Article

Water Quality Control Options in Response to Catchment Urbanization: A Scenario Analysis by SWAT

Hong Hanh Nguyen *, Friedrich Recknagel and Wayne Meyer

Department of Ecology and Environmental Sciences, University of Adelaide, Adelaide SA 5005, Australia; friedrich.recknagel@adelaide.edu.au (F.R.); wayne.meyer@adelaide.edu.au (W.M.)

* Correspondence: hanh.nguyen@adelaide.edu.au; Tel.: +61-044-919-2658

Received: 7 November 2018; Accepted: 11 December 2018; Published: 13 December 2018

Abstract: Urbanization poses a challenge to sustainable catchment management worldwide. This study compares streamflows and nutrient loads in the urbanized Torrens catchment in South Australia at present and future urbanization levels, and addresses possible mitigation of urbanization effects by means of the control measures: river bank stabilization, buffer strip expansion, and wetland construction. A scenario analysis by means of the Soil and Water Assessment Tool (SWAT) based on the anticipated urban population density growth in the Torrens catchment over the next 30 years predicted a remarkable increase of streamflow and Total Phosphorous loads but decreased Total Nitrogen loads. In contrast, minor changes of model outputs were predicted under the present urbanization scenario, i.e. urban area expansion on the grassland. Scenarios of three feasible control measures demonstrated best results for expanding buffer zone to sustain stream water quality. The construction of wetlands along the Torrens River resulted in the reduction of catchment runoff, but only slight decreases in TN and TP loads. Overall, the results of this study suggested that combining the three best management practices by the adaptive development of buffer zones, wetlands and stabilized river banks might help to control efficiently the increased run-off and TP loads by the projected urbanization of the River Torrens catchment.

Keywords: SWAT; urbanization; nutrient loads; constructed wetlands; buffer zones; river bank stabilization

1. Introduction

Urbanization is the most common trend in land use changes worldwide, with approximately half of the global population residing in disproportionately small areas of land [1–3]. The urbanization of catchments is associated with sealing, compaction, degradation, and mixing of natural soils with imported soils [4,5], and requires informed sustainable management. Increased runoff and erosion rates, degraded water quality, reduction in biodiversity, wetland loss, and eutrophication are some of the consequences of rapid urbanization [6,7]. Analysis of 106 river catchments worldwide found that the proportion of catchments with streamflow being fragmented and disturbed by dams in urban areas is projected to increase to 70% by 2050 [7]. In Australia, natural catchments have been drastically altered since European settlement by land clearing and development of cities. Approximately 90% of the Australian population is living in urban areas [1] and many catchments face the risk of elevated nutrient loads and substantial algal blooms [8–10]. Thus, studies that allow quantitative evaluation of effects of urbanization are of great importance for the future water-sensitive design of Australian cities [11]. Catchment modeling has been defined as an important tool to assist this target [11,12].

The Soil and Water Assessment Tool (SWAT) is a widely used catchment modeling tool that allows to predict streamflow and non-point source pollutants under varying soil, land use and

management conditions worldwide [13–15]. The SWAT model was originally developed to simulate rural catchments, but algorithms describing urban processes were later incorporated in the model [15]. Results from many studies by the SWAT have suggested that urbanization causes significant alterations in the water budget of catchments by increasing surface runoff and decreasing baseflow in streams [16–20]. Some studies have also reported a linear relationship between the speed of urbanization and the increase in sediment and nutrient loads [21,22]. In the study by Lee et al. [23], the projection of urbanization for 2030 suggests increases of total nitrogen and total phosphorous in many catchments by up to 24% and 111%, respectively. As stated by Wang and Kalin [22], substantial urbanization on forest lands is expected to cause higher peaks for sediment and total phosphorous loads during wet seasons, whereas rapid urbanization may even have a stronger effect on nitrogen and phosphorous than projected climate change [24]. In the case of Australia, most studies on catchment urbanization have focused on hydrological impacts [25] whilst studies on nutrient loads have been applied to agricultural catchments [26–28].

The River Torrens catchment covers an area of 200 km² and is located in the central part of Adelaide, the capital of South Australia. It supplies drinking water, environmental flow, and fulfills recreational and conservational purposes for the capital city [29]. Urban development is affecting water quality of its tributaries and creeks [8].

This study focuses on modelling effects of urbanization on streamflow and nutrient loads in the Torrens catchment using the SWAT model. The study also examines the effectiveness of potential mitigating control options in response to future catchment urbanization, and improves understanding of this issue for urban catchment managers and policy makers. This case study may also of interest to modelers working on similar environmental problems around the world.

2. Materials and Methods

2.1. Study Area

The urban section of the River Torrens catchment below Gorge weir (hereafter called the Urban Torrens catchment) was used throughout this study for the SWAT model application. The study area includes the First to Fifth Creek and the River Torrens, which pass through the Adelaide Central Business District (CBD). The catchment lies between latitude $-34^{\circ}51'23''$ and $-34^{\circ}56'53''$ S and longitude $138^{\circ}32'55''$ to $138^{\circ}43'52''$ E. The altitude of this area ranges from 9 to 681 m with an average value of 214 m. The Mediterranean climate of the study area is characterized by a low average annual rainfall of 600 mm that is mostly concentrated in sporadic storm events in summer or during the wet winter.

2.2. Input Data

2.2.1. Soil Data

The soil inputs required for the SWAT model comprise of soil maps and soil attribute data (Figure 1). The soil maps of the study area include the map of South Australia, which was provided by the South Australian Department of Agriculture, and a map of the urban area which was extracted from a project on mapping soils around metropolitan Adelaide by the Department of State Development [30]. This project was carried out to explore the properties of Metropolitan Adelaide soils, which include some reactive soils and clays that are sensitive to seasonal and human-induced changes and have caused severe failure of masonry buildings in many urban regions around Adelaide. Both maps were provided at the resolution of 1:100,000 and were clipped to prepare unique raster map using a geographic information system (GIS) tool.

Figure 1. Soil maps of the study area.

For the SWAT database, the major soil information was provided by the Australian Soil Resource Information System (ASRIS) [31], while the attributes of soils in the missing information area (Figure 1) were constructed on the basis of data available from the Drill Core Reference Library, published literature [30] and expert knowledge. Information from 27 data points drilled to 10 m depth [28] was combined to develop eight major soil classes: black earth (BE), brown solonized (BS), estuarine sediments (EM), podzolic (P2), red-brown earths (RB3, RB5, RB6), and solodic (SK) soils. These soil classes were further characterized by soil attributes comprised of soil layers, soil hydrological groups, plant root depth, soil dry bulk density, soil organic content, and percent of clay, silt, sand, and rock fragments. Some soil parameters were estimated using the following functions [32,33]:

$$\theta_p = 0.132 - 2.5 \times 10^{-6} \times e^{0.105 \times \%sand} \quad (1)$$

$$K_{sat} = 750 \times \left(\frac{\theta_{sat} - \theta_d}{\theta_d} \right)^2 \quad (2)$$

where θ_p ($\text{m}^3 \text{H}_2\text{O}/\text{m}^3$ soil) is the soil available water content (SOL_AWC) ($\text{mm H}_2\text{O}/\text{mm soil}$), K_{sat} is the saturated hydraulic conductivity (SOL_K) (mm/day), θ_{sat} is the upper limit of water content that is possible in a soil of known bulk density and θ_d ($\text{m}^3 \text{H}_2\text{O}/\text{m}^3$ soil) is the volumetric drained upper limit water content.

θ_{sat} was calculated from Soil bulk density (ρ_d) (g/cm^3) using the following formula:

$$\theta_{sat} = 1.0 - \frac{\rho_d}{2.65} \quad (3)$$

θ_d was calculated from the gravimetric drained upper limit w_d ($\text{kg H}_2\text{O}/\text{kg Soil}$) and ρ_d :

$$\theta_d = w_d \times \rho_d \quad (4)$$

$$w_d = 0.186 \times \left(\frac{sand}{clay} \right)^{-0.141} \quad (5)$$

These equations have been successfully applied to derive soil characteristics for a range of soils in south eastern South Australia [34]. The soil erodibility (USLE_K) parameter ($0.013 \text{ (metric ton m}^2 \text{ h) / (m}^3\text{-metric ton cm)}$) was estimated from relative proportions of sand, silt, and clay in each soil layer using the method provided in the SWAT manual [15].

The resulting attributes of the soil profile of the Urban Torrens catchment are provided in Table 1. These include average data for two soil layers of soil classed which are estimated from drill hole information and more detailed data on five soil layers of soil classes provided by the ASRIS source.

Table 1. Characteristics of soil database in the Urban Torrens catchment.

Soil Profile	Layer (s)	Soil Parameters *										Data Source
		SOL_Z	SOL_BD	SOL_AWC	SOL_K	SOL_CBN	CLAY	SILT	SAND	SOL_ALB	USLE_K
1	975	1.379	0.131	21.6	2.25	43	27	30	0.17	0.051	Drill holes [30]
	2	4071	1.389	0.132	23.3	0.50	43	30	27	0.17	0.051
1	126	1.403	0.129	31.0	2.76	16	18	66	0.18	0.051	ASRIS [31]
	2	217	1.503	0.126	20.7	0.73	16	13	71	0.18	0.051	
	3	349	1.428	0.132	7.0	0.49	43	37	20	0.18	0.058	
	4	498	1.437	0.132	7.1	0.25	38	36	25	0.18	0.058	
	5	876	1.344	0.130	4.8	0.14	26	25	38	0.18	0.050	

Note: * Soil parameters: SOL_Z: soil depth (mm); SOL_BD: moist bulk density (mg/m^3); SOL_AWC: available water capacity (mm/mm soil); SOL_K: saturated hydraulic conductivity (mm/h); SOL_CBN: organic carbon content (%); CLAY: clay content (%); SILT: silt content (%); SAND: sand content (%); SOL_ALB: moist albedo; USLE_K: Universal Soil Loss Equation (USLE) equation soil erodibility (K) factor ($0.013 (\text{metric ton m}^2 \text{ h})/(\text{m}^3\text{-metric ton cm})$).

2.2.2. Other Input Data

In addition to soil data, application of the SWAT to the Urban Torrens catchment requires a number of input data types and maps:

- Digital elevation model (DEM): the 10 m resolution DEM was interpolated from a 10 m contour map provided by the SA Water Corporation.
- Flow burn-in layer: The river network was superimposed onto the DEM to adjust the location of some downstream urban creeks that were not well predicted by DEM due to modification effects from urban land development. The burn-in river layer was provided by the SA Water Corporation.
- Land use maps: a historical land use map at a scale of 1:100,000, which was completed in 2007 and updated with recent data on locations and land uses of the Torrens catchment, was provided by the Department of Environment, Water and Natural Resources. The map classifies the catchment into urban residential, commercial, institutional, industrial, transportation, water, and grassland land uses. For the past land use scenario, a historical map of 2001 of the whole South Australia was provided by the Department of Planning, Transport and Infrastructure.
- Climate data: this includes maximum and minimum air temperature, rainfall, relative humidity, and solar radiation. The daily data for these variables from 2008 to 2015 from five weather stations was extracted from the Scientific Information for Land Owners (SILO) website [35].
- Streamflow and nutrient data: data of daily streamflow and monthly composite Total Nitrogen (TN) and Total Phosphorous (TP) loads at the outlet of the study area (Holbrooks Road Station, A5040529) were provided by the Adelaide and Mount Lofty Ranges Natural Resources Management Board [36]. Data were extracted for the period from 2008 to 2015.

2.3. Soil and Water Assessment Tool (SWAT) Model Set-Up

SWAT (ArcSWAT version 2012 revision 637, USDA, Washington, DC, USA) is a continuous-time, semi-distributed simulator developed to assist water resource managers in predicting impacts of land management practices on water quality, including various species of nitrogen and phosphorous [13,15]. Spatially, the model subdivides a catchment into sub-basins, which are further delineated into hydrological response units (HRUs) based on physical characteristics of topography, soil, and land uses. In this study, application of the SWAT model resulted in a subdivision of the Urban Torrens catchment into 23 sub-basins and further into 125 HRUs using the multiple HRU thresholds method of soil, land use, and slope at 10, 20, and 10%, respectively. A modified Soil Conservation Service (SCS) curve number technique was used to estimate the streamflow, while the instream processes of TN and TP loads were estimated using the Enhanced Stream Water Quality Model (QUAL2E) [37]. Local information on management practices was imported into the model on the basis of expert knowledge. All land operations were scheduled by specific application date [15]. The growing season was defined from 1 June to 30 May for all urban land categories. In order to simulate management activities along land uses by agriculture, pasture, and orchards, the approach designed by Nguyen et al. [28] has been applied.

The parameter optimization of the SWAT model was based on sensitivity analysis, model calibration, model validation, and uncertainty analysis. These steps are in accordance with Neitsch et al. [15] and Arnold et al. [38], and will be discussed in the following section.

2.3.1. Parameter Sensitivity Analysis

The sequential uncertainty fitting (SUFI2) algorithm [38] of the SWAT Calibration and Uncertainty Program (SWAT-CUP, EAWAG, Dübendorf, Switzerland) allows analysis of global and one-at-a-time sensitivity. Here we applied the global sensitivity analysis to identify parameters for the calibration and validation steps.

2.3.2. Model Calibration, Validation and Uncertainty

The parameter optimization was performed on a monthly time step using the generalized likelihood uncertainty (GLUE) algorithm that showed better calibration results for this case study when compared to the results of the SUFI2 program. GLUE performs a combined calibration and uncertainty analysis and accounts for all sources of uncertainties [39–41]. The calibration was conducted consecutively beginning with the streamflow followed by loads of sediment (TSS), TN and TP by means of the observed data from 2008 to 2015 and using the first three years as a warm-up period for model stabilization. Data from 2011 to 2013 were used for calibration, and validation was performed for the years 2014 and 2015. 5000 iterations were applied and the Nash-Sutcliffe (NS) [42] behavioral threshold of 0.5 was used for both streamflow and nutrient simulations. The coefficient of determination (R^2), percent bias (PBIAS) [43], and NS efficiency coefficient were used as statistical criteria for evaluation of simulated results.

$$NS = 1 - \frac{\sum_i (Q_{m,i} - Q_{s,i})^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad (6)$$

where: Q is the streamflow variable, m and s are measured and simulated values respectively, i is the i th datum, and the bar stands for average values.

The threshold for R^2 and NS greater than 0.5 for streamflow, TN and TP loads, and PBIAS ranging between $\pm 25\%$ for streamflow and $\pm 70\%$ for TN and TP loads, respectively, were considered as satisfactory modelling results [44]. The model uncertainty was expressed using the 95% prediction uncertainty index (95PPU) and statistically was evaluated based on the percentage of observation points bracketed by the prediction uncertainty band (p-factor) and the degree of uncertainty (r-factor). The values close to 1 were selected as satisfactory criteria for p- and r-factors [45].

2.4. Scenario Analysis

The calibrated model was used to simulate present and future scenarios of urbanization, and determine best-management practices (BMPs). The past (P) and present (BS) urbanization scenarios were represented through land use maps generated in ArcGIS, which indicated a substantial shift in the period from 2001 to 2015 from grassland to urban lands of low residential, institutional, and commercial lands (Figure 2). For the future urbanization scenario (FS0), the urban land budget will not change significantly according to the 'The 30 year Plan for Greater Adelaide' report, even though the urban population density is expected to triple [46]. Therefore, we maintained the relative percentage of land uses from 2015 (Figure 2), and reclassified the land use from low residential to high residential. The change in residential land use was reflected by an increase in the fraction of total impervious areas (FIMP) from 0.12 to 0.6, the amount of solids allowed to build up on impervious area (DIRTMX) from 125 to 225 kg/curb km, TN concentration in suspended solid loads from impervious area (TNCONC) from 360 to 550 mg N/kg sediment, and TP concentration in suspended solid loads from impervious area (TPCONC) from 96 to 223 mg P/kg sediment [15]. Values of parameters for the high-residential land use were extracted from the default database, while data for the low-residential land use were manually calibrated prior the auto-calibration step [47]. Meteorological input data were kept unchanged for all urbanization scenarios.

In order to determine potential BMPs for mediating water deterioration issues by urbanization, the following scenarios were designed:

- Scenario 'Stream bank stabilization' (S1) was set up by increasing vegetative cover (CH_COV2) and Manning's stream roughness coefficient (CH_N2), and reducing the stream erosion (CH_EROD) values by 50% [48–50].
- Scenario 'Buffer strip application' (S2) was set up by extending the 30-m width of the filter strip of alfa grass along the main river using the FILTERW parameter in SWAT '.mgt' input file [51].

- Scenario ‘Wetland development’ (S3) was represented by a wetland with a maximum surface of 3445 m² and volume of 3700 m³ in the ‘.pnd’ input file, as suggested by Kasan [52]. The nitrogen and phosphorous settling rates were set to 20 m/year using the maximum default value in the ‘.pnd’ input file for systems with high removal efficiency [38]. The bottom hydraulic conductivity was set at 2.3 mm/h [53], and sediment concentration in the wetland was defined at 10 mg/L. The same parameter values were applied to all wetland scenarios of this study.
- Combined scenario (Sm) which simulated together the three aforementioned scenarios.

Results for the past and future urbanization scenarios (P and FS) were compared with results of the present urbanization scenario BS. Results of the scenarios S1, S2 and S3 were compared with the scenario FS0. The statistical significance of scenarios of urbanization and BMPs were evaluated by means of a paired Wilcoxon test using an R tool according to the criteria $\rho < 0.05$.

Figure 2. Characteristics of past (P), present (BS), and future (FS0) land use changes in the Urban Torrens catchment from 2001 to 2045.

3. Results

3.1. Model Sensitivity

The global sensitivity analysis identified the runoff curve number (CN2), the baseflow alpha factor for bank storage (ALPHA_BNK) and the moist bulk density (SOL_BD) as most sensitive parameters for streamflow simulation whereas soil parameters SOL_BD, SOL_K, and SOL_AWC were amongst the 10 most sensitive parameters (Table 2). In contrast, the organic N in the baseflow (LAT_ORGN), the denitrification exponential rate coefficient (CDN) and denitrification threshold water content (SDNCO) proved most sensitive parameters for TN-load.

Table 2. Soil and Water Assessment Tool (SWAT) parameters used for model calibration.

Parameters	Description	Unit	Fitted Value	Parameter Sensitivity		
				t-Stat	p-Value	Rank
Streamflow						
CN2.mgt	Moisture condition II runoff curve number	-	-0.25 ^b	-63.56	0.00	1
ALPHA_BNK.rte	Baseflow alpha factor for bank storage	-	0.72	29.20	0.00	2
SOL_BD (1,2) ^a .sol	Moist bulk density	g/cm ³	-0.19 ^b	-24.50	0.00	3
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	mm H ₂ O	1854	17.00	0.00	4
ESCO.hru	Soil evaporation compensation factor	-	0.75	-11.91	0.00	5
SOL_K (1,2) ^a .sol	Saturated hydraulic conductivity	mm/h	-0.17 ^b	-8.66	0.00	6
SOL_AWC (1,2) ^a	Available water capacity of the soil layer	mm H ₂ O/mm soil	-0.02 ^b	7.40	0.00	7
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	mm/h	59.6	-7.08	0.00	8
CH_N2.rte	Manning's "n" value for the main channel	-	0.04	-5.98	0.00	9
GW_REVAP.gw	Groundwater "revap" coefficient	mm H ₂ O	0.19	3.66	0.00	10
GW_DELAY.gw	Groundwater delay	days	221.3	3.51	0.00	11
RCHRG_DP.gw	Deep aquifer percolation fraction	-	0.17	-2.94	0.00	12
Total Suspended Solid Load						
USLE_P.mgt	USLE equation support practice factor	-	0.39	-63.26	0.00	1
CH_COV1.rte	Channel erodibility factor	-	0.32	1.98	0.05	2
SPEXP.bsn	Exponent parameter for calculating sediment re-entrained in channel sediment routing	-	1.12	1.76	0.08	3
CH_EROD.rte	Channel erodibility factor	-	0.56	1.30	0.19	4
SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	-	0.006	0.38	0.70	5
CH_COV2.rte	Channel cover factor	-	0.62	0.04	0.97	6
Total Nitrogen Load						
LAT_ORGN.gw	Organic N in the baseflow	mg/L	6.33	-167.44	0.00	1
CDN.bsn	Denitrification exponential rate coefficient	-	0.56	-7.49	0.00	2
SDNCO.bsn	Denitrification threshold water content	-	0.73	3.8	0.00	3
ERORGN.hru	Organic nitrogen enrichment ratio	-	1.27	-1.08	0.28	4
NPERCO.bsn	Nitrogen percolation coefficient	-	0.15	-0.23	0.82	5
Total Phosphorous Load						
PHOSKD.bsn	Phosphorus soil partitioning coefficient	-	187.03	-0.88	0.38	1
PSP.bsn	Phosphorus sorption coefficient	-	0.06	-0.78	0.43	2
ERORGP.hru	Organic phosphorus enrichment ratio	-	2.51	0.49	0.62	3

Note: ^a Values in parentheses indicate the soil layer; ^b Indicated value refers to a relative change in the parameter.

3.2. Model Calibration, Validation and Uncertainty

Calibrations for streamflow, TN, and TP resulted in coefficients of determination R^2 of 0.77, 0.62, and 0.56, NS of 0.77, 0.62, and 0.51, and PBIAS of −4.18, −2.91, and 24.87 respectively (Figure 3) that according to Moriasi et al. [44] indicate to be satisfactory. Validation for streamflow achieved $R^2 = 0.97$, NS = 0.96, and PBIAS = −9.21, for TP $R^2 = 0.88$, NS = 0.84, and PBIAS = −28.4 and for TN with $R^2 = 0.67$, NS = 0.66, and PBIAS = −2.60. The p-factor for the uncertainty for flow ranged between 0.39 and 0.42, for TN between 0.83 and 0.71, for TP between 0.56 and 0.54, and the r-factor ranged between 0.75 and 0.79 for flow, 1.32 and 0.96 for TN, and 1.00 and 0.83 for TP during calibration and validation, respectively. The simulated peaks of streamflow, TN and TP loads corresponded well with monthly average precipitation in this urbanized catchment.

Figure 3. Hydrographs of observed and simulated streamflow and TN and TP loads of the Urban Torrens catchment during the calibration (2011–2013) and validation (2014–2015) periods.

3.3. Urbanization Scenarios

Results of the scenario BS indicated an overall increase of 0.6% in monthly streamflow due to an increase of surface streamflow by 1% and a decrease of baseflow by approximately 2% (Figure 4). Whilst scenario BS also predicted an increase of the TP load by the 2.9% forecasted, TN loads changed insignificantly compared to the past urbanization scenario. The trends for streamflow, TN and TP are relatively similar for all months of the year. The scenario FS0 (future urbanization) suggested a significant increase in total runoff by 13.3% when compared to present urbanization. The partitioning of streamflow under the scenario FS0 (Figure 4) indicates a similar trend of an increasing surface streamflow from 77 to 82%, while baseflow is further decreasing from 23 to 18%. There is also a significant increase by 36.4% of the TP-loads at the catchment outlet suggested. Meanwhile, model results suggest a noticeable decrease in TN loads of 6.9%. From the results of the future urbanization scenario it is also evident that higher rates of nutrient load variations are observed for the rainy period in winter (June to August). Overall, the trend is clear and similar when the effects of past, present and future urbanization scenarios are compared with more pronounced effects of future urbanization versus present urbanization.

Figure 4. Streamflow, TN and TP responses to scenarios past urbanisation (P), present urbanisation (BS) and future urbanization (FS0). Pie charts show the relative proportion of different hydrological components. Bar graphs show the average streamflow, TN, and TP loads. Error bars show one standard deviation.

3.4. Scenarios of Management Practices

The Table 3 suggests that the scenario ‘30-m buffer strips’ may achieve the highest reduction of the TN loads by 19.88% and of the TP loads by 4.13% compared to 1.22% and 2.73%, respectively, by the scenario ‘river bank stabilization’. However, both scenarios predicted statistically insignificant changes in the catchment outflow. The scenario ‘wetland development’ showed a slight decrease in TN and TP loads, and buffering effects for the increased run-off into the main stream. The scenario that combined the three feasible management practices predicted a decreased runoff and the highest reduction in nutrient loads compared to results of the scenarios of the three single measures.

Table 3. Results of best management scenarios for flow, TN and TP loads at the Urban Torrens catchment. The relative change of best-management practices (BMP) scenarios are compared with the results of the FS0 scenario.

Scenarios	Flow		TN Load		TP Load	
	Mean Values (m ³ /s)	Relative Change (%)	Mean Values (tons/year)	Relative Change (%)	Mean Values (tons/year)	Relative Change (%)
River bank stabilization—S1	0.88	<1	31.65 ^a	−1.22	2.57 ^a	−2.73
30-m buffer strips—S2	0.88	<1	25.67 ^a	−19.88	2.53 ^a	−4.13
Wetland development—S3	0.86 ^a	−2.27	31.76 ^a	−0.87	2.58 ^a	−2.44
Combined BMPs—Sm	0.86 ^a	−2.28	25.21 ^a	−21.30	2.47 ^a	−6.40

^a indicates a significant different value (p -value < 0.05) for a BMP scenario as compared with the FS0 scenario based on the paired Wilcoxon test.

4. Discussion

This study applied SWAT for modelling impacts of urbanization on the Torrens catchment that is of high relevance Australia-wide.

With regards to model optimization, it proved to be advantageous to include field-based soil database of the Torrens catchment as model input that resulted in satisfactory streamflow simulation of both peak and base flows (Figures 3 and 5) and improved simulation results for nutrient loads when compared with results for the urban catchment Aldgate of a previous study by Shrestha et al. [27] that was based on a coarser representation of soils.

Figure 5. Flow duration curve of observed and simulated streamflow of the Urban Torrens catchment for the period from 2011 to 2015.

All urbanization-related scenarios predicted increased streamflow as a result of increased surface flow and decreased baseflow that corresponds well with findings by Richards et al. [16] and Sunde et al. [19]. The trends of predicted TP loads as appeared to be strongly positively correlated with streamflow since phosphorus is primarily transported by sediments in surface streamflow. The model predicted annual increases of TP loads by 4 g/ha/year in scenario BS and 65 g/ha/year in scenario FS0. In contrast, the scenario results showed that urbanization may decrease TN load most likely because of reduced soil leaching by up to 26 g/ha/year and up to 2 g/ha/year less nitrogen in the baseflow as revealed by the comparison between the scenarios FS0 and BS. The highest changes in

nutrient loads were recorded during autumn and winter months when pollutants are often released and transported in river catchments during short periods of intensive rainfall [8,54].

The comparison between the scenarios P and FS0 revealed significant increases in streamflow by 13.3% and in TP loads by 36.4% whilst TN-loads decreased by 6.9%. A possible explanation lies in the fact that pervious urban lands are modelled in SWAT as Bermuda grass, which in this study is configured similarly to pasture and grassland. Thus, the conversion of the low-residential land use accounting for 38.6% of the total land budget of scenario P to high-residential land by scenario FS0 corresponded to an increase of overall impervious surface in the study by approximately 20%. According to the study of Brun and Band [55], 20% is the threshold at which a dramatic change in runoff can be observed. It is also important to mention that in the case of the Urban Torrens catchment, the sewage system is completely separated from the stormwater drainage network. Therefore, an increasing urban population is projected to cause more fragmented housing sites and smaller-sized yards but not necessarily an increase in surface flow by waste water, and simulated streamflows and nutrient loads are only driven by stormwater.

In an attempt to determine measures for counteracting the impacts of urbanization we have examined three management options. The scenario that simulated the extension of the grassed buffer zone proved to be efficient in reducing TP loads whilst developing wetlands may buffer the flow into the main rivers. However, the implementation of these two measures in combination with river bank stabilization promises to be the best management practice in response to future urbanization of the Urban Torrens catchment.

5. Conclusions

As outcomes of this study, the following conclusions were drawn:

- Growing urbanization increases surface flow and TP loads whereas baseflow and TN loads decrease due to extending impervious area.
- Expanded buffer zones and stabilized river banks can retain nutrients while constructing adjacent wetlands may reduce run-off from tributaries to the main stream.
- A combined application of the three management options at pinpointed tributaries and river sites may prove to be the best management practice (BMP) in response to urbanization of the Torrens catchment.

The SCS curve number approach performed well in this case study, but the results of streamflow calibration can be improved for densely urbanized sub-catchments by the Green and Ampt method in the SWAT model as suggested by Tassdighi et al. [56]. The results of scenario analyses in this study are restricted by simplified assumptions related to the default configuration of urban land uses in SWAT, and affected by some uncertainty. However, the results are showing most likely trends and magnitudes of expected effects of different land use developments and mitigation solutions on the catchment. Future research will build on outcomes of this study by extending the research to the downstream estuary region in order to address the effects of urbanization, and other potential sources that could combine with urbanization to cause significant threat to the riparian and coastal ecosystems.

Author Contributions: All authors contributed to the study design. Data acquisition and preparation were performed by H.H.N. Development of soil data for modelling was assisted by W.M. Modelling and writing of the original draft was done by H.H.N., F.R. and W.M. reviewed thoroughly the manuscript for submission. The final version of the manuscript was prepared by H.H.N.

Funding: This research was funded by the SA Water Corporation (grant number SW100309) and the Department of Environment, Water and Natural Resources (grant number F0000108271).

Acknowledgments: The authors acknowledge Malcolm Sheard for his professional advice and data support during the development of soil database for this study. We would like to thank Leon van der Linden, Brooke A. Swaffer and Robert Daly for their constructive comments on the study outputs. The authors also wish to thank Margaret Cargill for editing the manuscript for linguistic quality.

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

References

1. United Nations. *Urban and Rural Areas 2007*; United Nations: New York, NY, USA, 2007. Available online: http://www.un.org/esa/population/publications/wup2007/2007_urban_rural_chartpdf (accessed on 1 May 2017).
2. Saier, M.H. Are megacities sustainable? *Water Air Soil Pollut.* **2007**, *178*, 1–3. [[CrossRef](#)]
3. Xian, G.; Crane, M.; Junshan, S.J. An analysis of urban development and its environmental impact on the Tampa Bay watershed. *J. Environ. Manag.* **2007**, *85*, 965–976. [[CrossRef](#)] [[PubMed](#)]
4. Evans, C.V.; Fanning, D.S.; Short, J.R. Human-influenced soils. In *Managing Soils in an Urban Environment*; Brown, R.B., Huddleston, J.H., Anderson, J.L., Eds.; ASSA-CSSA-SSSA Publishers: Madison, WI, USA, 2000; pp. 33–67. ISBN 0891181431.
5. Doichinova, V.; Zhiyanski, M.; Hursthouse, A. Impact of urbanization on soil characteristics. *Environ. Chem. Lett.* **2006**, *3*, 160–163. [[CrossRef](#)]
6. Whitehead, P.G.; Lapworth, D.J.; Skeffington, R.A.; Wade, A. Excess nitrogen leaching and C/N decline in the Tillingbourne catchment, southern England: INCA process modelling for current and historic time series. *Hydrol. Earth Syst. Sci.* **2002**, *6*, 455–466. [[CrossRef](#)]
7. Zhang, Y.; Xia, J.; Shao, Q.; Zhai, X. Water quantity and quality simulation by improved SWAT in highly regulated Huai River Basin of China. *Stoch. Environ. Res. Risk Assess.* **2013**, *27*, 11–27. [[CrossRef](#)]
8. Ilman, M.A.; Gell, P.A. *Sediments, Hydrology and Water Quality of the River Torrens: A Modern and Historical Perspectives*; Three Projects for the River Torrens; Water Catchment Management Board; Department of Geographical and Environmental Studies, University of Adelaide: Adelaide, Australia, 1998; pp. 10–53.
9. Clark, T.; Humphrey, G.; Frazer, A.; Sanderson, A.; Maier, H. Effectiveness of flow management in reducing the risk of cyanobacterial blooms in rivers. In *Proceedings of the Hydrology and Water Resources Symposium, Melbourne, Australia, 20–23 May 2002*; Institution of Engineers: Barton, Australia, 2002.
10. Brookes, J.D. *River Torrens Water Quality Improvement Trial—Summer 2011/12*; Goyder Institute for Water Research Technical Report Series No. 12/4; The Goyder Institute for Water Research: Adelaide, Australia, 2012.
11. Wong, T.H.F. *Australian Runoff Quality—A guide to Water Sensitive Urban Design Engineers Australia*; Engineers Media for Australian Runoff Quality Authorship Team: Queensland, Australia, 2006.
12. Zoppou, C. Review of urban storm water models. *Environ. Model. Softw.* **2001**, *16*, 195–231. [[CrossRef](#)]
13. Arnold, J.G.; Srinivason, R.; Muttiah, R.R.; Williams, J.R. Large area hydrologic modeling and assessment Part I: Model development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [[CrossRef](#)]
14. Gassman, P.W.; Reyes, M.R.; Green, C.H.; Arnold, J.G. The soil and water assessment tool: Historical development, applications, and future research directions. *Trans. Am. Soc. Agric. Eng.* **2007**, *50*, 1211–1250. [[CrossRef](#)]
15. Neitsch, S.L.; Arnold, J.G.; Kinir, J.R.; Williams, J.R. *Soil and Water Assessment Tool: Theoretical Documentation*; Technical report no 406; Texas Water Resources Institute-Texas A&M University: College Station, TX, USA, 2011.
16. Richards, C.E.; Munster, C.L.; Vietor, D.M.; Arnold, J.G.; White, R. Assessment of a turfgrass sod best management practice on water quality in a suburban watershed. *J. Environ. Manag.* **2008**, *86*, 229–245. [[CrossRef](#)]
17. Zhou, F.; Xu, Y.; Chen, Y.; Xu, C.Y.; Gao, Y.; Du, J. Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. *J. Hydrol.* **2013**, *485*, 113–125. [[CrossRef](#)]
18. Qiu, Z.; Wang, L. Hydrological and Water quality assessment in a Suburban watershed with mixed land uses using the SWAT model. *J. Hydrol. Eng.* **2014**, *19*, 816–828. [[CrossRef](#)]
19. Sunde, M.; He, H.S.; Hubbart, J.A.; Scroggins, C. Forecasting streamflow response to increased imperviousness in an urbanizing Midwestern watershed using a coupled modeling approach. *Appl. Geogr.* **2016**, *72*, 14–25. [[CrossRef](#)]
20. Schütte, S.; Schulze, R.E. Projected impacts of urbanisation on hydrological resource flows: A case study within the uMngeni Catchment, South Africa. *J. Environ. Manag.* **2017**, *196*, 527–543. [[CrossRef](#)]
21. Jordan, Y.C.; Ghulam, A.; Hartling, S. Traits of surface water pollution under climate and land use changes: A remote sensing and hydrological modeling approach. *Earth-Sci. Rev.* **2014**, *128*, 181–196. [[CrossRef](#)]

22. Wang, R.; Kalin, L. Combined and synergistic effects of climate change and urbanization on water quality in the Wolf Bay watershed, southern Alabama. *J. Environ. Sci.* **2018**, *64*, 107–121. [[CrossRef](#)]
23. Lee, T.; Wang, X.; White, M.; Tuppad, P.; Srinivasan, R.; Narasimhan, B.; Andrews, D. Modeling Water-quality loads to the reservoirs of the Upper Trinity River basin, Texas, USA. *Water* **2015**, *7*, 5689–5704. [[CrossRef](#)]
24. El-Khoury, A.; Seidou, O.; Lapen, D.R.; Que, Z.; Mohammadian, M.; Sunohara, M.; Bahram, D. Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *J. Environ. Manag.* **2015**, *15*, 76–86. [[CrossRef](#)] [[PubMed](#)]
25. Saha, P.P.; Zeleke, K. Rainfall-Runoff Modelling for Sustainable Water Resources Management: SWAT Model Review. In *Sustainability of Integrated Water Resources Management Water Governance, Climate and Ecohydrology*; Setegn, S.G., Donoso, M.C., Eds.; Springer International Publishing: Basel, Switzerland, 2015.
26. Vanderkruk, K.; Owen, K.; Grace, M.; Thompson, R. Review of Existing Nutrient, Suspended Solid and Metal Models. Scientific Review for Victorian Department of Sustainability and Environment. Available online: https://ensymdsevicgovau/docs/DSE_EnSym_WQ_Review_RT051009_final_correctionpdf (accessed on 5 January 2017).
27. Shrestha, M.K.; Recknagel, F.; Frizenschaf, J.; Meyer, W. Assessing SWAT models on single and multi-site calibration for the simulation of flow and nutrients loads in the semi-arid Onkaparinga catchment in South Australia. *Agric. Water Manag.* **2016**, *175*, 61–71. [[CrossRef](#)]
28. Nguyen, H.H.; Recknagel, F.; Meyer, W.; Frizenschaf, J.; Shrestha, M.K. Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment—Reservoir system of South Australia. *J. Environ. Manag.* **2017**, *202*, 1–11. [[CrossRef](#)]
29. Gale, R.J.B.; Gale, S.J.; Winchester, H.P.M. Inorganic pollution of the sediments of the River Torrens, South Australia. *Environ. Geol.* **2006**, *50*, 62–75. [[CrossRef](#)]
30. Shread, M.J.; Borrmann, G.M. *Soils, Stratigraphy and Engineering Geology of near Surface Materials of the Adelaide Plains*; Department of Mines and Energy South Australia: Adelaide, Australia, 1996.
31. Australian Soil Resources Information System (ASRIS). Available online: <http://www.asris.csiro.au/mapping/viewer.htm> (accessed on 1 March 2015).
32. Ritchie, J.T.; Gerakis, A.; Suleiman, A. Simple model to estimate field measured soil water limits. *Trans. ASAE* **1999**, *42*, 1609–1614. [[CrossRef](#)]
33. Suleiman, A.; Ritchie, J.T. Estimating saturated hydraulic conductivity from soil porosity. *Trans. ASAE* **2001**, *44*, 235–239. [[CrossRef](#)]
34. Meyer, W.S. Land use potential for forestry (Radiata Pine and Blue Gum). In *South East Water Science Review: Prepared for Lower Limestone Coast Taskforce*; South Australian Department of Water, Land and Biodiversity Conservation (DWLBC): Adelaide, Australia, 2010; p. 32.
35. Scientific Information for Land Owners (SILO). Available online: <https://www.longpaddock.qld.gov.au/silo/ppd/index.php> (accessed on 15 July 2016).
36. AMLR. Available online: <http://amlr.waterdata.com.au/Amlr.aspx> (accessed on 10 March 2016).
37. Winchell, M.; Srinivasan, R.; Di Luzio, M.; Arnold, J. *ArcSWAT Interface for SWAT 2012, User's Guide*; United States Academic Decathlon (USDA): Mankato, MN, USA, 2013.
38. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; van Griensven, A.; Van Liew, M.W.; et al. SWAT: Model use, calibration, validation. *Trans. ASABE Am. Soc. Agric. Eng.* **2012**, *55*, 1491–1508. [[CrossRef](#)]
39. Abbaspour, K.C.; Johnson, C.; van Genuchten, M.T. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone J.* **2004**, *3*, 1340–1352. [[CrossRef](#)]
40. Abbaspour, K.C.; Rouholahnejad, E.; Vaghefi, S.; Srinivasan, R.; Yang, H.; Kløve, B. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *J. Hydrol.* **2015**, *524*, 733–752. [[CrossRef](#)]
41. Ficklin, D.L.; Lue, Y.; Zhang, M. Watershed modelling of hydrology and water quality in the Sacramento River watershed, California. *Hydrol. Process.* **2013**, *27*, 236–250. [[CrossRef](#)]
42. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models: Part I A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [[CrossRef](#)]
43. Beven, K.J.; Binley, A.M. The future of distributed models: Model calibration and uncertainty prediction. *Hydrol. Proc.* **1992**, *6*, 279–298. [[CrossRef](#)]

44. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]
45. Abbaspour, K.C. *SWAT-CUP: SWAT Calibration and Uncertainty Programs—A User Manual*; Swiss Federal Institute of Aquatic Science and Technology: Dübendorf, Switzerland, 2015.
46. DPLG. The 30-Year Plan for Greater Adelaide. A Volume of the South Australian Planning Strategy, Department of Planning and Local Government, 2010. Available online: https://livingadelaidesagovau/_data/assets/pdf_file/0007/278332/The_30-Year_Plan_for_Greater_Adelaide_2010_compressedpdf (accessed on 10 January 2017).
47. Nguyen, H.H.; Recknagel, F.; Meyer, W. Modelling the runoff, nutrient and sediment loadings in the Torrens river catchment, South Australia using SWAT. In Proceedings of the 22nd International Congress on Modelling and Simulation, Tasmania, Australia, 3–8 December 2017; pp. 1–7.
48. Tuppad, P.; Kannan, N.; Srinivasan, R.; Rossi, C.; Arnold, J. Simulation of agricultural management alternatives for watershed protection. *Water Resour. Manag.* **2010**, *24*, 3115–3144. [CrossRef]
49. Moriasi, D.N.; Steiner, J.L.; Arnold, J.G. Sediment Measurement and Transport Modeling: Impact of Riparian and Filter Strip Buffers. *J. Environ. Qual.* **2011**, *40*, 807–814. [CrossRef] [PubMed]
50. Motsinger, J.; Kalita, P.; Bhattarai, R. Analysis of Best Management Practices Implementation on Water Quality Using the Soil and Water Assessment Tool. *Water* **2016**, *8*, 145. [CrossRef]
51. Nielsen, A.; Trolle, D.; Wang, M.; Luo, L.; Han, B.P.; Liu, Z.; Olesen, J.E.; Jeppesen, E. Assessing ways to combat eutrophication in a Chinese drinking water reservoir using SWAT. *Mar. Freshw. Res.* **2013**, *64*, 475–492. [CrossRef]
52. Kasan, N.A. Nutrient Retention Capacity of a Constructed Wetland in the Cox Creek Sub-Catchment of the Mt. Bold Reservoir, South Australia. Ph.D. Thesis, University of Adelaide, Adelaide, Australia, 2011.
53. White, J.D.; Prochnow, S.J.; Filstrup, C.T.; Byars, B.W. A combined watershed-water quality modeling analysis of the Lake Waco reservoir: II. Watershed and reservoir management options and outcomes. *Lake Reserv. Manag.* **2010**, *26*, 159–167. [CrossRef]
54. Fleming, N.; Cox, J.; He, Y.; Thomas, S.; Frizenschaf, J. *Analysis of Constituent Concentrations in the Mount Lofty Ranges for Modelling Purposes*; Technical Report; eWater Cooperative Research Centre: Adelaide, Australia, 2010; pp. 1–37.
55. Brun, S.E.; Band, L.E. Simulating runoff behavior in an urbanizing watershed. *Comput. Environ. Urban Syst.* **2000**, *24*, 5–22. [CrossRef]
56. Tasdighi, A.; Arabi, M.; Harmel, D. A probabilistic appraisal of rainfall-runoff modeling approaches within SWAT in mixed land use watersheds. *J. Hydrol.* **2018**, *564*, 476–489. [CrossRef]

© 2018 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 (<http://creativecommons.org/licenses/by/4.0/>).