Tools for Modeling of Stormwater Management and Economics of Green Infrastructure Practices: a Review

Tools for modelling of Stormwater Management and Economics of Green Infrastructure Practices: A Review

Jayasooriya V.M [a] and A.W.M. Ng [a]

[a] *College of Engineering and Science, Victoria University, Melbourne 14428, AUSTRALIA*
Email: Varuni.Jayasooriya@live.vu.edu.au

Abstract

Green Infrastructure (GI) practices have been identified as a sustainable method of managing stormwater over the years. Due to the increasing popularity of GI as an integrated urban water management strategy, most of the current catchment modelling tools incorporate these practices, as inbuilt modules. GI practices are also viewed as economically viable methods of stormwater management when compared to conventional approaches. Therefore, cost benefit analysis or economics of GI are also emerging as obligatory components of modelling tools. Since these tools are regularly upgraded with latest advancements in the field, an assessment of tools for modelling stormwater management and economic aspects of GI practices is vital to developing them into more sophisticated tools. This review has undergone a three phase process starting with twenty identified modelling tools available in the literature followed by a detailed review of a selection of ten most recent and popular modelling tools, based on their accessibility. The last phase of the review process is a comparison of the ten modelling tools along with their different attributes. The major aim of this review is to provide readers with the fundamental knowledge of different modelling tools currently available in the field, which will assist them with screening for a model, according to their requirements from the number of tools available. A secondary aim is to provide future research directions on developing more comprehensive tools for GI modelling and recommendations have been presented.

Keywords: Green Infrastructure (GI), Stormwater Management, Economics, Cost Benefit Analysis, Modelling Tools

1. Introduction

With the rapid urban growth and development, the quality of green space available in the earth surface is consequently been degrading. Furthermore, many land characteristics have been altered such that the whole water cycle has been significantly changed. Some of the considerable adverse effects occur by these changes include the increase of runoff which can lead to flooding and the poor quality of receiving waters. Therefore, to improve the quality of prevailing surface conditions whilst managing the stormwater, Green Infrastructure (GI) have been introduced which is becoming one of the promising practices of non-point source stormwater pollution control measures, by restoring the natural environment across many countries around the world.

The term GI in the literature is commonly referred as Low Impact Development (LID), Best Management Practices (BMP), Sustainable Urban Drainage Systems (SUSD), Water Sensitive Urban Design (WSUD) and Low Impact Urban Design and Development (LIUDD) in different contexts (Elliott and Trowsdale, 2007). GI in broader terms can be defined as an "interconnected network of green space that conserves natural systems and provides assorted benefits to human populations"(Benedict and McMahon, 2006).Moreover, recent research studies have identified that, implementation of GI practices as not only a stormwater management strategy that improves both water quantity and quality within the water cycle, but also provide other important Eco-System Services (ESS). Apart from managing stormwater, other ESS that GI practices provide are energy savings, air quality improvement, mitigation of climate change by reducing greenhouse gases, reduction of Urban Heat Island (UHI), improvement of community liveability which include aesthetics, recreation, and improvement of habitats amongst others(Centre for Neighbourhood Technology, 2010).

GI can be grouped into two main categories, structural and non-structural practices. Structural GI includes green roofs, rainwater tanks, wetlands, bio swales, pervious pavement, stormwater detention systems, planter boxes, cisterns, rain barrels and downspout disconnection amongst others. Non-structural GI is designing the buildings or roads to minimize the imperviousness, improvement of the infiltration ability of soils by amending the properties and improving the vegetation of a specific site or region (Elliott and Trowsdale, 2007). Structural measures can be further categorized according to their processes such as storage/infiltration GI's and channelized GI's(Cheng et al., 2009).

The incorporation of GI within catchment modelling tools has been emerged in order to get an idea on the behavior of different GI practices in stormwater management. Stormwater management modelling tools have been used extensively by researchers and professionals in order to understand various aspects related to stormwater. These tools require different site specific parameters as inputs such as: catchment size, scale, human activities, climate, and natural characteristics. Outputs of these modelling tools include: run off volume reduction, reduction of runoff rate and reduction of pollutant loading, due to the implementation of different GI practices. Some of these tools also include modules for analysis of whole life cycle costs of GI. There are a number of simple spreadsheet tools available for the economic analysis of these practices. However, in this review the main focus will be to have a discussion on the modelling tools which are currently in use for the modeling of stormwater management and economic aspects of GI.

Only three reviews have been done on stormwater modelling tools by researchers in terms of both quality and quantity of stormwater that can be managed by GI practices. One review was done over a decade ago and another over seven years ago, and due to that most of the particular tools included in those reviews are currently outdated. The remaining review that was done two years ago was limited to three models. Zoppou (2001) has discussed the approach of mathematical modelling in urban stormwater management modelling tools by concentrating on aspects of quality and quantity. This study has also provided details on some existing stormwater modelling tools but does not consider the effect of incorporating GI practices within those stormwater modelling tools. Another review was done by Elliott and Trowsdale (2007) to study the modelling tools which include GI in urban stormwater drainage modelling. The scope of this study was limited to investigating how the selected software tools with GI can affect the stormwater quality and quantity with a more in depth discussion on their hydrologic modelling aspects. Ahiablame et al. (2012) did a study on the effectiveness on GI practices for stormwater management and discussed only three different stormwater modelling tools which addressed the quality and quantity of runoff. To date, no reviews have been done on modelling tools that have the capabilities of modelling of economics of GI practices. This review will investigate twenty modelling tools which are currently available for the modelling of stormwater management and/or economics of GI practices. Important attributes related to modelling processes of ten selected models will then be discussed that will provide a screening process for water resource modelers to select the most appropriate modelling tool according to their requirements. Finally, the paper will suggest future research areas for GI model developers.

1.1 GI Practices and the development of Modelling Tools

GI is a network of green spaces that provides habitat, flood protection, cleaner air and cleaner water. This has earlier been introduced as an alternative to conventional stormwater management strategies and at present it has been also proven that apart from managing stormwater, GI can provide a wide range of ESS such as reducing urban heat island, air quality improvement, climate change adaptation, improving community liveability and improving aesthetics. However, in site or neighborhood scale GI is most commonly defined as a way of managing the stormwater runoff by making the water infiltrate into a surface or by collecting for reuse (Wise, 2008).

Software tools have been used for water resource management since the mid-1960s and the modelling tools that have the ability of simulating the stormwater runoff quality and quantity started emerging from 1970s(Zoppou, 2001). After the GI controls were identified as an important method of managing urban stormwater, these tools were updated with the components that can evaluate the effectiveness of GI practices. The primary goal of most of these new tools was to assess the ability of GI practices in managing urban stormwater runoff quality and quantity. The economic modules of these tools include, measures for cost benefit analysis, operation, installation and maintenance costs of GI practices.

1.2 Review Process

The review was carried out in three phases. The first phase was to identify the software modelling tools that can simulate the performance of different types of GI. According to the literature there are a number of modelling tools that incorporate GI practices for stormwater modelling which are commercially available and are used by researchers. Among the wide range of tools available, twenty modelling tools have been first identified in the literature review. The details of those 20 tools which are currently available with GI components are summarized in Table 1.

In the second phase, from amongst these twenty modelling tools, ten were selected for the detailed review. These 10 could simulate stormwater management and/or economic aspects of GI practices. These selected modelling tools are identified as being popular tools among stormwater management professionals and are also being widely used in research. Also, these ten modelling tools are selected on the basis of having sufficient documentation to conduct a review and the availability of updated versions of software. The ten selected modelling tools are further described in detail with regard to five major criteria:1) representative GI practices 2) spatial scales 3) algorithms used for modelling 4) data inputs and outputs 5) user interface and handling of the tool.

In the third phase, categorization and comparison of ten selected tools was conducted. Some of these tools are developed specially for a particular region and some are used in general for research and decision making. Therefore, these modelling tools were compared with each other in terms of; number of GI practices they can represent, modelling approaches, data requirements, accuracy and regional limitations. However, it should be noted that this paper does not intend to discuss in depth hydrologic or hydrologic modelling features of these tools focusing on their simulations. This review will serve as a reference for researchers looking for simple open source and proprietary software tools which contain GI controls. This review will provide assistance for the user community on initial screening of tools according to their requirements, from the number of different tools available.

2. Overview of Selected Modelling Tools for the Review

Among the twenty models referenced above, ten models were selected to conduct a comprehensive review for this study. These are known to be widely accepted by water resource researchers. These ten tools are further classified into three major categories as;

1) Models that address the stormwater management ability of GI in terms of quantity and quality,
2) Models that have the capability of conducting the economic analysis of GI and
3) Models that can address both stormwater management and economic aspects together.

A literature review for each of the tools is conducted extensively by refereeing their user guides, design manuals, fact sheets, case studies, journal articles, conference proceedings and book chapters.

The product information on the ten selected modelling tools such as; model description, owner details, availability and intended use are summarized in Table 2. In the following sections each tool is reviewed with regard to five different criteria mentioned in the review process in section 1.2. Finally, a comparison between tools is presented with a discussion about the attributes of different modelling tools, in order to emphasize the importance of developing more holistic stormwater management tools with GI controls which addresses both stormwater management and economic aspects.

Table 1- Tools for Green Infrastructure Modelling

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
Environmental Protection Agency (EPA) Green Long Term Control- EZ Template	(Schmitt et al., 2010)	Green Roofs, Vegetated Swales, Bio Retention Basins, Permeable Pavements, Rain Barrels	• Planning tool for combined sewer overflow control. • Can be used in small communities.
Water Environmental Research foundation (WERF) BMP SELECT Model	(Reynolds et al., 2012)	Extended Detention ,Bio retention, Wetlands, Swales, Permeable Pavements	• Examines the effectiveness of alternative scenarios for controlling stormwater pollution. • Water quality parameters that can be simulated are Total Suspended Solids, Total Nitrogen, Total Phosphorus and Total Zinc.
Virginia Runoff Reduction Method (VRRM)	(Bork and Franklin, 2010)	Green Roofs, Downspout Disconnection, Permeable Pavements, Grass Channels, Dry Swales, Bio Retention, Infiltration, Extended Detention Ponds, Wet Swales, Constructed Wetlands, Wet Ponds	• Incorporates built-in incentives for environmental site design, such as forest preservation and the reduction of soil disturbance and impervious surfaces.
WERF BMP and LID Whole Life Cycle Cost Modelling Tools	(Reynolds et al., 2012)	Green Roof, Planters, Permeable Pavements, Rain Gardens, Retention Ponds, Swales, Cistern, Bio Retention, Extended Detention Basins	• Planning level cost estimation for GI practices. • Different spreadsheet tools are designed for different practices.
Centre for Neighborhood Technology(CNT) Green Values National Stormwater Management Calculator	(Jaffe, 2011, Guo and Correa, 2013)	Green Roofs, Planter Boxes, Rain Gardens, Cisterns, Native Vegetation, Vegetation Filter Strips, Amended Soils, Swales, Trees, Permeable Pavements	• Allows the user to select a runoff reduction goal and select the combination of GI practices that provides the optimum runoff reduction in a cost effective way.
CNT Green Values Stormwater Management Calculator	(Kennedy et al., 2008, Wise et al., 2010, Jaffe et al., 2010)	Roof Drains, Rain Gardens, Permeable Pavements, Trees, Porous Pavements, Drainage Swales	• Tool which helps to get an approximation of financial and hydrologic conditions for a user defined site.

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
Chicago Department of Environment Stormwater Ordinance Compliance Calculator	(Emanuel, 2012)	Green Roofs, Planter Boxes, Rain Gardens, Native Vegetation, Vegetated Filter Strips, Swales, Trees	• Used to evaluate the opportunities of GI with regard to the guidelines of Chicago's stormwater management ordinance.
EPA Stormwater Management Model (SWMM)	(Huber and Singh, 1995, Tsihrintzis and Hamid, 1998, Huber, 2001, Khader and Montalto, 2008, Rossman, 2010)	Bio Retention, Infiltration Trenches, Porous Pavement, Rain Barrels, Vegetative Swales, Green Roofs, Street Planters, Amended Soils	• Planning, analysis and design related to stormwater runoff, combined sewer overflows and drainage systems. • Complex model with variety of features. • One of the most popular software among catchment modelers.
Delaware Urban Runoff Management Model (DURMM)	(Lucas, 2004, Lucas, 2005)	Filter Strips, Bio Retention Swales, Bio Retention, Infiltration Swales	• Spreadsheet tool to assist GI design.
Stormwater Investment Strategy Evaluator (StormWISE) Model	(McGarity, 2006, McGarity, 2010, McGarity, 2011)	Riparian Buffers ,Filter Strips, Wetland/Rain Garden, Bio Retention/Infiltration Pits, Rain Barrel/Cisterns, Land Restoration By Impervious Surface Removal, Permeable Pavements, Green Roofs	• Studies on GI projects based on pollutant load reduction and cost benefits.
Program for Predicting Polluting Particle Passage through Pits, Puddles, & Ponds (P8 Urban Catchment Model)	(Elliott and Trowsdale, 2007, Obeid, 2005)	Detention Tanks, Ponds, Wetlands, Infiltration Trenches, Swales, Buffer Strips	• Model the generation and transportation of pollutants through urban runoff and the effectiveness of GI for improving the water quality.
Long-Term Hydrologic Impact Assessment (L-THIA)	(Tang et al., 2005, Bhaduri, 1998, Bhaduri et al., 2001, Engel et al., 2003)	Bio Retention/Rain Gardens, Grass Swale, Open Wooded Space, Permeable Pavement, Rain Barrel/Cisterns, Green Roof.	• Consists of calculations for Stormwater runoff and pollutant loading.
GI Valuation Tool Kit	(GiVAN, 2010)	Green Cover	• Evaluate the dollar value of environmental and social benefit of GI.

Modelling Tools	References and Case Studies	Supported GI Practices	Comments
EPA System for Urban Stormwater Treatment Analysis and Integration (SUSTAIN)	(Lai et al., 2006, Lai et al., 2007, Lai et al., 2009, Lai et al., 2010, Shoemaker et al., 2013)	Bio Retention, Cisterns, Constructed Wetlands, Dry Ponds, Grassed Swales, Green Roofs, Infiltration Basins, Infiltration Trenches, Permeable Pavements, Rain Barrels, Sand Filters (Surface And Non-Surface),Vegetated Filter Strips ,Wet Ponds	• Implementation planning for flow and pollution control. • Selects the most cost effective solution in stormwater quality and quantity management.
RECARGA	(Dietz, 2007, Atchison et al., 2006)	Bio Retention, Rain Garden, Infiltration	• Performance evaluation of bio retention rain garden and infiltration practices.
Model for Urban Stormwater Improvement Conceptualization(MUSIC)	(Wong et al., 2002, Deletic and Fletcher, 2004, Wong et al., 2006, Dotto et al., 2011)	Bio Retention Systems, Infiltration Systems, Media Filtration Systems, Gross Pollutant Traps, Buffer Strips, Vegetated Swales, Ponds, Sedimentation Basins, Rainwater Tanks, Wetlands, Detention Basins.	• Assists in decision making of GI selection for stormwater management in urban development.
Low Impact Development Rapid Assessment (LIDRA)	(Montalto et al., 2007, Behr and Montalto, 2008, Yu et al., 2010)	Green Cover	• Evaluates the effectiveness of green space in reducing stormwater runoff.
WinSLAMM (Source Loading and Management Model for Windows)	(Pitt and Voorhees, 2002)	Infiltration/Bio filtration Basins, Street Cleaning, Wet Detention Ponds, Grass Swales, Filter Strips, Permeable Pavement	• Evaluates how effective the GI practices in reducing runoff and pollutant loadings. • The cost effectiveness of practices and their sizing requirements can also be modeled.
Street Tree Resource i-Tree i-Tree Streets /Analysis Tool for Urban Forest Managers (STRATUM)	(McPherson et al., 2005, Soares et al., 2011)	Street Trees	• Assessment of the street trees in terms of current benefits, costs and management needs.
i-Tree Hydro	(Kirnbauer et al., 2013)	Trees, Green Cover	• Simulate the effect of trees and green cover on water quality.

2.1 Modelling Tools that Address Stormwater Quality and Quantity

GI practices attempt to replicate the pre development scenarios of a site in order to reduce the runoff quantities and improve the runoff quality(Davis, 2005). Three models which have the ability of predicting the responses of different GI practices on runoff management are discussed within this category.

2.1.1 RECARGA Model

RECARGA is a tool developed to address the reduction of runoff volume as a way of indirectly improving the water quality (Wang et al., 2013).This can be achieved by the proper designing of GI and the tool can be used to size and evaluate the performance of bio retention facilities, rain gardens and infiltration practices. The modelling tool simulates infiltration of water through three distinct soil layers with user defined climatic conditions (Atchison and Severson, 2004). RECARGA is used to size individual GI practices and therefore it is the main tool used in site or neighborhood scales.

Initial abstraction and TR-55 methodologies are used for the runoff calculation in RECARGA for impervious and pervious areas(Gaffield et al., 2008). The Green-Ampt infiltration model is used for initial infiltration into the soil surface and the van Genuchten relationship is used for drainage between soil layers (POTTER, 2005, Montgomery et al., 2010, Brown et al., 2013). Another important feature of the modelling tool is that it can capture the soil moisture and evapotranspiration during a storm event(Atchison and Severson, 2004, Atchison et al., 2006).

The inputs to the tool include hourly precipitation record or event precipitation, hourly evapotranspiration record, drainage area, impervious area, previous area curve number, soils properties and rain garden properties. Design specific parameters for different GI such as ponding zone depth, root zone thickness and properties, under drain flow rate should also be provided to assess the performance of the GI practice. The outputs are ponding times, number of overflows, water balance and total tributary runoff from both impervious and pervious areas. Though RECARGA is developed using the MATLAB computer program, it has been incorporated into a graphical user interface which provides more user friendliness.

2.1.2 Program for Predicting Polluting Particle Passage through Pits, Puddles, & Ponds (P8 Urban Catchment Model)

P8 is a model developed to predict runoff generation and transportation from urban catchments(Walker Jr, 1990).The tool is primarily applied to evaluate the design requirements for GI in order to achieve 70-85% of Total Suspended Solids(TSS) removal. The GI practices that can be modeled using the tool are retention ponds, infiltration basins, swales and buffer strips.P8 is identified as a tool that is best suited for the conceptual level preliminary design of GI practices for a catchment scale(Elliott and Trowsdale, 2007).The model can be applied for either site or catchment scale GI planning activities.

The underlying runoff modelling algorithms of P8 are derived from a number of other catchment models such as SWMM, STORM, Hydrological Simulation Program – Fortran (HSPF) and TR-20. Runoff from the pervious areas are calculated from the Soil Conservation Service (SCS) curve number method and runoff from the impervious areas are assumed to be the rainfall once the depression storage is achieved. The classes of particles are defined by factors which control catchment export and behavior of treatment devices such as settling velocity, decay rate and filtration efficiency. Water quality components are defined by their weight distributions across particle classes(Walker Jr, 1990).

Table 2 – Reviewed Modelling Tools

Modelling Tools	Owner	Availability	Intended Uses in GI Modelling	Reference
RECARGA	University of Wisconsin-Madison, water resources group	Freely available to download http://dnr.wi.gov/topic/stormwater/standards/recarga.html	To design and understand performances of bio retention, infiltration basins and rain gardens.	(Atchison and Severson, 2004)
Program for Predicting Polluting Particle Passage through Pits, Puddles, & Ponds (P8 Urban Catchment Model)	William W. Walker, Jr., Ph.D. Environmental Engineer Massachusetts	Freely available to download http://www.wwwalker.net/p8/	To predict the generation and transportation of pollutants in urban runoff and design GI to achieve Total Suspended Solids Reduction	(Walker Jr, 1990)
EPA Stormwater Management Model (SWMM)	United States Environmental Protection Agency	Freely available to download http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/	To plan, design and analysis of the performances of different GI in runoff quality improvement and quantity reduction	(Huber et al., 1988, Rossman, 2010)
Water Environment Research Foundation(WERF) BMP and LID Whole Life Cycle Cost Modelling tools	Water Environment Research Foundation, Alexandria	Freely available to download http://www.werf.org/i/a/Ka/Search/ResearchProfile.aspx?ReportId=SW2R08	To evaluate whole life cycle cost for GI practices	(Water Environment Research Foundation, 2009)
The Green Infrastructure Valuation Toolkit	Natural Economy North West UK	Freely available to download http://www.greeninfrastructurenw.co.uk/html/index.php?page=projects&GreenInfrastructureValuationToolkit=true	To evaluate the environmental and economic benefit of GI in monetary terms	(Natural Economy Northwest, 2010)

Modelling Tools	Owner	Availability	Intended Use in GI Modelling	Reference
Centre for Neighborhood Technology (CNT) Green Values National Stormwater Management Calculator	Center For Neighborhood Technology, Chicago	Free online assessment tool http://greenvalues.cnt.org/national/calculator.php	To compare GI cost, performance and benefits	(Center for Neighborhood Technology, 2009)
EPA System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN)	United States Environmental Protection Agency	Freely available to download http://www.epa.gov/nrmrl/wswrd/wq/models/sustain/	To develop implementation plans for flow and pollution control, evaluate cost effectiveness of GI	(Lai et al., 2007)
Model for Urban Stormwater Improvement Conceptualization (MUSIC)	eWater , Australia	Proprietary software http://www.ewater.com.au/products/ewater-toolkit/urban-tools/music/	To evaluate GI practices in order to achieve stormwater quantity reduction, quality improvement and cost effectiveness.	(Wong et al., 2002)
Low Impact Development Rapid Assessment (LIDRA)	eDesign Dynamics, New York	Open Source Web Based tool http://www.lidratool.org/database/database.aspx	To study runoff cost reductions with GI	(Yu et al., 2010)
WinSLAMM (Source Loading and Management Model for Windows)	PV & Associates USA	Proprietary software http://winslamm.com/winslamm_updates.html	To study the quality of urban runoff and the role of GI in runoff quality improvement	(Pitt and Voorhees, 2004)

The major inputs to the model are ; characteristics of catchments and the GI devices, particle and water quality component characteristics, precipitation and air temperature (Palmstrom and Walker, 1990, Walker Jr, 1990). The simulations of the model are based on continuous hourly rainfall data. The model outputs are presented in tabular format and screen only outputs as water and mass balances, removal efficiencies, comparison of flow, loads and concentration across devices, elevation and outflow ranges for each device, sediment accumulation rates, mean inflow or outflow concentration, detailed statistical summaries , continuity checks on simulation data and time series graphs. The program is designed in a user friendly manner with several tabular and graphic formats which could be easily adapted by engineers and planners.

2.1.3 EPA Storm Water Management Model (SWMM)

EPA SWMM is one of the most popular runoff modelling tools among water resource professionals and researchers. SWMM has the capability of evaluating the performance of several GI practices such as permeable pavements, rain gardens, green roofs, street planters, rain barrels, infiltration trenches and vegetated swales. SWMM can be applied in a wide range of spatial scales varying from site to catchment scale. SWMM incorporates a sub catchment based approach to simulate runoff generated from rainfall where the runoff can be diverted to different storage or treatment devices(Rossman, 2010).

SWMM consists of four components: “RUNOFF”, EXTRAN”, “TRANSPORT” and “STORAGE/TREATMENT (S/T)” blocks which are used to simulate different stages of the hydrological cycle(Tsihrintzis and Hamid, 1998). Storage processes are well simulated within all the blocks while the (S/T) block is used for the modelling of a majority of the processes occurring in GI for water quality improvement. First order decay processes are applied in RUNOFF, TRANSPOSRT and S/T blocks. Settling velocities are used in the TRANSPORT block when simulating the sedimentation process that occurs in GI. Biological processes can be only simulated by first order decay or removal equations through RUNOFF, TRANPORT or S/T blocks(Huber et al., 2004).

The catchment characteristics need to be first defined as the input data for SWMM which are, area, width and slope of the sub catchment, rainfall data, percentage imperviousness, manning’s “n” values and depression storage for pervious and impervious areas. Finally, the sizing characteristics of different GI practices are required to simulate their effectiveness on managing urban runoff. An output report file is generated from the data used for each model run which also contains the status of the simulation. The output report file is used by the model interface to create time series graphs, tables and statistical analysis of the simulation results. SWMM has a user friendly GUI which enables more visualization of the study area by importing CAD or GIS files. Handling of SWMM requires knowledge of fundamental processes in regards to hydrological modelling which limits its application to within specific user groups(Huber et al., 1988, Huber and Singh, 1995, Huber, 2001, Huber et al., 2004, Abi Aad et al., 2010).

2.2 Modelling Tools that Address Economics of GI

The tools that analyze the economics of GI vary from whole life cycle cost models to cost benefit analysis models. Most of these tools are available as simple spreadsheet tools which contains costing details for a specific site or a region. Four tools which are popular worldwide in evaluating the economics of different GI practices are reviewed here.

2.2.1 WERF BMP and LID Whole Life Cycle Cost Modelling Tools

WERF modelling tools contain a set of Excel spreadsheets which facilitates the evaluation of whole life cycle costs of GI for stormwater management. These tools have the ability to express monetary values associated with GI in regards to capital outlay, operation and maintenance costs. The modelling tools are developed for nine GI practices, they being; extended detention basin, retention pond, swale, permeable pavement, green roof, large commercial cisterns and residential rain garden, curb-contained bio retention and in-curb planter vault. WERF tools are mainly suitable for conducting planning level cost estimates(Water Environment Research Foundation, 2009).

WERF modelling tools contain cost details which are derived from US literature, interviews and expert judgments. The default values for cost analysis can be altered by users whenever the site specific data are available for the area.

The user inputs for the model are general information of the treatment devices such as system size, drainage area and system type. After evaluating the whole life cycle costs for the construction, operation and maintenance stages, a cost summery is provided to the user. Furthermore, the tool gives users an option of selecting the sensitivity analysis in the planning and designing stage. Illustration of the results by present value graphs is another important output that WERF BMP modelling tools can produce. Three different present value graphs can be obtained from the modelling tools such as annual present value of cost expenditure, cumulative discounted cost with time and discounted costs with time(Houdeshel et al., 2009). WERF modelling tools for LID and BMP comes with an interface for the data entry in the format of an excel spreadsheet which makes the handling of software easy for different levels of user groups(Water Environment Research Foundation, 2009).

2.2.2 Green Infrastructure Valuation Toolkit

Green Infrastructure valuation tool kit is an excel spreadsheet tool which can calculate the costs and benefits associated with different GI. The tool can be used in decision making for selecting the best investment among existing partners and compare the benefits of GI over conventional development and to select the best practice from a possible set of opportunities. The target user groups are, managers developers or other stakeholders who are interested in investment of GI(Ozdemiroglu et al., 2013). The difference between the GI Valuation Toolkit and the other tools reviewed earlier are, the tool calculates benefits of GI not only for stormwater management but also for ten other different aspects. The eleven different aspects that the tool addresses in evaluating the economic benefit include: stormwater and flood management, climate change adaption and mitigation, place and communities, health and wellbeing, land and property values, investment, labor productivity, tourism, recreation and leisure, biodiversity and land management(Natural Economy Northwest, 2010, Evans et al., 2012). The tool calculates economic benefits by considering the land area or green space covered with any GI practice.

Costs and benefits related to different services of GI are calculated using the market prices of the area. At instances where the market values are not available the non-market values can be applied. The modelling approach for calculating the economic benefit uses various evaluation methods such as contingent valuation, hedonic pricing, travel cost method, effects on production, preventative expenditure, benefit transfer and specific values. (Natural Economy Northwest, 2010).

The main input data required for the calculation are, the land area covered with green cover and the information on species of trees or plantation used. The cumulative economic benefit of all the eleven aspects can be calculated as the final outcome. The return on investment of the GI implementation can be also calculated which can be a decision aid for the stakeholders. Though this is designed as a simple and easy to use spreadsheet tool, the support of an expert such as an economist is recommended during the cost benefit analysis process.

2.3 Modelling Tools that Address both Aspects

There are some tools developed which can address combined aspects of GI such as reduction of runoff quantity, improving of runoff quality and economic analysis. Five modelling tools are selected for the review within this category and they are: CNT National Green Values Calculator, SUSTAIN, MUSIC, LIDRA and WinSLAMM.

2.3.1 CNT Green Values National Stormwater Management Calculator

The Center for Neighborhood Technology (CNT) national stormwater management calculator which is also known as National Green Values Calculator (GVC) is a tool that was developed to compare the performance, costs and benefits of GI with conventional stormwater management practices(Kennedy et al., 2008). The step by step procedure of the calculator allows the users to set up a runoff reduction goal for their sites by considering the optimum runoff reduction efficiency through a set of GI practices. The GI practices that are incorporated in national GVC include; green roof, planter boxes, rain gardens, cisterns/rain barrels, native vegetation, vegetated filter strips, amended soils, roadside swales, trees, swales in parking lot, permeable pavement on parking, permeable pavement on drive ways and alleys, and permeable pavement on sidewalks. The calculator is designed to be used in site scale and therefore the tool is incapable of handling evaluations from neighborhood scale to catchment scale(Wise, 2008, Center for Neighborhood Technology, 2009).

CNT uses the Soil Conservation Service (SCS) runoff curve number method to calculate the volume of runoff generated. The effect on the GI for infiltration, evapotranspiration and reusing the stormwater runoff is calculated by modelling the ability of each and every practice's ability to capture runoff(Kauffman, 2011). The construction and maintenance costs for different GI practices is calculated and added to get the total life cycle cost for the project. The cost module includes the design life cycle of the project and gives the ability for the user to analyze costs and benefits for: 5, 10, 20, 30, 50, and 100 year spans. The cost valuations for infrastructure maintenance and design are obtained from the relevant literature and the latest industry data for the relevant GI construction item(Center for Neighborhood Technology, 2009).

The user inputs for national GVC contains site specific parameters such as land cover distribution, soil type, runoff reduction goal and attributes of the different GIs that are being used for the analysis. Runoff volume reduction and cost benefit analysis results of different GI are displayed directly on screen in different tabs, as outputs. National GVC is available as a web based freely available tool and the simple interface makes it easy to handle for users at any knowledge level. However, the tool cannot be applied for different geographical regions since it contains data for US based context only.

2.3.2 EPA System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN)

SUSTAIN is an ArcGIS based decision support system developed by the US EPA to guide water resource management professionals for the design and implementation of management plans to preserve water and meet water quality goals in catchment scales. It also includes the application of GI controls in stormwater management projects and allows the users to optimize practices in terms of both environmental and economic perspective. SUSTAIN consists of seven key components, being: framework manager, ArcGIS interface, catchment module, BMP module, optimization module, post-processor, and Microsoft Access database(Lai et al., 2007). The currently supported GI practices by SUSTAIN includes: bio retention, cistern, constructed wetland, dry pond, grassed swale, green roof, infiltration basin, infiltration trench, porous pavement, rain barrel, sand filter (surface and non-surface),vegetated filter strip and wet pond.

The economic component for GI, BMP construction, has a more sophisticated manner, compared to others, for analyzing the unit costs of individual segments.The cost estimation and cost optimization module in SUSTAIN are the main two components of the software used to analyze the economic benefits of the GI in stormwater management (Lai et al., 2006, Lai et al., 2009, Lai et al., 2010). The cost data in the cost estimation module are obtained directly from industry and the unit cost approach in SUSTAIN is designed to minimize the errors that can result by considering the bulk construction cost of GI on a country wide basis. The GI optimization module uses a tiered approach for the analysis of cost effectiveness of individual and combined catchment scale applications. The decision criteria in SUSTAIN is user defined and to meet that criteria, evolutionary optimization techniques are used. The two search algorithms currently in use for this application are scatter search and non-dominated sorting generic algorithm-II. An optimal cost effectiveness curve is the outcome of this module for the desired water quantity or water quality control targets (Lai et al., 2007).

The input data required for the model are, the land use data, catchment data and the designing details of different GI practices. This will give the outputs as the performances of different GIs in runoff quality improvement and quantity reduction. The model can be used to select optimal GI scenarios according to their cost effectiveness. SUSTAIN integrates GIS data for the analysis which makes the data input to the program more comprehensive and the level of complexity is higher. Therefore, the end user needs to have sufficient knowledge of stormwater management practices and GIS software packages (Lee et al., 2012, King Country, 2013). Thus the software program is mainly suitable for large scale projects which need more accuracy on the basis of both environmental and economic aspects.

2.3.3 Model for Urban Stormwater Improvement Conceptualization (MUSIC)

MUSIC is a conceptual level planning and designing tool used for the performance assessment of different GI practices in improving stormwater quality. This modelling tool enables the users to determine, the quality of runoff produced by catchments, the performances of different GI measures on improving the runoff quality in order to achieve target reduction levels with the option to select the best possible GI scenarios based on their life cycle cost assessment. MUSIC can be operated in a range of spatial scales varying between 0.01 km^2 to 100 km^2(Wong et al., 2002). MUSIC supports a number of GI practices such as bio retention systems, infiltration systems, media filtration systems, gross pollutant traps, buffer strips, vegetated swales, ponds and sedimentation basins, rainwater tanks, wetlands and detention basins.

The underlying model algorithms of MUSIC were developed by modifying the properties of a previous model known as SimHyd, developed by Chiew and McMahon (1997), which enables the disaggregation of daily runoff into sub-daily temporal patterns. The runoff generation from impervious and pervious areas is modeled separately in MUSIC. A stochastic approach with dry and wet weather events mean concentrations are used for the pollutant generation simulations of MUSIC (Dotto et al., 2011, Dotto et al., 2008). The life cycle costing data were gathered from a number of stormwater managers from different cities across Australia. These data are further analyzed by means of regression and statistical methods to develop a representative set of data for different GI treatment measures(music by eWater User Manual, 2013).

MUSIC contains inbuilt meteorological data and climatic data from 50 reference areas within Australia. Users also have the ability to include meteorological data for specific study areas. Catchment characteristics include impervious area and land use. Design specifications of the device (treatment type, size, area) are the other input data required for the MUSIC modelling tool. The outputs generated from the model are flow reduction capability, pollutant removal efficiencies and the life cycle costs of different GI scenarios. The output is illustrated as time series graphs, tabular statics and cumulative frequency graphs(Wong et al., 2002, Wong et al., 2006). The tool is designed for professionals with more technical knowledge in stormwater management and the target user group includes urban stormwater engineers, planners, policy staff, state, regional and local government agencies.

2.3.4 Low Impact Development Rapid Assessment Tool (LIDRA)

LIDRA is a tool that assesses the cost effectiveness of different GI practices by using hydrological and cost accounting methods. The modelling tool contains a rainfall generator, hourly water balance calculations, the opportunity of selecting over 30 different GI strategies with 16 different street possibilities and most importantly a built in database that contains the life cycle costs with a phased life cycle costs algorithm for GIs for the cost benefit analysis(Spatari et al., 2011). LIDRA is web based online assessment tool and GI planning is done in the catchment scale(Montalto et al., 2007, Montalto et al., 2011).

The model contains a stochastic precipitation generator and the runoff calculation is based on a physically based water budgeting procedure. The precipitation data are stochastically generated by historical rainfall data sets by using a Markov Chain and bootstrapping method. The difference in runoff from pre and post development of different GI scenarios are calculated using a water balance based on the Thornthwaite Mather approach(Aguayo, 2010). For the economic component, the model uses a 30 year life cycle costing algorithm which reports capital, operation and maintenance costs(Yu et al., 2010).

The major data inputs required in LIDRA modelling tool are: hourly precipitation data, parcel characteristics of the area, land use data, soil types and parameters of GI practices. Some of the outputs of this tool are the amount of runoff that can be reduced annually, the annual or cumulative costs for the practices, the comparison of cost effectiveness of different practices compared to one another and the rate variability of results that the user needs to deal with when uncertainty and changes occur in cost, climate and inflation rates(Yu et al., 2010) .LIDRA is an online web based program with a user friendly interface that makes it easy to handle by different levels of users.

2.3.5 Source Loading and Management Model for Windows (WinSLAMM)

WinSLAMM was initially developed as a model to study the relationship between pollutants of urban runoff and runoff quality. With the advancement of GI as a stormwater source control measure, the tool has been upgraded by adding modules which have the capability of modelling the performances and life cycle costs of different practices such as infiltration/bio filtration basins, street cleaning, wet detention ponds, grass swales, filter strips and permeable pavements(Pitt and Voorhees, 2002, Pitt and Voorhees, 2004). The tool supports modelling in different spatial scales such as site, catchment and regional scales.

WinSLAMM is commonly used as a planning tool and can be applied for the hydrology of different types of storms including small storms. The model can evaluate long series of rain events and the impacts of urban soils on runoff are also considered. The biological conditions of the receiving waters are calculated according to the type of GI practice which has been used and the characteristics of the site. Cost details of the different practices can be directly obtained from the model run. WinSLAMM can be integrated with a number of other drainage models when a detailed analysis of runoff is required. The model also contains inbuilt Monte- Carlo components for considering uncertainties(Pitt and Voorhees, 2004, Pitt, 2006).

The tool uses directly measured input parameters such as areas and characteristics of contributing catchments to the catchments and the pollutants associated with particulate solids in these areas. The calculated model outputs from the WinSLAMM model are runoff volumes and quality of pre development and post development with GI and total control costs in terms of capital costs, land costs, annual maintenance costs, present value of all costs and annualized value of all costs. One of the important features of this model is that the outputs can be imported to a number of other models and also can be integrated in Geographic Information Systems (GIS) platform. The users require fundamental knowledge of urban hydrology and stormwater management procedures in order to handle the model (Pitt and Voorhees, 1995, Pitt and Voorhees, 2002, Pitt and Voorhees, 2004, Pitt, 2006).

3. Comparison of Modelling Tools

In this section, a comparison has been conducted on the ten modelling tools in terms of the number of GI practices they can represent, modelling approaches, data requirements, accuracy and regional limitations.

3.1 Number of GI Practices that the Tools can Support

Different models support different GI practices and it is important for the users to have an idea of the GI practices each tool can model when selecting a model.Some of the tools discussed here can model the performance or economics of a wide range of GI practices while some are limited. SWMM,WERF, CNT, SUSTAIN, MUSIC and WinSLAMM can model rain gardens, infiltration practices, retention ponds, constructed wetlands and swales as a common set of GI practices. RECARGA is limited in modelling bio retention, rain garden and infiltration based GI practices.P8 can only model a limited number of GI such as detention ponds, infiltration basins, swales and buffer strips. LIDRA and GI Valuation Toolkit can analyze the performance of GI in stormwater management with their economics for wide range of practices including urban green space. CNT is the only tool that can assess amended soils as a GI practice and it also has the capability of separately modelling the impact of permeable pavement for different locations such as parking lots, driveways and alleys.

3.2 Modelling and Simulation Approach

Among the ten models selected for the review, except for WERF and GI Valuation Toolkit, all the other models simulate the runoff generated by rainfall in assessing the performance of GI.RECARGA, P8, SWMM, SUSTAIN, MUSIC, LIDRA and WinSLAMM models can facilitate continuous and single event simulation while CNT can be used for event based simulation only. CNT contains an inbuilt database of hourly rainfall data for the USA. In RECARGA, P8 and LIDRA, these models use hourly time steps for simulations. SWMM, SUSTAIN, MUSIC, WinSLAMM can simulate runoff for hourly or shorter time steps.

In the modelling of economic aspects, GI Valuation Toolkit uses complex economic pricing and evaluation methods for the cumulative cost benefit calculations. Tools that have the capability of calculating the lifecycle costs for GI (CNT, MUSIC, LIDRA and WERF) contain inbuilt databases for the construction, maintenance and operation costs for GI practices specifically for the region where the model has been developed.

3.3 Data Requirements

The general data requirements for almost all the tools are climatic data, soil profile and land use data. RECARGA,P8, LIDRA and WinSLAMM models require fewer inputs compared to complex hydrologic and hydraulic models such as SWMM. Therefore, these models are suitable for planning level GI implementation activities rather than detailed design. Most of the input data required for these models can be obtained from literature, drainage plans, local councils or soil surveys. MUSIC and CNT models also have low input requirements in runoff modelling since most of the regional specific parameters (climatic data, soil types, hydraulic conductivity etc.) are inbuilt with the software as default values. SUSTAIN model inputs are integrated with a GIS interface. Thus the GIS based inputs such as catchment information, land use, land cover and digital elevation profiles are required and this can be found easily from local mapping sources. For the costing data MUSIC, WERF, SUSTAIN, LIDRA and GI Valuation Toolkit comes with inbuilt input databases which makes the data requirements for economic analysis much more user friendly. However, user defined input costing data can also be provided to these models when more specific valuations are required.

3.4 Model Accuracy

The uncertainty associated with any modelling tool is an attribute that cannot be avoided and which can have a significant impact on accuracy of the outcome. However, uncertainty can be reduced to a certain level by calibrating and validating the model results whenever the data are available. When looking at the accuracy levels of the different models reviewed, SWMM and WinSLAMM provide the highest level of accuracy as detailed design tools. WinSALMM contains built in Monte Carlo sampling procedures to reduce the uncertainties associated with data inputs. This procedure creates model output more accurately by representing them in probabilistic terms(O'Bannon Ph et al., 2008). A number of literature studies on SWMM modelling indicates that SWMM can produce reasonably accurate results when the model outcomes are calibrated and validated.

RECARGA, P8, CNT and LIDRA are the most suitable for GI planning level activities, due to the uncertainties and the variation of input parameters that can significantly affect the outcome of these models. SUSTAIN model incorporates an aggregated modelling approach to represent distributed GI in larger scale catchment planning applications. Though this methodology has been introduced to reduce the computational times and efforts, it can lead to uncertainties in the model output. MUSIC is also a tool that is only accurate as a conceptual designing tool since it does not include the necessary algorithms for the detailed sizing of GI practices.

The inbuilt cost data in WERF and GI Valuation Toolkit models have limited accuracy levels to be used in different applications since they are obtained by using a reference data set. Therefore, users need to define their own cost data using a number of references in order to get more accurate results. The GI Valuation Toolkit also does the cost benefit analysis based on a number of other Eco System Services. Therefore, some of the benefits of these services can be subject to the scenario of double counting. This can also create some uncertainties in the results by over estimating the benefits of GI. The CNT model does not include the costing details for pipes or detention ponds since the model does not predict the peak flow. Therefore, CNT cannot be accurately used to determine the costing required for storage and sizing of the overflows(Center for Neighborhood Technology, 2009).

3.5 Regional Applications and Limitations

Though there are number of different tools available for GI modelling, one of the major limitations of them are that the majority of the models are designed to be applied within a specific country or region where they were developed. There are very few tools available that can are transferable to any geographic location since most of them contain inbuilt databases related to the region or location where they were developed.

RECARGA is a tool that uses the Department of Natural Resources (DNR) conservation practice standards for Wisconsin, USA and P8 is calibrated with the catchment data of Rhode Island. Therefore, these two tools have limited applications only for a particular area outside of those locations.. MUSIC is the most popular tool in Australia for modelling GI which contains the inbuilt climatic data of Australia. However, MUSIC has been latterly developed to use under UK conditions as well. WERF, SUSTAIN, and LIDRA are developed with inbuilt data bases for a specific context but all three modelling tools have got the flexibility for users to include their own data for the required modelling purposes. Since CNT is an online tool which comes up with cost benefit data for a range of different cities in the USA, the usage of the tool is only limited to there. The GI Valuation Toolkit which was developed in the UK can also be used in any other region with the inclusion of cost benefit data of that particular region. WinSLAMM was initially developed for use in North America and has recently extended its usage for overseas. Among the ten models SWMM is one of the most sophisticated model which can be used in any geographic region if the particular data are provided.

4. Summary

A comprehensive is review is conducted by considering tools that are currently used for the modeling of stormwater management and /or economics aspects of GI. After the initial screening process, ten modelling tools which have the capability of simulating the economics of GI practices and/or their performance in stormwater management have been reviewed by comparing their attributes in detail. These tools ranged from simple spreadsheet models to complex watershed modeling tools. RECARGA, P8, SWMM, MUSIC, SUSTAIN and WinSLAMM support continuous simulation which provides more accurate results in runoff and GI performance modeling. By looking at the different aspects these tools can address, and in particular a stormwater management objective, SWMM compared to others can be used in more complex large scale projects up to and including the detailed design of GI. When comparing accuracy, algorithms and the scales, SWMM appears to be the most sophisticated tool in modeling stormwater quality, quantity and GI performance. Another advantage of SWMM is that it is an open source software. Of the tools which are used for planning level GI performance evaluation, MUSIC appears to be the most reliable tool with the number of supportive GI practices and with a good range of spatial scales. However, regional barriers are a limitation of using MUSIC that should be considered.

5. Areas for Future Research

With the evolution of GI as an economically feasible and sustainable stormwater management strategy, a number of new modelling tools have been developed which have the capability of simulation of performances of these practices. However, there are still some challenges and limitations that exist with most of these tools varying from their data requirements to the uncertainty of model outcomes. Therefore, identification of areas for future research is important in developing more sophisticated tools with reduced uncertainty. Of the various issues related to GI models, major areas of concern were identified and are discussed in detail in the sections below.

5.1 Increasing the Stakeholder Participation

GI modelling is an interactive process which involves a number of different stakeholders such as water resource engineers, urban planners, economists, land owners and also the general public from, planning to designing stages. Therefore, this increases the pressure of making appropriate decisions when there are contrasting opinions from different stakeholders. It is a challenge to cover all issues and concerns in one platform when planning GIs to be implemented in communities. Even though it has been identified that stakeholder participation is increasingly becoming important in environmental decision making, there is still a lack of research on how to involve stakeholders, with different levels of expertise, in catchment management decision making(Korfmacher, 2001).

Strategies should be identified for involving more stakeholder participation in current GI modelling practices. This can be achieved by introducing best practices such as introducing transparent modelling procedures, determining clear objectives of the GI implementation and continuous involvement of the participants in each of the different stages of the planning process(Korfmacher, 2001, Glasbergen, 2002, Voinov and Bousquet, 2010).

5.2 Development of Model Driven Decision Support Systems

Model driven Decision Support Systems (DSS) in environmental modelling are becoming more popular presently rather than the stand along modelling tools which provide only a direct outcome. The major reason for that is, DSS is a platform which combines both comprehensive modelling along with other important aspects such as social, technical and economic considerations which are becoming equally important in catchment modelling. However, along with the advancement of model driven DSS there still exist some areas which need be addressed in regards to increasing their accuracy and effectiveness. Some of the challenges identified in model driven DSS are issues related to storage and retrieval of data for different models, methodologies in obtaining participant interaction, issues related to the validation of the final outcomes and the designing of user friendly interfaces with combined complex simulation and development of easy to use user interfaces for the participants in decision making(Rizzoli and Young, 1997, Power and Sharda, 2007, Matthies et al., 2007).

5.3 Providing more Capabilities for GIS and Remote Sensing Integration

Remote sensing and GIS technologies are now extensively used for large scale distributed catchment modelling and urban planning activities for processing, analyzing and visualizing digital spatial data (Goodchild et al., 1996, Hinton, 1996). GIS provides a more sophisticated means of obtaining the major input data for the models such as land use, drainage, climatic and water quality data that and this can also save the modelling times. Though some of the tools described here already have GIS integration capabilities, most of the models are still in their infancy in regards to using GIS as a tool for increasing the effectiveness and visual interpretation of the model output. The GI modelling can be done more efficiently if the tools can support more remotely sensed data sets such as land use, land cover and geology of the study areas. This also requires development of GIS and remote sensing mapping databases, developing links between models and the spatial software and enabling of the import and export of data sets between two platforms which itself needs to be further researched in the future.

5.4 Development of more Web Based Simulation Methods

Web based simulation provides a more integrated approach in modelling due to the ability to access a wider range of spatially distributed data sets. The technologies for developing web based modelling systems for catchment management are emerging rapidly, as an extensive amount of research is currently conducted on areas such as Object Oriented GIS (OOGIS) and Geography Markup Language (GML) (Choi et al., 2005). Some of the advantages of using web based simulation methods are ease of handling, the ability to network and communicate with other user groups via the web, the ability to use them without licensing, cross platform capability, controlled access options and wide availability(Byrne et al., 2010). In GI modelling applications web based simulation appears to provide a wide range of benefits combined with some of the other previously discussed options such as stakeholder participation, decision support and GIS integration. Therefore, this area should be further researched and new methodologies in developing web based simulation modelling tools for GI should be identified.

5.5 Enhancement of Optimization Modelling Based on Different Objectives

The current modelling approach for most of the models discussed here is based on the selection of a best practice based on either the performances of GI in stormwater management or the economic benefit of the practice, either of which is a single objective. However, in long term and larger scale projects this approach tends to be less efficient due to the limitation in the methodology to maximize aggregate aspects. A multi objective optimization based modelling approach can address this problem by providing the ability for users to identify the practices which perform best under minimum cost and other different user specified objectives. Currently, number of studies exists in applying multi objective optimization algorithms for GI planning nevertheless limited efforts were taken into incorporating the methodology into modelling tools. But there is an extensive literature base available for the different optimization methods used in catchment modelling and urban planning activities. Future research studies need to be done in selection of the best optimization algorithms for particular GI selection processes. These optimization algorithms should also consider model runtimes and data handling capacities.

5.6 Increasing the Capabilities of Model Coupling

To understand the behavior of regional or catchment scale GI practices, the coupling of the hydrologic and atmospheric models are important. These interactions can provide a more sophisticated means of identifying the performances related to different climatic conditions and in an efficient manner. Currently there exists a trend in global research in coupling of hydrological and atmospheric models to improve the flow and atmospheric simulation(Jasper et al., 2002, ROSBJERG, 2007). The future research needs to particularly focus on better modelling structures and parameterization through better understanding of physical processes related to the water cycle and atmosphere which are currently poorly understood(Soulis et al., 2005).

5.7 Introducing Methodologies to Reduce the Model Uncertainties

To model the performances of GI in stormwater management, runoff models need to be developed and one of the major problems in rainfall runoff models are the high uncertainties. The major reason for the presence of uncertainties is the number of different parameters present in hydrological modelling. To reduce the uncertainties, it is always recommended to calibrate and validate the models. However, limited monitoring data are available in most of the regions which can be used for the calibration of hydrological models. Therefore, regional wide stormwater monitoring networks should be developed in order to get more accurate model results. Also databases should be developed with the worldwide data related to the performances of different GI practices. The BMP database(International Stormwater BMP Database, 2004) is an example of a database which is currently providing data related to GI performances and can be accessed by users worldwide. Similar databases should also be developed for the economic analysis of GI based on the world wide costing details since most of the data on current economic modelling tools are limited to certain areas.

The labor and time required for the manual calibration of hydrological models is also one of the major concerns which can create problems in model calibration which can also create uncertainties. Therefore, the modelling tools need to include less time consuming calibration techniques such as automatic calibration(Sorooshian and Gupta, 1983, Yapo et al., 1996). Genetic Algorithms (GA) are one of the most popular methods used for automatic calibration(Khazaei et al., 2013). The modelling tools can be made more reliable with future research work on integrating better calibration procedures within the models.

5.8 Application of Cyberinfrastructure

With recent technological advancements, methodologies which brings information technology and people together are becoming more predominant. Cyberinfrastructure is one such technology which is a combination of data resources, network protocols, computing platforms, and computational services that brings people, information, and computational tools together to perform data rich applications(Yang et al., 2010). There have been recent considerations on looking at the applicability of cyberinfrastructure for GI modelling, since the planning of optimum GIs is an aggregate process between computer based modelling and simulation along with stakeholder perspectives.

The benefit of looking at advanced technologies such as cyberinfrastructure for GI modelling is that the stakeholders can directly participate in the planning process, which is an important concern as discussed in section 5.1. At the same time cyberinfrastructure related applications can support services related to data acquisition and storage, data management, data visualization and data mining through the internet which will be a major advantage in hydrological modelling activities which requires extensive amounts of data. These data can be effectively transferred via the web for the development of distributed models, model calibration and validation which will be a major improvement on current modelling practices.

5.9 Introducing Modules to Model the Eco System Services of GI

Though GI practices were earlier identified as a replacement for the conventional stormwater management strategies, the recent research directions were more trended towards a number of other benefits they provide which are also known as Eco System Services (ESS). ESS such as air quality improvement, urban heat island reduction, energy savings and climate change. Adaptation of different GI practices were studied by researchers and the methodologies for the quantification of these benefits were identified in a number of different studies(Bass et al., 2002, Gill et al., 2007, Pugh et al., 2012). Models were also developed to evaluate the GI performances in assessing some of these ESS. Urban Forest Effects Model (UFORE) is one such tools which is specifically designed to model the effect of GI on air pollution, greenhouse gases and global warming(Currie and Bass, 2008). However, ESS modelling of GI is currently a forefront research area which also has complexities specially related to the hardships of data acquisition. When doing the cost benefit analysis of GI, most of the current models concentrate on their benefits of stormwater management which provides an underestimation of the total benefits these practices can provide. Therefore, it will be more effective in introducing ESS modelling capabilities to the current models, especially for the tools which asses the long term costs and benefits of GI. This will also provide sound information on decision making activities in project planning.

5.10 Application of Real Time Modelling for GI Performance Simulation

Real-time data refers to spatial and non-spatial data that becomes available to the real-time GIS, either at fixed time intervals or after the completion of certain events such as the arrival of data at a desired destination(Al-Sabhan et al., 2003). Though there are a number of models available for hydrologic simulations most of the models lack the suitability for real time applications. Currently there are a number of satellite based rainfall, climatic, elevation and other real time digital data available through the internet. With the advancements of high speed computers and the data communications most of these data can be easily downloaded in ready to use formats(Ebert et al., 2007). However, models need to be enhanced to use these technologies which will contribute to more accurate and less time consuming modelling operations.

6. Conclusion

Having a review on most recent and up to date tools which can model the performances and economics of GI, it can be concluded that there are number of issues and challenges still exists with most of these tools which can be improved by further research. Though majority of these tools are robust and user friendly, still there exists a lack of incorporating more stakeholder participation within the models which is becoming a more crucial aspect in current GI planning activities.

Also, these tools should be upgraded to be compatible with the latest technologies such as cyberinfrastructure, real time control, integration and coupling with different models to provide more robustness on the model outcome. Methodologies should be introduced to reduce the uncertainties present within the models to provide more reliable results. In particular, databases should be developed for the users to obtain input data easily and also monitoring networks should be designed to get data for the calibration and validation of models.

Another major drawback of most of the tools discussed here are, the majority of them are developed to be applied for a specific country or region. Therefore, more focus should be given in future model developments on making them applicable for different regions and the ability to run with user defined input should be increased. Tools that have the ability of evaluating the performance of GI over conventional stormwater management strategies have to be updated with more recent GI practices that are not included in most of the currently available modelling tools such as amended soils and urban floating wetlands. Green roofs, rain gardens, infiltration and bio retention are most commonly applied in almost all the tools available and GI practices such as curbs, planter boxes, downspout disconnection and permeable pavement are not addressed well compared to the former. Therefore, more sophisticated tools should be developed to address a wider range of GI practices available, with the ability for users to define new GI practices according to their requirements.

Majority of the current tools also trends to apply life cycle costing and cost benefit analysis of GI practices as inbuilt modules due to the number of benefits and low development cost when compared to conventional practices. However, apart from environmental and economic benefits, GI practices can provide social benefits such as improving aesthetics, habitats, community livability, human health and also increased land value. If these tools can also include modules for evaluating the social benefits of GI it will assist in the long run for promoting implementation of more GI within communities.

One of the trends that can be seen in most of the recently developed tools is models with a GIS interface. GIS can be efficiently used in catchment modelling and more tools should be developed with a GIS interface. .GI practices also provide a wide range of ESS apart from managing stormwater as discussed earlier. Currently, only a very limited number of tools exist which can model ESS and also the economic benefits that can be obtained by GI practices. New modules can be added to the existing GI modelling tools that can predict the environmental and economic benefits of different ESS. This will contribute to a new dimension in current GI modelling by not only looking at them as an integrated urban water management strategy but also a more profitable set of practices which provides a wide range of environmental, economic and social benefits.

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