Evaluation of Green Infrastructure Designs Using the Automated Geospatial Watershed Assessment Tool

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Abstract

In arid and semi-arid regions, green infrastructure (GI) designs can address several issues facing urban environments, including augmenting water supply, mitigating flooding, decreasing pollutant loads, and promoting greenness in the built environment. An optimum design captures stormwater, addressing flooding and water quality issues, in a way that increases water availability to support natural vegetation communities and landscaping in the built environment. A module was developed for the Automated Geospatial Watershed Assessment (AGWA) tool which supports the design and placement of a suite of GI practices, singularly or in combination, in order to simulate urban hydrology with and without GI features at the household and neighborhood scale.The GI tool takes 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-based GI assessment framework that automatically derives model parameters from widely available spatial data. It is also capable of manipulating GI features within a graphical interface to conveniently view and compare simulation results with and without GI features at a lot, neighborhood or small catchment scale. The new tool was used to assess a variety of GI designs across a subdivision in Sierra Vista, Arizona for the design objectives: maximize stormwater capture, maximize water augmentation, and maximize ecosystem services.

INTRODUCTION

Urbanization has numerous effects 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).

However, in arid and semi-arid environment the increase in runoff volumes can also be perceived as an opportunity by augmenting the water supply (Figure 1), which can be used to promote greenness and create a more livable, heathier environment (Jackson, 2003). Flooding and water quality are also important concerns, but maintaining runoff volumes and peak flows at the undeveloped levels is important for preserving riparian habitat (Stromberg 2001). Ideally, the "best" outcome to an integrated watershed plan would be to maintain peak flows and runoff volumes at the pre-development levels, minimize pollutant loads, and capture stormwater to augment water supply and potentially used for landscape irrigation. To this end not all Green Infrastructure (GI) practices are beneficial. Permeable surfaces (e.g. roads, driveways) could generate significant reductions in runoff volumes and peak flows, but the water would not be available for use, while rainwater harvesting captures the stormwater for later use while also reducing runoff volumes and peak flows (Bedan and Clausen 2009).

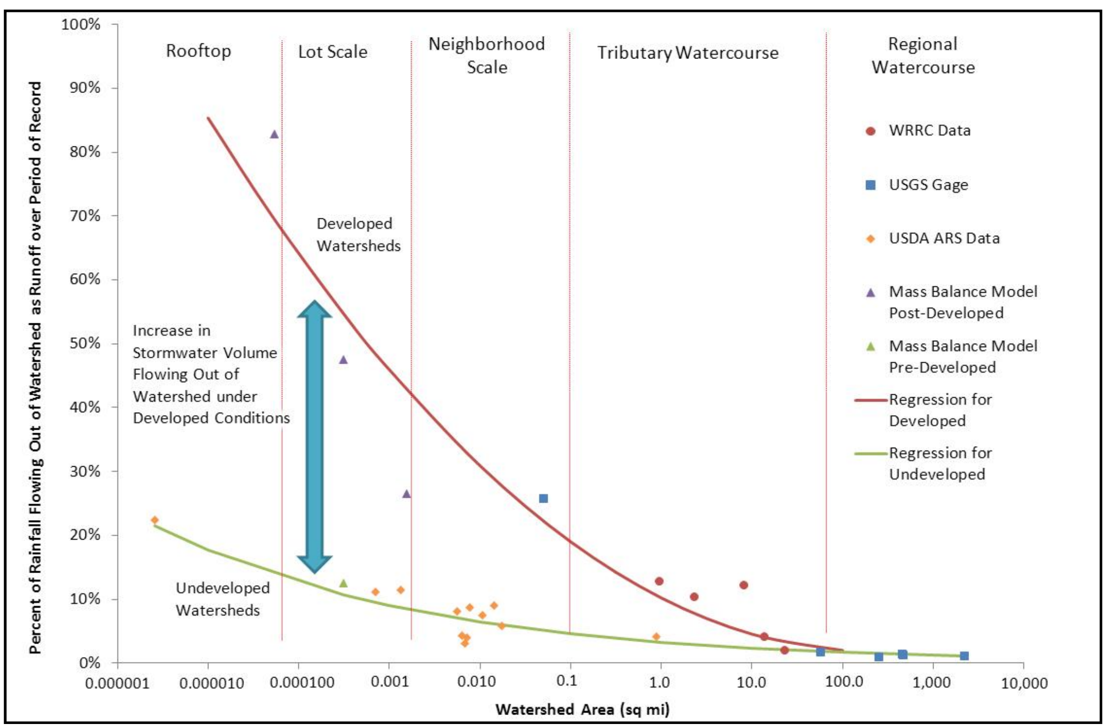

Figure 1: Potential Harvestable Water (Rainwater/Stormwater) in Tucson, Arizona. Developed by Dr. Evan Canfield, Pima County Flood Control, Tucson, Arizona.

Functionality was added to the Automated Geospatial Watershed Assessment tool (AGWA, see: www.tucson.ars.ag.gov/agwa or http://www.epa.gov/esd/land-sci/agwa/) to parameterize the KINEROS2 model (K2 – KINematic runoff and EROsion model, Smith et al. 1995; Goodrich et al. 2012) to represent a built environment with and without GI practices. The new tool supports the development of GI designs in a built environment.

Built Environment Tools

AGWA (Miller et al. 2007; Goodrich et al. 2012) is a Geographic Information System (GIS) based watershed modeling tool. The models currently incorporated in AGWA are KINEROS2 (K2 – KINematic runoff and EROsion model, Smith et al. 1995), RHEM (Rangeland Hydrology and Erosion Model, Nearing et al. 2011), and SWAT (Soil & Water Assessment Tool version 2000 and version 2005, Arnold and Fohrer 2005). AGWA supports modeling along a continuum of spatial and temporal scales, ranging from hillslopes (~hectares) to large watersheds (>1000 km^2) and from individual storm events (minute time steps) to continuous simulation (daily time steps over multiple years). AGWA supports the parameterization and execution of the hydrologic models for watershed modeling efforts by performing the following tasks: watershed delineation; watershed discretization into discrete model elements; watershed parameterization; precipitation definition; model simulation creation; model execution; and model results visualization. Various data are required to support this functionality, including: a raster-based DEM (digital elevation model); a polygon soil map (NRCS SSURGO, NRCS STATSGO, or FAO soil maps are supported); and a classified, raster-based land cover (NLCD, NALC, and SWGAP datasets are supported via provided look-up tables, however other datasets may also be used if accompanied with a respective look-up table). AGWA does not require observed precipitation or runoff to drive the models when used for relative assessment/differencing between scenarios, and can use user-defined depths and durations, user-defined hyetographs, or design storms to drive K2, and included weather station-based generated, daily precipitation (U.S. only) to drive SWAT. However, high-quality rainfall-runoff observations are required for calibration and confidence in quantitative model predictions (Goodrich et al., 2012).

K2 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.

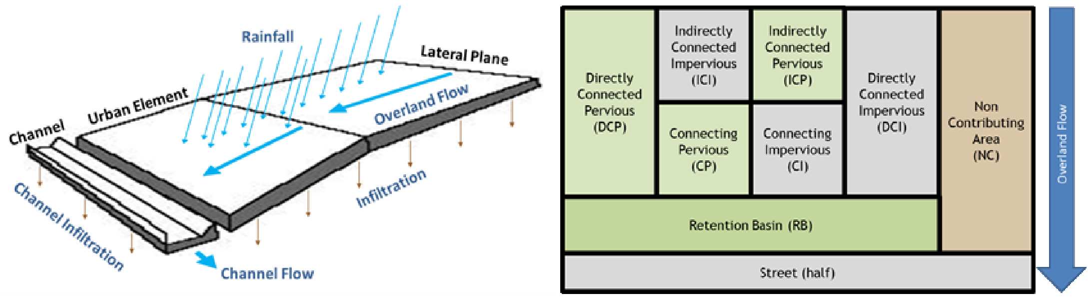

Figure 2. KINEROS2 element and "Urban" element components.

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 K2 and the GIS interface provided by AGWA creates the option to use these in unison to provide a powerful modeling platform for evaluating GI practices in urban development scenarios.

Based on the existing AGWA functionality, a modified workflow was designed to utilize K2 to simulate urban environments and develop GI designs. 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. K2 requires the path that water will follow from the lot to the basin outlet. The Urban element in K2 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 the 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. The user can modify these values for each parcel, in order to better represent the lot.

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

Green Infrastructure Design and Placement: The Green Infrastructure Design and Placement tool (GI 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, K2 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 driveway 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 using the driveway area defined in the Element Parameterization. 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 and the availability of water from rainfall or as flow-on from the roof area. Permeable Roads area are not implemented at this time.

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.

CASE STUDY

AGWA was applied to the La Terraza subdivision (13 ha) located in Sierra Vista, AZ (Figure 3). Nine scenarios were created for the case study (Table 1): pre-development, post-development w/o GI, Retention Basins (RB), Permeable Driveway Pavements (PDP), Rainwater Harvesting (RH), RB&PDP, RB&RH, PDP&RH, and RB&PDP&RH. Each scenario was simulated using rainfall applied at a constant intensity of 12.5 mm/hr for 120 minutes, using a SCS Type II design storm rainfall distribution. The rainfall intensity and duration were selected so that the element reached steady-state outflow rates. The pre-development land cover type was desert grassland.

Results: Table 2 contains the simulation results for one rainfall event for the nine scenarios. Development increased peak runoff by 7.14% and runoff volume by 4.33%. All GI practices reduced the peak runoff and runoff volume. Using all the GI practices would be the "best" option if the goal was to maximum flooding reduction and stormwater capture.

However, rainwater harvesting only, with a small decrease in peak runoff and a small increase in runoff volume maybe the best option for supporting ecosystem services. The rainwater harvesting scenario best maintained pre-development flow, with small augmented flow to support downstream riparian values. One hundred percent of the captured water can be used to augment water supply and can be used to promote greenness in the built environment.

Table 1. Description of the La Terraza subdivision scenarios.

Pre-development	Empty lots with street and soils attributes obtained from the NRCS SSURGO soils spatial database.
Post-development (w/o GI)	Each lot with a house area of 232 square meters and a 3.66 meters by 5.94 meters impermeable driveway (21.74 square meters).
Retention Basin	Post-development parameters with the addition of a retention basin with a hydraulic conductivity of 201 mm/hr (~8.3 in/hr) and sized with a surface area of approximately 6.69 square meters and a depth of 25.4 centimeters, yielding a retention capacity of 1.70 cubic meters (~449 gallons) on each lot.
Permeable Driveway Pavement	Post-development parameters with a permeable driveway with a hydraulic conductivity of 210 mm/hr (~8.3 in/hr) on each lot.
Rainwater Harvesting	Post-development parameters with a rainwater harvesting feature with a cistern capacity of 1.9 cubic meters (500 gallons) on each lot. The cistern is assumed to be empty at the beginning of the simulation.

Table 2: Simulation results for the nine scenarios on the La Terraza subdivision.

Scenario	Peak Runoff (m^3/s)	Peak Runoff (mm/hr)	% Change in Peak Runoff vs. Pre-development	Runoff Volume (m^3)	% Change in Runoff Volume vs. Pre-development
Pre-development	2.13	54.68	NA	3267.21	NA
Post-development without GI	2.28	58.59	7.14	3408.71	4.33
Retention Basin	2.24	57.40	4.97	3219.80	-1.45
Permeable Pavements	2.25	57.76	5.64	3355.96	2.72
Rainwater Harvesting	2.12	54.35	-0.60	3290.25	0.71
Retention Basin + Permeable Pavements	2.20	56.55	3.41	3171.28	-2.94
Retention Basin + Rainwater Harvesting	2.07	53.05	-2.98	3103.10	-5.02
Permeable Pavements + Rainwater Harvesting	2.08	53.51	-2.13	3237.50	-0.91
All GI practices	2.03	52.20	-4.53	3052.75	-6.56

Results can be visualized in both graphic and tabular formats. The "View Results" form in AGWA allows the user to visualize the results of the K2 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.

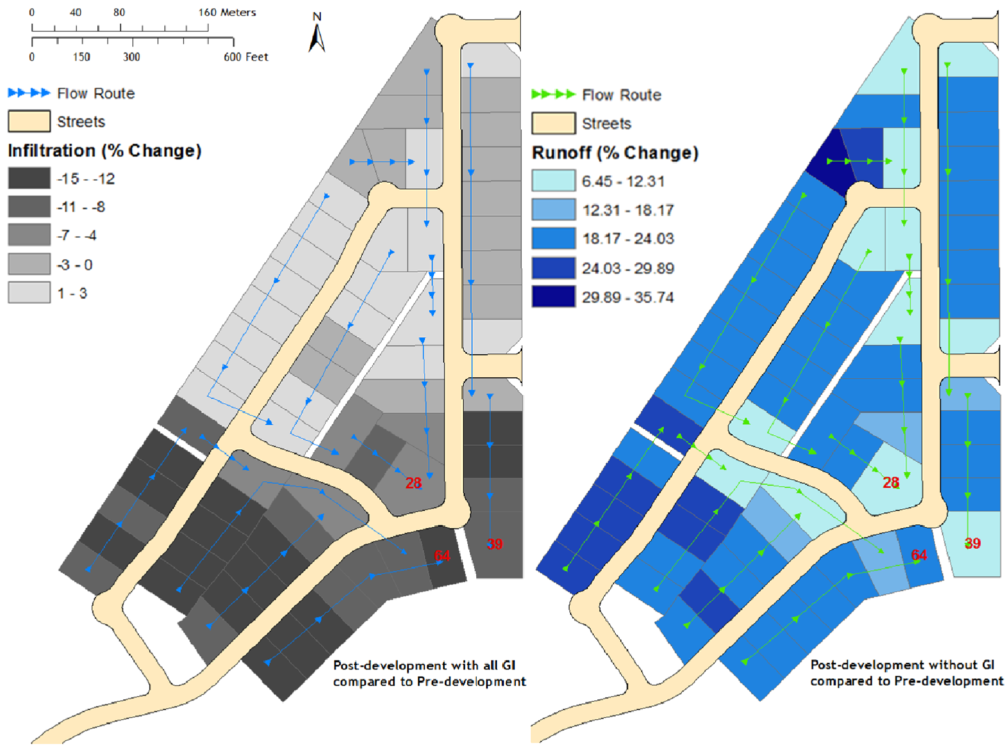

Figure 4. Visualization of the AGWA GI infiltration and runoff results for parcels for the percent change between post-development with all GI practices and pre-development.

CONCLUSIONS

The AGWA GI tool was designed and developed to represent retention basins, permeable pavements, and rainwater harvesting systems within the AGWA/K2 modeling environment. The "Urban" element in K2 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 K2 Urban GI model element. The "Flow Routing" tool allows the user to draw flow paths on the map, guiding stormwater 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

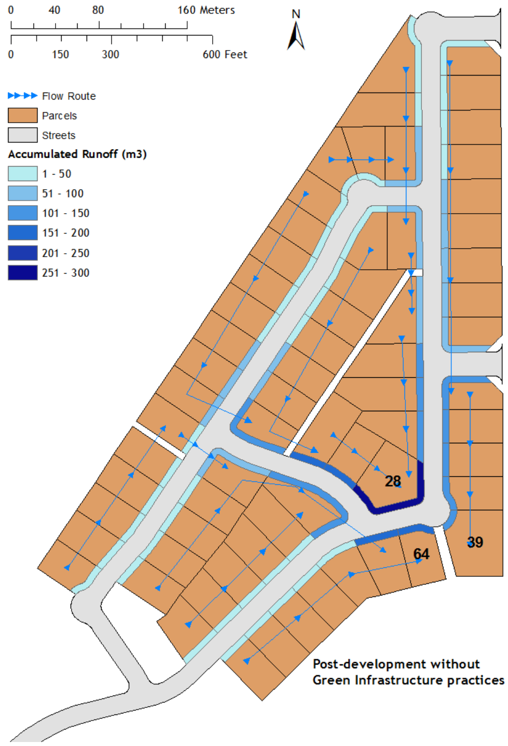

Figure 5. Visualization of the AGWA GI flow accumulation results on the roads.

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 AGWA GI tool can be a used to inform planning decisions related to built environments and stormwater management on lot-, subdivision-, and small catchment-scales. This information will be useful in understanding the expected differences in stormwater runoff between neighboring developments or natural environments. The effect of different combinations of GI practices can be assessed. In traditional post-development urban environments, the increase in stormwater runoff can negatively impact downstream natural resources. GI features have the potential to mitigate those effects by achieving pre-development runoff volumes to support an array of ecosystem services.

Future development of the GI tool will include adding more GI practices such permeable road pavement, swales, bioretention facilities, infiltration basins, and filter strips. The capability to model nitrogen and phosphorus loads will also be added in the future.

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