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Representing Green Infrastructure Management Techniques in Arid and Semi-arid Regions: Software Implementation and Demonstration using the AGWA/KINEROS2 Watershed Model

RESEARCH AND DEVELOPMENT

Representing Green Infrastructure Management Techniques in Arid and Semi-arid Regions: Software Implementation and Demonstration using the AGWA/KINEROS2 Watershed Model

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Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AGWA	Automated Geospatial Watershed Assessment Tool
ARS	Agricultural Research Service
BMP	Best Management Practice
BMPDSS	Best Management Practice Decision Support System
CGP	Connecting Grid Pavers
CN	Curve Number
EPA	U.S. Environmental Protection Agency
ESRI	Environmental Systems Research Institute
GI	Green Infrastructure
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
HSPF	Hydrologic Simulation Program – Fortran
IHACRES	Integrated Hydrologic Analysis – Center for Resources and Environmental Studies
IMP	Integrated Management Practice
KINEROS2	Kinematic Runoff and Erosion Model
LID	Low Impact Development
L-THIA-LID	Long-term Hydrologic Impact Assessment – Low Impact Development
NRCS	Natural Resources Conservation Service
ORD	Office of Research and Development
PC	Pervious Concrete
PICP	Permeable Interlocking Concrete Pavers
SCS	Soil Conservation Service
SSURGO	Soil Survey Geographic Data Base
SUSTAIN	System for Urban Storm Water Treatment and Analysis Integration
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
USDA	U.S. Department of Agriculture

1.0 Abstract

Increasing urban development in the arid and semi-arid regions of the southwestern United States has led to greater demand for water from a region of limited water resources which has fundamentally altered the hydrologic response of developed watersheds. Green Infrastructure (GI) practices are being widely adopted to mitigate the impacts of development on water quantity and quality. However, Geographic Information System (GIS)-based watershed tools that operate from the lot-to-subdivision-to-watershed level for rapid GI planning assessments are lacking. The Automated Geospatial Watershed Assessment (AGWA) tool was modified to allow the design and placement of a small set of GI practices in order to simulate urban hydrology with and without GI features. This software development effort was undertaken to take advantage of the advanced, physically-based infiltration algorithms and geometric flexibility of the Kinematic Runoff and Erosion (KINEROS) 2 watershed model. The resulting software provides an up-to-date GIS GI assessment framework that automatically derives model parameters from widely available spatial data. It is also capable of manipulating GI features and simulating at the lot scale within a graphical interface to conveniently view and compare simulation results with and without GI features. These features distinguish the approach presented herein from existing GI hydrology tools. The AGWA GI software was then tested at the lot level with and without GI features to ensure programming integrity and hydrologically sound results. Further testing was conducted at the subdivision level without GI features as high-resolution rainfall-runoff observations were available from a subdivision in Sierra Vista, Arizona. This testing also confirmed programming integrity and the capability to realistically simulate urban hydrology. A set of case study simulations was then conducted for the Sierra Vista subdivision with various combinations of the implemented GI features. Results indicate that the resulting software was robust at the lot, subdivision, and small watershed level and it can realistically represent and simulate storm runoff responses for the selected GI features. The AGWA GI tool offers a foundation for the incorporation of a broader array of GI features.

2.0 Introduction

Urbanization has numerous effects on a watershed as it replaces vegetation and pervious open areas with impervious surfaces such as roofs, driveways, parking lots, and roads. The introduction of impervious surfaces has significant impacts on watershed hydrology, especially in regard to drastic reductions in infiltration of rainfall, resulting in increased runoff volumes, peak discharges, and higher energy releases. Increased runoff results in lower groundwater recharge and base flows in humid regions (Leopold, 1968; Makepeace et al., 1995; Rose and Peters, 2001). In semi-arid regions urbanization will increase runoff, as in humid regions, but can also result in increased groundwater recharge by concentrating runoff in areas with higher infiltration capacity, such as ephemeral alluvial channels (Scanlon et al., 2003; Goodrich et al., 2004).

Soil compaction and lower infiltration also result in lower soil storage volume, and rapid soil saturation with rainfall events (Booth and Jackson, 1997; Dunne and Leopold, 1978; Kennedy et al., 2013). Larger runoff volume increases downstream discharge and flood magnitudes (Norman et al., 2010). Urbanization may increase small floods by a factor of 10 or more depending on the percentage of paved area (Hollis, 1975). Higher peak discharge and runoff volumes can significantly alter stream morphology (White and Greer, 2006). Bank erosion and down-cutting of stream beds due to higher discharge volumes results in wider and deeper streams (Booth, 1991; Hammer, 1972). Research suggests that watersheds with as little as 10 to 20 percent impervious area have the potential to increase stream instability (Bledsoe and Watson, 2001).

Nonpoint source pollution is the major cause of urban water quality problems. Storm water runoff collects and concentrates contaminants as it flows over impervious areas (Characklis and Wiesner, 1997; Russ and Russ, 2002). Commonly known pollutants include heavy metals such as copper, lead, zinc and iron; suspended solids; fecal coliform bacteria; nutrients in the form of nitrogen and phosphorus; and hydrocarbons (Bedan and Clausen, 2009; Duda et al., 1982; Norman et al., 2008a).

Traditional storm water management techniques involve transporting the water away from urban areas as quickly as possible; reducing lag times, and increasing runoff volume and peak flows (Booth et al., 2002; Hammer, 1972; Hollis, 1975; Hood et al., 2007; Leopold, 1968). Sustainable planning for urban growth has also been used as a technique which can reduce downstream impacts by decreasing growth in erosion or high-flow hot spots (Norman et al., 2008b). These techniques have numerous impacts on downstream hydrology. New storm water management approaches focus on handling and treating water at the source and reducing downstream impacts. These so-called Low Impact Development (LID) Best Management Practices (BMP) or Green Infrastructure (GI) practices aim at managing rainwater at the site level before it reaches channels.

The Department of Environmental Resources of Prince George's County, Maryland, pioneered LID to mitigate the urbanization impact of increasing impervious surfaces (County, 1999). As opposed to traditional storm water management practices, LID aims to preserve the pre-development hydrology using a variety of cost effective on-site design techniques that store, infiltrate, evaporate, and detain runoff. The overall goal is to encourage source control practices to manage storm water. Prince George's County introduced a new concept of Integrated Management Practices (IMP), that include many LID controls such as bioretention cells or basins, dry wells, filter strips, vegetated buffers, level spreaders, grassed swales, rain barrels, cisterns, and infiltration trenches. LID controls help reduce the need for more traditional storm water management techniques such as curb-and-gutter systems or large detention basins.

Following the guidelines set forth by Prince George's County, there have been multiple implementations of LID practices in urban developments. One example of a large scale housing development was the Jordan Cove Urban Watershed project in Waterford, Connecticut that included monitoring water quality and quantity during and after construction (http://jordancove.uconn.edu). The Jordan Cove Urban Watershed National Monitoring Program Project was a ten-year study funded through the Connecticut Department of Environmental Protection by the U.S. Environmental Protection Agency's (EPA) Section 319 National Monitoring Program (Clausen, 2007). This study employed a paired-watershed approach, wherein, one watershed was developed using traditional development practices (referred to as the "traditional" watershed and a second watershed was developed using LID practices (referred to as the "BMP" watershed). The study’s goal was to determine water quality and quantity benefits of urban residential storm water and pollution prevention BMPs. This project focused on assessing the cumulative impact of LID controls such as rain gardens, cul-de-sacs, grassed swales, porous paver roads, shared pervious driveways, and permanent open spaces. The project was successful in maintaining pre-development runoff peaks and volumes using LID controls. Runoff volume was observed to have decreased by 74 percent in the BMP watershed as compared to the traditional watershed.

LID BMPs have been implemented and evaluated all around the world. Much effort has been put into the modeling of these practices to aid in decision making with respect to design, cost, efficiency, and effectiveness (Ahiablame et al., 2012a; Dietz, 2007; Elliott and Trowsdale, 2007; USEPA, 2000). Models that simulate LID practices include the Storm Water Management Model (SWMM) (Rossman and Supply, 2010), Long-term Hydrologic Impact Assessment – Low Impact Development (L-THIA-LID) model (Ahiablame et al., 2012b), System for Urban storm water Treatment and Analysis Integration (SUSTAIN) (Lee et al., 2012), Hydrologic Simulation Program – Fortran (HSPF) (Bicknell et al., 2001), and BMP Decision Support System (BMPDSS) (Cheng et al., 2009).

The goal of this study is to design and develop a decision support tool to assist in the planning and application of GI practices in urban developments and integrate it into a Geographic Information System (GIS) framework. As the majority of GI/LID work has been developed and applied in humid landscapes this study will focus on arid and semi-arid watersheds. The AGWA GI software will serve as the decision tool and be applicable at the lot, subdivision, and small watershed scales and utilize several of the features of the KINEROS2 rainfall-runoff and erosion model that are well suited to arid and semi-arid watersheds (Goodrich et al. 2012).

3.0 Literature Review

The literature review will discuss several modeling systems that have been developed to estimate and assess the hydrologic and water quality impacts of urbanization and the use of various GI/LID features. A small subset of GI features, commonly used in arid and semi-arid regions, was selected for incorporation into the modeling tool for this study. A brief review of these GI features and a sampling of how they have been used is also presented.

3.1 Modeling Approaches to GI Practices

Various models can be used to simulate and evaluate the hydrological effects of multiple green infrastructure combinations at different scales, varying from lots, to neighborhoods, to watersheds. A review paper compared ten models for low impact urban storm water drainage based on uses, temporal and spatial resolution and scale, catchment representation, runoff generation, flow routing, contaminant treatment, green infrastructure practices, and user interfaces (Elliott and Trowsdale, 2007). Numerous studies have used these models to evaluate the performance of green infrastructure practices in various areas (Ahiablame et al., 2012b; Ahiablame et al., 2013; Brander et al., 2004; Damodaram et al., 2010; Gilroy and McCuen, 2009; Jia et al., 2012; Kronaveter et al., 2001; Lee et al., 2012; Loucks et al., 2004; Williams and Wise, 2006). A discussion of the most widely used models and a subset of studies follows.

The Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) model uses the Soil Conservation Service Curve Number (SCS-CN) method to simulate runoff and infiltration behavior of LID practices (Ahiablame et al., 2012b; Ahiablame et al., 2013). LID features are considered within a sub-catchment using the concept of Hydrologic Response Units (HRUs) that use an area-weighted average of soil and land cover characteristics to compute a CN. A lot-level LID screening tool is available for one lot at a time but it cannot simultaneously describe and simulate multiple lots of different types (e.g. residential next to commercial) within an urban area. It does not treat runoff-runon from one LID feature into another. L-THIA GIS (ver. 2013) does provide some spatial functionality by providing watershed delineation, computing an area-weighted CN for a sub-catchment, and multi-gauge precipitation data. The GIS generated information can then be imported into the L-THIA spreadsheet calculator.

Ahiablame et al. (2012b) utilized L-THIA-LID to demonstrate a computational procedure to assess theoretical impacts of urban developments on pre-development hydrology and analyze the possible impacts of six LID practices (bioretention, rain barrels and cisterns, green roofs, open wooded space, porous pavement, and permeable patios) in a residential subdivision in Lafayette, Indiana. The authors recommend using this procedure as a quick assessment and screening tool, before proceeding to site-specific data to calibrate and validate the model. Ahiablame et al. (2013) calibrated and validated the L-THIA-LID model for two urbanized watersheds near Indianapolis, Indiana. This calibrated model was used to simulate six different scenarios for retrofitting the urban watershed with rain barrels/cisterns and porous pavements. Both these studies were successful in the theoretic evaluation of LID practices. However, for practical applications, the study recommends field studies and detailed calibration and validation.

SWMM5 is a dynamic rainfall-runoff simulation model used for hydrologic and hydraulic modeling of urban areas using an object oriented framework. It is a relatively comprehensive model with an atmospheric compartment to track dry deposition, and land surface, groundwater and transport compartments. It treats snow and snowmelt but its strength is in hydraulic modeling of the constructed environment. The transport compartment represents a “network of conveyance elements (channels, pipes, pumps, and regulators) and storage/treatment units that transport water to outfalls or to treatment facilities” using node and link objects (U.S. EPA, 2010, p. 33). Within a conduit link, steady, kinematic and dynamic routing options are available. The components of the transport compartment are modeled with node and link objects. SWMM5 has the capability to model the capture and retention of rainfall/runoff using various types of LID practices (Damodaram et al., 2010; Jia et al., 2012).

The non-proprietary version of SWMM5 does not have a GIS interface and attributes of contributing area objects must be manually entered. The user is responsible for dividing the overall catchment into sub-catchments, and for identifying their outlet points. The contributing areas outside the urban environment are modeled in a relatively simple manner as sub-catchments represented by a non-linear reservoir. Within these sub-catchments, LID’s cannot be implemented at the lot-level of a proposed subdivision and cannot represent LID features in series with runoff out of one LID flowing into another. Numerous applications of SWMM for LID assessments have been made. As an example, Aad et al. (2010) modeled rain barrels and rain gardens using the sub-catchment object in SWMM5 with the Green-Ampt infiltration equation. The study claimed to be successful in theoretically representing the rain barrels and rain gardens using SWMM5, but did not provide any comparison to observed data.

The EPA developed SUSTAIN as a decision-support system for the selection and placement of LID BMPs in urban watersheds (Lee et al., 2012). SUSTAIN is more focused on the effectiveness of these BMPs in terms of costs and efficiencies. SUSTAIN aggregates distributed BMPs and focuses on the overall impact of the BMPs at the subdivision/watershed scale. Like SWMM5 it cannot implement LID BMPs at the lot level. SUSTAIN contains an optimization module that develops cost-effective BMP placement and selection strategies based on input parameters such as potential sites, applicable BMP types, and size ranges. This module performs numerous searches for the optimal combination of BMPs that meet user-defined decision criteria. SUSTAIN calculates hydrological processes using components that are derived from version 5 of the Storm Water Management Model (SWMM5). SUSTAIN also provides a GIS framework to design and place LID BMPs. However, the non-proprietary version of SUSTAIN is no longer supported and has not been updated to ArcGIS 10.x.

The freely available versions of both SWMM and SUSTAIN do not automatically estimate model infiltration and hydraulic roughness parameters from commonly available GIS data layers for soils and land cover. Nor do any of the models discussed above have the capability to spatially display simulation results and readily difference non-LID vs LID simulations to aid in targeting LID features.

3.2 Green Infrastructure Practices

A. Bioretention

Bioretention systems are depressions filled with highly permeable soil, and planted with vegetation. These systems allow storm water to pond and infiltrate, thereby supporting vegetation growth while achieving storm water retention, pollutant removal, and groundwater recharge. Smaller scale bioretention systems are also referred to as rain gardens and their design and effectiveness are more dependent on lot sizes and placement within the watershed. Bioretention system design is highly dependent on the soil type, site conditions, and land use. A typical bioretention system would include a sand/soil/organic media for the treatment of infiltrating runoff, a surface mulch layer, native vegetation, and a depression to allow storm water ponding. Davis et al. (2009) and Roy-Poirier et al. (2010) review bioretention technology to address existing design considerations, hydrologic and water quality performance, modeling efforts, and research needs.

Bioretention systems have been shown to be highly efficient in reducing peak flows, detaining storm water runoff, increasing infiltration and groundwater recharge in more humid regions, increasing evapotranspiration, and sustaining native vegetation (Aad et al., 2010; Davis, 2008; DeBusk and Wynn, 2011; Dietz and Clausen, 2005; Dussaillant et al.; 2004; Emerson and Traver, 2008; Hatt et al., 2009; Heasom et al., 2006; Hoskins and Peterein, 2013; Hunt et al., 2006; Hunt et al., 2008; James and Dymond, 2012; Jenkins, et al., 2010; Li et al., 2009; Olszewski and Davis 2013;Sharkey, 2006).

Bioretention basins are also effective for pollutant removal from storm water runoff, by taking advantage of the chemical, biological, and physical properties of plants, soils, and microbes (Brown and Hunt, 2011; County, 2002; Davis et al., 2006; Davis, 2007; Davis et al., 2001; Davis et al. 2003; DeBusk and Wynn, 2011; Dietz and Clausen, 2005; Hatt et al., 2009; Hsieh and Davis, 2005; Hunt et al., 2006; Hunt et al., 2008; Sharkey, 2006).

B. Permeable Pavements

Permeable pavements are paved surfaces that reduce runoff by allowing infiltration. These are usually designed as a matrix of concrete paver blocks with voids filled with sand, gravel, or soil. These voids encourage infiltration of storm water into the underlying soil layer. Two review papers address the various design considerations for permeable pavements and their performance in terms of water quality and hydrology (Pratt, 1995; Scholz and Grabowiecki, 2007).

Numerous studies evaluating permeable pavements have illustrated their effectiveness in increasing infiltration, reducing peak flows and surface runoff volumes, and increasing groundwater recharge in humid regions (Andersen et al., 1999; Bean et al., 2007a; Bean et al., 2007b; Booth and Leavitt, 1999; Brattebo and Booth, 2003; Collins et al., 2008; Dreelin et al., 2006; Gilbert and Clausen, 2006; Pagotto et al., 2000; Rushton, 2001; Schlüter and Jefferies, 2002).

Permeable pavements have also been successfully installed to help reduce the concentrations of storm water pollutants, including heavy metals, nutrients, and hydrocarbons

(Bean et al., 2007b; Booth and Leavitt, 1999; Brattebo and Booth, 2003; Dreelin et al., 2006; Gilbert and Clausen, 2006; Legret and Colandini, 1999; Pagotto et al., 2000; Rushton, 2001).

C. Rainwater Harvesting

Rainwater harvesting includes the use of rain barrels and cisterns to retain rooftop runoff for future use. Rain barrels tend to have a storage capacity of less than 0.38 cubic meters (100 gallons) and are usually placed above the ground. Cisterns have a capacity of more than 0.38 cubic meters and can be self-contained, above-ground, or below-ground systems. Rainwater harvesting system designs are based on the average annual precipitation, drainage area or roof area, runoff coefficient, expected storage requirements, and expected water use out of the cisterns (French, 1988; Jones and Hunt, 2010; Shuster and Rhea, 2013; Thurston et al., 2008).Various research papers have used analytical models to aid in the sizing of rainwater harvesting systems based on the above parameters (Abdulla and Al-Shareef, 2009; Ghisi et al., 2007; Guo and Baetz, 2007; Jennings et al., 2013; Sample et al., 2012; Ward et al., 2010; Ward et al., 2012; Waterfall 2004).

Various studies have analyzed the use of rain barrels to reduce storm water runoff (Aad et al. 2010; Boers and Ben-Asher, 1982; Fewkes, 2000; French, 1988; Ghisi et al., 2007; Guo and Baetz, 2007; Jennings et al., 2013; Jones and Hunt, 2010; Kim and Yoo, 2009; Sands and Chapman, 2003;Shuster et al., 2008; Shuster and Rhea, 2013; Thurston et al., 2008; Trieu et al., 2001; Ward et al., 2010). The results from these studies indicate a decrease in the runoff with the implementation of rain barrels/cisterns. However, to have a significant impact on storm water management, the studies recommend the implementation of a large number of rain barrels/cisterns to obtain a cumulative effect on the capture of roof runoff.

4.0 Objectives and Scope

The scope of this study is to develop publically available prototype software within a GIS environment. The purpose is to address some of the limitations in the models reviewed above with emphasis on application to arid and semiarid environments. The prototype will be built within the Automated Geospatial Watershed Assessment (AGWA; Miller et al., 2007) tool using the KINEROS2 rainfall-runoff-erosion watershed model (Goodrich et al., 2012). AGWA can automatically delineate and describe sub-catchments that flow into or lie downstream of proposed areas for development. Using nationally available topography, soils, and land cover spatial data layers it can automatically derive initial model parameter estimates for KINEROS2. KINEROS2 has advanced physically-based infiltration algorithms, runoff-runon routing capability, and geometric flexibility so that GI features can be realistically represented, and their hydrologic response behavior can be simulated at the lot-level. The following objectives guided development and testing of the AGWA GI prototype software.

1. Develop software that can be used to represent a limited set of GI features within the AGWA/KINEROS2 ArcGIS modeling environment.

2. Enable GI representation, parameterization, and simulation at the lot-level with runoff-runon capability for multiple GI features within a lot.

3. Model subdivision level GI implementation and response across multiple lots and streets.

4. Verify the hydrologic behavior of GI features at the lot level.

5. Verify the subdivision representation of lots with observed rainfall-runoff observations.

The scope of the project will attempt to develop a tool that strikes a balance between the L-THIA-LID and SUSTAIN/SWMM models. The AGWA GI tool, like L-THIA-LID, can be used for rapid screening assessments to evaluate subdivision level GI practices, but do so in a more complex fashion by representing a hypothetical configuration of lots and streets. In many arid and semi-arid developments, subsurface storm drainage features are not used due to infrequent rainfall. Therefore this project did not go to the level of complexity to incorporate subsurface storm drainage features that are comprehensively treated in SUSTAIN/SWMM. Incorporation of economics and optimization on the number and placement of GI features, also treated by SUSTAIN/SWMM is beyond the scope of this project but could be incorporated in the future.

Only a small number of GI design features, those reviewed above, have been incorporated into the prototype. However, it should be stressed that the functionality of KINEROS2 already is capable of simulating infiltrating channels and grass or vegetated swales. In addition, the two-layer infiltration algorithms in KINEROS2 can simulate the effects of soil compaction as part of subdivision site preparation or importation of off-site soils for fill material (Smith et al., 1995). However, it should be stressed that, local post-construction infiltration measurements should be made for realistic simulations of infiltration.

We tested the implementation of the AGWA GI tool at two scales. At the lot scale (Objective 4) a typical lot configuration will be constructed with the AGWA GI tools and subjected to a constant rainfall intensity for a sufficient duration so that an equilibrium or steady state runoff rate is achieved. In the second case, a constant intensity storm of known total rainfall depth is applied to the lot with GI features. The storm depth selected (12.5 mm) corresponds to relatively small event (less than a 1-year return period, 1-hour design storm in southern Arizona where the test was conducted). The small storm was selected so that the impact of the LID/GI features would be apparent and not overwhelmed by a large event. Knowing the constant rainfall intensity and the detention and infiltration properties of the GI and constructed features on the lot it is possible to independently compute the steady state runoff rate from the lot and ensure that routing and runoff-runon routing is correctly represented in the code. The overall water balance of the various components (rainfall, runoff, infiltration, etc.) will also be computed to further verify that the model is functioning properly.

At the subdivision scale we will test the integrity of the code for multiple lots and for lot-to-street-to-outlet connectivity and routing capability on an actual watershed in southeastern Arizona in the City of Sierra Vista (Objective 5). A subdivision within this watershed was selected for this study because high-quality rainfall-runoff observations are available as well as detailed watershed characterization data. This watershed, consisting of a natural undeveloped sub-catchment that drains into the La Terraza subdivision, and associated observations are discussed in more detail in Kennedy et al. (2013) and Kennedy (2007). A map of the study area, measurements and instrumentation locations is contained in Figure 1. A primary objective of the Kennedy et al. (2013) study was validation of the KINEROS2 urban model element discussed in more detail below. Unfortunately, the La Terraza subdivision does not contain any GI features. Ideally high-quality rainfall-runoff observations in an arid or semiarid subdivision with a variety of GI features would be available for more thorough verification of the AGWA GI tool.

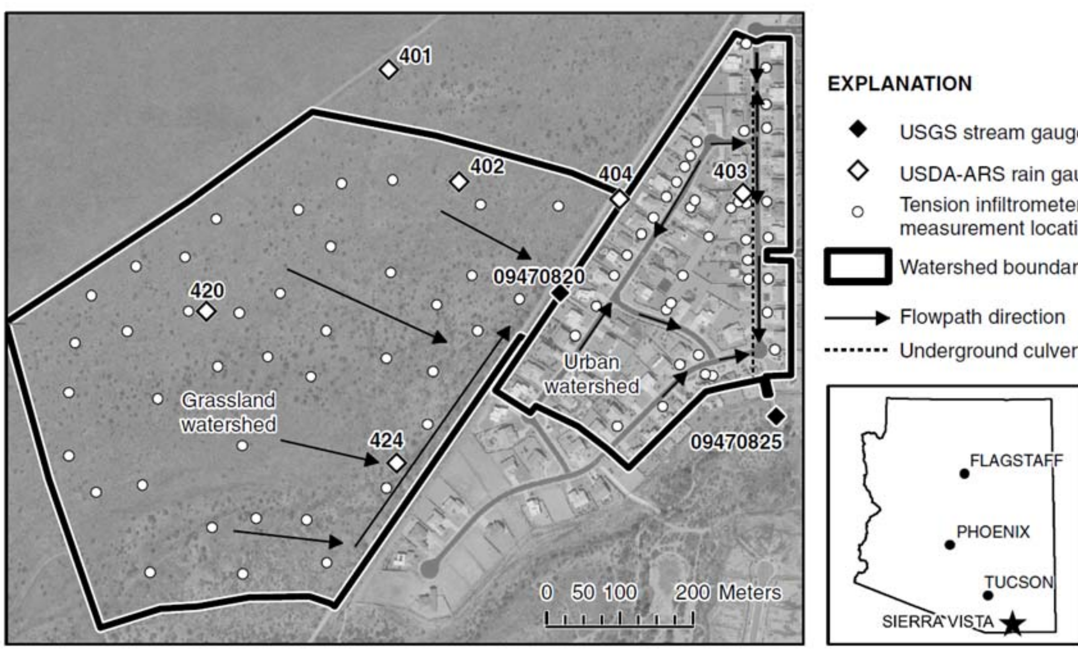

Figure 1: Study Area Map Showing Gauge Locations, Infiltration Measurement Locations, and Watershed Boundaries; Area in Upper Right of Urban Watershed Drains Directly to Watershed Outlet Through an Underground Culvert; Runoff from Remaining Area is Routed Along Streets (Background Image Courtesy USGS Earth Resources Observation and Science Center)(from Kennedy et al., 2013).

The intent is that testing at the two scales will provide some level of assurance that the AGWA GI tool can be used to provide realistic assessments of the effects of GI features at the lot, subdivision, and small watershed scales. In addition, when site specific data is lacking, the AGWA GI tool can be confidently used for the relative change assessments discussed in Goodrich et al. (2012) if it passes the two levels of testing. As noted above a thorough validation can only be achieved with a more comprehensive set of observations for the site being assessed.

As noted above the GI simulation prototype will be developed to operate in the AGWA ArcGIS environment and build on many of the core hydrologic and routing capabilities of KINEROS2. A brief overview of AGWA and KINEROS2 is provided in the following section.

5.0 AGWA and KINEROS2

The AGWA tool provides a GIS user interface for two hydrologic models - the Kinematic Runoff and Erosion model (KINEROS2) and the Soil and Water Assessment Tool (SWAT) (Daniel et al., 2011, Miller et al., 2007). AGWA is a customized toolbar in ArcMap that uses existing spatial datasets in the form of digital elevation models, land cover maps, soil maps, and weather data as inputs (Figure 2). These inputs are processed to prepare input parameters for hydrologic models. The simulation results are quantified and imported back into AGWA for spatial display and analysis. The interoperability of KINEROS2 and AGWA is described in Goodrich et al. (2012).

KINEROS2 is a distributed, physically based model which simulates runoff and erosion for small watersheds. It utilizes kinematic equations to simulate overland flow over rectangular planar or curvilinear hillslopes and channelized flows through open trapezoidal channels (Figure 3) (Woolhiser, et al., 1990; Goodrich et al., 2012). In addition to the standard overland flow (planar or curvilinear) and channel modeling elements, KINEROS2 also has an "Urban" modeling element (Figure 4) which consists of up to six overland flow areas that contribute to one-half of a paved, crowned street with the following configurations: (1) directly connected pervious area, (2) directly connected impervious area, (3) indirectly connected impervious area, (4) indirectly connected pervious area, (5) connecting pervious area, and (6) connecting impervious area. The “Urban” modeling element represents an abstraction of a typical subdivision. The La Terraza study illustrated in Figure 1 evaluated the urban element and results from this study were successful in indicating that KINEROS2 could be used to model urban residential watersheds with this abstract representation of different surface types and runoff-runon combinations (Kennedy et al., 2013).

Various case studies that have been reviewed have proven that there are a number of useful modeling approaches and tools to evaluate how green infrastructure systems will affect runoff responses. However, very few packages exist that can provide a decision-support system with spatial, robust, and accurate modeling capabilities. Popular models from these case studies lack the physical routing of water through the watershed, running continuous simulations, provisions for erosion modeling, or the use of a spatial tool. The robustness of KINEROS2 and the GIS interface provided by AGWA creates the option to use these in unison to provide a powerful modeling platform for GI practices in urban development scenarios.

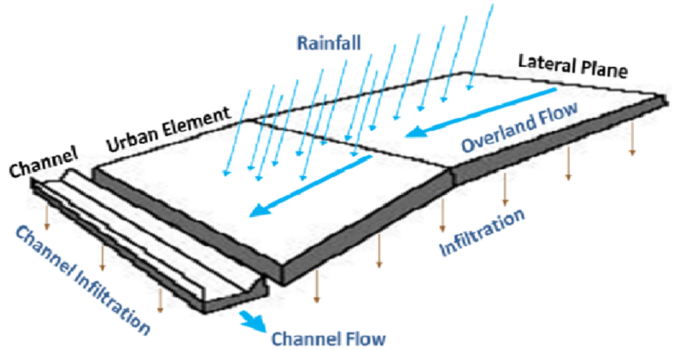

Figure 3: KINEROS2 Elements.

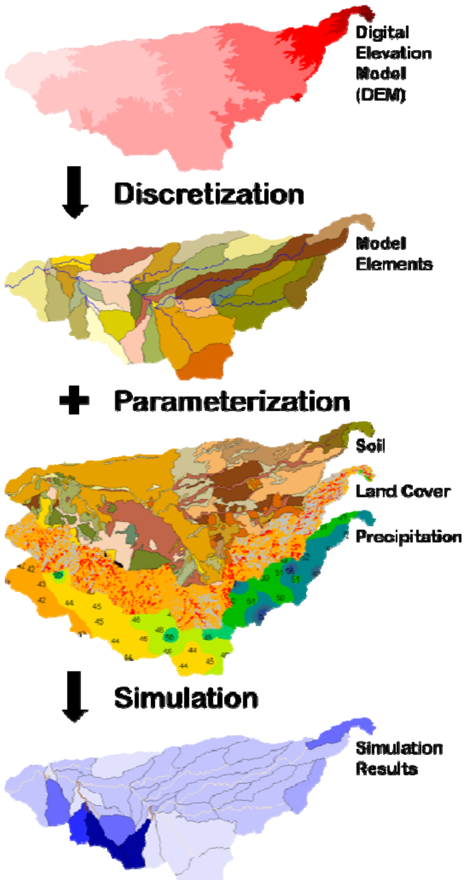

Figure 2: AGWA Workflow.

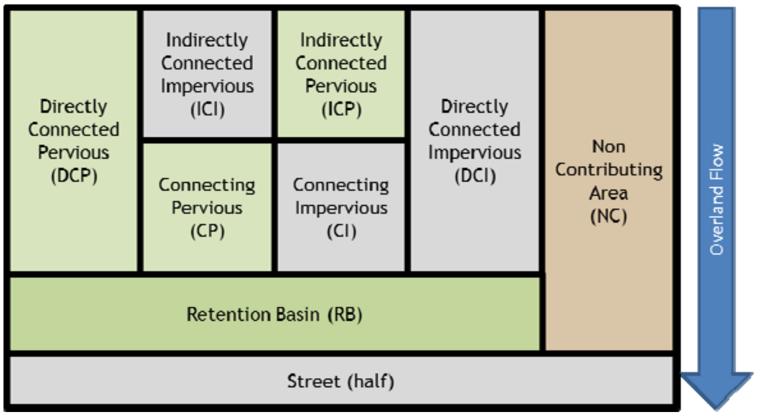

Figure 4: KINEROS2 Urban Element Components.

6.0 Design and Development

Based on the study objectives, and the existing AGWA functionality, a modified workflow was designed to utilize KINEROS2 to simulate urban environments and GI practices. Limitations of the KINEROS2 model are discussed in Goodrich et al. (2012). The modified workflow was developed in the .NET Framework using Microsoft Visual Studio 2010. C# and VB.NET were the programming languages used. Environmental Systems Research Institute (ESRI) provides an ArcObjects software development kit for the .NET Framework to build Windows applications with GIS functionalities. With the help of ArcObjects, windows based forms were developed which could use existing GIS functionalities in ArcMap. The description for each step in the workflow is given below.

Setup Urban Geodatabase

The Setup Urban Geodatabase form allows the user to provide a location and a name for the geodatabase, and a “discretization” name. The geodatabase becomes the workspace for feature classes and tables that are created in subsequent processes and the discretization name is used to identify them. The user also provides the subdivision parcels and a corresponding road layer in the form of polygon feature classes. It is necessary that the parcel feature class attribute table has a column that defines the width of each parcel adjoining the street.

Once the inputs are supplied, the program creates the geodatabase in the workspace location and copies the two feature classes into it. An “ElementID” column is added to the new parcel feature class that uniquely identifies each parcel.

Flow Routing

Flow routing is an important step in simulating an urban subdivision as post construction flow paths are typically different from pre-development topography. KINEROS2 requires the path that water will follow from the lot to the basin outlet. The Urban element in KINEROS2 assumes all of the rainfall to flow from the lot towards the street. The street is assumed to be crowned to allow the routing of water along the streets. The flow routing step accepts a routing name from the user which uniquely identifies the route. The user then draws flow paths on the parcel feature class using the built-in drawing tools in ArcMap. Once saved, the flow paths are checked by the software to ensure that all parcels are associated with a flow path, and that they fall within the boundaries of the parcels. Using these flow paths, the “FROM” and “TO” parcels are extracted to create a conceptual flow map draining towards the outlet. The program also generates route identifiers, which will identify the flow when writing the parameter file for KINEROS2. The flow route is stored in the “FlowRouting_<routingName>” table (Table 1) in the urban geodatabase.

Table 1: Description of Fields in the Flow Routing Table.

Column	Description
ROUTE_ID	Identifies Every Line Drawn by the User.
FROM_PARCEL	Identifies the Parcel from where the Flow is Initiated.
TO_PARCEL	Identifies the Parcel where the Flow Ends.
FLOW_ID	Identifies the Sequence of the Flow in Decreasing Order, from Origin to Parcel Before the Outlet.

Parameterization

The Parameterization step defines KINEROS2 input parameters based on geometry, land cover, and soils properties for each parcel. Existing AGWA functionality was modified to parameterize parcel elements, land cover, and soils for subdivisions. The user provides a unique name for the parameterization and provides inputs to the Element Parameterization form and the Land Cover and Soils form. The first form defines element parameters, including the parcel width field from the parcel feature class, house area, driveway area, slope, street width, cross slope, and grade, all of which can also be defined using fields from the feature classes or with user defined values. The second form defines land cover and soils parameters including canopy cover fractions, impervious fractions, pervious fractions, street roughness, and impervious and pervious interception values. A Soil Survey Geographic Data Base (SSURGO) soil map is required along with the corresponding database to prepare soil parameters. User-entered values in both forms are applied to all the parcels in the feature class uniformly.

The user can edit these values outside of AGWA, by editing the parameterization table in the corresponding geodatabase. The parameters are stored in a table (Table 2) with the name "<discretizationName>_u_parLUT" in the urban geodatabase.

Table 2: Description of Fields in the Parameterization Table.

Column	Description	Units
X	X Coordinate of the Parcel Centroid	
Y	Y Coordinate of the Parcel Centroid	
LOT_AREA	Area of the Parcel Generated from Feature Class Geometry	Square Meters
LENGTH	Overland Flow Length of the Parcel Perpendicular to the Street Calculated Using "WIDTH" and "LOT_AREA"	Meters
WIDTH	Width of the Parcel Parallel to the Street (Street Length)	Meters
SLOPE	Overland Slope of the Parcel, Perpendicular to the Street	Percent
HOUSE_AREA	Area of the House on the Parcel Corresponding to the Indirectly Connected Impervious Area	Square Meters

Column	Description	Units
DWAY_AREA	Area of the Driveway on the Parcel Corresponding to the Directly Connected Impervious Area	Square Meters
DWAY_LENGTH	Length of the Driveway Perpendicular to the Street	Meters
DWAY_WIDTH	Width of the Driveway Parallel to the Street	Meters
LANE_WIDTH	Width of the Street	Meters
CROSS_SLOPE	Lateral Street Slope from Gutter to Street Centerline	Percent
GRADE	Slope of the Street Corresponding to the Flow Direction	Percent
IMP_N	Manning's Roughness Coefficient for Impervious Surfaces	
PERV_N	Manning's Roughness Coefficient for Pervious Surfaces	
STREET_N	Manning's Roughness Coefficient for Street Surfaces	
IMP_INT	Interception Depth for Impervious Surfaces	mm
PERV_INT	Interception Depth for Pervious Surfaces	mm
CANOPY	Canopy Cover Fraction of Surface Covered by Intercepting Canopy	
CV	Coefficient of Variation of Saturated Hydraulic Conductivity	
KSAT	Saturated Hydraulic Conductivity	
G	Mean Capillary Drive	mm
DIST	Pore Size Distribution Index	
POR	Porosity	
ROCK	Volumetric Rock Fraction	

Green Infrastructure Design and Placement

The Green Infrastructure Design and Placement tool allows users to design and place retention basins, permeable pavements or rainwater harvesting systems on one or more parcels in a subdivision.

Retention Basins: A retention basin design requires the width, length and depth (in feet) in order to calculate the area and volume associated with the retention basin. In addition to the above dimensions, KINEROS2 requires the hydraulic conductivity of the retention basin in inches/hour or mm/hour.

Permeable Pavements: Design parameters for permeable pavements can be provided in the form of length and width or selecting the “Same as driveway area” option. With the “Same as driveway area” option, AGWA calculates the permeable pavement area from the driveway area in the parcel feature class. A hydraulic conductivity value in inches/hour or mm/hr is also required.

Rainwater Harvesting: For the design of a rainwater harvesting system, the volume of the rain barrel can be provided in gallons or cubic meters or can be calculated using height and diameter (both, in feet or meters) of the rain barrel.

Each of these designs can be saved in the Geodatabase with a unique name. The designs are saved in the Retention Basin Designs (Table 3), Permeable Pavement Designs (Table 4), and Rainwater Harvesting Designs (Table 5) tables. The user provides a unique name for the placement plan. The user also selects a design and applies it to one or more parcels using the selection tool in ArcMap. Each placement plan is then saved in the “PlacementPlans_<placementPlanName>” table (Table 6) in the urban geodatabase.

Table 3: Description of Fields in the Retention Basin Designs Table.

Column	Description	Units
RB_UNITS	Units of the Design Parameters: ENGLISH/METRIC	
RB_NAME	Retention Basin Design Name	
RB_LENGTH	Length of the Retention Basin Parallel to the Road	Feet or Meters
RB_WIDTH	Width of the Retention Basin Perpendicular to the Road	Feet or Meters
RB_DEPTH	Depth of the Retention Basin	Feet or Meters
RB_HYDCON	Hydraulic Conductivity of the Retention Basin	in/hr or mm/hr

Table 4: Description of Fields in the Permeable Pavement Designs Table.

Column	Description	Units
PP_UNITS	Units of the Design Parameters: ENGLISH/METRIC	
PP_NAME	Permeable Pavement Design Name	
PP_LENGTH	Length of the Permeable Pavement. -99 Indicates "Same as Driveway Area"	Feet or Meters
PP_WIDTH	Width of the Permeable Pavement. -99 Indicates "Same as Driveway Area"	Feet or Meters
PP_SAMEASDRIVEWAY	YES/NO. Indicates if the Permeable Pavement Area is calculated using the driveway area	
PP_AREA	Area of the Permeable Pavement. -99 indicates "Same as Driveway Area"	Square Feet or Square Meters
PP_HYDCON	Hydraulic Conductivity of the Permeable Pavement	in/hr or mm/hr

Table 5: Description of Fields in the Rainwater Harvesting Design Table.

Column	Description	Units
RH_UNITS	Units of the Design Parameters: ENGLISH/METRIC	
RH_NAME	Rainwater Harvesting Design Name	
RH_VOLUME	Volume of the Rain Barrel	Cubic Feet or Cubic Meters
RH_VOLUME_GAL	Volume of the Rain Barrel in US Gallons	Gallons
RH_DIAMETER	Diameter of the Rain Barrel. -99 Indicates Volume Provided by User	Feet or Meters
RH_HEIGHT	Height of the Rain Barrel. - 99 Indicates Volume Provided by User	Feet or Meters
RH_UTILIZATION	Percentage Daily Utilization of Rainwater	Percent

Table 6: Description of Fields in the Placement Plans Table.

Column	Description
ElementID	Uniquely Identifies the Parcel in the Parcel Feature Class
RB_NAME	Retention Basin Design Name Applied to the Corresponding Parcel
PP_NAME	Permeable Pavement Design Name Applied to the Corresponding Parcel
RH_NAME	Rainwater Harvesting Design Name Applied to the Corresponding Parcel

Precipitation

KINEROS2 accepts rainfall data in the form of time-intensity pairs or time-accumulated depth pairs. AGWA allows the user to provide rainfall data in the form of precipitation frequency grids, design storm tables, user-defined depths, or user-defined hyetographs. Rainfall is assumed to be applied uniformly over the entire subdivision area. The user specifies a unique name for the precipitation file and is stored as “<precipitationName>.pre” This functionality remains unchanged from the original AGWA implementation. More information can be found in the AGWA Documentation on the AGWA website (www.tucson.ars.ag.gov/agwa/ or http://www.epa.gov/esd/land-sci/agwa/).

Write Input Files

In the “Write Input Files” step, AGWA aggregates all the inputs that were provided in the preceding steps and prepares files required by the KINEROS2 model. The following files are required by the KINEROS2 model.

.par: This file is written based on the inputs provided and the parameters generated in the flow routing, parameterization and BMP placement steps. Parameters are written in “urban” blocks for each parcel using the sequence generated in the flow routing step.

.pre: The precipitation file, which was created in the Precipitation step, is copied from the precipitation directory into the simulations directory.

lid.fil: This file stores the initial volumes for the retention basin and rainwater harvesting systems respectively. AGWA assumes zero starting volumes for both.

kin.fil: KINEROS2 control file which directs the model with the input parameter filename, input precipitation filename, output filename, and duration of the simulation.

file.bat: this is the batch file that executes the KINEROS2 model.

k2lid.exe: The KINEROS2 model executable which is copied from the AGWA directory.

The user selects the flow routing table, parameterization, placement plan table, precipitation file, and provides a unique name for the simulation. AGWA creates a table (Table 7) “Simulations_<discretizationName>” in the geodatabase, which stores this information. AGWA creates a new directory in the workspace with the given simulation name. The lid.fil, kin.fil, file.bat, precipitation file and “<simulationName>.par” are written and saved in this directory.

Table 7: Description of Fields in the Simulations Table.

Column	**Description**
SIMULATION	Name of the Simulation
ROUTING_TABLE	Name of the Routing Table
PARAMETERIZATION	Name of the Parameterization Stored in the Parameterization Look up Table
PLACEMENT_PLAN	Name of the Green Infrastructure Placement Plan Table
PRECIPITATION	Name and Location of the Precipitation File

Execute KINEROS2 Model

In the “Execute KINEROS2 Model” step, the user selects the discretization and an associated simulation and runs the KINEROS2 model. AGWA executes the file.bat created in the “Write Input Files” step. A command prompt displays the progress of the simulation and whether it was successful or if it encountered any errors. The output file (.out), which summarizes the hydrology for each urban element, is created in the simulations directory by the model. AGWA imports these values in the next step.

View Results

The “View Results” form allows the user to visualize the results of the KINEROS2 simulation. The user can import results from previously run simulations into AGWA. This step creates a results table from the simulation output, and joins it to the parcel attribute table. AGWA allows the user to visualize the output for each parcel in the form of infiltration, runoff and accumulated runoff volumes. AGWA also allows the user to visualize the absolute/percent difference between two simulations. Infiltration and runoff volumes results are visualized for each individual parcel. Accumulated runoff, which is comprised of the runoff from each parcel along with the runoff from the upland parcel, can be visualized along the street.

7.0 Testing

7.1 Lot Scale

Verification of the Urban element at the lot scale was approached by confirming the following 1) that event volumes of hydrologic components are balanced properly; and, 2) that the steady-state runoff rates are as expected. To test both, an element was created representing a typical lot in the La Terraza subdivision (Figure 5) that was used in six scenarios (Table 8): pre-development; post-development w/o GI; retention basins; permeable pavements; rainwater harvesting; and all GI practices. The GI practices for the verification exercise were setup to illustrate the impact of the practices. Each scenario was simulated using rainfall applied at a constant intensity of 12.5 mm/hr for 120 minutes. The rainfall intensity and duration were selected so that the element reached steady-state outflow rates.

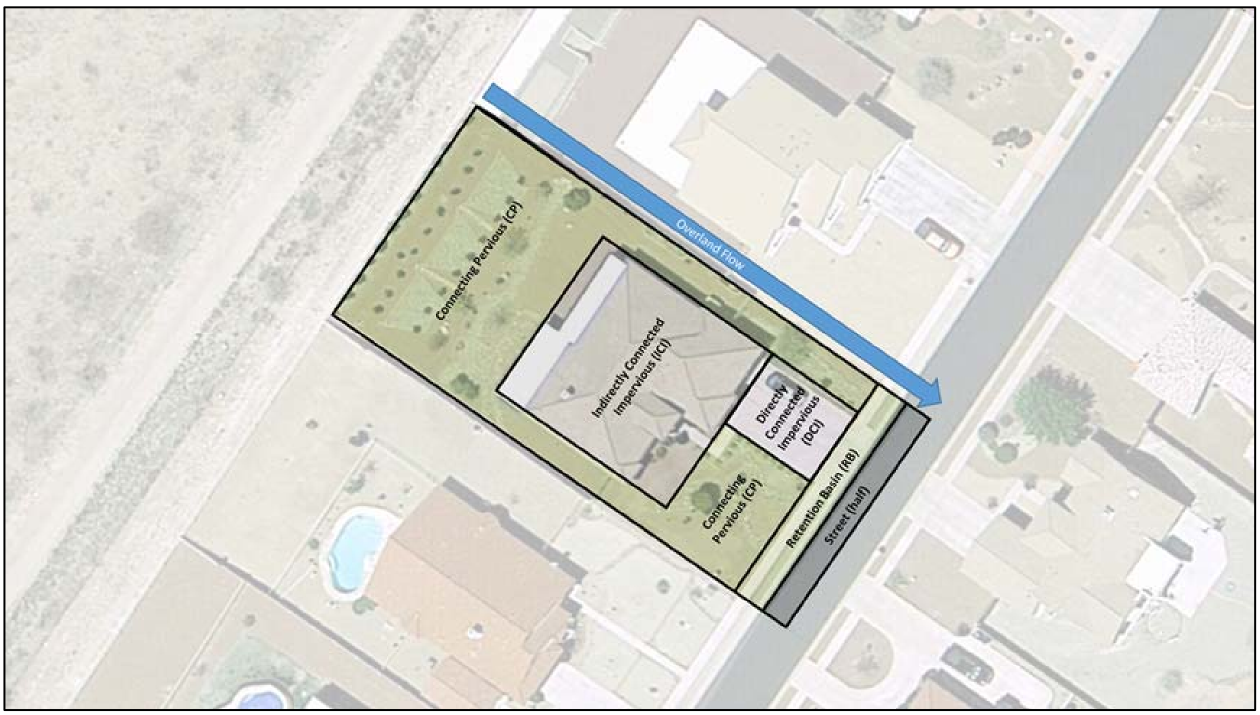

Figure 5: Lot Scale Representation of the KINEROS2 Urban Element.

Table 8: Description of the Lot Scale Verification Scenarios.

Pre-Development	Empty Lot with a Street and Soils Attributes Obtained from the NRCS SSURGO Soils Spatial Database
Post-Development (w/o GI)	Lot with a House Area of 2500 Square Feet and a ~12 by 19.5 Foot Impermeable Driveway (21.76 Square Meters)
Retention Basin	Post-Development Parameters with the Addition of a Retention Basin with a Hydraulic Conductivity of 8.3 in/hr (~210 mm/hr) and Sized with a Surface Area of Approximately 72 Square Feet and a Depth of ~10 Inches, Yielding a Retention Capacity of ~60 Cubic Feet (~444 Gallons or 1.68 m3)
Permeable Pavement	Post-Development Parameters with the Conversion of the Driveway to Permeable Pavement with a Hydraulic Conductivity of 8.3 in/hr (~210 mm/hr)
Rainwater Harvesting	Post-Development Parameters with a Rainwater Harvesting Feature with a Capacity of ~500 Gallons (1.9 m3)
All GI Practices	Post-Development Parameters Along with all of the Above GI Practices

Verifying the water balance is a basic accounting exercise that ensures model inputs equal model outputs plus any change in storage. In this exercise, a 12.5 mm/hr rainfall event was applied for a two-hour duration onto a lot size of 0.1933 hectares, yielding a total rainfall of 96.66 m^3; this is the model input. Model outputs include interception, infiltration, storage, and outflow in m^3. Table 9 includes a summary of the inputs and outputs for six different development scenarios. The error term represents the percent difference between the sum of the inputs and sum of the outputs and storage. For all scenarios, the error is less than 1%.

Table 9: Volume Balances of the Lot Scale Verification Scenarios.

	Pre-Development	**Post-Development (w/o GI)**	**Rainwater Harvesting**	**Retention Basin**	**Permeable Pavement**	**All GI Practices**
Rain (m^3)	48.33	48.33	48.33	48.33	48.33	48.33
Interception (m^3)	0	0	1.9	0	0	1.9
Infiltration (m^3)	28.76	24.90	24.82	29.28	25.45	29.72
Stored (m^3)	0	0.00006	0.00006	0.00006	0.00003	0.00003
Outflow (m^3)	19.73	23.76	21.90	19.36	23.22	16.98
Error (%)	-0.33	-0.68	-0.60	-0.64	-0.70	-0.56

Effective hydraulic conductivity is defined as the rainfall rate minus outflow rate. Because each scenario reached steady-state outflow rates, the effective hydraulic conductivity could be compared to the expected steady-state weighted saturated hydraulic conductivity calculated from the different overland flow areas of the Urban element. The weighted hydraulic conductivity is calculated by converting the infiltration capacity in mm/hr to m^3 for each of the overland flow areas of the Urban element. Conversion to a volumetric rate is necessary so that contributing volumes can be subtracted out when overland flow areas that receive input from upslope (e.g. the retention basin – Figure 4) have higher infiltration capacities than the rainfall rate.

Table 10: Effective Versus Steady State, Weighted Hydraulic Conductivities for the Lot Scale Verification Scenarios.

	Pre-Development	**Post-Development (w/o GI)**	**Rainwater Harvesting**	**Retention Basin**	**Permeable Pavement**	**All GI Practices**
Effective Ks (mm/hr)	7.05	5.98	5.98	6.33	6.26	6.61
Steady state weighted Ks (mm/hr)	7.01	5.94	5.94	6.29	6.22	6.57
Difference	-0.57%	-0.67%	-0.67%	-0.64%	-0.64%	-0.61%

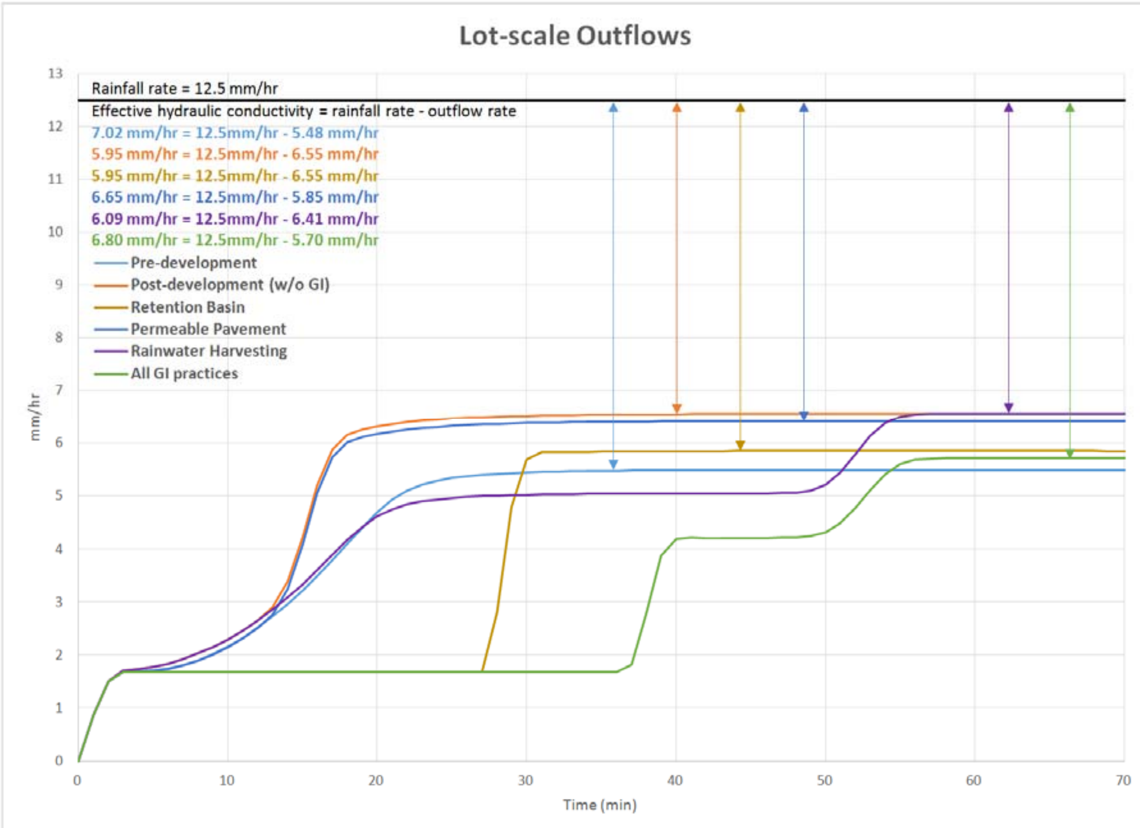

Figure 6: Hydrographs of Lot Scale Testing Scenarios, Illustrating Effective Hydraulic Conductivities Versus Theoretical, Steady-State Hydraulic Conductivities.

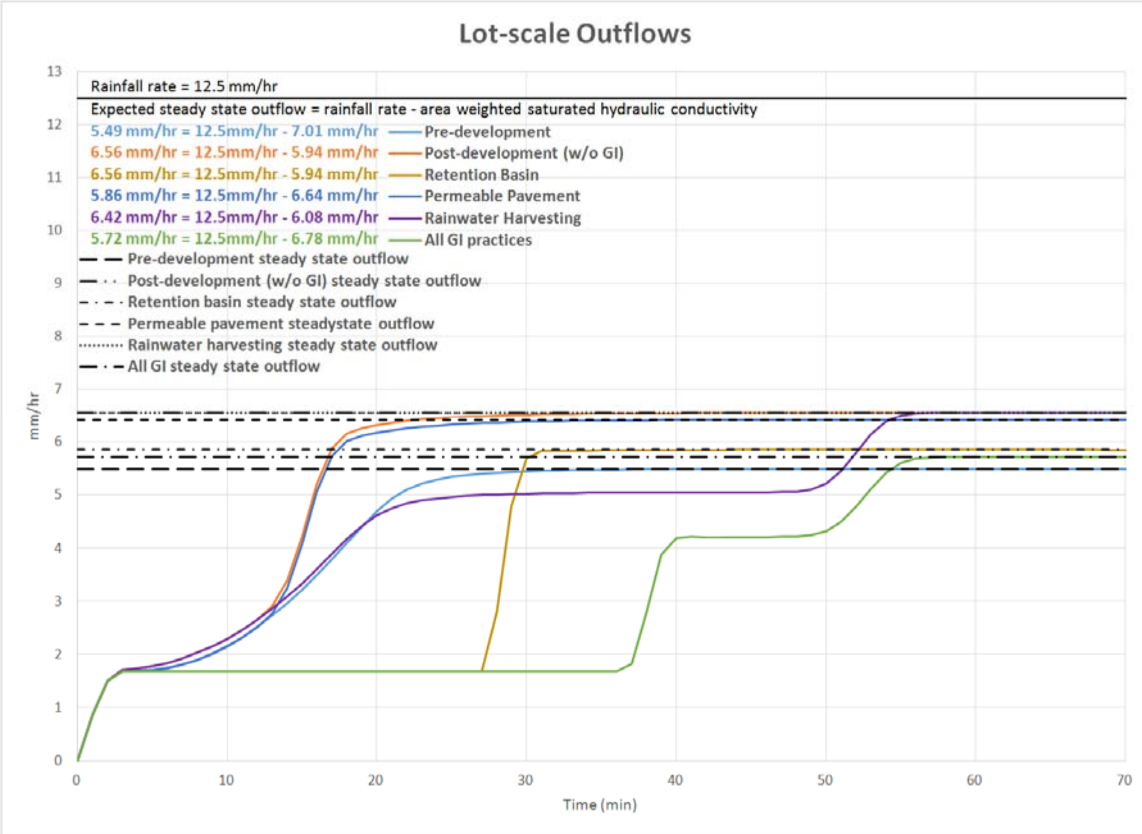

Figure 7: Hydrographs of Lot Scale Testing Scenarios, Comparing Modeled Outflow to Theoretical Steady-State Outflow.

7.2 Subdivision Scale

Verification of the model for the La Terraza subdivision (Figure 1) was conducted using observed rainfall and runoff data collected from July 2005 through September 2006 (Kennedy, 2007). Rainfall was measured by four recording rain gauges, with areal average rainfall event totals ranging from 2 to 35 mm (events less than 2 mm were not used). Runoff both into and out of the La Terraza subdivision was measured by v-notch weirs. Runoff events that overtopped the outlet weir were excluded, giving a high-quality data set of 47 events.

The parameter file created by AGWA was modified to incorporate some of the parameters used by Kennedy (2007) as well as the measured inflows from the adjacent undeveloped watershed. The altered parameters included the interception and Manning n values, and street slopes were reduced from 0.02 to 0.01 to better reflect the values measured by Kennedy. Initial soil saturation values for each event were also obtained from Kennedy.

The total event runoff volumes and peak flow rates for the 47 simulated events compared to measured values are shown in Figure 8. Both volumes and peaks yielded Nash-Sutcliffe efficiencies (coefficients of determination) greater than 0.9, with very little tendency to over or under predict the observed values. This test provides assurances that with high-quality rainfall-runoff observations, the AGWA GI tool can realistically simulate the effects of subdivision scale development for multiple lots and streets within a larger watershed with upslope contributions from a natural, undeveloped sub-catchment. Ideally, a development containing GI features with high-quality rainfall-runoff observations could be located to provide real world testing of the AGWA GI tool. Until such data becomes available, this test coupled with the successful lot level testing described in the prior section, provides a measure of confidence in the ability of the AGWA GI tool to simulate the selected GI features in arid and semiarid areas at the lot, subdivision, and small catchment scale. GI features were added to lots in the La Terraza subdivision to illustrate the capability of the AGWA GI tool to simulate the effects at the subdivision case study level.

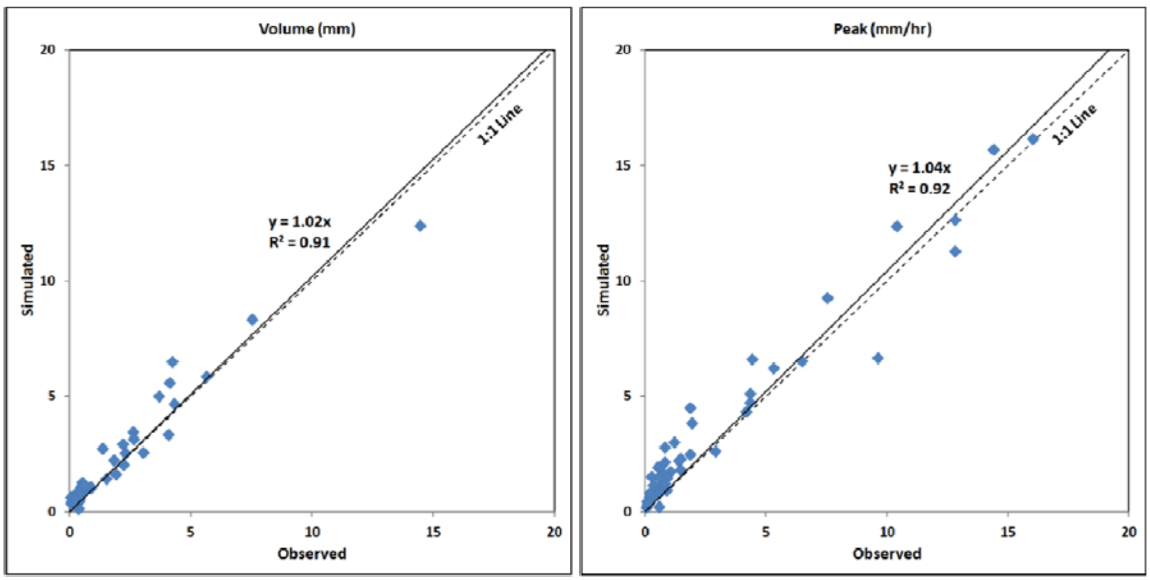

Figure 8: Simulated Versus Observed Event Runoff and Peak Flows (n = 47) for July 2005 through September 2006 for the La Terraza Subdivision.

8.0 Case Study

As discussed in the scope and objectives section, the La Terraza subdivision in Sierra Vista, Arizona (Figure 1) was used to demonstrate and test the AGWA GI tool. Sierra Vista is part of Cochise County and thus, the parcel feature class for this subdivision was obtained from the Cochise County IT department (http://cochise.az.gov/cochise_gis.aspx?id=6688). Sixty-six parcels were extracted to create the “terraza_parcels” feature class. A polygon layer, comprising the streets for La Terraza, was also extracted to create the “terraza_streets” feature class.

For the flow routing phase, the study mimicked the flow of water from Kennedy et al. (2013). For representation purposes, we draw the flow paths on the parcels. However, KINEROS2 interprets these flow paths as flow that exits the parcel and follows the direction along the road towards the outlet. In our case, parcels ID 28, 39, and 64 act as terminal parcels before the flow exits the subdivision. The parameters used in the simulations are listed in Table 11. Three of the six simulation scenarios from the lot level testing (Figure 8) were simulated for the entire subdivision: pre-development, post-development without GI practices and post-development with all GI practices. Each of these scenarios were run for a time period of 275 minutes using observed rainfall from July 31, 2005 (Kennedy et al., 2013).

Table 11: Parameter Values for Pre-Development and Post-Development Simulations.

Parameter	**PRE-DEVELOPMENT**	**POST-DEVELOPMENT**
Parcel Width	From "Parcels_d1" Feature Class	From "Parcels_d1" Feature Class
House Area	0	232.26 m^2 (2500 ft^2)
Driveway Width	0	3.65 m (12 ft)
Driveway Length	0	6.10m (20 ft)
Overland Slope	2 % Rise	2 % Rise
Lane Width	From "Streets_d1" Feature Class	From "Streets_d1" Feature Class
Cross Slope	2 %	2 %
Grade	1 %	1 %
Manning’s Roughness		
Impervious Surfaces	0.012	0.012
Pervious Surfaces	0.020	0.020
Streets	0.014	0.014
Interception		
Impervious Surfaces	1 mm	1 mm
Pervious Surfaces	2 mm	2 mm
Canopy Cover	1 mm	1 mm
Soils	SSURGO	SSURGO

Figure 9: La Terraza Subdivision and Flow Routed Towards Outlet. (Sierra Vista, AZ).

For the pre-development simulation (Figure 10), each parcel is represented by a directly connected pervious area draining towards the street. For post-development without GI practices (Figure 11), the house area is assumed to be equal to the roof size, which is represented by the indirectly connected impervious area. The driveway is represented by the directly connected impervious area, and the remaining lot area is represented by the connecting pervious area. For post-development with GI practices (Figure 12), a retention basin area is added right before the street. The driveway acts as permeable pavement and the roof area contributes runoff to the volume that is stored in the rain barrel. In Figure 10 through Figure 12, values represent percent of lot area.

Figure 13 shows the infiltration output that the AGWA GI tool provides. In this case, percent change in infiltration for post-development with and without GI practices are compared to pre-development. Percent change is calculated using the following formula:

(post-development w/o GI - pre-development)/pre-development * 100

(post-development with GI - pre-development)/pre-development * 100

The results indicate an overall increase in infiltration with the addition of GI practices. This can be observed from the higher number of lighter shaded parcels, indicating lower percent change when compared to pre-development.

AGWA also provides a spatial view of the runoff results from the simulation (Figure 14). In this case, percent change in runoff for post-development with and without GI practices are compared to pre-development. Percent change is calculated using the abovementioned formula.

Without GI practices, there is an increase in runoff from each of the parcels. However, with all of the GI practices, our results indicate a decrease in runoff when compared to pre-development.

The lower half of the subdivision showed a visible increase in infiltration volumes (Figure 13) and a decrease in runoff volumes (Figure 14) as compared to the upper half. This trend can be explained by the underlying soil survey boundaries depicted in Figure 9. There are two distinct soil types that split the subdivision into two parts contributing to the difference in infiltration and runoff volumes. SSURGO captures some of the soil variability within the subdivision, however some direct measurements of soil properties in post-preparation lots would help capture more information at a finer resolution that will impact the spatial variability of changes in hydrology. For example, compaction of the soils can also affect infiltration properties on prepared lots (Kennedy et al., 2013). Whether direct measurements are available or not, the AGWA Urban tool allows users to alter soil infiltration characteristics supporting multiple simulations with a range of soil infiltration parameters which enables the exploration of relative impacts that lot preparation may have in addition to the application of GI features. For the purpose of this study, direct measurements of soil properties in post-preparation lots were not taken or incorporated into the simulations.

Figure 15 shows the third output type, Accumulated Runoff (cubic meters) that the AGWA GI tool is able to provide. Results indicate an overall reduction in accumulated runoff with the addition of all GI practices. Parcel ID 28 shows higher flow accumulation as compared to parcels ID 64 and 39 because it accumulates a runoff volume from a larger number of preceding parcels as can be seen from the flow route.

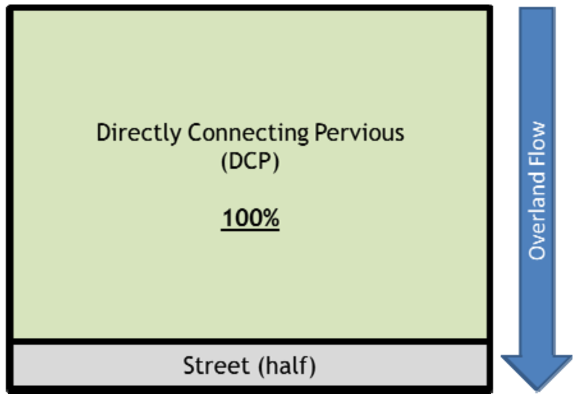

Figure 10: KINEROS2 Representation of a Pre-Development Parcel.

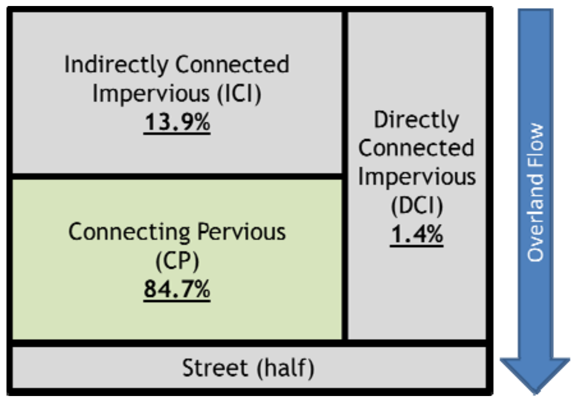

Figure 11: KINEROS2 Representation of Parcel ID 7 for Post-Development without GI Practices.

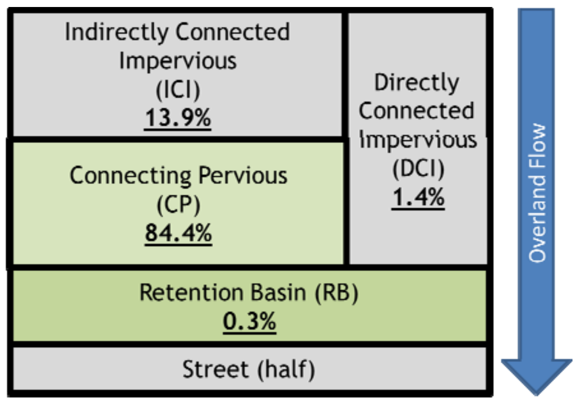

Figure 12: KINEROS2 Representation of Parcel ID 7 for Post-Development with all GI Practices.

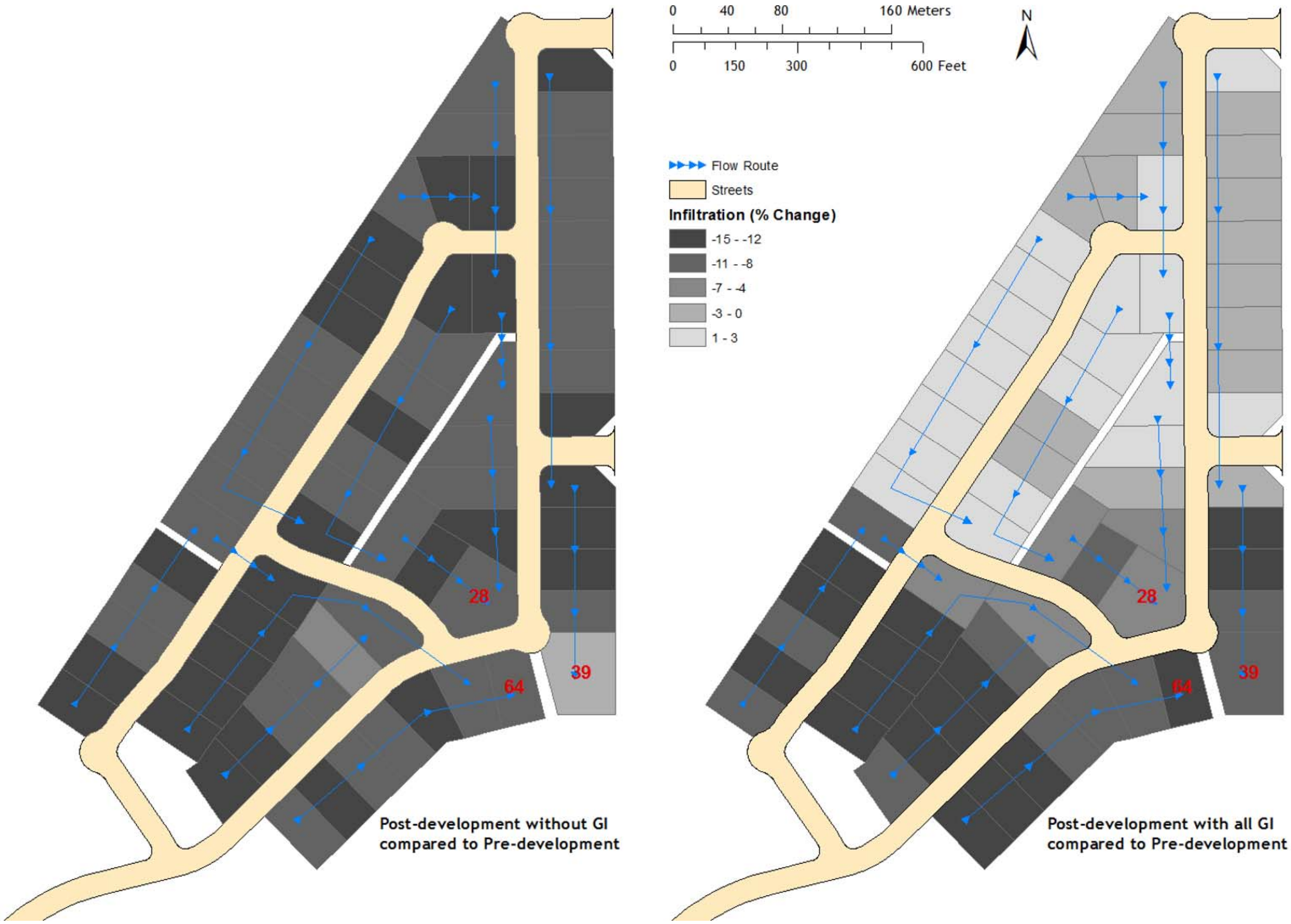

Figure 13: Percent Change in Infiltration for Post-Development with and without GI as Compared to Pre-Development.

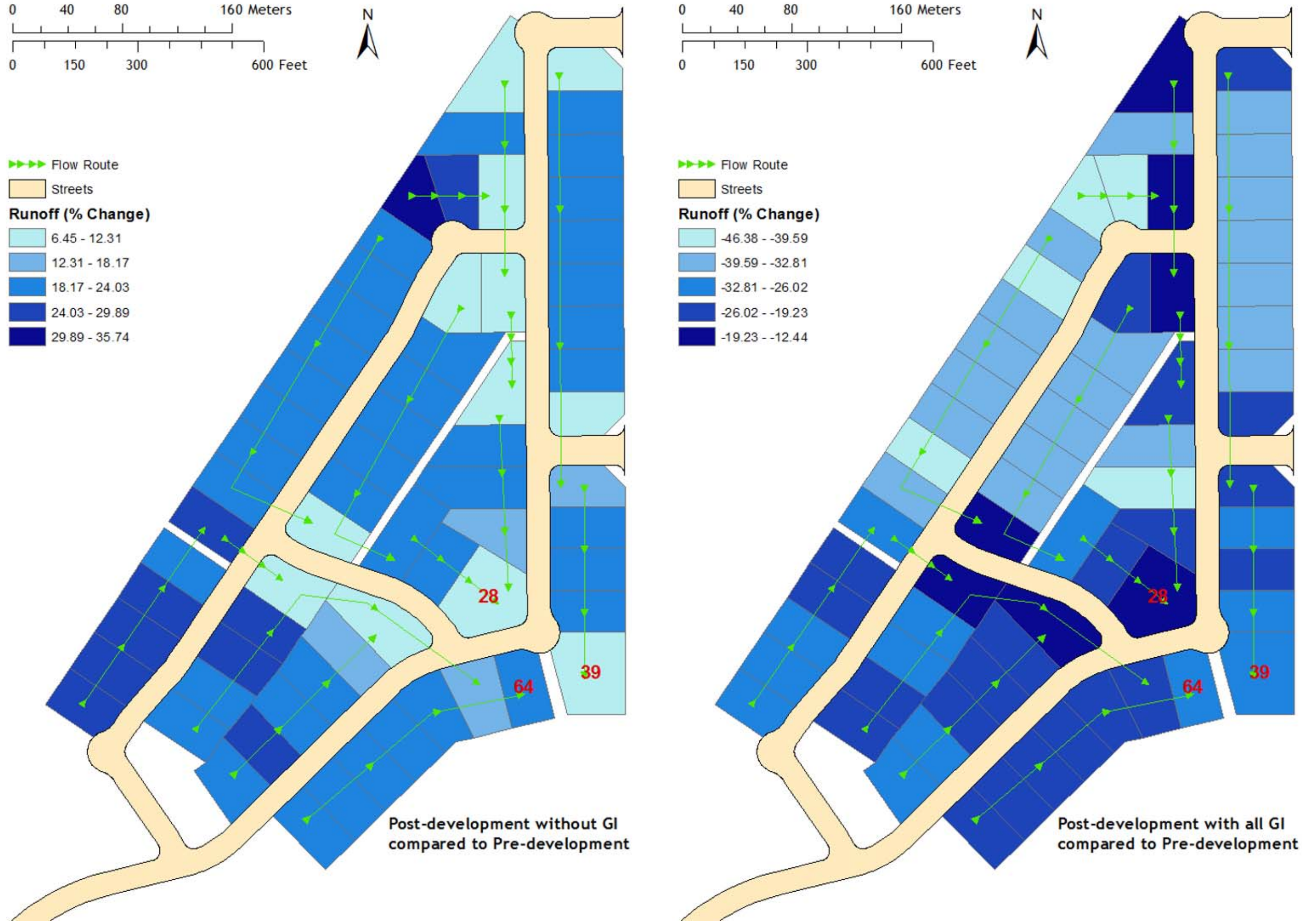

Figure 14: Percent Change in Runoff for Post-Development with and without GI Practices as Compared to Pre-Development.

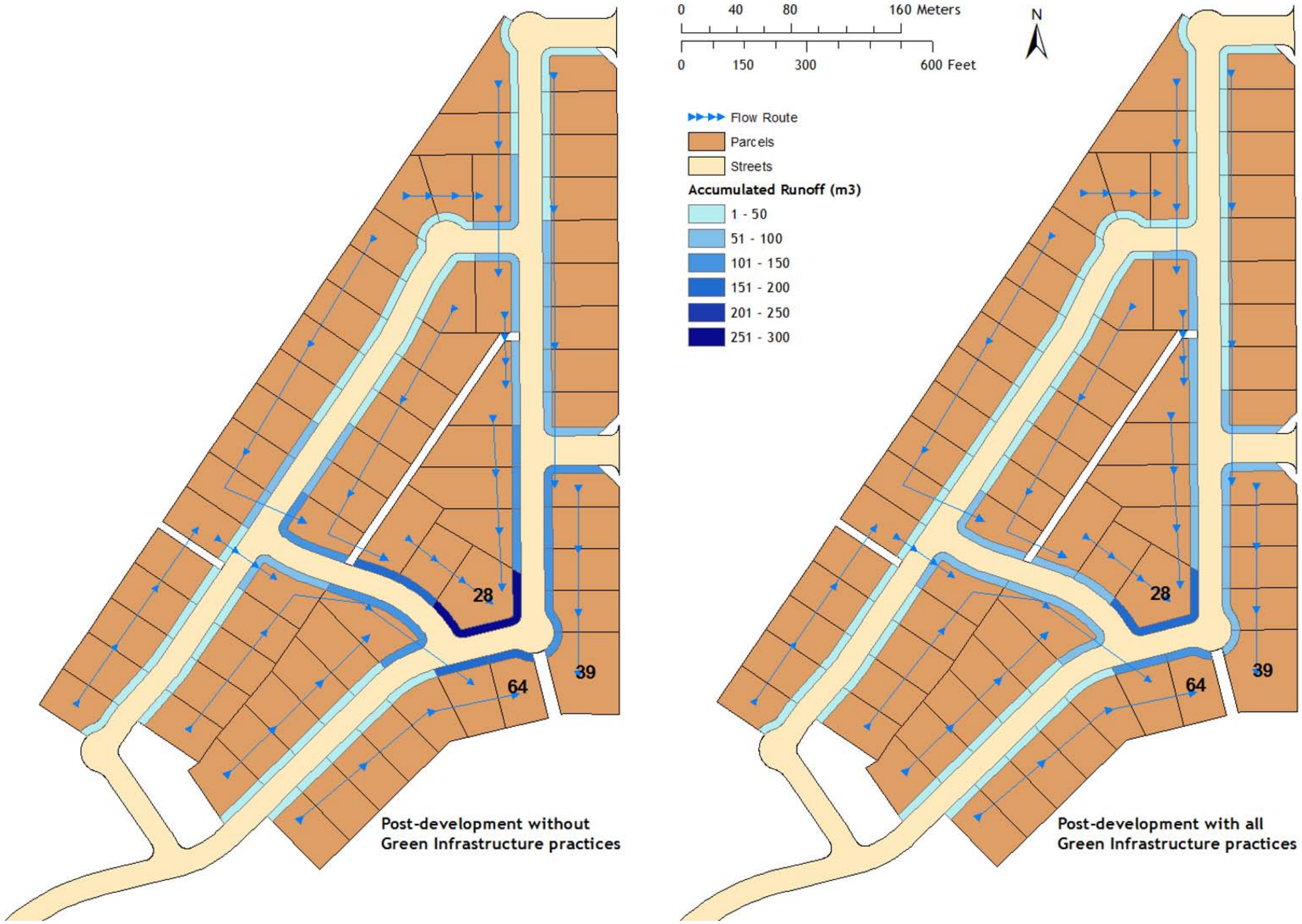

Figure 15: Comparison of Flow Accumulation for Post-Development with and without GI Practices.

9.0 Limitations and Issues

Limitations of the KINEROS2 model are discussed in Goodrich et al. (2012). It is an event-based model and will not simulate plant water use, soil water movement between events, or track snow accumulation and melt. Before simulating an event, it requires an initial estimate of soil moisture. The event-based version precludes modeling of the changes in soil moisture due to drainage, evaporation, and plant water use. This could have an impact when attempting to realistically simulate how water captured by rain harvesting GI features is drawn down for watering through different weather scenarios. Within an event, this version of KINEROS2 will not model snowfall or frozen soil conditions, or route subsurface water flow. It can include circular conduits in the channel network, but flow must remain below capacity (no surcharging or pressurized flow). The representation of two-soil layer infiltration available in KINEROS2 has not been implemented within the AGWA GI tool. Unless site specific post-development soils and infiltration data is available this limitation is not viewed as a major shortcoming for the AGWA GI tool.

While KINEROS2 can compute infiltration and route runoff on planar or curvilinear overland flow elements the Urban GI element is restricted to a planar surface with one slope designated for the non-street components and another slope for the one-half street component. The urban element assumes water flows directly to the street, and the street is assumed to be crowned to allow independent routing of water on each side of the street. Flow from one lot will not cross the mid-line of the street to the other half so street runoff is uniquely associated with one lot. The Urban GI element in KINEROS2 assumes all of the runoff generated will flow from the back of the lot towards the street. In reality, lot-generated runoff could flow out the back of the lot or onto adjacent lots.

If high-quality post construction topographic data from lidar were available it would be possible to further sub-divide a lot into more than one overland flow element coupled with a Urban GI element to these cases. This is most easily done by altering the KINEROS2 parameter file outside of the AGWA GIS environment. This limitation is not seen as a major shortcoming as the primary application envisioned for the AGWA GI tool is for rapid relative change assessments to evaluate the hydrologic response effects of GI features where minor flow path deviations should not have a major effect on the overall assessment of the value of adding GI features. Dead storage, such as a swimming pool or walled yard that effectively traps and holds runoff, cannot currently be represented in the Urban GI element.

10.0 Conclusions

The AGWA GI tool was designed and developed to represent retention basins, permeable pavements and rainwater harvesting systems within the AGWA/KINEROS2 ArcGIS modeling environment. The “urban” element in KINEROS2 was modified to provide a realistic representation of individual housing lots and the placement of the GI features noted above. Two new tools were developed as part of the AGWA GI to spatially prepare parameters for the KINEROS2 Urban GI model element. The “Flow Routing” tool allows the user to draw the flow paths on the map, guiding storm water along platted or post-development drainage paths and to the outlet. This is important as analysis of pre-development topography from nationally or locally available digital elevation model (DEM) data will not typically result in flow paths similar to the constructed development. Even in urbanized areas with high-resolution DEM data on the scale needed to construct 0.3 m (1 foot) contour intervals, accurate flow paths can often be difficult to discern with automated drainage analysis due to small drainage control features such as curbs and gutters.

The “GI Design and Placement” tool allows the design and placement of retention basins, permeable pavements, and rainwater harvesting systems at each lot in a subdivision. Additionally, various combinations of GI placements can be designed and simulated for an entire subdivision. The case study highlights the three output types provided by the AGWA GI tool, i.e. infiltration, runoff, and accumulated runoff. Comparisons using these outputs can be made between pre-development and post-development with or without GI practices.

The hydrologic behavior of GI features was tested at the lot level by verifying: 1) that event volumes of hydrologic components were balanced properly; and 2) the steady-state runoff rate reflected the independently computed effective hydraulic conductivity. Six scenarios (Table 8): Pre-development; Post-development without GI; Retention basins; Permeable pavements; Rainwater harvesting; and a combination of all GI practices implemented were tested. Each of the simulated scenarios had water balance errors that were less than 1%. The second verification showed that simulated and expected effective hydraulic conductivity all agreed within 1%, resulting in the expected steady-state peak runoff rates. Verification of the model at the subdivision scale was conducted on the La Terraza subdivision using a high-quality set of observed rainfall and runoff data. Simulated runoff volumes and peak flow rates yielded high Nash-Sutcliffe efficiencies (>0.9) and very little bias compared to the observed data. Based on these tests, the AGWA GI tool performed as expected.

Currently, the AGWA GI tool only allows the design and development of retention basins, permeable pavements, and rainwater harvesting systems. However, there are many other practices which are being considered for implementation in the AGWA GI tool. At present the AGWA GI tool only focuses on hydrology. Some limitations mentioned related to KINEROS2 will be addressed when the continuous version is available which includes plant growth functionality and biogeochemistry (K2-O2; Massart et al., 2010). Once integrated into AGWA, the continuous version of KINEROS2 will enable simulation of numerous water quality effects of GI features. Considering its current capabilities, the AGWA GI tool can be a used to inform planning decisions related to urban development and storm water management on lot, subdivision, and small catchment scales. This information will be useful in understanding the expected differences in storm water runoff between neighboring developments or natural environments. In traditional post-development urban environments, the increase in storm water runoff can negatively impact downstream natural resources. GI features have the potential to mitigate those effects by achieving pre-development runoff volumes.

11.0 References

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