers, 1995).

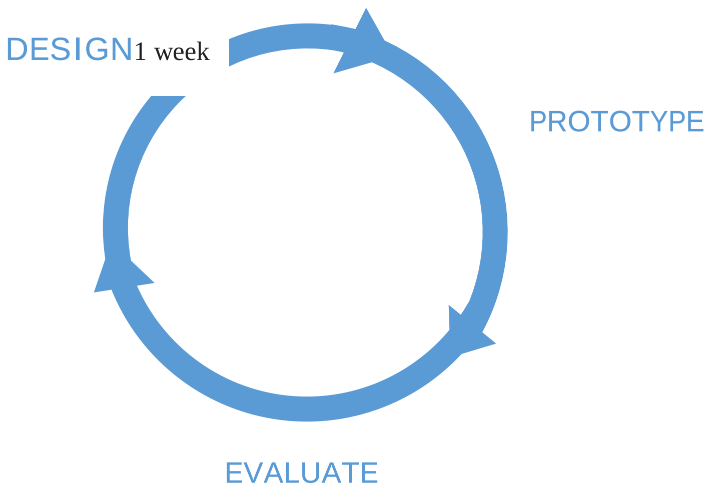

Figure 7.1: Iterative design process

For the design phase of the iterative process, sketching is used as a powerful tool by the design team for conceptualising and sharing design ideas (Buxton, 2010). That is, designers can use sketching to externalise their ideas and communicate them better. It allows for rapid experimentation with a proposed design, or certain details thereof (Arnheim, 1993), for critiquing ideas and accepting or rejecting them, as well as for developing these ideas further (Craft & Cairns, 2009).

After conceptualising the ideas, the low-fidelity sketches are turned into high-fidelity wireframes. Wireframes are non-graphical layouts of the system and help establish the interactions and the navigation by visualising the underlying information architecture. High-fidelity wireframes are used for rapid prototyping since they provide a high level of detail, very close to the implemented system. The main issues that can be effectively addressed by the high-fidelity prototype include the navigation systems and the arrangement of elements on each screen of the system, as well as information placement and prioritisation.

7.2.2 The Prototype

Given the guidelines derived from the initial workshop, the design team, consisting of one senior designer with more than 10 years of experience in designing interactive systems and one junior with 4 years of experience, gathered to create the system's low-fidelity prototype. Sketching on paper was preferred, as it is a great tool to help the design team and research team (which conducted the requirement-gathering phase of the project and consisted of two researchers with more than 6 years of experience in requirement-gathering and user-testing) to identify additional requirements and stages of the system process flow quickly and effortlessly. Simple shapes, such as circles and arrows, enabled quick communication of the design concepts. A sample of the sketches of the system is displayed in Figure 7.2.

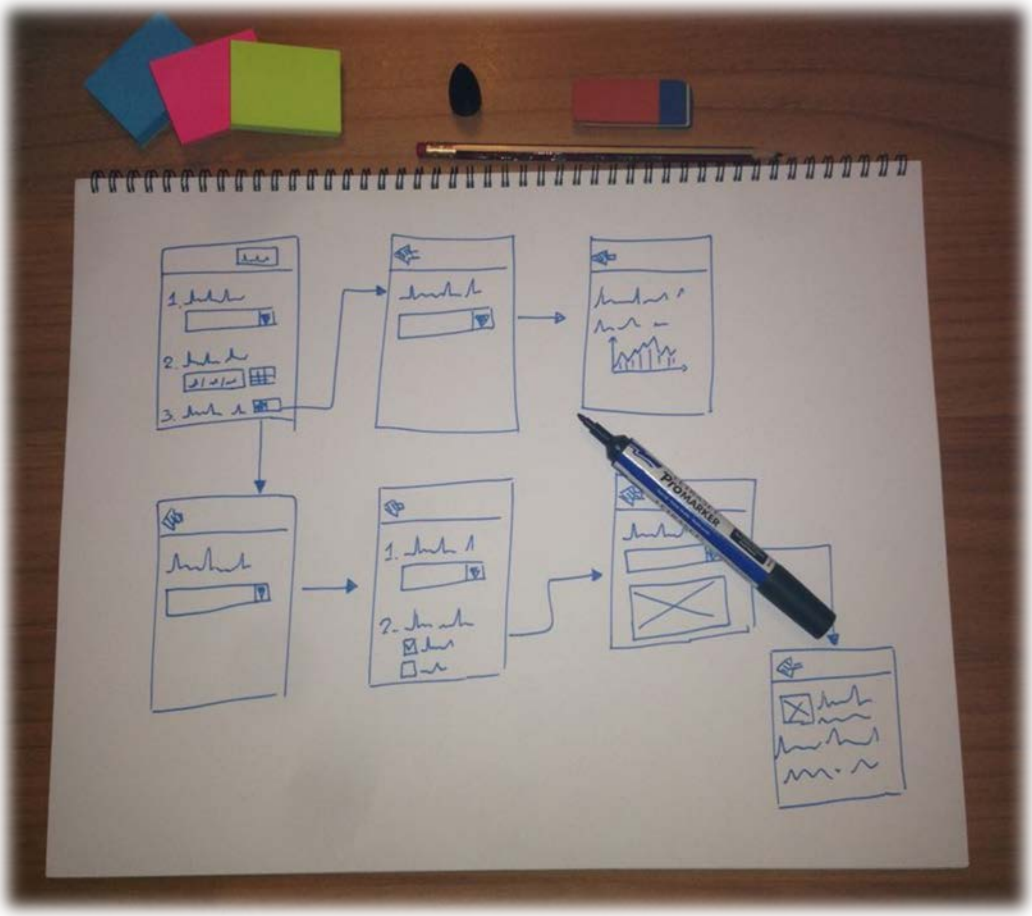

Figure 7.2: Sketching

This phase was informal and included mainly sketching by, and discussions among, the members of both the teams. At the beginning, the guidelines were reviewed and some typical usage scenarios and user tasks were discussed between designers and research team members. The latter were able to answer various questions designers had regarding what tasks are likely to be more common than others, what tasks are related to each other, etc. - the information crucial to deciding how to present the content and functionality in the most efficient and user-friendly way. Afterwards, designers started conceptualising the design guidelines as low-fidelity sketches on paper. The designers worked separately and created several user interface ideas each so that diverse ideas were created and later compared in order to avoid focusing on the first idea created. After the first drafts had been created, the design and development teams met again and discussed each concept and the advantages and disadvantages they offered. Some improvements were suggested, as well as some ideas for joining two different concepts together in order to utilise the advantages of both. Together, it was decided which approach would best serve the users' needs and be more usable and simple, based on team members' working experience in the user-experience field. They all agreed on a solution which resulted in one joint low-fidelity prototype that incorporated all the changes and suggestions and had all the desired functionality and ensured that the proposed taxonomy (i.e., the organisation of the information and the flow from screen to screen) required the least possible effort from the user.

Subsequently, the low-fidelity prototype was reviewed by a researcher with 4 years' experience in user-testing and reviewing existing systems and proposed designs. This researcher had not been engaged in any previous phase of the project, so the prototype could be evaluated from an outsider's perspective; having been involved in the project previously, the team members could not look at the prototype from the viewpoint of a new user. The researcher received a briefing about what the system is expected to do, what the typical user goals and tasks are and who the typical users are expected to be. After reviewing the system, he was also asked to map the DGs to the prototype and ensure that they were all followed. It was decided that it would be better if a person who was not involved in designing did the mapping, in order to avoid biases and ensure that this was done in a critical way; therefore, the task was assigned to this researcher. No documents were produced during this phase but the external researcher discussed the possible pain points with the research and design teams. No DGs were missing from the low-fidelity prototype. After discussion, they all agreed on which suggestions would be included in the final low-fidelity prototype, and how.

The final low-fidelity sketched prototype, representing both the mobile application and the administrator panel, was then transformed to the high-fidelity clickable prototype that was used in the evaluation phase. The high-fidelity prototype incorporated more fidelity and functionality, thus giving users the impression of a fully-developed system. In order to implement the high-fidelity prototype, a rapid prototyping tool that required no coding was used (i.e., Axure PR). Objects were dragged to the workspace and arranged accordingly. The required transitions from screen to screen were then added, resulting in a fully functional prototype implemented for a predefined set of data.

No aesthetic design was applied at this phase, as the main purpose of the prototype was to gain insights and identify any pain points that would affect the user experience and require fixing as early as possible. The final version of the high-fidelity prototype was again reviewed by the external researcher to ensure all the DGs had been implemented. The researcher concluded that they had, and suggested a few small changes to the layouts that were likely to increase usability (e.g., making buttons more recognisable by using a different colour), which were immediately implemented as the rapid prototyping tool allowed changes to be made easily.

Some of the designed screens of the prototype of the mobile application are displayed in Figures 7.3–7.8 below. These screens are provided to front-end users, enabling them to view, search and provide various pluviometric data on several locations and for different time periods; DRs DR13-16, DR38-34, DR48-52 and DR61-74 are implemented.

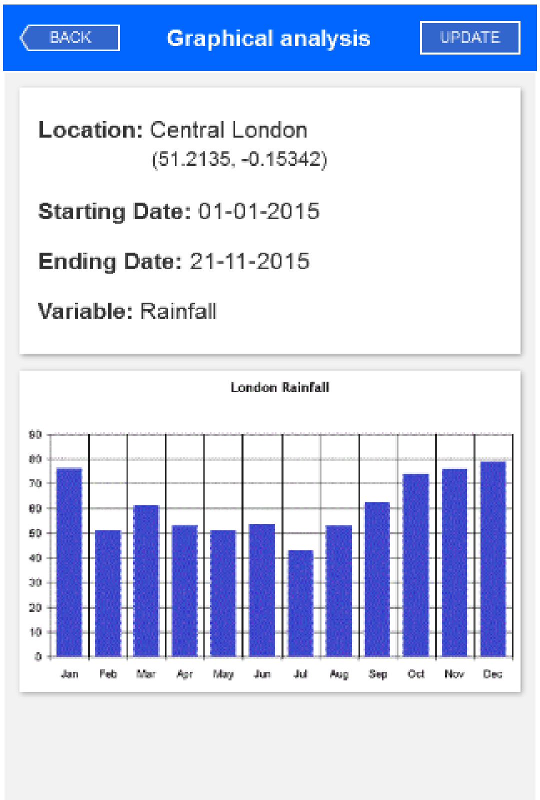

Figure 7.3 Graphical analysis screen

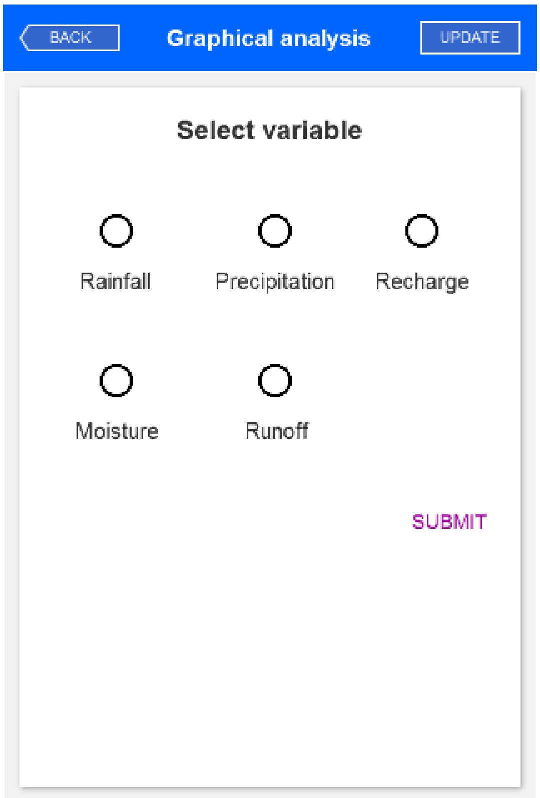

Figure 7.4: Graphical analysis screen

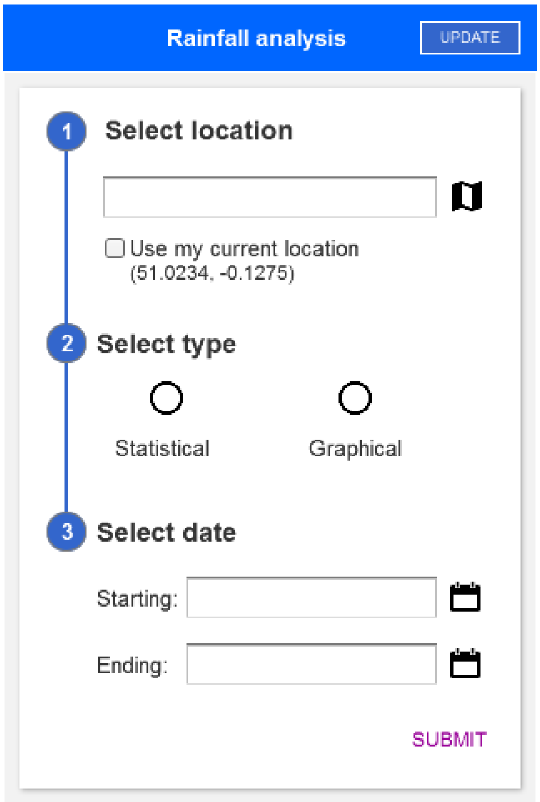

Figure 7.5: Landing screen

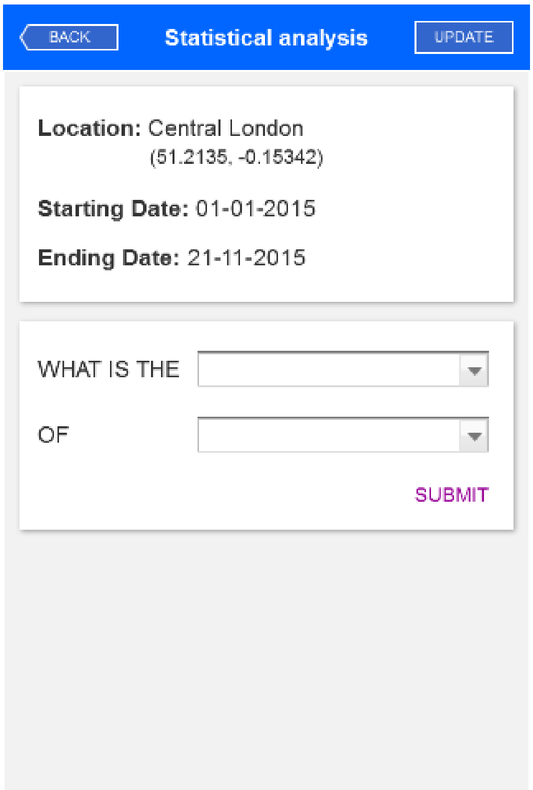

Figure 7.6 Statistical analysis

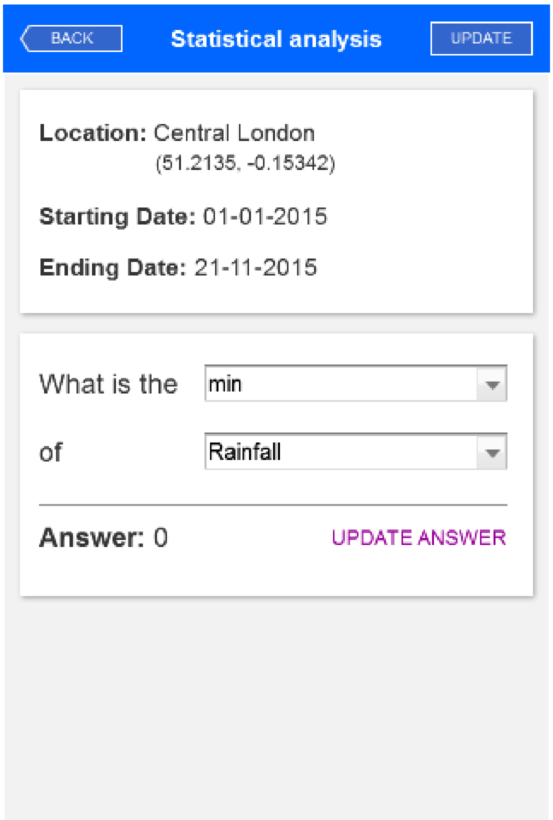

Figure 7.7: Statistical data screen

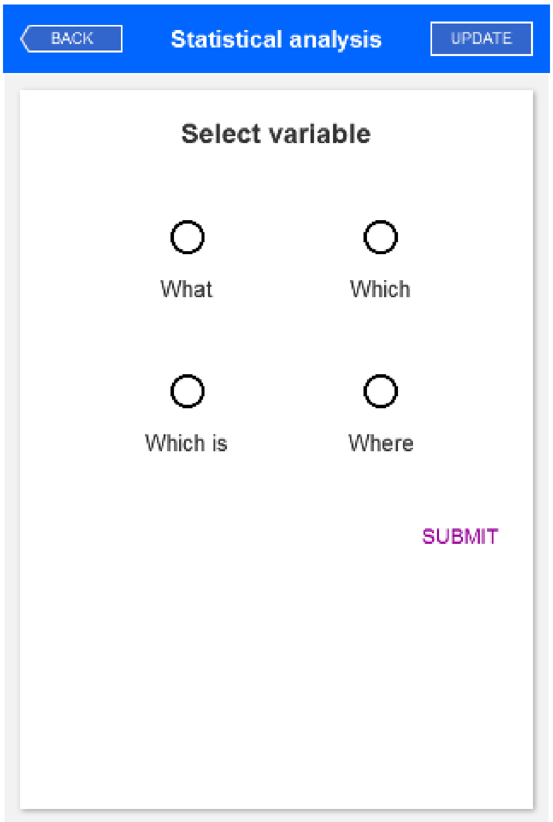

Figure 7.8: Statistics initialisation screen

7.3 Methodology

An evaluation study was carried out with potential system users to evaluate the designed prototype to ensure that it met user needs and was intuitive. The users were first introduced to the system and its main aims, then given a set of tasks to carry out. They were asked to think aloud as they were going through each task; meanwhile, the facilitator asked clarifying questions that encouraged the users to externalise their thoughts. The think-aloud (TA) protocol that was used is among the primary tools used for conducting usability tests (Olmsted-Hawala et al., 2010). This method is considered one of the most popular methods of evaluation testing, due to its simplicity and low cost. Usability practitioners use the TA protocol because they cannot directly observe what a user is thinking. Nevertheless, there are numerous disadvantages to the TA approach. Merchie and Keer (2014) summarise the advantages and disadvantages of using TA protocols, as shown in Table 7.1. In the present study, the facilitator took notes during the process, which were combined with observations from the session and provided valuable insight into the users' interaction with the proposed design.

Table 7.1: Advantages and disadvantages of the think-aloud protocol

Think-aloud protocol	
Advantages	Disadvantages
1. Uncovers thought processes and reveals the content of working memory.	1. Ability and reactivity to verbalise thought processes can compromise assessment.
2. Data are gathered directly, without delay.	2. Verbalisation stops can disrupt comprehension
3. The learner does not give thought-interpretations and is not required to bring them into a predefined form.	3. Time- and labour-insensitive analysis; not easily usable or efficient with large samples.
4. Reduces memory failure.	4. Can influence strategic action or later

	recalls.
	5. Data-incompleteness: learners can edit or omit thoughts that come to mind.

7.3.1 Environment

The study was conducted in a quiet room, appropriately designed and decorated to make the users feel comfortable. To enhance this feeling, a user was offered a drink. No food was offered during the session, as this would have interrupted the user's expression of thoughts. It was decided to use a single device without screen duplicating to ensure the users would not feel they were being observed, as this could have had an impact on their behaviour. Therefore, a facilitator was essential in order to guide the user through the process. The user and the facilitator sat next to each other, facing a table where the device was placed; the user was allowed to hold the device.

Each testing session lasted about an hour and ten minutes and was divided into three stages. The first stage lasted five minutes, during which the user was introduced to the system/protocol. The second stage of the session lasted sixty minutes and the users were asked to carry out a set of predefined tasks. The third and last stage lasted five minutes and included the wrap-up of the session. The users were allowed to ask for a short break during the session and could ask to terminate the session for any reason and at any time.

7.3.2 Participants

With everyone being a potential user of the system, it was important that there was maximum variation in the age, gender and education level of the study participants. Since we were aiming for insights at this stage, we decided to recruit eight representative users. Despite the common assertion that five participants are enough to find most usability problems (Virzi, 1992; Nielsen, 2000), recent findings suggest that the number of users should be adjusted according to the needs of each project and that larger groups seem to provide better results, with less deviation of the number of identified usability issues (Faulkner, 2003); besides, a higher number of participants was needed due to a relatively high number of tasks (there were separate tasks for each user type) and our preference for short testing sessions, which will be discussed further in section 7.3.5.2. For the purposes of this evaluation study, since the system was not very complicated, eight sessions were considered sufficient, given time and budget limitations and the need for a reasonable cross-section of user types.

Participants were recruited through a recruitment agency, and by email and telephone, using the recruitment screener provided in Appendix D. Tables 7.2 and 7.3 show the characteristics of the participants. Participants were asked to rate their experience of using mobile applications and GISs, as well as weather systems, on a five-point Likert-type scale, from 1 to 5, with 1 being not experienced and 5 being very experienced. During the recruitment process, only those people who could contribute to variability were selected. For example, at the beginning of the recruitment process, all the people who were willing to participate were female; subsequently, therefore, only males were recruited to ensure variability. Although we did not have fixed quotas for different genders, age groups, mobile experience levels, etc., effort was made to ensure that the participants were not too similar, and thus less representative of the general population, and that there was some variability across all characteristics. However, people who do not use weather systems or mobile applications were not selected, since they are not part of the target audience, do not have a basic understanding in the area and are unlikely to use the system in real life.

Table 7.2: Participants' demographics

PARTICIPANTS' CHARACTERISTICS	
Age range	21–41
Mean age	30
Gender	4 females 4 males
Education level	2 undergraduate students 2 graduates 2 postgraduate students 2 PhD holders
Mean mobile application experience	4.1 / 5
Mean weather system experience	4.3 / 5
Mean familiarity with GISs	3.4 / 5

Table 7.3: Participants' experience levels

Participant	Gender	Age	Education Level	Mobile app experience	Weather system experience	GIS experience	Group
Part 1	Female	31	Graduate	4/5	5/5	4/5	G 1
Part 2	Female	25	Postgraduate	4/5	4/5	3/5	G 1

Part 3	Male	21	Undergraduate	5/5	4/5	2/5	G 1
Part 4	Male	21	Undergraduate	5/5	4/5	3/5	G 1
Part 5	Male	26	Postgraduate	3/5	4/5	3/5	G 2
Part 6	Female	34	Graduate	3/5	4/5	3/5	G 2
Part 7	Male	41	PhD holder	4/5	5/5	5/5	G 2
Part 8	Female	41	PhD holder	5/5	4/5	4/5	G 2
Group 1	2M/2F	24.5 ± 4.1	2 UG / 1 G / 1 PG	4.5 ± 0.5	4.3 ± 0.4	3.0 ± 0.7	
Group 2	2M/2F	35.5 ± 6.2	1 G / 1 PG / 2 PhD	3.8 ± 0.8	4.3 ± 0.4	3.8 ± 0.8	
All	4M/4F	30.0 ± 7.6	2 UG /2 G /2PG / 2Phd	4.1 ± 0.8	4.3 ± 0.4	3.4 ± 0.9	

7.3.3 Ethics

Since the evaluation study involved real users, the project had to be in compliance with the Data Protection Act (1998). The users had to be informed in advance as to the content of the testing session, understand their rights during the session and know what personal data would be held about them. Therefore, they were provided with a data protection statement that detailed how their personal information would be used by the team and were then asked to sign a consent form before taking part in the session. Ethical approval for the study has been obtained from Brunel university.

7.3.4 Pilot Study

To ensure that the testing session had been designed efficiently and effectively, a pilot study was carried out. The main aims were to ensure that the testing session would run smoothly, the tasks were easy to comprehend and the facilitator would be able to get the required information and modify the test plan accordingly. Two participants, aged 21 and 25, both female, took part in the pilot study.

Table 7.4: Participants' demographics

PARTICIPANTS' CHARACTERISTICS	
Age range	21–25
Mean age	23
Gender	2 females
Education level	1 undergraduate student 1 university graduate
Mean mobile application experience	4.0 / 5
Mean weather system experience	3.5 / 5
Mean familiarity with GISs	3.5 / 5

Table 7.5: Participants' experience levels

Participant	Gender	Age	Education Level	Mobile app experience	Weather system experience	GIS experien ce
Part 1	Female	25	Graduate	4/5	4/5	4/5

Part 2	Female	21	Undergraduate	4/5	3/5	3/5

The pilot study ran smoothly, with the main issue being excessive note-taking by the facilitators. Therefore, it was decided to record the testing sessions to ensure the facilitators would spend more time interacting with the participants. In addition, in stage three of the study, the facilitators had to guide the participants with questions; it was thus decided to create a set of predefined questions for this stage, which would only be used to encourage the final discussion with the participants where necessary.

7.3.5 Main Study

The main study was divided into three stages, as discussed earlier. Each stage is detailed in the following sub-sections.

7.3.5.1 First Stage: Induction

The first five minutes of the testing session were dedicated to introducing the users to the purpose of the session and creating a pleasant feeling that would ensure they were comfortable enough to express their thoughts. It was also ensured that they understood the process that would be followed during the session.

They were informed of how the provided data would be used and stored and were asked to read the Data Protection Act and sign a consent form. Then, the facilitator described the purpose of the system and informed the user about the limited functionality of the prototype to ensure this would not have an impact on their impression of the proposed system. The user was then reassured that it was the system being tested during the session, not the user, and was encouraged to think aloud as they were carrying out the tasks, as per the TA approach outlined above (Wright & Monk, 1991; Nielsen et al., 2002).

7.3.5.2 Second Stage: Task Completion

The second stage of the session lasted sixty minutes, during which the users were asked to carry out a set of predefined tasks. The facilitator (our research team members acted as facilitators since they have the relevant expertise) encouraged the users to think aloud as they were going through the tasks - to say what came into their minds while they were attempting to carry out a task, what they were currently looking at and what they were thinking or feeling - to help the facilitator understand the participants' cognitive processes, not just their actions, and to discover their misconceptions and misinterpretations. Since thinking aloud is not something that people naturally do and almost all participants had not done it before, they received a quick demonstration from facilitators (facilitators carrying out a simple task and thinking aloud) and a very simple practice task, namely, finding the name of the highest mountain in Europe on Google while thinking aloud. The practice task was intended to be simple, so that participants felt confident in their thinking-aloud skills. Afterwards, participants proceeded with carrying out real tasks while thinking aloud. However, participants were not pushed too much to think aloud, in order not to make it too unnatural. Facilitators tried not to provide answers or hints on how to do tasks; when participants were not sure how to do something or asked questions, facilitators avoided giving advice and asked participants to do what they would do if they were doing it on their own, at home.

Facilitators asked questions whenever observing a behaviour that was not expected or predicted by the team, always being careful not to guide the answer of the user (Nørgaard & Hornbæk, 2006). However, when asking questions, effort was made not to disturb the participants' natural user journey when carrying out tasks, and questions were asked at appropriate moments, such as when a participant was offering some comments, asked questions or naturally interrupted his work. This was so as not to distract users from tasks with questions. While observing participants, facilitators looked for emerging patterns of behaviour and themes, and whether subsequent participants showed these as well, which was needed to make the subsequent data analysis easier.

During the session, data were recorded by a camera and a screen-recording software to capture the user’s reaction, both verbal and behavioural (e.g., raised eyebrows when something was unexpected), the triggering questions of the facilitator and the user's answers and, finally, the navigation through the prototype.

The eight participants were divided into two groups of four in order to manage the allocated time more efficiently. A facilitator was assigned to each group, and each participant had to complete nine tasks in fifteen minutes. In total, there were twenty-four tasks, which were assigned to each participant in such a way that each task was performed by three different participants. Despite tasks being relatively easy to complete, we chose to have short sessions, in order to avoid any mistakes made by the users due to loss of focus. Our decision to have each task performed by three users was in line with Nielsen's (2012) suggestion that for very simple tasks and systems testing, as few as two users would be enough to identify any pain points. Since our system is simple, but we were not entirely sure whether it qualifies as *very* simple, we chose to test it with three users. In addition, there was an overlapping of the screens that should be used for different tasks; therefore, we concluded that we would have enough data on the interactions to draw safe conclusions as to the usability of the prototype. Besides, since it is a qualitative study, we aimed for qualitative insights, rather than precision without a full understanding of why problems actually happened. Finally, the TA protocol is a time- and labour-intensive analysis, not easily usable or efficient with large samples; therefore, we chose to have the smallest number of users per task possible without compromising the quality of the study. Since there were 24 tasks to be carried out 3 times each in total (72 non-unique tasks) and 8 participants, each participant had to carry out 9 tasks. The team members estimated that it should take approximately 15 minutes to carry out 9 tasks without rushing, and the pilot study confirmed this estimate as realistic.

The participants who had not performed the tasks were not able to see or hear the participants performing the tasks, as they were in different rooms. Those participants who had performed the tasks were also kept in different rooms from those who had not. The participants were asked to perform different sets of tasks, including tasks from the three task groups based on the three user roles, ensuring that each task would be completed at least by three participants.

The tasks the users were asked to perform were divided into three groups, according to user role, and derived from the DPs of the high-fidelity prototype. We aimed to have at least one task per principle, so that all of them were tested. Some DPs had more than one task associated with them, as they were believed to be more complex or wide, being, for example, applicable to different user goals. Tasks aimed to be realistic and encourage action (so that participants actually used the interface instead of saying what they would do, action words such as “create” and “edit” were used). There were no hidden clues on how to do them in their descriptions. The coding in the parenthesis stands for the corresponding DP:

A. Tasks for administrators:
    1. Login to the back-end system. DR1, DR2, DR3, DR4
    2. Reset the password of a given system user. DR9, DR10, DR23, DR36
    3. Create a new map. DR37, DR54, DR84
    4. Delete an existing map. DR37, DR75, DR84
    5. Edit an existing location by changing its latitude. DR37, DR53, DR54, DR55, DR61, DR62, DR84
    6. Enter pluviometric data for a given location. DR46, DR47,

	DR60
7. Upload a CSV file of valid pluviometric data for a given location.	DR48, DR49

W. Tasks for weather-station users:

1. Push daily rainfall data to the system.	DR6, DR7, DR18, DR19, DR32, DR33, DR34, DR41
2. Upload data in raw format.	DR6, DR7, DR30, DR31, DR32, DR33, D48, DR49
3. Get the data setting a given query.	DR18, DR32, DR33, DR41, DR76
4. Logout.	DR1, DR2, DR3, DR4

F. Tasks for front-end users:

1. View the rainfall values in London during November.	DR5, DR14, DR56, DR57, DR58, DR63, DR64
2. View the daily precipitation during last August.	DR5, DR14, DR57, DR58, DR63

3. Find the minimum rainfall level from October 12 to October 19.	DR5, DR14, DR15, DR39, DR45, DR51, DR57, DR58
4. Find the average moisture level in Bristol during the summer.	DR5, DR15, DR39, DR45, DR51, DR57, DR58
5. Find the time and amount of the highest runoff in the country during the summer.	DR5, DR15, DR39, DR45, DR51, DR57, DR58
6. Find the number of consecutive days it rained in London last year.	DR5, DR14, DR15, DR39, DR45, DR51, DR57, DR58
7. Find which city of the country had the most rainfall last year.	DR5, DR15, DR39, DR45, DR51, DR57, DR58
8. Find when the rainfall levels were between 300 and 400mm.	DR5, DR15, DR16, DR39, DR45, DR51, DR57, DR58
9. Show a bar graph of a rainfall data for 31 December 2014.	DR5, DR15, DR52
10. Estimate which area has the highest	DR5, DR15,

level of moisture. DR39, DR63

11. Perform a slope image of a DEM. DR5, DR59

12. Render the map in greyscale. DR55, DR65

13. Get help about the map view. DR82

DRS DR27-29, DR65-74, DR79-80 are related to the overall system functionality, performance and appearance, and are thus indirectly evaluated in the aforementioned tasks. The DRs concerning communication mechanisms were beyond the scope of the high-fidelity prototype. The allocation of the tasks is presented in the following table:

Table 7.6: Task Allocation

	User 1	**User 2**	**User 3**	**User 4**	**User 5**	**User 6**	**User 7**	**User 8**
Task A1	✓		✓					✓
Task A2		✓			✓		✓	
Task A3				✓		✓		✓
Task A4	✓				✓		✓	
Task A5		✓		✓		✓		
Task A6			✓				✓	✓
Task A7		✓		✓		✓		
Task A8		✓	✓				✓	

Task B1	✓			✓	✓			
Task B2	✓						✓	✓
Task B3			✓		✓	✓		
Task B4		✓				✓		✓
Task C1	✓		✓	✓				
Task C2					✓		✓	✓
Task C3		✓		✓		✓		
Task C4			✓		✓		✓	
Task C5	✓			✓				✓
Task C6		✓	✓			✓		
Task C7	✓				✓		✓	
Task C8		✓				✓		✓
Task C9			✓	✓	✓			
Task C10	✓	✓					✓	
Task C11			✓			✓		✓
Task C12	✓			✓	✓			

7.3.5.3 Third Stage: Wrap-Up of Session and Conclusions

The third stage lasted five minutes, in which the users of each group were asked to comment on the session, make any observations and identify the main advantages and disadvantages of the system. Again, a camera was used to record the users' comments. Finally, the facilitator thanked the users for their help and informed them that the session had ended. Facilitators immediately made additional notes when needed, noted their reflections, organised their notes and observations, added additional comments needed for future analysis, etc. It was important to do all this immediately after the sessions in order to minimise loss of details due to the limitations of human memory and to ensure maximum accuracy.

7.4 Results

After completing the testing sessions, the research team (who were also facilitators) proceeded to the analysis of the recordings. Since the data collected were qualitative in nature, no statistical analysis needed to be done; instead, researchers tried to obtain various insights from the data they had obtained in order to see the pain points and areas for improvement, as well as the paths which participants took to achieve their goals, their comments, unexpected ways of carrying out tasks, etc. They also looked for various patterns and themes that would help in understanding which areas needed improvement. The focus was on why the problems were occurring and how, not on the number of issues. Since a lot of data were collected (recordings, observations, participants' answers), it was important to reduce the data and identify what was important and what was meaningful. The two researchers shared and discussed their notes and observations, viewed the recordings independently and took note of every issue they observed or which had been mentioned by the participants for each task. Next, the issues they identified were mapped to each screen and grouped. Grouping by user type (front-end, admin and weather-station) and mapping to screens was preferred by both researchers as the way to organise findings. Whenever an issue was associated with transitions between two screens, it was agreed to use the starting screen as a reference. Each issue group was assigned a corresponding name by each researcher. At the end of this phase, the two researchers discussed the results of their analysis, combined their findings and agreed upon the names of the issues. The list of issues derived from the process, along with their impact on the user and a recommendation on how to overcome them (in order to make the findings actionable), are included in the next table.

Table 7.7: Identified Issues

Screen	**Issue Identifier**	**Description**	**Impact**	**Recommendation**
Administrators				
All screens	A1	The horizontal menu at the top of the screen was inconvenient.	Users stated that the horizontal menu resulted in slowing their automated processes down due to having to scan the whole width of the screen.	Provide the menu vertically to the right to enable the users to quickly access to admin panel menu items.
Weather-station users				
Statistics screen	W1	The prototype does not support combined information-seeking.	Users have to start a new query to answer different questions for the same data.	Ensure the prototype allows for combining queries.
Front-end users				
Landing screen	F1	Users were confused by the statistical and graphical types option.	Users were confused about spatial and non-spatial data and unsure of the meaning of graphical and statistical types.	Ensure there is a clear distinction between the statistical and graphical information.
Graphical analysis screen	F2	The prototype did not allow for quickly making modifications to the presented results.	Users were annoyed with having to go to the previous screens to make small modifications to the presented data.	Provide a quick and easy way to modify the search on the same screen.

Statistics initialization screen	F3	The prototype does not support combined information-seeking.	Users have to start a new query to answer different questions for the same data.	Ensure the prototype allows for combining queries.
All screens	F4	Update has to be executed manually by the user.	This functionality adds a secondary task to the user. As such, it may be forgotten or overlooked, which would mean outdated data were presented.	Ensure any require updates are executed automatically. The users should be informed as to when the last update took place.
N/A	F5	The prototype does not provide any information on the location of the presented data.	The user is unaware of which location the presented data refer to.	Present location-based information related to the data.
N/A	F6	The prototype does not provide any information on the location of the weather stations.	The user is unable to check whether there is a weather station near a location.	Provide a map with all the available weather stations.

Once the main issues were identified, the researchers proceeded to make a general overview of front-end user and admin interfaces, based on the original requirements and the qualitative feedback, resulting in the discussion about what changes needed to be made to the prototype.

7.4.1 Mobile Application Interface

The interface of the end-user part of the system was considered clear overall, with the users being able to complete most of the predefined tasks. The final discussion with the users revealed the primary information points they wished to use as statistical and graphical data. The main activities, as they resulted from the study and the scenario-based design discussed in the previous chapter, were:

- View current location of the device and when it was last updated;
- View information for a day, a month, a year or a selected timeframe in regard to one of the following variables: rainfall, precipitation, moisture, runoff and recharge;
- Find the minimum, maximum and average values of the aforementioned variables for a day, a month, a year or a predefined timeframe;
- Perform analysis on a map such as Aspect, Accuflux, etc.
- Check the number of available samples from a specific weather station;
- Get help on how to use the system;
- View information in regard to the last update of the data for a selected location.

A main issue that resulted from the analysis of the testing sessions was that the distinction between statistical and graphical information was not clear to the users, and they were not able to understand the underlying information of each type. Therefore, the refined prototype of the system should clearly distinguish between the two different types of data.

The process of viewing information on the first prototype was found frustrating, especially when the users wanted to make a quick change (e.g., to the dates, or to update the displayed information). They explicitly stated that they wanted to be able to update the displayed information without having to step back and restart the process. The new prototype should provide a section where statistical questions are answered, allowing the users to quickly refine the search data on the same screen and view the updated results.

Another issue raised during the sessions was the possibility of viewing combined information, such as answers to ‘what’ and ‘when’ questions. The current design does not allow this functionality, although the users stated that it would be useful to be able to answer more than one question at the same time.

When asked about the update action, the users stated that they would prefer the update to be automatic but that they wanted be able to see when the data of the system were last updated.

The users were confused about the location of the statistical and graphical data provided since the prototype did not provide any information either about locations to which the data were related or about the available weather stations. Accordingly, the refined prototype should display the user’s location and should update it periodically. It should also display the available weather stations on a map to enable the user to quickly see whether there are available data for a specific location.

7.4.2 Administrator Interface

Regarding the administrator interface, the findings were quite unambiguous. The users wanted to have quick access to all the main activities; thus, the menu should provide them with web-links to these activities. The main activities, as they resulted from the study and the scenario-based design discussed in the previous chapter, are:

1. Configuration of the account settings, such as display name, credentials and contact email address;
2. Management of the system maps, supporting the addition of new maps and the deletion and update of existing maps. The sub-tasks are available to the users after they have entered the maps management page;
3. Management of the supported locations, similar to the maps management mechanism. The users can create new locations and update or delete old ones. They have access to the aforementioned sub-tasks after they have entered the locations management page;
4. Management of the pluviometric data, supporting the creation of new data and the deletion of old data. The new pluviometric data are imported to the system via a CSV file-uploading mechanism, which

validates the proper file format. The deletion of old pluviometric data is based on the selection of start and end dates;

5. Setting a spatial analysis query. Through this functionality, the users are able to set and request a query, defining the variables of the pluviometric information (e.g., rainfall level), the start date and the time range (e.g., one week);
6. Setting sophisticated queries about what, which and when. Through this functionality, the users are able to set and request sophisticated queries mixing different types. These two queries functionalities could also be used for testing and validation purposes;
7. Testing the map feature, which can be used by users to test and validate the navigation on the maps and the various transformation effects that are applied to them.

Along with these features, which should be represented as menu items, two more components are identified: the home page and the logout mechanism. Regarding the type of menu, the users preferred to have quick access to it, and hence would prefer to have it on the right side of the screen, so they could easily have control over it when using a mobile device (e.g., a tablet), as the majority of users are right-handed. Therefore, a vertical menu on the right side would be more appropriate. The customisable menu should be more usable, as each user will be able to personalise the interface. However, such a feature would increase the complexity of the system and, since the majority of users will not have access to the administrator panel, this mechanism was discarded during the current design stage.

7.5 Design Requirements Update

It appeared from the user study results that all the new DRs were considered useful and relevant, although some required functionality was not included and thus, based on the provided recommendations, the requirements per user were updated. Note that the numbering of the requirements continues from section 6.5.

Table 7.8: New Design Requirements

#	Description	User Type	Issue addressed
DR88	The menu should be displayed vertically to the right side of the screen.	Administrator	A1
DR89	Users should be able to make sophisticated queries combining different types of information. The queries are normally stated as what, which and where types and can be applied to all or a selection of the data stored in the system.	Weather station, Front-end users	W1, F3
DR90	The system data should be updated automatically and the user should be able to view when they were last updated.	Front-end users	F4
DR91	Users should be able to view weather station-related information, such as location on a map and available samples.	Front-end users	F6
DR92	Spatial and non-spatial data should be easily distinguishable by users.	Front-end users	F1
DR93	Queries should be supported independently and should be easy to access.	Front-end users	

7.6 Prototype Update

The new requirements were used to feed into the redesign of the prototype. A new information architecture approach was implemented, which matches the users' perception and mental model of how to search and find spatial and non-spatial data. A map view of the areas with available data was considered a valuable add-on to the user's interface of the system. Finally, in order to ensure the system is expandable and to satisfy the users' need to be able to view their current location on a map, a LBSs section was added. This will currently only host the user's location but can be easily expanded in the future to host more LBSs.

Figures 7.9 – 7.14 show some updated prototype screens.

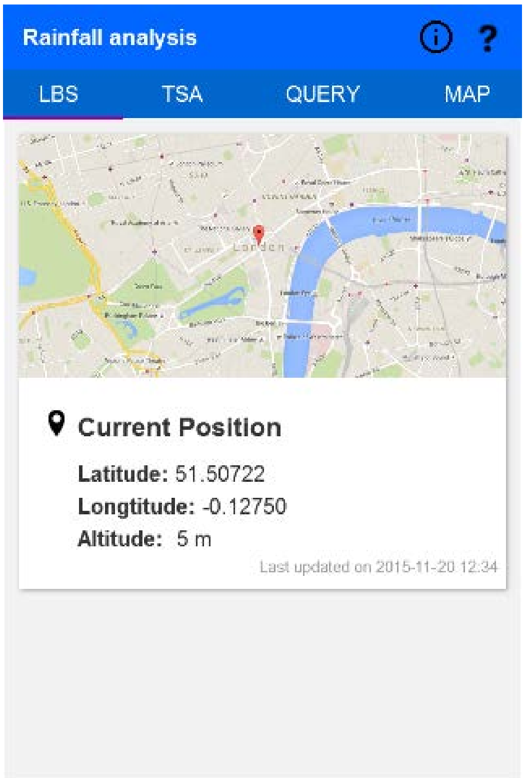

Figure 7.9: Location-based service screen

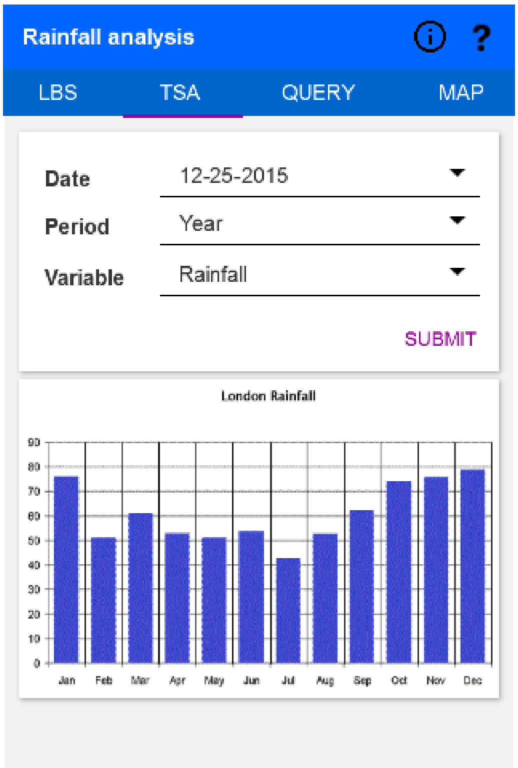

Figure 7.10: Time series screen

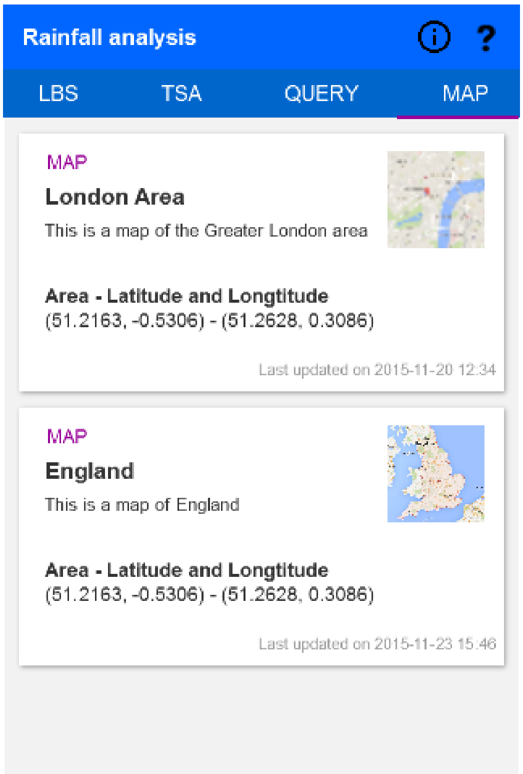

Figure 7.11: Map screen

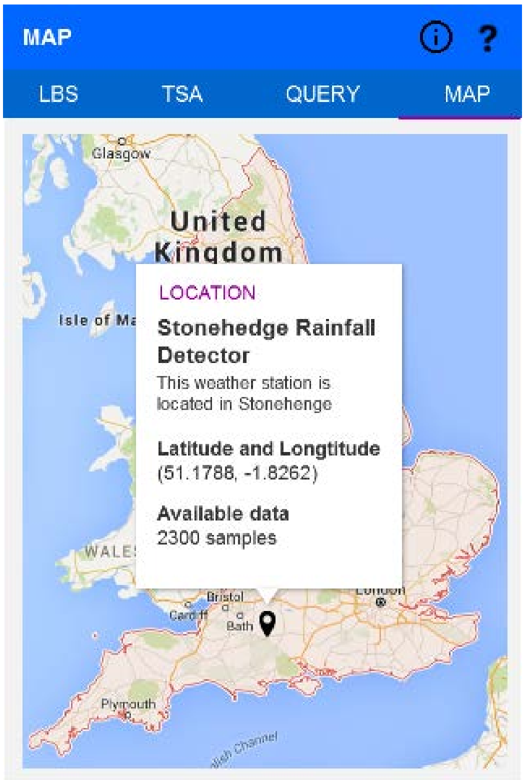

Figure 7.12: Map details screen

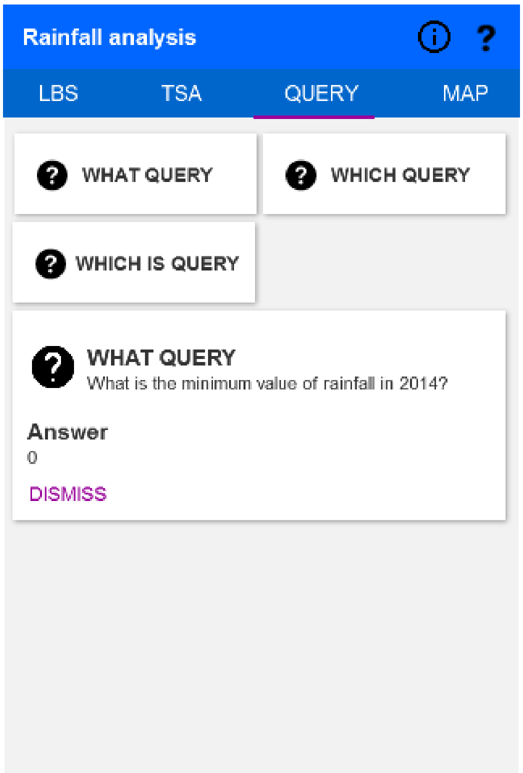

Figure 7.13: Query screen

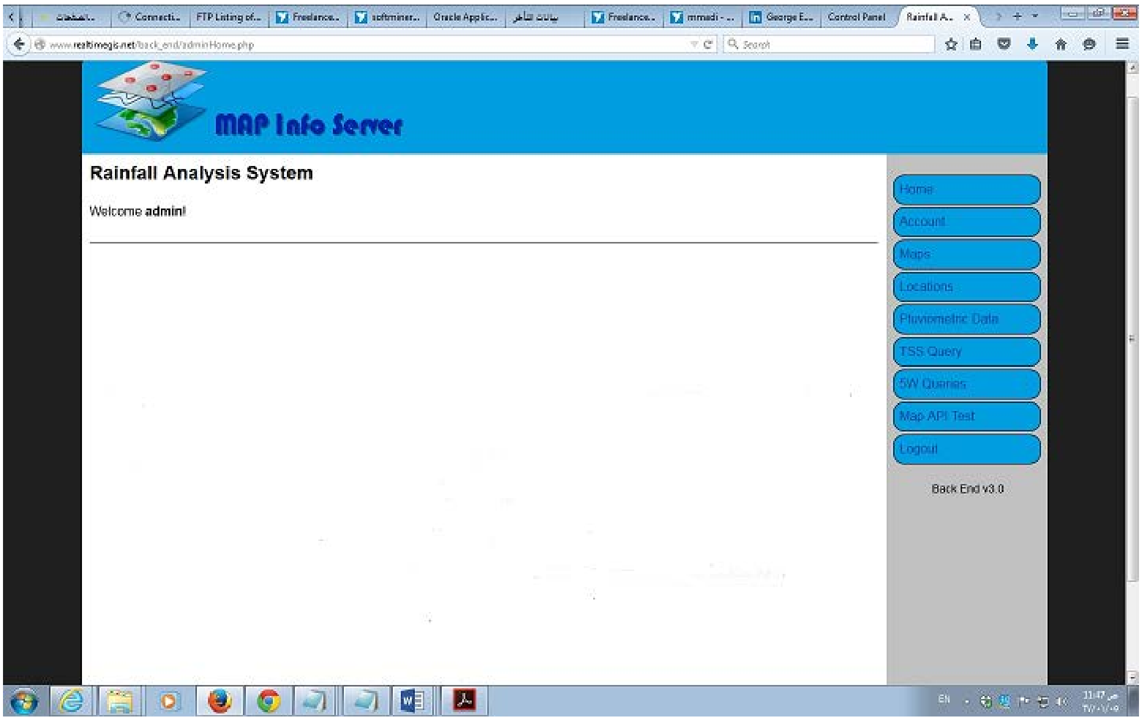

Figure 7.14: Main page - Implements DR88: vertical menu appears on the right-hand side of the screen.

7.7 Conclusion

This phase of the project included the design and implementation of the first prototype of the system, which was then tested with real users and refined based on the user testing results, following an iterative design approach. The design team, using the DGs as they were formulated in the first phase of the project, firstly sketched out some abstract ideas and then selected the most appropriate solution which met all the criteria and was believed to be intuitive. This was then turned into a high-fidelity prototype to be tested and investigated to see whether the proposed taxonomy matched the user's mental model.

Bringing users to the lab and having them test the system under controlled conditions and with the facilitator's help and guidance allowed the design team to gain valuable insight into the proposed design. The predefined tasks allowed for exploring all the aspects of the system and revealed pain points that could not have been identified otherwise at this stage.

Conducting the study allowed the design and research teams to better understand users’ perception of how certain tasks should be performed. For administrators and weather-station users, the proposed design matched the mental models of the end-users; therefore, it was only necessary to make some slight modifications to enhance the user experience. On the other hand, the initial proposed design did not match front-end users' expectations. Therefore, a new proposed taxonomy was implemented which was designed to be in line with the users’ mental models, which were derived from observing the users during the testing sessions and from discussing the sessions with them afterwards. The new taxonomy is expected to better meet the users’ needs, as it enables them to quickly distinguish between the two major types of data provided by the system, providing at the same time quick access to a weather station’s location and sampling data, and information about the currently selected location.

The design team reviewed the DGs of section 6.5 and, based on the results of the study, found no modifications were required although some functionality was missing. A set of additional guidelines per user type was proposed after analysing the user testing data; these address the main issues with the current prototype. Thus, the identified guidelines per user type presented in section 7.5 were added.

The final stage of this phase was the prototype re-design. New functionality was added to the refined prototype in order to better match users’ expectations and enhance the system’s credibility.

The changes were believed to be effective by the team members, based on a combination of their expertise and the insights gained from user testing; however, a further round of testing is needed to examine this belief, which is described in the next section.

Chapter 8 Evaluation

8.1 Introduction

In this section, we present the last part of our HCD approach: the second round of user testing conducted on the final prototype before proceeding to the implementation phase. The final prototype, which had been refined based on the insights from the first round of testing, was used to evaluate the usability of the system in terms of effectiveness, efficiency, ability to learn and ability to use. In order to make the results generalisable, a quantitative approach was adopted at this phase.

This chapter is organised as follows: firstly, the evaluation of the system is presented by detailing the methodology of the second-round testing, along with the methods of collecting the data in order to statistically analyse them, and then by presenting the outcome of the analysis. The section ends with a critical discussion of the design approach used for this project, where the three stages of the design are critiqued, as well as by an introduction of the full user interface of the system.

8.2 Final System Evaluation

Having refined the designed prototype based on qualitative analysis of the first-round testing results, a second round of testing followed. The team aimed for quantitative data in this round in order to evaluate the performance of the users in completing the tasks and the usability of the proposed system against the initial requirements and, finally, to use statistics to generalise the findings. Nevertheless, it was considered useful to allow for discussion between the researcher and the participants to help the researcher better understand observed behaviour; thus, more than one evaluation method was used in this second round of testing.

In this section, the methodology used in the testing is detailed, including information about the evaluation methods used, the testing environment and the participants, after which the study results are presented.

8.2.1 Methodology

The testing sessions were organised in the following three stages:

- **Stage 1:** the users were introduced to the purpose of the session and an overview of the system's aims was provided. They were also introduced to the lab equipment to avoid time being wasted in the second stage by their having to become familiar with the equipment.
- **Stage 2**: they were given time to complete a set of tasks with the facilitator observing and helping them where necessary.
- **Stage 3**: after completing all the tasks, they were asked to complete a questionnaire in regard to their experience with the system, at the end of which the facilitator was able to ask any clarification questions about observed behaviours or identified pain points, as well as some predefined questions.

8.2.1.1 Evaluation Methods

As discussed earlier, combining several evaluation approaches enabled a more complete picture of the system. Accordingly, it was decided to use:

- Questionnaires

  The questionnaires were used to collect demographic data and to evaluate the participants' experience in regard to the proposed system. Questionnaire results are quick and easy to quantify, which enables collection of large amounts of data in a very short time.

- Participant observation and interviews

  Participant observation served to observe the interaction with the system and track any unexpected behaviour. However, the observation was kept as discreet as possible (i.e., with no unnecessary intervention by the facilitator). The reason for this is that the users tend to lower their performance when others intervene when performing their tasks (Lepper & Greene, 1975; Koestner et al., 1984). Therefore, the facilitators should be highly experienced and properly prepared, as was ensured in the present study.

  Interviews were used in order to ask about the experience of using the system as well as any questions that could help to understand unexpected user behaviour when performing tasks. The approach was unstructured, with researchers at liberty to probe and encourage the participants to elaborate on their thoughts.

8.2.1.2 Environment

The study was conducted in a quiet room appropriately designed and decorated to make the users feel comfortable. Each user was seated at a desk with a computer and a mobile device placed in front of them. A facilitator led the users to the room, introduced them to the session procedure and then remained quietly in the background to assist if required.

8.2.1.3 Participants

Fifty-eight participants were recruited through a recruitment agency to take part in the second round of testing. Recruitment was based on the recruitment screener found in Appendix E. Again, we aimed for the maximum variation based on age, gender and education level while excluding people with no experience in mobile applications or weather-oriented systems and those who were completely unfamiliar with the GIS field. Potential participants were asked to rate their experience in using mobile applications and weather systems on a five-point, Likert-type scale, from 1 to 5, with 1 being “not experienced” and 5 being “very experienced.” They were also asked to rate their familiarity with GISs, again on a five-point scale from 1 to 5, with 1 being “not familiar” and 5 being “very familiar.” Tables 8.1 and 8.2 show the characteristics of the participants.

Table 8.1: Summary of participant characteristics

PARTICIPANT CHARACTERISTICS	
Age range	19–67 years
Mean age	32.9 ± 13.3 years
Gender	28 females (48%) 30 males (52%)
Education level	12 undergraduate students (21%) 9 postgraduate students (15%) 5 PhD holders (9%) 26 professionals (45%) 6 retired (10%)
Mobile application experience	4.4/5 ± 0.6 (min: 3/5, max: 5/5)
Weather system experience	3.9/5 ± 0.6 (min: 3/5, max:5/5)
Familiarity with GIS systems	3.3/5 ± 0.9 (min: 2/5, max:5/5)

Table 8.2: Participant characteristics

	Age	Gender	Education/Professional Level	Mobile app experience	Weather system experience	GIS
1	19	Male	Undergraduate student	4/5	4/5	3/5
2	28	Male	PhD holder	4/5	5/5	4/5
3	24	Male	Postgraduate student	4/5	4/5	3/5
4	30	Female	Professional	5/5	4/5	4/5
5	21	Male	Undergraduate student	5/5	4/5	3/5
6	25	Male	Postgraduate student	5/5	4/5	3/5
7	24	Female	Postgraduate student	4/5	4/5	4/5
8	67	Male	Retired	3/5	4/5	4/5
9	31	Male	Professional	5/5	5/5	5/5
10	34	Female	Professional	4/5	4/5	3/5
11	27	Male	Postgraduate student	5/5	4/5	4/5
12	41	Female	Professional	4/5	3/5	4/5
13	22	Female	Undergraduate student	5/5	4/5	4/5
14	20	Male	Undergraduate student	4/5	3/5	3/5
15	35	Female	Professional	5/5	4/5	2/5
16	31	Male	PhD holder	3/5	4/5	3/5

17	30	Female	Professional	5/5	4/5	4/5
18	28	Female	Professional	4/5	3/5	3/5
19	38	Male	Professional	4/5	3/5	2/5
20	68	Female	Retired	4/5	5/5	5/5
21	65	Female	Retired	4/5	5/5	4/5
22	37	Male	Professional	4/5	4/5	2/5
23	39	Female	Professional	5/5	4/5	4/5
24	23	Male	Postgraduate student	5/5	4/5	3/5
25	41	Male	Professional	5/5	3/5	3/5
26	21	Male	Undergraduate student	5/5	4/5	3/5
27	21	Female	Undergraduate student	4/5	4/5	2/5
28	34	Female	Professional	5/5	4/5	4/5
29	34	Male	Professional	4/5	3/5	2/5
30	38	Female	Professional	4/5	3/5	2/5
31	29	Female	Professional	5/5	4/5	4/5
32	30	Male	PhD holder	4/5	4/5	4/5
33	25	Female	Postgraduate student	5/5	3/5	2/5
34	37	Male	Professional	4/5	4/5	5/5
35	35	Female	Professional	4/5	4/5	4/5

36	30	Male	Professional	5/5	5/5	4/5
37	19	Female	Undergraduate student	4/5	3/5	2/5
38	28	Female	Professional	5/5	4/5	2/5
39	21	Male	Undergraduate student	5/5	4/5	3/5
40	29	Male	PhD holder	4/5	4/5	4/5
41	41	Female	Professional	5/5	4/5	4/5
42	32	Male	Professional	4/5	4/5	3/5
43	44	Female	Professional	4/5	5/5	5/5
44	20	Male	Undergraduate student	4/5	3/5	2/5
45	20	Male	Undergraduate student	5/5	3/5	2/5
46	35	Female	Professional	5/5	4/5	4/5
47	68	Male	Retired	3/5	5/5	5/5
48	24	Female	Postgraduate student	5/5	3/5	2/5
49	30	Female	Professional	5/5	4/5	3/5
50	30	Male	Professional	4/5	4/5	2/5
51	21	Male	Undergraduate student	4/5	4/5	3/5
52	18	Male	Undergraduate student	5/5	4/5	4/5
53	67	Female	Retired	4/5	4/5	5/5
54	25	Female	Postgraduate student	5/5	3/5	3/5

55	32	Male	Professional	5/5	3/5	3/5
56	27	Female	Postgraduate student	4/5	4/5	2/5
57	66	Male	Retired	4/5	4/5	4/5
58	28	Female	PhD holder	4/5	3/5	4/5

8.2.1.4 Ethics

Since the evaluation study involved real users, the project had to be in compliance with the Data Protection Act (1998). The users had to be informed as to the content of the testing session and had to understand their rights during the session and what personal data would be held about them. Therefore, they were provided with a data protection statement (detailing how their personal information would be used by the team) and were subsequently asked to sign a consent form before taking part to the session. Ethical approval for the study has been obtained from Brunel university.

8.2.1.5 Pilot Study

Before the main study was run, a pilot study was conducted to ensure the testing sessions would run smoothly and for any essential adjustments in terms of time or procedure to be made. Two participants, aged 24 and 30, one female and one male, took part in the pilot study. The characteristics of the participants are displayed in tables 8.3 and 8.4.

Table 8.3: Summary of participant characteristics for pilot study

PARTICIPANT CHARACTERISTICS	
Age range	24-30
Mean age	27
Gender	1 female 1 male
Education level	2 professionals
Mean mobile application experience	4.0 / 5
Mean weather system experience	4.5 / 5
Mean familiarity with GISs	3.5 / 5

Table 8.4: Participant characteristics for pilot study

#	Age	Gender	Education/ Professional Level	Mobile app experience	Weather system experience	GIS experience
1	24	Male	Professional	4/5	4/5	3/5
2	30	Female	Professional	4/5	5/5	4/5

The pilot study provided an estimation of the time to complete the tasks. Initially, it was estimated that ten minutes would be sufficient; however, after running the pilot study, it was decided to allocate two minutes for each task. Therefore, it was decided to give the participants 15 minutes to complete all seven tasks, giving one minute of extra time in case it took some time to switch between very different tasks.

In addition, the pilot study raised a procedural issue, indicating clearly that better instructions should be provided in regard to the procedure. The facilitator should inform the participants that they had to apportion their time to ensure sufficient to try to perform each task; furthermore, if someone became stuck on a task for more than two minutes, they should be encouraged to move to the next one and try to complete the unfinished task(s) after having tried to complete all of them.

Having made the appropriate adjustments after running the pilot study, the team was ready to run the main study.

8.2.1.6 Main Study

As discussed earlier, the evaluation study was divided into three stages. The first was the introductory phase, followed by the main stage, in which the participants were asked to complete a number of tasks. The study ended with the evaluation of the user experience, based on interviewing and questionnaire-filling. The three stages are detailed in the next three sub-sections. Figure 8.1 shows the three stages.

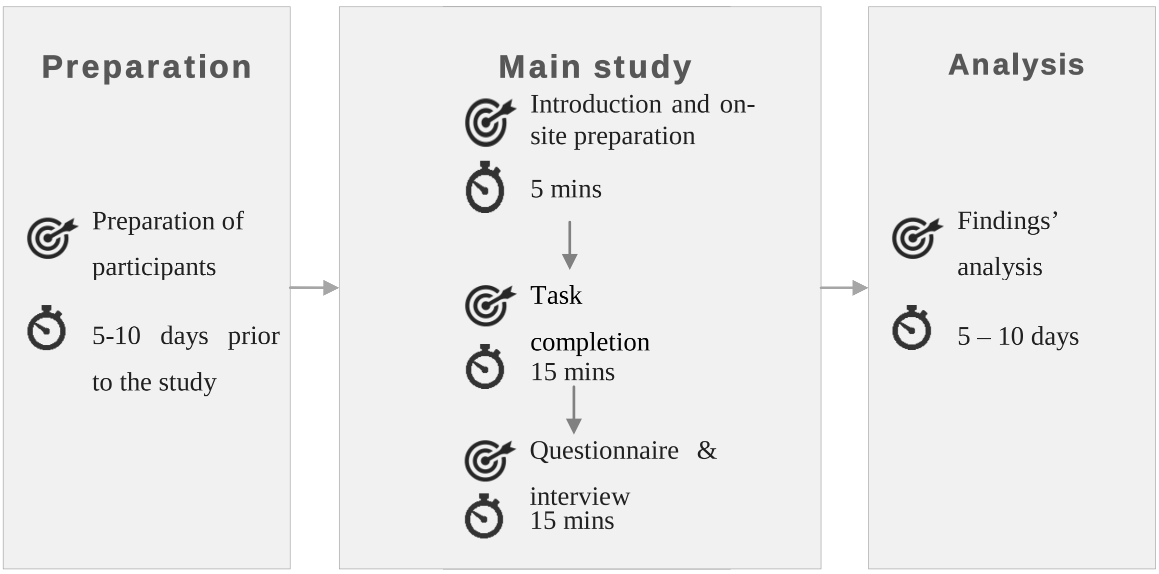

Figure 8.1: The three stages of research.

8.2.1.6.1 First Stage: Introduction

The first stage lasted about five minutes and was dedicated to introducing the participants to the purpose of the study and the software system, creating a pleasant and comfortable feeling and ensuring that they would be able to express their thoughts openly and had a clear picture of the whole process.

As required by research ethics, the participants were informed that the gathered data would be stored anonymously and used only for the purposes of the current evaluation study. After signing a consent form, the participants were given a brief description of the software system and its aims and were informed about the process of the study. There was time for questions, after which the participants proceeded to the second stage.

8.2.1.6.2 Second Stage: Task Completion

During the second stage of the study, the participants were asked to use the system to complete seven tasks in fifteen minutes. They could express their thoughts loudly, and the facilitators could keep notes of these, and of overall participant behaviour. Facilitators were also allowed to develop conversations with participants about a task or any issue raised during a session. However, they were not allowed to guide participants to complete tasks, ask leading questions or guide their answers.

In order to compress the time, the group of fifty-eight participants was divided into five sub-groups. Therefore, five facilitators were required to run five sessions in parallel in different rooms and under the same conditions for all participants. Hence, this stage lasted three hours.

A detailed schedule was delivered to the participants, so they were notified about the time they would be taking part in the study. However, they were asked to be at the study location twenty minutes before their allocated time. They were also encouraged to ask for any schedule change based on their individual needs and schedules.

This time the tasks were fewer in number, focusing on the core principles and objectives of the system and the front-end users only (the front-end user interface appeared to be the most problematic in the previous testing stage).

Two research team members worked together in order to create a short set of tasks that could cover most DPs and DRs (related to front-end users), while at the same time looking to see whether the new taxonomy and the updated prototype were clear to users. The same guidelines were tested in the previous stage; however, this time the focus was on quantitative data and discovering additional usability problems since testing with 3 users per task does not guarantee the maximum problem-discovery rate. Another round of testing was necessary since changes to the prototype had been made; although the tasks did not directly correspond to the changes, they covered the areas that had been changed. Therefore, it could be tested whether the updated prototype with the new taxonomy was easy to understand. The aim was to have tasks that tested the basic tasks of the system, at the same time allowing users to use the updated taxonomy and interact with the recently-made changes.

Each of the researchers created a list of tasks that covered the main elements to be tested, that is, those that covered the most appropriate DGs were selected. The aim was to have as few tasks as possible; for this reason, during the discussion regarding which tasks to choose, 7 appeared to be the most suitable as covering the most of the areas that needed testing. 7 tasks were therefore selected.

<u>The selected tasks were the following:</u>

1. View the average rainfall during November (Task 1);
2. Find the location with the maximum available samples (Task 2);
3. Find the location with the lowest precipitation between September and November (Task 3);
4. Perform an accuflux of an existing DEM (Task 4);
5. Find which areas had rainfall that was between 20 and 23 millimeters during the summer (Task 5);

6. Estimate which area had the highest moisture levels on the 15th of November (Task 6);
7. Display a rainfall graph for the month of Jan 2012 (Task 7).

These tasks assessed, this time in a quantitative way, the DPs and DRs were listed in table 8.5 that were also tested qualitatively in the previous phase of the research.

Table 8.5. DPs and DRs assessed through the 7 proposed tasks

Task	DPs assessed	DRs assessed
1	DP5, DP9, DP10, DP11	DR5, DR15, DR14, DR56, DR57, DR58, DR63, DR64, DR39
2	DP5, DP7, DP8, DP9	D5, DR16, DR14, DR15, DR39, DR51, DR52, DR55,
3	DP5, DP11, DP8, DP9, DP10	DR5, DR14, DR15, DR63, DR45, DR51, DR64, DR57, DR58, DR52, DR53
4	DP5, DP9, DP10	DR5, DR51, DR52, DR59,
5	DP5, DP11, DP8, DP9, DP10, DP11	DR5, DR14, DR15, DR63, DR45, DR51, DR64, DR58,
6	DP5, DP11, DP7, DP8, DP9, DP10	DR5, DR14, DR15, DR39, DR45, DR51, DR57, DR58
7	DP5, DP8, DP9	DR5, DR14, DR15, DR52, DR57

The session facilitators were keeping notes about the metrics of the session, including:

1- Task-completion statuses (completed or not completed)
2- Task-completion times for completed tasks
3- Number of errors users made

They were also instructed to look at whether the challenges identified in the previous stages of research were not causing problems in this stage: noticing when data was getting updated, viewing weather-station-related data, distinguishing between spatial and non-spatial data and noting ease of access of queries.

The findings are quantified and analysed in the results section. Various observations of participants' unexpected behaviour were also noted and supplemented by other non-quantitative data collected during interviews. These are discussed in the next sub-section.

8.2.1.6.3 Third Stage: USE Questionnaire & Interviews

USE Questionnaire:

After the completion of the tasks, the users were asked to complete a questionnaire consisting of twenty-one questions that the research team had prepared. The questionnaire items were based on the USE method proposed by Lund (2001), which is a credible measure tool regarding usability (Albert & Tullis, 2013; Kelly, 2009). The USE tool has been used in various studies related to the field of our proposed project (Daniels et al., 2013; Ramalho & Chambel, 2013; Kortum & Sorber, 2015). This questionnaire focuses on the subjective reactions to the usability of a user interface and on the perception of its usefulness and usability, not on tasks' performance metrics. This way it supplements collecting various metrics, e.g., task-completion times, and a balanced look can be obtained about how successful participants are in performing tasks and how they feel about their performance. It is possible for a system to be less efficient but appear to be effective and easy to use and visa-versa; therefore, a balance is needed between metrics and subjective perceptions, which is the reason this method was needed in this particular study.

Interviews:

An interview with each participant followed the task-completion phase, focusing primarily on their experiences with the mobile application. Each interview was carried out one-to-one with one of the facilitators. During the interviews, they tried to clarify any questions they might have had regarding the user behaviour and experience during the evaluation session.

Participants were also asked to comment on the aesthetic side of the user interface and which tasks they found to be the hardest.

During participant observation, researchers looked into whether the issues discovered by front-end users during the prototype testing in the previous stage had been solved, aiming to identify issues in these areas and ask about them during interviews, if necessary.

Rich insights could be gained, as the participants had a more holistic and clear picture of the system after the task completion and questionnaire. This stage lasted fifteen minutes for each participant. Therefore, the total time allocated to each participant was thirty-five to forty-five minutes: five minutes for the introduction stage, fifteen minutes for the task-completion stage, fifteen minutes for the questionnaire and the interview, and ten minutes that could be used by them in any way they thought most appropriate or for any minor delays that could occur during the study.

8.2.1.6.4 Overview of usability metrics

The ISO 9241-11 standard defines usability as *“the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”*. Hence, usability is not single-dimensional, but an outcome of three factors, which are:

- **Effectiveness**:

According to ISO-9241, product effectiveness is *“accuracy and completeness of user goal achievement*”. Effectiveness can be calculated as the percentage of users successfully achieving their goals vs. the total number of users: normally, as a result of coming through user scenarios, users either achieve their goals or fail to achieve them (completion rate). Referred to as the fundamental usability metric, the completion rate is calculated by assigning a binary value of ‘1’ if the test participant manages to complete a task and ‘0’ if he/she does not.

Effectiveness metrics include:

1. Effectiveness (Task-completion rate)

Effectiveness can be represented as a percentage by using this equation:

$$\bar{E} = \frac{\sum_{j=1}^{R}\sum_{i=1}^{N} n_{ij}}{RN} \times 100\%$$

where, N is the total number of tasks; R is the number of participants; nij is the result of coming through task i by participant j (nij=1 if the task has been completed successfully and user goal has been achieved, and nij=0, if the task is unsuccessful and the user failed to achieve the goal).

The effectiveness statistic error is calculated through the following formula:

$$\sigma_E = \sqrt{\frac{\bar{E}(100 - \bar{E})}{R}}$$

2. Overall system effectiveness

Overall system effectiveness is the average completion rate of all tasks described as:

$$E = \bar{E} \pm \sigma_E$$

3. Proportion of users who made a mistake during a task

– **Efficiency**:

According to ISO-9241, product efficiency is "*resources spent by user in order to ensure accurate and complete achievement of the goals*". With regards to software products and information systems, the key measured resource is time spent by the user in order to complete the tasks and accomplish the goals. Efficiency metrics include:

1. <u>Time to complete a task</u>

Efficiency is measured in terms of task time, i.e. **the time a participant takes to successfully complete a task**. The time taken to complete a task can then be calculated by subtracting the start time from the end time as shown in the equation below

$$t_{task} = t_{start} - t_{end}$$

2. <u>Standardised time</u>

- Standardised time = (Time needed to finish 1 task – time expected to finish this task) / Standard deviation
- The Quality level is then calculated as the probability from the standardised Z-table

3. <u>Overall time-based user efficiency</u>

This is the **average number of tasks performed by the effective user per unit time**. It is an absolute value.

$$\bar{P}_t = \frac{\sum_{j=1}^{R} \sum_{i=1}^{N} \frac{n_{ij}}{t_{ij}}}{NR}$$

where N is the total number of tasks; R is the number of participants, n_{ij} is the result of task i by participant j (if the user successfully completes the task, then $n_{ij} = 1$, if not, then $n_{ij} = 0$); t_{ij} is the time spent by participant j to complete task i. If the task is not successfully completed, then time is measured till the moment the user quits the task.

4. <u>Relative time-based efficiency</u>

This is defined as the **ratio of effective users' work-time to all users' work-time:**

$$\bar{P} = \frac{\sum_{j=1}^{R} \sum_{i=1}^{N} n_{ij} t_{ij}}{\sum_{j=1}^{R} \sum_{i=1}^{N} t_{ij}} \times 100\%$$

The denominator is the total time spent by all users performing 1 or more tasks (tij is the time spent by each user in a specific task. The numerator is the total time spent by effective users performing the same number of tasks (tij is multiplied by nij for each participant and 1 if the result of the task was success and 0 if it is a failure).

5. Time-based expert efficiency

This is the highest theoretically possible speed of work with our software system. This was calculated by introducing the maximum possible user-speed and a priori successful completion. In order to estimate the task-time for experienced users who commit no errors, we used the Keystroke-Level Model for Advanced Mobile Phone Interaction framework (Holleis et al., 2007), which was based on the ground-truth Keystroke Level Modelling (KLM) framework (Card et al., 1980). The timings are shown in Appendix F.

The time-based expert Efficiency is calculated from the expert's time through the following equation:

$$\overline{P_{te}} = \frac{\sum_{i=1}^{N} \frac{1}{t_{0i}}}{N}$$

where t_{0i}, the ideal time needed by an expert to complete scenario i.

6. Relative time-based expert efficiency

Relative expert time-based Efficiency is:

$$\overline{P_E} = \bar{E} \times \frac{R \sum_{i=1}^{N} t_{0i}}{\sum_{j=1}^{R} \sum_{i=1}^{N} t_{ij}}$$

where t_{0i} is the ideal time needed by an expert to complete task i and E is the overall system effectiveness. The physical meaning of the relative expert efficiency is the measure of potential efficiency relative to actual system efficiency with regards to its user effectiveness.

- **System quality/Satisfaction**:

The evaluation of the system quality from the user’s point of view and the satisfaction metric of usability was based on the USE questionnaire (Lund, 2001); the findings were later supplemented with the findings of interviews. The questions are divided into four parts:

- Usefulness (Questions 1 to 6):
  - The application helps me be more effective;
  - The application helps me be more productive;
  - The application is useful;
  - The application makes the things I want to accomplish easier to get done;
  - The application saves me time when I use it;
  - The application does everything I would expect it to do.
- Ease of use (Questions 7 to 13):
  - The application is easy to use;
  - The application is simple to use;
  - The application is user-friendly;
  - Using the application is effortless;
  - I can use the application without written instructions;
  - I don't notice any inconsistencies as I use the application;
  - I can use the application successfully every time.
- Ease of learning (Questions 14 to 16):
  - I learned to use the application quickly;
  - I easily remember how to use the application;
  - It is easy to learn to use the application.
- Satisfaction (Questions 17 to 21):
  - I am satisfied with the application;
  - I would recommend the application to a friend;
  - The application is fun to use;
  - The application is pleasant to use;

- o The application works the way I want it to work.

In order to ensure that the participants would answer the questionnaire and any additional questions honestly, the facilitator reassured them that it was the system that was being tested, not the user. The facilitator also emphasised that it is important to get information about the positive and negative aspects of the system, because this will help design a better, more user-friendly system that satisfies user needs.

The users were asked to indicate a number from one to five on a Likert-type scale as displayed in Table 8.6.

Table 8.6: Degree of agreement and disagreement

Indicator	**Degree of agreement/disagreement**
1	Strongly disagree
2	Disagree
3	Neither agree nor disagree
4	Agree
5	Strongly agree

The representation of the question format in the questionnaire given to each participant is displayed in Figure 8.2.

Statement, e.g. "*I would recommend the application to a friend*"				
○ Strongly disagree	○ Disagree	○ Neither agree nor disagree	○ Agree	○ Strongly agree

Figure 8.2: Question format

8.2.2 Results

The analysis of the results is based on the previously-discussed dimensions and metrics of usability; subsequently, qualitative findings are discussed as well.

8.2.2.1 Effectiveness

In the following table, the task-completion results are shown.

Table 8.7: Task completions

Participant	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
1	Yes	Yes	Yes	No	Yes	Yes	Yes
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	Yes	Yes	Yes	Yes	Yes	No	Yes
6	Yes	Yes	Yes	Yes	Yes	Yes	Yes
7	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8	Yes	Yes	Yes	Yes	Yes	Yes	Yes
9	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10	Yes	No	Yes	Yes	Yes	Yes	Yes
11	Yes	Yes	Yes	No	Yes	Yes	Yes
12	Yes	Yes	Yes	Yes	Yes	No	Yes
13	Yes	Yes	Yes	Yes	Yes	Yes	Yes

14	Yes	Yes	Yes	Yes	Yes	Yes	Yes
15	No	Yes	Yes	Yes	Yes	Yes	Yes
16	Yes	Yes	Yes	Yes	Yes	Yes	Yes
17	Yes	Yes	Yes	Yes	Yes	Yes	No
18	Yes	Yes	Yes	Yes	Yes	Yes	Yes
19	Yes	Yes	Yes	Yes	Yes	Yes	Yes
20	No	No	Yes	Yes	Yes	No	Yes
21	Yes	Yes	Yes	Yes	Yes	Yes	Yes
22	Yes	Yes	No	Yes	Yes	Yes	Yes
23	Yes	Yes	Yes	Yes	Yes	Yes	Yes
24	Yes	Yes	Yes	Yes	Yes	Yes	Yes
25	Yes	Yes	Yes	No	No	Yes	Yes
26	Yes	Yes	Yes	Yes	Yes	Yes	Yes
27	Yes	Yes	No	Yes	Yes	Yes	Yes
28	Yes	Yes	Yes	Yes	Yes	Yes	Yes
29	Yes	Yes	Yes	Yes	Yes	Yes	Yes
30	Yes	No	Yes	Yes	Yes	Yes	Yes
31	Yes	Yes	Yes	Yes	Yes	Yes	No
32	No	Yes	Yes	Yes	Yes	Yes	Yes
33	Yes	Yes	Yes	Yes	Yes	Yes	Yes

34	Yes	Yes	Yes	Yes	Yes	Yes	Yes
35	Yes	Yes	Yes	No	Yes	Yes	No
36	Yes	Yes	Yes	Yes	Yes	Yes	Yes
37	Yes	Yes	No	Yes	Yes	Yes	Yes
38	Yes	Yes	Yes	No	Yes	Yes	Yes
39	Yes	Yes	Yes	Yes	Yes	Yes	Yes
40	Yes	No	Yes	Yes	Yes	Yes	Yes
41	Yes	Yes	Yes	Yes	No	Yes	No
42	Yes	Yes	Yes	Yes	Yes	Yes	Yes
43	Yes	Yes	Yes	Yes	Yes	Yes	Yes
44	Yes	Yes	Yes	Yes	Yes	Yes	Yes
45	Yes	No	Yes	No	Yes	Yes	Yes
46	No	Yes	Yes	No	Yes	No	Yes
47	Yes	Yes	Yes	Yes	Yes	Yes	No
48	Yes	Yes	Yes	Yes	Yes	Yes	Yes
49	Yes	Yes	Yes	Yes	Yes	Yes	Yes
50	Yes	Yes	Yes	Yes	Yes	Yes	Yes
51	Yes	Yes	Yes	Yes	Yes	Yes	Yes
52	Yes	Yes	Yes	Yes	Yes	Yes	Yes
53	Yes	Yes	Yes	Yes	Yes	Yes	Yes

54	Yes	Yes	Yes	Yes	Yes	Yes	Yes
55	Yes	No	Yes	Yes	Yes	Yes	No
56	Yes	Yes	Yes	Yes	No	Yes	Yes
57	Yes	Yes	Yes	Yes	Yes	Yes	Yes
58	Yes	Yes	No	Yes	Yes	Yes	No

1) Effectiveness

According to several studies (Sauro & Lewis, 2005; Sauro & Kindlund, 2005; Lewis & Sauro, 2006), the average task-completion rate is 78% (based on an analysis of 1,100 tasks). In order to have a completion rate in the top quartile (75%), the completion rate should be higher than 92%.

Effectiveness (Task completion rates) were calculated as shown in Table 8.8:

Table 8.8: Effectiveness (Task completion rates)

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**
$\bar{E}$	93.10%	89.66%	93.10%	87.93%	94.83%	93.10%	87.93%
σ_E	3.33%	4.00%	3.33%	4.28%	2.91%	3.33%	4.28%

Four of the seven tasks were classified as top-quartile (task 1, task 3, task 5 and task 6) and three of them as second-quartile (task 2, task 4 and task 7). These three tasks would be identified through interviews later as the three most difficult tasks. Figures 8.3 and 8.4 illustrate task completions.

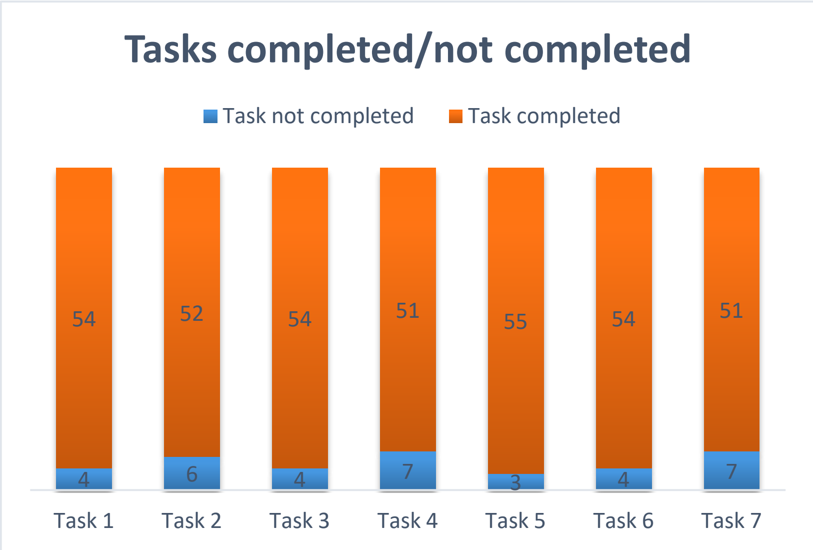

Figure 8.3: Task completion (count)

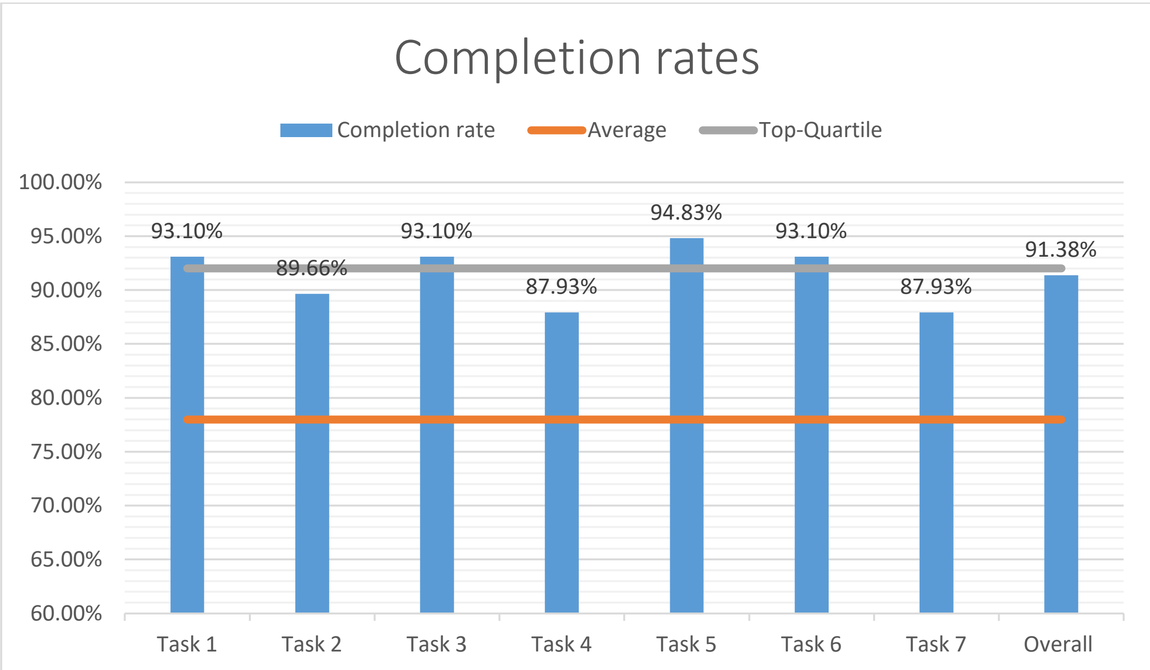

Figure 8.4: Task-completion rates compared to average and top-quartile completions

2) <u>Overall system effectiveness (based on the overall task-completion rates for all users:</u>

The overall system effectiveness (previously defined in the methodology section) is $\mathbf{91.38} \pm \mathbf{1.39}\,\%$ (more than or approached 90% in all the tasks). The great majority of the participants (91.38%) were able to complete the given task in the given time, and without the guidance of a facilitator. The 95% confidence interval for the overall completion rate was 88% to 98.7% which means that, on average, each person will be able to complete all the tasks with a success rate that ranges from 88% to 98.7%, which is significantly higher than the average success rate (78%) and very close to the top-quartile level (92%); the objective of effectiveness is thus accomplished.

3) Proportion of users who made one or more errors during a task

Another measurement involves counting the number of errors a participant makes when attempting to complete a task. Errors can be unintended actions, slips, mistakes or omissions that a user makes while attempting a task. Although it can be time-consuming, counting the number of errors does provide excellent diagnostic information. The numbers of errors made by each participant on each task are displayed in the next table.

Table 8.9: Errors per task per user

Participant	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
1	1	1	0	2	1	0	2
2	1	1	1	1	1	1	0
3	2	1	0	2	0	1	2
4	0	1	1	0	0	1	0
5	0	2	1	1	0	1	1
6	0	2	0	1	1	1	1
7	0	1	0	0	0	2	1
8	1	0	0	2	1	0	2

9	1	1	0	1	1	1	0
10	0	1	0	1	1	2	0
11	0	0	1	1	0	2	0
12	2	0	1	1	1	2	1
13	0	0	1	0	1	1	1
14	0	1	0	1	1	0	1
15	1	1	1	1	1	0	0
16	0	1	1	0	1	1	0
17	0	0	1	2	1	0	1
18	1	0	0	1	1	1	1
19	1	2	1	2	1	0	0
20	2	1	1	0	0	2	1
21	0	1	0	2	1	1	1
22	0	1	2	0	0	0	2
23	1	1	0	2	0	1	1
24	1	1	1	2	0	0	1
25	0	2	2	1	1	1	2
26	1	2	1	2	1	0	1

27	2	1	1	1	1	0	1
28	2	1	0	1	1	0	1
29	1	1	1	0	1	1	1
30	1	1	0	2	1	1	1
31	1	2	0	2	0	0	1
32	1	1	1	1	0	0	1
33	1	1	1	1	0	0	2
34	1	0	2	2	0	1	0
35	1	0	1	2	0	1	2
36	0	0	1	0	0	0	1
37	1	2	2	1	0	1	2
38	1	0	0	2	0	0	0
39	1	1	0	1	1	1	1
40	2	2	1	0	0	1	0
41	0	0	0	2	1	0	1
42	1	0	0	2	1	1	1
43	2	2	1	2	0	2	1
44	1	0	1	1	0	0	0

45	0	1	1	2	1	1	0
46	1	0	2	1	0	2	1
47	0	1	1	2	0	1	1
48	1	1	0	1	0	1	2
49	1	1	1	1	0	0	1
50	1	2	1	1	1	0	2
51	1	0	1	0	0	0	1
52	0	1	1	0	0	1	1
53	2	2	0	1	0	1	0
54	0	1	0	0	0	2	1
55	1	2	0	0	1	2	2
56	1	2	0	1	1	1	0
57	2	1	0	0	1	2	0
58	1	1	2	0	1	1	2
Made an error (count) or more	39	43	34	43	30	37	42
Did not make an error (count)	19	15	24	15	28	21	16

Each task had a different error potential; some of them required interacting with more components, increasing the number of error opportunities (Sauro &

Kindlund, 2005). Therefore, it was decided to calculate the proportion of users who made one or more errors with 95% confidence intervals instead of calculating the average number of errors per task.

Table 8.10. Proportion of users who made 1 or more errors and confidence intervals

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
Proportion who committed 1 or more errors	67.2%	74.1%	58.6%	74.1%	51.7%	63.8%	72.4%
95% upper limit	79%	85%	71%	85%	64%	76%	84%
95% lower limit	55%	62%	46%	63%	38%	51%	61%
Expected proportion according to Sauron's analysis	67%						
P value (Chi-Square)	P >0.05	P >0.05	P >0.05	P >0.05	P >0.05	P >0.05	P >0.05

According to Sauro, 2 out of every 3 individuals make 1 or more errors (66.7%). This was observed in the current study and the proportions for all questions did not differ significantly from what was expected (P > 0.05 for all comparisons using Chi Square G test) and the 95% confidence interval for task error rate included 67%, which confirms that the results produced from the current study are approximate to what should be expected.

In Sauro's analysis, only 10% of the observed tasks were performed without any errors, leading to the conclusion that it is perfectly normal for users to make errors when performing tasks. Although none of the tasks were completely error-free (0%), there was no statistically significant difference between the percentage of error-free tasks and those observed by Sauro (0% in the current study vs. 10% in Sauro's analysis, p=0.6462) using Chi-Square test of independence. This shows that the effectiveness of the app is similar to what should be expected.

For each individual included in the study, the average number of errors made was only 1 for every 2 minutes of the total test time (15 minutes). There was a significant positive correlation between the average number of errors committed by each participant and the average time needed to finish a task ($r=0.43$, $P < 0.05$). This suggests, as may be expected, that the time needed to finish a task increases as the number of errors committed increases, as users who do not know how to perform a task make more errors and are expected to spend more time finishing the task.

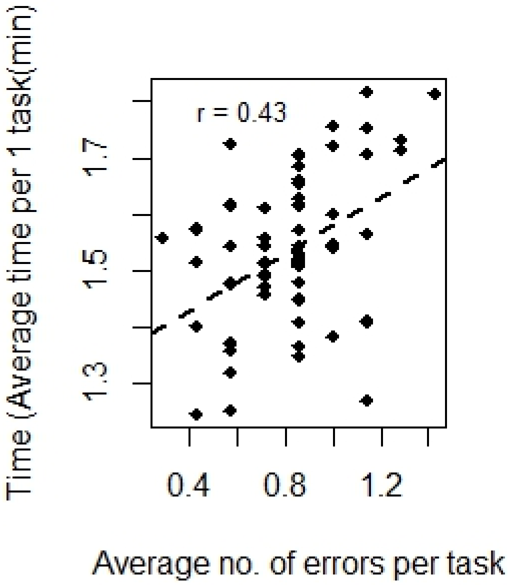

Figure 8.5. Association between errors made and time needed to finish a task

8.2.2.2 Efficiency

- <u>Time needed to successfully complete a task</u>

The task-completion times are displayed in Table 8.11.

Table 8.11: Task-completion time in seconds

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
1	124	68	97	n/a	65	77	126
2	85	115	74	122	79	78	80
3	125	86	81	117	71	113	124
4	94	123	63	99	78	99	80
5	69	126	62	122	74	n/a	80
6	55	130	82	93	69	125	95
7	85	127	43	94	85	123	91
8	109	73	49	124	70	100	114
9	46	128	67	124	75	110	77
10	108	n/a	46	108	65	122	88
11	99	58	78	n/a	66	113	80
12	122	72	46	100	65	n/a	103
13	45	100	48	94	69	91	79
14	106	73	51	100	61	87	93

15	n/a	62	101	111	74	70	107
16	104	125	82	109	99	101	105
17	61	64	111	130	95	95	n/a
18	121	58	83	114	98	87	94
19	97	119	37	116	101	77	100
20	n/a	n/a	68	95	81	n/a	88
21	81	105	90	110	67	102	82
22	51	97	n/a	94	99	76	128
23	77	69	90	126	78	116	104
24	120	129	36	112	84	101	113
25	76	127	116	n/a	n/a	86	115
26	103	126	119	119	72	96	128
27	117	129	n/a	92	76	103	115
28	127	92	58	121	77	108	115
29	81	55	101	92	82	119	79
30	100	n/a	96	121	109	107	87
31	63	111	99	120	83	80	n/a
32	n/a	66	103	114	65	88	94
33	50	70	120	83	64	79	126

34	86	92	116	112	75	99	99
35	90	64	79	n/a	75	107	n/a
36	97	102	67	91	88	92	118
37	111	123	n/a	95	95	77	116
38	50	66	48	n/a	95	86	104
39	52	129	80	96	78	118	83
40	125	n/a	55	92	63	109	103
41	78	52	39	123	n/a	104	n/a
42	52	73	56	123	79	111	80
43	126	111	59	126	95	122	123
44	109	82	114	111	73	85	87
45	107	n/a	69	n/a	103	75	105
46	n/a	52	111	n/a	96	n/a	125
47	80	82	119	119	102	112	n/a
48	111	53	45	80	69	93	116
49	106	118	88	104	60	97	104
50	129	121	106	88	97	82	113
51	122	50	73	90	101	70	83
52	82	82	87	100	100	124	104

53	120	117	102	94	60	123	92
54	71	117	56	81	78	121	97
55	83	n/a	91	106	80	110	n/a
56	110	125	59	100	n/a	105	87
57	124	63	60	93	95	113	87
58	71	50	n/a	99	78	83	n/a

In order to measure the confidence intervals for completion times for all tasks, the natural logarithm is used. Below, the summary for each task is displayed:

Table 8.12: Mean and confidence intervals for average time needed per task

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**
Arithmetic Mean	**92.46**	**92.44**	**77.33**	**105.90**	**80.56**	**99.02**	**100.30**
Arithmetic St Dev	25.49	28.29	24.93	13.65	13.46	16.08	15.78
Geometric mean	88.56	87.95	73.2	104.99	79.48	97.7	99.1
Median	97	92	78.5	106	78	100.5	100
N	**54**	**52**	**54**	**51**	**55**	**54**	**51**
SD	**25.49**	**28.29**	**24.93**	**13.65**	**13.45**	**16.08**	**15.78**
Min	**45**	**50**	**36**	**80**	**60**	**70**	**77**

max	**129**	**130**	**120**	**130**	**109**	**125**	**128**
95% Confidence Interval	81.4 – 96.4	80.3 – 96.3	66.7 – 88.4	101.2 – 108.9	76 – 83.1	93.3 – 102.3	94.8 – 103.6

Task-completion time is not sufficient alone to give an indication of the efficiency of performing a task, although it can allow a rough estimation of tasks that took longer than others. Task 4 and 7 took longest; it appeared from the subsequent analysis that these were the tasks that users found the hardest.

The timings could be grouped in three groups: tasks which were completed in under 81 seconds (task 3 and task 5); tasks which were completed in between 81 and 99 seconds (task 1 and task 2); and tasks which were completed in over 99 seconds (task 4, task 6 and task 7). Figure 8.6 displays low, high and average task-completion times.

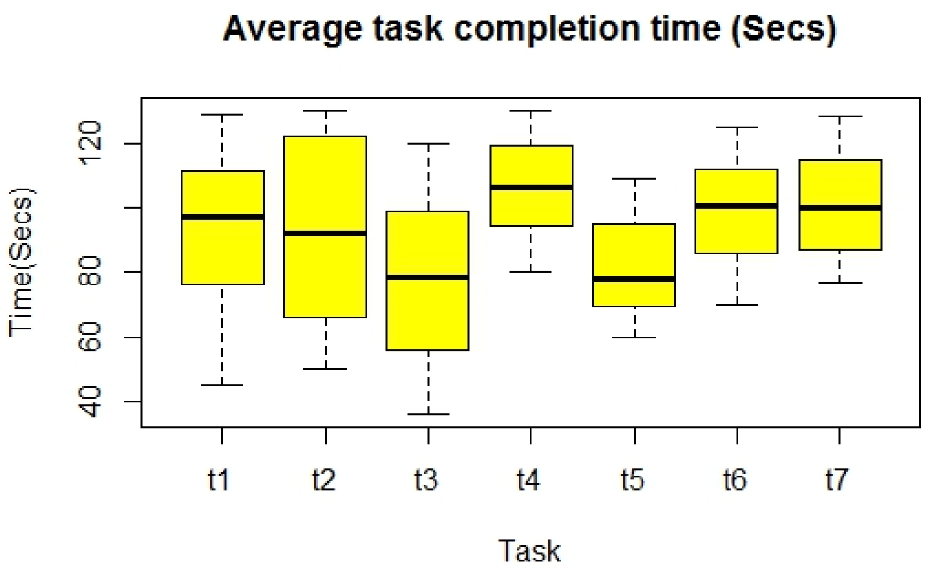

Figure 8.6: Task-completion timings

- Standardised task-completion time (Six-Sigma approach)

The estimated time to complete each question was 2 minutes per task with an overall of 15 minutes to perform all tasks. Standardised times were calculated by subtracting 2 minutes from each task time (average expected time for each task) and dividing by the standard deviation of the time needed for each task, giving an average standardised time for the task. This would give a better estimate regarding the quality and usability of the app as raw times alone cannot be expected to give any estimate as some tasks are naturally longer than others.

  - Standardised time = (time needed to finish 1 task – time expected to finish this task) / standard deviation
  - The Quality level is then calculated as the probability from the standardised Z-table

Table 8.13: Standardised task-completion times for the tasks given to users

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Standardised time	-1.08	-0.97	-1.71	-1.03	-2.9	-1.3	-1.2
Quality level	86%	83.5%	95.6%	84.9%	99.8%	90.4%	89.4%
Defective rate	14%	16.5%	4.4%	5.1%	0.2%	9.6%	10.6%

The quality level for the standardised times for each of the tasks was close to 90% which provides a good measure regarding the time taken by the participants to fulfil each task. It indicates that participants completed the tasks, on average, in 90% of the time proposed for the task. The quality level of over 80% for all tasks is what is expected from apps that have a high usability (Sauro & Kindlund, 2005). Participants who did not complete a task were not included in the standardised task-completion time analysis. Although the findings are promising, there is a limitation to this approach: participants who could not complete a task in 2 minutes were encouraged to leave the task and move on.

- Overall time-based user efficiency

The overall time-based user efficiency was 0.69 task/min which means that, on average, users were able to complete 70% of each task in 1 minute. Given the fact that the tasks required visiting more than one screen and actively interacting, this was a positive finding.

- Relative time-based efficiency and relative time-based expert efficiency

Table 8.14: Relative time-based efficiency and expert-time based efficiency

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**
$\overline{P}$ **Relative time-based efficiency**	87.40%	81.65%	85.29%	81.08%	89.14%	88.13%	80.24%
$\overline{P_E}$ **Relative time-based expert efficiency**	41.67%	24.30%	50.16%	20.22%	52.96%	38.04%	26.16%

The relative time-based efficiency, according to the table above (Table 8.14), is, on average, 84.7%. None of the tasks had a relative time-based efficiency less than 80%. High relative efficiency (which is the case in this study) indicates that users did not have trouble performing any of the tasks (Fehnert & Kosagowsky, 2008) which indicates a good usability of our app.

Comparing the performance of participants to that of experts (relative time-based expert efficiency) gave insights into those tasks that may have been more difficult than others. Tasks 2 and 4 were harder to perform for new users than the other tasks, which explains why these tasks had lower success scores than others, and higher error rates (although still within the expected range).

Table 8.15 Summary of the efficiency metrics

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7
Time $_p$ (Task completion time)	92.46±25.49	92.44±28.29	77.33±24.93	105.90±13.65	80.56±13.45	99.02±16.08	100.30±15.78
Time $_E$	44.09	27.51	45.48	26.4	47.86	42.74	32.71
Standardised time	-1.08	-0.97	-1.71	-1.03	-2.9	-1.3	-1.2
Quality level	86%	83.5%	95.6%	84.9%	99.8%	90.4%	89.4%
$\overline{P}$ (relative time-based efficiency)	87.40%	81.65%	85.29%	81.08%	89.14%	88.13%	80.24%
$\overline{P_E}$ (relative expert time-based efficiency)	41.67%	24.30%	50.16%	20.22%	52.96%	38.04%	26.16%

Overall, the completion timings and other efficiency metrics for the tasks provided the research team with great insights regarding the effort of the participants to complete the given tasks. All findings stayed within the expected range, which provided confirmation that the level of usability is as expected. Some tasks had a lower efficiency; however, the findings were still within the expected range.

An interesting finding was that the tasks that had lower completion rates (task 4 and task 7) had higher average task-completion times, indicating that it was hard for participants to perform these tasks.

The fact that non-completed tasks were not considered on the timing analysis should be taken into account.

8.2.2.3 System Quality/Satisfaction

Table 8.16: Answers to USE questionnaire

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	4	4	4	3	4	4	3	4	3	5	5	4	3	3	4	3	4	3	4	4	5
2	3	3	5	5	3	4	3	5	4	4	5	5	5	5	5	5	3	3	5	5	5
3	4	5	4	3	3	3	5	5	4	5	4	4	3	3	5	5	3	3	3	3	5
4	3	4	4	5	3	5	5	4	4	4	4	4	3	4	4	5	5	5	4	4	4
5	4	5	4	4	5	3	4	5	5	4	4	4	5	5	5	4	5	5	5	5	5
6	4	3	4	4	3	4	4	5	4	4	3	4	3	4	5	3	3	5	5	5	4
7	5	4	5	2	3	5	3	5	3	2	5	4	5	3	4	4	3	5	4	4	4
8	4	3	4	5	2	5	4	3	2	4	5	3	5	5	5	3	5	5	3	5	4
9	3	4	5	4	3	3	4	3	2	4	3	3	3	5	3	4	4	4	3	4	5
10	3	5	4	4	4	3	5	5	3	3	3	3	5	3	4	3	5	3	4	4	5
11	4	5	4	5	4	4	4	4	4	3	4	5	4	5	3	4	5	3	4	4	4
12	3	4	5	4	2	3	5	3	2	4	4	4	5	4	3	4	5	3	5	3	4
13	4	3	4	5	2	4	5	5	3	4	5	4	4	5	5	5	5	3	4	4	4
14	4	4	4	5	4	4	3	3	4	3	5	3	3	3	4	3	3	4	4	4	5
15	4	3	4	4	3	4	5	5	3	2	3	5	4	3	4	3	5	5	3	5	4
16	5	5	5	4	2	5	3	4	4	4	3	3	5	5	5	5	4	5	4	4	5
17	5	4	4	4	2	5	5	3	4	4	3	4	5	3	5	4	3	4	4	5	4
18	4	4	5	4	2	5	4	5	4	4	3	4	5	4	5	5	3	4	5	5	5

19	4	5	5	2	4	3	3	5	3	3	5	3	3	3	5	3	5	5	5	5	4
20	4	4	4	4	4	5	3	4	5	4	4	5	5	5	5	5	4	5	5	3	5
21	3	5	3	3	5	5	5	5	3	4	3	3	4	3	3	4	5	5	4	5	3
22	3	4	4	5	3	4	4	5	5	5	5	3	3	4	5	3	5	5	4	4	4
23	4	5	4	4	3	3	4	5	3	5	5	4	3	5	4	3	5	3	3	4	4
24	5	4	5	5	4	4	3	3	3	5	5	4	3	3	3	4	3	2	2	4	4
25	4	3	5	4	4	5	4	5	3	5	4	5	5	4	5	5	4	2	5	3	4
26	4	5	5	5	3	5	5	5	3	5	5	3	3	5	5	5	4	4	5	5	5
27	3	3	5	4	3	3	4	4	4	3	4	3	3	3	4	5	5	5	5	3	5
28	3	4	4	4	5	3	5	4	4	4	4	5	4	3	4	5	4	2	2	5	5
29	3	3	4	4	3	4	5	3	3	4	5	5	3	4	4	5	3	4	5	5	4
30	3	4	5	5	4	5	3	3	5	3	5	3	3	3	4	4	3	2	5	5	5
31	4	3	5	4	3	5	3	5	3	5	3	4	4	3	5	5	5	5	4	2	4
32	3	4	4	4	3	5	5	4	4	3	5	4	5	3	4	4	5	3	4	2	4
33	5	4	4	4	3	3	4	3	3	3	4	3	5	5	5	3	3	3	5	5	4
34	4	5	3	3	3	4	3	4	4	4	3	3	5	3	5	3	4	3	5	5	3
35	5	5	4	5	4	4	4	4	4	3	4	3	3	5	3	5	5	4	4	3	5
36	3	4	5	4	4	4	5	5	3	3	4	5	5	4	5	5	5	3	2	3	4
37	4	5	3	3	3	5	4	3	3	3	4	5	4	3	5	4	3	4	3	5	3
38	4	5	4	5	3	3	5	3	4	3	5	5	3	5	3	4	5	3	2	4	5
39	3	5	4	2	4	3	3	3	3	4	4	5	4	5	4	4	3	4	4	5	4
40	3	3	4	4	4	3	4	5	4	3	4	5	4	4	4	3	3	4	5	2	5

41	3	4	4	5	3	5	4	4	4	4	3	5	3	4	3	5	3	3	5	2	4
42	5	5	3	3	3	5	5	4	3	3	4	4	4	4	3	3	3	2	4	5	3
43	5	5	4	5	2	4	4	3	3	4	4	5	3	4	5	4	4	5	2	4	4
44	3	4	5	5	4	4	2	4	3	4	2	4	2	3	3	4	5	5	2	4	5
45	3	3	4	5	4	3	4	3	3	2	4	4	2	4	3	5	4	5	5	5	4
46	4	3	5	4	2	5	5	5	2	2	4	4	4	5	3	5	4	4	5	5	5
47	5	3	5	4	2	4	5	5	3	3	4	4	4	5	5	4	5	5	4	2	4
48	5	3	5	3	4	5	4	5	4	2	5	4	5	5	3	5	5	5	3	4	5
49	4	5	4	2	2	4	4	4	4	2	4	5	4	3	3	4	4	3	5	4	4
50	5	4	3	4	4	4	4	4	4	4	4	5	4	4	3	5	4	4	2	3	3
51	4	4	5	4	3	5	4	5	3	4	4	4	5	4	4	3	3	5	4	4	4
52	3	4	4	3	2	4	4	4	2	3	5	5	5	4	4	3	5	2	3	5	5
53	5	5	4	4	3	4	4	4	3	2	5	5	4	3	5	5	4	5	3	4	5
54	5	3	5	4	4	4	4	5	2	2	4	4	5	3	5	4	3	5	2	4	4
55	4	5	5	2	4	5	4	5	4	4	4	4	4	5	5	3	3	3	3	4	4
56	4	5	4	4	4	4	4	4	3	3	4	4	5	5	4	5	3	4	4	5	4
57	5	4	5	3	4	4	5	4	4	5	5	4	4	3	4	4	4	3	5	3	4
58	4	4	3	4	4	4	4	5	5	5	5	4	5	5	5	4	3	2	4	5	4
AVG	3,91	4,09	4,28	3,95	3,29	4,10	4,07	4,19	3,45	3,60	4,12	4,07	3,98	3,97	4,17	4,10	4,02	3,83	3,90	4,07	4,29
SD	0,75	0,77	0,64	0,88	0,83	0,76	0,76	0,80	0,79	0,93	0,77	0,74	0,90	0,85	0,81	0,80	0,86	1,05	1,03	0,94	0,62
Min	3	3	3	2	2	3	2	3	2	2	2	3	2	3	3	3	3	2	2	2	3

Max	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

In order to understand whether the questions in this questionnaire all reliably measure the same latent, a Cronbach's alpha was run on a sample size of fifteen system users. The scale had a high level of internal consistency, as determined by a Cronbach's alpha of 0.819.

In order to better visualise the results of the study, the graphical method of spider chart is used. The next figures display the comprehensive results for each of the four dimensions. Figure 8.7 shows the graph regarding the usefulness of the application; 8.8 shows that for ease of use of the application; 8.9 shows that regarding the ease of learning of the application; 8.10 shows the graph of user satisfaction of the application; and 8.11 shows the graph regarding overall system quality.

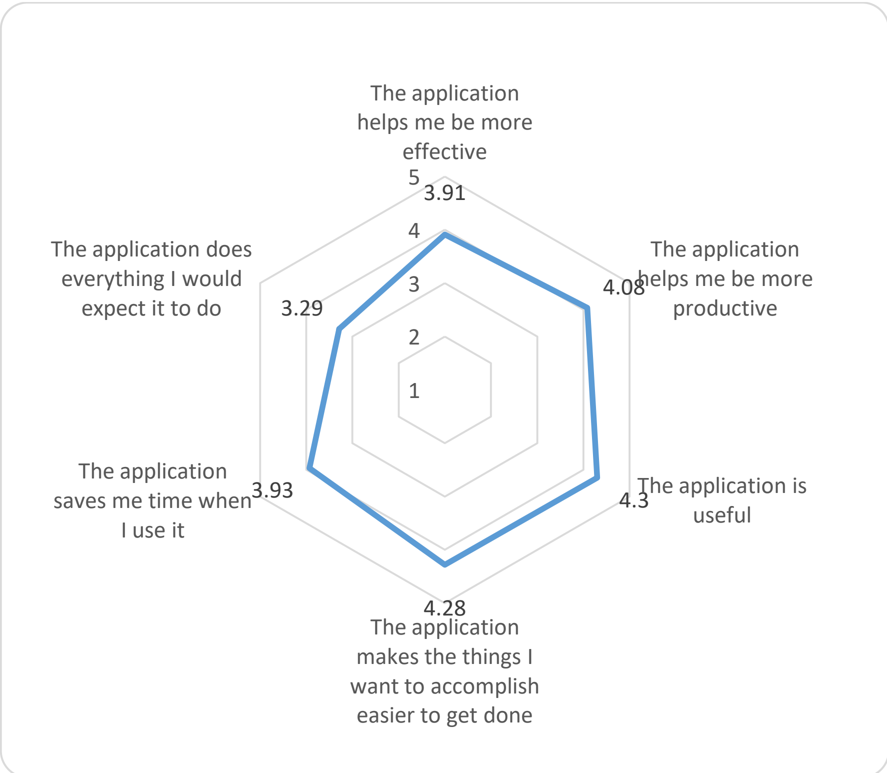

Figure 8.7: The graph regarding the usefulness of the application

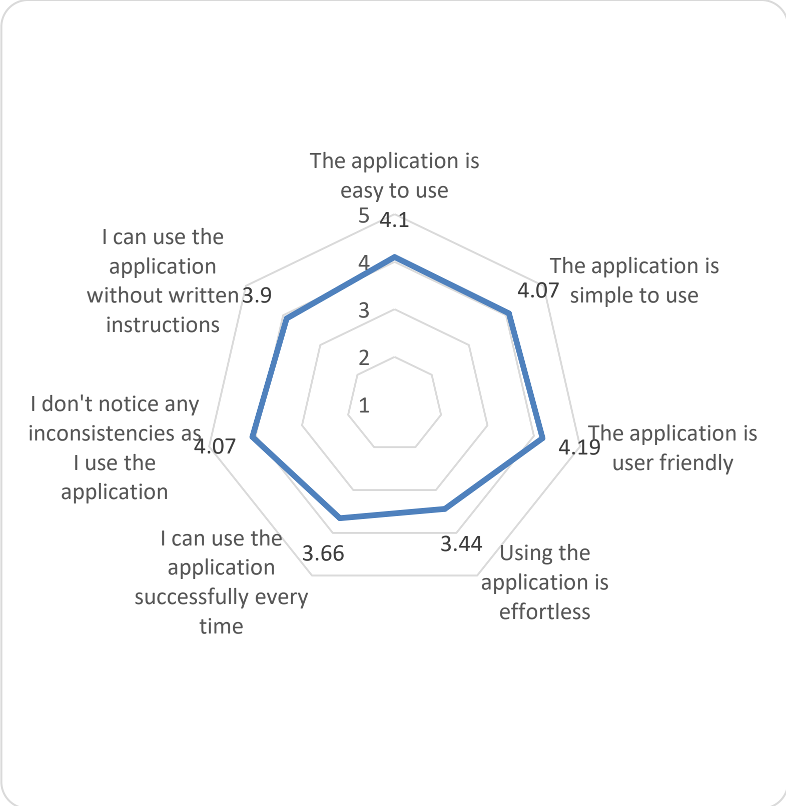

Figure 8.8: The graph regarding the ease of use of the application

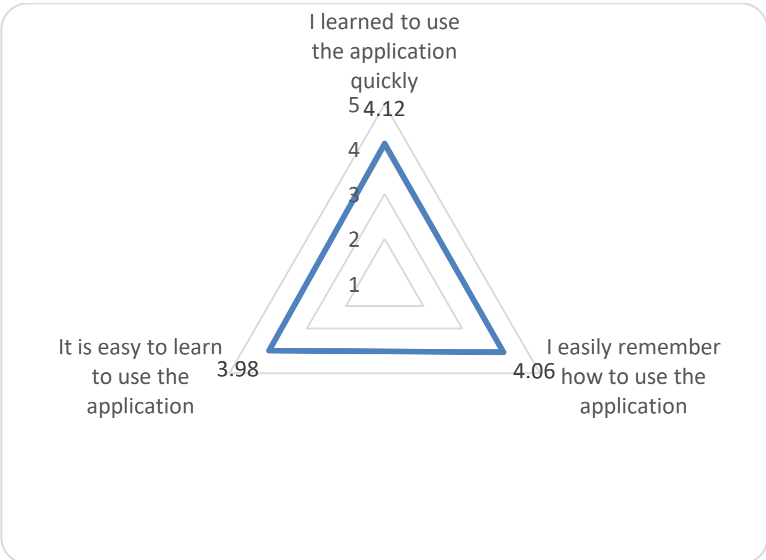

Figure 8.9: The graph regarding the ease of learning of the application

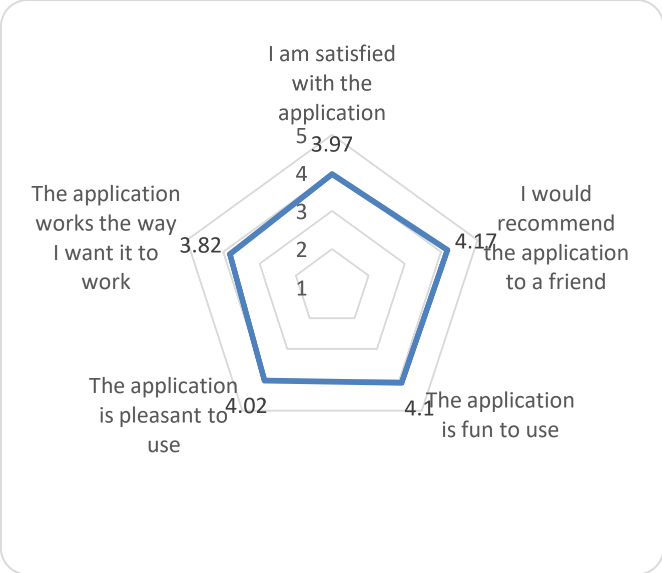

Figure 8.10: The graph regarding the satisfaction of the users of the application

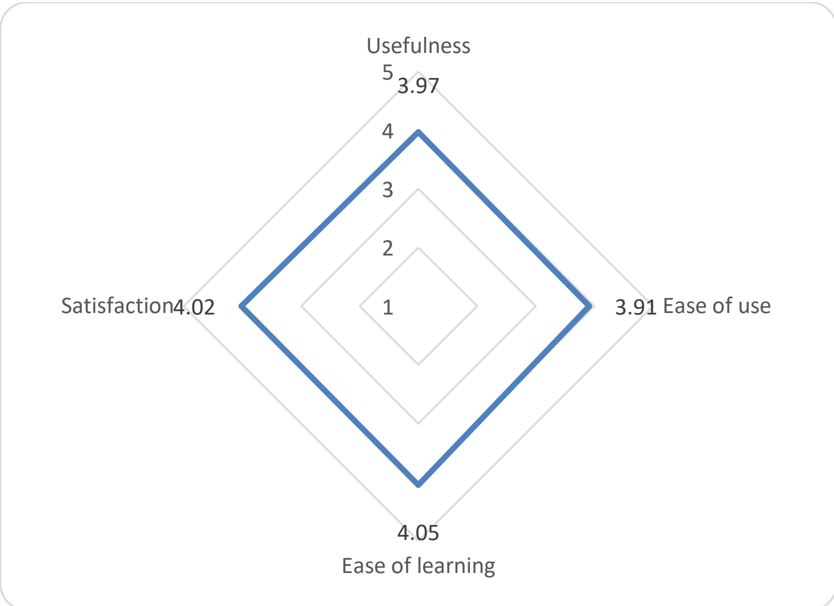

Figure 8.11: The graph regarding overall system quality

As observed from the spider charts, the users found the system beneficial regarding_usefulness, ease of use, learning of the system and satisfaction.

<u>Usefulness</u>

Users found the app extremely useful for executing and completing their tasks, as it helped them be more effective and productive. Furthermore, they could accomplish what they wanted to do more easily than they used to; the application therefore saved them time and effort. Moreover, they tended to agree that it does everything they would expect it to do; nevertheless, it seems that they wanted it to do even more.

Ease of use

Participants found the app quite easy. In particular, they found it easy and simple to use, with a user-friendly interface that helped them accomplish their objectives. They did not notice inconsistencies while they were using it and, in general, they seemed confident that they could use it successfully in most cases. However, they were not so sure if they could use it without instructions, or if its use was effortless.

Learning of the system

The users agreed that they learned to use it quickly, that they easily remember how to use it and that there was no difficulty in learning how to use it. The fact that there was no training stage before the users used the application should be considered, as it can be expected that repeated use would quickly complete the learning phase.

Satisfaction

The results were very encouraging in this aspect as well. In particular, users were overall satisfied by the system. They found its use engaging and pleasant and they would definitely recommend it to a friend.

Table 8.17: Summary of USE questionnaire results

Criterion	Usefulness	Ease of use	Ease of learning	Satisfaction	Overall
Mean Score	3.94	3.93	4.08	4.02	4
SD	0.34	0.33	0.5	0.41	0.23
Lower 95% C.I	3.86	3.83	3.95	3.9	3.93
Upper 95% C. I	4	4	4.2	4.12	4.05

Prior research through numerous studies has found that systems with good usability have a mean score of 4 on a scale from 1 to 5. When this was investigated in the current study (Table 8.17), all tested dimensions evaluated had approximately a mean score of 4 and the overall score was 4. This provides an extra measure of the quality of the app (Sauro & Kindlund, 2005). Moreover, the 95% confidence interval for the true mean also includes 4 for all areas assessed by the USE questionnaire. When the overall usability of the app was assessed through the questionnaire, the mean score was 4 [95% C.I 3.93 - 4.05]. This indicates a good usability which is illustrated in Figure 8.12.

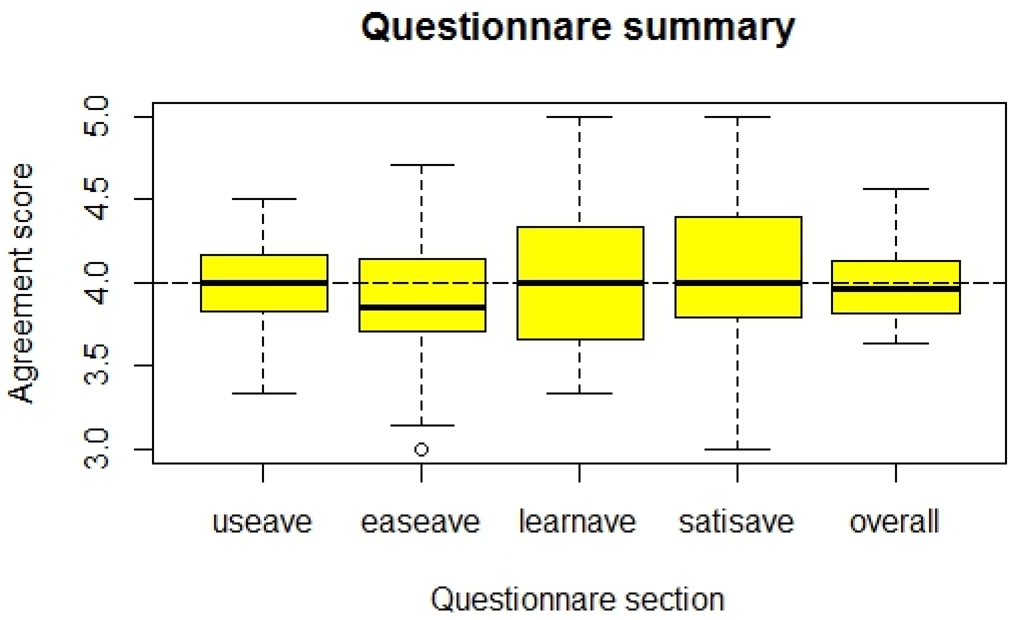

Figure 8.12 Mean score for each dimension of USE questionnaire/Overall score

8.2.2.4 Interviews

The interview recordings were analysed by two researchers. They also viewed the recordings of participants performing tasks, in order to put the participants' comments during interviewing into context, and took note of every issue mentioned by the users for each task and looked for any pattern or themes emerging, e.g., users being confused about a specific concept.

An encouraging finding was that the issues identified in the previous stage of research no longer caused any problems; none of the participants mentioned any similar problems when giving feedback on the system. The weather-station related information appeared to be clearly accessible through the prototype and the users who actually visited this tab described it as very informative and useful. Users were also able to see when the information had been updated, as was confirmed during interviews. In regards to requirement DR92, the new taxonomy was considered very straightforward and users were able to find the information in regard to spatial and non-spatial data efficiently.

This finding further supports DR93, with users being able to find their way in responding to queries quickly and effortlessly. The map view of the areas with available data was considered a valuable add-on to the user's interface of the system; viewing the current location on a map was considered very straightforward and the future addition of hosting more LBSs was very well-received by the users.

However, some additional issues were discovered by the researchers. The list of issues derived from the process, along with their impact on the user and a recommendation on how to overcome them, is included in the next table.

Table 8.18: Additional usability problems discovered

Issue Identifier	**Description**	**Impact**	**Recommendation**
I1	Participants found help information insufficient.	It made it harder for less-experienced users to carry out tasks since they still had some questions after reading the help sections. It is likely that more information in the help section could have increased the percentage of tasks carried out successfully. Several users expressed that they would have read the help sections more if they had more time; therefore, this part of the user interface is very important.	Make the help sections more detailed, also making the most important words in bold so that users do not need to read everything to find information about what they need.
I2	There was no progress indicator.	Some processes took more than a fraction of second to complete; several participants mentioned that they were unsure about whether the system works, and whether they really pressed a relevant button. Although the slowness was prototype-related, it is likely that in real life some users will have slower	A progress indicator needs to be added for processes that do not provide an immediate result.

		internet, which would create a problem.	

These issues will be addressed by the next implementation.

The interview process also examined overall user experience. Hence, the study participants were asked questions about their overall interaction experience. In particular, they were asked about the aesthetic design of the mobile application. The majority (45/58) stated that they liked it and that they found the mobile application graphics attractive. Ten (10) participants stated that the graphical appearance does not differ from other applications they had installed, implying that the design is pleasant and consistent as it follows the manufacturer's guidelines (e.g., Android design guidelines). Three (3) of them stated that they did not like it much, emphasising mainly the tabs view. In the long run, an alternative view could be added; however, it is beyond the scope of the current stage of the project.

The participants were asked to say which were the two most difficult tasks they had to perform. Their responses were clustered and listed in the following table, and are in line with the findings of the aforementioned subsections.

Table 8.19: The most difficult tasks

	Task 1	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**
1	x			x			
2		x		x			
3	x						x
4		x				X	
5				X		X	

6		X					X
7		X				X	
8	X			X			
9		X		X			
10		X				X	
11				X		X	
12	X					X	
13		X					X
14	X			X			
15	X			X			
16		X					X
17			X				X
18	X			X			
19		X		X			
20		X				X	
21		X		X			
22			X				X
23				X		X	
24	X	X					

25				X	X		
26		X					X
27			X				X
28	X						X
29			X			X	
30		X		X			
31		X					X
32	X			X			
33			X				X
34		X		X			
35				X			X
36		X					X
37		X	X				
38				X	X		
39		X				X	
40	X	X					
41				X			X
42				X		X	
43	X			X			

44	X		X				
45		X		X			
46	X			X			
47			X				X
48	X						X
49		X					X
50		X		X			
51	X				X		
52			X				X
53		X				X	
54		X				X	
55		X					X
56		X			X		
57	X					X	
58			X				X
Overall	**29.31%**	**46.55%**	**17.24%**	**41.38%**	**6.90%**	**24.14%**	**34.48%**

Tasks 2, 4 and 7 appeared to be the most difficult. These tasks had the highest error rates; the high number of errors explains why users perceived these tasks as the most difficult. Several participants mentioned that it would have been easier to perform tasks if more detailed documentation was provided; thus, it is likely that adding it is going to improve the usability.

8.2.2.5 Overall User Experience Analysis

The overall user experience was evaluated from observation of the participants during the study session, the performance metrics, the USE questionnaire and the interviews which followed. The user experience consists of four interdependent parameters: branding, usability, functionality and content.

Branding

Branding is formed by the aesthetic and graphic design approach of the mobile application, promoting creativity and innovation and determining how clearly the vendor expresses the messages and the scope of the application.

The USE questionnaire and interviews revealed the following:

- The participants found the graphical interface of the application quite aesthetically pleasing and minimal and thus were not distracted from their objectives, but highly engaged.
- The design was memorable, as many participants were able to recall the steps they followed in order to complete a task with high accuracy. The fact that the design of the mobile application followed the device manufacturer's UI guidelines meant the participants who had previous experience with the device needed less time and effort to engage with the study process.
- The findings of system quality and satisfaction analysis showed that, in general, participants found the application pleasant and enjoyable to use. This was confirmed by interview findings, as the majority of the users stated that the design of the mobile application was clear and aesthetically pleasant. The iterative process of the user-centred design approach followed in this project ensures that the appropriate improvements will be made later to keep the design attractive and user-friendly, taking into consideration not only the participants' comments but global trends on how to better visualise information.

Functionality

The functionality of the system was ensured during the design process, which the research team followed in order to deliver all the significant interactive services and mechanisms to the users to complete their objectives.

The following was concluded:

- The task-completion ratios and timings, along with the questionnaires, indicate the proper functionality of the system, which was also confirmed by the interviews.
- The completion rate was very high ($91.38 \pm 1.39\,\%$), taking into consideration that it is not a critical system and participants used it for the first time; besides, not all participants had much previous knowledge.
- The most difficult tasks (tasks 2, 4 and 7), although difficult, had high completion rates (89.66%, 87.93% and 87.39%). These tasks were mentioned by the study participants as the most difficult tasks and had higher error rates. Although in the longer run these areas need more focus, as the findings show, the completion rates and user satisfaction were acceptably high; therefore, changes to these parts do not need to be made immediately. This is something that could be further investigated later.
- A high number of participants would like the application to expand its services and cover more queries (e.g., predicting flooding of other countries and comparing the flooding in different countries). They raised a number of new possibilities and provided great insights for the expansion of the application; however, given the scope of this project, the objectives covered by the application are sufficient, and working smoothly and accurately.

Usability

The design process aimed to ensure usability and success in this respect was also confirmed during the present study. Two additional usability issues were, however, discovered at this stage of research and will be addressed at the implementation stage. Several users had some minor difficulties with the navigation, which they easily overcame. That does not constitute a usability problem but information architecture is something for researchers to bear in mind during the later stages of the project. Moreover, despite the research team's having considered participants with disabilities, few took part in the study; hence, a more thorough study may be required in order to ensure that accessibility issues are properly addressed.

Content

Finally, the content parameter refers to the content of the mobile application (e.g., text, graphs, maps and the information architecture).

The following emerged:

- The content was understood clearly by the participants, who mentioned that the graphic elements (e.g., icons and maps) were extremely familiar to them.
- The provided content was considered up-to-date, accurate and accessible, which enhanced the user experience.

8.3 Critical review of methodology and next steps

After completing the design phase, the prototype was handed to the development team (together with clear instructions on how the identified usability problems should be addressed) in order to implement the proposed system. The system design was based on HCD methods, meaning that users were engaged throughout the design process, providing valuable input in terms of insights and feedback for the design.

Starting the critical review from the first phase of the project, where the aim of the design approach was to create a set of DGs based on user needs and expectations in combination with business requirements, the proposed methodology was very effective.

Activity theory as a design framework enabled the researchers to gain a better understanding of the system and the environment of the system. The reasons for carrying out a task using the system, and what this task means to the user, were included in the design analysis and enabled the designers to better understand the designed technology in context. The involvement of users at this phase added valuable insights into the users' view of the system.

The use of nominal groups in the scenario-brainstorming phase was very efficient, yielding a total of sixty-three distinct scenarios. Deciding on the scenarios that would be used in order to extract the DGs was a challenging task, mainly due to the large number of produced scenarios. However, at the same time, the large number of scenarios enabled the design team to gain insight into all the possible aspects of the system and ensure the design would reflect the possibility of future expansion.

Filling the extended activity theory diagram was a very engaging and influential task. Breaking the scenarios into subjects, objects, instruments, rules, community and division of labour was, in fact, a second brainstorming task, since many of the scenarios were not very descriptive and the group had to discuss and decide on the missing information. The diagram encouraged the group to examine the interrelationships between the six aspects and better understand the system as part of the greater ecosystem. Participants were very active during this part, mainly due to the fact that they felt comfortable, knowing that their ideas would not be judged.

The analysis of the diagram was very time-consuming but it provided the researchers with all the necessary insights and a very deep understanding, enabling them to produce an effective set of DGs. The DGs were used at the second phase in order to create a consistent experience and ensure the system would be able to perform all the required tasks.

The second phase of the design started with creating a low-fidelity prototype using sketching. This was another brainstorming session conducted by the design team. The designers sketched out their ideas and selected the one they judged (based on their experience) would be the most appropriate approach and would meet all the requirements, while allowing room for future expansion. The selected sketch was refined until the desired result was reached. The final sketch of the system was then turned into a high-fidelity prototype which was used for conducting the first round of usability testing.

The use of a high-fidelity prototype was considered suitable because of the similarity to the final system, although it was important to make it clear to the users that what they were seeing was not a functional system in order to ensure they would not be frustrated by the lack of functionality. The high-fidelity prototype was also a valuable tool for the designers, as they were able to draw strong conclusions about how users' behaviour would relate to use of the system.

Having implemented the prototype, the next step was the first round of usability testing. This aimed for qualitative results rather than quantitative. Qualitative results were analysed in terms of insights and some adjustments to the prototype were proposed. Having adjusted the prototype based on the feedback from the first round of usability testing, a second round of usability testing followed.

The aim of this phase was to get quantitative results that could then be generalised. This provided the design team with the necessary reassurance that the proposed design was usable, intuitive, effective and efficient and satisfied the users, meaning that the project was now ready to proceed to the implementation phase.

8.4 The final user interface

The following section introduces the final user interface of the application.

High Level Design

The rainfall analysis application has been developed according to various device formats, from mobile phones to tablets, with screens from 4 to 10 inches; support for a large set of versions of the Android Operating System while keeping the same look & feel; support for screen orientation; and an ability for reliable data transmission with the web server to happen in the background (i.e., download must continue in the background, even if the application is closed and re-opened due to a screen orientation change).

The support for different devices and screen sizes has been accomplished by using dynamic layouts. All the graphical components will automatically rescale on the screen. In addition, in order to provide the best user experience, all the screens where user interaction is requested have different layouts for portrait and landscape orientation.

By using the Android support libraries, we can ensure that the user interface (including the look and feel) will always be the same, whatever version of the OS is used. More specifically, the rainfall analysis application is able to run on devices running Android 4.0.3 and higher (up to the newly released Android 6.0 Marshmallow).

Supporting dynamic screen orientation introduces several challenges and difficulties. Android manages screen orientation by closing and restarting the app. For this reason, each component of the programme must be able to save its state and restore itself when it is restarted.

Having data exchange in the background requires the use of asynchronous tasks. This is a common practice in Android. However, without taking proper actions, a change in the screen orientation would also kill the stream of data, forcing the transmission to restart from scratch. The result is the complete loss of the connection and of the data being transmitted.

Mobile Application UI Flow

The diagram below (Figure 8.13) shows the flow of the user interface of the Android application. The main interface is composed of four different tabs.

Figure 8.13: Four tabs of the main interface

Figure 8.14: Detailed view of the data

Some screens allow the opening of a more detailed view of the data. From the TSA tab, it is possible to zoom in on a chart. From the map tab, it is possible to open the map viewer and navigate through the map. Figure 8.14 shows a detailed view of the data.

<u>Location-Based Services Tab</u>

This tab in the interface is Location-Based Services. LBSs are services offered through a mobile device and provide users with personalised 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. At the present time, the application only provides the user with their current location. The position is automatically updated every 10 to 60 seconds according to the speed of the device. Figure 8.15 shows the LBS interface.

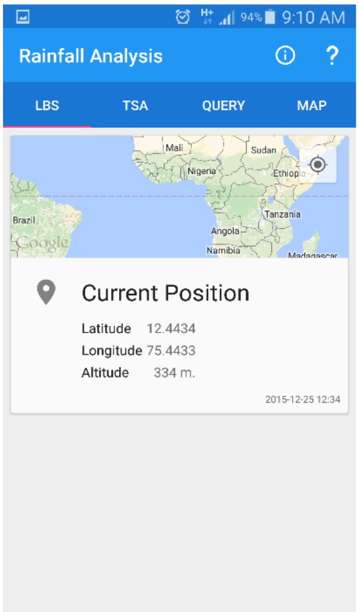

Figure 8.15: The LBS interface

<u>Time-Series Analysis Tab</u>

The time-series analysis (TSA) tab interacts with non-spatial data and produces a time-series hydrograph. A hydrograph is a graph of flow rate versus time and is used frequently in storm-water management. Since most printed records report flow daily, hydrographs for large watersheds are also reported daily. However, if the rainfall excess passes from the watershed in less than a day, a hydrograph must report hourly, or possibly more often.

To query the time-series database, one specifies a period and function desired (Max, Min or Avg.). For example, one can determine the average rainfall within a specified period. One can also specify several variables and produce a list that includes the date(s), time(s), and value(s) of the time-series data in question.

This tab allows the interaction with non-spatial data in the database, asking questions like ‘What are the rainfall values during one month?’.

The user can specify several variables and generate a list that includes the date(s), time(s) and value(s) of the time-series data in question. The user can select the variable (rainfall, temperature etc.) and a daily, monthly or yearly period. In addition, the option to choose a period ranging from an initial date up to the present has also been added. The selection is completed by specifying an initial date.

- When the monthly period is chosen, the data returned range over one month starting from the initial date.
- When the yearly period is chosen, the data set in the form is reset to the first day of that month and the values corresponding to 12 months starting from the selected month are returned by the server and displayed by the application.
- When the ‘up to now’ option is chosen, the date is reset to the first day of the year and the server returns one sample for each year of data availability starting from the selected year.

When data is received, the application automatically shows different cards containing graphs and tables of data. Clicking on each graph will open in full screen allowing users to zoom and scroll for better viewing and analysis. The daily graphs and tables report just the value of the measured sample. Monthly, yearly and ‘Up to now’ graphs and tables reporting minimum, maximum and average values are included. Figure 8.16 shows the TSA interface.

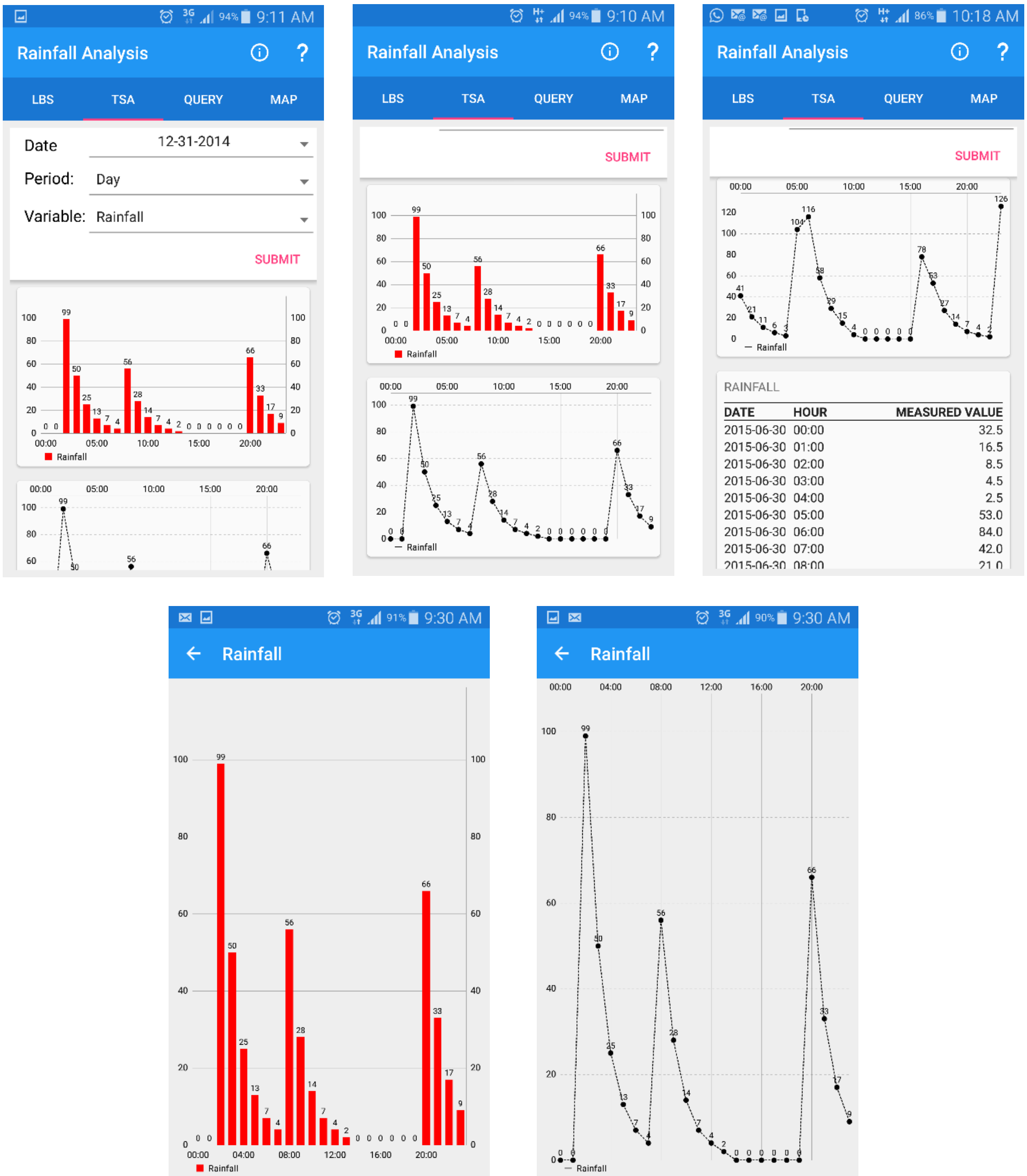

Figure 8.16: The TSA interface

Query Tab

The spatial database interface provides flexibility through a series of drop-down lists. One selects a query (What, When, Where or Which), a function (Min or Max), and a variable (Rainfall, Precipitation, Soil Moisture, Runoff or Recharge).

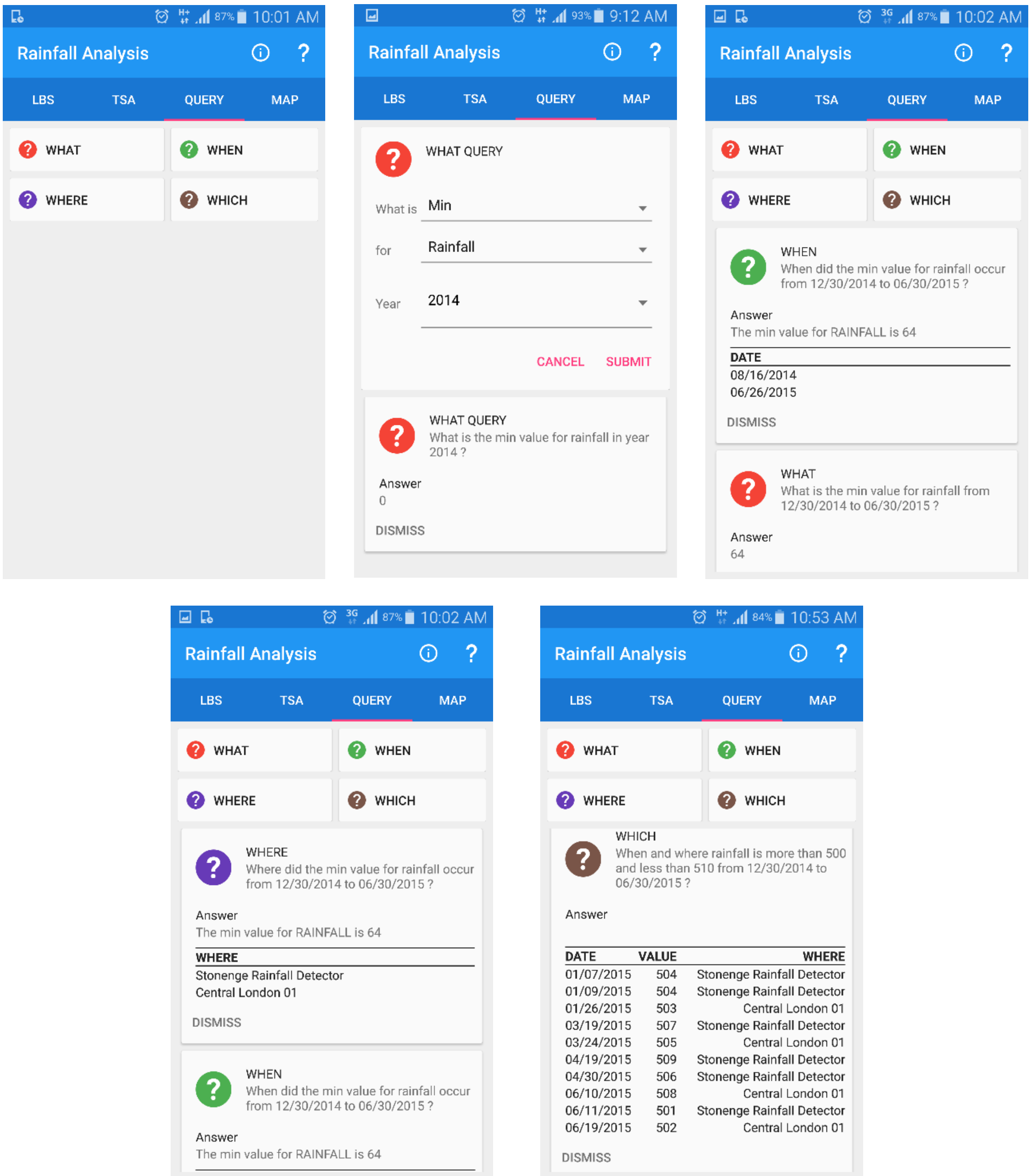

Figure 8.17: The different interfaces for the query tab

From these variables, a query is constructed to satisfy given conditions (i.e., to specify what database row is to be projected by specifying conditional operators that identify the tuples to be retrieved). Example queries are:

- *What* is the lowest soil moisture value occurring in a specified time-period?
- *When* is the highest rainfall value that occurred in a specified time-

period?

- *Where* in the catchment is the lowest rainfall value that occurred in a specified period?
- *Which (where and when)* is the rainfall value that is less than a specified value AND greater than a specified value?

This tab performs three different queries on the database: what, which and which is. Each query can be executed by tapping on the specific card. The queries are identified with a specific icon. The What query; a brown circle with a white question mark identifies the IMG query; and a purple circle with a white question mark identifies the Which query.

'This' is also repeated in the answer to allow fast and easy association of each question with its answer. Figure 8.17 shows the different interfaces for the query tab.

Map Tab

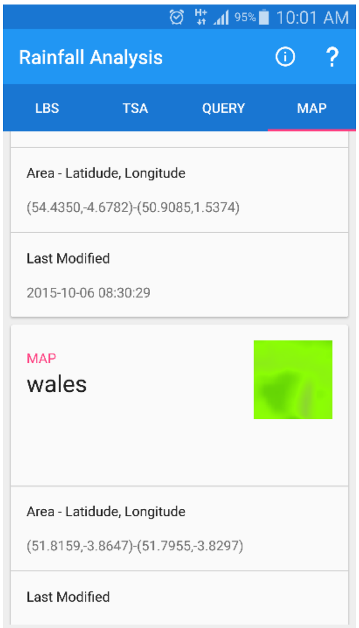

Figure 8.18: The map tab interface

The map tab shows the list of available server maps. For each map, the app shows the name and description of the map, the thumbnail of the identified area (this data is directly retrieved from the server), the latitude and longitude of the area covered by the map and the date when the map was last modified.

A new window appears which allows the navigation of the map through a tap on a card. Figure 8.18 shows the map interface.

<u>Map Viewer</u>

This screen allows the navigation of the map selected in the MAP tab. All the locations falling within the area covered by the map are indicated by interactive markers. By tapping on a marker, the name, geographical coordinates and number of available samples available on the database for that location are shown.

 Turns the map into greyscale

 Turns the map into colour mode

 Shows a sliding panel with all the available map transformations

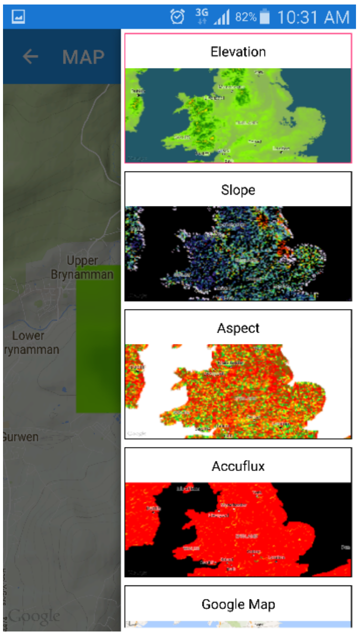

Figure 8.19: The map viewer interface

The sliding panel can be revealed with a swipe from right to left. This will allow the user to perform map analyses, such as slope, aspect or accuflux. In this way, basic geographical points are shown and can be kept as references during scrolling. Figure 8.19 shows the map viewer interface.

8.5 Conclusion

In this chapter, the final evaluation of the system was presented. Firstly, the methodology used was detailed and then the results of the study were presented. Overall, the system was considered efficient and effective, with users being satisfied by its use and finding the system both easy to use and easy to learn. In our analysis of the results, we have calculated efficiency, effectiveness and satisfaction; we found that they were lying in very satisfactory levels. The final interviews with the users reassured us that the proposed design was considered usable and was ready to proceed to the implementation phase.

Throughout the design phase, we made use of HCD approaches by engaging users from the very early stages. Their contribution to the design was very important as they added valuable insights and enabled the design team to view and better understand the user’s needs and expectations of such systems through analysing their behaviour or discussion with them. This design experience allowed us to enrich our design knowledge and enabled us to proceed to the next phase being confident in the proposed design solution.

Chapter 9 Conclusion

9.1 Introduction

This chapter presents a summary of the present work and its outcomes, and then discusses directions for further research and development of the prototype system. Section 9.2 summarises this research and presents its experimental findings. This includes the exploration of the use of GISs and hydrological modelling on mobile devices, and of whether HCI can improve the usability of such systems. Section 9.3 presents the limitations of the proposed system. Finally, Section 9.4 expounds the directions for future research in this area, with a particular focus on the development of the prototype devised and used in the present study.

9.2 Summary of the Study and its Contributions

This thesis set out to investigate the use of GIS and hydrological modelling on mobile devices. The study then investigated whether HCI can improve the usability of such systems on mobile devices. Based on this investigation and the design approach outlined below, the study developed a GIS-based hydrological model on mobile devices, and the experimental results show that subjective satisfaction on each construct was significant. That is, the system is user-friendly and aesthetically pleasing for users, and was not overly difficult for users to learn. Therefore, the designers successfully took into consideration not only the technological aspects of the system, but also the users' cognitive model, so that the system resulted in successful interaction with the user.

During the course of this project, the relevant background, theory and models were integrated to develop a framework for a real-time forecasting and warning system through a mobile device. An effective spatio-temporal hydrological analysis tool was developed to perform mobile watershed simulation and analysis that can support understanding and decision-making, containing a usable mobile interface and server-side GIS system, coupled with a real-time dynamic hydrological model. The prototype developed is the first GIS system to be coupled with real-time dynamic hydrological modelling.

9.2.1 The Prototype Hydrological Model—Features and Benefits

The prototype was implemented with mobile and web-mapping interfaces and facilitates monitoring and prediction of flood events. It gives a foundation for early warning and mapping of flood disasters. The general public, researchers and students can access the website and browse the information in their geographic area of interest. They can also visualise the impact a flood event on the area where they live. This research provides the foundation for improvements to decision-support systems that can result in improvements in the prevention and mitigation of, response to, and recovery from, flood events. This research has demonstrated a method to develop a spatial dynamic modelling tool with a high level of integration with environmental models in a GIS system. This integration provides an intuitive visualisation and spatial-analysis functions that are not available in traditional simulation models. The advantages of this integration are:

- Full integration of GIS functionality for manipulation of input and results
- No overhead for conversions between the GIS and models
- Rapid development of new models
- No separation between the model data and the GIS data
- No redundancy problems due to several instances of the same database
- Easy maintenance of models

An important objective was to find ways to access large amounts of information and a range of application tools. While existing models are confined mostly to research laboratories and academic institutions, and not widely accessible to the public, this prototype allows users to access and interact with a model directly through a mobile interface**.** The prototype demonstrates that mobile-based GISs are useful vehicles for accessing distributed spatial data and conducting GIS processing and spatial modelling by a particular user community. Geographic and physical constraints are removed, and the need is reduced for users to own the data or software system. Finally, the public can interact with processed data, such as the output of a flood plain model, rather than raw data. This is important because, regarding public access and participation, studies by Princeton Economic Research Inc. (1998) and Haklay (2003) demonstrate that public interest in processed data is far greater than in raw data. In the present study, accessibility was achieved because of user interface familiarity, portability across many platforms, and the ability to display different multimedia and hypermedia formats.

The present study provides insight into the applicability of mobile-based GISs in developing open Spatial Decision Supporting Systems (SDSSs). A decision-making process for solving spatial problems requires significant feedback from the public. Interactive SDSSs provide an interface that allows non-specialists to test different hydrological variables and management scenarios by linking dynamic models with GIS data, analysis tools and visualisation tools. Combined, these qualities permit, and indeed encourage, scenario testing and experimentation.

The approach taken in the present study has a number of significant advantages over traditional methods. It overcomes the difficulties of data access and participation by developing an interactive mobile-based GIS and dynamic modelling tool. With these interactive pages, users can access and analyse various hydrological and environmental data from computers at public libraries, schools or their homes. Another benefit of the present approach is that the interactive modeling and analysis environments are highly visual.

The prototype is a GIS system coupled with real-time dynamic hydrological modelling. This research demonstrates that such an advance is possible using a mobile and the Web as cost-effective communications equipment. Finally, this research provides a good model for individuals and small organisations that seek to provide services with limited resources. It is the author's wish to contribute to the GIS community by promoting discussion about this particular mobile-based GIS. A reader of this thesis can develop skills in user interface design, programming, computer network administration and software engineering. Readers are encouraged to explore the development of mobile-based GISs based on this work.

9.2.2 Design Guideline Development

Little of the related research focuses on the combination of a well-designed interface and GIS-based hydrological models. Therefore, the main aim of the user interface design part of the project was to use HCI techniques to produce interface guidelines for mobile real-time flood forecasting and warning systems, and to create and test a prototype that uses these guidelines. Much effort was put into creating, testing and adjusting the prototype; however, simultaneously, the guidelines were evaluated and updated in order to make them extensive and potentially relevant beyond the particular prototype. A range of HCI approaches and methodologies was used to achieve the user interface goals – user-centered design, Activity theory, iterative design – all with the same goals of understanding the needs of potential users, the complexity of user interaction with mobile GIS-based flood prediction and warning systems and the context of their use; and of using the knowledge to tailor the prototype and the guidelines to the needs of the users.

In order to apply the Activity theory to this particular project, participatory design was used. The aim was to invite a sample of potential users and experts in relevant fields to come together and brainstorm ideas of when and where the proposed mobile real-time flood-forecasting and warning system could be used, based on their needs and their experience.

Chapter 6 provided a starting point for creating an early prototype of the system to be designed. The first stage of the project was reviewing the Activity theory and its potential for use in the field of HCI. The ensuing literature review highlighted its strengths in understanding the complexity in the context of use of a software system, taking into account not only the technical capabilities of a software system and a particular user, but also the various objectives of the user, the community in which the use of the system takes place, various rules, divisions of labour etc. Analysing and understanding all this provides a strong potential to create a system that is fully accepted and used by the target audience because it could be easily understood by them, and considered useful

After analysing those scenarios, a set of concrete user-interface guidelines for the system was created in the form of those DPs and DRs which were selected as the most important by the participants. The scenarios were analysed in terms of instruments, subjects, objects, rules, community and division of labour by creating an activity diagram, during the process of which various insights and a fuller understanding of the system and its context of use emerged, as well as various interrelations of different components of the activity diagram. All the above provided an in-depth understanding of what was needed. The findings of the process were later transformed into a set of DGs for different roles of users of the system. Each guideline was derived from the findings of the activity analysis and the expertise of various team members; some technical or design requirements did not directly arise from the activity diagram created by participants, but from the expertise of team members who suggested what, exactly, a finding of the analysis of the diagram means in terms of user workflows, technical set-up or design. The guidelines aimed to be clear, extensive and reusable, thus potentially contributing to other similar digital products.

Chapter 7 detailed the design and implementation of the first prototype of the system, which was then tested with real users and refined based on the user testing results. Asking each of the participants to create some scenarios of use of such a system provided a multitude of ideas of how such a system could be used, and what users actually need. The subsequent group discussion of the scenarios and the selection of the most important ones enabled the researchers to critically evaluate the proposed ideas, and to look at them from more than one person's perspective.

Afterwards, a simple user interface prototype was created, based on the identified user-interface guidelines and the requirements for the aforementioned GIS-based system. Both researchers and designers participated in its creation in order to ensure that it met users' needs. The guidelines proved to be a very useful asset in designing the user interface since they provided an in-depth list of requirements of what was needed; it was also possible to evaluate whether a created design fully matched the identified requirements as it was possible to go through the list of these and check that nothing was missing, a task carried out by another researcher.

The design team, using the DGs as they were formulated on the first phase of the project, firstly sketched out the abstract ideas, and then turned the most appropriate of these into a high-fidelity prototype. The prototype was later evaluated by carrying out user testing with a sample of users who were diverse in terms of demographic characteristics and levels of relevant expertise. The aim of the evaluation was to evaluate the prototype and the guidelines in order to understand whether the guidelines had been identified correctly, and whether there was a need for user-interface refinement. The tasks that participants had to carry out were related to the identified guidelines and were predefined, to allow for exploration of all the aspects of the system, and revealed the pain points that could not have been identified otherwise. During the first round of user testing, qualitative methodology was used in order to gain some insights into how users would use the proposed system in order to achieve some predefined goals, and what the areas of uncertainty and problems were. Some areas for prototype refinement and additional guidelines were identified as the result of this stage or research, which proved that not everything had been taken into account at the previous stage of research, and that it is hard to create a useful and user-friendly interface at the first attempt.

Finally, after analysing the user-testing data, the design team proposed a new taxonomy closer to the one described by the users during the testing sessions. New functionalities were added to the refined prototype in order to better match the users’ expectations, and were believed to enhance the system’s credibility.

The refined prototype underwent another stage of testing (however, this time for front-end users' tasks only, since that area most needed additional testing). The process of user testing not only helped to refine the prototype to make it more user-friendly but also helped to develop and improve understanding of the mobile context of use of mobile forecasting and warning systems, user needs and preferences. This understanding will be useful in later stages of improving and extending the system.

Chapter 8 presents the evaluation of the final prototype. Unlike in the previous round of testing, this time the approach was quantitative with the aim being to measure usability. However, more than one research method was used and some qualitative data was collected as well, to supplement the usability metrics and to identify additional areas for improvement, which were later addressed. The findings were promising (although there were some areas for improvement) and met expectations; thus implementation proceeded of a full user interface for a mobile-based system that interacts with a GIS-based hydrological model for real-time flood forecasting and warning. This was subsequently reflected in the methodology and the outcomes.

The process of user testing not only helped to refine the prototype to make it more user-friendly but also helped to develop and improve understanding of the mobile context of use of mobile forecasting and warning systems, and user needs and preferences. This understanding will be useful in later stages of improving and extending the system.

Overall, the result of this project was twofold: firstly, a prototype for a mobile-GIS based forecasting and warning system was created and refined, based on in-depth research and understanding of users' needs. Secondly and more importantly, a contribution was made to the field of HCI by proposing a working methodology for developing and evaluating user interfaces for mobile technology for interacting with real-time dynamic hydrological modelling, by providing some insights into the complexity of such interaction as well as by providing clear guidelines that could be incorporated into other similar projects.

9.2.3 The Importance of HCI-Based Design for Mobile GIS Development

Mobile GISs in general, and those for flood-prediction system and warning in particular, are being prioritised in the research agenda of several scientific disciplines within the geoinformation community. In addition, the user base is increasing exponentially, generating high demand on mobile GISs. However, deeper cooperation between different research areas such as Hydrology, Computer Science and GISs is required in order to integrate, rather than duplicate, the research efforts. The adopted methodologies of this work serve as a pattern for related research. This study implemented HCI concepts to analyse the system, and users' requirements and needs to discover problems, and incorporated concepts of mobile HCI to design a friendly user interface in the development of near-real-time flood predicting and warning.

Even though the prototype does not have the polish of a professional software product, it does provide many valuable contributions for the general public, concerned citizens, and hydrology and GIS students. For example, the prototype can be used as an educational tool; running the model is simple, and the output is portrayed clearly and concisely; it facilitates and promotes teaching and active learning of a particular concept or technique in GISs or hydrology; and it provides dynamic graphics for enhanced visual representations.

While there is a lot of research on the usability of these applications, few studies have concerned GIS-based hydrological-model usability testing, and the absence of modern technical solutions poses a series of shortcomings, as listed below.

9.3 Limitations

9.3.1 Development Limitations

The GIS industry is focusing on mobile GIS applications and the development of mobile hardware or software (Peng & Tsou, 2003; Tsou & Sun, 2006), such as Mapinfo's MapXtend, ESRI's ArcPAD and mobile Google Maps. However, major impediments remain for the development of mobile GISs.

The first impediment is the absence of comprehensive user interfaces designed specifically for a mobile GIS. Most existing mobile GIS software still falls in line with older concepts of desktop GIS interfaces. The small, sensitive stylus pen and the small on-screen keyboard input method are impractical for a mobile GIS in the emergency context. Direct voice commands and an easy, touchable screen are more appropriate for emergency responders and in-field workers.

A second problem is the integration of spatial analysis and GIS modelling into a mobile GIS. Many emergency tasks and disaster-management works will need sophisticated GIS analysis functions that require significant computing power and memory; however, mobile GIS devices today are small and have very limited computing capability. Accordingly, the pre-processing and post-processing time for spatial analysis and remote sensing of images might prevent the adoption of mobile GISs for real-time response tasks because of inadequate hardware. At this time, the solution is to send the complicated GIS model and spatial functions via the Internet to remote GIS engine services, after which the results are sent back to the mobile GIS devices via the network.

A third issue is the lack of alternative display methods for mobile GISs. Since most mobile GIS devices are small and fragile, emergency responders and managers might be reluctant to use small screens on pocket PCs or cellular phones to share their maps with others. One possible alternative is to print out paper maps directly from mobile GIS devices, since paper maps are easy to carry and there will then be no need for batteries in the field. It would be useful if users could print paper maps directly from their mobile GIS devices via wirelessly portable printers or from a built-in printer inside a Pocket PC or a notebook computer.

9.3.2 Limitations of the Proposed System

There are two types of limitations, namely, the shortcomings of the prototype and the shortcomings of the usability study. Limitations to the prototype are as follows.

The computational power needed by the analysis tools and the complex algorithms for imaging analysis require a large amount of memory in the user's machine to work effectively. Thus, to accommodate an increased number of calculations, the computational power of the computer must be improved. In addition, a real-time rendering system requires sufficient memory to work properly; to this end, the server-side can be equipped with a powerful CPU and a large amount of memory for minimal cost per user. When performing database queries such as *question 1* and *2*, memory usage usually varies between 25 and 35Mb. When answering *question 3*, memory usage can increase a great deal. The database engine employed in this prototype is a free, lightweight, relational-database management system. MySQL is designed for the fast retrieval of small amounts of data. Therefore, the database engine in the prototype should be replaced with a database engine designed for fast retrieval of large amounts of data, especially if this data is to be retrieved from a website.

Regarding the shortcomings of the usability studies, the following are germane. Usability testing proved to be an essential part of the design and implementation of such an application. Although conducted based on very limited research, mobile GIS-based hydrological-model usability testing is very promising. During this research, the special requirements, limitations and advantages of mobile GIS-based hydrological models were studied, along with the usability testing methods and techniques that can be applied to their evaluation. The variables of usability that were chosen in order to be assessed in user surveys were the fundamental usability variables of effectiveness, efficiency and user satisfaction. The method and techniques that were selected as appropriate were Think Aloud, observation, tape recording and a questionnaire after the survey. A possible shortcoming of the system is whether the advanced functions could be added and applied to a more complex service. Services with large databases may also present problems. In such services, it is possible that the study may not be appropriate because of the potential difficulties of more complex systems.

9.4 Future Work

The study identified several aspects to be considered for further research; specifically, in the coming project phases, the results of a domain analysis and usability tests will be incorporated.

First, the prototype has much room for improvement in terms of functionality and usability. The next stage is to improve the system based on users' suggestions and then obtain a deeper analysis from usability experts and wide-ranging participants to extend and improve the functionality of the system. The modelling algorithm is another important subject for improvement in future work. Using different and new functions to approximate the trend of increasing water level, better approximate the curve, and consequently make better future forecasts, is yet another important avenue for work. Finally, web services, email or SMS text notification of predicted basin-depth thresholds can be used in the future to provide lead-time for proactive measures or hydrologic prediction.

Second, the research and design approach taken in the present study could be further refined. The study should be extended by applying the same research and development model on another paradigm of mobile computing, such as context-aware, in which applications can discover and take advantage of contextual information (such as user location, time of day, nearby people and devices, and user activity). This would involve enabling the service to detect the user's location and then to provide location-specific information, possibly within user-defined parameters, such as, within a one hundred metre radius, or within a one-kilometre radius of their current location. There are more usability testing methods and techniques that could be used for the usability testing. It would be interesting to combine additional methods in order to see whether the outcomes differ as a result. In addition, this study confirmed that several methods need to be used in order to evaluate user experience. In future work, in addition to the interviews and observations, more efficient ways to gather information about the user's emotions and experiences, concerning, for example, collection and interpretation of gestures and facial expressions, are needed. In order to collect authentic emotions, the test condition should be organised so that it is as natural as possible. Finally, since this kind of application sometimes needs to be used in the field, we will show that closed laboratory settings are not sufficient for mobile usability evaluations, although they reduce external impact factors.

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Appendix A: Recruitment screener

Study Time

One session of the study will be held in the form of a workshop in our offices on Tuesday 24th of April 2013 at 10:00 am. The study will last for about two and a half to three hours.

Participant Types

The team has agreed to recruit from the following groups:

- 5 representative users;
- 1 software developer;
- 1 software designer;
- 1 business analyst;
- 2 GIS experts.

If the availability of participants necessitates a change to this list, the change will be discussed among the team and the recruiters will act accordingly.

Recruitment methods and incentives

The recruitment of participants will be done via email and telephone.

Provisions have been made to provide a 200 AED incentive to encourage audiences to participate.

Screening Scripts and Guidance

Email

Hello,

We are writing on behalf of a research project from Brunel University conducting some research on the design of a new system in regards to using mobile technology for flooding data and analysis.

We are looking for people to help us out for about between two and a half and three hours on Tuesday 24th of April 2013 at 10:00 am. This will help us to gain a detailed understanding about how different people and groups would use such a system and will allow us to design the new system to provide better support.

The research would involve you participating in a group session with nine other participants and two members of our team. During the session, you will be asked to perform a number of tasks and discuss with the other group members. Most importantly, we will be asking about your opinion based on your personal knowledge and experience.

An incentive will be provided for your participation.

If you are interested in participating in this research, please reply to this email and provide your name and number so that we can discuss the session further.

Thank you for your assistance,

Telephone - Opening Script

Good morning/afternoon/evening, my name is ______________. We are calling on behalf of a research group conducting some research on the design of a new system in regard to using mobile technology for flooding data and analysis.

We are looking for people to help us for about two and a half to three hours on Tuesday 24th of April 2013 at 10:00 am.

They would be very grateful if you would be able to help us. Can I explain a bit more about the research, and ask if you would possibly be available on Tuesday 24th of April 2013 at 10:00 am?

[ ] Yes

[ ] No – CLOSE

This will help us to gain a detailed understanding about how different people and groups would use such a system and will allow us to design the new system to provide better support.

The research would involve you visiting our location and participating in a group session with nine other participants and two members of their team. During the session, you will be asked to perform a number of tasks and discuss with the other group members. Most importantly, they will be asking about your opinion based on your personal knowledge and experience.

The session will last for about and a half to three hours and in return you will be given 200 AED plus lunch and appropriate travel costs as appreciation of your assistance.

I do have a few questions to ask to ensure that you are suitable for the research. This will only take a few minutes.

Are you interested in helping with this research?

[ ] Yes

[ ] No – CLOSE

We are committed to preserving your privacy and to protecting any personal information that you may provide to us.

Do you consent to us collecting this type of information?

[ ] Yes

[ ] No – CLOSE

We want you to understand how we intend to use and protect any information which you may provide to us. Personal information supplied by you will be used for carrying out research to understand how people use a particular system or service and what they think about when doing so, in order to understand how well it is meeting the needs of people that use it. However, no information that could be used to identify you will be collected; the questions would be about your education, job, age (no need for a full date of birth).

Do you consent to us using your information in this way?

[ ] Yes

[ ] No – CLOSE

Please note that your information will be processed and held by us in accordance with the Data Protection Act 1998.

You are also entitled to see the personal information held about you. If you wish to do this, you can contact us.

Information will be recorded and kept confidential; however, we ask that you do not discuss the session or its contents with others.

Are you happy to proceed?

[ ] Yes

[ ] No – CLOSE

[Recruitment screener questions should now be asked.]

Recruitment Screener Questions

No	Question	Answer	Action
Q1	What is your gender?	[ ] Male [ ] Female	
Q2	What is your age?		Take note of the age
Q3	What is your education level?	[ ] School graduate [ ] University undergraduate student [ ] University graduate [ ] University postgraduate student [ ] Phd Holder	
Q4	How often do you use the Internet?	[ ] Daily [ ] Once or twice a week [ ] Once a fortnight [ ] Once a month [ ] Less than once a month	Less than once a month - CLOSE
Q5	Do you use mobile applications?	[ ] Yes [ ] No	No -CLOSE
Q5	How experienced would you say you are with mobile applications?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced	

		[ ] Very experienced	
Q6	How experienced would you say you are with weather systems? For example, how often do you use online weather forecast services?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced [ ] Very experienced	
Q7	How familiar would you say you are with geographic information systems? Which ones have you used?	[ ] Not familiar [ ] A little familiar [ ] Neither familiar nor unfamiliar [ ] Somewhat familiar [ ] Very familiar	
Q8	Are you	[ ] Software Developer [ ] Software Designer [ ] Business Analyst [ ] GIS Professional [ ] None of the above	For Software Developer and Software Designer – Go to Q9 For GIS Professionals – Go to Q10
Q9	Do you design/develop systems that require big data analysis and representation?	[ ] Yes [ ] No	Yes - RECRUIT No - CLOSE
Q10	How long have you been working as a GIS expert?	[ ] Less than 5 years [ ] More than 5 years	Less than 5 years – CLOSE More than 5 years - RECRUIT

Close Script ('CLOSE')

Okay, that's great. Many thanks for taking the time to talk to me today, but I am afraid that we will not need you to continue in this research, because your profile does not meet the requirements.

Recruit Script ('RECRUIT)

Okay, that's all the questions completed and we would like you to take part in the study.

Will you be available on Tuesday 24th of April 2013 at 10:00 am? You will receive 200 AED plus lunch and appropriate travel costs in appreciation of your assistance with the research.

The session will be held in our offices in the University of Sharjah. The address for this office is: Lab 10, Ground Floor, Building M5, University of Sharjah.

We may need to contact you on the day; do you have a mobile number or telephone number we will be able to use? <record participant telephone number>.

We would like to send you instructions in regard to the study prior to your visiting the office. Could you provide us your email address? <record participant email address>

That's great, we will expect you to be there on Tuesday 24th of April 2013 at 10:00 am.

Appendix B: Instructions for participants

Introduction

We would like to thank you for agreeing to participate in our study. In order to get ready for the study, we would like you to read the following instructions to familiarise yourselves with the process of the study.

Time and location

The study will last for between two and a half and three hours and will take place in our offices on Tuesday 24th of April 2013 at 10:00 am. Please ensure you arrive on time. If you need any help with transportation, we will be happy to help you. During the study, we will provide food and drinks.

What is this project about?

The study entails you contributing to the design phase of a system which will provide flooding data and analysis to end-users through a mobile application, and should include an administration panel that enables the administrator to manage the system and analyse data. The goal is to create a system that ensures that the users achieve their goals. However, no design work or testing will be carried out at this stage, only idea generation.

Do not worry if the terminology sounds complicated – no previous expertise or knowledge is required.

Who are the participants?

For the purposes of this phase, we have recruited ten people, including potential end-users, business analysts, software developers and designers, and GIS experts. Regardless of which group you belong to, your voice is really important in this process. There are no right or wrong answers and good or bad ideas. Every idea is important and should be expressed.

What will the study involve?

N.B. - there is no need to memorise any of this information as researchers will *guide you during the process; the aim is to inform you in advance so that you know what to expect.*

The study will be divided into the following stages:

Introduction: The members of our User Experience Research Team will talk you through the objective of the study and will provide details on the system to be designed. Please feel free to ask any questions during the introduction and to familiarise yourself with the room and meet all the attendants.

Stage 1: The attendants will be divided into two groups of five. Initially, you will be asked to think of user cases in which you imagine the aforementioned system could be used, and write them down on provided cards.

Next, the members of our User Experience Research Team will collect the scenarios of each group and share them round robin-fashion (i.e. one scenario per person each time). During this task, you will be allowed to ask for clarification; discussion and enrichment of the scenarios will be encouraged. This stage will not last more than forty (40) minutes.

Break 1: After finishing this task you will get a thirty- (30) minute break. Our researchers will write all the discrete scenarios on a whiteboard during the break.

Stage 2: During this stage, the two groups will be merged into one of ten participants, and each person will be asked to individually evaluate the scenarios on the whiteboard and anonymously vote for those that—in their opinion and according to their experience, or their needs and expectations in the case of users—should be addressed by the system. Voting instructions will be provided on site. The votes will be collected and tabulated and then a discussion around those that received the most voting points will be held. This stage will last about forty-five minutes.

Break 2: A 15-minute break will be given.

Stage 3: During the third stage, all participants, along with the researchers, will analyse the scenarios; researchers will guide the discussion. More details will be provided on site. This stage will last about half an hour and will be the final part of our research.

Completion: You will then be paid for your contribution and the study will be finished.

Help & Support

Two members of our User Experience Research Team will be with you throughout the study to help you out and guide you through the process. They will be happy to answer any questions you may have.

Will your participation in the project remain confidential?

No information that could personally identify participants will be stored.

Do you have to take part in the study?

No, your participation in this project is entirely voluntary.

Informed consent form

Please read and sign the consent form below.

CONSENT TO PARTICIPATE IN A RESEARCH PROJECT

You were selected as a participant in this study. During the study, you will be asked to brainstorm some usage scenarios for a system described in the Instructions Sheet you have received, as well as to vote on and discuss other participants' scenarios. Please read the information below; you can ask any questions about it before deciding whether or not you agree to participate.

- This participation is voluntary and is expected to last for about 2.5-3 hours.
- The information will be used for a research project, read by some academic and industry stakeholders.
- No personal information which can identify participants will be stored.
- You can withdraw at any time, no questions asked.
- You can choose not to answer some questions.
- The questions are unlikely to cause any distress and concern.

I understand the above and agree to participate in the study.

Name...

Signature..

Date...

Appendix C: Derived scenarios

List of produced scenarios

ID	Scenario	Points
1	The weather condition and changes are transmitted to local emergency forces in order to be prepared for the threats and confront hazard situations. × *Excluded because rejected by stakeholders for being beyond the project scope*.	**X**
2	Alice uses the application in order to learn more about environmental threats, such as floods, by playing in-app mini-games. × *Excluded because of a very low number of points; there was a clear lack of excitement regarding the mini-game idea among the participants.*	**26**
3	Alice uses the user-friendly web interface of the application to upload some data about the location where she currently lives, and keep the community aware of the new facts. However, Martin, the weather station officer, should first check and then activate the given data. ✓ *Included because of a high number of points and generally positive participants' remarks.*	**69**
4	System administrators use the system in order to manually adjust the models and the threat parameters, based on each location characteristics. × *Excluded because of a low number of points and GIS experts' suggestions that it could be at least semi-automatic; user experience researchers and stakeholders shared this opinion.*	**47**
5	Visualised data, in multiple forms such as charts, plots, text, images, infographics, etc. are displayed to each user. Each user is able to adjust the way each data parameter is presented. × *Excluded because of a very low number of points and participants' remarks that it is likely to make everything more complicated when users can adjust everything.*	**42**
6	Bob connects to his personal weather station for a deeper dive into the weather data he cares about. × *Excluded because of a very low number of points*	**24**
7	The mobile system is used by pilots, rescue workers and anyone else who wants to stay ahead of the storm, by displaying accurate points of the predicted storms. × *Excluded because of a very low number of points; also, it is likely that robust and highly reliable systems exist for this purpose for pilots and rescue workers, whereas the aim of this application is to provide weather information to normal users. As for normal users, accurate points of predicted storms might be hard to understand and interpret, whereas general warnings would be more understandable.*	**23**
8	Since the system provides information about rainfall, precipitation, moisture and so on, it would be extremely helpful for Bob, a farmer, in order to help him pick the best dates to plant his vegetables. ✓ *Included, because of a very high number of points; perceived as having a high potential by team members as well.*	**87**
9	Bob virtually explores each weather station by taking advantage of the web camera service provided by each station. × *Excluded because rejected by stakeholders for being beyond the project scope*.	**X**
10	A recommendation service is provided to farmers by the application, providing them with valuable insights about the best cultivation location. × *Excluded because rejected by stakeholders for being beyond the project scope.*	**X**
11	Bob uses the application in order to instantly check parameters such as the temperature and moisture level of any location he wants.	**35**

	× *Excluded because of a very low number of points, as well as participants' observation that existing smartphone applications do that. These are often on phones' main screens, thus only one click is required to access the information – they would not use a more complicated application for that. Also, implementing scenario 8 will implement this scenario as well, thus it is safe to exclude it.*	
12	Bob uses the application's GPS mechanisms in order to get information (moisture level, soil ingredients, etc.) about the location where he is. × *Excluded because of a very low number of points and perceived irrelevance. However, this feature might be implemented later – the implementation of scenario 8 would show similar data for any location a user enters, and automatic location recognition might be potentially useful. However, soil ingredients are beyond the scope of this system.*	**40**
13	The local authorities use the mobile application to notify and warn the community about imminent hazards. × *Excluded because of a very low number of points; local authorities have other ways to share the data, weather-station users should do this. However, due to its significance, communication mechanisms will be incorporated in the system. Automatic notifications should also be supported by the system.*	**34**
14	Alice is planning a road trip next weekend and wants to check the likelihood of rainfall on the route she going to follow. × *Excluded because of participants' observation that existing smartphone applications do that. These are often on phone's main screens, thus only one click is required to access the information – they would not use a more complicated application for that. Besides, this functionality will be implemented by scenario 18 and thus it is safe to exclude it.*	**59**
15	The system has been out of service, but the administration team works on the network, database and security of the system to put it back online in a few minutes, ensuring its proper functionality. ✓ *Included, because of a high number of points and a general agreement that it is important; stakeholders also emphasised it as being important.*	**68**
16	Bob checked the rainfall data but he wants to know if the data are accurate and thus he is using the application to view the weather station official statements. × *Excluded because of a very low number of points. It would also include extra work for weather stations to issue statements.*	**21**
17	Alice has just moved, and wants to compare the rainfall levels of the new town. × *Excluded because of a very low number of points; other applications provide monthly rainfall level data for various cities anyway. However, it is partially covered by scenario 23, which was included in the final round.*	**49**
18	Bob wants to travel to London this weekend, but he doesn't know the weather and the likelihood of rainfall and other weather parameters, so he uses the application to get the desired information. ✓ *Included, because of a high number of points. Although it is similar to scenario 14, which was rejected, this scenario includes a range of other weather parameters, which other applications might not provide.*	**93**
19	Bob wants to check tomorrow's weather forecast and he is using the application to do it. × *Excluded because of a very low number of points: other applications provide this data. However, implementing other scenarios will lead to this feature being implemented anyway.*	**25**
20	There was heavy rainfall last night in the town, and Bob's storehouse flooded. Bob uses the application to find out how he may save his storehouse. × *Excluded because of a very low number of points.*	**33**
21	Martin, who is a weather station officer, noticed that there is an increased likelihood of flood in the next few days, and uses the application to send a warning. × *Excluded because of a low number of points. The study participants said that notifications and messages should be issued by the system, but this is a functionality*	**51**

	covered by other scenarios which already had more points.	
22	Bob has just checked the rainfall information, but he wants to know where the weather station that provided the data is located. × *Excluded because of a low number of points; participants expressed that such information is hardly ever needed.*	**56**
23	Alice has just moved to a town, and she is quite curious to find out what the weather conditions (e.g., rainfall), are there so she uses the system to view historical data of such characteristics. ✓ *Included because of a very high number of points. Although it is similar to scenario 17, this scenario implies a broader range of data and, potentially, a more gradual view of data – e.g., viewing historical data by week, not month.*	**94**
24	The city authority is notified by the local weather station that there is an increased likelihood of flood in the next two days. The system, using data and models, informs the local authority of the risk of flood. ✓ *Included, because of a very high number of points. Even though it is similar to scenario 21, participants, especially GIS members, expressed their opinion that this is a preferred approach - that local authorities should be involved in handling the situation, providing advice as to when to send notifications, etc.*	**105**
25	A weather station owner wants to install another weather station and uses the system to get information about the place the new station should be installed. × *Excluded because of a low number of points*	**17**
26	Bob uses the application in order to synchronise plant systems placed in his farms regarding the weather conditions. × *Excluded because of a low number of points*	**13**
27	A system user, e.g. Bob, creates a new local weather station and introduces it to the system. × *Rejected by stakeholders.*	**X**
28	Windsurfers use the application to check waves and overall sea condition in order to windsurf. × *Excluded because of a low number of points. However, it is worth considering adding this functionality to the system later, after the initial launch.*	**53**
29	Bob uses the application in order to get a deep analysis of the soil and other ingredients on any location supported by the system. × *Excluded because of a low number of points – also, soil analysis is beyond the scope of the weather system.*	**41**
30	Alice uses the application to compare weather conditions in different places all over the world (e.g., the USA and India). × *Excluded because of a low number of points; however, by implementing scenario 18, this scenario will be at least in part implemented as well. It will not be a side-by-side comparison; however, it will still be a way to get the data for different locations.*	**42**
31	Research institutes use the application to get data about climatic history in order to analyse it and perform research based on it. × *Excluded because of a low number of points; it is likely that research institutes have more robust, scientist-focused tools.*	**53**
32	Bob uses the application in order to be notified when the likelihood of flooding in the various places he has entered is high, in order to take the actions required to address the threat and safeguard his properties. A quick guide on how to address the threat of flooding would be extremely beneficial. ✓ *Included because of a very high number of points.*	**78**
33	Special and emergency forces use the mobile application in order to locate where a	**35**

	house has been flooded, in order to send aid. × *Excluded because of a low number of points; it is likely that emergency forces have more robust tools than an application designed for casual users. However, in the long run the possibility of fully serving this scenario will be discussed.*	
34	An online API provided by the weather system enables web developers to exploit pluviometric and other data, and build customised services. × *Rejected by stakeholders.*	**X**
35	Martin uses the online system in order to analyse the current situation and build prediction models for future scenarios. × *Excluded because of a low number of points. The participants gave fewer points to this scenario, as the majority of them understood that the system users themselves would be able to create prediction models, etc. However, this is something that would be handled by the system, and thus the system users would be able to use such functions (see scenario 18, for example).*	**19**
36	Alice, who moved to the town recently, uses the mobile application in order to exchange her experiences with hazardous situations with the system community. × *Excluded because of a low number of points.*	**20**
37	The stored data have been lost or are inaccurate, hence the system administrator enters the system to manage, check and restore the data (e.g., pluviometric data and DEMs of the monitored areas). ✓ *Included because of a very high number of points. Stakeholders also suggested this is an important scenario.*	**73**
38	Statistical and prediction models are built automatically based on the system analysis, and used by weather station officers in order to analyse future scenarios. × *Excluded because of a low number of points. The study participants stated that they think that such functionality is integrated in other, more holistic, scenarios which had more points (for example, scenarios 18 and 47).*	**45**
39	Authorised weather station personnel use the mobile application to update and view the work schedule of each supported weather station. × *Rejected by stakeholders.*	**X**
40	Bob uses the application in order to contact the local authorities about a flood. × *Rejected by stakeholders.*	**X**
41	Learning online activities are provided through the mobile application to children, in order to raise awareness about the environmental changes in hazards. × *Rejected by stakeholders.*	**X**
42	Community followers use the system to arrange appointments and team meet-ups, in regards to environmental issues, in various locations. × *Excluded because of a low number of points; it was expressed that there are better and more commonly-used tools for organising meetings.*	**27**
43	Martin is one of the officers in weather station X, which is connected to the system infrastructure; he noticed a change in the precipitation and moisture levels, so he uses the system to update the current values. ✓ *Included because of a very high number of points.*	**98**
44	Bob uses the mobile application to evaluate the current pluviometric data, such as average monthly temperature and rainfall, for his town. × *Excluded because of a low number of points; this information is currently available online on many websites, even often on Wikipedia.*	**47**
45	The textual information is too chaotic/confusing for Alice. She would definitely prefer to view the data visualised in charts or graphs. ✓ *Included because of a high number of points; stakeholders also agreed it is an important feature.*	**61**

46	A weather-sensitive system protecting Bob's farm is connected with the mobile application and, based on the weather prediction, it adjusts the protection mode of the farm automatically. × *Rejected by stakeholders.*	**X**
47	The local authority and the local weather stations record the floods of the previous years and evaluate the risky periods and locations. They produce a guide informing citizens about the threat of flooding and what they should do to be better prepared. ✓ *Included because of a high number of points and positive participants' comments.*	**64**
48	In order to find the best place and date frame to cultivate his favorite fruit, Bob uses the application to compare different locations at different periods of time. ✓ *Included because of a high number of points; also, there are not many applications that could do that, thus it is a niche.*	**64**
49	Bob wants to ask information about the weather in order to protect his farm, so he chats with the station officer using the application. × *Excluded because of a low number of points; it goes beyond the role of station officers to chat with people (this was also strongly rejected by GIS-aware members).*	**36**
50	System administrators are able to create different types of users, providing them with different types of data. × *Rejected by stakeholders.*	**X**
51	Martin, the weather station officer, sends notifications to all mobile application users about weather changes. × *Excluded because of a low number of points; users should not receive notifications unless there is a severe weather event.*	**43**
52	Data regarding storms or wind power are used to enrich the visualisation scheme of the maps on the supported locations. × *Rejected by stakeholders.*	**X**
53	External pluviometric analysis tools and services use the data provided by the system to build predictive models based on pluviometric characteristics, such as precipitation measures or moisture levels. × *Rejected by stakeholders.*	**X**
54	Gamification mechanisms are integrated to the mobile application to make it more pleasant, and engage more users. × *Rejected by stakeholders.*	**X**
55	Bob uses the mobile application for his course unit about statistics, in order to auto-analyze the collected data and build prediction models. × *Rejected by stakeholders.*	**X**
56	Martin, who is the weather station officer, uses the application to communicate with the rest of the weather station officers using an Intranet-like network, so they can update data collaboratively. × *Rejected by stakeholders.*	**X**
57	Collected pluviometric data are used by the mobile application to recommend the best-fit outdoor activities to its users. × *Rejected by stakeholders.*	**X**
58	Pluviometric data of different locations are used to cluster locations with similar data, and provide the local authorities with techniques and tools to mitigate the risks using a machine-learning recommendation algorithm. × *Rejected by stakeholders.*	**X**
59	The system provides sophisticated web services, which are used by 3rd party software systems, which notify their users about floods, weather, humidity, etc. × *Rejected by stakeholders.*	**X**

60	Alice is on vacation and is notified by the app that her apartment has been flooded. She activates any anti-flood mechanisms in her apartment remotely in order to mitigate the effect. ✗ *Rejected by stakeholders.*	**X**
61	Bob uses the mobile application in order to see stats about weather in the location he is currently at, taking advantage of the tracking built-in tool of his mobile device. However, if he wants to view stats of different locations, or stats about data other than general weather data, he needs to upgrade his mobile application. ✗ *Rejected by stakeholders.*	**X**
62	Location-based systems are used to collect and analyse pluviometric data, which enrich the current system model, after the authorised confirmation of weather-station administrators. ✗ *Rejected by stakeholders.*	**X**
63	Martin, who is the primary weather station administrator, uses the system in order to identify potential risks based on the collected pluviometric data, and notifies through web services the local authorities and the citizens of the vulnerable city about the forthcoming event, providing them with insightful recommendations on how to handle the situation. ✗ *Rejected by stakeholders.*	**X**

Votes per scenario

ID	**U01**	**U02**	**U03**	**U04**	**U05**	**U06**	**U07**	**U08**	**U09**	**U10**	**U11**	**U12**	**TOTAL**
1	-	-	-	-	-	-	-	-	-	-	-	-	**X**
2	4	1	3	1	2	3	1	1	3	2	3	2	**26**
3	6	6	6	5	6	7	6	5	6	5	6	5	**69**
4	5	5	4	6	5	5	2	2	3	6	2	2	**47**
5	3	3	5	2	5	3	3	5	3	3	4	3	**42**
6	1	1	1	3	3	2	1	6	2	1	2	1	**24**
7	1	2	1	4	2	2	1	3	1	3	2	1	**23**
8	6	6	6	6	10	9	7	6	8	6	7	10	**87**
9	-	-	-	-	-	-	-	-	-	-	-	-	**X**
10	-	-	-	-	-	-	-	-	-	-	-	-	**X**
11	4	4	4	4	2	2	3	4	3	3	1	1	**35**
12	1	1	1	5	1	5	3	3	6	6	5	3	**40**
13	2	3	2	3	2	5	3	2	3	4	2	3	**34**
14	7	3	4	4	3	3	7	4	8	5	6	5	**59**
15	7	8	7	7	2	5	6	6	5	3	6	6	**68**
16	1	2	2	2	1	1	3	1	2	1	1	4	**21**
17	4	5	4	3	3	5	3	6	3	5	4	4	**49**
18	7	7	9	9	7	10	10	7	6	9	7	5	**93**
19	2	3	2	2	6	3	1	1	1	1	1	2	**25**
20	3	4	2	2	2	1	4	6	1	3	2	3	**33**
21	5	1	7	6	1	2	3	8	3	6	4	5	**51**
22	4	5	6	4	5	6	4	2	5	5	7	3	**56**
23	8	8	7	10	6	8	8	9	7	7	10	6	**94**

24	9	10	10	7	9	7	9	10	8	10	9	7	**105**
25	1	1	1	3	1	1	2	1	3	1	1	1	**17**
26	1	1	1	2	1	1	1	1	1	1	1	1	**13**
27	-	-	-	-	-	-	-	-	-	-	-	-	**X**
28	5	5	3	4	3	4	6	6	4	4	5	4	**53**
29	5	2	5	3	1	3	4	3	3	5	4	3	**41**
30	5	3	4	4	1	5	5	4	2	3	3	3	**42**
31	5	4	1	6	4	6	5	4	6	5	1	6	**53**
32	7	8	7	9	6	7	6	9	6	5	4	4	**78**
33	2	3	1	3	3	6	2	3	3	3	3	3	**35**
34	-	-	-	-	-	-	-	-	-	-	-	-	**X**
35	1	1	1	1	1	6	1	1	1	2	1	2	**19**
36	2	1	1	2	2	3	2	1	1	2	1	2	**20**
37	5	4	5	5	7	5	6	7	8	7	7	7	**73**
38	5	5	2	2	4	3	7	5	2	4	2	4	**45**
39	-	-	-	-	-	-	-	-	-	-	-	-	**X**
40	-	-	-	-	-	-	-	-	-	-	-	-	**X**
41	-	-	-	-	-	-	-	-	-	-	-	-	**X**
42	4	2	2	1	1	4	1	5	2	2	2	1	**27**
43	10	9	8	8	8	6	7	8	10	8	8	8	**98**
44	3	5	3	2	4	4	3	5	5	5	4	4	**47**
45	4	5	4	5	5	6	7	6	5	5	5	4	**61**
46	-	-	-	-	-	-	-	-	-	-	-	-	**X**
47	7	6	6	4	6	3	9	4	6	4	4	5	**64**
48	8	5	6	5	6	4	8	3	6	3	5	5	**64**
49	2	2	2	4	4	2	3	4	2	3	4	4	**36**
50	-	-	-	-	-	-	-	-	-	-	-	-	**X**
51	6	5	4	5	5	2	2	1	4	5	2	2	**43**
52	-	-	-	-	-	-	-	-	-	-	-	-	**X**
53	-	-	-	-	-	-	-	-	-	-	-	-	**X**
54	-	-	-	-	-	-	-	-	-	-	-	-	**X**
55	-	-	-	-	-	-	-	-	-	-	-	-	**X**
56	-	-	-	-	-	-	-	-	-	-	-	-	**X**
57	-	-	-	-	-	-	-	-	-	-	-	-	**X**
58	-	-	-	-	-	-	-	-	-	-	-	-	**X**
59	-	-	-	-	-	-	-	-	-	-	-	-	**X**
60	-	-	-	-	-	-	-	-	-	-	-	-	**X**
61	-	-	-	-	-	-	-	-	-	-	-	-	**X**
62	-	-	-	-	-	-	-	-	-	-	-	-	**X**
63	-	-	-	-	-	-	-	-	-	-	-	-	**X**

Appendix D: Recruitment Screener

Study Time

User testing sessions of the study will be held in our offices on Monday 10th June 2013 at 10:00am. Each session will last one hour and ten minutes.

Participant Types

The team has agreed to recruit 8 representative users.

If the availability of representative users necessitates a change to this, the change will be discussed among the team and the recruiters will act accordingly.

Recruitment methods and incentives

The recruitment of participants will be done via email and telephone.

Provision has been made to provide a 200 AED incentive to encourage the audience to participate.

Screening Scripts and Guidance

Email

Hello,

We are writing on behalf of a research project from Brunel University conducting some research on the design of a new system in regard to using mobile for flooding data and analysis.

We are looking for people to help them out for about an hour and ten minutes on Monday 10th June 2013 at 10:00am. This will help us to gain a detailed understanding about how different people and groups use such a system and identify any pain points in a new proposed design in order to make any required changes at the very early stages of the system's lifecycle, and ensure it meets the end-users' needs.

The research would involve you participating in a session with a facilitator of the research team. During the session, you will be asked to perform a number of tasks using the proposed design and express your concerns, your ideas etc. based on your experience with the system you will be interacting with. Most importantly, facilitators will be asking about your opinion based on your personal knowledge and experience.

An incentive will be provided for your participation.

If you are interested in participating in this research, please reply to this email and provide your name and number so that we can discuss the session further.

Thank you for your assistance,

Telephone - Opening Script

Good morning/afternoon/evening, my name is _____________. We are calling you on behalf of a research group conducting some research on the design of a new system in regard to using mobile for flooding data and analysis.

We are looking for people to help them out for about an hour on Monday 10th June 2013 at 10:00am.

We would be very grateful if you would be able to help. Can I explain a bit more about the research, and ask if you would possibly be available on Monday 10th June 2013 at 10:00am?

[ ] Yes

[ ] No – CLOSE

This will help them to gain a detailed understanding about how different people and groups use such a system and will allow them to design the new system to provide a better support.

The research would involve you visiting our location and participating in a testing session with a facilitator of their research team. During the session, you will be asked to perform a number of tasks using a proposed design and express your concerns, your ideas etc. based on your experience with the design you will be interacting with. Most importantly, the facilitators will be asking about your opinion based on your personal knowledge and experience.

In return, you will be given 200 AED plus lunch and appropriate travel costs as appreciation of your assistance.

I do have a few questions to ask to ensure that you are suitable for the research. This will only take a few minutes.

Are you interested in helping with this research?

[ ] Yes

[ ] No – CLOSE

We are committed to preserving your privacy and to protecting any personal information that you may provide to us.

Do you consent to us collecting this type of information?

[ ] Yes

[ ] No – CLOSE

We want you to understand how we intend to use and protect any information which you may provide to us. Personal information (including sensitive personal information) supplied by you will be used for carrying out research to understand how people use a particular system or service and what they think about when doing so, in order to understand how well it is meeting the needs of people that use it.

Do you consent to your information being used that way?

[ ] Yes

[ ] No – CLOSE

Please note that your information will be processed and held in accordance with the Data Protection Act 1998.

You are also entitled to see the personal information held about you. If you wish to do this, you can contact us.

Information will be recorded and kept confidential; however, we ask that you do not discuss the session or its contents with others.

Are you happy to proceed?

[ ] Yes

[ ] No – CLOSE

[Recruitment screener questions should now be asked.]

Recruitment Screener Questions

No	Question	Answer	Action
Q1	What is your gender?	[ ] Male [ ] Female	
Q2	What is your age?		Take note of the age
Q3	What is your education level?	[ ] School graduate	

		[ ] University undergraduate student [ ] University graduate [ ] University postgraduate student [ ] Phd Holder	
Q4	How often do you use the Internet?	[ ] Daily [ ] Once or twice a week [ ] Once a fortnight [ ] Once a month [ ] Less than once a month	Less than once a month - CLOSE
Q5	Do you use mobile applications?	[ ] Yes [ ] No	No -CLOSE
Q5	How experienced would you say you are with mobile applications?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced [ ] Very experienced	If not experienced - CLOSE
Q6	How experienced would you say you are with weather systems?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced	If not experienced - CLOSE

		[ ] Very experienced	
Q7	How familiar would you say you are with GIS systems?	[ ] Not familiar [ ] A little familiar [ ] Neither familiar nor unfamiliar [ ] Somewhat familiar [ ] Very familiar	

Close Script (‘CLOSE’)

Okay, that’s great. Many thanks for taking the time to talk to me today, but I am afraid that we will not need you to continue in this research.

Recruit Script (‘RECRUIT)

Okay, that’s all the questions completed and we would like you to take part in the study.

Will you be available on Monday 10th June 2013 at 10:00am? You will receive 200 AED plus lunch and appropriate travel costs in appreciation of your assistance with the research.

The session will be held in University of Sharjah. The address for this office is: Lab 10, Ground floor, Building M5, University of Sharjah.

We may need to contact you on the day; do you have a mobile number or telephone number we will be able to use? <record participant telephone number>.

That’s great, we will expect you to be there on Monday 10th June 2013 at 10:00am.

Appendix E: Recruitment Screener

Study Time

User testing sessions of the study will be held in our offices on Monday 19th May 2014 from 10:00am. Each session will last for about 45 minutes.

Participant Types

The team has agreed to recruit 58 representative users.

If availability of representative users necessitates a change to this list, the change will be discussed among the team and the recruiters will act accordingly.

Recruitment methods and incentives

The recruitment of participants will be done via email and telephone.

Provisions have been made to provide a 200 AED incentive to encourage audiences to participate.

Screening Scripts and Guidance

Email

Hello,

We are writing to you on behalf of a research project from Brunel University which is conducting some research on the design of a new system in regard to using mobile for flooding data and analysis.

We are looking for people to help out for about 45 minutes on Thursday 28th May 2015 at 10:00 AM. This will help the client to gain a detailed understanding about how different people and groups use such a system, and identify any pain points in a new proposed design in order to make any required changes at the very early stages of the system's lifecycle and ensure it meets the end users' needs.

The research would involve your participating in a session with a facilitator of their research team. During the session, you will be asked to perform a number of tasks using the proposed design and express your concerns, your ideas etc. based on your experience with the system you will be interacting with. Most importantly, they will be asking about your opinion based on your personal knowledge and experience.

An incentive will be provided for your participation.

If you are interested in participating in this research, please reply to this email and provide your name and telephone number so that we can discuss the session further.

Thank you for your assistance,

Telephone - Opening Script

Good morning/afternoon/evening, my name is _____________ We are calling on behalf of a research company conducting some research on the design of a new system in regard to using mobile for flooding data and analysis.

They are looking for people to help them for about 45 minutes on Monday 19th May 2014 at 10:00 AM.

We would be very grateful if you would be able to help. Can I explain a bit more about the research, and ask if you would possibly be available on Monday 19th May 2014 at 10:00 AM?

[ ] Yes

[ ] No – CLOSE

The research would involve you visiting our location and participating in a session with a facilitator of their research team. In return you will be given 200 AED plus lunch and appropriate travel costs as appreciation of your assistance.

I do have a few questions to ask to ensure that you are suitable for the research. This will only take a few minutes.

Are you interested in helping us with this research?

[ ] Yes

[ ] No – CLOSE

We are committed to preserving your privacy and to protecting any personal information that you may provide to us.

Do you consent to us collecting this type of information?

[ ] Yes

[ ] No – CLOSE

We want you to understand how we intend to use and protect any information which you may provide to us. Personal information (including sensitive personal information, which is, however, not identifiable) supplied by you will be used for carrying out research to understand how people use a particular system or service and what they think about when doing so, in order to understand how well it is meeting the needs of people that use it.

Do you consent to your information being used in this way?

[ ] Yes

[ ] No – CLOSE

Please note that your information will be processed and held in accordance with the Data Protection Act 1998.

You are also entitled to see the personal information held about you. If you wish to do this, you can contact us.

Information will be recorded and kept confidential; however, we ask that you do not discuss the session or its contents with others.

Are you happy to proceed?

[ ] Yes

[ ] No – CLOSE

[Recruitment screener questions should now be asked.]

Recruitment Screener Questions

No	Question	Answer	Action
Q1	What is your gender?	[ ] Male [ ] Female	
Q2	What is your age?		Take note of the age
Q3	What is your education level?	[ ] School graduate [ ] University undergraduate student [ ] University graduate [ ] University postgraduate student [ ] Phd Holder	

		[ ] Retired	
Q4	How often do you use the Internet?	[ ] Daily [ ] Once or twice a week [ ] Once a fortnight [ ] Once a month [ ] Less than once a month	Less than once a month - CLOSE
Q5	Do you use mobile applications?	[ ] Yes [ ] No	No -CLOSE
Q5	How experienced would you say you are with mobile applications?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced [ ] Very experienced	If not experienced - CLOSE
Q6	How experienced would you say you are with weather systems?	[ ] Not experienced [ ] A little experienced [ ] Neither experienced nor inexperienced [ ] Somewhat experienced	If not experienced - CLOSE

		[ ] Very experienced	
Q7	How familiar would you say you are with GIS systems?	[ ] Not familiar [ ] A little familiar [ ] Neither familiar nor unfamiliar [ ] Somewhat familiar [ ] Very familiar	If not familiar - CLOSE

Close Script ('CLOSE')

Okay, that's great. Many thanks for taking the time to talk to me today, but I am afraid that we will not need you to continue in this research.

Recruit Script ('RECRUIT)

Okay, that's all the questions completed and we would like you to take part in the study.

Will you be available on Monday 19th May 2014 at 10:00 AM? You will receive 200 AED plus lunch and appropriate travel costs in appreciation of your assistance with the research.

The session will be held at the University of Sharjah. The address for this office is: Lab 10, Ground floor, Building M5, University of Sharjah. We would appreciate it if you arrived 20 minutes before the agreed time.

We may need to contact you on the day; do you have a mobile number or telephone number we will be able to use? <record participant telephone number>.

Appendix F: KLM Timings

The KLM timings indicate the time needed by an expert to accomplish a routine task without errors using an interactive computer system. The basic actions and times for the KLM model for mobile application, according to Holleis et al. (2007), are:

Action	Time (seconds)
Initial act (I)	1.18
Mental act (M)	1.35
Pointing (P)	1.00
Keystroke or Button Press (K)	0.39

The calculated time based on the model proposed by Holleis et al. (2007) for each task of study is:

Task 1		Task 2		Task 3		Task 4		Task 5		Task 6		Task 7	
Action	Time	Action	Time	Action	Time	Action	Time	Action	Time	Action	Time	Action	Time
I	1,18	I	1,18	I	1,18	I	1,18	I	1,18	I	1,18	I	1,18
M	1,35	M	1,35	M	1,35	M	1,35	M	1,35	M	1,35	M	1,35
P	1	P	1	P	1	P	1	P	1	P	1	P	1
K	0,39	K	0,39	K	0,39	K	0,39	K	0,39	K	0,39	K	0,39
I	1,18	I	1,18	I	1,18	I	1,18	I	1,18	I	1,18	I	1,18
M	1,35	M	1,35	M	1,35	P	1	M	1,35	M	1,35	P	1
P	1	P	1	P	1	K	0,39	P	1	P	1	K	0,39
K	0,39	K	0,39	K	0,39	P	1	K	0,39	K	0,39	P	1

P	1	P	1	P	1	3*K	1,17	P	1	P	1	3*K	1,17
K	0,39	K	0,39	K	0,39	P	1	K	0,39	K	0,39	P	1
I	1,18	I	1,18	I	1,18	2*K	0,78	I	1,18	I	1,18	2*K	0,78
M	1,35	M	1,35	M	1,35	P	1	M	1,35	M	1,35	P	1
P	1	P	1	P	1	5*K	1,95	P	1	P	1	5*K	1,95
K	0,39	K	0,39	K	0,39	I	1,18	K	0,39	K	0,39	I	1,18
P	1	P	1	P	1	M	1,35	P	1	P	1	M	1,35
K	0,39	K	0,39	K	0,39	P	1	K	0,39	K	0,39	P	1
I	1,18	I	1,18	I	1,18	K	0,39	P	1	I	1,18	K	0,39
M	1,35	M	1,35	M	1,35	P	1	2*K	0,78	M	1,35	P	1
P	1	P	1	P	1	K	0,39	I	1,18	P	1	K	0,39
K	0,39	K	0,39	K	0,39	I	1,18	M	1,35	K	0,39	I	1,18
I	1,18	P	1	I	1,18	M	1,35	P	1	I	1,18	M	1,35
P	1	K	0,39	P	1	P	1	K	0,39	P	1	P	1
K	0,39	I	1,18	K	0,39	K	0,39	P	1	K	0,39	K	0,39
P	1	M	1,35	P	1	P	1	K	0,39	P	1	P	1
3*K	1,17	P	1	3*K	1,17	K	0,39	P	1	3*K	1,17	K	0,39
P	1	K	0,39	P	1	P	1	2*K	0,78	P	1	P	1
2*K	0,78	P	1	2*K	0,78	K	0,39	P	1	2*K	0,78	I	1,18
P	1	K	0,39	P	1	R	1	K	0,39	P	1	M	1,35
5*K	1,95	M	1,35	5*K	1,95			P	1	5*K	1,95	P	1
M	1,35	R	1	M	1,35			3*K	1,17	P	1	K	0,39

P	1			P	1			P	1	K	0,39	P	1
K	0,39			K	0,39			2*K	0,78	P	1	K	0,39
P	1			P	1			P	1	K	0,39	P	1
K	0,39			K	0,39			5*K	1,95	P	1	K	0,39
P	1			P	1			M	1,35	3*K	1,17	R	1
3*K	1,17			3*K	1,17			P	1	P	1		
P	1			P	1			K	0,39	2*K	0,78		
2*K	0,78			2*K	0,78			P	1	P	1		
P	1			P	1			K	0,39	5*K	1,95		
5*K	1,95			5*K	1,95			P	1	M	1,35		
M	1,35			P	1			3*K	1,17	P	1		
P	1			K	0,39			P	1	K	0,39		
K	0,39			M	1,35			2*K	0,78	P	1		
P	1			P	1			P	1	K	0,39		
K	0,39			K	0,39			5*K	1,95	R	1		
R	1			P	1			M	1,35				
				K	0,39			P	1				
				R	1			K	0,39				
								P	1				
								K	0,39				
								R	1				