International Journal of
Geo-Information

Article

Hydrological Modeling of Green Infrastructure to Quantify Its Effect on Flood Mitigation and Water Availability in the High School Watershed in Tucson, AZ

Yoganand Korgaonkar [1,2,*], David Phillip Guertin [2], Thomas Meixner [3] and David C Goodrich [4]

[1] School of Geography, Development and Environment, University of Arizona, Tucson, AZ 85721, USA
[2] School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA; dpg@arizona.edu
[3] Hydrology and Atmospheric Sciences, University of Arizona, Tucson, AZ 85721, USA; tmeixner@arizona.edu
[4] Southwest Watershed Research Center, USDA-ARS, Tucson, AZ 85719, USA; dave.goodrich@usda.gov
* Correspondence: yoganandk@arizona.edu

Citation: Korgaonkar, Y.; Guertin, D.P.; Meixner, T.; Goodrich, D.C. Hydrological Modeling of Green Infrastructure to Quantify Its Effect on Flood Mitigation and Water Availability in the High School Watershed in Tucson, AZ. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 443. https://doi.org/10.3390/ijgi10070443

Academic Editors: Peter M. Bach, Martijn Kuller and Wolfgang Kainz

Received: 19 May 2021
Accepted: 24 June 2021
Published: 29 June 2021

Abstract: Green Infrastructure (GI) practices are being implemented in numerous cities to tackle stormwater management issues and achieve co-benefits such as mitigating heat island effects and air pollution, as well as water augmentation, health, and economic benefits. Tucson, Arizona is a fast-growing city in the semiarid region of the southwest United States and provides a unique landscape in terms of urban hydrology and stormwater management, where stormwater is routed along the streets to the nearest ephemeral washes. Local organizations have implemented various GI practices, such as curb cuts, traffic chicanes, roof runoff harvesting, and retention basins, to capture the excess runoff and utilize it on-site. This study models the 3.31 km^2 High School watershed in central Tucson using the Automated Geospatial Watershed Assessment (AGWA) tool and the Kinematic Runoff and Erosion (KINEROS2) model. Each parcel in the watershed was individually represented using the KINEROS2 Urban element to simulate small-scale flow-on/flow-off processes. Seven different configurations of GI implementation were simulated using design storms, and we stochastically generated 20 years of precipitation data to understand the effects of GI implementation on flood mitigation and long-term water availability, respectively. The design storm analysis indicates that the configuration designed to mimic the current level of GI implementation, which includes 175 on-street basins and 37 roof runoff harvesting cisterns, has minimum (<2%) influence on runoff volume. Furthermore, the analysis showed that the current level of GI implementation caused an increase (<1%) in peak flows at the watershed outlet but predicted reduced on-street accumulated volumes (>25%) and increased water availability via GI capture and infiltration. When the GI implementation was increased by a factor of two and five, a larger reduction of peak flow (<8% and <22%, respectively) and volume (<3% and <8%, respectively) was simulated at the watershed outlet. The 20-year analysis showed that parcels with roof runoff harvesting cisterns were able to meet their landscape irrigation demands throughout the year, except for the dry months of May and June. Additionally, stormwater captured and infiltrated by the on-street basins could support xeric vegetation for most of the year, except June, where the water demand exceeded volume of water infiltrated in the basins. The current level of GI implementation in the High School watershed may not have significant large-scale impacts, but it provides numerous benefits at the parcel, street, and small neighborhood scales.

Keywords: green infrastructure; GIS; KINEROS2; AGWA; hydrological modeling

1. Introduction

Arid and semiarid regions of the southwestern United States have limited water resources but growing demands due to rapid urbanization [1]. In addition to water supply, urbanization also increases runoff by replacing pervious areas with impervious surfaces such as roofs, driveways, and streets. Green Infrastructure (GI) practices are being widely adapted to mitigate the impacts of urbanization. GI practices (also known as low-impact development, or source control practices) aim to detain runoff on-sites through storage or infiltration [2]. Readers are guided to other papers that have reviewed the evolution, implementation, performance, and effectiveness of GI practices with respect to stormwater management [3–6]. In addition to stormwater management benefits, GI has been found to deliver multiple co-benefits such as mitigating heat island effects [7–10] and air pollution [11–14], as well as health benefits [15–18]. Hopton et al. (2015) reviewed reports, journal articles, and conference proceedings to summarize the various GI practices considered for various benefits across the United States [19].

The city of Tucson provides a unique case study on urban stormwater routing and GI implementation in a semiarid environment as compared to other cities in the United States. Traditionally, stormwater has been routed to nearest ephemeral washes using streets. The use of subsurface drainage is minimal and has been implemented only in a few areas around the city. As a result, nuisance flooding on the streets due to high-intensity, short-duration precipitation events is common in various parts of the city. There is a lot of potential to capture and reuse stormwater on-site and off the streets using GI practices. Several organizations, such as the city and county offices and agencies, non-profit organizations, and neighborhood associations, have been responsible for the push to implement GI practices as a measure for flood mitigation and water availability and to achieve simultaneous co-benefits. However, the effectiveness of these implementations has not been documented or thoroughly studied. This study attempts to quantify the impact of GI implementation on flood mitigation and water augmentation in the High School watershed in central Tucson using the Automated Geospatial Watershed Assessment (AGWA) tool and the Kinematic Runoff and Erosion (KINEROS2) model.

KINEROS2 is a physically based, spatially distributed, event-driven model that simulates runoff and erosion for small watersheds [20,21]. KINEROS2 uses kinematic wave equations to simulate overland flow, while the three-parameter Parlange equation is used to simulate infiltration [22]. KINEROS2 also has capability of modeling the urban environment by representing a single parcel using the Urban modeling element [23–25]. The Urban modeling element (Figure 1) provides up to 13 sub-components to represent various pervious (yards), impervious (roofs and driveways), GI practices, and street overland flow areas. In general, "directly connected" areas connect to a street half without any interruptions, whereas "indirectly connected" areas connect to the street half via an intermediary "connecting" area subcomponent. Roofs are represented by the indirectly connected impervious (ICI) area, and the runoff from ICI can be stored in a cistern to simulate roof runoff harvesting. Side and front yards can be represented by directly connected pervious (DCP) and connecting pervious (CP) areas, respectively, and each can have a retention basin represented by RB_DCP and RB_CP, respectively. Driveways can be represented using the directly connected impervious (DCI) area and can implement a retention basin using RB_DCI. Water sinks, such as swimming pools, and nondraining backyards can be represented by the noncontributing area (NC). On-street basins can be represented using the Curbcut (CC) area that intercepts all runoff flowing down the street. Each urban element has its own set of land cover and soil parameters, allowing discrete representation at a small scale. The runoff is assumed to flow over each parcel, via each of the subcomponents, to the street half. More than one parcel can be connected to represent neighborhoods or larger watersheds, and the runoff is routed from street half to street half as it flows toward the watershed outlet.

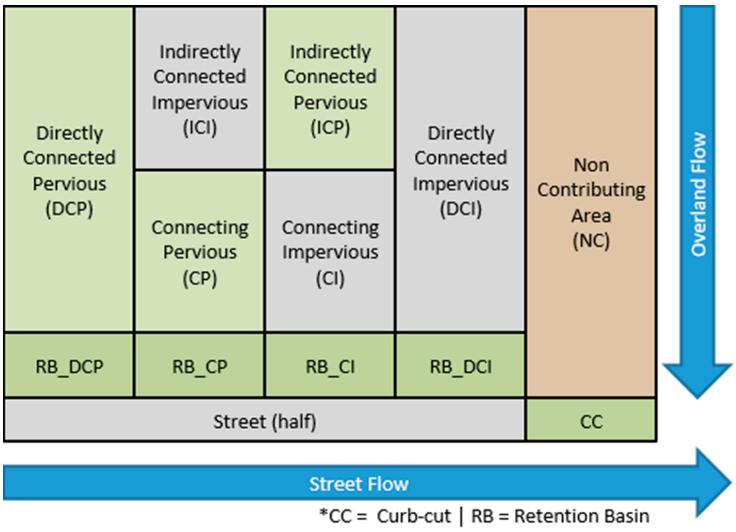

Figure 1. The KINEROS2 modeling element provides up to 13 modeling subcomponents that can be used to represent a single parcel.

The AGWA tool [26] is a Geographic Information System (GIS)-based tool that uses spatial datasets to derive initial parameters estimates for hydrological models, such as the Soil and Water Assessment Tool (SWAT) [27], the Rangeland and Hillslope Erosion model (RHEM) [28], and KINEROS2. The AGWA tool includes an urban tool to simulate urban hydrology and GI practices at various scales, including parcels, subdivisions, neighborhoods, and watersheds, using the KINEROS2 model. The AGWA Urban tool prepares parameters for KINEROS2 using spatial data in the form of parcel and soils datasets. A summary of KINEROS2 model inputs can be found in Table 1, and a detailed description of the AGWA Urban tool has been described by Korgaonkar et al. (2018) [24]. The strength of the AGWA Urban tool lies in its ability to utilize spatial datasets to create a model, where each parcel acts as an individual modeling element in KINEROS2. The small-scale representation allows the modeling of flow-on/flow-off processes occurring on a single parcel, and enables a deeper understanding of the effects of GI practices, which are essentially designed to work at this scale. The AGWA Urban tool add-in and the KINEROS2 model can be downloaded from the AGWA website hosted by USDA-ARS at https://www.tucson.ars.ag.gov/agwa/, accessed on 28 June 2021.

Table 1. Summary of KINEROS2 model inputs and outputs.

Model Inputs	Parameters
Parcels via Geospatial Data	Dimensions, slope, fractional areas of urban overland flow areas
Streets via Geospatial Data	Width, grade, and cross slope
Land Cover	Hydraulic roughness, interception depths, and canopy cover fractions
Soils via SSURGO soils data	Hydraulic conductivity, coefficient of variance of Ks, mean capillary drive, porosity, pore distribution index, and volumetric rock fraction
GI Practices	Location, size, depth and hydraulic conductivity of basins, and volume of cistern
Model Outputs	**Parameters**
Parcel Scale	Runoff volume, infiltration volume, peak flow, and GI storage volumes
Watershed Scale	Total runoff volume, total infiltration volume, and peak flow at outlet

The objectives for this study are: (1) To study the effects of GI implementation at various scales for parcels, streets, neighborhoods, and urban watersheds; (2) to quantify the effects of the current level of GI implementation in terms of flood mitigation and water availability; and (3) to predict water availability for plant growth via active and passive rainwater harvesting.

2. Materials and Methods

2.1. Study Area

The High School watershed (Figure 2) is a 3.31 km^2 watershed in central Tucson, Arizona. It encompasses the University of Arizona, the Rincon Heights, and Sam Hughes neighborhoods. This area receives an annual average precipitation of 303 mm, with an annual average temperature of 21 °C. The watershed consists of 2177 parcels with an average parcel area of 1292 m^2 and total impervious area of 2.16 km^2. Most of these parcels are residential, but the watershed also includes commercial parcels distributed throughout the watershed, a large park, and the University of Arizona campus toward the north-west of the watershed. The total roof, driveway, and street area constitutes 24%, 16%, and 25% of the total watershed area, respectively. Stormwater is routed along the streets as it flows toward the High School wash, which is a 1732 m-long natural vegetated channel with concrete culverts under cross streets. A pressure transducer measuring flow depths acts as the watershed outlet for our study. The Rincon Heights neighborhood has many on-street GI practices in the form of curb cuts with retention basins and chicanes (in-street practices that reduce the width of the traffic lane and allow water to collect and infiltrate in basins). Additionally, several houses have installed cisterns to capture roof runoff. Most of the landscape in this neighborhood can be classified as a xeriscape with native vegetation.

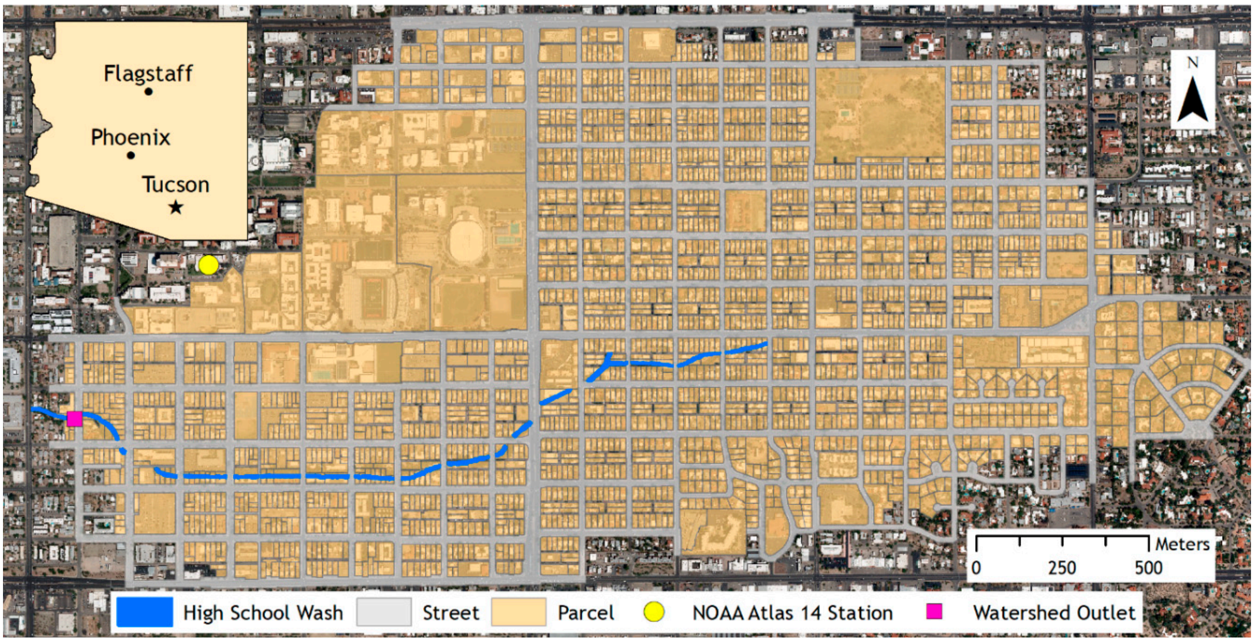

Figure 2. High School watershed comprising of 2177 parcels.

2.2. KINEROS2 Model

The AGWA Urban tool was used to setup the parameters for the KINEROS2 model. Watershed boundary and stormwater routing was derived from a 0.5 m resolution digital elevation model (DEM) created from LiDAR point clouds. Parcel and street files were obtained from Pima County GIS, along with a land-use/land-cover raster dataset. The parcel dimensions, street widths, and roof and driveway areas were extracted from these spatial datasets. The High School wash was split into 11 channel elements, of which the dimensions and slope were extracted from high-resolution imagery and DEM, respectively. Each parcel was assumed to have a front yard area and noncontributing area equal to 10% of the total parcel area, 2% overland and street cross slope, and 1% street grade.

Roughness was assumed to be 0.02 (equivalent to graveled surfaces) for impervious areas and streets, 0.15 (equivalent to short grass prairie) for pervious areas, and 0.035 (equivalent to main channel with stones and weeds) [29] for the channel. Interception was set to 1 mm for impervious and 2 mm for pervious surfaces, with a canopy cover fraction of 1. Soil parameters were obtained from the Soil Survey Geographic Database (SSURGO).

2.3. Model Configurations

The KINEROS2 model as described above serves as the NO GI base configuration model. This configuration was validated using 33 observed precipitation events between July 2016 and August 2018. NEXRAD digital precipitation rate (DPR) Level III data was obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information website for the KEMX Tucson NEXRAD station. Spatial datasets at 5 min intervals were downloaded using NOAA's Weather and Climate toolkit. These datasets were processed to create time-intensity pairs (required by KINEROS2) for each NEXRAD tile over the High School watershed. Simulated runoff volumes and peak flows were compared to those derived from stage-height data from a pressure transducer installed at the watershed outlet (Figure 2). Five more configurations were created to test a variety of GI implementation scenarios (Table 2). All configurations were designed and implemented in the KINEROS2 model using the AGWA Urban tool.

Table 2. Summary of KINEROS2 model configurations to simulate various GI implementation scenarios.

Configuration	Description
NO GI	No GI implementation
CURRENT	Current GI Implementation: 175 On-street basins [1] and 37 roof runoff harvesting cisterns [2]
CURRENT ×2	350 On-street basins [1] and 84 roof runoff harvesting cisterns [2]
CURRENT ×5	840 On-street basins [1] and 185 roof runoff harvesting cisterns [2]
PRE-DEV	Pre-development: No impervious area (i.e., houses, driveways, or streets)
MAX GI	99% of front yard and side yard, and 10% of driveway area converted to a retention basin, 0.3 m deep with hydraulic conductivity of 210 mm/h; 3.78 m^3 cistern to capture roof runoff; and on-street basin based on City of Tucson guidelines, adhering to minimum right of way

[1] On-street basins: Average area 14.56 m^2, average Depth = 0.16 m, hydraulic conductivity = 210 mm/h. [2] Cisterns: Average capacity = 5.25 m^3.

The CURRENT configuration was created to represent the current level of GI implementation based on survey data of on-street basins (curb cuts, and chicanes) as well as roof runoff harvesting data from the Tucson Water rebate program (Figure 3, top). However, due to the lack of data on the number and sizes of on-parcel GI practices, i.e., basins on private property within a parcel, this configuration is limited from being a 100% representation of current conditions. In total, 175 on-street basins were surveyed, with basins averaging surface area 14.56 m^2 and average depth 0.16 m. The hydraulic conductivity for all basins was assumed 210 mm/h. We identified 37 parcels to have roof runoff harvesting cisterns with an average capacity of 5.25 m^3 from the rebate dataset.

Two more configurations were created to represent hypothetical scenarios using the basin and cistern sizes from the CURRENT configuration. The CURRENT ×2 configuration represents double the current level of GI implementation, with on-street basins assigned randomly to 350 parcels, and 74 parcels were randomly fitted with roof runoff harvesting cisterns (Figure 3, middle). Similarly, the CURRENT ×5 configuration represents 5-times the current level of GI implementation (Figure 3, bottom). On-street basins were randomly fitted on 840 parcels, and roof runoff harvesting cisterns were assigned to 185 parcels. The GI designs for both these configurations were randomly selected from the survey and rebate design set. Configuration PRE-DEV simulates pre-development conditions in the watershed by removing houses, driveways, and streets. The goal is to create a scenario that mimics the natural watershed before any development was undertaken.

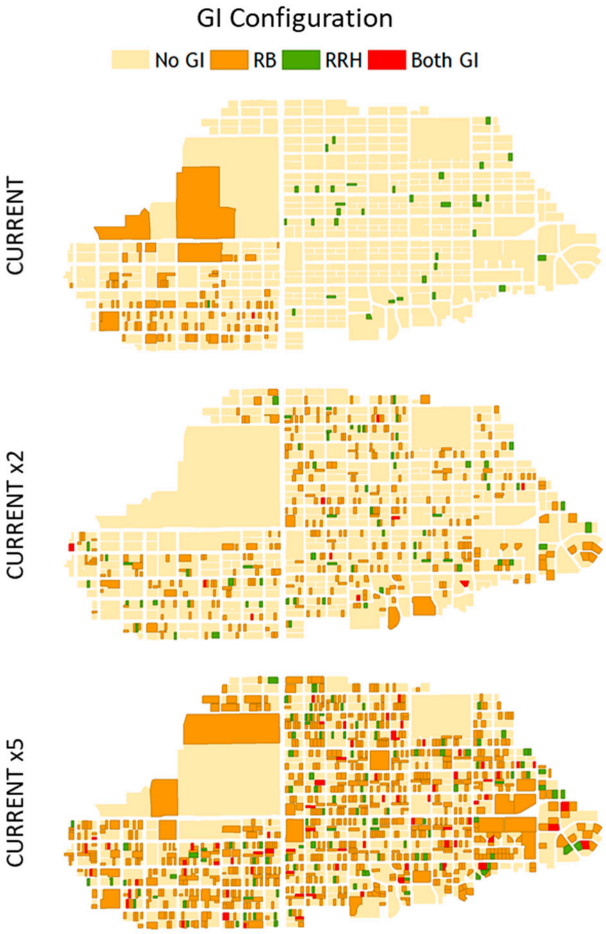

Figure 3. Spatial comparison of the distribution of the GI practices for configurations CURRENT (**top**), CURRENT ×2 (**middle**) and CURRENT ×5 (**bottom**). CURRENT ×2 and CURRENT ×5 configurations represent a hypothetical random distribution of GI practices and only uses basin and cistern sizes from the CURRENT configuration. RB: On-street basins. RRH: Roof runoff harvesting cistern.

To test the potential of GI implementation in the High School watershed, a hypothetical (albeit nonpractical) configuration MAX GI was created to represent maximum GI implementation. Each parcel was installed with a 3.78 m^3 cistern to harvest roof runoff. Additionally, 99% of the front yard and side yard areas and 10% of the driveway areas were converted to retention basins with depths of 0.3 m. On-street basins with depth of 0.2 m were installed on the street half of each parcel based on city of Tucson guidelines for chicanes, maintaining minimum right-of-way street widths. All basins were assumed to have a hydraulic conductivity of 210 mm/h representative of a sandy soil texture.

Note that the saturated hydraulic conductivity assumption of 210 mm/h for the basins is a conservative estimate. Anderson et al. (2018) performed infiltrometer tests on several on-street basins installed in the High School watershed as well as another nearby watershed [30]. The average hydraulic conductivity for 40 basins was found to be approximately 423 mm/h, which is double the hydraulic conductivity of sand assumed in this study.

Two precipitation datasets were used for this study. First, the “Design Storm” dataset used three 1-hour design storms based on NOAA Atlas 14 Point Precipitation Frequency Estimates for the Tucson NWSO station located on the University of Arizona campus (Figure 1). The 5-year, 25-year, and 100-year estimates, with depths of 34 mm, 48 mm, and 61 mm, respectively, were selected to encompass varying levels of precipitation. Rainfall hyetographs were created by fitting the SCS Type II curve to the depth and duration of each of these 3 estimates using the AGWA Urban tool. Second, the "20-Year" precipitation dataset used CLIGEN-generated rainfall depths [31] for a period of 20 years from the University of Arizona station to understand the long-term water availability due to GI implementation. CLIGEN is a stochastic weather generator that produces daily estimates of precipitation peak intensity and duration using monthly means, standard deviations, and skewness derived from historic measurements at a given station. These estimates were fitted on a SCS Type II curve using the AGWA Urban tool. A few assumptions were made while designing the implementation of this simulation. First, antecedent soil moisture was assumed to be 0.2 (20% of the fillable porosity) for dry conditions and 0.46 for wet conditions [32]. Antecedent soil moisture was reset to dry conditions before a precipitation event if there was more than 1 day in between events and was set to wet conditions for consecutive days of precipitation. Second, the harvested runoff stored in the cistern was reduced before every event based on water usage calculated using Equation (1) [33] when there was more than 1 day between consecutive precipitation events. ET_o is the standardized monthly reference evapotranspiration rates, plant factor is the percent of ET_o that is needed by the plant (described as low, medium, or high), and area is the total irrigated area. ET_o values for Tucson were obtained from Waterfall (2006) [33]. The irrigated area was assumed 20% of the total pervious area in the parcel, and a 0.355 plant factor was used based on medium water use [33] for calculating the water demand.

$$\text{Demand} = (\text{ET}_\text{o} \times \text{PLANT FACTOR} \times \text{IRRIGATED AREA}) \tag{1}$$

3. Results & Discussion

3.1. Model Validation

In total, 33 simulated and observed peak flows and volumes calculated from stage measurements using a pressure transducer were compared to validate the High School watershed model (Figure 4). By forcing the intercept to zero, regression equation slopes of 1.34 and 0.74 indicate reasonable model predictions. However, runoff volumes are generally overpredicted, whereas peak flow rates are underpredicted. R^2 of 0.82 for runoff volumes is indicative of good model performance. On the other hand, R^2 of 0.48 for peak flow means that the model could do a better job predicting peak flows. These results were deemed satisfactory for our study, and a formal calibration process was not undertaken as a result. There are numerous reasons that could affect the accuracy of the model. The validated model did not represent current GI implemented in the watershed as discussed above. Additionally, there is some uncertainty associated with the observed pressure transducer data used to calculate observed peak flow and volumes due to debris being lodged at the measurement site during runoff events. The model also assumes uniform precipitation over the 250 × 1000 m area grids obtained from NEXRAD, which may not represent the high spatial variability that is sometimes seen in the Tucson region.

3.2. Design Storm Analysis

All configurations were simulated using the three design storm events. Results are summarized for each configuration by calculating percent change (Equation (2)) as compared to the NO GI configuration.

$$\text{Percent Change} = \left(\frac{\text{CONFIGURATION} - \text{NO GI}}{\text{NO GI}}\right) \times 100 \tag{2}$$

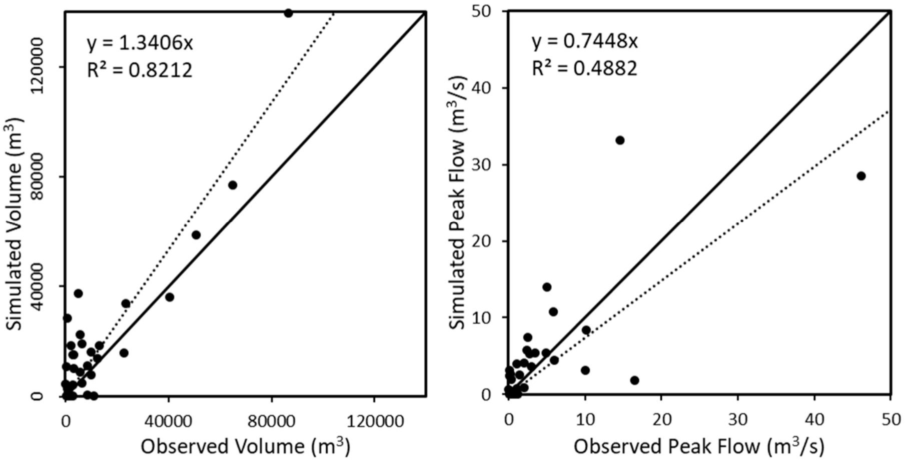

Figure 4. Validation of simulated runoff volumes (**left**) and simulated peak flows (**right**) at the watershed outlet as compared to observed values.

Configuration CURRENT was created to mimic the current level of GI implementation in terms of on-street GI practices and roof runoff harvesting cisterns. As expected, runoff volumes at the outlet showed a slight reduction (<1.5%) for all design storms, with decreasing percent reduction with the increase in event size (Table 3). However, the peak flow at the outlet showed an increase of less than 0.75% for all events. Delayed release of runoff due to basins reaching capacity in the lower part of the watershed, along with the time of concentration of the runoff from the upper part of the watershed routed through the High School wash, is one possible explanation for the minor increase in peak flow. Configuration CURRENT may not have a significant impact at the watershed scale. However, it does have localized impact, especially at the street scale (Figure 5) for the 25-year design storm. The streets with on-street basins showed a reduction of around 25% in runoff accumulation in the lower part of the watershed for the 25-year event (Figure 5), whereas the upper watershed showed less than 5% reduction in runoff accumulation in areas where cisterns were installed. These cisterns were able to capture an average of 5–5.25 m^3 of roof runoff for the 37 parcels for the 25-year event (Figure 6). The on-street basins not only mitigated on-street nuisance flooding, but also augmented water available for plant growth in them. The co-benefits of slowing traffic, increasing the aesthetic green value of the street, and the cooling effect due to trees may outweigh the benefits for flood mitigation, and is a potential avenue for further research. Out of 2177 parcels in the watershed, only 37 were reported to have a roof runoff harvesting cistern installed, which highlights an avenue for improvement.

Table 3. Percent change in peak flow (Q_p) and runoff volume (V) at the watershed outlet as compared to the NO GI configuration for the 3 design storm events.

Configuration	**Percent Change as Compared to NO GI**					
	5 YR 1 HR		**25 YR 1 HR**		**100 YR 1 HR**	
	Q_p	**V**	**Q_p**	**V**	**Q_p**	**V**
CURRENT	0.23	−1.47	0.57	−0.98	0.75	−0.75
CURRENT × 2	−7.23	−2.97	−6.76	−2.01	−6.51	−1.53
CURRENT × 5	−21.10	−7.24	−19.57	−4.92	−18.81	−3.76
PRE-DEV	−38.63	−32.99	−28.52	−24.01	−22.78	−19.08
MAX GI	−100.00	−100.00	−99.05	−99.72	−96.50	−97.29

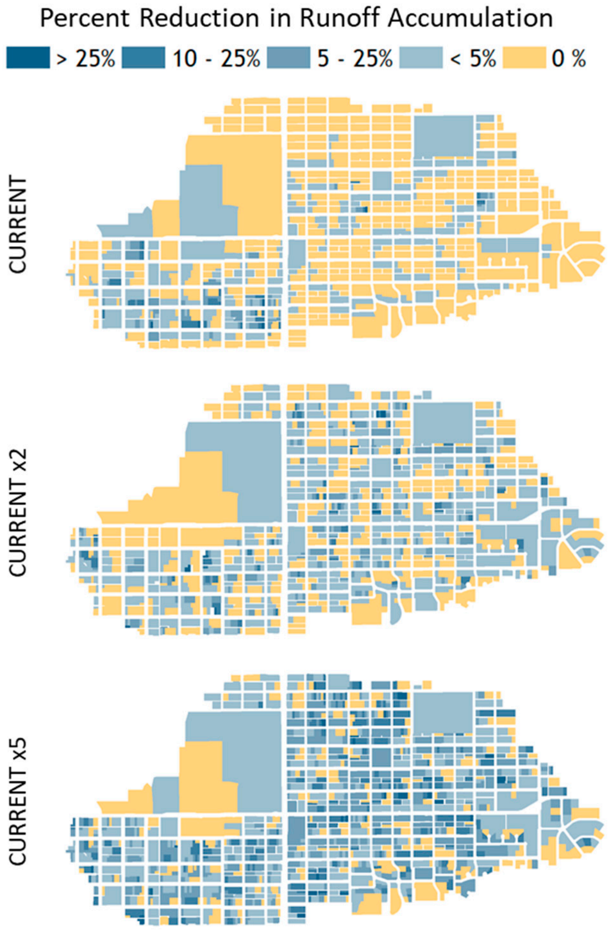

Figure 5. Spatial comparison of the percent reduction in runoff accumulation on the street half for configurations CURRENT (**top**), CURRENT × 2 (**middle**), and CURRENT × 5 (**bottom**) as compared to the NO GI configuration for the 25-year design storm event. RB: On-street basins. RRH: Roof runoff harvesting cistern.

Configurations CURRENT × 2 and CURRENT × 5 are "what-if" scenarios designed to assess the impacts of increasing the current level of GI implementation by factors of two and five, respectively. Increasing the current GI implementation by twice the amount resulted in reduction of peak flows up to 7.3%, and volumes up to 3% at the watershed outlet (Table 3). Similarly, the peak flows and volumes were reduced up to 21.1% and 7.24%, respectively, when the GI implementation was increased five times. These are significant decreases in peak flow and runoff volumes at the watershed outlet as compared to configuration CURRENT. Note that the percent reduction is largest for the 5-year event and decreases for the 25-year and 100-year events, indicating the reduced effectiveness of GI practices with increase in event size. The localized effect on runoff accumulation reduction as well as runoff capture increased as the number of GI practices increased (Figure 5). The number of parcels with more than 25% reduction in runoff volume accumulation on the street, and with more than 25 m^3 of rainwater captured (Figure 6), is significantly larger for CURRENT × 5 as compared to CURRENT × 2 and CURRENT for the 25-year event.

The PRE-DEV configuration reveals that runoff volumes increased by more than 19% due to the addition of impervious areas in the form of roofs, driveways, parking lots, and streets (Table 3). Similarly, peak flows increased by more than 22% at the watershed outlet. If pre-development peak flows and runoff volumes are desirable in High School watershed, GI implementation significantly larger than CURRENT × 5 is necessary. The PRE-DEV configuration results act as a good starting point to consider the optimization of GI implementation to achieve local benefits while maintaining pre-development hydrology downstream of the watershed.

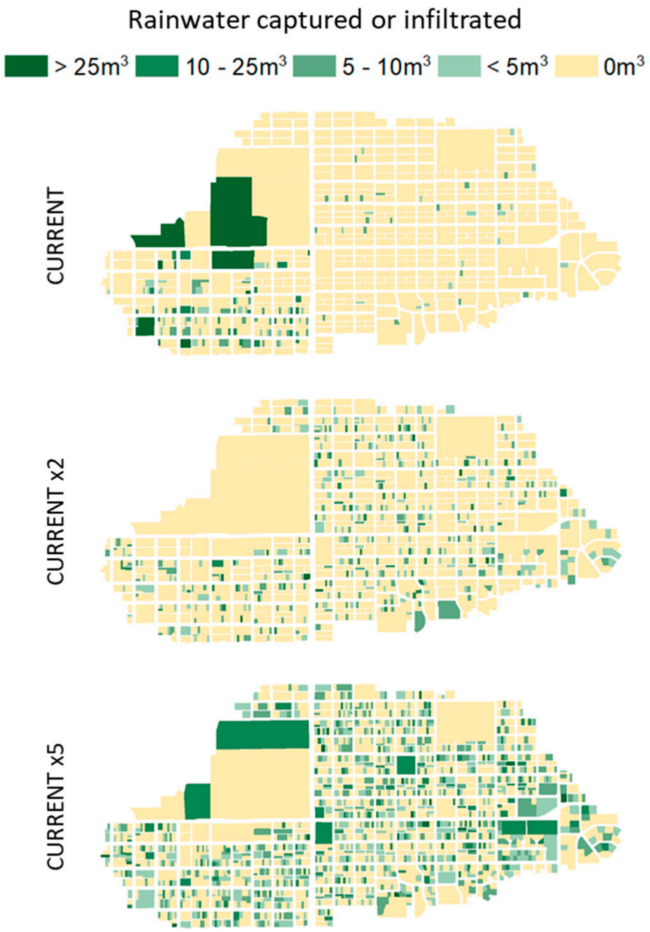

Figure 6. Spatial comparison of the volume of rainwater captured in cisterns or infiltrated in basins for configurations CURRENT (**top**), CURRENT × 2 (**middle**), and CURRENT × 5 (**bottom**) as compared to the NO GI configuration for the 25-year design storm event. RB: On-street basins. RRH: Roof runoff harvesting cistern.

The MAX GI configuration can reduce the runoff volume and peak flow at the watershed outlet by more than 96% for all design storms (Table 3). In fact, there was no runoff generated, and consequently no peak flow, for the 5-year design storm. MAX GI was created to test the maximum limits of GI implementation and its effect at the watershed outlet. There is potential to retain all the runoff on the watershed and have zero runoff, especially for the smaller events. This configuration assumes that any pervious area on every parcel acts as a retention basin, which may be impractical due to natural underlying terrain. The goal of simulating this configuration was to predict what was possible in an ideal world and how that compares to what is actually implemented. Results from this simulation are good indicators of the upper boundaries of runoff and peak flow reduction possible in the High School watershed. However, this may not be desirable considering downstream impacts.

The design storm analysis of the various configurations shows that, to have a significant reduction of peak flow and runoff volume at the watershed outlet, the GI implementation must be substantial, especially for a large watershed like the High School watershed. However, any amount of GI implementation is capable of localized runoff reduction, and its benefits may be substantial to the stakeholders in those areas. For example, the on-street basins installed in the Richland Heights neighborhood reduces the runoff volume on the streets and promotes the growth of xeric vegetation through passive rainwater harvesting in the basins. The vegetation, consequently, reduces heat island effects in that area and increases the aesthetic value of the neighborhood. The addition of chicanes has also reduced traffic on these streets and the city has allocated these streets as bike boulevards, promoting safe and alternative transportation.

3.3. 20-Year Analysis

Configuration CURRENT was simulated using the 20-year precipitation dataset to understand the performance of on-street basins and roof runoff harvesting cisterns in terms of water availability with changing soil moisture conditions and water usage from cisterns based on irrigation demands. PID 566 has the largest cistern volume of 8.91 m^3, PID 678 has the smallest cistern capacity of 1.91 m^3, and PID 1219 represents the mean cistern capacity of 5.19 m^3 from 37 cisterns currently installed in the High School watershed (Table 4; Figure 7).

Table 4. Summary of configuration of 3 parcels with roof runoff harvesting cisterns.

PID	Parcel Area (m^2)	Roof Area (m^2)	Irrigated Area (m^2)	Cistern Capacity (m^3)	# of Days [1] Cistern Was	
					Full	Empty
566	879.89	148.27	113.68	8.71	2301	521
1219	650.41	223.34	77.79	5.19	1371	735
678	785.52	226.31	95.05	1.91	505	605

[1] Total number of days in the 20-year analysis period = 7305.

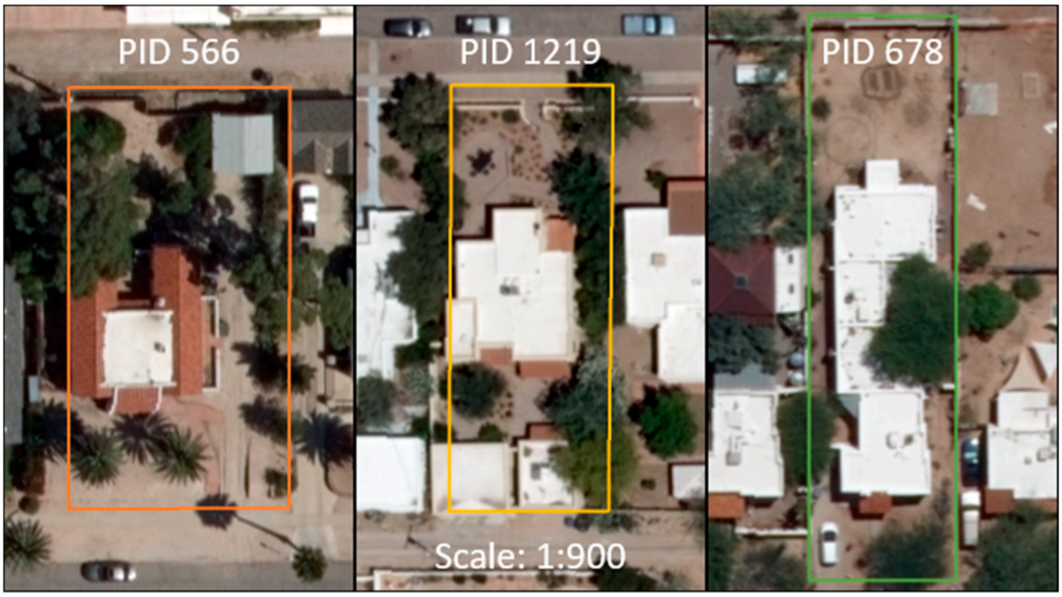

Figure 7. Parcels PID 566 (**left**), PID 1219 (**middle**), and PID 678 (**right**) represent the maximum, mean, and minimum cistern capacity for roof runoff harvesting, respectively.

The irrigation demand for PID 1219 is lowest considering the smaller irrigated area as compared to the other two parcels and highest for PID 566, which has the largest irrigated area (Figure 8). The rising limb in Figure 8 indicates water captured by the cistern, whereas the falling limb is an indicator of water used. There was a clear drop in cistern volume for the months of May and June, with the cisterns filling up again at the start of the monsoon season in July. Following the monsoons, the cisterns can store water through the rest of the year until the dry months of May and June. In the drier years (years 5, 7, 12, and 17), the largest cistern on PID 566 was unable to each capacity, potentially due to the smaller roof area. However, the comparatively smaller cisterns were still able to reach capacity for the same events. The cistern on PID 566 reached capacity on 2301 days out of 7305 (Table 4), indicating that it was oversized for the roof area and irrigation demands. On the other hand, the cistern on PID 678 reached capacity on 505 days, which is an indicator of constant water use and limited storage. The number of days a cistern reaches capacity indicates that number of times roof runoff was not captured completely and allowed to overflow. These results demonstrate that cisterns must be sized based on available roof area as well as irrigation demands on any particular parcel to optimize capture, storage, and use.

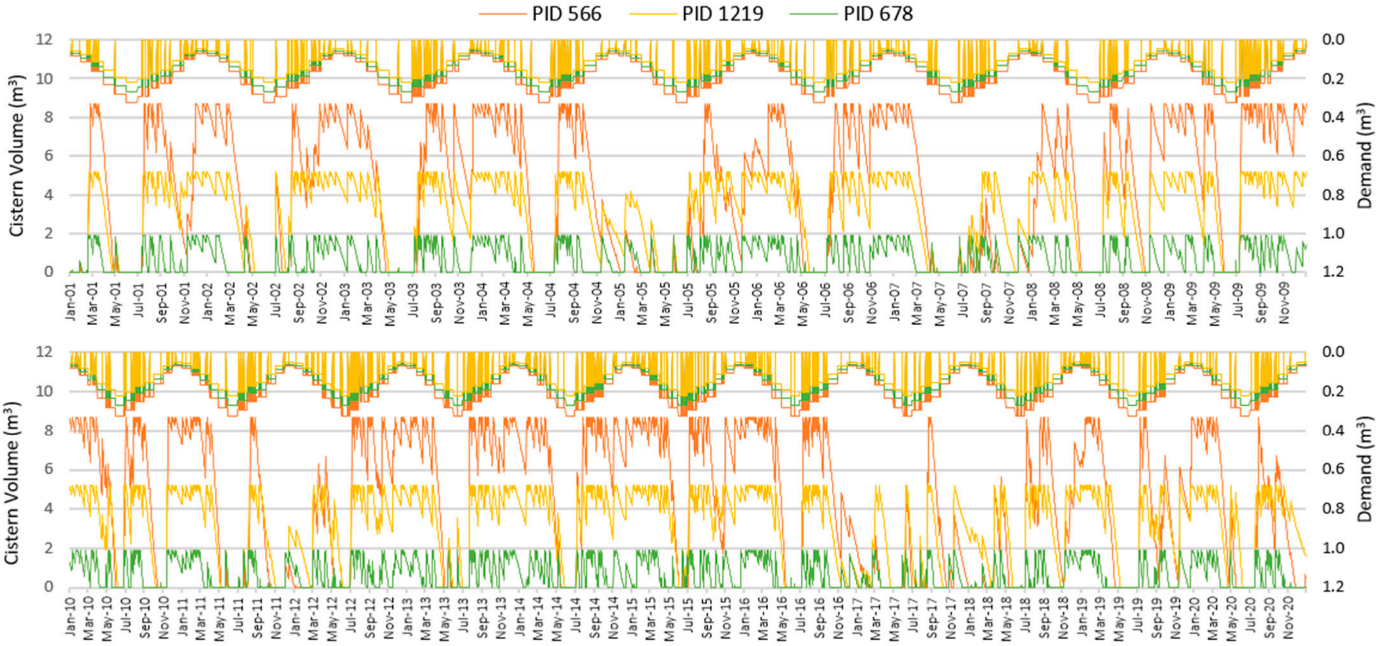

Figure 8. Irrigation demand (secondary axis) and rainwater captured (primary axis) in cisterns for the 20-year time period (years 1–9 on **top** and years 10–20 on **bottom**). PID 566 represents the largest cistern capacity (8.91 m^3), PID 1219 represents the mean cistern capacity (5.19 m^3), and PID 678 represents the smallest cistern capacity (1.91 m^3) in the watershed.

Water demand for irrigation per square meter of basin area, based on reference evapotranspiration rates in Tucson, was highest from April to August, which is the summer growing period for plants, and lowest during the winter months (Figure 9). However, average infiltrated volumes were highest during the months of July and August, when the precipitation frequency is high. In general, water demand can be met by on-street basin installations for most of the year, except for June, when the demand exceeds infiltration.

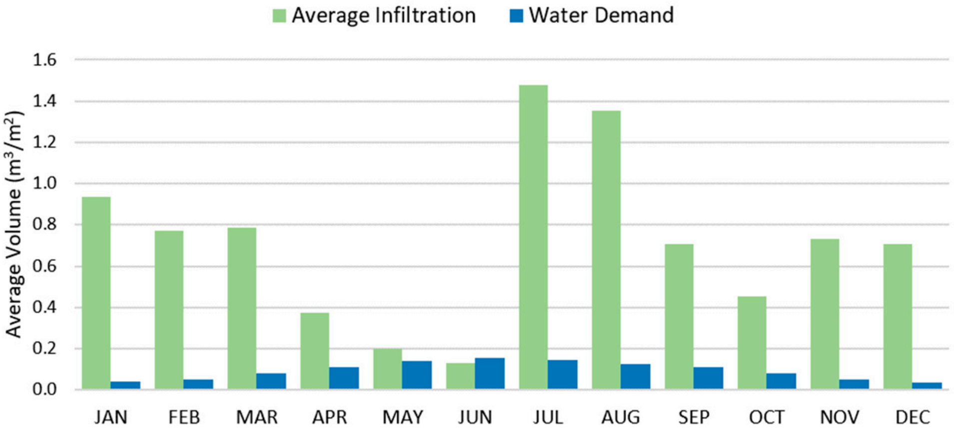

Figure 9. Average infiltrated volumes per square meter of surface area of on-street basins based on the 20-year analysis for configuration CURRENT and estimated irrigation demands per square meter for high water use plants based on calculations from Waterfall (2006).

The 20-year analysis highlights the long-term benefits of roof runoff harvesting and infiltration of runoff in on-street basins. There is potential for consistent capture of rainwater during the winter months, where precipitation occurs over longer duration with lower intensities. As a result, GI can be more effective during these months as compared to the summer monsoon months with flashier, high-intensity, short-duration precipitation events, where GI practices become overwhelmed during the first few minutes of the events in spite of the large volume of rainwater available to capture over the entire event. Results indicate that there is tremendous potential to capture roof runoff and reuse the water for landscaping purposes. Additionally, the water infiltrated in on-street basins can support long-term vegetation growth, especially drought-tolerant species of trees [34–36].

4. Conclusions

GIS-based hydrologic models can be helpful to understand the hydrology and effects of GI implementation at various scales in an urban environment. In this study, the AGWA Urban tool was used to prepare and execute the KINEROS2 model for the High School watershed in Tucson, AZ. Key findings from this study are summarized as follows:

1. In the High School watershed, the current level of implementation of GI practices (175 on-street basins and 37 roof runoff harvesting cisterns) does not significantly impact peak flow and runoff volumes at the watershed outlet. However, on-street basins do have an impact at the street and neighborhood scale in reducing nuisance flooding and increasing infiltration, thereby enabling the growth of xeric vegetation. Similarly, roof runoff harvesting cisterns have an impact at the parcel scale by storing and providing water for landscaping purposes.
2. This study highlights the need for greater GI implementation to achieve large-scale benefits, and the opportunity for improvement does exist in this watershed. Only 37 parcels out of 2177 in the watershed have roof runoff harvesting cisterns. Similarly, only the lower part of the watershed has on-street basins implemented. Increasing GI implementation by a factor of two has the potential to reduce peak flow and runoff volume at the watershed outlet by up to 7% and 3%, respectively. Similarly, a five-fold increase in GI implementation has the potential of reducing peak flow up to 22% and runoff volume up to 7%. To meet pre-development levels of volume and peak flow in the watershed, GI implementation must exceed more than the five-fold the current implementation. However, it is important to consider whether pre-development numbers are desirable and the impact they might have on water availability for use throughout the watershed. Impervious area due to streets is 25% of the total area in the High School watershed. It would be prudent to target the capture of stormwater generated from this highly connected network of impervious area as discussed by studies for other locations [37,38].
3. Based on the 20-year simulation, the volume of water infiltrated in on-street basins can support vegetation for most of the year, except for the month of June, when vegetation may need to rely on active irrigation to meet water needs. Similarly, parcels with roof runoff harvesting cisterns can meet their landscape irrigation demands throughout the year, except for the dry months of May and June. Thus, xeriscape water requirements can be substantially augmented by capturing roof runoff in this region. Additionally, cisterns must be sized appropriately to optimize capture, storage, and water use on any parcel.

This study focused on immediate benefits from GI implementation, such as flood mitigation and water availability. However, the push for GI is not limited to these benefits, but to co-benefits that extend beyond water management. For example, Braden and Johnston (2004) highlighted the economic benefits from stormwater management based on its impact on reduced flooding, smaller drainage infrastructure, reduced pollution treatment, reduced erosion and sedimentation, improved water quality, improved in-stream biological integrity and stream aesthetics, and increased ground water recharge [39]. Alves et al. (2019) discussed how rainwater harvesting offers greater benefits than costs when co-benefits are considered [40]. Other studies have highlighted similar co-benefits of GI in other cities [41–44].

The High School watershed community can utilize the results presented here to understand the effectiveness of the implemented GI practices and aid in deciding which GI practices need to be implemented and in which locations. By understanding the current benefits of the implemented GI practices, questions can be asked about the factors that are impeding or limiting more GI implementation in this region. The methodology used in this study and results form the stepping stones to creating optimization scenarios, where decisionmakers can work with different GI designs and implementation to achieve targeted runoff and peak flow reduction or runoff capture and infiltration in this watershed. We recommend the use of the High School watershed model, created as part of this study, for future scenario planning and assessing the impact of various GI implementation scenarios that can enable critical decision-making processes.

Tucson belongs to a semiarid environment, where augmenting water supply is a key challenge toward a sustainable future. As such, GI has been identified as a solution to water supply issues in this region. The results of this study highlight the potential achievements of implementing GI practices for homeowners, communities, developers, and downstream stakeholders. Homeowners can capture roof runoff in cisterns and use this water for irrigating landscapes, as well as for indoor use. Appropriately sized cistern can substantially account for irrigation needs throughout the year, thereby reducing dependence on municipal water use. For communities, there is significant potential to capture street runoff in retention basins. Rainwater infiltration in on-street basins have the potential to support vegetation, thus increasing the overall “greenness” of the community while reducing the water accumulation on the streets. The Pima County Flood Control District, which the city of Tucson is part of, recommends the design of GI practices to accommodate rainfall events between 0.5 and 1.5 inches, equivalent to a 5-year, 1-hour rainfall event in this region [45]. Developers in Arizona must show that enough renewable water supplies exist to meet the demands of developments for 100 years in active water management areas around the state. New commercial developments must provide for 50% of the landscape water budget via rainwater harvesting on-site in the city of Tucson. These demands can be augmented, if not met, with the help of GI practices discussed in this study. Developers can utilize the discussed approach to design and analyze new developments by optimizing cost and implementation of GI practices to meet state requirements. Even with the goal of capturing rainwater with the help of GI practices, it is also essential to understand the downstream impacts of water availability. It is important to maintain pre-development natural hydrology to ensure downstream water rights, and this acts as a threshold for upstream water capture by GI practices.

We recommend the use of the AGWA Urban tool and the KINEROS2 model to analyze different GI implementation scenarios to meet the various water demands in an urban environment. The approach discussed in this study relies on readily available data as well as implemented policies and ordinances. GI has the potential to mitigate floods as well as meet water demands in a semiarid environment. These results can enable decision-making as well as aid in policy implementation to achieve a sustainable future. The AGWA Urban tool aims to fulfill the need for a comprehensive tool featuring a hydrologic model to enabling decision-making in the urban environment.

Author Contributions: Conceptualization, Yoganand Korgaonkar, David Phillip Guertin, Thomas Meixner, and David C Goodrich.; methodology, Yoganand Korgaonkar, David Phillip Guertin, Thomas Meixner, and David C Goodrich; software, Yoganand Korgaonkar; formal analysis, Yoganand Korgaonkar; investigation, Yoganand Korgaonkar, David Phillip Guertin, Thomas Meixner, and David C Goodrich; supervision, David Phillip Guertin, Thomas Meixner, and David C Goodrich. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by NSF Sustainability Research Network (SRN) Cooperative Agreement 1444758.

Data Availability Statement: Data is available via Mendeley Data. Please contact corresponding author with questions regarding the data. Citation: Korgaonkar, Yoganand (2021), "HighSchoolWatershed", Mendeley Data, V1, doi:10.17632/m9rg25ddnc.1.

Acknowledgments: Carl Unkrich modified and debugged the KINEROS2 model. Mandla Kunnie compiled the Tucson GI database that provided cistern sizes and location data. Neha Gupta and her team of undergraduate students implemented the pressure transducers to collect stage height data and surveyed the on-street basin GI database for High School watershed. The 2015 Orthophoto imagery was obtained from Pima Association of Governments.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Gober, P. Desert urbanization and the challenges of water sustainability. *Curr. Opin. Environ. Sustain.* **2010**, *2*, 144–150. [CrossRef]
2. County, P.G.S.; June, M.D. *Low-Impact Development Design Strategies: An Integrated Design Approach*; Department of Environmental Resources, Programs and Planning Division: Prince George's County, MD, USA, 1999. Available online: http://water.epa.gov/polwaste/green/upload/lidnatl.pdf (accessed on 28 June 2021).
3. Dietz, M.E. Low impact development practices: A review of current research and recommendations for future directions. *Water Air Soil Poll.* **2007**, *186*, 351–363. [CrossRef]
4. Eckart, K.; McPhee, Z.; Bolisetti, T. Performance and implementation of low impact development—A review. *Sci. Total Environ.* **2017**, *607*, 413–432. [CrossRef]
5. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Mikkelsen, P.S. SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
6. Liu, Y.; Engel, B.A.; Flanagan, D.C.; Gitau, M.W.; McMillan, S.K.; Chaubey, I. A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. *Sci. Total Environ.* **2017**, *601*, 580–593. [CrossRef]
7. Li, D.; Bou-Zeid, E.; Oppenheimer, M. The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environ. Res. Lett.* **2014**, *9*, 055002. [CrossRef]
8. Norton, B.A.; Coutts, A.M.; Livesley, S.J.; Harris, R.J.; Hunter, A.M.; Williams, N.S. Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc. Urban Plan.* **2015**, *134*, 127–138. [CrossRef]
9. Santamouris, M. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **2014**, *103*, 682–703. [CrossRef]
10. Yang, J.; Bou-Zeid, E. Scale dependence of the benefits and efficiency of green and cool roofs. *Landsc. Urban Plan.* **2019**, *185*, 127–140. [CrossRef]
11. Abhijith, K.V.; Kumar, P.; Gallagher, J.; McNabola, A.; Baldauf, R.; Pilla, F.; Pulvirenti, B. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments—A review. *Atmos. Environ.* **2017**, *162*, 71–86. [CrossRef]
12. Bottalico, F.; Chirici, G.; Giannetti, F.; De Marco, A.; Nocentini, S.; Paoletti, E.; Travaglini, D. Air pollution removal by green infrastructures and urban forests in the city of Florence. *Agric. Agric. Sci. Proc.* **2016**, *8*, 243–251. [CrossRef]
13. Jayasooriya, V.M.; Ng, A.W.M.; Muthukumaran, S.; Perera, B.J.C. Green infrastructure practices for improvement of urban air quality. *Urban For. Urban Green.* **2017**, *21*, 34–47. [CrossRef]
14. Ortolani, C.; Vitale, M. The importance of local scale for assessing, monitoring and predicting of air quality in urban areas. *Sustain. Cities Soc.* **2016**, *26*, 150–160. [CrossRef]
15. Coutts, C.; Hahn, M. Green infrastructure, ecosystem services, and human health. *Int. J. Environ. Res. Publ. Health* **2015**, *12*, 9768–9798. [CrossRef]
16. Douglas, O.; Lennon, M.; Scott, M. Green space benefits for health and well-being: A life-course approach for urban planning, design and management. *Cities* **2017**, *66*, 53–62. [CrossRef]
17. Suppakittpaisarn, P.; Jiang, X.; Sullivan, W.C. Green Infrastructure, green stormwater infrastructure, and human health: A review. *Curr. Landsc. Ecol. Rep.* **2017**, *2*, 96–110. [CrossRef]
18. Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landsc. Urban Plan.* **2007**, *81*, 167–178. [CrossRef]
19. Hopton, M.; Simon, M.; Borst, M.; Garmestani, A.; Jacobs, S.; Lye, D. Green Infrastructure for Stormwater Control: Gauging its Effectiveness with Community Partners. 2015; EPA/600/R-15/219. Available online: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100NE3S.txt (accessed on 28 June 2021).
20. Smith, R.E.; Goodrich, D.C.; Woolhiser, D.A.; Unkrich, C.L. KINEROS-A kinematic runoff and erosion model. *Comput. Models Watershed Hydrol.* **1995**, *20*, 627–668.
21. Goodrich, D.C.; Burns, I.S.; Unkrich, C.L.; Semmens, D.J.; Guertin, D.P.; Hernandez, M.; Levick, L.R. KINERSO2/AGWA: Model use, calibration, and validation. *Trans. Am. Soc. Agric. Biol. Eng.* **2012**, *55*, 1561–1574. [CrossRef]

22. Parlange, J.Y.; Lisle, I.; Braddock, R.D.; Smith, R.E. The three-parameter infiltration equation. *Soil Sci.* **1982**, *133*, 337–341. [CrossRef]
23. Kennedy, J.R.; Goodrich, D.C.; Unkrich, C.L. Using the KINEROS2 modeling framework to evaluate the increase in storm runoff from residential development in a semiarid environment. *J. Hydrol. Eng.* **2013**, *18*, 698–706. [CrossRef]
24. Korgaonkar, Y.; Guertin, D.P.; Goodrich, D.C.; Unkrich, C.; Kepner, W.; Burns, I.S. Modeling Urban Hydrology and Green Infrastructure using the AGWA Urban Tool and the KINEROS2 Model. *Front. Built Environ.* **2018**, *4*, 58. [CrossRef]
25. Korgaonkar, Y.; Meles, M.B.; Guertin, D.P.; Goodrich, D.C.; Unkrich, C. Global sensitivity analysis of KINEROS2 hydrologic model parameters representing green infrastructure using the STAR-VARS framework. *Environ. Modell. Software* **2020**, *132*, 104814. [CrossRef]
26. Miller, S.N.; Semmens, D.J.; Goodrich, D.C.; Hernandez, M.; Miller, R.C.; Kepner, W.G.; Guertin, D.P. The automated geospatial watershed assessment tool. *Environ. Modell. Softw.* **2007**, *22*, 365–377. [CrossRef]
27. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large-area hydrologic modeling and assessment: Part, I. *Model Development. J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
28. Nearing, M.A.; Wei, H.; Stone, J.J.; Pierson, F.B.; Spaeth, K.E.; Weltz, M.A.; Hernandez, M. A rangeland hydrology and erosion model. *Trans. Am. Soc. Agric. Biol. Eng.* **2011**, *54*, 901–908. [CrossRef]
29. Chow, V.T. Open-channel hydraulics. In *Open-Channel Hydraulics*; McGraw-Hill: New York, NY, USA, 1959.
30. Anderson, J.; Ferre, T.; Whitaker, M.; Winter, L. Analysis and Classification of Semi-Arid Bioswales in an Urban Setting. Ph.D. Thesis, The University of Arizona, Tucson, AZ, USA, 2018.
31. Nicks, A.D.; Gander, G.A. CLIGEN: A weather generator for climate inputs to water resource and other models. *Proc. Fifth Int. Conf. Comput. Agric.* **1994**, *4*, 903–909.
32. Rawls, W.J.; Brakensiek, D.L.; Saxtonn, K.E. Estimation of soil water properties. *Trans. ASAE* **1982**, *25*, 1316–1320. [CrossRef]
33. Waterfall, Patricia. *Harvesting Rainwater for Landscape Use*; The University of Arizona: Tucson, AZ, USA, 2011; Available online: http://hdl.handle.net/10150/144825 (accessed on 28 June 2021).
34. Cable, D.R. Seasonal use of soil water by mature velvet mesquite. *Rangel. Ecol. Manag. J. Range Manag. Arch.* **1977**, *30*, 4–11. [CrossRef]
35. Stabler, L.B.; Martin, C.A. Irrigation regimens differentially affect growth and water use efficiency of two southwest landscape plants. *J. Environ. Hortic.* **2000**, *18*, 66–70. [CrossRef]
36. Martin, C.A. *Landscape Water Use in Phoenix, Arizona*; CALS Publications Archive: New York, NY, USA, 2015; Available online: http://hdl.handle.net/10150/554334 (accessed on 28 June 2021).
37. Yang, Y.; Endreny, T.A.; Nowak, D.J. Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude. *Urban For. Urban Green.* **2015**, *14*, 361–367. [CrossRef]
38. Zellner, M.; Massey, D.; Minor, E.; Gonzalez-Meler, M. Exploring the effects of green infrastructure placement on neighborhood-level flooding via spatially explicit simulations. *Comput. Environ. Urban Syst.* **2016**, *59*, 116–128. [CrossRef]
39. Braden, J.B.; Johnston, D.M. Downstream economic benefits from storm-water management. *J. Water Resour. Plann. Manag.* **2004**, *130*, 498–505. [CrossRef]
40. Alves, A.; Gersonius, B.; Kapelan, Z.; Vojinovic, Z.; Sanchez, A. Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *J. Environ. Manag.* **2019**, *239*, 244–254. [CrossRef]
41. Meerow, S.; Newell, J.P. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landsc. Urban Plann.* **2017**, *159*, 62–75. [CrossRef]
42. Calderón-Contreras, R.; Quiroz-Rosas, L.E. Analysing scale, quality and diversity of green infrastructure and the provision of Urban Ecosystem Services: A case from Mexico City. *Ecosyst. Serv.* **2017**, *23*, 127–137. [CrossRef]
43. Elmqvist, T.; Setälä, H.; Handel, S.N.; Van Der Ploeg, S.; Aronson, J.; Blignaut, J.N.; De Groot, R. Benefits of restoring ecosystem services in urban areas. *Curr. Opin. Environ. Sustain.* **2015**, *14*, 101–108. [CrossRef]
44. Nickel, D.; Schoenfelder, W.; Medearis, D.; Dolowitz, D.P.; Keeley, M.; Shuster, W. German experience in managing stormwater with green infrastructure. *J. Environ. Plan. Manag.* **2014**, *57*, 403–423. [CrossRef]
45. Pima County. Low Impact Development and Green Infrastrcuture Guidance Manual. 2015. Available online: https://webcms.pima.gov/UserFiles/Servers/Server_6/File/Government/Flood%20Control/Floodplain%20Management/Low%20Impact%20Development/li-gi-manual-20150311.pdf (accessed on 28 June 2021).