water

MDPI

Article

Adaptation of SWAT Watershed Model for Stormwater Management in Urban Catchments: Case Study in Austin, Texas

Roger Glick [1], Jaehak Jeong [2,*], Raghavan Srinivasan [2], Jeffrey G. Arnold [3] and Younggu Her [4]

[1] Watershed Protection Division, 300 Austin Ave, Waco, TX 76702, USA; rglick@wacotx.gov
[2] Texas A&M AgriLife Research, Temple, TX 76502, USA; r-srinivasan@tamu.edu
[3] Agricultural Research Service, United States Department of Agriculture, Temple, TX 76502, USA; jeff.arnold@ars.usda.gov
[4] Agricultural and Biological Engineering Department/Tropical Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Homestead, FL 33031, USA; yher@ufl.edu
* Correspondence: jeongj@tamu.edu; Tel.: +1-254-774-6118

Abstract: Computer simulation models are a useful tool in planning, enabling reliable yet affordable what-if scenario analysis. Many simulation models have been proposed and used for urban planning and management. Still, there are a few modeling options available for the purpose of evaluating the effects of various stormwater control measures (SCM), including LID (low-impact development) controls (green roof, rain garden, porous pavement, rainwater harvesting), upland off-line controls (sedimentation, filtration, retention–irrigation) and online controls (detention, wet pond). We explored the utility and potential of the Soil and Water Assessment Tool (SWAT) as a modeling tool for urban stormwater planning and management. This study demonstrates how the hydrologic modeling strategies of SWAT and recent enhancements could help to develop efficient measures for solving urban stormwater issues. The case studies presented in this paper focus on urban watersheds in the City of Austin (COA), TX, where rapid urbanization and population growth have put pressure on the urban stormwater system. Using the enhanced SWAT, COA developed a framework to assess the impacts on erosion, flooding, and aquatic life due to changes in runoff characteristics associated with land use changes. Five catchments in Austin were modeled to test the validity of the SWAT enhancements and the analytical framework. These case studies demonstrate the efficacy of using SWAT and the COA framework to evaluate the impacts of changes in hydrology and the effects of different regulatory schemes.

Keywords: urban stormwater; green infrastructure; LID; SWAT; flood control

check for updates

Citation: Glick, R.; Jeong, J.; Srinivasan, R.; Arnold, J.G.; Her, Y. Adaptation of SWAT Watershed Model for Stormwater Management in Urban Catchments: Case Study in Austin, Texas. *Water* **2023**, *15*, 1770. https://doi.org/10.3390/w15091770

Academic Editors: Xing Fang and Yongwei Gong

Received: 22 March 2023
Revised: 10 April 2023
Accepted: 19 April 2023
Published: 5 May 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Hydrologic models can be an effective tool for urban planning and assessing the post-development effects of land development. With rapid development in earth observation and geographic information system (GIS) technologies [1], modern watershed models provide efficient tools to assess the hydro-environmental consequences of anthropogenic or natural events such as land use change [2], climate change [3–5], or floods/drought events [6,7]. However, urban catchments are often complicated, with various land uses and (pervious and impervious) land covers connected along the flow paths. Only a few stormwater modeling tools are capable of considering the heterogeneity of runoff simulation.

Changing land uses due to urbanization can have destructive effects on urban lands and streams, with soil erosion and aquatic health impairment [8]. Increases in impermeable surfaces in the drainage area after urban development negatively influence the connection between surface and subsurface flow pathways, causing stormwater runoff peaks steeper in magnitude and shorter in duration [9]. Negative impacts of flooding, erosion and water pollution make it a challenge for local governments to protect the community's lives, property and natural resources [10]. In many fast-growing municipalities such as the City of Austin (COA) in Texas, one of the chief drivers is urbanization. As land transforms from rural to suburban to urban, hydrologic regimes change, typically resulting in increased flooding, erosion and pollution, as well as the degradation of overall stream health [1,11]. The lack of effective stormwater infrastructure means that populations living in highly concentrated urban lands are left vulnerable to flooding and water contamination. There are generally accepted models and procedures to evaluate the impacts of these changes with respect to floods that are associated with extreme rainfall events [12]; however, tools and procedures to evaluate overall stream health at the watershed scale are either non-existent or very early in the developmental stages.

Urban catchments are characterized by the prevalence of impervious covers such as roads, parking lots and rooftops for which lands were converted from forest, rangeland, or cropland. These pavements tend to keep surface water, such as overland flow after rainfall or channel flow, from infiltrating to soils and recharging aquifers. Therefore, the contribution of stormwater runoff increases with groundwater return flow, making channel flows flashy and intermittent. These urban creeks have flows that exhibit shorter durations and higher peaks than natural creeks.

The SWAT is a watershed model frequently employed to assess the hydrological impacts of land use changes [13–15]. The model is known to be a robust and capable tool that simulates long-term hydrologic processes, including direct runoff routing and infiltration of rainfall and surface flow into the soil profile and into shallow aquifers. SWAT also has a graphical user interface embedded in common GIS software applications, including ArcGIS and QGIS. SWAT has traditionally been used to simulate hydrological processes of agricultural watersheds as it includes routines for plant growth and agricultural management [13]. Advancements in sensors and data technology have made data of high spatio-temporal resolution available at the watershed scale in recent decades. High resolution time series, data such as long-term subdaily precipitation data, are useful for capturing the dynamics of urban stormwater flow [16].

Recently, several enhancements have been made to the SWAT model to simulate urban catchment systems at fine spatial and temporal scales for application in urban watersheds, enabling subdaily simulation of rainfall–runoff processes [17,18], soil erosion, sediment transport [19], various types of urban stormwater management practices and green infrastructure applications [20–22]. Recent case studies comparing the daily curve number (CN) method and the subdaily Green and Ampt method found that both approaches yielded reliable outputs on streamflow estimation, although the CN method exhibited a slightly better performance in peri-urban watersheds in Europe [23,24]. Urban stormwater management influences stream health and aquatic life communities. A case study conducted in the Blunn Creek watershed in Texas suggested that a combination of permeable pavement and raingardens was most effective in reducing peak flows and increasing aquatic life potential among several types of low-impact development (LID) [25]. A reduced peak flow often promotes stormwater infiltration and increases baseflow [26].

In the early years of the 21st century, COA identified the need for a long-term continuous simulation model to assess overall stream health and a framework to better assess future land use changes and regulatory controls. The desired model would need to simulate long-term hydrology (longer than 20 years) for several reasons: (1) to capture variabilities in rainfall patterns; (2) to include runoff, surface flow and groundwater interactions in order to evaluate overall health; (3) to operate on a sub-hourly time-step to capture the rapid changes of runoff hydrograph in small urban catchments; (4) to include routines to simulate typical stormwater control measures (SCM) physically; and (5) to have a graphical interface for ease of use. No model met all of these criteria at the time, so model enhancements were required.

This paper demonstrates the potential use of SWAT for urban stormwater planning and management using multiple case studies. Primarily, this study investigated its ability as a tool for (1) simulating urban catchment dynamics, including surface runoff, soil erosion and stormwater control measures at sub-daily scales; (2) evaluating urban stream health; (3) assessing the hydrologic effects of urban development; and (4) evaluating the effectiveness of SCMs.

2. Materials and Methods

2.1. Study Area

The SWAT model was applied to five urban watersheds in Austin, TX, to examine the effects of land use changes and predict the impacts of development ordinance changes. The watersheds have varying drainage areas and urbanization levels (Figure 1). Austin is located in central Texas, separating the Texas Hill Country from the prairies to the east (Figure 1). It is the 11th most populous city in the United States and has experienced rapid growth in its population in recent decades. The growth rate of the Austin metro was the fastest in the nation in the past few years. Since 2010, the population has increased by nearly 400,000 residents, or 68% [27]. The climate is classified as humid subtropical, characterized by long and hot summers with high temperatures, up to 34–36 °C, in July and August and short and mild winters, with low daytime temperatures of 16 °C in January. The annual average rainfall is 872 mm, which is distributed evenly throughout the year.

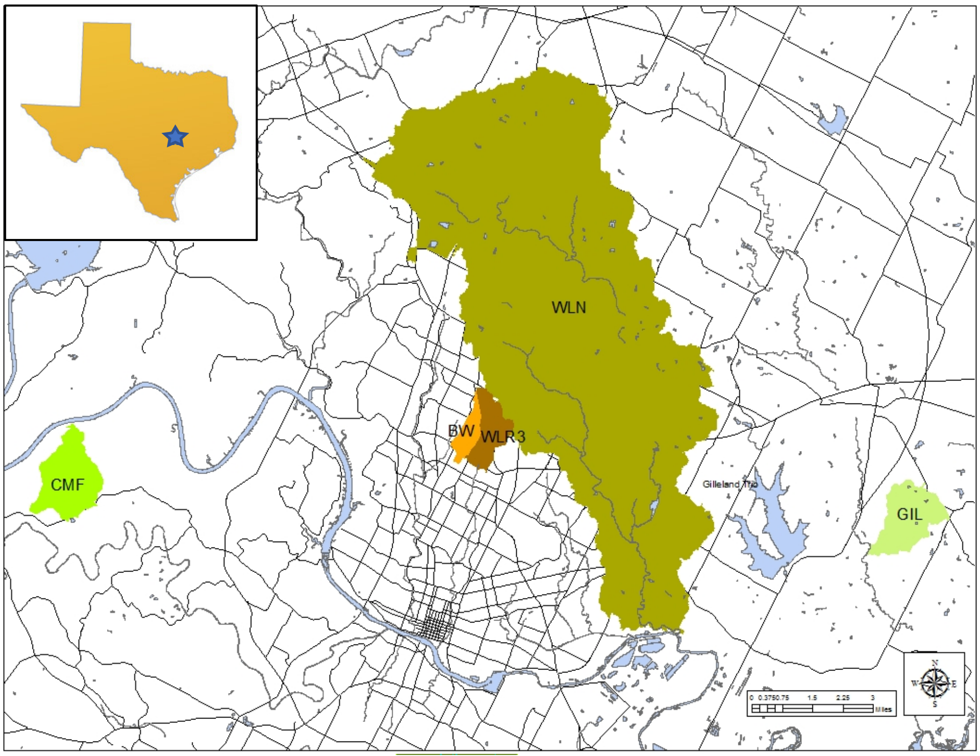

Figure 1. City of Austin case study locations (WLN: Walnut Creek, CMF: Commons Ford, GIL: Gilleland Tributary, BW: Brentwood Tributary, WLR3: Upper Waller Creek). The City of Austin is located in central Texas (starred in the state map on the top left corner of the map).

2.2. SWAT Model for Subdaily Simulation

The original SWAT model did not operate on a sub-hourly time-step or include any urban SCM routines. Thus, the first and most wide-reaching upgrade to SWAT made it operable on a sub-hourly time-step, which is required for modeling urban catchments where the time to peaks is relatively short compared to agricultural watersheds. The Green and Ampt (GA) method, modified by Mein-Larson [28], was implemented instead of the conventional Soil Conservation Service (SCS)—curve number (CN) method so that the sub-hourly rainfall–runoff processes of an urban catchment could be simulated [29]. Such a modification allows the runoff simulation to operate at the time step of rainfall data. The sub-hourly simulation module has been tested at various rainfall intervals on a small catchment in Austin, Texas [17].

Changing to sub-hourly runoff simulation required upgrades to modules for not only runoff generation, but also flow routing. The existing SCS triangular unit hydrograph method added a coefficient to allow a user to adjust the time base of the hydrograph. An alternative gamma function unit hydrograph was added, allowing for more runoff control at sub-daily time intervals. The lag coefficient, which controls timing in overland flow routing (i.e., SURLAG), was modified to account for sub-daily routing and simulation time intervals. The Muskingum flow routing method [30] was added [17] to simulate sub-hourly channel flow routing; thus, the variable storage coefficient routing method could be enhanced for dynamic stream flow routing [18]. In addition, sub-daily erosion and sediment transport simulation modules were added to SWAT so that the splash erosion by the kinetic energy in rain droplets, as well as the overland flow erosion caused by shear velocity in rills and inter-rills overland flow, could be simulated [19]. On the other hand, other "slow" routines for plant growth, nutrient cycling and groundwater that vary relatively less at sub-hourly time intervals are calculated at a daily time step to maintain computational efficiency.

2.3. Stormwater Control Measures (SCMs)

The second significant modification to SWAT was the inclusion of urban SCMs that (1) influence stream channels or online SCMs, (2) treat upland runoff or off-line SCMs, or (3) control landscape processes, also known as low-impact development (LID) SCMs (Table 1). Hydrological and water quality processes associated with such SCMs were simulated, and the SCMs were modeled either individually or in combination in SWAT.

Table 1. Stormwater control measures available for simulation in SWAT 2012.

Type	Name	Inflow *	Outflow **	Placement	Reference
Upland LID	Rain garden	Rainfall, urban stormwater, discharge from green roof	Q_{ovr}, Inf, ET	HRU	[21]
	Green roof	Rainfall	Q_{ovr}, ET		
	Porous pavement	Rainfall	Q_{ovr}, Inf, EV		
Off-line BMP (Upland)	Sedimentation basin	Runoff from urban HRUs (or urban stormwater)	Q_{pipe}, Inf, EV	Subbasin	[20]
	Sand filter	Urban stormwater, discharge from LIDs/sedimentation pond	Q_{pipe}, Inf, ET		
	Retention–irrigation basin	Urban stormwater, discharge from LIDs	Q_{irr}, Inf, EV		[22]
On-line BMP (Channel)	Wet pond	Streamflow in main channel	Q_{pipe}, Inf, ET	Reach outlet	[31]
	Detention pond	Streamflow in main channel	Q_{weir}, Inf, ET		

Note(s): * All SCMs account for direct rainfall to the structure as a part of water input. ** Q_{ovr}: overland flow; Q_{pipe}: flow through drainage pipes; Q_{irr}: water-irrigated; Q_{weir}: weir flow; Inf: infiltration; ET: evapotranspiration; EV: evaporation.

Online SCMs, detention basins and wet (or retention) ponds operate at the reach level, influencing discharges and water quality from all subbasins above them. Detention basins are typically dry, and their primary function is temporarily holding stormwater so downstream hydrographs' peak flows can be lowered. The user can define the detention structure as a combination of orifices and weirs which may include a stage–discharge relationship. The routine computes the volume behind the structure based on topography. Usually, detention basins are designed to control flows from more significant rainfall events, allowing smaller events to occur uncontrolled. Wet ponds, on the other hand, are designed with permanent pools to allow for the settling of solids and biological uptake of other pollutants, so they are typically used for smaller storms and allow more significant storms to pass uncontrolled. SWAT automatically determines the sizes of wet ponds based on the existing

COA's Environmental Criteria Manual (available at https://library.municode.com/TX/Austin/codes/Environmental_Criteria_Manual?nodeId=15306, accessed on 6 April 2023). In practice, wet ponds and detention basins can be combined into one SCM, or "stacked". For such a configuration, SWAT allows both to be simulated at the same location on a reach.

Upland SCMs currently in SWAT include retention–irrigation basins, sedimentation basins, sand filters and combined sedimentation–filtration basins. These SCMs operate on the subbasin level and do not need to be physically located there. A user can define the portion of runoff from a subbasin going to each type of SCM, and one synthetic SCM for each type is used for the simulation. Users may employ automatic design parameters based on the COA's design criteria or manually design the SCM. The user may also define the land uses contributing to runoff to the SCMs. These SCMs typically treat runoff from smaller rainfall events. Runoff is captured in a retention basin and applied to an irrigation area after the rainfall ends. The only surface discharge from this type of SCM is bypass flow when the retention basis is full. Sedimentation, filtration and combined sedimentation–filtration operate similarly and will be discussed together. Runoff is captured in a basin and then treated either by settling or filtration based on the type of SCM; runoff is released at a design flow rate. If the basin is full, the runoff will bypass treatment. In a combined sedimentation–filtration system, runoff first passes through a sedimentation basin for treatment, then to a filtration basin for further treatment. Water quality for these SCMs can be computed by either physical processes or effluent probability.

LID controls include cisterns, green roofs, rain gardens and porous pavement, and operate on the HRU level in SWAT [21]. The primary treatment mechanism for these SCMs is the infiltration and capture of runoff from the connected impervious cover (Figure 2). Cisterns capture a design volume of runoff from rooftops and release it slowly to pervious areas. Green roofs consist of porous media with plants growing in them. They can capture and hold direct rainfall up to the field capacity of the media. Additional rainfall percolates through the media and is released as runoff to the connected impervious cover. Green roofs may be used in conjunction with cisterns. Rain gardens are surface depressions that capture runoff and allow it to infiltrate. Rain gardens may also have a drain system, providing some filtration function and then discharging the infiltrated rainwater into the stormwater drainage. Porous pavement consists of a porous layer in the impervious area that prevents water from infiltration. Once the layer is saturated, additional rainfall generates runoff from the site.

2.4. Evaluation of Flooding

The effectiveness of such stormwater controls is typically evaluated by investigating the watershed responses to design rainfall events of different return periods. These are typically extreme events, with probabilities of 0.01 to 0.10 occurring in any given year. Design hyetographs can be incorporated into rainfall records for SWAT assessment to generate design runoff hydrographs for floodplain mapping (note: SWAT is not currently an approved FEMA hydrologic model for this purpose). While this methodology can be simple and useful, it does not take full advantage of the long-term simulation capabilities of SWAT. Instead of using design rainfall events, the long-term hydrologic record created by the SWAT simulations can be used to identify partial-record peak series and predict changes in the magnitude of frequent events (such as 3-month return period) as well as less frequent events (such as 25-year storms). The partial record peak series were fit into a Weibull distribution using the following equation:

$$T = \frac{N+1}{m} \tag{1}$$

where T is the average recurrence interval in years, N is the number of years in the record and m is the rank of the event [32]. Measured precipitation can be used for these analyses if the record of sub-hourly rainfall is sufficient.

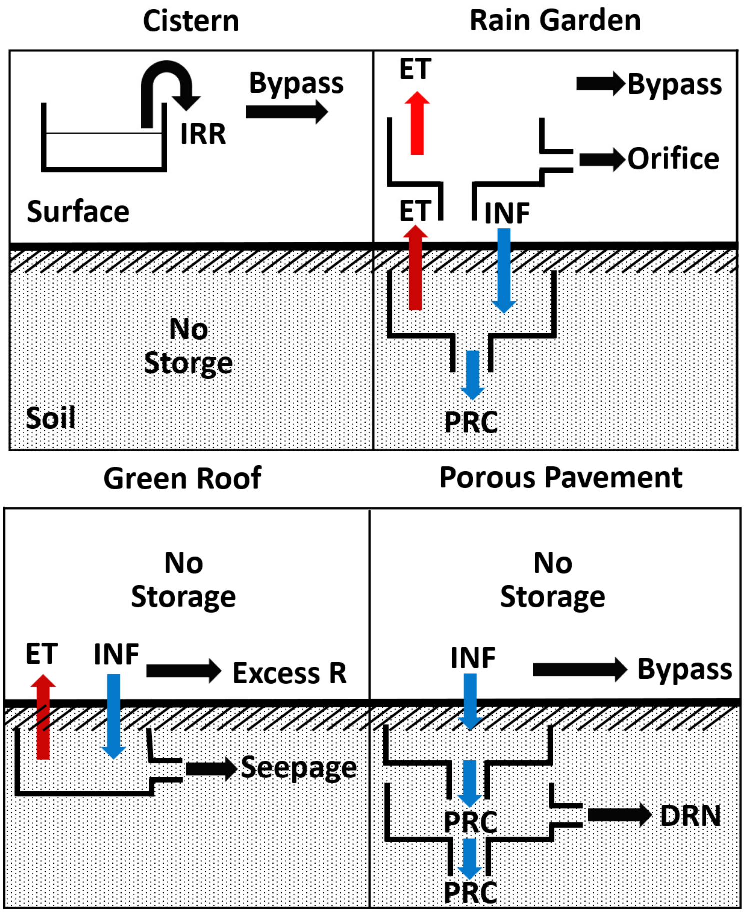

Figure 2. Water balance and hydraulic processes of the LID practices (ET: evapotranspiration, INF: infiltration, Excess R: excess rainfall, PRC: percolation of soil water, IRR: irrigation and DRN: lateral drainage of soil water). The figure is modified from [21].

2.5. Evaluation of Channel Erosion

Channel cross-sections at the locations of interest are used to develop flow-to-shear relationships using WinXSPro [33]. Site assessments are required in order to determine the median particle size (d_{50}) used to compute the critical shear for the site. Combining the flow-to-shear relationship with the critical shear information allows for the prediction of the average annual excess shear for multiple locations within a catchment. Shear and critical shear were computed using the following equations:

$$\tau = \gamma_w \cdot D_H \cdot S_w \tag{2}$$

and

$$\tau_c = \theta_c \left(S_g - 1\right) \cdot \gamma_w \cdot d_{50} \tag{3}$$

where τ is shear stress (Pa), τ_c is critical shear (Pa), γ_w is the water density (kg/m^3), D_H is the water depth (m), S_w is channel slope (m/m), S_g is the specific gravity of soil, d_{50} is the median particle diameter (m) and θ_c is the critical Shield's parameter (=0.047). Thus, sediment erosion (ES) is defined as:

$$ES = \sum (\tau - \tau_c) \text{ for all } \tau > \tau_c \tag{4}$$

This methodology allows for the spatial evaluation of potential future erosion problems under different scenarios. In cases where the channel has already been degraded, a target median particle size may be used to evaluate potential stream restoration scenarios.

2.6. Water Quality/Aquatic Health Evaluation

The primary drivers for water quality concerns in Austin, TX, are contact recreation and aquatic life support. Few industrial or wastewater discharges in the city make the non-point source (NPS) pollution the primary concern for water quality. From the perspective of aquatic life, another major concern is the drastically altered hydrologic regime associated with urbanization. Urbanization tends to reduce baseflow and increase flow variability (more rapid changes in hydrographs and more wet/dry cycles). To develop a framework to evaluate water quality and aquatic health, addressing hydrologic regimes would be critical since many of the tools to fix this would also address pollution concerns.

Using measured USGS stream gauge data from streams and aquatic life data collected by COA, a set of hydrologic metrics was developed that correlated well with the aquatic life [11,12,34] (Table 2). Limiting the changes in these metrics or moving them toward a less developed state would make the hydrologic regime more conducive to sustaining a natural ecosystem in the stream. The metrics fall into two general groups, those representing flow variability and those representing flow permeance. The first group includes SD, $+_{mean}$, $-_{mean}$, F_{Hd} and F_{Hn}, and the second group includes T_{dry}, BFR, F_{Ld} and F_{Ln}. These represent the primary mechanisms that degrade aquatic life in streams undergoing urbanization: flow variability, disrupting habitats, and limited flow, disrupting life cycles.

Table 2. Descriptive flow statistics used for analyses.

Hydrologic Variable	Units	Description
SD	–	The standard deviation of the daily flow rates during the period
Q90	cm	The 90th percentile flow rate; 90% flow is below this value
Qpeak/Area	cm/km^2	Peak flow rate normalized for drainage area
$+_{mean}$	cm	The mean positive differences between consecutive rising values, rise rate [12]
$-_{mean}$	cm	The mean negative differences between consecutive falling values, fall rate [12]
F_{Hd}	days	The mean duration of high pulses during the period with a high pulse defined as a flow greater than the 75th percentile [34]
F_{Hn}	–	The average number of times the mean daily flow was greater than the 75th percentile flow per year during the period [34].
T_{dry}	decimal	The fraction of time during the period that the flow was less than 0.003 cm [34]
BFR	decimal	The fraction of flow that is considered baseflow
F_{Ld}	days	The average length of time the mean daily flow was below 0.003 cm per year for the period [34].
F_{Ln}	–	The average number of times the mean daily flow was below 0.003 cm per year during the period [34].

Aquatic life assessments integrate the cumulative effects of various stressors. WPD staff developed hydrologic metrics for all available USGS and COA flow sites for which biological data were also available and developed regression models correlating hydrologic metrics, biological measures and aquatic health [35]. The Aquatic Life Potential model, using the best predicted parameters, resulted in r2 = 0.8216 and adjusted R^2 = 0.6493. It is shown below:

$$AQP = 87.7539 - 1.5961 \times (Qpeak/Area) + 4.3842 \times \ln(Q90) - 21.2655 \times (+_{mean}) \quad (5)$$

It should be noted that climate and natural hydrology can play a significant role in determining the best metrics to predict aquatic life potential. Baseflow, in particular, can be a limiting factor to healthy aquatic communities. In Austin, for example, developed areas with more impervious cover are often coupled with a little or no baseflow. Small watersheds with limited capture area are also susceptible to loss of baseflow.

3. Results and Discussion

3.1. Aquatic Life Assessment (Walnut Creek)

The initial use of SWAT in Austin was to simulate the hydrology in Walnut Creek (Figure 3), and it was also the first use of the sub-hourly rainfall–runoff assessment. Walnut Creek is a 145.8 km^2 watershed running from northwest Austin to the east, draining into the Colorado River. In this watershed, there have existed stream gages maintained by the USGS and COA near the mouth of the watershed since 1967, and the watershed transitioned from mainly rural to urban/suburban during that time.

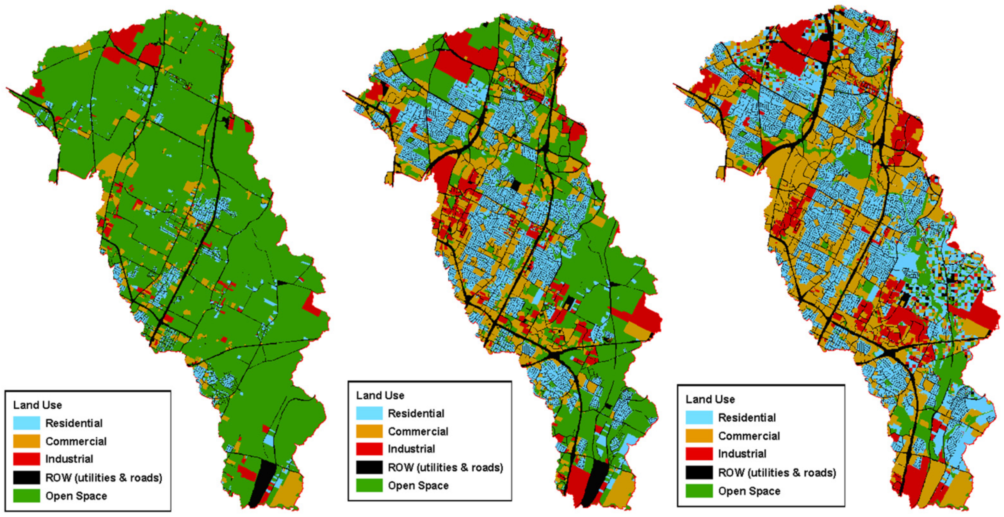

Figure 3. Land use assumptions for Walnut Creek watershed. Land use for 1964 is shown on the **left**, 2003 in the **center** and 2040 (full build-out) on the **right**.

A model was developed using land use data of 2003 from COA and calibrated against a 15 min flow from USGS station 08158600 on Walnut Creek at one of the sub-watershed outlets (FM 969). The SWAT model demonstrated acceptable performance when reproducing daily and sub-daily hydrographs with Nash–Sutcliffe ratios (NSE) of 0.86 and 0.74, respectively. The model took advantage of the gamma function for the unit hydrograph for runoff routing and the Muskingum method for channel flow routing to improve its performance. Other calibration parameters included two groundwater parameters (Alpha_bf and GW_delay), Manning's roughness coefficient and channel conductivity. The model tended to underpredict total flow, most likely due to non-rainfall-generated flow.

Two additional models were created using land use layers representing 1964 and the full build-out of the watershed (Figure 3). The 1964 land use layer was developed using historical aerial photographs, and the full build-out land use was developed by COA staff using existing development regulations. The model was validated using the 1964 land use data and USGS flows from 1967 to 1970, with a daily NSE of 0.57. Subdaily validation was impossible due to the lack of sub-daily flow records for that period. The validation also suffered because the land use did not match the validation period, and only hourly rainfall was available. Despite these shortcomings, the validation demonstrated that land use layers might change, and good results could be produced for the purpose of comparing scenarios. It should be noted that the model tended to overpredict total flow by 10%, leading credibility to the assumptions of non-rainfall-generated flows in the previous model.

The three models were run using 15-min rainfall from 1990 to 2007, and the results were compared for data on floods, erosion and water quality missions at multiple locations in the watershed. Flood and erosion analyses were conducted at four locations along the main stem of Walnut Creek (Figure 4a), and aquatic life was assessed at twelve sites in the watershed (Figure 4b).

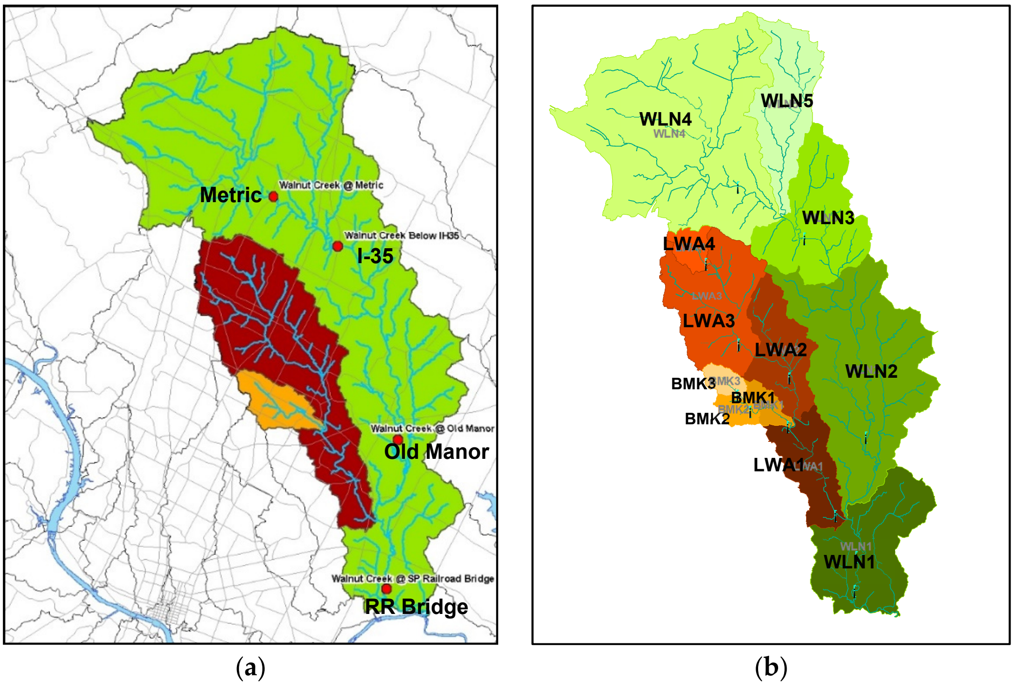

Figure 4. Walnut Creek assessment: (**a**) Flood and erosion potential evaluation locations (**left**); (**b**) aquatic life assessment locations (**right**).

Flood analyses were conducted based on exceedances of existing bank-full conditions. The number of times the bank-full flow was exceeded yearly increased with the development by 33–50%, and by an additional 25–30% with full build-out of the watershed (Figure 5). While the number of exceedances increased, the average duration of the exceedances decreased. Flashy responses to storm events with a shorter duration of runoff events are typical of urbanized catchments. The flood analyses were based on constant channel cross-sections, but the erosion portion of the study indicated that this may not be the case.

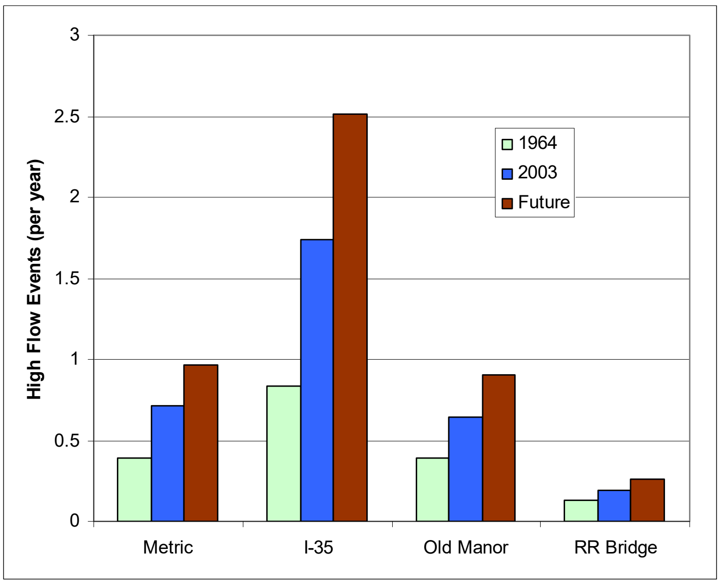

Figure 5. The average number of high-flow events in Walnut Creek based on the land use scenarios presented in Figure 3.

Excess shear increased at all locations, but the potential solutions and causes differed. The most significant percentage increase in excess shear was at the I-35 crossing, but the net increase was minimal, while the largest net increase was at the railroad crossing. This is due to the slope and d_{50} at the railroad bridge (Figure 5).

Analyses of flow related to aquatic life indicate that, in the Buttermilk and Little Walnut tributaries, primarily developed between 1964 and 2003, there was a significant decrease in aquatic life potential during that period and little or no change after that (Figure 6). Similar reductions were seen between 1964 and 2003 and between 2003 and the build-out on the main stem of the creek. These results follow the generally accepted theory that increased development impacts stream aquatic life [36–38]. However, the decrease is attributed to hydrology changes and not pollution.

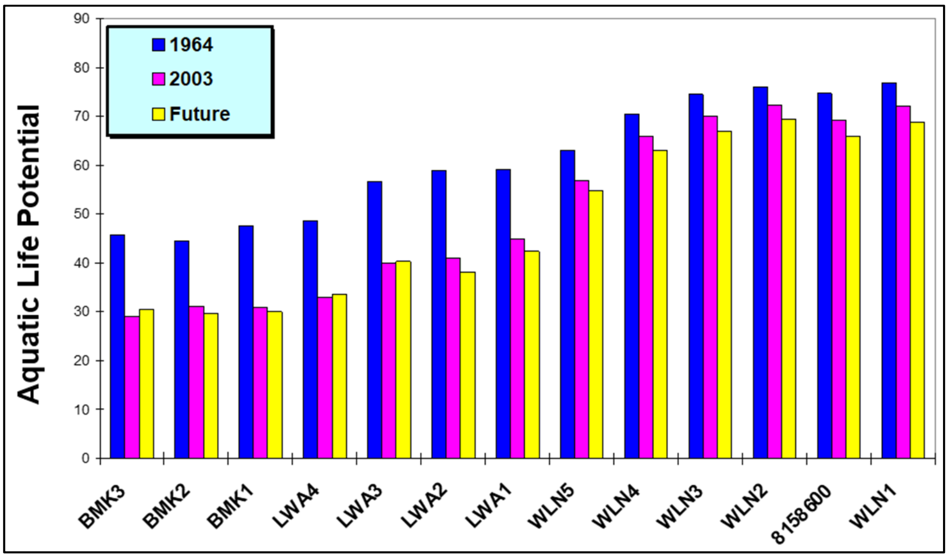

Figure 6. Aquatic life potential based on the land use scenarios presented in Figure 3.

3.2. SCMs (Commons Ford)

The Commons Ford watershed in western Austin was modeled to assess the impacts of sedimentation–filtration (SF) and retention–irrigation (RI) SCMs on hydrology. This was the first use of these SCM routines in SWAT. Commons Ford is a 5.93 km^2 ungauged watershed with little development at the time of the study. Two SWAT models were developed using land use data from 2003 and an estimate of full built-out conditions. Multiple SCMs, including SF and RI, were incorporated into the second model based on existing COA regulations. The models were run using 15 min rainfall and weather for 20 years (1990–2009). The simulated hydrographs from the models were analyzed for impacts on flood, erosion and aquatic life. No monitoring data were available for model validation in the Common Ford watershed.

Flood analyses indicated that SF and RI SCM had negligible impacts on the peak runoff from infrequent design storms; however, they did reduce the probability of exceeding the current 2-year peak runoff rate in the built-out condition (Figure 7). The probability exceedance for a 2-year peak runoff rate increased by 70%, with no SCMs incorporated under the build-out scenario. SWAT SCM scenarios indicated that implementing SF would reduce the 2-year peak exceedance by 65%. RI basins have been demonstrated to provide a greater reduction in the peak exceedance, by 94%. This would be important in areas where frequent flooding is a concern, especially low-water crossings.

Erosion analyses indicated (Figure 8) that including SF SCMs reduced the excess stream power of the build-out condition to slightly below that for the current development conditions, while RI SCMs further reduced it. The use of peak shaving based on the 2-year peak slightly reduced the excess stream power of the build-out condition, but it was still more significant than the current condition. This indicates that SCMs typically used for flood control have little impact on limiting erosion.

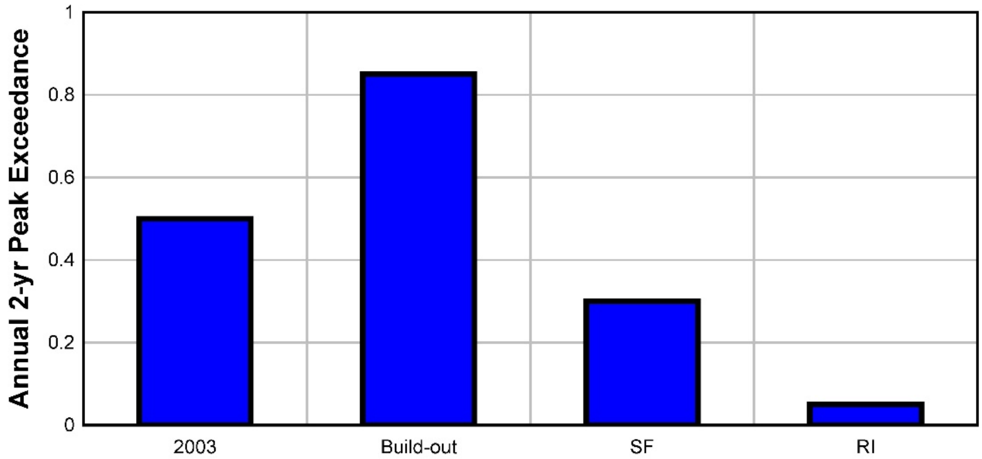

Figure 7. Annual probability of exceeding the current 2-year peak flow.

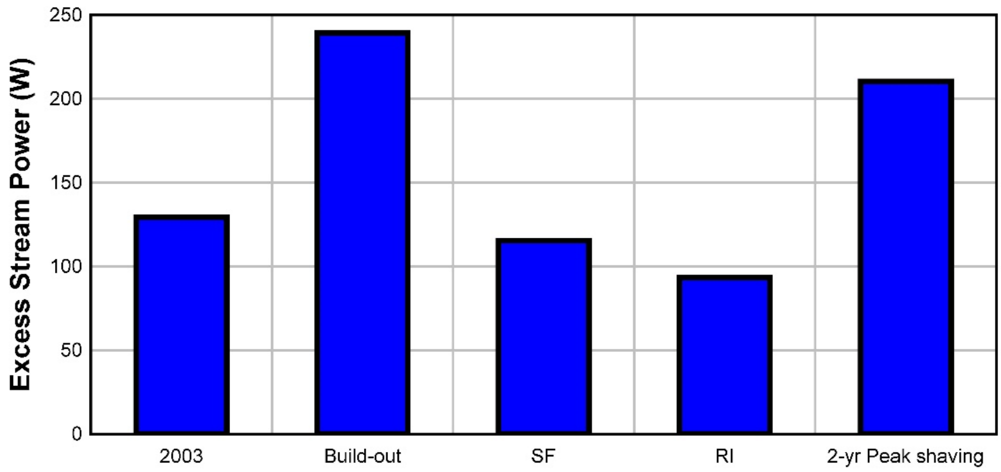

Figure 8. Average annual excess stream power for Commons Ford watershed based on differing development conditions and runoff controls.

Analyses of stream flow metrics related to aquatic life (Table 3) indicated that including SCMs would benefit the hydrologic regime. RI SCMs provide the most significant benefits in returning stream flow to current conditions, probably due to their infiltration components. Both types of SCMs mitigate the increases in flow variability associated with development. The benefits of SCMs to hydrology may be masked somewhat in this watershed due to its small size and natural lack of baseflow.

Table 3. Hydrologic flow metrics that correlate to aquatic life potential for Commons Ford watershed, developed using the SWAT model, and different development scenarios.

Metric	Current (2003)	Build-Out	SF	RI
T_{dry}	0.240	0.268	0.265	0.248
BFR	0.714	0.550	0.606	0.701
F_{Ld} (days)	7.0	2.8	3.2	6.4
F_{Ln}	19.0	44.8	40.5	20.5
$+_{mean}$ (cm)	0.021	0.36	0.021	0.019
$-_{mean}$ (cm)	0.010	0.016	0.008	0.009
F_{Hd} (days)	3.5	1.5	1.9	3.1
F_{Hn}	26.9	56.7	47.7	30.2

3.3. Post-Development Assessment (Gilleland Tributary)

In 2013, COA updated its watershed ordinance, and SWAT was used to examine the impacts of the proposed ordinance changes concerning flooding, erosion and aquatic life in the area stream. The developed conditions were compared to undeveloped (UND) ones under four regulatory scenarios based on the COA code: no regulations (PRE); waterways ordinance (WO), from 1974; comprehensive watershed ordinance (CWO), from 1986; and the proposed watershed protection ordinance (WPO). A 5.0 km^2 undeveloped tributary to Gilleland Creek was selected for flood assessment. The tributary was ungauged, so the SWAT model was "calibrated" using calibration parameters developed from other watersheds. Land use layers and SCMs for the models were developed based on the various ordinance requirements. Both detention and SF were incorporated into the model for the first time. The models were run using generated weather and measured 15 min rainfall from 1987–2012.

Flood analyses of the simulated hydrographs indicated significant increases in peak flows across the range of return periods for the developed conditions without SCMs (see Figure 9). The 0.25-year peak tripled while the 24-year peak almost doubled, indicating an increased flood risk to those near the stream.

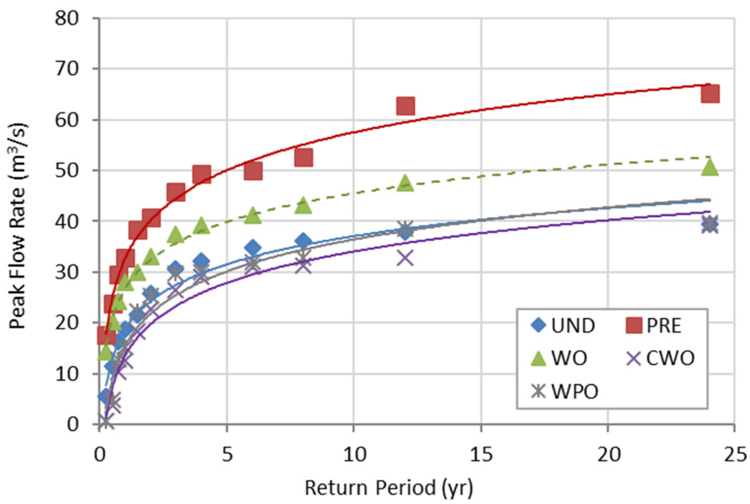

Figure 9. Peak flow analyses for the Gilleland tributary, simulated with SWAT, under different regulatory scenarios.

The WO simulation indicated increased peak flows with urban development compared to undeveloped ones, but the peak flows under undeveloped conditions were lower than with development without detention. The detention basin included as part of the WO simulation was placed in the middle of the watershed, thus allowing the lower peak to pass first, detaining the peak from the upper watershed and requiring a smaller detention basin. This did work to some degree, but the peak at the outlet still increased. Since the detention basins were only designed to control flows greater than those of the 2-year peak, larger increases were seen for smaller storms before the SCM became effective.

The peak flow rates for the CWO and WPO scenarios were similar, and closely resembled the undeveloped condition. This demonstrated the need for detention SCMs along with SCMs that control smaller events such as sedimentation filtration. It should be noted that the most frequent peak runoff rates (<1 year) were reduced below that of the undeveloped condition.

The erosion part of this study, based on a d_{50} of 19 mm, found that excess shear at the watershed outlet in the channel almost tripled without SCMs (Figure 10), but it increased slightly more once the detention basin was added in the WO scenario. This is due to the detention basin releasing flow from large events over a longer period and maintaining the flow rate above the critical flow for a longer period. The CWO and WPO scenarios reduced excess shear below the undeveloped condition, indicating that the SF SCMs addressed the smaller events—which are often the source of most excess shear—and mitigated the impacts caused by including detention.

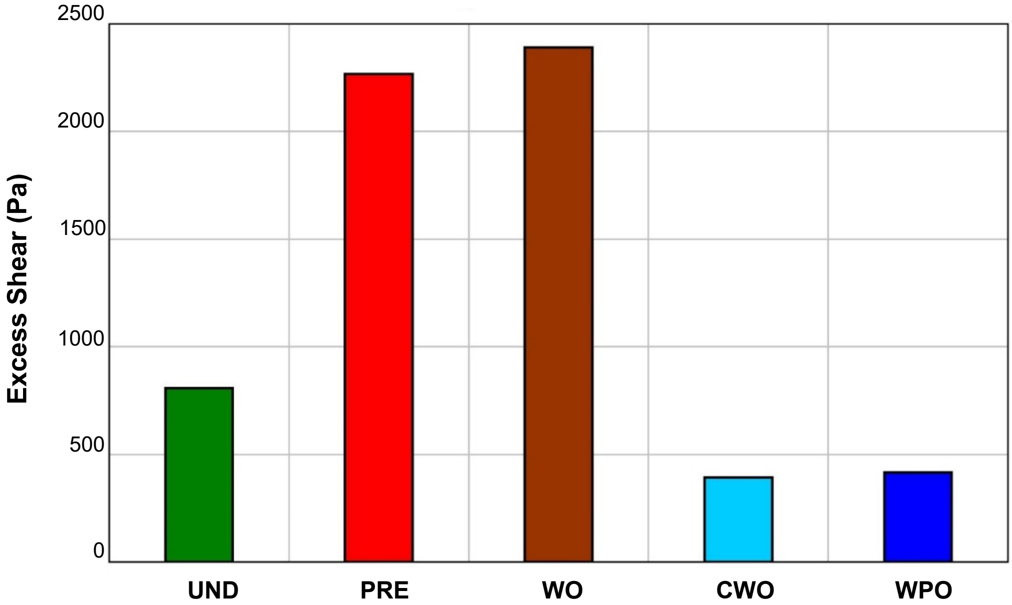

Figure 10. Average annual excess shear for five different development scenarios in the Gilleland tributary, assuming a 19 mm median particle diameter.

The effects of SF sizing and drawdown rates can be significant on excess shear across a range of d_{50} sizes. This study found that longer drawdown rates tended to reduce excess shear, except for $d_{50} \geq 38$ mm, and larger capture volumes tended to increase excess shear for $d_{50} \leq 12.5$ mm. Both of these values resulted from the SCMs maintaining the flow above the critical flow for a longer period. Longer drawdown rates resulted in more flow bypassing the SCM and increasing the excess shear for the larger particles only. Increasing the capture volume resulted in higher flow rates (holding drawdown constant), and in the case of the smaller particles, that flow rate was higher than the critical flow, thus increasing excess shear.

Hydrologic metrics related to aquatic life are presented in Table 4. Development without SCMs (PRE) and with detention only (WO) tended to reduce the time that the stream was dry and shifted the flow regime from baseflow to direct runoff. This is a typical result of urbanization. The number of low periods also increased, but the duration was reduced. This indicates a stream progressing through numerous wet/dry cycles, which could be detrimental to the life cycle of some aquatic species. Including SF SCMs in CWO and WPO scenarios decreased the number of wet/dry cycles and increased the baseflow in the stream. In the UND condition, the stream had fewer, but longer, dry periods; the overall impact on aquatic species if baseflow is increased is not known.

The metrics associated with flow variability indicate that development without SCMs increased high pulses and shortens their duration; the daily rate of change also increased, implying more variable flow. Implementing SCMs under the WPO/CWO scenarios increased baseflow by four times compared to the no-control scenario (PRE), which was greater than the undeveloped scenario by 84%. The significant increase in BFR implies that the SCMs effectively captured and infiltrated stormwater runoff into the drainage area. However, detention SCMs (WO) had an insignificant impact on flow variability. Including SF SCMs in CWO and WPO mitigated the variability. The number and duration of flashy events increased partly due to the low high-pulse threshold based on the UND scenario. The average daily raising flow rate was near that of the UND scenario, but the decrease in the daily rate was much lower due to the drawdown of the SF SCMs.

Table 4. Hydrologic flow metrics associated with aquatic life potential in the Austin, TX area for different regulatory scenarios in the Gilleland tributary.

Metric	UND	PRE	WO	CWO	WPO
T_{dry}	0.52	0.24	0.26	0.01	0.10
BFR	0.37	0.15	0.15	0.64	0.63
F_{Ln}	15.78	27.04	28.83	10.87	8.65
F_{Ld} (day)	16.41	4.88	4.63	4.13	4.39
F_{Hn}	16.83	84.09	79.22	26.65	23.91
F_{Hd} (day)	2.30	0.16	0.19	4.61	5.19
$+_{mean}$ (cms)	0.100	0.246	0.244	0.113	0.106
$-_{mean}$ (cms)	0.046	0.076	0.077	0.26	0.26

3.4. LID SCMs (Brentwood Tributary)

The first study incorporating the LID SCMs into SWAT was in the Brentwood tributary to Shoal Creek in downtown Austin, TX [21]. The SWAT model was calibrated for a two-year period between 2013–2014 using 15-min interval streamflow at the watershed outlet (NSE = 0.88, R^2 = 0.89). The calibrated model was validated for a one-year period in 2014 at the same stream gage where the model was calibrated (NSE = 0.71, R^2 = 0.71). This 1.5 km^2 catchment was developed before any SCM requirements, and the residents experience frequent flooding of their yards and streets, with some flooding of residences. The cost to retrofit the stormwater infrastructure to current standards would be prohibitive (up to USD 200 million). This study looked at the cost-effectiveness of implementing widespread LID controls for flooding, including rain gardens, cisterns and porous pavement.

A previous study suggests that LID-type SCMs perform at varying levels in terms of stormwater runoff reduction in this watershed [21]. Among the evaluated LIDs, rain gardens showed the highest runoff reduction rate (77%) at when fully implemented, followed by porous pavement (29%) and green roofs and cisterns at the lowest reduction rate (15%). In the realistic scenario in which all LIDs were implemented simultaneously, the stormwater runoff was reduced by 30%. Our study found that widespread implementation of LID-type SCMs reduced the 2-year peak runoff rate by approximately 24%, and the current 2-year peak had a recurrence interval of about 6 years (Figure 11). Nevertheless, the increased flood protection had an associated cost of USD 18 million. LID controls alone were not able to provide the same level of service as retrofitting the watershed could.

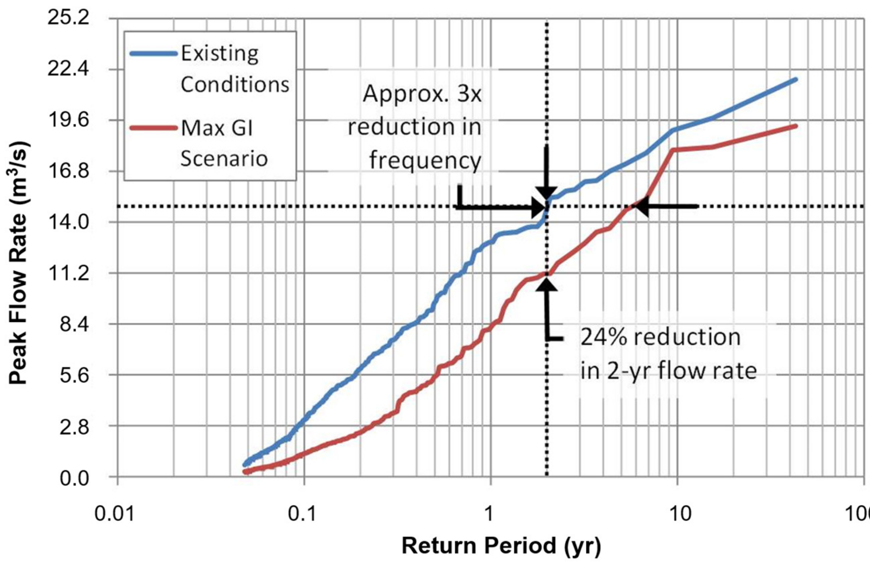

Figure 11. Peak flow rate distribution for the Brentwood tributary, with and without LID controls.

3.5. LID SCMs (Upper Waller)

Like the Brentwood watershed, the upper Waller Creek watershed was developed before the requirements of SCMs and the stream system degraded. This study examined the possibility of restoring the hydrology of the 2.80 km^2 watershed using cisterns and rain gardens at different implementation levels. LID SCMs were chosen in this study because, even if funds are available to retrofit SCMs in a certain area, land for traditional SCMs may not be available.

A model was developed based on existing conditions and calibrated against the flow from USGS using SWAT-CUP. The resulting model had an NSE of 0.68 for sub-daily flows and 0.90 for daily flows. The model was run using simulated weather and measured 15min rainfall for 1987–2014 using three different SCM scenarios. The first two years of the simulated hydrographs were omitted from analyses to serve as a "warm-up" period.

Table 5 includes the hydrologic metrics associated with the different LID implementation scenarios. The LID SCMs changed the hydrologic metrics, aiming to restore the hydrology to a less developed state. While these scenarios represent aggressive adoption rates of LID SCMs in the watershed, they could significantly increase the aquatic life potential.

Table 5. Hydrologic flow metrics associated with aquatic life potential in the Upper Waller creek for different LID implementation scenarios in the upper Waller watershed.

Metric	Current	Low (Δ)	High (Δ)	Max (Δ)
BFR	0.12	0.13 (13.9%)	0.18 (54.6%)	0.26 (122.2%)
$+_{mean}$ (cms)	0.059	0.049 (−18.2%)	0.35 (−41.1%)	0.024 (−59.5%)
$-_{mean}$ (cms)	0.44	0.036 (−18.9%)	0.025 (−41.7%)	0.030 (−30.9%)
T_{dry}	0.86	0.85 (−1.3%)	0.82 (−4.5%)	0.8 (−7.6%)
F_{Ld}	4.7	4.59 (−2.1%)	4.46 (−5%)	4.38 (−6.6%)
F_{Ln}	67.04	67.62 (0.8%)	67.38 (0.5%)	66.35 (−1%)
F_{Hd}	0.77	0.82 (6.7%)	0.96 (24.7%)	1.12 (45.2%)
F_{Hn}	65.73	66.46 (1.1%)	67.65 (2.9%)	66.73 (1.5%)
TQE	0.18	0.18 (3.2%)	0.19 (4.5%)	0.25 (40.8%)
F_{En}	18.77	16 (−14.7%)	10.81 (−42.4%)	6.88 (−63.3%)
F_{Ed}	1.26	1.18 (−6.4%)	1.17 (−7.3%)	1.22 (−3.2%)

4. Conclusions

In all five watersheds evaluated using SWAT, the effect of land use change due to urbanization was demonstrated to increase the frequency and volume of channel flow significantly. Implementing SCMs in these catchments showed varying performance levels in terms of controlling high flows and improving aquatic health. In all case studies, SCMs were effective in increasing stormwater infiltration, reducing peaks and increasing low flows. The results from the Commons Ford watershed indicate that aquatic health is more sensitive to hydrologic indices than water quality, although further research is needed to validate this claim. Predicting the overall impacts of land development projects or environmental regulations on watershed health is complicated. In the past, years would pass before the actual effects were known, and, in many cases, good intentions often had negative impacts that outweighed the positive benefits. Long-term modeling was either unavailable or based on simplified assumptions that proved to be wrong.

The advances in the SWAT model and analysis techniques for urban stormwater modeling created a flexible and dynamic tool to allow planners and engineers to assess projects, evaluate regulatory changes and plan future growth while looking at the overall impacts on a watershed. The case studies introduced in this paper demonstrate the capacity and potential of the SWAT model as a helpful tool that can aid in minimizing the future cost to municipalities and protecting waterways. As shown in this study, this advanced mathematical model could effectively consider the information contained in raw data and records showing the status of urbanization and provide information that can enable planners and engineers to make guided decisions in order to make sustainable urban development possible.

Author Contributions: Conceptualization, R.G. and R.S.; methodology, R.G., J.J. and J.G.A.; software, J.J. and R.S.; formal analysis, R.G. and J.J.; resources, R.G.; writing—original draft preparation, R.G. and J.J.; writing—review and editing, Y.H. and J.G.A.; project administration, J.J.; funding acquisition, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the USDA National Institute of Food and Agriculture, Hatch project [TX09544]. SWAT model enhancement was supported by the City of Austin.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors appreciate the COA Watershed Protection Department staff for providing the field data which were used in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nirupama, N.; Simonovic, S.P. Increase of flood risk due to urbanisation: A Canadian example. *Nat. Hazards* **2007**, *40*, 25. [CrossRef]
2. Bussi, G.; Whitehead, P.G.; Thomas, A.R.C.; Masante, D.; Jones, L.; Jack Cosby, B.; Emmett, B.A.; Malham, S.K.; Prudhomme, C.; Prosser, H. Climate and land-use change impact on faecal indicator bacteria in a temperate maritime catchment (the River Conwy, Wales). *J. Hydrol.* **2017**, *553*, 248–261. [CrossRef]
3. Bekele, E.G.; Knapp, H.V. Watershed Modeling to Assessing Impacts of Potential Climate Change on Water Supply Availability. *Water Resour. Manag.* **2010**, *24*, 3299–3320. [CrossRef]
4. Faramarzi, M.; Abbaspour, K.C.; Ashraf Vaghefi, S.; Farzaneh, M.R.; Zehnder, A.J.B.; Srinivasan, R.; Yang, H. Modeling impacts of climate change on freshwater availability in Africa. *J. Hydrol.* **2013**, *480*, 85–101. [CrossRef]
5. Gautam, S.; Mbonimpa, E.; Kumar, S.; Bonta, J.; Lal, R. Agricultural Policy Environmental eXtender model simulation of climate change impacts on runoff from a small no-till watershed. *J. Soil Water Conserv.* **2015**, *70*, 101–109. [CrossRef]
6. Allen, P.; Arnold, J.; Skipwith, W. Prediction of channel degradation rates in urbanizing watersheds. *Hydrol. Sci. J.* **2008**, *53*, 1013–1029. [CrossRef]
7. Brocca, L.; Liersch, S.; Melone, F.; Moramarco, T.; Volk, M. Application of a model-based rainfall-runoff database as efficient tool for flood risk management. *Hydrol. Earth Syst. Sci. Discuss.* **2013**, *10*, 2089–2115. [CrossRef]
8. Glick, R.; Gosselink, L.; Bai, B.; Herrington, C. *Impacts of Stream Hydrologic Characteristics on Ambient Water Quality and Aquatic Health in the Austin, Texas Area*; SR-10-18; The University of Texas at Austin: Austin, TX, USA, 2010; p. 38. Available online: https://repositories.lib.utexas.edu/handle/2152/64735 (accessed on 21 March 2023).
9. Zhang, L.L.; Wang, C.Y.; Liang, G.X.; Cui, Y.L.; Zhang, Q.L. Influence of Land Use Change on Hydrological Cycle: Application of SWAT to Su-Mi-Huai Area in Beijing, China. *Water* **2020**, *12*, 3164. [CrossRef]
10. Johnson, C.L.; Priest, S.J. Flood risk management in England: A changing landscape of risk responsibility? *Int. J. Water Resour. Dev.* **2008**, *24*, 513–525. [CrossRef]
11. Finkenbine, J.K.; Atwater, J.; Mavinic, D. Stream Health after Urbanization 1. *JAWRA J. Am. Water Resour. Assoc.* **2000**, *36*, 1149–1160. [CrossRef]
12. Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174. [CrossRef]
13. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool Theoretical Documenrtation*; Grassland, Soil and Water Research Service: Temple, TX, USA, 2011.
14. Gassman, P.; Reyes, M.; Green, C.; Arnold, J. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE* **2007**, *50*, 1211–1250. [CrossRef]
15. Gassman, P.W.; Arnold, J.; Srinivasan, R.; Reyes, M. The worldwide use of the SWAT model: Technological driver, networking impacts, and simulation trends. *Trans. ASABE* **2010**, *50*, 1211.
16. Cortes-Hernandez, V.E.; Zheng, F.F.; Evans, J.; Lambert, M.; Sharma, A.; Westra, S. Evaluating regional climate models for simulating sub-daily rainfall extremes. *Clim. Dyn.* **2016**, *47*, 1613–1628. [CrossRef]
17. Jeong, J.; Kannan, N.; Arnold, J.; Glick, R.; Gosselink, L.; Srinivasan, R. Development and Integration of Sub-hourly Rainfall–Runoff Modeling Capability Within a Watershed Model. *Water Resour. Manag.* **2010**, *24*, 4505–4527. [CrossRef]
18. Jeong, J.; Williams, J.R.; Merkel, W.H.; Arnold, J.G.; Wang, X.; Rossi, C.G. Improvement of the variable storage coefficient method with water surface gradient as a variable. *Trans. ASABE* **2014**, *57*, 791–801.
19. Jeong, J.; Kannan, N.; Arnold, J.G.; Glick, R.; Gosselink, L.; Srinivasan, R.; Harmel, R.D. Developmnt of Sub-Daily Erosion and Sediment Transport Algorithms for SWAT. *Trans. ASABE* **2011**, *54*, 1685–1691. [CrossRef]

20. Jeong, J.; Kannan, N.; Arnold, J.G.; Glick, R.; Gosselink, L.; Srinivasan, R.; Barrett, M.E. Modeling sedimentation-filtration basins for urban watersheds using Soil and Water Assessment Tool. *J. Environ. Eng.* **2012**, *139*, 838–848. [CrossRef]
21. Her, Y.; Jeong, J.; Arnold, J.; Gosselink, L.; Glick, R.; Jaber, F. A new framework for modeling decentralized low impact developments using Soil and Water Assessment Tool. *Environ. Model. Softw.* **2017**, *96*, 305–322. [CrossRef]
22. Kannan, N.; Jeong, J.; Arnold, J.; Gosselink, L.; Glick, R.; Srinivasan, R. Hydrologic Modeling of a Retention Irrigation System. *J. Hydrol. Eng.* **2014**, *19*, 1036–1041. [CrossRef]
23. Koltsida, E.; Mamassis, N.; Kallioras, A. Hydrological modeling using the Soil and Water Assessment Tool in urban and peri-urban environments: The case of Kifisos experimental subbasin (Athens, Greece). *Hydrol. Earth Syst. Sci.* **2023**, *27*, 917–931. [CrossRef]
24. Bauwe, A.; Kahle, P.; Lennartz, B. Hydrologic evaluation of the curve number and Green and Ampt infiltration methods by applying Hooghoudt and Kirkham tile drain equations using SWAT. *J. Hydrol.* **2016**, *537*, 311–321. [CrossRef]
25. Shannak, S. Assessment of Low-Impact development for managing aquatic ecosystem. *Ecol. Indic.* **2021**, *132*. [CrossRef]
26. Avellaneda, P.M.; Jefferson, A.J. Sensitivity of Streamflow Metrics to Infiltration-Based Stormwater Management Networks. *Water Resour. Res.* **2020**, *56*, e2019WR026555. [CrossRef]
27. Bureau, U.S.C. *Annual Estimates of the Resident Population for Incorporated Places of 50,000 or More, Ranked by July 1, 2017 Population: April 1, 2010 to July 1, 2017*; Population Division, US Census Bureau: Washington, DC, USA, 2018.
28. Mein, R.; Larson, C. Modeling infiltration during a steady rain. *Water Resour. Res.* **1973**, *9*, 384–394. [CrossRef]
29. SCS. *National Engineering Handbook, Section 4, Hydrology*; US Soil Conservation Service: Washington, DC, USA, 1972.
30. Overton, D. Muskingum flood routing of upland streamflow. *J. Hydrol.* **1966**, *4*, 185–200. [CrossRef]
31. Jeong, J.H.; Kannan, N.; Srinivasan, R. *Development of SWAT Algorithms for Modeling Urban Best Management Practices*; BREC Report No. 11-03; Texas A&M AgriLife Research: Temple, TX, USA, 2011.
32. Logan, G.D. The Weibull distribution, the power law, and the instance theory of automaticity. *Psychol. Rev.* **1995**, *102*, 751–756. [CrossRef]
33. Hardy, T.B.; Panja, P.; Mathias, D. *WinXSPRO: A Channel Cross Section Analyzer: User's Manual Version 3.0*; US Department of Agriculture, Forest Service, Rocky Mountain Research: Fort Collins, CO, USA, 2005.
34. Richter, B.D.; Baumgartner, J.V.; Braun, D.P.; Powell, J. A spatial assessment of hydrologic alteration within a river network. *Regul. RiversRes. Manag. Int. J. Devoted River Res. Manag.* **1998**, *14*, 329–340. [CrossRef]
35. Gosselink, L.; Glick, R.H. Applying the Sub-Daily SWAT Model to Assess Aquatic Life Potential under Different Development Scenarios in the Austin, Texas Area. In Proceedings of the 2011 International SWAT Conference, Toledo, Spain, 15–17 June 2011.
36. Wiederkehr, F.; Wilkinson, C.L.; Zeng, Y.W.; Yeo, D.C.J.; Ewers, R.M.; O'Gorman, E.J. Urbanisation affects ecosystem functioning more than structure in tropical streams. *Biol. Conserv.* **2020**, *249*, 108634. [CrossRef]
37. Luo, K.; Hu, X.B.; He, Q.; Wu, Z.S.; Cheng, H.; Hu, Z.L.; Mazumder, A. Impacts of rapid urbanization on the water quality and macroinvertebrate communities of streams: A case study in Liangjiang New Area, China. *Sci. Total Environ.* **2018**, *621*, 1601–1614. [CrossRef]
38. Sullivan, J.; Grubb, J.; Willis, R.; Boozer, D.; Flickinger, B.; Dixon, C.E. Cohesive Channel Response to Watershed Urbanization: Insights from the Sand River, Aiken SC. *Water* **2020**, *12*, 3441. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.