REPRESENTING GREEN INFRASTRUCTURE MANAGEMENT TECHNIQUES IN ARID AND SEMI-ARID REGIONS: SOFTWARE IMPLEMENTATION AND DEMONSTRATION USING THE AGWA/KINEROS2 WATERSHED MODEL

Yoganand Korgaonkar, Graduate Student, University of Arizona, Tucson, AZ, yoganandk@email.arizona.edu; I. Shea Burns, Senior Research Specialist, University of Arizona, Tucson, AZ, shea.burns@ars.usda.gov; Jane Barlow, Graduate Student, University of Arizona, Tucson, AZ, jbarlow@email.arizona.edu; D. Phillip Guertin, Professor, University of Arizona, Tucson, AZ, dpg@email.arizona.edu; Carl Unkrich, Hydrologist, USDA-ARS, Tucson, AZ, carl.unkrich@ars.usda.gov; David C. Goodrich, Research Hydraulic Engineer, USDA-ARS, Tucson, AZ, dave.goodrich@ars.usda.gov; William Kepner, Research Ecologist, EPA/ORD/NERL, Las Vegas, NV, kepner.william@epa.gov.

Abstract: Increasing urban development in the arid and semi-arid regions of the southwestern United States has led to greater demand for water in a region with limited water resources and 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 for rapid GI planning and assessment that operate from the lot-to-subdivision-to-watershed level 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 (KINEROS2) watershed model. The resulting software provides an up-to-date GIS GI assessment framework that automatically derives model parameters from widely available spatial data. The software 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. The AGWA GI software was tested at the lot level with and without GI features to validate the water balance and to verify steady state runoff rates. Testing was also conducted at the subdivision level, without GI features, as high-resolution rainfall-runoff observations were available from a subdivision in Sierra Vista, Arizona. Testing at both these scales confirmed programming integrity and the capability to realistically simulate urban hydrology, indicating that the software 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.

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)

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 (Hood et al., 2007; Leopold, 1968). The Department of Environmental Resources of Prince George's County, Maryland, pioneered Green Infrastructure (GI, also referred to as Low Impact Development or LID) to mitigate the urbanization impact of increasing impervious surfaces (County and June, 1999). As opposed to traditional storm water management practices, GI aims to preserve the pre-development hydrology using a variety of cost effective on-site design techniques that store, infiltrate, evaporate, and detain runoff. Prince George's County introduced a new concept of Integrated Management Practices (IMP), that include many GI practices such as bioretention cells or basins, dry wells, filter strips, vegetated buffers, level spreaders, grassed swales, rain barrels, cisterns, and infiltration trenches. GI practices help reduce the need for more traditional storm water management techniques such as curb-and-gutter systems or large detention basins.

GI practices 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; Elliott and Trowsdale, 2007). Models that simulate GI 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).

This paper demonstrates the use of the Automated Geospatial Watershed Assessment (AGWA) tool to design and model GI practices in urban environments. The AGWA GI software serves as a decision support tool, applicable at the lot-, subdivision-, and small watershed-scales. It utilizes 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).

GREEN INFRASTRUCTURE PRACTICES

A small subset of GI practices, commonly used in arid and semi-arid regions, was selected for incorporation into the modeling tool. These include bioretention systems, permeable pavements and rainwater harvesting systems.

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.

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.

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.

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 ESRI ArcMap that uses existing spatial datasets in the form of digital elevation models, land cover maps, soil maps, and weather data as inputs (figure 1). 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).

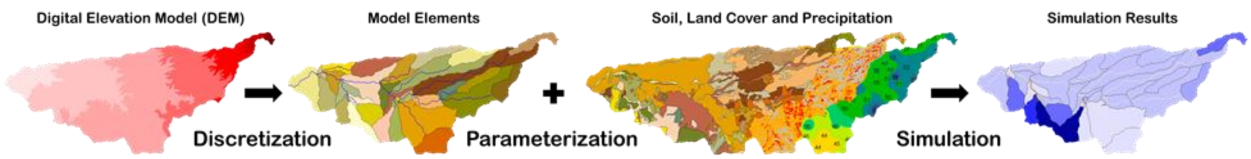

Figure 1 AGWA Workflow

KINEROS2 is a distributed, physically based model that 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 2) (Woolhiser, et al., 1990; Goodrich et al., 2012). KINEROS2 has dynamic infiltration in which the infiltration is coupled with the routing, and flow depth is computed with a finite difference solution of the kinematic wave equations and the Smith-Parlange infiltration equation at each finite difference node. This makes the model particularly well suited to simulate runoff-runon conditions over surfaces with distinctly different infiltration or cover characteristics. In addition to the standard overland flow (planar or curvilinear) and channel modeling elements, KINEROS2 also has an Urban modeling element (figure 2) that 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 pervious area, (4) indirectly connected impervious area, (5) connecting pervious area, and (6) connecting impervious area. The Urban modeling element represents an abstraction of a typical subdivision. Kennedy et al. (2013) evaluated the urban element and concluded that KINEROS2 could successfully model urban residential watersheds with this abstract representation of different surface types and runoff-runon combinations.

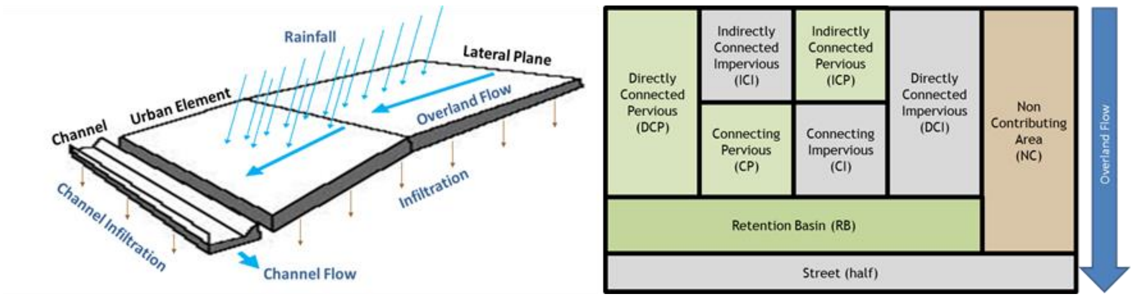

Figure 2 KINEROS2 element and Urban element components.

Very few software packages exist that can provide a decision-support system with spatial, robust, and accurate modeling capabilities. Popular models lack the physical routing of water through the watershed, 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.

WORKFLOW

Based on the existing AGWA functionality, a modified workflow was designed to utilize KINEROS2 to simulate urban environments and GI practices. The modified workflow was developed in the .NET Framework using Microsoft Visual Studio 2010. C# and VB.NET were the programming languages used. 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 ESRI 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 a geodatabase, which becomes the workspace for feature classes and tables that are created in subsequent processes. The user also provides the subdivision parcels and a corresponding road layer in the form of polygon feature classes.

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 flows from the lot towards the street. The street is assumed to be crowned to allow the routing of water along the streets. With the help of the Flow Routing form, the user draws flow paths on the parcel feature class using built-in drawing tools in ESRI 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, a conceptual flow map (figure 3) draining towards the outlet is created.

Parameterization: The Parameterization step defines KINEROS2 input parameters based on geometry, land cover, and soils properties for each parcel. The user 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, 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, pervious, and street roughness; and impervious and pervious interception values. A Soil Survey Geographic (SSURGO) soil map is required along with the corresponding database to prepare soil parameters. For each soil mapping unit in SSURGO soil map, AGWA applies these parameters uniformly to all the parcels in the subdivision that intersect that soil mapping unit, and spatially, averages the parameters when parcels intersect multiple soil mapping units. Additionally, AGWA stores all of these parameters in tables, which allows the user to modify these values using data from field surveys or other sources.

Figure 3 Flow routes drawn by the user on the La Terraza subdivision in Sierra Vista, AZ.

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. Each design can be saved in the Geodatabase with a unique name. A combination of these designs can be saved as a "Placement Plan".

Retention Basins: A retention basin design requires the width, length, and depth of the retention basin in order to calculate the area and volume associated with it. In addition to the above dimensions, KINEROS2 requires the soil saturated hydraulic conductivity of the retention basin. Water from the lot is assumed to flow into the retention basin before flowing on to the street half.

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. Using this option, AGWA calculates the permeable pavement area based upon the driveway area defined in the Element Parameterization step. A soil saturated hydraulic conductivity value is also required. The permeable pavement driveways allow infiltration of water based on the hydraulic conductivity provided by the user.

Rainwater Harvesting: For the design of a rainwater harvesting system, the volume of the rain barrel (or cistern) can be provided, or can be calculated using the height and diameter of the rain barrel. Rainwater falling on the roof of the house is captured by this rainwater harvesting system.

Precipitation: KINEROS2 accepts rainfall data in the form of time-intensity pairs or time-depth (where depth represents 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. If observed rainfall is available from more than one rain gauge, KINEROS2 employs a piece-wise planar space-time interpolation scheme that can also accommodate radar-rainfall estimates. 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 input files required by the KINEROS2 model. The user selects the flow routing table, parameterization, placement plan table, and precipitation file, and provides a unique name for the simulation.

Execute KINEROS2 Model: In the Execute KINEROS2 Model step, the user selects a simulation and runs the KINEROS2 model. 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. AGWA allows the user to visualize the output for each parcel in the form of infiltration, runoff, and accumulated runoff volumes, as well as absolute and percent differences between two simulations. Infiltration and runoff volumes (figure 4) results are visualized for each individual parcel. Accumulated runoff (figure 5), which is comprised of the runoff from each parcel along with the runoff from the upland parcel, can be visualized along the street.

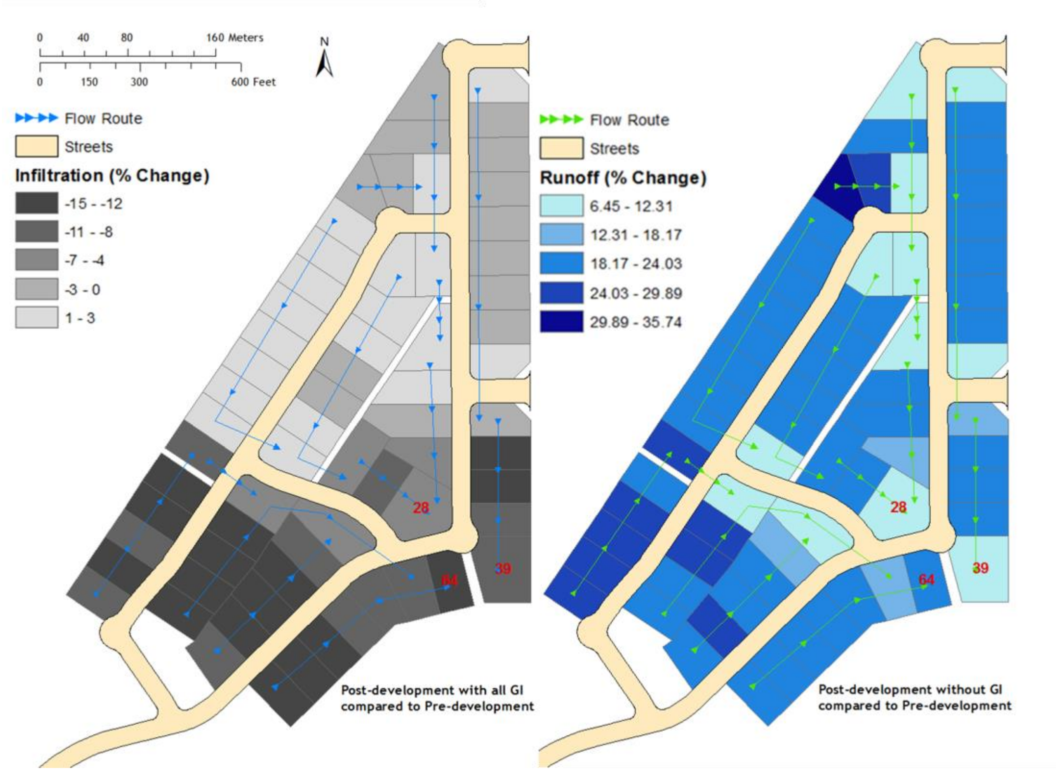

Figure 4 Visualization of the AGWA GI infiltration and runoff results for parcels.

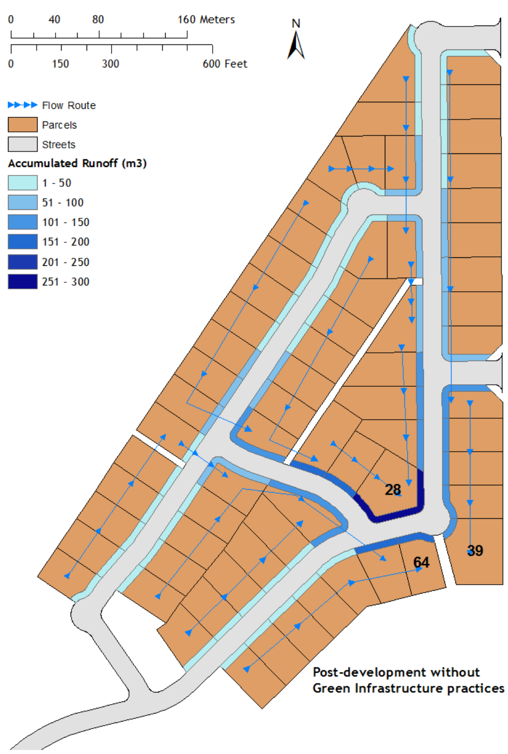

Figure 5 Visualization of the AGWA GI flow accumulation results on the roads.

TESTING

Lot Level: Verification of the Urban element at the lot-scale was approached by confirming the following: 1) Event volumes of hydrologic components are balanced properly; and, 2) Steady-state runoff rates based on a constant rainfall intensity with a configuration of areas with known infiltration rates. To test both, an element was created representing a typical lot in the La Terraza subdivision and was used in six scenarios (Table 1): pre-development; post-development without GI; retention basins; permeable pavements; rainwater harvesting; and all GI practices.

Table 1 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 (without GI)	Lot with a house area of 2500 square feet and a ~12 feet by 19.5 feet 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)
Permeable Pavement	Post-development parameters with a permeable driveway 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 cubic meters)
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 duration of two-hours onto a lot size of 0.1933 hectares, yielding a total rainfall volume of 96.66m^3; this rainfall volume is the model input. Model outputs include interception, infiltration, storage, and outflow in cubic meters. For all scenarios, the error for the water balance was less than 1 percent.

Effective hydraulic conductivity is defined as the rainfall minus outflow rate at steady-state (figure 6). 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 cubic meters for each of the overland flow areas of the 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 have higher infiltration capacities than the rainfall rate.

Subdivision Level: Verification of the model for the La Terraza subdivision (figure 3) 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.

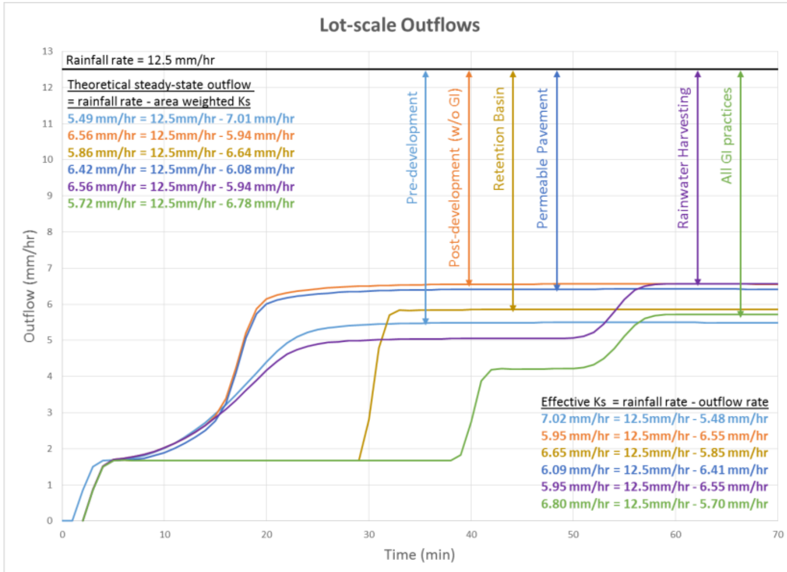

Figure 6 Hydrographs illustrating effective hydraulic conductivities for lot-scale testing.

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 (2007). Initial soil saturation values for each event were also obtained from Kennedy (2007).

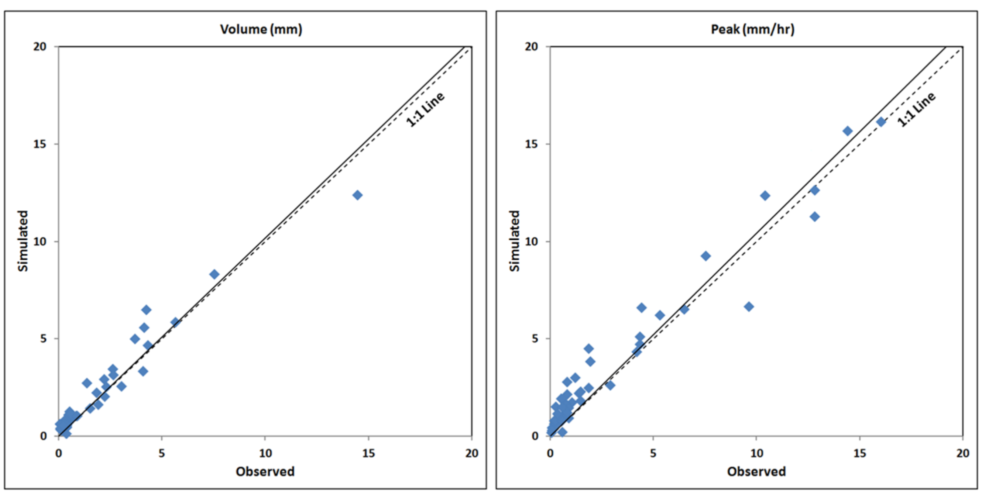

Figure 7 Simulated versus observed event runoff volume (mm) and peak flows mm/hr (n = 47) for July 2015 through September 2006 for the La Terraza subdivision.

The total event runoff volumes and peak flow rates for the 47 simulated events compared to measured values are shown in figure 7. 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.

LIMITATIONS AND ISSUES

Limitations of the KINEROS2 model are discussed in Goodrich et al. (2012). KINEROS2 is currently an event-based model and will not simulate plant water use, soil water movement between events, or track snow accumulation and melt, or subsurface flow. 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 practices is drawn down for watering through different weather scenarios. 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 onto adjacent lots. KINEROS2 provides a representation for dead storage, such as a swimming pool or walled yard that effectively traps and holds runoff, however, the AGWA GI tool currently lacks the ability to incorporate this.

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 an Urban GI element in these cases. Currently, this is most easily done by altering the KINEROS2 parameter file outside of the AGWA GIS environment, but tools to subdivide elements will be supported in AGWA in the future. 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.

CONCLUSIONS

The AGWA GI tool was designed and developed to represent retention basins, permeable pavements, and rainwater harvesting systems within the AGWA/KINEROS2 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 GI tools were developed to spatially prepare parameters for the KINEROS2 Urban GI model element. The Flow Routing tool allows the user to draw 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 post-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. Three output types are 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 practices 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. 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.

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 practices. 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.

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