Developing a Mobile GIS Application for Facilitating Information Communications in Agri-Environmental Programs

By

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ABSTRACT

DEVELOPING A MOBILE GIS APPLICATION FOR FACILITATING INFORMATION COMMUNICATIONS IN AGRI-ENVIRONMENTAL PROGRAMS

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In recent decades, information communication has been identified as an important factor facilitating farmers to adopt agricultural beneficial or best management practices (BMPs) to improve water quality. The purpose of the study is to develop a mobile GIS application to facilitate communications of BMP economic cost and environmental effectiveness information in agri-environmental programs. At the first step, a framework was developed to define the required information content and how information should be produced and disseminated. Second, the framework was implemented to develop an open-source mobile GIS application for Android operating systems with the Gully Creek watershed of southern Ontario as the case study area. The system or interface has two main modules: One is to examine the cost and effectiveness of user-defined BMP exploratory scenarios and the other is to define BMP policy/management scenarios in which optimized BMP types and locations are identified based on environmental targets or financial constraints.
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1 Introduction

1.1 Problem statement

Agricultural intensification in Canada has been identified as a major contributor to water quality degradation (Logan, 1993). Water quality degradation due to excessive agricultural non-point source (NPS) pollutants, released from agricultural fields to watercourses, has negatively affected aquatic organisms and potentially has increased the incidence of eutrophic events (Böhlke, 2002). Excessive Nitrogen (N) and Phosphorus (P) will (a) increase the rate of algae blooms, which can lead to the widespread death of aquatic plants and fish, (b) also contaminate groundwater (Cahoon & Ensign, 2004). In Ontario, for example, agriculture is a major contributor to water quality problems in the Great Lakes Basin, and largely responsible for the eutrophication of Lake Erie (Weersink et al., 1998).

To mitigate these negative effects, agri-environmental programs (AEPs) have been established to encourage farmers to adopt beneficial or best management practices (BMPs) such as conservation tillage, nutrient management and cover crop to reduce pollution loadings to water bodies (Piorr, 2003, Shao et al., 2017). The Environmental Farm Plan (EFP), Greencover Canada Program, National Farm Stewardship Program (NFSP), and the National Water Supply Expansion Program (NWSEP) are some examples of AEPs in Canada. Participating in these programs is primarily voluntary and farmers are provided with financial incentives for BMP adoption (McCallum, 2003). Although financial incentives are provided to compensate for the cost of BMPs implementation and maintenance by farmers (Shao et al., 2017), empirical evidence showed that information
communication between the stakeholders in AEPs is an important factor affecting BMP adoption (Baumgart-Getz et al., 2012). For example, information on BMP costs and effectiveness such as phosphorus reduction can help farmers to understand BMP impacts. Information on prioritized BMP types and locations based on environmental targets or financial constraints can help conservation managers to make investment decisions (Argent and Mitchell 2003, Shao et al. 2017).

In recent decades farm economic modelling, watershed hydrological modelling, and integrated economic hydrologic modelling have been increasingly developed to estimate the economic costs, water quality benefits, and cost effectiveness of agricultural BMPs (Yang et al. 2007, Shao et al. 2017). While very useful, integrated modelling systems are typically complex. A challenge exists on how to make the modelling information accessible and understandable by conservation stakeholders. For example, a desktop GIS based interface was developed to allow users to conduct BMP assessment based on an integrated economic and hydrological modelling (Shao et al. 2017). However, the desktop GIS interface is still more suitable for technical users. There is a need to further improve user access to BMP modelling information via Web and/or mobile interfaces.

In recent years, mobile GIS-based applications have been developed in various environmental studies (Tsou M., 2004). The adoption of mobile GIS technologies has the potential to change the way that conservation managers communicate with farmers (Tsou M., 2004). For agri-environmental applications, an information framework needs to be developed to identify specific information content for communication and define the details of information communications in terms of information sources, targets and channels. Then, the framework can be implemented to develop a mobile GIS application to facilitate information communications based on agricultural BMP assessment information generated by integrated economic-hydrologic modelling.
1.2 Research purposes and objectives

The purpose of the research is to develop an open-source mobile GIS-based application to facilitate BMP information communications in agri-environmental programs. Specifically, this research has three interrelated objectives:

1. Identify BMP information communication needs in agri-environmental programs
2. Develop a framework for a mobile GIS application to support BMP information communications in agri-environmental programs
3. Implement the framework to develop a prototype of the mobile GIS application for facilitating communications of BMP economic costs, water quality benefits, and cost effectiveness with Gully Creek watershed of southern Ontario as the case study area.
2 Literature Review

This chapter covers three research subjects. The first section reviews the agri-environmental programs and corresponding information needs related to BMP adoption. The second section examines the application of watershed hydrologic modelling for evaluating BMP effects and also integrated economic-hydrologic modelling for evaluating BMP economic costs, environmental benefits and cost effectiveness. The third section reviews the application of the latest GIS technologies in modelling and interface development. The review helps to identify the necessity of developing mobile GIS-based applications to support BMP information communications in agri-environmental programs.

2.1 Agri-environmental programs and BMP adoption process

This section reviews agri-environmental programs mostly in Canada and the United States and then discusses the challenges in information communications. A common theme amongst all these programs is providing financial support to compensate for the BMP implementation and maintenance expenses by farmers. The information required for stakeholders in BMP adoption process is also a very important component.

Agri-environmental programs

Agri-environmental programs aim to promote agricultural BMP adoption to mitigate the negative effects of agricultural intensification on the environment (Sawicka et al., 2016). Environmental Farm Plan (EFP), Greencover Canada program, National Farm Stewardship Program (NFSP), and
the National Water Supply Expansion Program (NWSEP) are several agri-environmental programs established in Canada. Participation in these programs is primarily voluntary and typically financial incentives are provided to farmers. Examples of these programs in the United States include the Conservation Reserve Program (CRP) and the Environmental Quality Incentive Program (EQIP) (Stubbs, 2014). Interactions with program coordinator or technical experts (e.g. government agricultural staff, etc.), as well as supporting materials (e.g. workbooks and factsheets) are common ways in these programs for enhancing farmers’ knowledge about the environmental risks resulted from their farming practices. In some programs, farmers are provided with an Action Plan detailing the appropriate BMPs to mitigating those risks.

The EFP, established in 1993 in Canada, addresses environmental aspects of farming practices while maintaining the land for agricultural production (Robinson, 2005). As such, this program focuses on conservation practices such as conservation tillage and nutrient management, as opposed to land retirement. The second Farm Environmental Management Survey (FEMS) conducted by Agriculture and Agri-food Canada (2006) revealed that over 27 percent of all farms in Canada had EFP for their agricultural practices. Also, this report indicated that over 50 percent of farms in EFP program in Ontario and Quebec implemented all the BMPs in their EFP and over 90 percent participants in Canada applied at least one of the BMPs in their EFP. There is a growing trend in participating in EFP program by farmers in Canada and more farmers are adopting the BMPs identified in their EFP.

Through the local workshop process and workbooks in the EFP program, farmers and their families are in a position to better understand and address environmental concerns relating to their operations. Financial assistance, while vary from province to province in Canada, is also available
to assist in implementing BMPs (AAFC, 2004b). While agricultural BMPs have been supported by financial assistance measures, some BMPs have also been adopted without financial support. However, both technical and financial assistance have been identified as major factors in assisting and engaging farmers to continue BMP adoptions (AAFC, 2006).

The same structure with the EFP program can be observed in other agri-environmental programs. The Conservation Reserve Program (CRP) program in the United States also provides financial assistance for farmers to take environmentally sensitive land out of production and implement conservation practices (Stubbs, 2014). The lands enrolled in the CRP program must be retired for a period of 10 – 15 years (Sawicka et al, 2016). The CRP program has contributed to environmental benefits such as reducing soil erosion and fertilizer use, improving water quality and increasing wildlife habitat (Stubbs, 2014). To facilitate the uptake of conservation programs, the average US federal financial support up to $2 billions per year has been allocated in parallel with offering educational opportunities to enhance the farmers’ environmental awareness (Sawicka et al., 2016).

**Information needs for BMP adoption**

Empirical evidence showed that BMP adoption is a process of information communication (Rogers, 1995; Robinson, 2006). Farmers need information to improve their environmental awareness and develop a better understanding of agricultural BMP techniques, costs and effectiveness to support their BMP adoption decisions. MacKay (2010) stated that relevant information about BMPs’ environmental and economic effects is essential for raising 25%-41% of BMP adoption rate in Canada.
In-person communication and attending workshops are two common ways of educating farmers and providing relevant information in agri-environmental programs (Rogers, 1995). Local discussions, disseminating farm newspaper articles and program award contests are amongst the other ways to disseminate BMP knowledge to a much broader of the audience. Rogers (1995) also noted that networking and information communication amongst farmers could effectively motivate producers to adopt agricultural BMPs.

Farmers are sensitive to the cost of BMP implementation and studies revealed that farmers are more likely to adopt when they have information on BMP cost and financial incentives they can receive (Robinson, 2006). The information on environmental benefits can also motivate farmers to adopt BMPs. Furthermore, BMP economic costs, environmental benefits, and cost-effectiveness information can help conservation managers to develop two types of BMP policies including how to minimize the costs under a level of environmental improvement target and how to maximize the environmental benefits under a financial constraint (Shao et al. 2017).

2.2 Watershed hydrologic and integrated economic-hydrologic modelling for agricultural BMP adoption

The following sub-sections provide an overview of watershed hydrological modelling for assessing BMP effectiveness and integrated economic-hydrologic modelling for evaluating BMP economic costs, environmental benefits, and cost effectiveness.
Watershed hydrologic modelling

The Soil and Water Assessment Tool (SWAT), Agricultural Nonpoint Source (AGNPS), and Annualized Agricultural Nonpoint Source (AnnAGNPS) are examples of watershed models for evaluating water quantity and quality effects of agricultural BMPs. Other frequently used models for evaluating BMP effectiveness are Hydrological Simulation Program-FORTRAN (HSPF), Generalized Watershed Loading Function (GWLF), and Limburg Soil Erosion Model (LISEM) (Xie et al., 2015). More recent models have a GIS interface to support spatial data processing and visualization for improving user-friendliness (Xie et al., 2015).

The SWAT model has been widely used by a large number of studies to evaluate BMP effectiveness in mitigating agricultural non-point source pollution (Arnold et al., 1998). Strauch et al. (2013) used the SWAT model to evaluate the effects of different BMPs on sediment loading in Pipiripau River Basin, in Brazil. The results revealed that up to 40% of sediment load reduction can be achieved by establishing terraces and small sediment basins in the Basin. Maringanti et al. (2009) used the SWAT model for NPS pollution control in the L’Anguille River watershed, in Arkansas. They noted that buffer strips in agricultural fields could lead to a potential reduction in sediment, phosphorus, and nitrogen loads by 33%, 32%, and 13%, respectively. Furthermore, Yang et al. (2013) developed a Water and Sediment Control Basin (WASCoBs) module to empower the SWAT model in simulating the water quality and quantity effects of establishing WASCoBs in agricultural fields.

Likewise, other watershed hydrological models have been applied to evaluate BMP effectiveness. For example, Yuan et al. (2008) used the AnnAGNPS to evaluate BMP effects in the Mississippi Delta. The result showed that by applying conservation practices, the sediment reduction can be
achieved by up to 77%. This model also was used by Srivastava et al. (2002) for optimizing the selection of BMPs on a field basis in a study area in Pennsylvania. The research results showed that this model is able to identify BMP schemes that can reduce pollutant load by up to 56% and increase net annual return by around 109%.

**Integrated economic-hydrologic modelling**

Integrated economic-hydrologic modelling has been increasingly developed to jointly examine the economic and environmental effects of agricultural BMPs. These models, if well-calibrated and validated, can be utilized to examine spatial variations of BMP cost effectiveness measured by the ratios of water quantity/quality benefits and economic costs, and prioritize spatial locations for BMP implementation where the most pollution abatements are more likely to be achieved for a relatively lower cost. Yang et al. (2007) developed an integrated economic-hydrological modelling framework for the Watershed Evaluation of BMPs (WEBs) program in Canada which included an on-farm economic model, a farmer adoption behavior model, a watershed modelling toolbox and a non-market valuation economic model. The framework was used to guide the WEBs integrated modelling component which aimed to incorporate hydrologic, economic and social (behavioural) factors into a decision framework to assess and display the combined environmental (water quality), economic (costs and benefits) and social (likelihood of BMP adoption) effects of BMP implementation.

An integrated SWAT model and on-farm economic model was developed by Oginskyy (2014) to estimate environmental benefits and BMP costs in the Gully Creek watershed, Ontario. Results revealed that adopting nutrient management reduced farm costs by $11 for each kg of N abated,
and adopting zero tillage raised farm costs by $49 for each kg of N abated. Using a similar method, Gaddis et al. (2014) applied spatial optimization techniques in combination with hydrologic and economic models to maximize the total reduction of phosphorus loadings to streams by implementing selected BMPs in a watershed in Northern Vermont. Riparian buffers, control basins, filter strips, and tile drain filters were selected for BMP placement in the study area. The research showed that 0.29 kg ha\(^{-1}\) of P abatement is attainable at a cost of $138 ha\(^{-1}\). Maringanti et al. (2011) also applied a multi-objective optimization tool to combine the results of the SWAT model and a BMP cost model in the Wildcat Creek Watershed, in northcentral Indiana. The results showed that a combination of BMPs including residue management, parallel terraces, filter strips, zero tillage, and contour farming can result in 37–76% of P and 23–49% of N abated for a cost of $25–$275 ha\(^{-1}\).

Given the complexity of using hydrological and integrated economic-hydrologic models, the accessibility of the models and their results is challenging for farmers and conservation practitioners who are typically interested in solutions, not the models and applications (Miller et al., 2004; Yang, 2011). Hence, many studies recently have been conducted to develop graphical interfaces to facilitate the interaction with the models. Meanwhile, geographic information systems (GIS) have a lot to offer in providing graphical user interfaces for visualizing hydrological and integrated modelling results.
2.3 GIS applications for BMP assessment

This section reviews literature on GIS applications for improving spatial data preparation, analyzing, and visualizing for watershed hydrologic and integrated modelling. Future directions on GIS applications for evaluating BMP effectiveness and cost effectiveness will be discussed.

GIS and watershed modelling

GIS has the advantage of managing spatial data and also preparing modelling inputs and visualization results for watershed hydrologic modelling (Rao et al., 2006). GIS has been successfully integrated with many environmental models such as ANSWERS (Beasley and Huggins, 1982), AGNPS (Young et al., 1987), BASINS (Lahlou et al., 1998), QUAL2E (Srinivasan and Arnold, 1994), EPIC (Rao et al., 2000), and SWAT (Di-Luzio et al., 2002). ArcSWAT tool, a GIS extension, was developed as an ArcGIS interface for the SWAT to conduct data preparation and simulation tasks (Olivera et al., 2006).

In recent years, studies have been carried out to develop user-friendly GIS interfaces to facilitate modelling interaction with end-users. For example, Shao et al. (2017) developed an open-source desktop GIS interface for an integrated economic-hydrologic model for evaluating the cost-effectiveness of different BMP scenarios in the Gully Creek watershed of southern Ontario. Various GIS-based interfaces have been developed to set up, calibrate, and validate watershed hydrologic models (Olivera et al., 2006) and apply the established models to evaluate water quantity and quality effects of agricultural BMPs (Maringanti et al., 2009; Panagopoulos et al., 2012). While leveraging GIS technologies and spatial data processing methods empowers environmental models, interacting with complex modelling through desktop GIS interfaces is still
challenging for conservation practitioners due to technical barriers (Liu et al., 2015; Karki et al., 2017; Shao et al., 2017).

**WebGIS and mobile GIS applications for BMP assessment**

Utilizing the power of the Internet and the Web, advanced GIS technologies such as WebGIS and mobile GIS have created a new paradigm for public participation and collaboration in addressing environmental issues (Werts et al., 2012). A prime example of using WebGIS in environmental modelling is the SWATShare application developed by Rajab et al. (2015). This application is an innovative Web platform for online sharing, simulation, and visualization of the SWAT model with a broader community in a collaborative environment. Rao et al. (2006) developed a WebGIS decision support system (DSS) prototype to simulate the nutrient and sediment dynamics of a small watershed in Panhandle, Oklahoma. The application was based on integrating the ArcIMS as map server, a mapping component known as AFIRS, and the SWAT model. Duarte et al. (2016) developed a GIS-based web application for estimating soil erosion rate at the watershed scale using the RULSE method. The application was applied to Montalegre municipality in Portugal. The resulting RUSLE factor map suggested a low to moderate erosion risk in Montalegre in which 80% of the study area was characterized by very low soil erosion, 2% was classified as high and 2% as very high risk to soil erosion. Engel et al. (2003) also developed a web-based decision support system (DSS) to evaluate the water quantity/quality impacts of land-use change by integrating a long-term hydrological impact assessment model and WebGIS.

With significant advances in mobile technologies, mobile GIS-based applications go far beyond mapping and a broad range of mobile GIS applications have been developed for various purposes.
Some of these applications were developed by private sector companies for commercial proposes. Weather forecasting, acquiring market prices, and detecting plant diseases are a few examples of mobile GIS applications purposefully designed for agriculture. For example, Zheng et al. (2010) developed a remote farming management system using a mobile GIS-based application for monitoring several farming Personal Digital Assistants (PDAs) in a hosted PC. The PDAs can be supervised by the PC server and exchange data through a web service to receive GPS locations and deliver irrigation information. Tsou (2004) developed a mobile GIS tool to enhance environmental monitoring and management. Multiple resource managers’ mobile devices can access to GIS layers on a portable web server mounted in a vehicle through wireless local area network (WLAN). Also, Ahmed et al. (2017) developed an Android mobile application called “My City, My Environment” to improve decision-making in addressing environmental issues in Bangladesh. Through a web service, users can report environmental issues in a participatory environment for decision-making by experts.

However, mobile GIS applications specifically designed for applying watershed hydrologic and integrated models have not been developed yet. Running watershed models over mobile devices is likely not feasible due to significant memory and resources requirements for complex computation. However, mobile GIS technologies offer opportunities to visualize results of complex watershed models using online Internet mapping services such as Google Map service. Mobile GIS applications have great potential to be used to support the communication of BMP assessment information in agri-environmental programs.
2.4 Knowledge gaps and research opportunities

BMP information communications play an important role in facilitating BMP adoption in agri-environmental programs. Watershed hydrologic and integrated economic-hydrologic modelling have been applied to provide information on BMP effects including economic costs, environmental benefits, and cost effectiveness. Desktop GIS based interfaces have been developed to make BMP modelling information accessible by users. However, technical barriers still exist on using desktop-based GIS and Web platforms for communicating BMP assessment information to users.

To complement the existing in-person communications, education materials, and desktop- and Web-based platforms, mobile GIS tools have a great potential to allow farmers and conservation managers to access BMP assessment information more easily. While it is not feasible to run watershed hydrologic and integrated economic-hydrologic modelling over mobile devices, mobile GIS interfaces can be developed to access modelling results from a server machine through the Internet.
3 A Framework for the Mobile GIS Application to Support BMP Adoption

This chapter develops a framework for the mobile GIS application to support BMP adoption in agri-environmental programs. The first part of the framework is an information model which defines information content and how information should be produced and disseminated in the BMP adoption process. The second part is a system architecture for the mobile GIS application. The third part is the mobile GIS application components, the fourth part is software for mobile GIS system development, and the final part includes minimum resource requirements for system implementation.

3.1 An information model for agricultural BMP adoption

To develop a mobile GIS application, the information model for agricultural BMP adoption involves farmers as BMP adopters and conservation managers who develop BMP policy/management and provide financial incentives. The information model is designed to provide two primary modules to support BMP adoption through a mobile GIS application. The first module provides information content including economic cost, environmental benefits, and cost-effectiveness of BMPs to farmers and/or conservation managers based on user-defined BMP exploratory scenarios and via GIS information layers. The second module is for conservation managers to identify BMP policy/management scenarios that include prioritized BMP types and locations based on environmental targets or financial constraints. This module is designed to support BMP policy and management using an optimization module.
In this thesis, the integrated economic-hydrologic model for the Gully Creek watershed of Ontario was used to produce the information. The model was developed via integrating the SWAT model and an on-farm economic model, by the Watershed Evaluation Group of the University of Guelph, to examine the economic costs, environmental benefits, and cost-effectiveness of four representative BMPs including conservation tillage, nutrient management, cover crop, and water and sediment control basin (WASCoB) in the Gully Creek watershed from 2002 to 2011 (Yang et al., 2013).

Figure 3-1 depicts the subsystems in the information model regarding the aforementioned functionalities. These functionalities are explained in more details later in this chapter.
Figure 3-1 Key functions in the information model for agricultural BMP adoption
3.2 A system architecture of the mobile GIS application for supporting agricultural BMP adoption

Figure 3-2 depicts a system architecture for developing the mobile GIS application in this research. In this architecture, client represents the mobile GIS application and server represents a server machine hosting a web server, web service, and databases including BMP assessment result database and user profile database. In this client-server architecture, communication happens through the Internet, using request/response message-pair over the HTTP protocol. A mobile GIS client initiates an HTTP request and will receive an HTTP response by the designated web service from the server machine. The web service will convert the information content to a standard format understandable for either side of the communication. Meanwhile, the web server is responsible for handling multiple simultaneous requests coming from clients and providing the corresponding responses.

Figure 3-2 - A system architecture of the mobile GIS application
3.3 Mobile GIS application components

The mobile GIS application, in this research, is structured as a multi-layer (multi-tier) application consisting of a Presentation layer on the client (mobile devices) and a Business Logic layer, a Data Processing layer, and Databases on the server (Figure 3-3). The Presentation layer on the client is the mobile GIS application accessible by users. On the server, the Business Logic layer comprises modules for logical and calculation processes, and the Data Processing layer has modules for database queries that interact with databases including BMP assessment result database and user profile database. Hosting Business Logic layer on server machine reduces the required CPU and RAM resources for mobile GIS application functionalities. Besides, residing BMP assessment database and user profile database in the server machine is a more secure infrastructure, because it will limit exposing the modelling results to end-users. Basically, designing an application architecture with separate layers is crucial for extensibility, maintainability, and improve security.
Figure 3-3 - Mobile GIS application components
In this architecture, the graphical user components with an interactive map are incorporated into the Presentation layer in the mobile GIS application (client-side). The information content resulted from mobile GIS application functionalities will be presented on top of the interactive map. This layer is connected with Business Logic and Data Processing layers, through a designed web service over the Internet. Through the web service, the open standard XML format is utilized to make communications between the client and the server over the Internet. Each layer and their relevant components will be described in more details in the following sections.

3.3.1 Server-side system components

Data Processing Layer and Databases

Any database connection and interaction commands are encapsulated into the Data Processing layer, residing on the server machine. This will avoid accessing to BMP assessment result database directly by other layers and will reduce complexity.

The database query commands are programmed, in NetBeans application, using java programming language. They are developed in Structured Query Language (SQL) format, using the corresponding user-defined parameters. The following sections describes two main mobile GIS application databases includes BMP assessment result database which hosts the BMP assessment modelling outputs of the four aforementioned BMPs in the Gully Creek watershed and the second user profile database which stores key information of users’ credential information.
BMP Assessment Result Database Structure

The BMP assessment result database include the differences between the watershed outlet results of implementing any aforementioned BMPs (three land management BMPs including conservation tillage, nutrient management, cover crop, and one structural BMP WASCoB) and a baseline (no BMP implementation) in different agricultural fields/locations of the Gully Creek watershed. The BMP assessment result are the economic costs and the environmental benefits or effectiveness of BMPs.

The BMP scenarios are evaluated using the integrated economic-hydrologic model, and the results are structured in the database. The modelling results including BMP economic costs and environmental benefits are organized into tables. For integrity consideration, each table in the database is devoted to one possible combination of four aforementioned agricultural BMPs. Figure 3-4 depicts the BMP combination tables in the database. As an example, when user only select cover crop and nutrient management BMPs to implement, the target BMP assessment data to explore will be “CC_NM”, where CC and NM would represent cover crop and nutrient management BMPs, respectively.
In each table, the watershed outlet BMP assessment result are presented for each agricultural field/location of the watershed. Each field/location has seven attribute columns - four environmental variables; Flow, Sediment, Nitrogen, and Phosphorus and three economic variables; Cost, Revenue, and Net Return. Also, for each field/location, ten rows of data, from 2002 to 2011, are stored in tables. Figure 3-5 shows the schema of a table with a sample field/location (ID: 1) during the period. The average value of the ten years of each variable would be the BMP economic cost (difference of net returns for land management BMPs and cost for WASCoBs) and/or environmental benefit variable through comparing BMP assessment result between the baseline scenario and the BMP scenario. Also, the BMP cost-effectiveness of each environmental variable would be calculated by dividing the average value of the environmental variable by the net return value. For example, for the sample field in Figure 3-5, the cost-effectiveness for phosphorus reduction would the result of dividing the average value for
“Phosphorus” column by average value of “NetReturn” column for land management BMPs and by average value of “Cost” column for WASCoB during the time period.

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Year</th>
<th>Flow</th>
<th>Sediment</th>
<th>Nitrogen</th>
<th>Phosphorous</th>
<th>Cost</th>
<th>Revenue</th>
<th>NetReturn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2002</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>1</td>
<td>2011</td>
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<td></td>
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</tr>
</tbody>
</table>

Figure 3-5 – The schema of a table in the BMP assessment result database

*User Profile Database Structure*

The system is also designed to keep users’ credential information. By registration process, the user information will be stored in the User Profile database (see Figure 3-6). Two standard roles for users are “Farmer” and “Conservation Manager”. Also, tables are designed to show information about scenarios, such as the number of scenarios created and completed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Password</th>
<th>Role</th>
<th>Email</th>
<th>FarmID</th>
</tr>
</thead>
</table>

Figure 3-6 – The schema of the user profile database
Business Logic Layer

The Business Logic layer is the logic center of the mobile GIS application to do calculations and coordinate the procedures before passing to the Data Processing layer. In this application, the Business Logic layer is physically decoupled from the presentation layer and resides on the server machine (see Figure 3-3). This will increase maintainability and reduce the performance penalty due to the lack of mobile gadget resources.

The functionalities of the Business Logic layer include controlling users’ application access to results, evaluating the user-defined BMP exploratory scenarios, and developing BMP policy/management scenarios. These functionalities of the Business Logic layer will be fulfilled using three modules; “user access control”, “BMP exploratory scenario”, and “BMP policy/management scenario” modules.

User Access Control Module

User access control is a security setup incorporated into the Business Logic layer to restrict the scenario results to users based on the authentication process. During the authentication process, users will provide their identity to access specific functionalities. Farmers will be only able to use the BMP exploratory scenario module to explore BMP results on their own properties, while conservation managers will have access to both the BMP exploratory scenario module and the BMP policy/management scenario module to examine scenario results for the entire watershed. See Figure 3-7 for the structure of user access control module.
**BMP Exploratory Scenario Module**

Using this module, users can construct customized BMP exploratory scenarios to simulate the impact of one BMP or multiple BMPs at a single field/location or multiple fields/locations. The BMP exploratory scenario module, in the Business Logic layer, is programmed to validate the user-defined scenario parameters including BMP types and locations and then call the database query functions in Data Processing layer to get the simulation results. A user-defined scenario for all BMPs includes three lists of desired fields for each aforementioned land management BMPs (i.e. conservation tillage, nutrient management, cover crop) and a list of desired point locations for WASCoB BMP. The BMP scenario result coming from BMP assessment result database (calling by Data Processing layer) will be sent back to the mobile GIS application through the web service. Users can then explore the economic costs, environmental benefits, and cost-effectiveness ratios of their specific BMP scenarios through the BMP assessment result layer on the map or chart. See Figure 3-8 for the structure of this module in the application.
BMP Policy/Management Scenario Module

In the third module, an optimization module is hosted on the server machine which is an integral part of the Business Logic layer. The optimization module is programmed to identify optimum BMP types and locations based on environmental targets or financial constraints, using an open-source Linear Programming Solver (lpsolver). This module is used to produce policy/management scenario information. The module supports users to examine two types of policies: the BMP environmental policy/management scenario, which minimizes the economic costs subject to environmental targets and the BMP economic policy/management scenario, which maximizes the environmental benefits subject to financial constraints.

The required parameters to trigger the module include policy/management type, pollutant type, fields/locations for optimization, and BMP policy/management constraint. For a BMP environmental policy/management scenario, the constraint is a range of environmental targets such
as phosphorus reductions (kg/year), while for a BMP economic policy/management scenario, the constraint is a range of the BMP costs (dollar/year). After receiving a request and required parameters through the web service coming from users, the optimization module would be called to generate a BMP policy/management scenario database which includes the information of optimum BMP configuration for selected field/locations and user-defined constraints. Then, the BMP policy/management scenario module would read the database to get the results and send them back to users. The output would be a GIS layer with the spatial configuration of identified optimum BMP types and fields/locations shown on the interactive map, in the Presentation layer. The information on trade-offs of BMP economic costs and environmental effectiveness is using a chart. Figure 3-9 depicts the structure of the BMP policy/management scenario module in the mobile GIS application.

*Figure 3-9 - Structure of the designing BMP policy/management scenario module*
Web service

The SOAP (Simple Object Access Protocol) web service is developed to enable communication among the clients (mobile applications) and the server. The web service acts as a bridge between the clients and the Business Logic layer. The web service resides in the server machine and is addressable through URL over the Internet by the clients.

The web service unpacks the request coming from the mobile GIS applications to get the user-defined parameters and then converts them to an understandable command in XML format to be executed by the server (See Figure 3-10). After completing the process by the Business Logic layer, the web service will repeat the steps in reverse order. It will unpack the response from the server and then send it back in XML format which is understandable for mobile GIS applications.

To elaborate this process, the following figures illustrate an example of the request/response pair of triggering the web service to call the BMP policy/management scenario module of the application for identifying a BMP economic policy/management scenario. Figure 3-11 depicts unpacking XML request coming from the mobile application and the information bundle into it to
call the module. The two important parameters: desired BMPs and the fields/locations are highlighted in the figure. All four designated BMPs in the fields/locations are examined in a BMP economic policy/management scenario. The scenario is designed to evaluate optimum BMPs to be implemented in the selected fields/locations to maximize environmental benefits considering economic cost or financial constraint from 0 to 26,129 $/year (“LowerLimit” and “UpperLimit” tags, respectively).

**Figure 3-11 – SOAP web service request for calling BMP policy/management scenario module**

Similarly, Figure 3-12 shows the XML format response of the web service unpacked by the application. The message shows the modelling database has been generated and ready to provide responses.

**Figure 3-12 – SOAP web service response to the mobile GIS application**
3.4 Client-side system components

Presentation Layer Component

The Presentation layer presents the mobile GIS interface components which enable user interactions through the graphical controls. Several graphical components have been utilized to develop a user-friendly interface. Also, input validation process, before calling the web service, is a key element of the Presentation layer. Without the validation process, the untrusted module parameters supplied by users will result in an application crash. With the validation, entering numbers out of the constraint range, calculated by the mobile GIS application in developing BMP policy/management scenario, will be caught before any further calculations in the Presentation layer.

To improve user experience, the interface is designed intelligently to show specific messages so that users know the background processes. These messages improve user experience when interacting with application controls. For example, after initiating a request to the server, users will receive a notification message and another message will come up after receiving the results layer from the server.

To better organize information content and required actions, the application interface has been separated into three main frames consisting of Map, User, and Help. The User frame requires users to provide their identity through login controls in the “Welcome” frame. The credential process is required to determine the level of exposing modelling results to users by the “User Access Control” module. The first use of the mobile GIS application requires users to register to the application through “Register” frame. Upon successful login, users will be directed to the application main panel. The Map frame is the main panel to fulfill users’ needs for evaluating BMP exploratory
scenarios through the “BMP Exploratory Scenario” module and developing BMP policy/management scenarios through the “BMP Policy/Management Scenario” module. General information and also guidelines for mobile GIS application functions are incorporated into the Help frame. Users can read the application manual in this frame. About frame presents general information about the application. These frames are described in more details in chapter 4.

3.5 Software for system development

The mobile GIS application includes a client and a server. A client is a mobile device and a server is a physical machine which hosts a web server, web service and databases. The server is responsible for storing data, performing analysis, and controlling users’ access.

Server-side software

The Java programming language is used in the backend (server) side for developing modules to perform database query functions, data processing, and security control domain. The NetBeans application is used as the server-side development environment. For data management, the SQLite database is used as a database engine to store BMP assessment result and users’ profile information. SQLite is a fast, free, and cross-platform database engine which is widely adopted in many mobile applications. To make a connection between the NetBeans application and the SQLite database, a java library (SQLite-jdbc) is incorporated into the NetBeans application.

Furthermore, the GlassFish server is utilized as a web server application, to respond to the requests from end-users (mobile GIS applications) and publish the BMP modelling results. The communication with the server takes place over the Internet using the port 8080.
Client-side software

Many programming languages can be used to develop a client or user interface for mobile applications. In this research, the Kotlin programming language was utilized to develop the client-side of the application. Google announced the Kotlin language as the official programming language for Android development in 2017. The programming language was used in Android Studio application. This open-source development environment with comprehensive and tightly coupled components is suitable for building mobile applications with the Android operating system. Furthermore, the Google Android Emulator was utilized in this application to examine the designed application functionalities across the most popular mobile devices.

The Google Maps JavaScript API was used to render the interactive map and leverage the mapping functionalities. This lightweight map library is accessible in the application after setting up map parameters such as map type, size, and scale. The API features basic map types such as roadmap and satellite. This library empowers developers to customize the interactive map with vector layers of information on BMP assessment result. GEOJSON format was also utilized to render spatial vector layer of the watershed features on the background interactive map (i.e. boundary and fields/locations).

Table 3-1 summarizes the used software products for mobile GIS system implementation in both client and server sides.
Table 3-1 - Software for system implementation

<table>
<thead>
<tr>
<th>Programming language/ Libraries</th>
<th>Integrated development environment (IDE)</th>
<th>Functions</th>
<th>Client/ Server</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kotlin</td>
<td>Android Studio</td>
<td>User Interface</td>
<td>Client</td>
</tr>
<tr>
<td>Google Maps</td>
<td>Android Studio</td>
<td>Online mapping</td>
<td></td>
</tr>
<tr>
<td>Google Android</td>
<td>Android Studio</td>
<td>Examine</td>
<td>Server</td>
</tr>
<tr>
<td>Java</td>
<td>NetBeans</td>
<td>Database inquiries,</td>
<td></td>
</tr>
<tr>
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<td>NetBeans</td>
<td>Database</td>
<td></td>
</tr>
<tr>
<td>GlassFish</td>
<td>NetBeans</td>
<td>Server role</td>
<td></td>
</tr>
<tr>
<td>SQLite</td>
<td>SQLite</td>
<td>Data management</td>
<td></td>
</tr>
</tbody>
</table>

3.6 Minimum resource requirements for system implementation

Server Machine

A server machine is required to host web service and the Business Logic layer, Data Processing layer and BMP assessment result database. This machine delivers functionalities to mobile applications after performing calculations (see Figure 3-13). To keep the high performance of the server, particularly in peak requesting time, adequate and appropriate hardware and software resources should be devoted to the server machine. Table 3-2 outlines the recommended settings for the server machine for the mobile GIS application in this research.

One important point to note is that a valid IP for server machine is required to make web service on the server-side accessible by users. Clients utilize this constant IP to discover the web service over the HTTP protocol.
Figure 3-13 - Server machine mechanism for the mobile GIS application

Table 3-2 - Recommended requirements for the server machine for the mobile GIS application

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>Minimum 1.6 GHz (32-bit or 64-bit)</td>
</tr>
<tr>
<td>Memory</td>
<td>Minimum 16.0 GB (Recommended 32.0 GB) RAM</td>
</tr>
<tr>
<td>Hard disk</td>
<td>3.0 GB of available disk space</td>
</tr>
<tr>
<td>Operating system</td>
<td>Windows 7 64-bit, 8.1 - 10</td>
</tr>
<tr>
<td></td>
<td>Windows Server 2008 R2 - 2012 - 2016</td>
</tr>
<tr>
<td></td>
<td>For the best experience, use the latest version of any operating system.</td>
</tr>
</tbody>
</table>

Client Machine

To install the application, mobile clients need to meet several minimum requirements. A wide range of smartphone and tablet devices with the Android operating system can install the mobile
GIS application. Table 3-3 outlines the minimum requirements for the client devices to install the mobile GIS application in this research.

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU type</td>
<td>Quad-Core (or more)</td>
</tr>
<tr>
<td>RAM</td>
<td>Minimum 4.0 GB</td>
</tr>
<tr>
<td>Memory</td>
<td>50 MB free space</td>
</tr>
<tr>
<td>Screen size</td>
<td>&gt;= 5 inches (for user comfort)</td>
</tr>
<tr>
<td>Android version</td>
<td>5.X, preferably higher</td>
</tr>
</tbody>
</table>
4 A prototype of the mobile GIS application for the Gully Creek Watershed

This chapter presents the implementation of the mobile GIS application framework for a representative study watershed. The first section starts with introducing the study watershed. The second section demonstrates the functionalities of the mobile GIS application prototype.

4.1 Study area

The study area for this research is the Gully Creek watershed in southern Ontario, located in the shoreline area of the Lake Huron (see Figure 4-1). The Gully Creek watershed covers 14-km² landscape predominantly covered by agricultural production (70%). Soybean, corn, and winter wheat are the prime crop rotation in this watershed. With a minimum slope of 0% in flat areas and a maximum slope of 95% in incised gully areas, the average slope of the watershed is 6% (Yang et al., 2013).

This watershed, in the service area of the Ausable Bayfield Conservation Authority (ABCA), is an environmentally sensitive area because nonpoint source pollution from agricultural activities is directly discharged into the lake. Thus, BMP implementation has become one of the important measures to mitigate these negative effects in the watershed. Four representative BMPs in the Gully Creek watershed are examined: three land management BMPs, including conservation tillage, nutrient management, cover crop; and one structural BMP WASCoBs.
4.2 A demonstration of the mobile GIS application functionalities

This section presents the mobile GIS application functionalities in the Gully Creek watershed. The application includes three main frames: Map, User, and Help. The corresponding functions of each frame are described in more detail in the following sections.
Map Frame Interface

The Map frame is the mainframe of the mobile GIS application incorporated with the Google Map API service to deliver map-based information to users (Figure 4-2). The roadmap basemap type is presented in the Map frame as a default and can be changed by users. Users can utilize touch screen functions to explore the interactive map and information layers effectively. Users can zoom in by double-tapping the screen, zoom out by pinching fingers on the touch screen, pan and scroll by swiping the map on the touch screen, and rotate the map using two fingers in each direction.

Figure 4-2 - Map frame of the mobile GIS application localized for the Gully Creek Watershed
This frame also presents several button controls, including Show basemap, BMP scenario module selection, Run, Chart, and Change basemap style.

- “Show basemap” displays only the basemap of the watershed by removing any existing GIS layers resulting from BMP scenario evaluation. It serves as a “Clear” function.
- “BMP scenario module selection” presents the list of the two BMP scenario modules.
- “Run” button implements the user-defined BMP scenarios.
- “Chart” presents a graphical representation of BMP assessment result for evaluated fields/locations in a scenario.
- “Change basemap style” enables users to toggle the basemap style between the default Roadmap and Satellite style.

Users are able to evaluate two BMP scenario types: “BMP Exploratory scenario” and “BMP Policy/Management scenario”. A panel is designed to coordinate the user selection after clicking the “BMP scenario module selection” button (Figure 4-3). These scenarios are further described in the following sections. Regardless of user-selected type of scenario, three GeoJSON GIS layers will be provided including watershed boundary, fields, and WASCoB locations, on top of the basemap, to draw the agricultural fields and WASCoB locations of the Gully Creek watershed.
BMP Exploratory Scenario

Evaluating a BMP exploratory scenario involves two steps: BMP scenario definition and BMP scenario implementation. The BMP exploratory scenario definition is a process of assigning BMPs to specific fields and WASCoB locations on the map. Then, BMP scenario implementation would
evaluate the defined BMP scenario using the BMP assessment result from the integrated economic-hydrologic model.

When users select the “BMP Exploratory Scenario” option and click on the “Select” button, the application will load the required controls to define a BMP exploratory scenario. Figure 4-4 shows the application layout for the BMP exploratory scenario definition.

![Figure 4-4 – BMP exploratory scenario interface](image)
The BMP selector in the BMP exploratory scenario interface, above the interactive map, allows users to select the BMPs one by one to define a BMP scenario. Some abbreviations have been used for agricultural BMPs in this panel: CC, CT, and NM represent cover crop, conservation tillage, and nutrient management BMPs, respectively. Agricultural fields for land management BMPs and locations for WASCoBs can be selected by clicking the corresponding features of GeoJSON layers on the mobile screen. Cover crop, conservation tillage, and nutrient management BMPs can only be assigned to agricultural fields, and the WASCoB BMP can only be assigned to WASCoB point locations.

Figure 4-5 displays a sample BMP exploratory scenario definition for some selected fields and WASCoB locations in the watershed. This step is accomplished by selecting BMPs one by one, followed by selecting fields and locations to assign the selected BMPs. The selected fields are highlighted in arctic blue, while selected WASCoB locations are highlighted in green. Users can still review and refine selected fields and WASCoB locations after the initial selection process. A single click on a feature will select the feature, while the second click will deselect it from the current selection of the BMPs assignment list.
Figure 4-5 - BMP assignment into agricultural fields and specific locations in the Gully Creek watershed
After defining the BMP exploratory scenario, the user can initiate a request to implement the BMP scenario. The BMP exploratory scenario implementation happens by clicking the “Run” button. This will trigger the web service to call corresponding modules in the Business Logic layer and afterwards the Data Processing layer on the server machine. This will result in reading the integrated economic-hydrologic modelling results stored in the “BMP assessment result” database. After receiving the response from the web service, the application will present the BMP exploratory scenario implementation results as GIS layers on the basemap.

The GIS thematic result layers are grouped into three categories: P (phosphorus), NI (nitrogen), S (sediment) and F (flow) in environmental variable group; C (cost), R (revenue), and NE (net return) in economic variable group; and CE_P (cost-effectiveness of phosphorus), CE_NI (cost-effectiveness of nitrogen), CE_S (cost-effectiveness of sediment), and CE_F (cost-effectiveness of flow) in cost-effectiveness group. Note that the differences of environmental variables and the differences of net return between the baseline and BMP scenarios represent environmental benefits and economic costs of land management BMPs, respectively.

Figure 4-6 depicts the information layer of an environmental variable (phosphorus), after implementing the defined BMP exploratory scenario. The selected information layer type “P” is highlighted on the left side of the interface. For other information types, users can click on the corresponding buttons. The legend represents the phosphorus reduction from -6.0 to +2.3 (kg/ha/year), resulting from implementing the BMP exploratory scenario. The negative numbers indicate the phosphorus reduction (environmental benefits), while the positive numbers represent increases in phosphorus values (environmental harm) by the user-defined BMP exploratory scenario implementation (Yang et al., 2013).
Figure 4-6 - Total phosphorus information layer resulted from implementing the BMP exploratory scenario

Figure 4-7 depicts a chart view of the phosphorus information layout to demonstrate BMP assessment modelling results. The chart can be activated by clicking the “Chart” button in the Map frame. It will be updated with BMP scenario assessment results for the selected field/location. “Y” axis values represent the selected (environmental or economic) variable during the simulation period (from 2002 to 2011) on the “X” axis. In the chart layout, the green line indicates the actual
values, while the yellow line represents the average values for the entire time period of the simulation.

Similarly, Figure 4-8 represents the results of net return differences or BMP economic costs (“NE” button is highlighted), as an economic variable, from -249.6 to +54.0 (dollars) in the fields/locations. The negative net return differences indicate the economic costs incurred by
implementing the BMPs and the positive net return differences indicate economic gains from implementing the BMPs in the BMP exploratory scenario (Yang et al., 2013).

Figure 4-8 - Net return differences information layer resulted from implementing the BMP exploratory scenario

The cost-effectiveness information of BMPs represents the combination of both economic and environmental results. The cost-effectiveness of agricultural BMPs in a BMP exploratory scenario is estimated by dividing the value differences of a specific environmental variable by the net return
differences or BMP economic costs (in comparing to the baseline scenario which means no BMP implementation) for each agricultural field/location. The BMP cost-effectiveness is represented as environmental changes for $1,000 BMP costs. The units for BMP cost-effectiveness are mm/$1,000 for flow, ton/$1,000 for sediment yield, and kg/$1,000 for TN and TP yield reductions, which indicate the water quantity/quality effects per $1,000 BMP costs (Yang et al., 2013). Figure 4-9 depicts the cost-effectiveness of BMPs on phosphorus reduction in the user-defined BMP exploratory scenario (as the “CE_P” button is highlighted).

Figure 4-9 - Cost-effectiveness of BMPs on total phosphorus reduction
Due to various combinations of water quantity/quality effects and BMP costs, the cost-effectiveness results may have negative or positive values. As a result, the interpretation of the results should be done with caution. Table 4-1 shows the possible combinations of cost-effectiveness result values. For example, the environmental benefits (negative values) are typically achieved with economic loss (negative value), which leads to positive cost-effectiveness (situation 1). The higher absolute value of cost-effectiveness indicates more cost-effectiveness.

Table 4-1 - Different combination of cost-effectiveness result signs

<table>
<thead>
<tr>
<th>Situation</th>
<th>Environmental benefits</th>
<th>Economic costs</th>
<th>Cost-effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pollutant reduction (-)</td>
<td>Net return reduction (-)</td>
<td>Result values (+)</td>
</tr>
<tr>
<td>2</td>
<td>Pollutant reduction (-)</td>
<td>Net return increase (+)</td>
<td>Result values (-)</td>
</tr>
<tr>
<td>3</td>
<td>Pollutant increase (+)</td>
<td>Net return reduction (-)</td>
<td>Result values (-)</td>
</tr>
<tr>
<td>4</td>
<td>Pollutant increase (+)</td>
<td>Net return increase (+)</td>
<td>Result values (+)</td>
</tr>
</tbody>
</table>


**BMP Policy/Management Scenario**

Developing a BMP policy/management scenario is done through the BMP policy/management scenario module incorporated into the Business Logic layer component. When users select the BMP policy/management scenario option (see Figure 4-3), they will be directed to the “BMP Policy/Management Scenario” interface. Figure 4-10 shows the interface and designated controls for defining and implementing a BMP policy/management scenario.
Figure 4–10 - BMP policy/management scenario interface

The interface supports two types of BMP policy/management scenarios: the BMP environmental policy/management scenario (presented by “En” in the interface), which minimizes economic costs to achieve environmental targets and the BMP economic policy/management scenario (presented by “Ec” in the interface), which maximizes environmental benefits under financial constraints. For pollutant types, “P”, “NI”, “S”, and “F” are used to represent Phosphorus, Nitrogen, Sediment, and Flow, respectively. Also, the “constraint range” box can allow users to
insert their own desired range for pollution reduction (for example phosphorus reduction) based on the default range.

After setting the required parameters for a BMP policy/management scenario, including desired BMPs in the scenario, policy/management type (environmental vs. economics), pollutant type (such as phosphorus), and selected fields/locations, the user can obtain a default range for BMP policy/management constraint by clicking on the “Get default range” button. This default range indicates the upper and lower limits of the environmental benefits (such as phosphorus reduction in kg/year) under the BMP environmental policy/management scenario, and the upper and lower limits of the economic costs (dollar/year) under the BMP economic policy/management scenario (Yang et al., 2013).

Figure 4-11 shows the default range resulting from a sample BMP policy/management scenario, after setting the economic for policy/management type, the phosphorus for pollutant type, and all four possible BMPs for some selected fields/locations for optimization. The default BMP economic cost range for policy/management constraint can be from $-8,425.7$ to $+38,327.2$ ($/year), indicating the minimum and maximum BMP costs on the selected fields/locations. Note that the signs for BMP economic costs in the BMP policy/management scenario module are opposite to those of the net return differences used in the BMP exploratory scenario module. This is because in the optimization model for the BMP policy/management scenario module, the net return differences are multiplied by (-1). Therefore (-8,435.7) indicates economic gains from implementing the BMPs while (+38,327.2) indicates economic costs incurred by implementing the BMPs.
Similarly, for a BMP environmental policy/management type with the total phosphorus (TP) as a pollutant type, the default BMP environmental benefit range for policy/management constraint is from -1,007.5 to 0.0 (kg/year), which indicates the maximum and minimum TP reductions after BMP(s) implementation in the selected fields/locations (see Figure 4-12, negative sign indicates TP reduction).
After receiving the default range, the user can revise the range to specify a desired BMP policy/management constraint, such as the range of financial constraints (BMP costs) and the range of environmental targets (pollutant reductions). The user-defined range is bounded by the proposed default range. For BMP environmental policy/management scenarios, users are able to set the user-defined range in two ways: based on actual value (“V”) or percentage (“P”) (see the range type
control on Figure 4-10). For example, for the defined environmental BMP policy/management scenario (Figure 4-12), the user range with actual value option should be between the minimum and maximum TP reduction (from -1,007.5 to 0.0 kg/year). By using percentage option, the user range will be bounded by percentage range (from -13.45% to 0.0%). For instance, users can simulate the BMP environmental scenario for phosphorus reduction -10% at the watershed outlet. However, for BMP economic policy/management scenarios, the only option for a user-defined range is based on the actual value of the presented default range.

After setting the BMP policy/management constraint, the user can click on the “Run Optimization” button to run the optimization model in the Business Logic layer to obtain the optimum BMP types. Figure 4-13 shows the results of implementing the defined BMP economic policy/management scenario with a user-defined BMP cost constraint range. The legend presents the optimum BMP types in different colors for the evaluated fields/locations in the BMP scenario regarding user-defined cost constraints. Eight combinations of three crop BMPs are presented by a different color in the legend. Optimum evaluated WASCoB locations are also highlighted using green in the layout. For this scenario, two point-locations are highlighted. The “New Scenario” button will clear the scenario results and setup all the parameters with default values to start a new BMP policy/management scenario definition.
In addition, a line chart is used to present the trade-off relationship between the BMP cost and environmental effectiveness within the range of constraints. Figure 4-14 represents the line chart of the BMP economic policy/management scenario results by clicking the chart button. The Y-axis of the chart indicates the BMP economic cost against the environmental benefits (phosphorus reduction) on X-axis. Ten points on the green curve represent ten sets of BMP configurations and each set has corresponding BMP cost and environmental effectiveness. The pattern shows that
more TP reduction will lead to higher BMP cost. The yellow curve indicates the maximum phosphorus reduction and the intersection of the two curves represents the selected BMP configuration types which is presented on the map.

Figure 4-14 - The interface for exploring the economical BMP policy/management scenario information
User Frame Interface

To access the application functionalities, users (i.e. farmers or conservation managers) must register to the mobile GIS application through the User frame. Figure 4-15 shows the User frame for Login and Registration, which is the entry point to the application. The registration panel allows users to enter the user name, password, role (Farmer or Conservation Manager), Email, and farm ID(s) to create a record in the User Profile database (Figure 4-16).

![User frame interface of the mobile GIS application](image)

Figure 1.2 - User frame interface of the mobile GIS application
Figure 4-16 – Registration form in the user frame of the mobile GIS application

The User frame defines user roles through the User Access Control module in the Business Logic layer of the mobile GIS application. Users must select a role: Farmer or Conservation Manager. These roles define accessible information content in the Map frame. Farmers can only access BMP scenario information on their own properties, while conservation managers can explore the information for the entire watershed.
Users who have already registered to the system can log into the mobile GIS application with their username and password. After authentication, users will be able to enter into other frames of the application. A message will be shown to users if the authentication fails.

**Help Frame Interface**

The “Help” frame of the application provides explanatory information through two sections: General information and User guide information. Each section is also separated into subsections to support users. Figure 4-17 depicts the layout of the “Help” frame.
Figure 4-17 - Help interface of the mobile GIS application

The map frame is the mainframe of the interface and incorporated with the Google Map API service to provide spatial information. Controls, in the bottom section of the map interface, provide ways to interact with the map and use the functionalities.
5 Conclusions

5.1 Summary

Information communications play an important role in facilitating BMP adoption in agri-environmental programs. Watershed hydrologic and integrated economic-hydrologic modelling have been increasingly applied to provide information on BMP effects including economic costs, environmental benefits, and cost effectiveness. Desktop-GIS and WebGIS based interfaces have been developed to make BMP modelling information accessible by users. However, technical barriers still exist in using these platforms for communicating BMP assessment information to users.

Extended from desktop-GIS and WebGIS based systems, this study develops an open-source mobile GIS application for disseminating modelling simulated BMP assessment information to farmers and conservation managers. The development starts with developing a framework for the mobile GIS application, which is composed of multiple clients or mobile devices and a server. The server hosts a BMP assessment database, a user profile database, a data processing layer, and a business logic layer to provide web service to mobile devices through the Internet. The mobile GIS users are classified into farmers and conservation managers with different scopes to examine the BMP assessment information based on the user profile. Farmers can only explore BMP assessment information on their own farms but conservation managers can examine BMP assessment information for the entire watershed. Users send BMP assessment requests through their own mobile devices and the requests are passed on to the server where the business logic
layer generates data processing requests such as query and optimization modelling instructions to interact with BMP assessment databases to generate specific BMP assessment result. Then the server works on a reverse order to pass the specific BMP assessment result back to clients or mobile devices which are programmed to display the information using maps or charts.

The mobile GIS application has two modules. The first module provides information content including economic cost, environmental benefits, and cost-effectiveness of BMPs to farmers and/or conservation managers based on user-defined BMP exploratory scenarios. Users can define BMP scenarios by selecting fields/locations and assigning BMP types based on an interactive map on a mobile device. After that the BMP scenario definition is passed on to the server for data processing and the BMP assessment result will be communicated back to the mobile device to be visualized using map or chart functions. The second module is for conservation managers to identify BMP policy/management scenarios which include prioritized BMP types and locations based on environmental targets or financial constraints. This module supports users to examine two types of policies: the BMP environmental policy/management scenario, which minimizes the economic costs subject to environmental targets and the BMP economic policy/management scenario, which maximizes the environmental benefits subject to financial constraints. The outcomes of the BMP policy/management scenarios include optimum BMP types and locations, which can be also visualized using map or chart functions.

A prototype of the mobile GIS application was developed for the Gully Creek watershed in the shoreline area of the Lake Huron in southern Ontario. The mobile GIS application utilized BMP assessment data generated by an integrated economic-hydrologic modelling for the Gully Creek watershed, which was developed by the Watershed Evaluation Group of the University of Guelph.
(Yang et al. 2013). The integrated modelling provided the economic costs, environmental benefits (flow, sediment, nitrogen, and phosphorus reductions), and cost-effectiveness of four representative BMPs including conservation tillage, nutrient management, cover crop, and water and sediment control basin (WASCoB) in the Gully Creek watershed from 2002 to 2011. The BMP assessment data was used for supporting queries to generate BMP evaluation results for the BMP exploratory scenario module and also an optimization model to identify optimum BMP types and fields/locations for the BMP policy/management module.

The mobile GIS application for the Gully Creek watershed demonstrated the potential of communicating complex BMP modelling results to farmers and/or conservation managers to support decision making in BMP implementation. Farmers can use the “BMP exploratory scenario” module to construct various BMP scenarios and compare the economic costs, environmental benefits, and cost effectiveness to select preferred BMP scenarios on their farms. In addition to use the “BMP exploratory scenario” module, conservation management can use a specifically developed “BMP policy/management scenario” module to explore optimal BMP configurations (BMP types and locations) according to various environmental targets or different levels of financial investments. Optimal BMP configurations can help conservation managers to identify prioritized locations to discuss BMP implementation and also allocate corresponding financial investment.

Complementary to desktop GIS and WebGIS based tools, the mobile GIS application significantly shortened the time that farmers and/or conservation managers require to have access to integrated BMP modelling results. Quick access to complex BMP modelling results can facilitate information communications in agri-environmental programs while farmers and/or conservation managers can
explore the BMP information on their own and also initiate discussions on the BMP information. Farmers can ask questions on the BMP information for conservation to respond. Farmers can discuss alternative BMP implementation options with conservation managers and then identify a feasible option. Conservation managers can also use BMP policy/management scenario results to suggest farmers to implement preferred BMP implementation option. Therefore, the mobile GIS application has the potential to play a role of facilitating BMP information communication in agri-environmental programs.

Information on BMP’s environmental and economic effects has been identified as an important factor facilitating BMP adoption (MacKay 2010) and a significant gap exists on communicating integrated BMP modelling information to users (Shao et al. 2017). This study contributes to address the gap by developing a mobile GIS application framework to facilitate farmers and conservation managers to acquire simulated BMP assessment information. The mobile GIS application framework enriches BMP adoption literature by outlining the information flow between sources (BMP information databases) and users (farmers and conservation managers) and corresponding technical components (such as business logic and data processing) to support the information flow. The development of the prototype mobile GIS application for the Gully Creek watershed demonstrates that framework is feasible for technical implementation.

5.2 Future study

The open-source mobile GIS application has the potential to be further developed to support a wider range of audiences.
1) The mobile GIS application is specifically designed and developed for the Android operating system. There is a potential to further develop the application for other mobile operating systems such as iPhone OS (IOS).

2) The mobile GIS application can have more function improvements. For example, the interactive map and corresponding tool buttons need to accommodate rotating to landscape screen to improve visualization experience. Hover-over text can be also added to provide annotations to various functions and tools.

3) The mobile GIS application can be developed to embed communication channels such as Google Talk messenger for instant communications with farmers in the field. In addition, voice and video chat can be also integrated into the application. These synchronous communication means can be used to improve information-sharing in agri-environmental programs.

4) The mobile GIS application is customized for the Gully Creek watershed to examine the four representative BMPs including conservation tillage, cover crop, nutrient management, and WASCoB. The application has the potential to be expanded to include more agricultural BMPs in the Gully Creek watershed. The application can be also transferred to other study watersheds. However, corresponding mobile GIS functions may need to be extended or redeveloped. Further, the integrated economic-hydrologic modelling should be conducted to provide economic costs, environmental benefits, and cost effectiveness for those BMPs in the Gully Creek watershed or other watersheds.

5) Finally, the mobile GIS application for the Gully Creek watershed can be evaluated by farmers and conservation managers to test its functionalities and user-friendliness.
References


Adnan R., Merwade V., Kim IL., Zhao L., Song C., and Zhe S. 2015. SWATShare a web platform for collaborative research and education through online sharing, simulation and visualization of SWAT models. Environmental Modelling & Software. 75 (2016) 498e512.


Yang, W., Liu, Y.B., Simmons, E.S., Oginskyy, A., McKague, K., 2013. SWAT modelling of agricultural BMPs and analysis of BMP cost effectiveness in the Gully Creek watershed. Final


