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Original Research Article

Effects of projected urbanization and climate change on flow and nutrient loads of a Mediterranean catchment in South Australia

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A B S T R A C T

Water-dependent ecosystems are highly vulnerable to climate change and human-induced alterations. This is especially true for ecosystems of urban catchments where aquatic habitats are already being degraded. This study examines prospective impacts of future climate change and anticipated urbanization on water quantity and quality in the urbanized Torrens catchment, South Australia. The eco-hydrological model SWAT has been applied to simulate flow, total nitrogen (TN) and total phosphorous (TP) for the following scenarios: (1) Scenarios based on future precipitation and temperature patterns for the period from 2021 to 2050, by means of two representative pathways (RCPs) of six downscaled global circulation models. (2) A scenario on the hypothetical urbanization of the Torrens catchment over the next 30 years, based on the projected population growth in the region. Scenario (1) suggests there will be a declining monthly flow due to increased temperature and decreased precipitation, and consequently reduced TN and TP loads. In contrast, scenario (2) predicts a higher monthly flow and TP loads resulting from extended impermeable areas due to urbanization, but lower TN loads due to the shrinking grassland taken over by urban land use. The combination of both scenarios shows the offset of their effects on the flow and TP loads, along with decreasing TN loads. The results of this study suggest that, in the long term, urbanization is of greater concern for the Torrens catchment than future climate change. Management decisions have to take into account the enhanced vulnerability of urban ecosystems under future local and global changes.

1. Introduction

Land use change and climate change are key factors that may cause significant alterations in the flow and degradation of the water quality in catchments worldwide (e.g. Whitehead et al., 2009; Piao et al., 2007; Wang et al., 2014). Changes in land use are predominantly driven by urbanization, as a result of rapid population growth (United Nations, 2007). Urbanization effects on catchments are often characterized by increased runoff, along with deteriorated physical, chemical, and microbiological properties that cause the degradation of receiving water bodies (e.g. Whitehead et al., 2002; Zhang et al., 2013). This applies to Australian catchments as well. According to the United Nations (2007), 89% of the Australian population resides in urban regions, posing risks of contamination and degradation to catchments, which are indicated by elevated nutrient levels and recurrent algal blooms (e.g. Ilman and Gell, 1998; Clark

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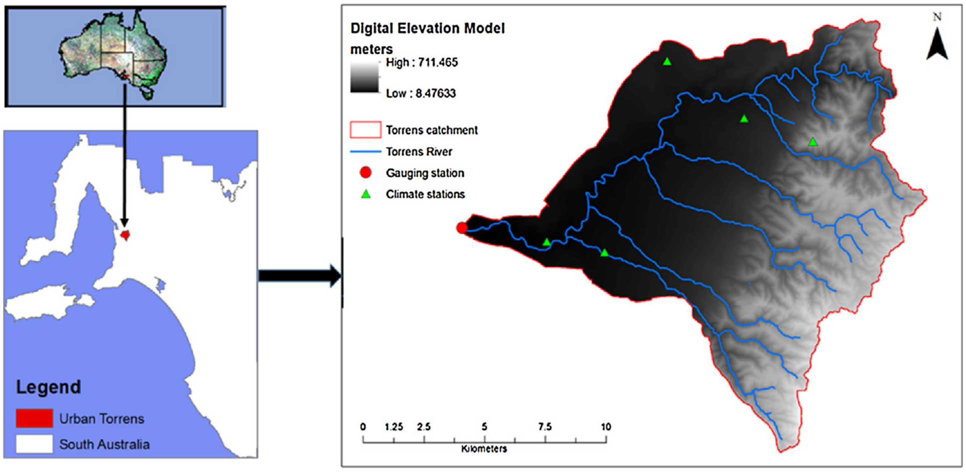

Fig. 1. Study area with topographic map and location of gauging and climate stations.

et al., 2002). The vulnerability of catchments in Mediterranean climates is even higher (García-Ruiz et al., 2011), since local ecosystems are not only affected by urbanization but also by highly variant climates. Shifts in species ranges and the loss of native ecosystems as a result of climate change have been reported for catchments in north-eastern and south-western Australia (e.g. Barron et al., 2012; Reside et al., 2017). Thus, studies that allow researchers to quantify the effects of urbanization and climate change are of great importance for sustaining urban catchments and ecosystems.

Catchment models increasingly serve as tools to support management decisions related to land use and climate change (Zoppou, 2001). Among them, the eco-hydrological model SWAT (Soil and Water Assessment Tool) is being applied world-wide to simulate streamflow and non-point source pollutants (Arnold et al., 1998; Neitsch et al., 2011). The SWAT model was originally developed to estimate pollution loads from rural catchments. Algorithms enabling it to simulate urban processes were incorporated later (Neitsch et al., 2011). Applications of the SWAT model suggest a linear relationship between the speed of urbanization and the increase in flow and nutrient releases from catchments (e.g. Jordan et al., 2014; Wang et al., 2014). Some studies reported that the combined effects of urbanization and climate change resulted in either more severe or diminished consequences to the environment (Wang et al., 2014; Wang and Kalin, 2018; Chang et al., 2016). While the global trend of the combined effects on catchment health is still not clear, studies in Australian catchments are more pragmatic and mostly focused on the hydrological impacts of agricultural systems (e.g. Vanderkruk et al., 2010; Westra et al., 2014; Shrestha et al., 2017). To the best of our knowledge, no research has yet studied the cumulative effects of climate change and urbanization on catchment water quality in Australia.

To fill this research gap, the primary objective of this study is to quantify the single and combined impacts of urbanization and climate variability on flow and nutrient loads for the next 30 years in the urbanized Torrens catchment in South Australia, based on scenario analyses using SWAT. The results of the scenarios may reveal how concerning impacts deriving from climate change or/and urbanization will be on catchment water quantity and quality. This study will also quantify the uncertainty of modelling outputs due to climate change data from various global climate models.

2. Materials and methods

2.1. Study area

The study was applied to the urbanized section of the Torrens catchment (Fig. 1) that is separated from its rural section upstream by the Gorge weir and is fed by five major urban creeks before reaching its outlet to the Southern Ocean. The catchment covers an area of about 200 km^2 and its elevation extends from 9 to 681 m. It has a Mediterranean climate with a low average annual rainfall of 600 mm, mainly falling in the winter months between April and August. Even though ongoing urbanization of the catchment is negatively affecting the water quality of its tributaries and creeks (Ilman and Gell, 1998), it provides an environmental flow and habitat for a wide diversity of native species (Gale et al., 2006). Rising phosphate and nitrate concentrations over the past 20 years have caused recurring instances of cyanobacterial bloom in the River Torrens (Ilman and Gell, 1998; Brookes, 2012), and projected climate change may further challenge the sustainability of this catchment (BOM, 2016).

2.2. Data for modelling

To run the SWAT model requires topographical, climate, soil and land use related data. A digital elevation model (DEM) (see Fig. 1) at a resolution of 10 m was obtained by interpolating the 10 m contour map provided by the South Australian Water Corporation, while land use and soil maps were prepared at the same resolution as the DEM. The detailed classification database of the historical land use map of the catchment provided by the Department of Environment, Water and Natural Resources was grouped

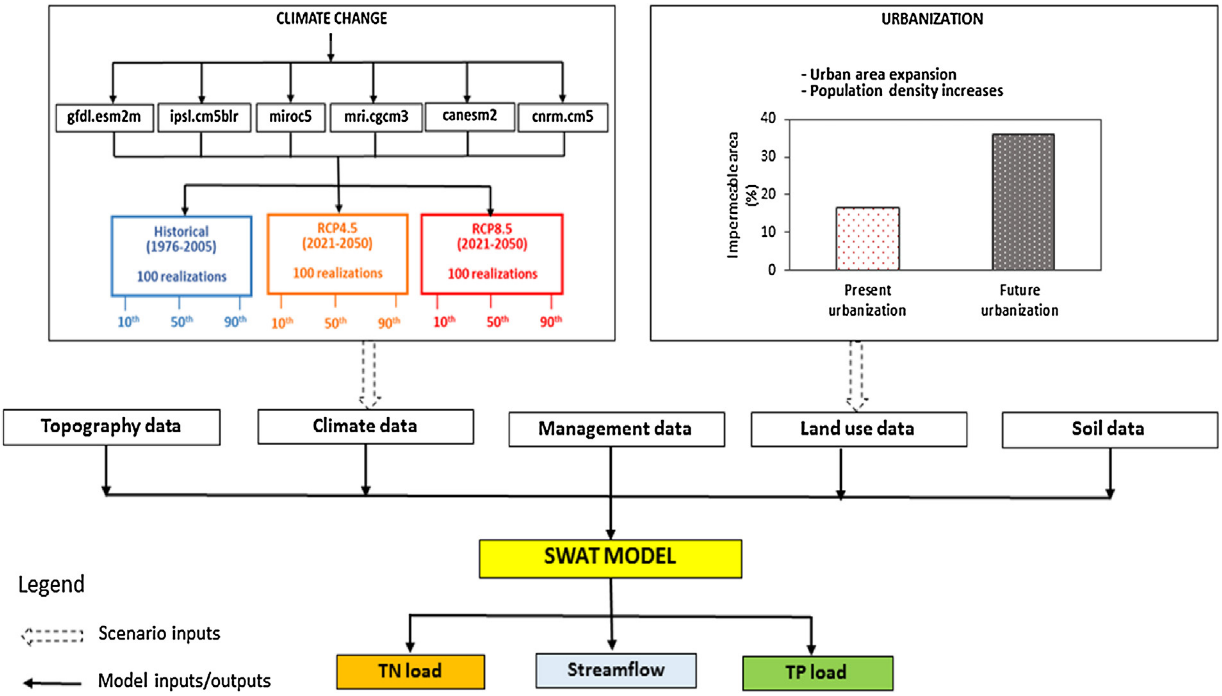

Fig. 2. Conceptual diagram of the study design.

into five main categories: residential (38.6%), commercial (7.6%), institutional (7.4%), grassland (16.5%), and others, including water. The soil database was extracted from the Australian Soil Resource Information System (ASRIS, http://www.asris.csiro.au/mapping/viewer.htm), the historical field data records from the South Australian Drill Core Reference Library, published literature (Shread and Borrman, 1994) as well as expert knowledge. It includes the attributes of eight major soil classes, of which some are reactive clays that are sensitive to fluctuating seasonal conditions, which have caused significant failure to buildings in many urban regions in the study area (Shread and Borrman, 1994). Daily climate data from 2007 to 2015 from five stations were provided by the Scientific Information for Land Owners (SILO) website (https://www.longpaddock.qld.gov.au/silo/ppd/index.php). These include patched point datasets on precipitation, maximum and minimum temperatures, solar radiation, and relative humidity parameters. Daily streamflow and monthly nutrient loads for the entire drainage area, measured at the Holbrooks Road Station (A5040529, see Fig. 1), were downloaded from the Adelaide and Mount Lofty Ranges Natural Resources Management Board (http://amlr.waterdata.com.au/Amlr.aspx).

2.3. Climate data projection

Projected daily climate data for the scenario analysis were extracted from Task 3 of the Goyder Institute Water Research (GIWR) Project (https://data.environment.sa.gov.au/Climate/SA-Climate-Ready). The CMIP5 Global Climate Models (GCMs) were applied, using the Nonhomogeneous Hidden Markov Modelling (NHMM) downscaling technique (e.g. Frost et al., 2011; Charles and Fu, 2015). This method calibrated the daily rainfall at multiple stations and resulted in 100 realisations of projected rainfall, which are the stochastic replicates generated by repeating the NHMM downscaling method 100 times for each combination of GCM/emissions scenarios. For non-rainfall variables, the downscaling was performed using a weather generator, with the projected changes obtained from the GCM grid-scale output and rainfall projected by the NHMM technique. This study uses an ensemble of six GCMs: CanESM2, CNRM-CM5, GFDL-ESM2M, IPSL-CM5B-LR, MIROC5, and MRICGCM3 (Fig. 2). These GCMs were recommended as the best estimations among 15 GCMs available for South Australia, based on their ability to reproduce important drivers such as the Indian Ocean Dipole and the El Nino Southern Oscillation (Cai et al., 2014). The GCM results were evaluated by comparing the historical data with the lower and higher Representative Concentration Pathways (RCPs) 4.5 and 8.5, which are comparable with the intermediate and high emission scenarios in IPCC AR4 (GIWR, 2015). The time scale of 30 years, from 1976 to 2005, was used to show a historic period, while the period from 2021 to 2050 was applied for the RCP 4.5 and RCP 8.5 scenarios in order to model future changes.

2.4. Model calibration and validation

The eco-hydrology model SWAT (ArcSWAT version 2012, revision 637) was used for this study. The model enables continuous-time, semi-distributed simulations for predicting the impacts of climate change and land management practices on water quality, including various species of nitrogen and phosphorous (Neitsch et al., 2011; Arnold et al., 1998). The model sub-divides the catchment into sub-basins and further delineates them into smaller hydrological response units (HRUs), which represent the lumped spatial area, comprising of unique combinations of soil, land use, and slope categories. In this study, this process resulted in the delineation of the catchment into 23 sub-basins and 125 HRUs. The SWAT model incorporates the modified Soil Conservation Service (SCS) Curve Number technique to estimate the streamflow, while the instream processes of the TN and TP loads were estimated using the Enhanced Stream Water Quality Model (QUAL2E) (Winchell et al., 2013). For the potential evapotranspiration (PET) estimation, the Hargreaves method was applied following the experience from previous studies (Nguyen et al., 2017).

For model calibration and validation, auto-calibration was performed using the Sequential Uncertainty Fitting (SUFI2) algorithm (Abbaspour et al., 2004), based on the experience of the previous study by Nguyen et al. (2017). SUFI2 incorporates One-at-a-time and Global sensitivity analyses along with automatic calibration. The Global sensitivity analysis was applied first to define the sensitive parameters. The model was then calibrated consecutively for streamflow, TN and TP variables on a monthly time step. The coefficient of determination (R^2), percent bias (PBIAS), and NS efficiency coefficient were used as statistical criteria for evaluation of the simulated results. The model achieved satisfactory to very good results during the calibration and validation steps for flow, TN, and TP loads, according to Moriasi et al. (2007). More details on results of the parameter sensitivity analysis, model calibration and validation are available in the Supplementary document (Fig. A, Table B).

2.5. Climate and land use scenario analysis

The calibrated model was implemented in this study to address three scenarios: climate change, urbanization, and a combined scenario of climate change and urbanization (Fig. 2).

The climate change scenario was based on the projected climate data of six global climate models (GCM), under two emission scenario RCPs. In addition to the two RCPs, three of the 100 realizations of each of the GCMs were selected for scenario runs. These realizations were selected from the 10th, 50th, and 90th percentiles of the projected annual precipitation of each GCM (see Fig. 2), while data from the same selected realization of precipitation were selected for other climate variables. As a result, a total of 36 climate scenarios (6 climate models, 2 emissions scenarios, and 3 realizations) were created to test the calibrated SWAT model. Other model inputs were fixed during the climate change scenario simulation.

For the urbanization scenario, the study assumes that the urban land budget will not change significantly, i.e. the overall percentage of the developed area remains constant, while the urban population density is expected to triple according to the '30 year Plan for Greater Adelaide' report (DPLG, 2010). This was modelled by preserving the relative percentages of land uses and adjusting the land use classification of residential, which accounts for 38.6% of the total land budget, from low residential into high residential categories. This change resulted in the increase of the fraction of total impervious areas (FIMP) of the residential land use from 0.12 to 0.60 (Neitsch et al., 2011) and the overall increase of catchment impermeable area from all urban lands from 16.7 to 35.2% (see Fig. 2). To conform to the climate scenarios, the baseline and future urbanization scenarios were run with historical climate data from six global climate models, rather than with the climate data of the calibration and validation periods.

The combined scenario of urbanization and climate change was tested by integrating the inputs of both the climate change projections and those of the urbanization scenario. In order to analyze the results, the relative change in percentage between the results of each scenario and those of the baseline scenario were calculated for flow, TN, and TP.

3. Results and discussion

3.1. Patterns of future climate change

The climate data projected by an ensemble of GCMs that are summarized in Table 1 show an overall decrease in the annual precipitation from 3.5 to 6.7%, and an increase in the annual temperature from 1.1 to 1.4 °C, averaged from six GCMs under the RCP 4.5 and 8.5 scenarios, respectively. The high emission scenario, RCP 8.5, resulted

Table 1
Changes in average daily precipitation and temperature under the intermediate RCP 4.5 and high RCP 8.5 scenarios for the projected period from 2021 to 2050.

No.	Climate model	Source	Precipitation change (%)		Temperature change (°C)	
			RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	canesm2	Canada	(−4.70; 1.03)	(−6.61; −1.98)	(1.33; 1.46)	(2.04; 2.11)
2	gfdl.esm2m	USA	(−7.43; −4.49)	(−9.78; −7.27)	(1.16; 1.29)	(1.20; 1.29)
3	cnrm.cm5	France	(−7.03; −6.58)	(−6.20; −4.68)	(1.06; 1.10)	(1.42; 1.52)
4	ipsl.cm5blr	France	(−8.82; −5.09)	(−4.72; −0.97)	(0.73; 1.32)	(0.96;1.30)
5	miroc5	Japan	(−5.08; −2.13)	(−9.09; −4.63)	(1.12; 1.21)	(1.21; 1.40)
6	mri.cgcm3	Japan	(−5.03; −2.90)	(−7.49; −4.67)	(0.65; 0.94)	(0.85; 1.19)
	Average		(−5.37; −3.46)	(−6.72; −4.32)	(1.06; 1.18)	(1.30; 1.43)

Note: Figures in brackets are the 10th and 90th percentile ranges of 100 realizations.

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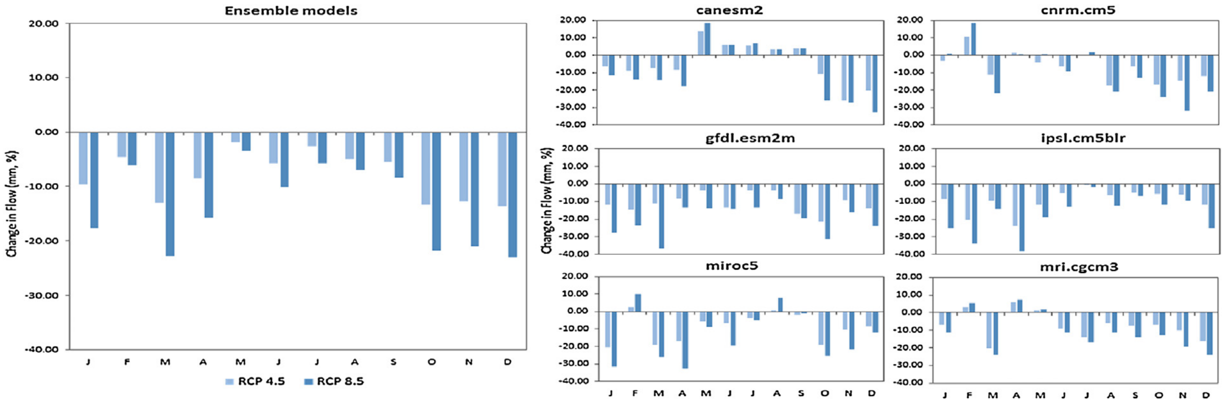

Fig. 3. Relative changes in monthly flow, showing the effects of different climate change projections for the period from 2021 to 2050.

in a greater increase in projected temperature and a greater decline in projected precipitation over the period from 2021 to 2050 (see Table 1). There were variations across the projection ranges for precipitation and temperature changes across the six GCMs. Overall, an increasing trend was observed in all the scenarios regarding temperature, while agreement on the overall trend was lower for precipitation, with one of the six models showing an opposite trend.

3.2. Impacts of climate change on flow and nutrient loads

3.2.1. Impacts on flow

Fig. 3 displays flows simulated by each GCM with two emission scenarios, RCP 4.5 and RCP 8.5, of the ensemble model. The changes in runoff under these climate change scenarios reflected the dominant effect of precipitation in comparison to temperature. Decreases in precipitation resulted in the decrease of the evapotranspiration, which accounted for approximately 61% of water loss from the Urban Torrens catchment, and the decrease in the overall water yield. Meanwhile, a higher air temperature caused a remarkable increase in the PET but did not result in an increase of the evapotranspiration ratio due to the water shortage from precipitation. As a result, the annual flow decreased on average by 8.0% and 13.6% under scenarios RCP 4.5 and RCP 8.5, respectively. This range is comparable with the projections by Shrestha et al. (2017) and Westra et al. (2014), which used the same climate projection input from the SILO source to predict the climate impacts on the flow of a nearby catchment. RCP 8.5 produced a lower flow than RCP 4.5 for all months of the year, according to the output of the ensemble climate model. In particular, the decrease in flow fluctuated from 1.8 to 13.7% and 5.7 to 23.4% under scenarios RCP 4.5 and 8.5. Seasonally, the most extreme declines are observed in spring and summer (Fig. 3, Table 2) which are already dry seasons in this catchment (Rebbeck et al., 2007).

There is a shift in the monthly patterns of the results across different climate models. While the gfdl.esm2m and ipsl.cm5blr models showed consistent agreement with the results of the ensemble modelling, other models indicated a slight increase in monthly runoff, mostly in autumn and winter seasons. In particular, the canesm2 scenario indicated an increase in flow for all the winter months, ranging from 3.4 to 13.8% under RCP 4.5 and 0.5 to 18.4% under the RCP 8.5 scenarios, respectively. This pattern was closely correlated with the relative change in seasonal rainfall, which indicated that rainfall is one of the most important factors affecting the catchment hydrology (Nassif and Wilson, 1975; Martinez-Mena et al., 1998). A comparative analysis among the predicted results pro-

Table 2
Relative changes in seasonal flow, TN, and TP loads under scenarios of climate change and urbanization.

Scenarios	Scenario RCP 4.5				Scenario RCP 8.5			
	Spring (S-O-N)	Summer (D-J-F)	Autumn (M-A-M)	Winter (J-J-A)	Spring (S-O-N)	Summer (D-J-F)	Autumn (M-A-M)	Winter (J-J-A)
Change in flow (%)								
Climate change	−10.55	−9.31	−7.79	−4.43	−17.07	−15.63	−14.02	−7.61
Urbanization	22.64	22.51	31.84	30.42	22.64	22.51	31.84	30.42
Combined scenario	4.67	10.26	23.80	21.90	3.94	8.21	15.89	17.81
Change in TN load (%)								
Climate change	−17.28	−16.78	−14.23	−7.32	−24.51	−26.15	−21.61	−12.61
Urbanization	−24.37	−50.73	18.27	17.91	−24.37	−50.73	18.27	17.91
Combined scenario	−52.17	−65.26	−4.83	14.01	−54.25	−73.70	−12.62	10.31
Change in TP load (%)								
Climate change	−25.31	−25.57	−14.64	−11.39	−36.19	−36.73	−22.54	−20.09
Urbanization	44.33	34.00	47.61	51.47	44.33	34.00	47.61	51.47
Combined scenario	7.20	−2.62	27.62	35.58	4.33	1.19	17.54	24.97

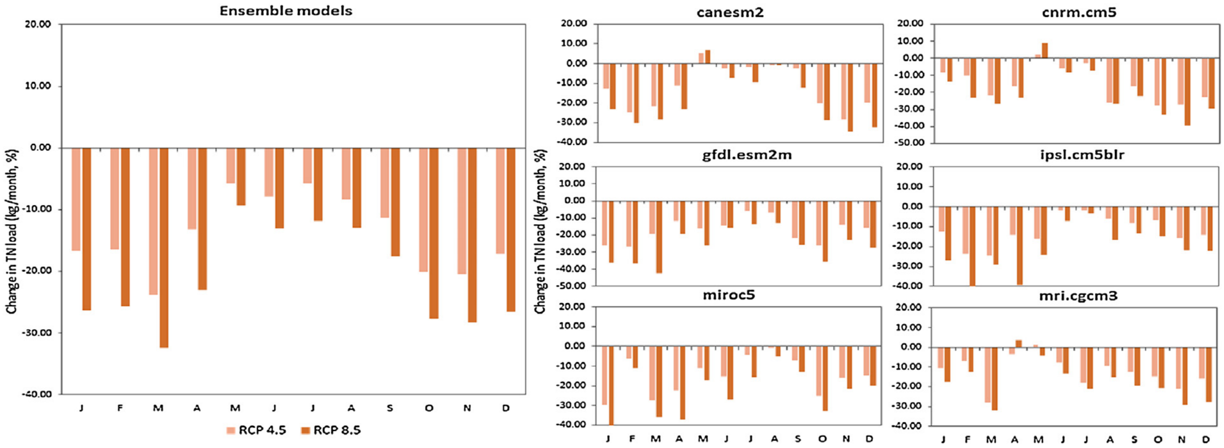

Fig. 4. Relative change of monthly TN deriving from the effects of different climate change projections for the period from 2021 to 2050.

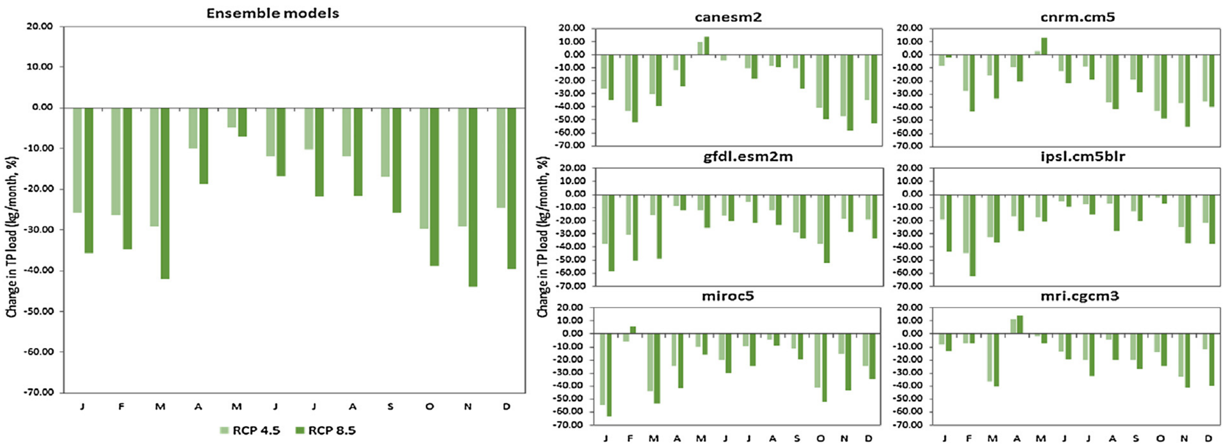

Fig. 5. Relative change of monthly TP deriving from the effects of different climate change projections for the period from 2021 to 2050.

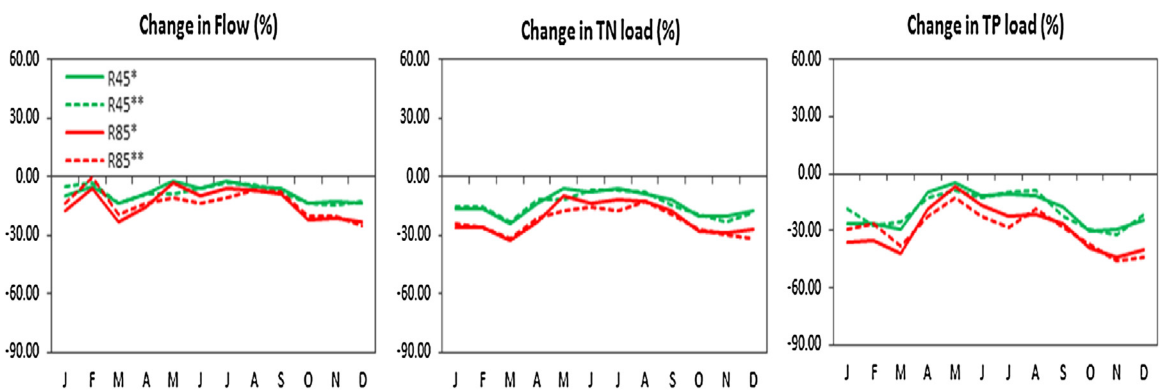

Fig. 6. Deviation of estimated average monthly flow, TN, and TP loads using median versus an ensemble of the 10th, 50th, and 90th percentile realizations of the climate projection data. *Note*: *Using climate data of 10th, 50th, and 90th realizations. **Using the climate data of the median realization solely

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duced by six single GCMs suggested an uncertainty across the different climate projections and that it is important to analyze the ensemble modelling approach in climate studies (e.g. Feyen and Dankers, 2009; Hovenga et al., 2016).

3.2.2. Impacts on nutrient loads

Monthly distributions of TN and TP loads, simulated by six GCMs and an ensemble of GCMs, are presented in Figs. 4 and 5. Flow predictions deriving from the ensemble model suggested an overall decline for both TN and TP over the period of thirty years, and that this would be most notable in the spring and summer months (Figs. 4 and 5, Table 2). Declining TN and TP loads were more pronounced for RCP 8.5, i.e. at 21.2 and 28.9% on an average annual time step. Similar to the ensemble model, the results of the single GCMs showed significant reductions in TN and TP loads when compared with the historical data. The drop in the annual average projected TN and TP loads at the catchment outlet were most significant for the gfdl.esm2m scenario (up to 26.2 and 34%, respectively), while a lower decrease belonged to the canesm2 scenario (up to 18.5 and 29.2%, respectively), following the pattern of flow reductions. The fluctuations in the predicted monthly values of different climate projections were notable, too, with some months of increasing nutrient loads (mostly in the wet periods of autumn and winter).

3.2.3. Uncertainty in climate change projections

The deviation in projected monthly values in comparison with the historical simulated data was remarkable across the different GCMs for climate change scenarios for all three model outputs (flow, TN and TP loads), which confirmed the importance of considering an ensemble approach for the climate impact studies. However, the uncertainty of each GCM projection, which was represented in this study by the simulated results using the median realization versus the combination of 10th, 50th, and 90th realizations of the climate data inputs, was low (Fig. 6). The variance in the projected flow using single and sets of three realizations of climate input data from six GCMs was minor (0.26 and 0.21% for RCP 4.5 and RCP 8.5, respectively). The deviations for the TP load simulations were on average less than 1% for two emission scenarios, and less than 1.5% for the TN load predictions. This suggests that the use of a median realization or a set of realizations from the same climate model may not cause important differences in the climate change projections.

3.3. Impacts of urbanization on flow and nutrient loads

The impacts of future urbanization on the Torrens River catchment were addressed in the present study using the historical climate data of 1976–2005 as a baseline period, rather than the calibrated period of 2011–2013. This study suggests that future urbanization may result in an overall increase of 26.9% in monthly flow, which corresponds to an increase of approximately 20% in the impervious surface of the study area. The discovered streamflow patterns affected by urbanization correspond well with findings from previous studies, such as those by Richards et al. (2008), Qiu and Wang (2014), and Schütte and Schulze (2017). The TP loads followed the same pattern as the streamflow, with a higher load of 44.4% released from the

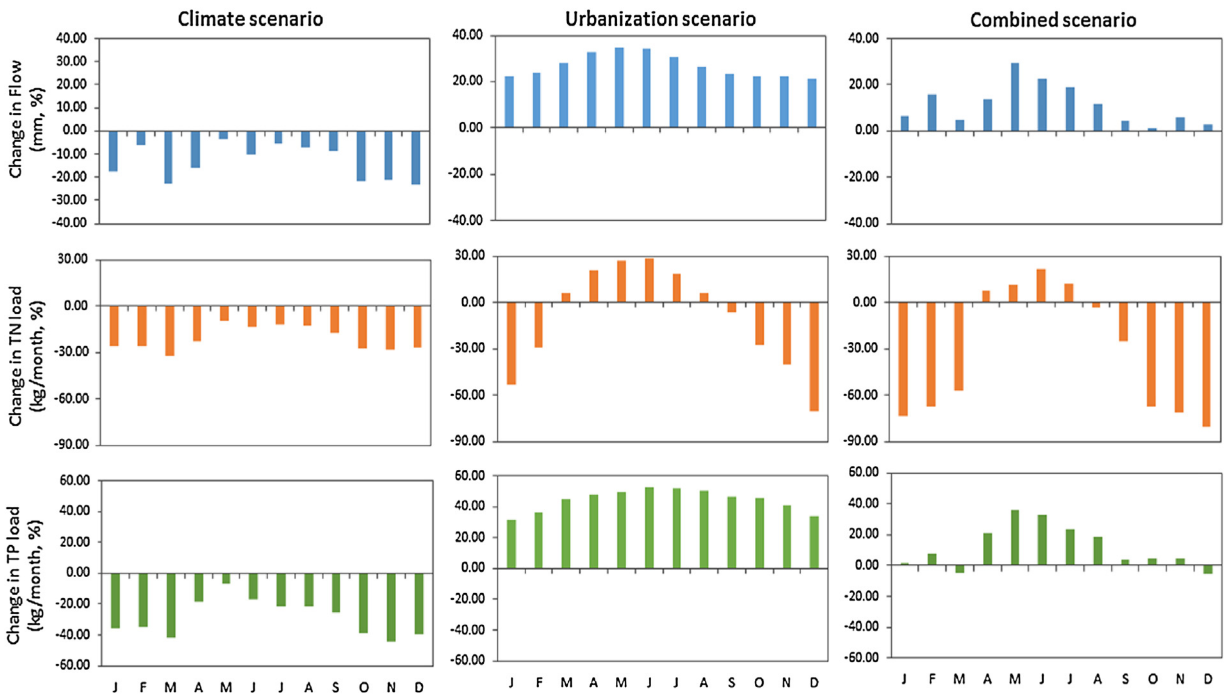

Fig. 7. Relative change of monthly flow, TN, and TP loads due to the effects of climate change, urbanization, and a combined scenario of climate change and urbanization under the high emission scenario RCP 8.5.

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catchment on an annual basis under future urbanization, in comparison with the historical period. The largest increases in the TP load, of 51.5%, occurred during winter due to the increase in precipitation and surface flow, and can be explained by the fact that phosphorus is primarily transported by sediments in the surface streamflow. Increases in streamflow caused an increase in the sediment yield, primarily from soil erosion of permeable grassland areas, and partially from sediment accumulated on the expanded areas of impermeable surface of residential land uses. This corresponded to the increase in annual organic phosphorous and soluble phosphorous in the surface flow at a rate of 9 and 41 g/ha/year, respectively. In the case of the TN load, the model predicted an opposite pattern. The TN decreased annually by 9.7% (Fig. 7) but increased during wet autumn and winter months by 18.3 and 17.9%, respectively (Table 2). The overall decrease in the annual TN load is mostly affected by the loss of sources of nitrogen due to leaching from fertilizer applied on grasslands, when the grasslands were converted to impermeable urban lands, and nitrogen loss from groundwater. Together, the rate of annual nitrogen loss from the two sources was recorded as 20 g/ha/year. During the wet seasons in autumn and winter, however, the increase in both TN and TP loads reflects the fact that a large amount of pollutants in this urban catchment are released to river catchments during intensive rainfall periods (Ilman and Gell, 1998; Clark et al., 2015). Alongside this, it is also important to mention that the sewage system in the study area is separated from the stormwater drainage network, thus, future urbanization will not necessarily drive an increase in waste water releases to the surface flow.

3.4. Combined impacts of climate change and urbanization on flow and nutrient loads

Coupling of future climate change and urbanization scenarios was simulated for each GCM and the results of an ensemble of six GCMs, as shown in Fig. 7. The results of this study showed an offsetting effect from the opposite trends of climate change and urbanization scenario projections on the flow and TP variables, while the trend was further strengthened by the combined scenario for the TN variable due to cumulative effects. This trend is consistent with previous studies on the topic of climate and land use changes (e.g. Teshager et al., 2016; Shrestha et al., 2017; Wang and Kalin, 2018).

The results of this study also suggested that the flow characteristics in the Torrens river catchment is affected by both climate, climate change, land use, and land use change through development policy. In particular, the results of the study showed the dominant effects of the urbanization scenario over the climate change scenario, which agrees with the review by Grimmond (2007). While there was a decrease in average annual flow under the ensemble climate change scenario, the increased area of impervious surfaces contributed to a decrease in water infiltration and caused an increase of 15.6 and 11.5% in annual water yield for the combined scenarios RCP 4.5 and RCP 8.5, respectively (Fig. 7). The variation of TP followed the flow trend as well, with an overall increase of 17.0 and 12.0% in the RCP 4.5 and RCP 8.5 scenarios, respectively. In the case of TN, the decrease in TN loads by 7.3% under the climate change scenario did not affect the overall increasing trend of TN loads by 14.0% for the combined scenario during winter periods, while the decrease of TN loads under sole urbanization and climate change scenarios by 9.7 and 21.2%, respectively (in the case of RCP 8.5) resulted in an overall decrease of 32.6% in the average annual TN loads in the combined scenario. These results suggest that in an already-dry climate, the effects of global climate change are not as serious as the effects of local urbanization. This finding is of particular importance for pollution control and mitigation, considering the increased pattern of both flow and nutrient loads during the winter months from May to July.

4. Conclusions

Impacts of climate change and urbanization on the flow and nutrient loads of the Torrens River catchment have been forecast for the period from 2021 to 2050 by feeding outputs of six GCMs into the SWAT model. The results indicated that:

(1) A future, drier climate may lead to a decline in both flow and nutrient loads, with the most remarkable decrease being projected for the spring and summer seasons under the high emission scenario RCP 8.5. The deviation of the simulation data caused by selecting a median realization or a combination of several realizations of each GCM was not noticeable when compared with the uncertainty in projected results across different GCMs.
(2) Future urbanization may cause higher flow and TP loads, while the TN loads are expected to decrease as a result of the impact of increased impermeable areas on grasslands.
(3) Even though climate change plays an important role in catchment conditions, urbanization is expected to have predominant control over the eco-hydrological state of the Torrens River catchment, in particular during the winter months.

The study currently applies the default configuration of urban.dat in SWAT for the static representation of land use changes. Thus, 'what-if' scenarios on urbanization focus currently at the extremes of possible impacts on the catchment. In order to reveal tipping points in transitional effects of urbanization, future work will apply the concept of dynamic land use changes (e.g. Wagner et al., 2016). Besides, unlike climate change, which cannot be controlled on a local scale, urban development should aim to sustain aquatic habitats. Minimizing the impacts of urbanization on the hydrology and water quality of catchments may mitigate the stresses on the already-degraded condition of aquatic environments.

Conflicts of interest

The authors declare no conflict of interest.

Ethical statement

The research was done according to ethical standards.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecohyd.2018.10.001.

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