Modelling effects of land-use and climate changes on catchment streamflow, sediment and nutrient loads by means of alternative and integrated models

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Abstract

Changes in land use and climate are key pressures affecting catchment ecosystems worldwide. These pressures are particularly severe in highly developed catchments, in which natural processes are greatly disturbed by anthropogenic activities. More catchment models are being developed to support management decisions related to these critical issues. The capability of models, either single or in combinations, to provide reliable and efficient estimations of effects of locally and globally driven stressors on catchments is of particular importance for decision making.

This thesis investigates the capability of modelling tools to address the complex scenarios of management practices, land use and climate change impacts on streamflow and water quality of a suburban catchment in South Australia. The primary modelling tool is based on the eco-hydrological model SWAT (Soil and Water Assessment Tool). However, the broader modelling framework also applies the newly developed catchment model SOURCE and the lake model SALMO in order to enable complex scenario analyses using integrated models. Monitoring data collected over three years at twelve sites along the urban part of the Torrens River catchment improved understanding of the catchment characteristics and the calibration of the models.

Simulation studies by means of the SWAT model suggest that increases in forest plantations will cause a decrease in water yield, while effects of farm dams depend on their purpose rather than on their volumetric capacities. Scenarios of past and future urbanisation have revealed that it is causing significant increases in flow and phosphate loads. A comparative scenario analysis indicated that the stress from future urbanisation is likely to be of greater concern than the projected effects of climate change on catchments with an already dry climate. Integrated catchment-reservoir modelling showed promising results for better understanding of the cascading effects of catchment processes on drinking-water reservoirs. A comparison of simulation results of the SWAT model and the Australian catchment model SOURCE for the same catchment demonstrated that both models produce similar good results for streamflow, and that SWAT provides better understanding of sediment and nutrient processes.

Overall, this thesis offers an improved understanding of catchment processes and responses to natural and anthropogenic stressors in a Mediterranean-climate catchment with mixed land use. The results from this study suggest that decision making about complex catchment issues asks too much of a single model, rather requiring an integrated modelling approach, and that the interpretation of the models' results needs to be portrayed carefully, taking into consideration the models' fit-for-purpose designs.

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List of Abbreviations

ASRIS	Australian Soil Resource Information System
AWBM	Australian Water Balance Model
BFS	Base-flow separation
BMPs	Best management practices
BOM	Bureau of Meteorology
BS	Baseline
CANMX	Maximum canopy storage
CBD	Central Business District
CH_COV1	Channel cover factor
CH_COV1	Channel erodibility factor
CH_K2	Effective hydraulic conductivity in main channel alluvium
CH_N2	Manning's "n" value for the main channel
CN2	Moisture condition II Curve number
DEM	Digital elevation model
DEW	Department for Environment and Water
DEWNR	Department of Environment, Water and Natural Resources
DLCD	Dynamic Land Cover Database
DWC	Dry Weather Concentration
EMC	Event Mean Concentration
EPA	Environmental Protection Administration
ET	Evapotranspiration
FU	Functional unit
GCMs	Global Climate Models
GIS	Geographic Information System
GIWR	Goyder Institute Water Research
GLUE	Generalised Likelihood Uncertainty
HRU	Hydrological response unit

HSPF	Hydrological Simulation Program FORTRAN
INCA	Integrated Nitrogen model for Catchments
IPCC	Intergovernmental Panel on Climate change
MUSLE	Modified Universal Soil Loss Equation
NHMM	Nonhomogeneous Hidden Markov Modelling
NS	Nash-Sutcliffe
NSE	Nash-Sutcliffe efficiency
OAT	One-at-a-time
OF	Objective function
PBIAS	Percent bias
PET	Potential evapotranspiration
PND	Pond
QUAL2E	Enhanced Stream Water Quality Model
R^2	Correlation coefficient
RCPs	Representative Concentration Pathways
RMSE	Root Mean Square Error
SA	South Australia
SALMO	Simulation by an Analytical Lake Model
SAW	SA Water Corporation
SCS	Soil Conservation Service
SILO	Scientific Information for Land Owners
SOL_AWC	Soil available water content
SOL_BD	Soil Moist bulk density
SOL_K	Saturated hydraulic conductivity
SUFI2	Sequential Uncertainty Fitting program
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT Calibration and Uncertainty Procedure
TN	Total Nitrogen

TP	Total Phosphorus
TSS	Total Suspended Solids
U-test	Independent-Samples-Mann-Whitney test
WaterCress	Water - Community Resource Evaluation and Simulation System

Table of Contents

Declaration ii
Abstract iii
Publications arising from this thesis iv
Grants and awards resulting from this thesis v
Acknowledgements vi
List of Abbreviations viii
Table of Contents xi
Chapter 1. Introduction 1
1.1. General Introduction 1
1.2. Literature review 1
1.2.1. Stressors of catchment water quantity and quality: An overview 1
1.2.2. Decision support for managing catchment water quantity and quality by means of models 2
1.2.3. Review of catchment models 3
1.2.4. Applications of catchment models 4
1.2.5. Research gaps and future development of catchment models 5
1.3. Research objectives and significance 7
1.4. Thesis structure 8
References 9
Chapter 2. Effects of Forest Cover and Irrigation Farm Dams on Streamflow in Water-Scarce Catchments in South Australia. A simulation study by means of the model SWAT 15
Chapter 3. Water quality control options in response to catchment urbanisation: A scenario analysis by SWAT 33
Chapter 4. Effects of projected urbanisation and climate change on flow and nutrient loads of a Mediterranean-climate catchment in South Australia 51
Chapter 5. Modelling the impacts of altered management practices and land-use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia 63
Chapter 6. Comparison of alternative models SOURCE and SWAT for predicting catchment streamflow and sediment and nutrient loads under the effect of land-use changes 77
Chapter 7. Discussion, conclusions and future research 92
7.1. Key outcomes and conclusions 92
7.2. Research assumptions and limitations 94
7.3. Future research 95
References 95
Appendix 1. International conference papers 97
Appendix 2. Monitoring results for the Torrens River Catchment, South Australia 100

Chapter 1. Introduction

1.1. General Introduction

Land-use and climate changes have both been recognised as major challenges to catchment water resources and their consequences are still uncertain. There is a growing demand for research tools that quantitatively estimate the combined effects of these pressures on catchment water quantity and quality.

This chapter outlines the motivation for my research on the topic 'the effects of land-use and climate changes on the water quantity and quality of a Mediterranean-climate catchment in South Australia'. It starts by reviewing local and global stressors that cause major problems in catchments worldwide in Section 1.2.1. The chapter continues by addressing catchment models as decision tools to manage these stressors (Section 1.2.2). Sections 1.2.3 and 1.2.4 summarise the currently available models in terms of their structure, complexity and applications. In Section 1.2.5, I summarise gaps to be addressed by future research in the field of catchment modelling. In Section 1.3, I define the objectives and significance of my research project, and outline the structure of the thesis.

1.2. Literature review

1.2.1. Stressors of catchment water quantity and quality: An overview

Land-use and climate changes are two critical factors that may cause significant alterations in water availability and quality in catchments worldwide (e.g. Whitehead et al., 2009; Piao et al., 2007; Wang et al., 2014).

Changes in land use for agriculture and urbanisation are often associated with pollutants being generated (Giri and Qiu, 2016). Urbanisation causes rivers to be regulated and increases runoff and pollutant concentrations (Zang et al., 2012, 2013). An analysis of 106 river catchments worldwide found that the proportion with streamflow being fragmented and disturbed by dams in urbanised regions is projected to increase to 70% by 2050 (Zang et al., 2012). Studies in Australia, the United States and South Africa have shown significant correlations between modified flow regimes and a decline in catchment water quality (Boon and Ravel, 2012). Agricultural practices, on the other hand, increase the amount of fertilisers, pesticides and dairy manure in croplands, and contribute to the pollution of river systems (Fadil et al., 2011). The direct and indirect impacts of these land-use changes eventually result in eutrophication of downstream rivers and lakes (Wang and Kalin, 2018).

Besides land-use change, climate change is increasingly considered as an important factor directly affecting water quantity and quality in river catchments (Fadil et al., 2011). Studies in parts of America, Africa, western Asia, and Australia project that average air temperatures in summer and winter will increase by approximately 1.5°C in the period from 2016 to 2035, while precipitation and runoff will decrease by 10-30% in certain dryland areas (Zhou et al., 2014; IPCC, 2018). The risks associated with extreme climate change events are found to be high, with an extra 1.5-2.0°C increase in average temperature projected, particularly in areas with scarce water resources like Mediterranean-climate zones (Erol and Randhir, 2012; IPCC, 2018). Increases in air temperature are expected to be followed by longer drought periods in catchments around Australia by the 2050s, which will then bring about changes in sediment flux and river morphology, and cause shifts in species ranges and the loss of fragile native ecosystems in north-eastern and south-western Australia (e.g. Barron et al., 2012; Reside et al., 2017). High seasonal variation of runoff in river catchments is another example of negative effects that is linked to climate change. Greater rainfall seasonality in the temperate U.K. has been predicted to result in potentially larger floods and serious economic losses (Jenkins et al., 2015).

While climate change contributes directly to changes in land use and catchment processes, it is also influenced by these processes (Lambin et al., 2003). Therefore, there is a need to quantify the potential combined effects of land-use and climate change stressors for the long-term management of catchments (Boon and Ravel 2012). As a result, studies of the impacts of climate and land-use changes on catchment water quantity and quality are becoming a major research focus in this century (Stonestrom et al., 2009; Wagner et al., 2017).

1.2.2. Decision support for managing catchment water quantity and quality by means of models

Numerous methods are proposed to examine the causes of impairment of catchments under the effects of locally and globally driven stressors, including *catchment models*. Models are increasingly being used to assess and explain various catchment processes for which direct observations are neither available nor timely and economically efficient to monitor (Parajuli, 2009; Baffaut et al., 2014).

Catchment modelling is defined as the process of simplifying a real complex system by representing key physical processes within the river catchment in mathematical terms by using computer algorithms. Key factors that are incorporated in catchment models include climatic conditions, land use/land cover status, hydrologic and soil parameters, and site-specific water quality parameters (Sadeghi and Arnold, 2002). Hydrological sub-models include rainfall, evapotranspiration, interception, depression storage, and generation of surface run-off and subsurface and groundwater flow (Hua Sun, 1998; Wellen et al., 2015). The scale of flow generation varies, depending on catchment vegetation cover, topography and soil attributes

(Raudkivi, 1979). Other model components representing biogeochemical cycles, allowing researchers to simulate nitrogen, sediment, and phosphorus transport, are coupled with the hydrological component (Wellen et al., 2015). The simulation of sediment and nutrient loads enables consideration of the linkage among various pathways through overland runoff and infiltration to groundwater, and takes into account various land-use practices such as manure and fertiliser application, tillage, and land-cover management (Evans et al., 2000; Neitsch et al., 2011).

Catchment modelling allows researchers to integrate all the relevant information. The final model ideally simulates past and present conditions of catchments, and predicts outcomes of future land-use and management scenarios. In this regard, catchment modelling provides a robust approach for evaluating alternative best practices in the field using scenarios. Thus, catchment models have been used extensively in hydrological sciences and are increasingly being applied to support management decisions related to long-term predictions of the effects of land-use and climate changes (e.g. Zoppou, 2001; Rode et al., 2010; Wellen et al., 2015).

1.2.3. Review of catchment models

Since a catchment model can hardly incorporate all the relevant data to simulate every process reasonably well, modelling typically focuses on aspects that are believed to be dominant, while less important variables are omitted or averaged in the model structure (Krysanova et al., 1997). As a result, models with various levels of complexity have been developed worldwide (Rode et al., 2010; Wellen et al., 2015).

Catchment models can be classified based on their spatial, temporal, and structural complexities (Zeckoski et al., 2015). Spatially, a catchment model can extend from *field scale* to *hillslope scale* to *catchment scale*, to cover multiple drainage systems with various types of land use. On a temporal scale, models are designed either for long-term *continuous* or *event-based* simulations to capture runoff and pollutant loads. The structure of catchment models varies from *empirical*, i.e. derived experimentally from observed data, to *process-based*, i.e. based on mathematical equations of physical, chemical or biological processes.

By distinguishing catchment models according to the parameterisation method, they can be classified as *lumped*, *semi-lumped*, or *distributed*. In a lumped model, characteristics of entire catchments are averaged over the simulated area, which simplifies the model input requirements but also limits the model's ability to address internal processes in the catchment such as land-use changes (Zeckoski et al., 2015). In contrast, a fully distributed model splits a catchment into small units with uniform characteristics of soil, land cover, slope, etc. This type of model enables a very detailed representation of the catchment processes, but in most cases it is hard to define the detailed inputs required for the model to simulate complex catchment processes of climate and land-use changes or to extend the application of the model to catchments with limited input availability. It is thus preferred to apply a semi-lumped model, which compromises between the strengths and limitations of the two extremes.

While models vary greatly in their structural designs and complexities, a *best practice assessment* procedure is being applied more and more commonly in catchment modelling in order to reduce the uncertainty in the models' results. This procedure involves calibration, validation, sensitivity and uncertainty analysis (Wellen et al., 2015). *Sensitivity analysis* gives a sense of accuracy and precision requirements by pin-pointing parameters, and defines inputs that exert a strong influence on the models' outputs. *Calibration and validation*, on the other hand, identify simulation outputs that match best with observed data (Saha et al., 2014). *Uncertainty analysis* estimates the degree to which a simulated value departs from the true observed value, by quantifying the sources of model uncertainty from model inputs, structures, parameters, and responses. In this way, best practices help to control the modelling process ,pre effectively and minimise common issues in hydrology and water quality models such as *equifinality* or *over-parameterisation* of certain parameters in the model.

1.2.4. Applications of catchment models

Catchment models are typically used for estimating point-source and non-point-source inputs of pollutants to receiving waters as well as predicting the effects of land-use and climate changes (Rode et al., 2010; Wellen et al., 2015).

Numerous catchment models are available to simulate streamflow and sediment-transport and nutrient-transport processes with diverse application purposes. For stream-flow estimation, the DRAINMOD model focuses on subsurface flow representation, and the MIKE SHE model includes specific storage for groundwater flow (Jaber and Shukla, 2012), while the percolation process is approximated by Darcy's law in the SWAT, CREAMS, APEX WARMF and SWIM3 models (Huth et al., 2012). The Integrated Nitrogen model for Catchments, INCA, (Whitehead et al., 2002) addresses the issue of diffuse nitrogen emissions, while the Hydrological Simulation Program Fortran HSPF (Brun and Band, 2000) focuses on in-stream processes of nitrogen, and the HBV-NP (Arheimer and Brandt, 1998) simulates sediment and nutrient transformation in large-scale catchments.

Globally, the SWAT model is being applied more commonly than other catchment models, since it is applicable to catchments of varying scales and climate conditions (Gassman et al., 2007; Neitsch et al., 2011). This model is classified as medium complexity and satisfies the requirements for scientifically sound studies by including model calibration and uncertainty analysis (Wellen et al., 2015). Gassman et al. (2007) thoroughly reviewed 220 peer-reviewed articles on catchment models that revealed the distinct advantages of the SWAT model. Similar conclusions on the robustness of SWAT, compared with other catchment models, in predicting nutrient losses are found in Douglas-Mankin et al. (2010), Tuppad et al. (2011), and Krysanova and Srinivasan (2015). Typical examples of applications of SWAT are found in Western Europe, China, India, and South Asia (Johanson, 2014; Wellen et al., 2015). In the U.S.A., SWAT is used to determine the Total Daily Maximum Load (TDML) for river basins (Gassman et al., 2007). The development of the European Water Framework Directive spurred the need to use SWAT as a tool for integrative catchment management (Arnold and Fohrer, 2005).

Catchment models using SWAT for sediment and nutrient analysis are well developed and studied in temperate, warm, and humid areas, while applications in arid and water-scarce climate regions are not yet as common (Wellen et al., 2015). In Australia, most SWAT studies have focussed on non-point sources in agricultural areas, and there is little published work on urban systems (Zhang et al., 2012; Saha et al., 2014). On the other hand, a growing number of hydrological studies have used the newly developed SOURCE and SOURCE-IMS (Dynamic SedNet Source Catchments) models, which ranked highest among 21 reviewed models in Australia because of their plug-in flexibility for integrating various functional models, and their performance under conditions of highly variable climates and flows of Australian catchments (Mannik et al., 2010).

1.2.5. Research gaps and future development of catchment models

This review of catchment model applications shows remarkable development in this field. However, because of the complex nature of the issues in catchment modelling, there are numerous unresolved questions that yet to be resolved. I have identified three research gaps to be addressed by this thesis:

a) Studies of land-use and climate-change impacts

Both land-use and climate changes greatly influence catchment hydrology and water conditions. However, effects of land-use change on climate-change phenomena and vice versa, and the consequences of these interactions for catchments, are uncertain in many regions in the world. For example, Kim et al. (2013) suggested that the effects of climate change on catchment streamflow will be more profound than those of land-use and land-cover changes. Mehdi et al. (2015) pointed out that catchment water quality will seriously deteriorate in the future under the effects of climate change, and that impacts on total nitrogen and phosphorus will be amplified when land-use changes occur simultaneously. In a case study of a Canadian catchment, El-khoury et al. (2015) suggested that changes in streamflow will be mainly driven by climate change, while land-use changes were projected to cause more effects on the catchment’s nitrate levels. A study by Shrestha et al. (2017) indicated that seasonal effects might be more serious during summer because of flow decreases and nutrient enrichment. Since these studies have pointed out that responses of catchments in different geographic locations to land-use and climate changes might be different, the relative impacts of both pressures modelled simultaneously are of great interest to catchment managers worldwide. Interest is particularly high for case studies in Australia, because of its already extreme climate conditions and the lack of catchment modelling tools for water quality estimation and prediction.

b) Studies on integrated catchment and reservoir models

An increasing number of man-made lakes and wetlands necessitates incorporation of reservoirs as sub-models of catchment models (Arnold et al., 1998; Zhang et al., 2012), which is supported by SWAT. In efforts to integrate reservoirs in SWAT for purposes such as simulating streamflow (Mishra et al., 2007) and improving management practices for reservoirs (White et al., 2010), the results did not properly simulate water deterioration under complex land-use and climate change scenarios (Gassman et al., 2007). It has been concluded that none of the four methods available in SWAT are suitable for application to reservoir-dense basins with complicated management systems and insufficient amounts of data (e.g. Zang et al., 2013; Arias et al., 2014). Furthermore, estimates of the impacts of climate change and land-use change on pollutant release and accumulation in catchments have shown high uncertainty due to the naturally extreme climatic variability that could cause different responses in flow and nutrient dynamics, while the responses of reservoirs are often not straightforward (Whitehead et al., 2009; Jeppesen et al., 2005). Analyzing complex scenarios of cumulative effects of climate and land-use changes on catchment and reservoir systems thus exceeds the scope of a single specific model.

As a solution, some studies have suggested the integration of the SWAT with other models. In these cases, SWAT is applied for flow and water quality variable simulations only, and the outputs from SWAT serve as inputs for other models. For instance, coupling SWAT with a simple regression model that inter-correlates the water level, water storage and water discharge enhanced the performance of reservoir modelling (Zang et al., 2013). Applying ensembles of catchment and reservoir models incorporates key processes in both catchments and reservoirs, reducing uncertainty in predictions of complex scenarios of land use and climate changes.

c) Comparative studies of alternative catchment models

While the number of catchment models is increasing, the process of selecting models that best suit the purpose of decision making needs to be supported accordingly. Some studies have selected models on the basis of accuracy in estimating pollutant loads as compared to observed data (e.g. Liu et al., 2015; Krysanova and Srinivasan, 2015). However, the credibility of certain models in relation to the circumstances of model application is not yet addressed well in the literature.

In the context of Australian catchments, there is great interest in applying the SWAT model as either an alternative or as a complementary tool to the SOURCE model. Both SOURCE and SWAT are time-continuous, spatially distributed, and process-based models that use digital elevation models, land-use maps and climate data to extract spatial information for creating sub-basin units. Both models are used to perform flow, nutrient and sediment simulations and provide best management practice under land-use and climate-change conditions. However, SWAT consists of a unique set of built-in sub-models while SOURCE needs various plug-in extensions that work outside the model platform and make the model complicated to handle. In addition, SWAT has been successfully adapted to conditions across the globe and an online database provides updates on successful SWAT applications worldwide, including in Australia (Saha et al., 2014; Krisanova and Srinivasan, 2015), while SOURCE's capacity to estimate water quality parameters is still questionable. Some successful SWAT studies have been reported for Australian catchments (Wilkinson et al., 2014; Mannik et al., 2010; Hughes and Croke, 2011).

1.3. Research objectives and significance

This thesis addresses the effects of land-use and climate changes on the suburban Mediterranean-climate River Torrens catchment in South Australia by applying the SWAT, SOURCE, and SALMO modelling tools with a focus on the following research questions:

(1) How do farm dams and reafforestation affect catchment hydrology as modelled by SWAT?

(2) How does urbanization affect catchment streamflow and nutrient loads, and what are the potential mitigation solutions suggested by SWAT?

(3) What are the single and combined effects of future urbanization and climate change on water quantity and quality in a Mediterranean-climate catchment analyzed by SWAT?

(4) What is the impact of changed management practices, land uses and climate in a Mediterranean-climate catchment on a downstream reservoir, as analyzed by the model ensemble SWAT- SALMO?

(5) How do the simulation results for catchment streamflow and sediment and nutrient loads before and after land-use changes compare between the alternative models SWAT and SOURCE?

Research questions (1) to (3) were related to improving understanding and decision support for catchment management at a local scale regarding farm dams and forestry, at a catchment scale regarding urbanisation, and at a global scale regarding climate change. Research question (4) aimed to establish one of the first studies on integrated catchment-to-reservoir modelling to reveal the combined impacts of catchment management practices and land-use and climate changes on a downstream drinking-water reservoir.

Research question (5) aimed to understand the effects of different structures of process-based catchment models on their credibility for complex scenario analyses by comparing the SWAT and SOURCE models.

The expected outcomes from this research include a well-calibrated set of models that synthesise long-term meteorological, hydrological, and water-quality data for decision making and a better understanding of catchment processes, and identify spatial and temporal hotspots of water pollution within the Torrens catchment. The results of my research are presented as a thesis by publication comprising five peer-reviewed publications in international journals and three conference papers.

1.4. Thesis structure

This thesis consists of seven chapters. The first chapter presents a general introduction and review of the overall research topic and defines research objectives, significance, and the structure of the thesis. Chapters 2, 3, 4, 5 are presented as published papers and Chapters 6 is a submitted manuscript in international peer-reviewed journals.

Chapter 2 presents a case study of an application of the SWAT model to simulate the hydrology of a Mediterranean-climate catchment and considers the effects on developing farm dams and forestry.

Chapter 3 extends the SWAT model to simulate not only hydrology but also nutrient loads under the effect of the most common land-use change, urbanisation, and suggests potential mitigation solutions by means of the best management practices (BMPs) tool available in SWAT.

Chapter 4 further extends the research in chapter 3 by considering the single and combined effects of both urbanisation and climate changes on catchment streamflow and nutrients in a heavily urbanised catchment.

Chapter 5 investigates how a combination of a catchment water quantity and quality model (SWAT) and a reservoir model (SALMO) influence the prediction of multiple environmental stressors.

A comparative study of the two process-based catchment models SWAT and SOURCE, with regard to catchment streamflow and nutrient and sediment loads under the effects of land-use changes, is presented in Chapter 6.

The final chapter 7 summarises the key findings, limitations and broader implications of the research and makes recommendations for further research in the field.

Additional results are incorporated as supplementary documents in the appendices, which include: (1) three abstracts of papers presented at international conferences and (2) summaries of field and laboratory data collected from multiple stream sites during 30 field trips in terms of streamflow velocity and catchment water quality.

References

- Arheimer, B; Brandt, M. Modelling nitrogen transport and retention in the catchments of southern Sweden. *Ambio* **1998**, *27(6),* 471-480.
- Arias, M.E.; Piman, T.; Lauri, H.; Cochrane, T.A.; Kummu, M. Dams on Mekong tributaries as significant contributions of hydrological alterations to the Tonle Sap Floodplain in Cambodia. *Hydrol Earth Sys Sci* **2014***, 18,* 5303-5315, DOI: 10.5194/hess-18-5303-2014.
- Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R Large area hydrologic modelling and assessment part I: model development. *J Am Water Resour Assoc* **1998***, 34(1),* 73-89, DOI: 10.1111/j.1752-1688.1998.tb05961.x.
- Arnold, J.G.; Fohrer, N. SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrol Process* **2005**, 19(3), 563-572, DOI: 10.1002/hyp.5611.
- Baffaut, C.; Dabney, S.M.; Smolen, M.D.; Youssef, M.A.; Bonta, J.V.; Chu, M.L.; Guzman, J.A.; Shedekar, V.S.; Jha, M.K.; Arnold, J.G. Hydrologic and water quality modeling: Spatial and temporal considerations. *T ASABE* **2014**, *58(6),* 1661-1680, DOI: 10.13031/2013.42256.
- Barron, O.; Silberstein, R.; Ali, R.; Donohue, R.; McFarlane, D.J.; Hodgson, G.; Smart, N.; Donn, M. Climate change effects on water-dependent ecosystems in south-western Australia. *J Hydrol* **2012**, *475*, 473-487, DOI: 10.1016/j.jhydrol.2012.02.028.
- Brun, S.E.; Band, L.E. Simulating runoff behavior in an urbanizing watershed. *Comput Environ Urban Syst* **2000**, *24*, 5–22, DOI: 10.1016/S0198-9715(99)00040-X.
- Boon, P.J.; Ravel, P.J. (Eds) River Conservation and Management. *John Wiley* **2012**, Chichester, pp.428.
- Douglas-Mankin, K.R.; Srinivasan, R.; Arnold, J.G. Soil and water assessment tool (SWAT) model: current developments and applications. *Trans ASAE* **2010**, *53*, 1423–1431, DOI: 10.13031/2013.34915.

- 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 Manage* **2015**, *15,* 76-86, DOI: 10.1016/j.jenvman.2014.12.012.
- Erol, A.; Randhir, T.O. Climate change impacts on the ecohydrology of Mediterranean watersheds. *Clim Change* **2012**, *114(2),* 319-341, DOI: 10.1007/s10584-012-0406-8.
- 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**; 33–67, ISBN-10: 0891181431.
- Fadil, A.; Rhinane, H.; Kaoukaya, K.; Kharchaf, K.; AlamiBachir, O. Hydrologic modelling of the Bouregreg watershed (Morocco) using GIS and SWAT model. *Journal of Geographic Information System* **2011**, *3(4),* 279-289, DOI: 0.1061/ (ASCE) 1084-0699(2002)7:4(270).
- 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(4),* 1211–1250, ISSN 0001-2351.
- Giri, S.; Qiu, Z. Understanding the relationship of land uses and water quality in Twenty First Century: A review. *J Environ Manage* **2016**, *173,* 41-48, DOI: 10.1016/j.jenvman.2016.02.029.
- Hua, S. Digital terrain modelling of catchment erosion and sedimentation. *Thesis (Ph.D.)*, University of Adelaide, Department of Civil and Environmental Engineering, **1998**.
- Hughes, A.O.; Croke, J.C. Validation of a spatially distributed erosion and sediment yieldmodel (SedNet) with empirically derived data from a catchment adjacent to the Great Barrier Reef Lagoon. *Marine Freshwater Resources* **2011**, *62(8),* 962-973, DOI: 10.1071/MF11030.
- Huth, N. I.; Bristow, K. L.; Verburg, K. SWIM3: Model use, calibration, and validation. *Trans ASABE* **2012**, *55(4),* 1303-1313, DOI:10.13031/2013.42243.
- 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* **1998**, 10-53.
- IPCC. Global Warming of 1.5ºC. Intergovernmental Panel on Climate change. Special Report, 2018. https://report.ipcc.ch/sr15/.
- Jaber, F. H.; Shukla, S. MIKE-SHE: Model use, calibration, and validation. *Trans ASABE* **2012**, *55(4),* 1479-1489, DOI: 10.13031/2013.42255.

- Jenkins, K.; Hall, J.; Surminski, S.; Crick, F. London Case Study: Flood risk and climate change implications for MSPs. ENHANCE deliverable 7.3: Risk scenarios and analysis, **2015**.
- Jeppesen, E.; Sondergaard, M.; Jensen, J.P.; Havens, K.E.; Anneville, O.; Carvalho, L.; Coveney, M.F.; Deneke, R.; Dokulil, M.T.; Foy, B.; Gerdeaux, D.; Hampton, S.E.; Hilt, S.; Kangur, K.; Kohler, J.; Lammens, E.H.H.R.; Lauridsen, T.L.; Manca, M.; Miracle, M.R.; Moss, B.; Noges, P.; Persson, G.; Phillips, G.; Portielje, R.; Romo, S.; Schelske, C.L.; Straile, D.; Tatrai, I.; Willen, E.; Winder, M. Lake responses to reduced nutrient loading and analysis of contemporary long-term data from 35 case studies. *Freshw Biol* **2005**, *50*, 1747-1771, DOI: 10.1111/j.
- Johansson, V. Modelling fate and transport of *Escherichia coli* and *Cryptosporidium* spp. using Soil and Water Assessment Tool within Staket drainage basin. Chalmers University of Technology. Master thesis, *University of Gothenburg* **2014**, pp. 64.
- Kim, J.; Choi, J.; Choi, C.; Park, S. Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River Basin, Korea. *Sci Total Environ* **2013**, *452*, 181-195, DOI: 10.1016/j.scitotenv.2013.02.005.
- Krysanova, V.; Srinivasan, R. Assessment of climate and land use change impacts with SWAT. *Reg Environ Change* **2015**, *15*, 431- 434, DOI: 10.1007/s10113-014-0742-5.
- Krysanova, V.; Muller-wohfeil, D.I.; Becker, A. Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. *Ecol Model* **1997**, *106*, 261-289, DOI: 10.1016/S0304-3800(97)00204-4.
- Lambin, E.F.; Geist, H.J.; Lepers, E. Dynamics of land-use and land-cover change in tropical regions. *Annu Rev Environ Resour* **2003**, *28*, 205-241, DOI: 10.1146/annurev.energy.28.050302.105459.
- Liu, M.; Chen, X.; Yao, H.; Chen, Y. A coupled modelling approach to evaluate nitrogen retention within the Shanmei Reservoir watershed, China. *Estuar Coast Shelf Sci* **2015**, *166*, 189-198, DOI: 10.1016/j.ecss.2015.06.008.
- Mannik, R.; Varley, I.; Holland, G.; Jordan, P.; Bartley, R.; Dilks, D.; Dettrick, D. Development of Water quality modelling framework for the Murray Darling Basing phase 1 – scoping study. Project report, Final report EN02950, 2010, http://www.mdba.gov.au/kid/files/1710-Development-WQ-framework-report.pdf.
- Mehdi, B.; Lehner, B.; Gombault, C.; Michaud, A.; Beaudin, I.; Sottile, M.F.; Blondlot, A. Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. *Agric Ecosyst Environ* **2015**, *213*, 47-60, DOI: 10.1016/j.agee.2015.07.019.

- Mishra, S.; Groebrich, J.; Gassman, P.W. Evaluation of the SWAT model for assessing sediment control structures in a small watershed in India. *Trans ASABE* **2007**, *50(2),* 469-478, DOI: 10.13031/2013.22637.
- Neitsch, S.L.; Arnold, J.G.; Kinir, J.R.; Williams, J.R. Soil and Water Assessment Tool: Theoretical Documentation 2009. *Texas Water Resources Institute-Texas A&M University, College Station (Technical Report No. 406 edn),* **2011**.
- Parajuli, P.B.; Mankin, K.R.; Barnes, P.L. Source specific fecal bacteria modelling using Soil and Water assessment tool model. *Bioresour Technol* **2009**, *100 (2)*, 953-963, DOI: 10.1016/j.biortech.2008.06.045.
- Piao, S.; Friedlingstein, P.; Ciais, P.; de Noblet-Ducoudré, N.; Labat, D.; Zaehle, S. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *P Natl Acad Sci* **2007**, *104,* 15242 - 15247.
- Raudkivi A.J. Hydrology – An Advanced Introduction to Hydrological Processes and Modelling. *Pergamon Press* **1979**, pp. 492, DOI: 10.1016/C2013-0-03167-2.
- Reside, A.E.; Van Der Wal, J.; Moran, C. Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. *Biol Cons* **2017**, *207,* 9 - 16, DOI: 10.1016/j.biocon.2017.01.004.
- Rode, M.; Arhonditsis, G.; Balin, D.; Kebede, T.; Krysanova, V.; van Griensven, A.; van der Zee, S.E. New challenges in integrated water quality modelling. *Hydrol Process* **2010**, *24*, 3447-3461, DOI: 10.1002/hyp.7766.
- Sadeghi, A; Arnold, J.G. A SWAT/microbial sub-model for predicting pathogen loadings in surface and groundwater at watershed and basin scales. In: Total Maximum Daily Load (TMDL) Environmental Regulations, *Proceedings of the Conference*, Fort Worth, TX, USA, **2002**, March 11–13, 56–63, DOI: 10.13031/2013.7529.
- Saha, P.P.; Zeleke, K.; Hafeez, M. Streamflow modelling in a fluctuant climate using SWAT: Yass River catchment in south eastern Australia. *Environ Earth Sci* **2014**, *71*, 5241-5254, DOI: 10.1007/s12665-013-2926-6.
- Shrestha, M.K.; Recknagel, F.; Frizenschaf, J.; Meyer, W. Future climate and land uses effects on flow and nutrient loads of a Mediterranean catchment in South Australia. *Sci Total Environ* **2017**, *590-591,* 186-193, DOI: 10.1016/j.scitotenv.2017.02.197.
- Stonestrom, D.A.; Scanlon, B.R.; Zhang, L. Introduction to special section on impacts of land use change on water resources. *Water Resour Res* **2009**, *45,* W00A00. DOI: 10.1029/2009WR007937.

- Tuppad, P.; Douglas-Mankin, K.R.; Lee, T.; Srinivasan, R.; Arnold, J.G. Soil and water assessment tool (SWAT) hydrologic/water quality model: extended capability and wider adoption. *Trans ASABE* **2011**, *54(5),* 1677-1684, DOI: 10.13031/2013.39856.
- Wagner, P.D.; Bhallamudi, S.M.; Narasimhan; B., Kumar, S.; Fohrer, N.; Fiener, P. Comparing the effects of dynamic versus static representations of land use change in hydrologic impact assessments. *Environ Model Softw* **2017**, 1-9. DOI: 10.1016/j.envsoft.2017.06.023.
- 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, DOI: 10.1016/j.jes.2016.11.021.
- Wang, R.; Kalin, L.; Kuang, W.; Tian, H. Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama, *Hydrol Process* **2014**, *28,* 5530 - 5546, DOI: 10.1002/hyp.10057.
- Wellen, C.; Kamran-Disfani, A.R.; Arhonditsis, G.B. Evaluation of the Current State of Distributed Watershed Nutrient Water Quality modelling. *Environ Sci Technol* **2015**, *49,* 3278-3290, DOI: 10.1021/es5049557.
- 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, DOI: 10.1080/07438141.2010.495315.
- 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(3),* 455–466, DOI: 10.5194/hess-6-455-2002.
- Whitehead, P.G.; Wilby, R.L.; Battarbee, R.W.; Kernan, M.; Wade, A.J. A review of the potential impacts of climate change on surface water quality. *Hydrol Sci J* **2009**, *54 (1),* 101-123, DOI: 10.1623/hysj.54.1.101.
- Wilkinson, S.N.; Dougall, C.; Kinsey-Henderson, A.E.; Searle, R.D.; Bartley, R Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. *Sci Total Environ* **2014**, *468-469,* 1210-1224, DOI: 10.1016/j.scitotenv.2013.07.049.
- Zeckoski, R.W.; Smolen, M.D.; Moriasi, D.N.; Frankenberger, J.R.; Feyereisen, G.W. Hydrologic and water quality terminology as applied to modelling. *Trans ASABE* **2015**, *58(6),* 1619-1635, DOI 10.13031/trans.58.10713.

- Zhang, Y.; Arthington, A.H.; Bunn, S.E.; Mackay, S.; Xia, J.; Kennard, M. Classification of flow regimes for environmental flow assessment in regulated rivers: The Huai River basin, China. *River Res Appl* **2012**, *28*, 989- 1005, DOI: 10.1002/rra.1483.
- 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, DOI: 10.1007/s00477-011-0546-9.
- Zhou, J.; Liu, Y.; Huaicheng, G.; He, D. Combining the SWAT model with sequential uncertainty fitting algorithm for streamflow prediction and uncertainty analysis for the Lake Dianchi Basin, China. *Hydrol Process* **2014**, *28*, 521-533, DOI: 10.1002/hyp.9605.
- Zoppou, C. Review of urban storm water models. *Environ Model Softw* **2001**, *16*, 195–231, DOI: 10.1016/S1364-8152(00)00084-0.

Chapter 2. Effects of Forest Cover and Irrigation Farm Dams on Streamflow in Water-Scarce Catchments in South Australia. A simulation study by means of the model SWAT

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Contribution to the Paper	Reviewed the literature. Prepared input and output data of the manuscript. Wrote the manuscript. Acted as the first and corresponding author I hereby certify that the statement of the contribution is accurate.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Contributed to ideas and helped to review the final manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14/12/2018

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Article

Analysing the Effects of Forest Cover and Irrigation Farm Dams on Streamflows of Water-Scarce Catchments in South Australia through the SWAT Model

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Abstract: To assist water resource managers with future land use planning efforts, the eco-hydrological model Soil and Water Assessment Tool (SWAT) was applied to three catchments in South Australia that experience extreme low flow conditions. Particular land uses and management issues of interest included forest covers, known to affect water yields, and farm dams, known to intercept and change the hydrological dynamics in a catchment. The study achieved a satisfactory daily calibration when irrigation farm dams were incorporated in the model. For the catchment dominated by extreme low flows, a better daily simulation across a range of qualitative and quantitative metrics was gained using the base-flow static threshold optimization technique. Scenario analysis on effects of forest cover indicated an increase of surface flow and a reduction of base-flow when native eucalyptus lands were replaced by pastures and vice versa. A decreasing trend was observed for the overall water yield of catchments with more forest plantation due to the higher evapotranspiration (ET) rate and the decline in surface flow. With regards to effects of irrigation farm dams, assessment on a daily time step suggested that a significant volume of water is stored in these systems with the water loss rate highest in June and July. On an annual basis, the model indicated that approximately 13.1% to 22.0% of water has been captured by farm dams for irrigation. However, the scenario analysis revealed that the purposes of use of farm dams rather than their volumetric capacities in the catchment determined the magnitude of effects on streamflows. Water extracted from farm dams for irrigation of orchards and vineyards are more likely to diminish streamflows than other land uses. Outputs from this study suggest that the water use restrictions from farm dams during recent drought periods were an effective tool to minimize impacts on streamflows.

Keywords: River Torrens; water-scarce catchment; SWAT; irrigation farm dams; eucalyptus; scenario analysis; drought

1. Introduction

Forecasting of streamflow provides critical information to water resource managers, local water supply authorities, and other stakeholders for adaptive management of catchments. However, streamflow modelling can be extremely challenging in catchments with semi-arid climates [1,2]. In these catchments, the amount of rainfall contribution to flows is generally low and is off-set by evapotranspiration [3,4]. Significant streamflows are usually restricted to winter months when rainfall volumes exceed evaporation [4].

Streamflows in South Australia experienced severe drought conditions in the period from 1998 to 2008 [5,6]. The consequent very low flows can seriously affect agricultural yield and the biodiversity of the system [7–9]. In order to protect water resources, extraction restrictions were placed on irrigation from storage water bodies, including farm dams during that time [5,10,11]. Farm dams operate as a critical component for dryland agriculture used to capture freshwater during rainy seasons in order to supply important portion of water need for irrigation [11,12]. Such restrictions on irrigation farm dams can increase the risk to the local economy as irrigated production is generally reduced and more resources are needed to carefully manage more limited water supplies [13,14]. In addition, natural catchments have a growing demand for development that further challenges the task of sustaining the quality of the water within a catchment.

To address these commonly occurring issues, some modelling tools such as Water—Community Resource Evaluation and Simulation System (WaterCress), Australian Water Balance Model (AWBM), or Source model have been developed [15–17]. Given the complexity of processes in catchments, there remains major concern as to the applicability of these lumped to semi-distributed models with various degrees of simplification and conceptualization of physical processes [18]. Another issue is the uncertainty associated with the input data required for modelling and the modelling processes that are not covered in these models. The challenge for local catchment managers is thus to identify a fit-for-purpose, reasonably accurate forecast tool given complex biophysical systems in a catchment, overlaid by highly variable climate scenarios, while being fully aware of data availability and the inherent uncertainties of the analysis methods.

SWAT [19] is a physically based semi-distributed model that takes spatial variations of climate, topography, land uses, and soils into account in model parameters. The model was proven as suitable for long-term analysis of hydrological processes [20–23]. Several studies of SWAT have demonstrated satisfying results when adapted to catchments with distinct climate and various geographic conditions [20,22,23]. This includes case studies of dry and variable climates [24]. Successful simulation of streamflow was provided for 29 major rivers across Europe with a broad range of semi-arid, Mediterranean, continental, oceanic, or Tundra climate [23]. Successful applications were also reported for the regions of arid climate across the U.S. [18] and Africa [25]. In the case of the driest inhabited continent of Australia [2], studies of hydrological modelling by SWAT are concentrated more in the southeastern part of the country [24] with Shrestha et al. [6] being the only known case study for South Australia.

In terms of calibration and validation of the SWAT models, there is no single criteria favoured for judging the model performance [21,22]. Most published SWAT applications that focus on hydrology use both graphical and statistical criteria [19,22]. Nash-Sutcliffe (NS) statistics have become increasingly used for SWAT model optimization compared to other metrics [20,22,26]. Some studies with a focus on dry time series using NS as objective functions showed both good and poor results [2,4,27–30]. A study by Saha et al. [2] achieved a satisfactory solution of NS statistical threshold at a monthly time step, but the highest value at a daily time step was 0.124 which is far below the satisfactory threshold. Study of Brown et al. [4] reached high daily NS during the calibration and validation period but failed during the period of persistent and severe drought. A significant improvement of daily NS was suggested by considering seasonal variability during model calibration [28]. Similar good results were reported when calibrating streamflow under wet and dry seasons separately in [29,30]. Since the NS efficiency metric applies to the whole simulation period, it was not recommended for application to low flow periods of streamflows [27,30].

Problems with simulating the streamflows in water limited catchments are associated with their naturally dry but also variable climate [2,8]. Along with very low flows, these catchments are characterised by extensive, extremely skewed, and exacerbated periods of no flows [14,26]. In addition to this, high flows can sporadically occur during the rainy seasons as well as from thunderstorms during the dry seasons [31]. Models for catchments dominated by low streamflows have been shown to often overestimate the low and underestimate the high flow events [2,4,6]. For long-term modelling of catchments with dominant low flows, it therefore seems to be advantageous to focus on methods that equally consider the contribution of both low and high flows as a whole rather than performing the discontinuous seasonal calibration.

In this context, this study develops and validates SWAT models for South Australian catchments that experience distinct low-to-zero streamflows. The study focuses on the research question regarding how forestry and irrigation affect simulated streamflows in South Australian catchments. Taking into account that farm dams are critical sources for irrigation of dryland agriculture, scenarios analyze the cases: (1) without farm dams; (2) with farm dams considered as natural water bodies; and (3) with farm dams to be used for irrigation.

2. Materials and Methods

2.1. Study Area

The study area is situated 30 km north-east of Adelaide (South Australia) and covers an area of 29,640 ha with an elevation range from 200 to 710 m above sea level (Figure 1a). The climate is Mediterranean with an average annual rainfall of 585 mm [30]. Whilst its average monthly rainfall in January and February is around 20 mm, rainless months are quite common [31]. Since 2000, the climate has been in a generally drier than average cycle with declining trend in annual rainfall over the past 100 years [9,32]. This change is causing local streamflows to become more unpredictable when paired with other effects such as increasing development within the catchment [9,32].

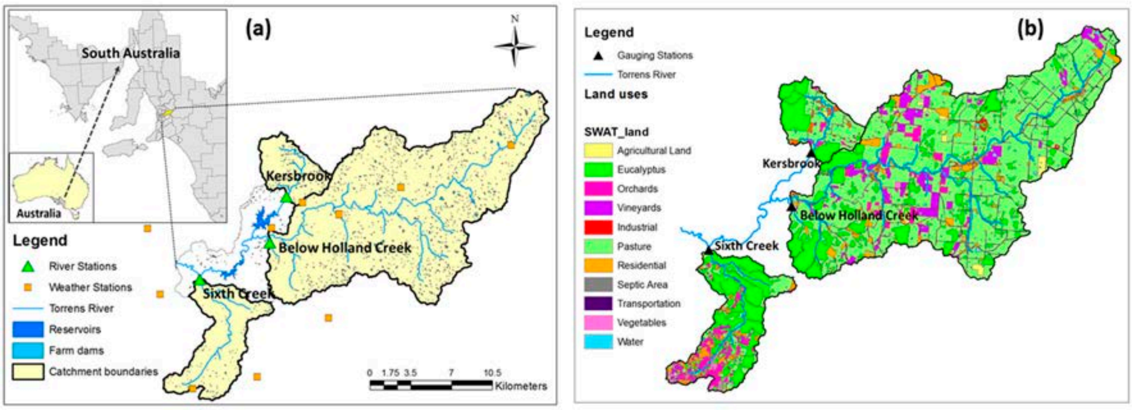

Figure 1. The study area: (**a**) Locations of gauging stations; (**b**) Land uses map.

2.2. SWAT Model Input Data

The inputs required for the study include topographic, land-use, soil, climatic, and stream flow data. Topography was defined by a digital elevation model (DEM). DEM was aggregated from a 10 m × 10 m contour interpolation that was obtained from the South Australian (SA) Water Corporation. The land use map of 2007 with a resolution of 1:100,000 provided updates on the boundaries, the locations and relative areas of protected zones, native eucalyptus forests, main agricultural lands, and water bodies (Figure 1b). A 1:100,000 soil map was provided by SA Department of State Development while a soil database of 117 soil types with detailed profile of five soil layers (Level 5 Soil Attributes) was extracted manually from the Australian Soil Resource Information System [33]. Daily climatic data from 1970 to 2014 of 10 stations were collected from the Scientific Information for Land owners (SILO) [34]. Maps and data records of streamflows in the Upper Torrens watershed were provided by the SA Water Corporation and SA Department of Environment, Water and Natural Resources (DEWNR).

Three available gauging stations in the study area include Below Holland Creek, Kersbrook, and Sixth Creek (Figure 1). The flows through these stations are the main natural sources that feed into the catchment reservoirs [11]. Apart from these, the Below Holland Creek station operates as part of the environmental flows monitoring program. As the average volume of runoff from the catchments does not meet the water demands of local communities, agriculture, and mining (Figures 1b and 2), water is diverted from the River Murray via the Mannum to the Adelaide pipeline as required rather than only during the driest periods [7,11].

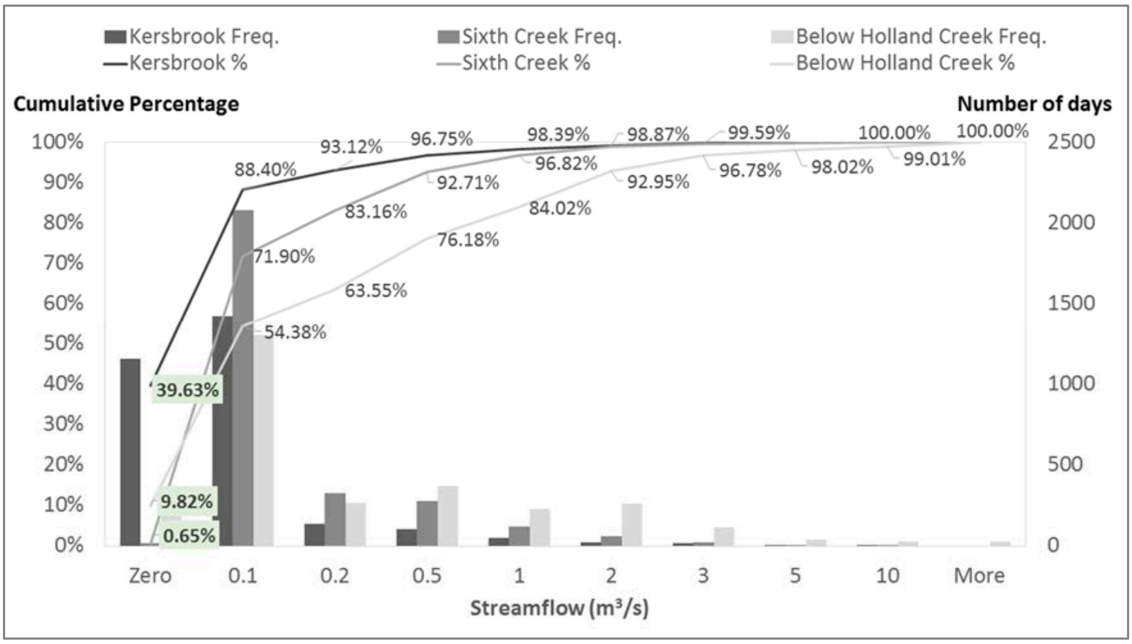

Figure 2. Frequency distribution of streamflows in the Kersbrook, Sixth Creek, and Below Holland Creek catchments.

2.3. SWAT Model Set-Up

The semi-distributed model SWAT (ArcSWAT version 2012) [35] was used to model the three catchments in this study. To characterize the three catchments, the threshold value of 200 ha was applied which resulted in the delineation of the Kersbrook, Sixth Creek, and Below Holland Creek catchments into 7, 9, and 31 sub-basins respectively. Unique combinations of land-uses, soil types, and slopes were aggregated to form the Hydrologic Response Units (HRU) using the percentage threshold method. In this step, the relatively small areas of horticulture, viticulture, and vegetables were exempted from the threshold dissolution to provide a realistic representation of main land uses of the catchments. The multiple HRUs option resulted in 372 HRUs for the study, which included 52, 98, and 222 HRUs for the Kersbrook, Sixth Creek, and Below Holland Creek catchments. The flows were calculated at the HRU level and then aggregated to the sub-basin scale [36].

The management operation section (.Mgt) in the SWAT edit was modified with regards to the management and irrigation practices. The default start and end of growth seasons, and auto irrigation schemes were replaced by the date's specific operations for main horticultural practices based on information from local farmers and expert knowledge. For orchards and vineyards, the plant growth season starts in September and ends by the end of March. Meanwhile, the growth seasons for vegetables often coincide with rainy periods with two cycles from January until May and from June until the end of September. The harvest option was applied for orchards and vineyards, and harvest and kill was used for vegetables. The irrigation amounts (as specified in the next section) were scheduled to be highest before and lowest after harvesting. In the case of forests and pasture land uses, start and end of growing seasons correspond with spring and late autumn, respectively, with no irrigations applied.

The surface runoff was calculated using the Soil Conservation Service (SCS) curve number [37]. For the potential evapotranspiration (PET) calculation, the Hargreaves method [38] was used over the alternative methods as it produces closest results comparing to the PET records from SILO [34]. For flow routing into channels, the study used the variable storage method. In this study, SWAT models were run on daily time steps.

A more detailed description of the SWAT model configuration applied for this study is available in [36,39].

2.4. Farm Dams Configuration

Agriculture in the three catchments is both rain-fed and irrigated [9]. On average, 22% of water need for agricultural practices is derived from farm dams' system, mainly for irrigation. Other water uses from farm dams include grazing land for livestock and livestock feeding but were temporarily restricted during the extreme drought years [5]. Recent investigation records approximately 1693 farm dams (Figure 1) with a storage capacity of 5957 ML within the study area [39].

Farm dams were incorporated as ponds by SWAT (Table 1) [36,39] with the following water balance equation:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \quad (1)$$

in which V indicates the overall volume (m^3) at the end of the day as the results of the volume V_{stored} at the beginning of the day, the volume of water V_{flowin} entering (m^3) and $V_{flowout}$ leaving (m^3) the pond during the day, the amount of precipitation V_{pcp} (m^3) contributed in and evaporation V_{evap} (m^3) lost from the pond, as well as the volume of water removed as seepage flow V_{seep} (m^3).

Since SWAT allows for considering only one pond in each sub-basin, all farm dams within a sub-basin were aggregated into one single pond. Similar to the reservoir configuration, in case of a pond, SWAT requires users to provide information on the surface area and volume at two levels, principal and emergency spillway. Because the actual rate of dams' development is not available, the study assumes that the capacities of dams within each sub-basins remained constant over the period of available data. The surface areas and storage volumes of ponds were aggregated as the sum of all farm dams present in a sub-basin. This information was calculated using farm dams' metadata provided by South Australian Government Data Directory (Data.SA) [40] and were assumed to be equal the maximum capacity of the pond when filled to the principal spillway. Meanwhile, initial areas and volumes of ponds were assumed to be 10% of the maxima and not completely drawn down. The parameter "Fraction of sub-basin area that drains into ponds" (PND-FR, 0-1) was used to quantify the proportion of runoff that had been captured by each pond. This parameter is dependent on the location, size, and densities of farm dams within a sub-basin. Large farm dams or those locate on-stream are assumed to capture 100% of runoff of the upstream sites while smaller off-stream dams have the runoff capture ratio less than 1.0 [11]. Surface evaporation coefficients for farm dams were set using a default ratio of 0.6.

Table 1. Farm dams input with initial and modelled values in SWAT.

Model Parameters	Abbreviation	Units	Initial Values			Modelled Values		
			Min	Max	Default	Min	Max	Mean
PND_FR	Fraction of sub-basin area that drains into ponds	fraction	0.00	1	0.00	0.00	1.00	0.40
PND_PSA	Surface area of ponds when filled to principal spillway	ha	0.10	20	5	0.00	30.24	7.55
PND_PVOL	Volume of water needed to fill ponds to the principal spillway	10^4 m^3	0.00	100	25	0.00	47.04	12.14
PND_VOL	Initial volume of water in ponds	10^4 m^3	0.00	100	0	0.00	4.70	1.21
NDTARG	Number of days to reach target storage	days	0	60	0	15	15	15

2.5. Estimation of Irrigation Inputs

Irrigation from farm dams was incorporated in the model. Information on irrigation volume applied for various crops and land uses (ML) was obtained from survey results of the Australian Bureau of Statistics (ABS) [5]. At the catchment scale, information is collected every five years to supplement the annual records available for the broad territory of the entire South Australia and the latest records for the Adelaide region were updated in June 2015 [5].

The irrigation amount was estimated at the HRUs level with the methodology as suggested by ABS [10]. The total area and area watered for all agricultural practices were assumed to remain constant over the period of study. Areas of land were assumed to be irrigated when they contained land uses of horticulture. Irrigation from agricultural land and pasture were not included as the proportion of area watered versus total area of the lands in the period from 2004 to 2014 was small (less than 1%) [5]. Irrigation volumes were estimated from the 10-year averaged total volumes in order to quantify the irrigation rate (ML/ha) for specific land uses. This resulted in the water application rate of 5.09, 1.26, and 4.82 ML/ha for orchards, vineyards, and vegetables, respectively. The irrigation water extraction (ML) for the HRUs level was calculated on the basis of the calculated adjusted application rate (ML/ha) and the total area of horticulture land uses (ha) in each sub-basin. The timing of irrigation was based on expert knowledge. Irrigation was set from November until March for orchards and vineyards, and in the periods of April–May and August–September for vegetables. Water abstraction during the no-irrigation season was set as 0.

The extraction of irrigation was adapted in SWAT by adjusting the average daily water removal from HRUs with specific land uses in the section Edit SWAT inputs. An option of water removal from ponds (Average daily water removal from the pond (WUPND), 10^4 m^3) was used as this source for irrigation was not available in the management section of SWAT. The application of irrigation was then returned to HRUs by means of irrigation operations (Management operation (MGT_OP) = 2) from an external source option (Irrigation source (IRR_SC) = 5).

2.6. Model Evaluation

Auto-calibration was performed using the SWAT Calibration and Uncertainty Procedure (SWAT-CUP4) [4,6,24,41]. It incorporates five methods of which the Sequential Uncertainty Fitting program (SUFI2) was selected in this study. SUFI2 provides two methods for sensitivity analysis, namely one-at-a-time sensitivity analysis (OAT) and global sensitivity analysis. OAT was tested first in order to select a set of sensitive parameters from available literature [2,4,6,41,42] for the model calibration. Global sensitivity analysis is incorporated with calibration in SUFI2 and results were used to evaluate the sensitivity of selected parameters. For model calibration, NS was selected as the Objective Function of SUFI2 method.

In case the NS goal type failed to define a solution, a modified version of NS called constant base-flow separation (BFS) was also tested [41]:

$$\mathrm{NS} = 1 - \frac{\sum_i (Q_{m,i} - Q_{s,i})^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2} \tag{2}$$

$$g = \sum_j w_j NS_j \tag{3}$$

where: Q is a variable (e.g., flow), m and s are measured and simulated value respectively, i is the i^{th} data, the bar stands for average, and w is the weight value of a partial variable.

The BFS method defines a threshold which allows the two parts of the flow, i.e., "above" and "below" the threshold, to have different weights during the calibration procedure. By assigning different weights, the less dominant flow part can have a higher contribution to the objective function as the dominant flow part. This approach is suggested for calibrating flows with unbalanced distribution of high and low flow parts [41].

Ten years of data were available for the study of which the three years from 2004 to 2006 was kept as a "warm-up" period. Five years' data from 2007 to 2011 which included both the low, medium, and high rainfall periods were used for calibration. The rest of the data from 2012 to 2014 which also represents both low and high rainfall periods was retained for validation.

The model performance of streamflows was judged on the basis of graphical, statistical, and uncertainty analysis. Three quantitative statistics, including correlation coefficient (R^2), Nash-Sutcliffe (NS), and percent bias (PBIAS) are commonly used in SWAT applications [21,22] and were selected for this study. According to Moriasi et al. [21], the model performance was considered satisfactory when R^2 and NS was greater than 0.5, and percent bias (PBIAS) ranged between $\pm$25% as for a monthly time step's simulation. These criteria are allowed to be relaxed when the model is applied to a daily time step [21].

An analysis of the model uncertainties was combined with model optimization in SUFI2 [4,23,42]. The uncertainties were evaluated based on the percentage of observation points bracketed by the prediction uncertainty band (p-factor), and the degree of uncertainty, calculated as an average thickness of the band divided by the standard deviation of the observed values (r-factor). The values close to 1 and below 1.5 were selected for p- and r-factors [41].

2.7. Scenario Analysis

The models were first calibrated without irrigation inputs. These were further compared with the calibrated models which incorporate irrigation farm dams to evaluate the effects of irrigation on the model performance.

The calibrated models with irrigation inputs were used as baseline (BS) for the two main scenarios. The first scenario tested the effects of land use covers by either increasing or decreasing the area of the natural eucalyptus forest with pasture land use using the land use update option (.lup) in SWAT. These are the two most dominant land uses in the area (Figure 1b) thus any potential changes in these land use will have a high probability to cause an effect on the catchment water balance [4,31]. Taking into account the role of the three catchments as the sole natural sources for water supply to the downstream reservoirs, no other land use scenarios were considered in this study.

The second scenario evaluated the streamflows with and without irrigation farm dams. The scenario of no farm dams was defined by adjusting the value of the parameter PND-FR to 0 and by removing irrigation operations. Next, the effects of farm dams in relation to irrigation were analyzed for catchments which indicated a significant effect. For this test, the scenarios with farm dams either used or not for irrigation were performed. The scenario of no irrigation from farm dams was configured by the removal of both irrigation operations (MGT_OP = 2) and water extractions from two sources (WUPND, WUSHAL) [36].

Graphical analysis was used to analyze the scenarios' outputs. In addition, the assessment of scenarios of irrigation farm dams was performed through the statistical analysis of an Independent-Samples-Mann-Whitney test (U-test) (R Core Team 2015). The U-test rejects the null hypothesis and states the alternative hypothesis that the two streamflow sample distributions are significantly different when p-value < 0.05.

3. Results and Discussion

3.1. Parameter Sensitivity Analysis

On the basis of 16 sensitive parameters defined through the OAT sensitivity analysis, the global sensitivity test showed the 14 most sensitive parameters for the three catchments. Initial model calibration without irrigation inputs showed that all groundwater parameters were ranked among the most sensitive parameters. Other sensitive parameters were related to soil, such as the moist bulk density (SOL_BD) and the saturated hydraulic conductivity (SOL_K). The base-flow alpha factor for bank storage (ALPHA_BNK) was categorized as the most sensitive parameter with a rank from one to two in three catchments. Similarly, the deep aquifer percolation fraction (RCHRG_DP) had a high sensitivity which ranked from two to four. The sensitivity rank of some parameters changed significantly when the models were calibrated with irrigation inputs. Among fourteen sensitive parameters, the Moisture condition II runoff curve number (CN2) was ranked as the most sensitive for all stations. Other sensitive parameters still belonged to the soil and groundwater compartments. For instance, values for the saturated hydraulic conductivity (SOL_K) decreased with increasing average slope length (SLSUBBSN). The groundwater "revap" coefficient (GW_REVAP) appeared to be very sensitive to the water recharged by shallow aquifer to the unsaturated root zone and increased for all the three sub-catchments (0.07–0.19). ALPHA_BNK remained as a sensitive parameter in two catchments. Meanwhile, RCHRG_DP played a less important role in the model calibration and ranked from 8 to 14. The parameters defined as sensitive in this study were similar to those selected in other studies with a focus on semi-arid catchments and low flow conditions [2,4,28,30].

3.2. Model Calibration and Validation

An inclusion of irrigation inputs indicated an improvement in the model performance with a better solution for the Six Creek and a satisfactory solution for the Below Holland Creek (Figure 3). The results for Sixth Creek calibration with irrigation inputs gained higher statistics for both calibration and validation of NS (0.63, 0.60) and a better graphical match; whilst model errors reduced with the lower PBIAS (−9.1, −27.4) and with more data points covered by the uncertainty band (p-factor = 0.70, 0.80) (Figure 3a). In the case of the Below Holland Creek, statistics appeared to be slightly below the criteria, which was partially due to the effects of the point source inlets and transfers of the Mannum—Adelaide pipeline (Figure 3b). During dry months, water is diverted from River Murray summit directly into this catchment via two point sources of Mount Pleasant and Angas Creek scours and partly diverted to the Millbrook reservoir. The pipeline system is located upstream of this gauging station. Overall, the timing and shapes of observed and simulated hydrographs of both stations matched well. Outputs of these case studies confirm that reliable predictions of hydrology in irrigated catchments need a relatively accurate knowledge of the irrigation practices at the catchment scale as was also suggested in [43].

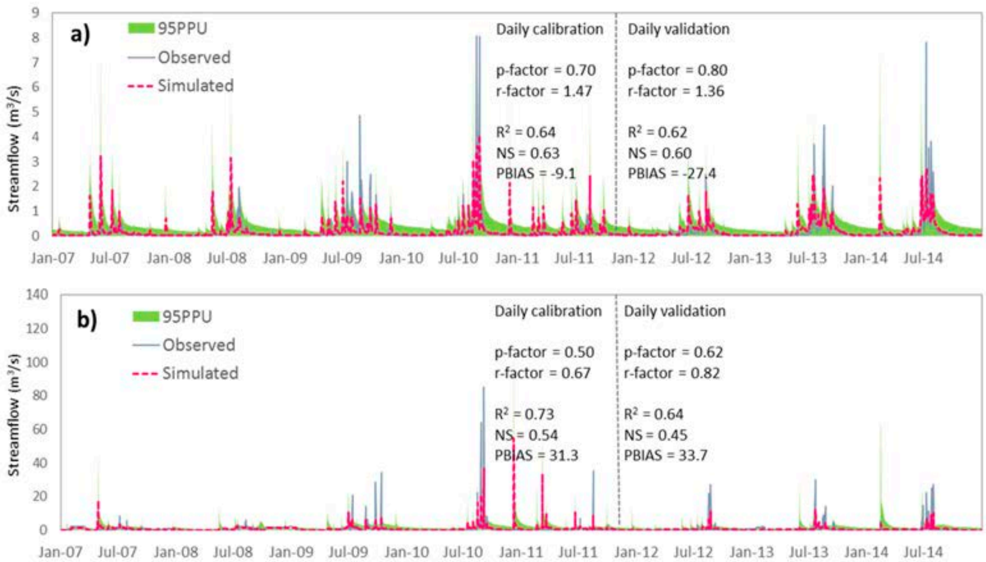

Figure 3. Model calibration and validation with daily time steps for (**a**) Sixth Creek and (**b**) Below Holland Creek.

However, statistics for daily modelling of the Kersbrook station were unsatisfactory as indicted in Table 2. The low performance of the SUFI2 optimization at this station was explained by the dominant zero flow with only two flow events greater than 5 m^3/s during the study period (Figure 2). SWAT modelling based on a NS efficiency optimization often relies more on peak flow behaviour, and successful results are reported more in regions with temperate climate [20,44]. Some authors suggested a separate calibration of the dry and wet seasons for improving the model performance [29,30]. However, seasonal variability may play a minor role in water-scarce catchments and there might be periods with no distinct seasons, particularly during drought years [45]. This situation applied to the time period covered in this study.

Alternatively, we tested the BFS method in SUFI2 as suggested by [41]. A threshold of 0.1 m^3/s for flow was applied. The best result was achieved with a weight of 0.5 and 1.0 for low and high flow parts, respectively. Results from the BFS optimization showed that both the errors associated with the overestimation of base-flows and underestimation of peak flows are minimized (Figure 4). Graphically, in comparison with original default simulation, the auto-calibration with NS tried to further reduce the peak flows in order to fit the dominant small flows. In contrast, with BFS, by reducing the weight of low flows, the model better simulated the high flows and this helped to better represent the low flows as well. The p-factor increased from 0.25 to 0.37 and 0.17 to 0.3 while the r-factor decreased slightly from 0.5 to 0.49 and 0.65 to 0.62 for calibration and validation, respectively. Since all the partial NS that were based on optimization of streamflows with low and high flow parts having different weights improved from ranges of 0.38–0.4 to 0.88–0.91, the final NS at Kersbrook also increased and met the validation criteria (Table 2). The improvement in the model optimization was also reflected in the increase of the number of behavioural simulations, i.e., simulations with NS value above the satisfactory criteria of 0.5.

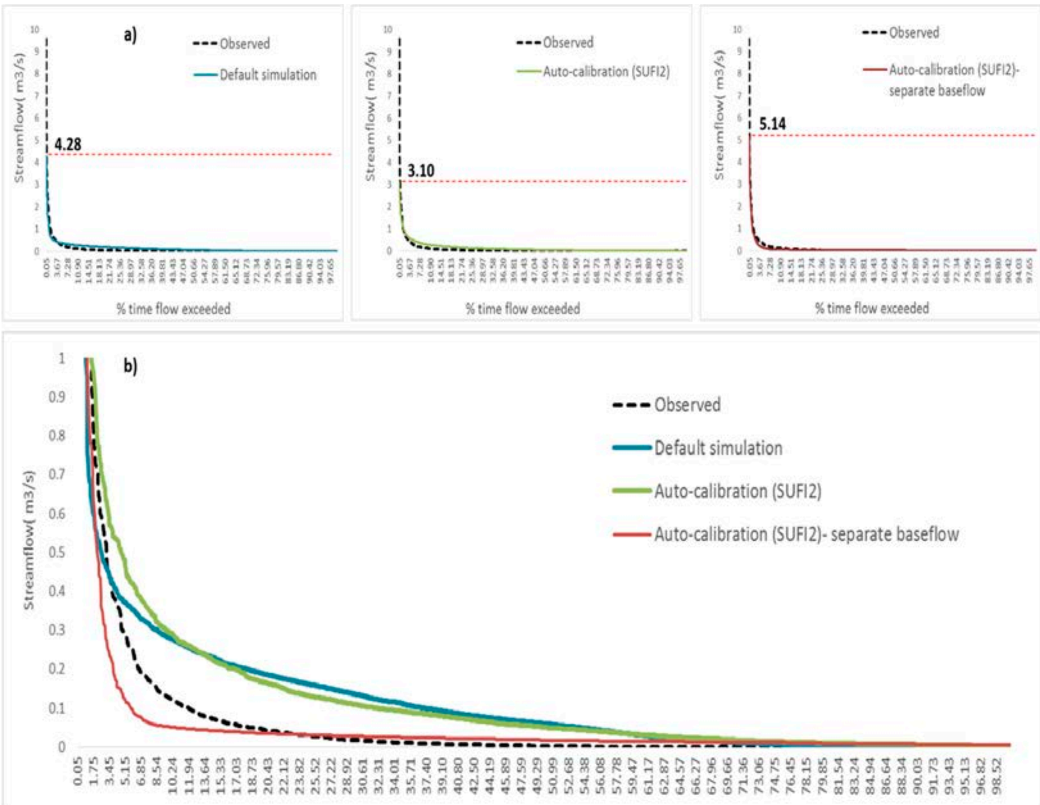

Figure 4. Daily observed and simulated flow duration curves of the Kersbrook catchment. (**a**) Highlight peak flow parts. Bold numbers indicate maximum flows; (**b**) Highlight low flow parts.

Table 2. SWAT model performance on a daily time step for the Kersbrook catchment using modified NS objective function (with separate base-flow).

Optimization	p-Factor	r-Factor	R^2	PBIAS	Objective Function (NS)		
					Final Goal	Best Partial Goal	No. of Behavioral Simulations
Calibration							
Default simulation	0.04	0	0.18	−274.5	−0.81	-	-
Auto-calibration (SUFI2)	0.25	0.5	0.4	−65.8	0.38	0.38	0/500
Auto-calibration (SUFI2) with separate base-flow	0.37	0.49	0.55	19.1	0.54	0.88	500/500
Validation							
Default simulation	0	0	0.32	−262.4	−1.07	-	-
Auto-calibration (SUFI2)	0.17	0.65	0.43	−59.1	0.4	0.4	0/500
Auto-calibration (SUFI2) with separate base-flow	0.3	0.62	0.53	−3.6	0.48	0.91	500/500

3.3. Effect of Forest Land Use Change

The calibrated models represent the water balance of the catchments well (Table 3). Rainfall range was low during the period of study (<900 mm/year) while the simulated annual average potential evaporation (PET) (mm) was significantly higher than the rainfall contribution. The models adequately simulated the base-flow contribution to the total flow, with the highest rate of 77% at the Sixth Creek, followed by 31% at the Below Holland Creek, and lowest of 7% at the Kersbrook. Similarly, the lowest water yield was simulated at the Kersbrook catchment.

It is interesting to evaluate the contrasting pattern in the water balance at the two forested catchments of Kersbrook (43.55% forest cover) and Sixth Creek (57.04% forest cover) (Table 4). The Kersbrook catchment has a limited rainfall contribution while the simulated evapotranspiration (ET) rate accounted for 89% of the rainfall amount. In addition, the soil profile in this catchment is dominated by the less permeable clay loam and medium clay with strong polyhedral structure [33]. With this type of soil, it is likely that the infiltration into the soil might be much slower than in catchments with more permeable soils and most of the rain would be transformed as surface runoff. This may explain why the streamflow at Kersbrook often gets dry during periods of no rainfall. In contrast, the Sixth Creek catchment is characterized by the well-drained soil lands and a higher rainfall availability which resulted in the higher water yield and a more stable base-flow contribution during the years (Table 3).

Table 3. Water budget components of the study catchments.

Catchment	Area (ha)	Mean Annual Basin Values				
		Rainfall (mm)	PET (mm)	ET (mm)	Water Yield (mm)	Baseflow/Total Flow (%)
Below Holland Creek	19,067.71	718	1261.94	478.21	144.86	31.00
Kersbrook	2238.14	692	1310.01	615.35	88.38	7.00
Sixth Creek	4301.49	896	1165.16	597.33	222.44	77.00

The response of the models to forest land use changes was directly reflected through the changes in the water balance components (Table 4). In case of the Below Holland Creek, the relative increase of forest area from 10% to 50% resulted in an increase of the lateral flow (up 1.8%) and the base-flow contribution to total flow (up 3.0%) while surface flow significantly decreased (up 10.93%). As opposed to the pattern at the Below Holand Creek, the deforestation of up to 50% of the original land cover at the Kersbook and Sixth Creek resulted in the significant increase of surface flow of 2.73% and 9.70% while base-flow slightly decreased by 1.0% and 1.3%, respectively.

The projected overall water yield of catchments is affected by the change in the ET and positively correlates with the change in the surface flow. The water yield at the Below Holland Creek, which is supported mainly by base-flow (69.0%) rather than surface flow, decreased slightly by 3.61% when the forest areas were expanded by 50% due to the higher ET rate of 5.12%. Meanwhile, in case of the

Kersbrook which received most water from surface flow (93% annually), additional pasture on the basis of 50% land of forest significantly increased the water yield by 6.95% as the result of the 2.73% increase in the surface flow. At the Sixth Creek, the slight decline in the base-flow contribution (1.00%) did not affect the overall increase in the water yield of the catchment as the direct effect of the strong increase in surface flow (9.7%) and the decrease in ET (2.37%).

Table 4. Scenarios on effects of forest cover on streamflows during the period from 2007 to 2014.

Scenario	Forest Cover (%)	Relative Change (%)				
		Surface Flow	Lateral Flow	Baseflow/Total Flow	Water Yield	ET
Below Holland Creek						
BS	19.02	-	-	-	-	-
BS Forest +10%	25.11	−2.16	0.39	1.00	−1.00	1.03
BS Forest +50%	49.48	−10.93	1.80	3.00	−3.61	5.12
Kersbrook						
BS	43.55	-	-	-	-	-
BS Forest −10%	40.24	0.54	−0.36	0.00	5.30	−0.06
BS Forest −50%	27.20	2.73	−1.82	−1.00	6.95	−0.29
Sixth Creek						
BS	57.04	-	-	-	-	-
BS Forest −10%	48.65	1.91	−0.12	0.00	0.98	−0.47
BS Forest −50%	27.03	9.70	−0.57	−1.30	4.97	−2.37

3.4. *Effect of Irrigation Farm Dams*

The agricultural sector of South Australia depends heavily on irrigation water from local catchments which includes the source from the surface runoff captured in farm dams [11]. Water from farm dams are stored mainly for irrigation. Thus, irrigated farm dams are expected to have important effects on the catchment hydrology as they affect the volume and movement of runoff [11,12]. A scenario analysis with and without farm dams revealed that the purpose of farm dams rather than the number of farm dams within a catchment area affected streamflow. The U-test for Below Holland Creek and Sixth Creek catchments indicated a clear difference in the streamflows between the scenarios with and without farm dams' presence even though their areas in the catchments are significantly lower compared to the Kersbrook catchment (Table 5). These two catchments are characterized with intensive irrigation for horticultural land uses. In contrast, the presence of large areas of farm dams in the Kersbrook catchment with a limited area of horticulture and with restricted to no extraction for pasture irrigation and animal stock during the period of study [5] indicated low effects on streamflows. This further confirms that the drought condition of Kersbrook streamflow might be more associated with the catchment natural characteristics rather than with the effects of farm dams.

Table 5. Statistical analysis of scenarios for stream flows with and without farm dams.

	Kersbrook	Sixth Creek	Below Holland Creek
Mann-Whitney (U-Test)			
p-value	0.61	1.03×10^{-4}	$<2.2 \times 10^{-16}$
Sensitivity	No	Yes	Yes
Catchment characteristics			
Farm dams area (km^2)	0.39 (1.74%) [a]	0.17 (0.39%) [a]	2.90 (1.29%) [a]
Horticulture-viticulture area (km^2)	0.75 (3%) [a]	7.13 (17%) [a]	17.69 (8%) [a]
- Orchards	0.72	5.06	3.86
- Vegetables	-	0.97	0.45
- Vineyards	0.03	1.10	13.39

Notes: [a] Values in the parenthesis indicate the relative percent of area compared to the catchment area.

This pattern was further addressed when comparing the scenarios of farm dams' effect in association with irrigation through the scenarios with farm dams not used for irrigation and with farm dams used for irrigation. This test was performed for the two catchments, i.e., Sixth Creek and Below Holland Creek which indicated a significant difference between cases with and without farm dams. The results showed that the scenario of no irrigation practices, although with farm dams' presence, did not vary greatly in comparison with the scenario of removing farm dams (magnitude of change <0.1 m^3/s). However, the scenario with irrigation application extracted from farm dams (BS_With irrigation) showed a significant change in the streamflows' pattern in comparison to the scenario of no irrigation from farm dams (Figure 5). This indicated that the irrigation practices rather than the source of irrigation is the reason for the effect on streamflows.

Further analysis of the scenario with irrigation in comparison to other scenarios showed that a larger relative decline in streamflows was evident in the catchment with a more intensive irrigation practice. This was the case of Sixth Creek which had an irrigation rate for orchard land use of 5.09 ML/ha in comparison to Below Holland Creek which had a lower rate of irrigation for vineyards of 1.26 ML/ha. At monthly time steps, the most evident effect of irrigation farm dams on the decrease of the peak streamflows occurred in the rainy months of June and July. Overall, the models suggest that approximately 13.1% and 22.0% of water have been annually diverted from the natural streamflow of Below Holland Creek and Sixth Creek for irrigation purposes. These results are comparable with the outputs from the study of Heneker [11] which was the sole publication so far focused on modelling the hydrology of the study area. It was predicted by Heneker [11] that the rate of water being captured from farm dams might increase up to 19.0% to 26.0% in the following years which were predicted as drier years. Comparing the outputs from the scenarios, the lower rate of the flow decline in our study indicates that the restriction on water use might be an efficient solution to help protect the streams during periods of drought.

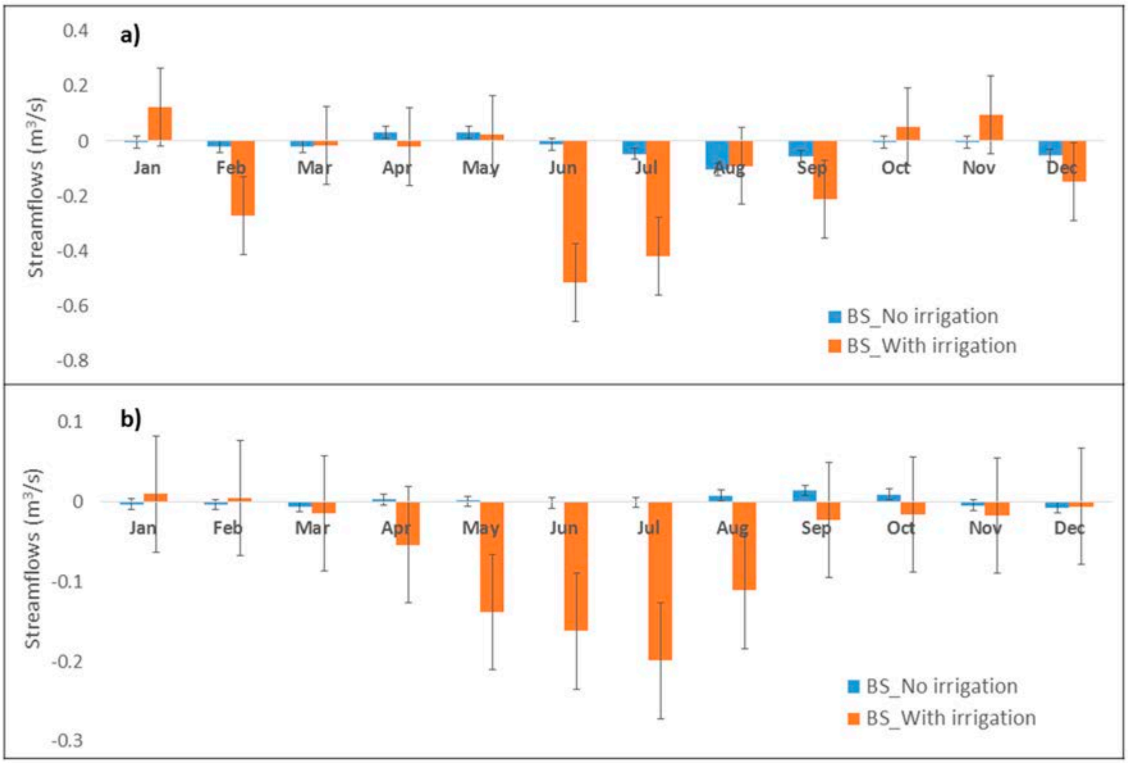

Figure 5. Changes in streamflows at Below Holland Creek (**a**) and Sixth Creek (**b**) for the scenarios with farm dams not used for irrigation (BS_No irrigation) and used for irrigation (BS_With irrigation). Error bars show one standard deviation.

Although the amount of water captured from irrigation farm dams during rainy periods was significant in quantity, it did not decrease the streamflow to the dry level. In the case of Below Holland Creek catchment, the presence of irrigation farm dams in dry months (especially in January) even suggested a slight increase in the flow level (Figure 5). This might be an effect of irrigated water on fields during a period of no rain. Meanwhile at Sixth Creek catchment, the effect on streamflow drought was not evident as the creek has a stable flow level all the year. A similar finding was reported in a nearby catchment of the Eastern Mount Lofty Ranges (South Australia) which stated that additional irrigation might provide appreciable benefits to the downstream area, particularly during periods of low flows including January [15]. Clarifying this effect would benefit the planning of local managers in sustaining the local environmental flow. The accuracy of simulation results by these models can be improved by collecting data on irrigation at the catchment scale more frequently and increasing the number of streamflow gauging stations within the study area.

4. Conclusions

This study tested the effects of forest cover and irrigation farm dams on the streamflows of the three water-limited catchments in South Australia by means of the process-based model SWAT. The results have shown that:

- The auto-calibration using NS as an objective function performed satisfactorily for catchments dominated by low flows (0.1 m^3/s). Calibration statistics and uncertainty values met the criteria better when irrigation practices were properly characterized, both spatially and temporally, in the model.
- The daily calibration improved significantly when the BFS method embedded in the NS analysis was applied for catchments dominated by zero flow.
- The projected extension of forest cover leads to a decrease in the simulated surface flow and water yield and an increase in the simulated ET and base-flow, while additional proportion of pasture caused the contrary pattern in water balance components.
- A scenario analysis indicated that the purpose of farm dams determined their effect on streamflows rather than the number of farm dams. Catchments with intensive irrigation by orchards and vineyards experienced more severe declines in streamflow during irrigation intensive seasons than catchments dominated by pastures.
- With water resources in the study area having recently been "prescribed" and extraction allocations being set, as well as extraction restrictions being applied during drought periods, modelling during the study time period suggested that effects of water extraction from farm dams had not significantly threatened natural streamflow conditions during those times. The model highlighted the importance of considering the effects of irrigation on the hydrology conditions of water limited catchments. The outputs from this study suggested a necessity to further investigate the effects of farm dams on the catchment hydrological dynamics apart from their roles solely as irrigation sources for the adaptive management of catchments.

The successful application of SWAT in this study provides a supplementary modelling tool for the more complex hydrological studies in comparison to the on-going developed Source model for Australian catchments. Successful hydrologic simulation in this study is a prerequisite for the further research with a focus on simulations of nutrient and pathogen loads within the integrated catchment. Future work will focus on the integration of the three catchments and adjacent drinking water reservoirs into comprehensive catchment models.

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

References

1. Van Otrop, F.F.; Vervoort, R.W.; Heller, G.Z.; Stasinopoulos, D.M.; Rigby, R.A. Long-range forecasting of intermittent streamflow. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 3343–3354. [CrossRef]
2. Saha, P.P.; Zeleke, K. Rainfall-Runoff Modelling for Sustainable Water Resources Management: SWAT Model Review in Australia. In *Sustainability of Integrated Water Resources Management. Water Governance, Climate and Ecohydrology (eBook)*; Setegn, S.G., Donoso, M.C., Eds.; Springer International Publishing AG: Cham, Switzerland, 2015; pp. 563–578.
3. Majumdar, D.K. *Irrigation Water Management: Principle and Practice*, 2nd ed.; Prentice-Hall of India: Delhi, India, 2013; p. 572.
4. Brown, S.C.; Versace, V.L.; Lester, R.E.; Walter, M.T. Assessing the impact of drought and forestry on stream flows in south-eastern Australia using a physically based hydrological model. *Environ. Earth Sci.* **2015**, *74*, 6047–6063. [CrossRef]
5. Australian Bureau of Statistics (ABS). Available online: http://www.abs.gov.au/AUSSTATS/abs@.nsf/second+level+view?ReadForm&prodno=4618.0&viewtitle=Water%20Use%20on%20Australian%20Farms~2007-08~Previous~26/05/2009&&tabname=Past%20Future%20Issues&prodno=4618.0&issue=2007-08&num=&view=& (accessed on 1 October 2015).
6. 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]
7. 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.
8. Smakhtin, V.U. Low Flow Hydrology: A Review. *J. Hydrol.* **2001**, *240*, 147–186. [CrossRef]
9. Rebbeck, M.; Dwyer, E.; Bartetzko, M.; Williams, A. *A Guide to Climate Change and Adaptation in Agriculture in South Australia*; South Australian Research and Development Institute, Primary Industries and Resources SA and Rural Solutions SA: Urrbrae, Australia, 2007; pp. 12–22.
10. Hawthorne, K. *A Methodology for Estimating Regional Agricultural Water Use*; Research Paper 4616.0.55.001; Australia Bureau of Statistics: Belconne, Australia, 2006. Available online: http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/0186AA6011A98B42CA2571EE001EE96E/\protect\T1\textdollarFile/4616055001_sep%202006.pdf (accessed on 6 January 2017).
11. Heneker, T.M. *Surface Water Assessment of the Upper River Torrens Catchment*; Report DWLBC 2003/2004; The Department of Water, Land and Biodiversity Conservation: Adelaide, Autralia, 2003; pp. 35–105.
12. Tingey-Holyoak, J.L. Water sharing risk in agriculture: Perceptions of farm dam management accountability in Australia. *Agric. Water Manag.* **2014**, *145*, 123–133. [CrossRef]
13. Pushpalatha, R.; Perrin, C.; Moine, N.L.; Andreassian, V. A review of efficiency criteria suitable for evaluating low-flow simulations. *J. Hydrol.* **2011**, *420–421*, 171–182. [CrossRef]
14. Demirel, M.C.; Booij, M.J.; Hoekstra, A.Y. The skill of seasonal ensemble low-flow forecasts in the Moselle River for three different hydrological models. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 275–291. [CrossRef]
15. Alcorn, M.R. *Hydrological Modelling of the Eastern Mount Lofty Ranges: Demand and Low Flow Bypass Scenarios*; Department for Water: Adelaide, Australia, 2011; pp. 2–42, ISBN: 978-1-921923-02-9.
16. Fleming, N.K.; Cox, J.W.; He, Y.; Thomas, S. *Source Catchment Hydrological Calibration in the Mount Lofty Ranges Using PEST Parameter Optimisation Tool*; eWater CRC: Canberra, Autralia, 2012; pp. 10–21, ISBN: 978-1-921543-63-0.
17. Alcorn, M.R. *Hydrological Model of the Onkaparinga Catchment, South Australia: Calibration Report*; DEWNR Technical Report 2015/02; Department of Environment, Water and Natural Resources: Adelaide, Australia, 2015; pp. 2–24, ISBN: 978-1-922255-29-7.

18. Marston, F.; Argent, R.; Vertessy, R.; Cuddy, S.; Rahman, J. *The Status of Catchment Modelling in Australia. Cooperative Research Centre for Catchment Hydrology*; Technical Report 02/04; Monash University: Melbourne, Australia, 2002.
19. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modelling and assessment part I: Model development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
20. 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. ASAE (Am. Soc. Agric. Eng.)* **2007**, *50*, 1211–1250. [CrossRef]
21. Moriasi, D.N.; Arnold, J.; Van Liew, M.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASAE (Am. Soc. Agric. Eng.)* **2007**, *50*, 885–900.
22. 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.
23. Abbaspour, K.C.; Rouholahnejad, E.; Vaghefi, S.; Srinivasan, R.; Yang, H.; Klove, 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]
24. Saha, P.P.; Zeleke, K.; Hafeez, M. Streamflow modelling in a fluctuant climate using SWAT: Yass River catchment in south eastern Australia. *Environ. Earth Sci.* **2014**, *71*, 5241–5254. [CrossRef]
25. Schuol, J.; Abbaspour, K.C.; Yang, H.; Srinivasan, R.; Zhender, A.J.B. Modeling blue and green water availability in Africa. *Water Resour. Res.* **2015**, *44*, 1–18. [CrossRef]
26. Pfannerstill, M.; Björn, G.; Fohrer, N. Smart Low Flow Signature Metrics for an Improved Overall Performance Evaluation of Hydrological Models. *J. Hydrol.* **2014**, *510*, 447–458. [CrossRef]
27. Krause, P.; Boyle, D.P.; Bäse, F. Comparison of different efficiency criteria for hydrological model assessment. *Adv. Geosci.* **2005**, *5*, 89–97. [CrossRef]
28. Muleta, M.K. Improving Model Performance Using Season-based Evaluation. *J. Hydrol. Eng.* **2012**, *17*, 191–200. [CrossRef]
29. Kim, H.S.; Lee, S. Assessment of a seasonal calibration technique using multiple objectives in rainfall-runoff analysis. *Hydrol. Process.* **2014**, *28*, 2159–2173. [CrossRef]
30. Zang, D.; Chen, X.; Yao, H.; Lin, B. Improved calibration scheme of SWAT by separating wet and dry seasons. *Ecol. Model.* **2015**, *301*, 54–61. [CrossRef]
31. Brindal, M.; Stringer, R. Water Scarcity and Urban Forests: Science and Public Policy Lessons from a Decade of Drought in Adelaide, Australia. *Arboric. Urban For.* **2013**, *39*, 102–108.
32. Bureau of Meteorology (BOM). Available online: http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml (accessed on 2 January 2016).
33. Australian Soil Resource Information System (ASRIS). Available online: http://www.asris.csiro.au/mapping/viewer.htm (accessed on 1 March 2015).
34. Scientific Information for Land Owners (SILO). Available online: http://www.longpaddock.qld.gov.au/silo/ppd/index.php (accessed on 1 February 2015).
35. Winchell, M.; Srinivasan, R.; Di Luzio, M.; Arnold, J. *Arc SWAT Interface for SWAT2012 User's Guide*; Texas AgriLife Research and United States Department of Agriculture: Temple, TX, USA, 2013.
36. Neitsch, S.L.; Arnold, J.G.; Kinir, J.R.; Wiliams, J.R. *Soil and Water Assessment Tool: Theoretical Documentation 2009*; Technical Report No. 406; Texas Water Resources Institute-Texas A&M University: College Station, TX, USA, 2011; pp. 29–180.
37. Soil Conservation Service (SCS). Section 4-Hydrology. In *SCS National Engineering Handbook*; USDA: Washington, DC, USA, 1972.
38. Hargreaves, G.H.; Samani, Z.A. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* **1985**, *1*, 96–99. [CrossRef]
39. Arnold, J.G.; Kiniry, J.R.; Srinivasan, R.; Wiliams, J.R.; Haney, E.B.; Neitsch, S.L. *Soil and Water Assessment Tool: Input/Output Documentation*; Technical Report; Texas Water Resources, Institute-Texas A&M University: College Station, TX, USA, 2012; Volume 439, pp. 2–620.
40. Data.SA (South Australian Government Data Directory). Available online: http://data.sa.gov.au/data/dataset/cc790713-4cf0-4bd4-bca8-f195d8e202b7 (accessed on 1 November 2015).

41. Abbaspour, K.C. *SWAT-CUP: SWAT Calibration and Uncertainty Programs—A User Manual*; Eawag: Dübendorf, Switzerland, 2015; pp. 16–70.
42. Abbaspour, K.C.; Yang, J.; Maximov, I.; Siber, R.; Boger, K.; Mieletner, J.; Zobrist, J.; Srinivasan, R. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J. Hydrol.* **2007**, *333*, 413–430. [CrossRef]
43. Githui, F.; Thayalakumaran, T.; Selle, B. Estimating irrigation inputs for distributed hydrological modelling: A case study from an irrigated catchment in southeast Australia. *Hydrol. Process.* **2015**, *30*, 1824–1835. [CrossRef]
44. Tuppad, P.; Douglas-Mankin, K.R.; Lee, T.; Srinivasan, R.; Arnold, J.G. Soil and Water Assessment Tool (SWAT) hydrologic/water quality model: Extended capability and wider adoption. *Trans. ASABE* **2011**, *54*, 1677–1684. [CrossRef]
45. Hulme, K.A. Eucalyptus Camaldulensis (River Red Gum). Biogeochemistry: An Innovative Tool for Mineral Exploration in the Curnamona Province and Adjacent Regions. Ph.D. Thesis, School of Earth and Environmental Sciences, University of Adelaide, Adelaide, Australia, 2008.

Chapter 3. Water quality control options in response to catchment urbanisation: A scenario analysis by SWAT

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iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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

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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 km^2 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°51′23″ and −34°56′53″ S and longitude 138°32′55″ to 138°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.

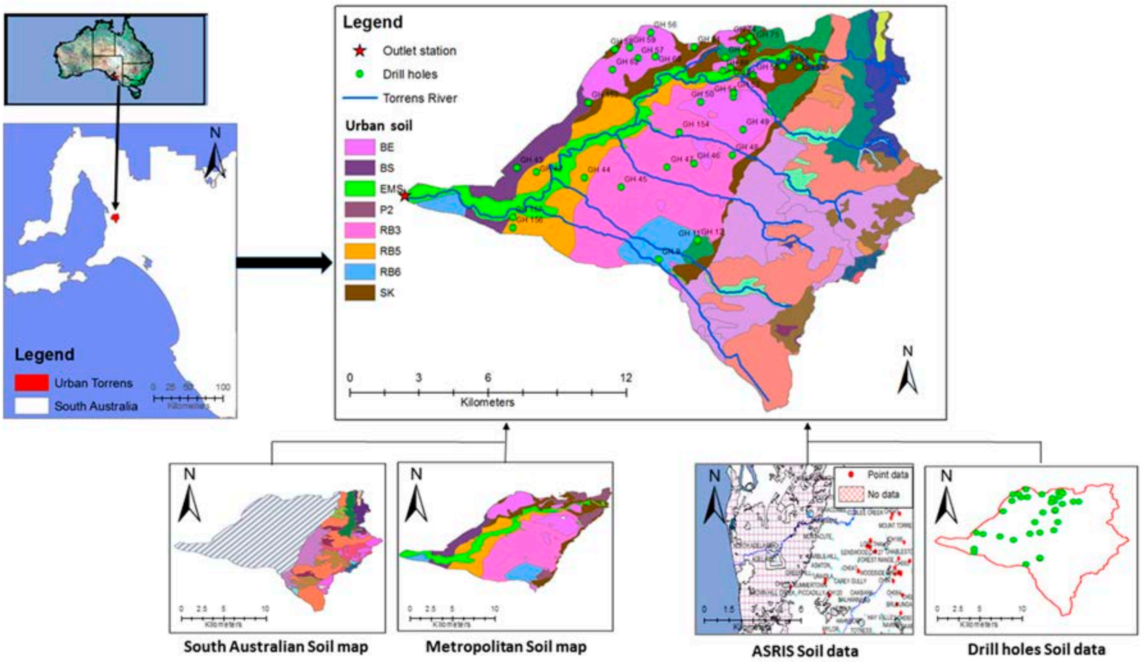

Figure 1. Soil maps of the study area.

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 (m^3 H_2O/m^3 soil) is the soil available water content (SOL_AWC) (mm H_2O/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 (m^3 H_2O/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 (kg H_2O/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 (metric ton m^2 h)/(m^3-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 (metric ton m^2 h)/(m^3-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.

$$\mathrm{NS} = 1 - \frac{\sum_i (Q_{m,i} - Q_{s,i})^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2} \tag{6}$$

where: Q is the streamflow variable, m and s are measured and simulated values respectively, i is the ith 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 ±25% for streamflow and ±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 m^2 and volume of 3700 m^3 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 $\rho < 0.05$.

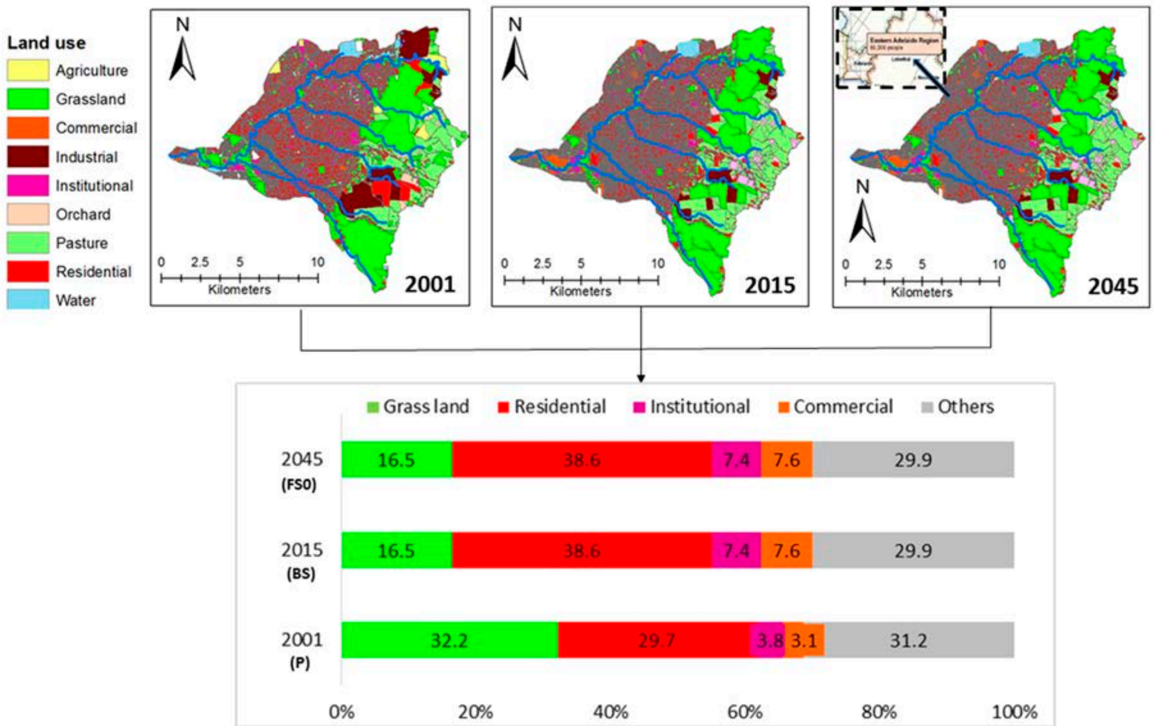

Figure 2. Characteristics of past (P), present (BS), and future (FS0) land use changes in the Urban Torrens catchment from 2001 to 2045.

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_2O	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_20/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_2O	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.

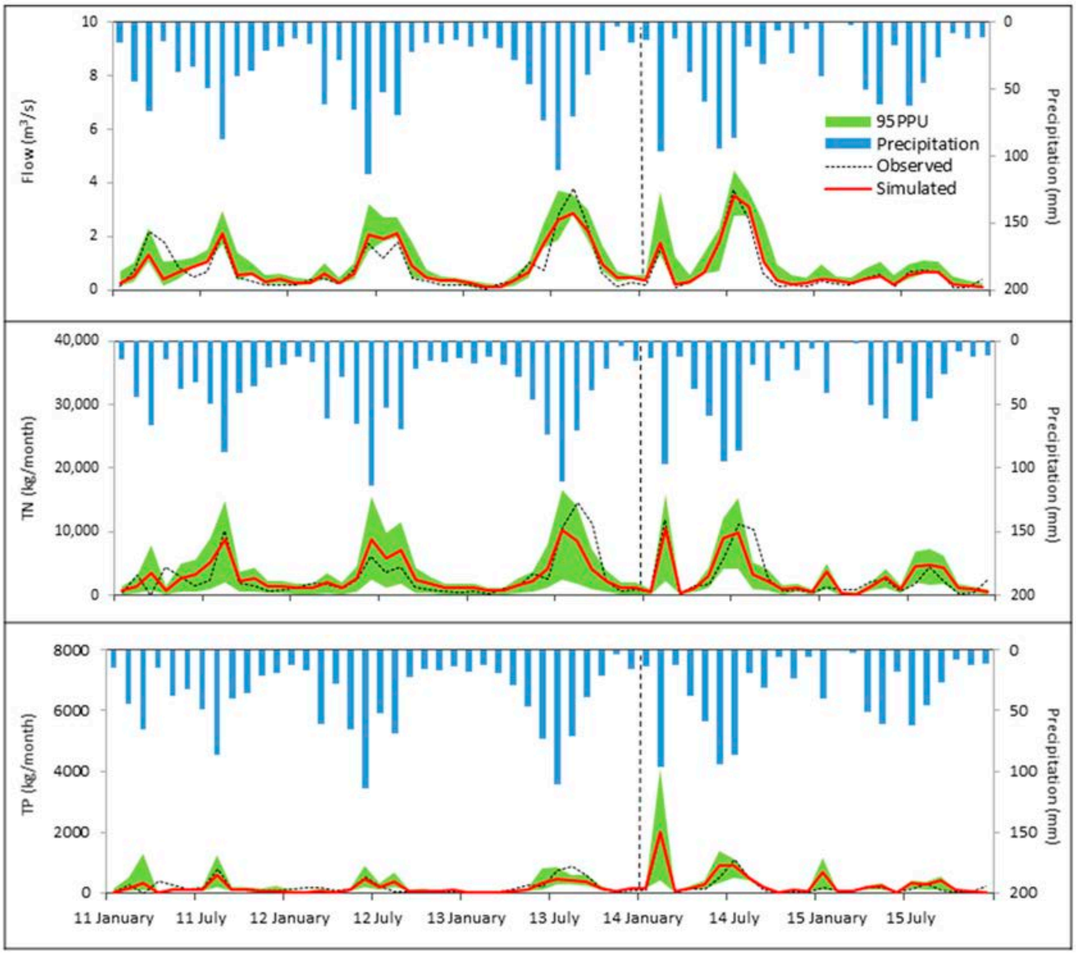

Figure 3. Hydrographs of observed and simulated streamflow and TN and TP loads of the Urban Torrens catchment during the calibration (2011–2013) and validation (2014–2015) periods.

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 versu s present urbanization.

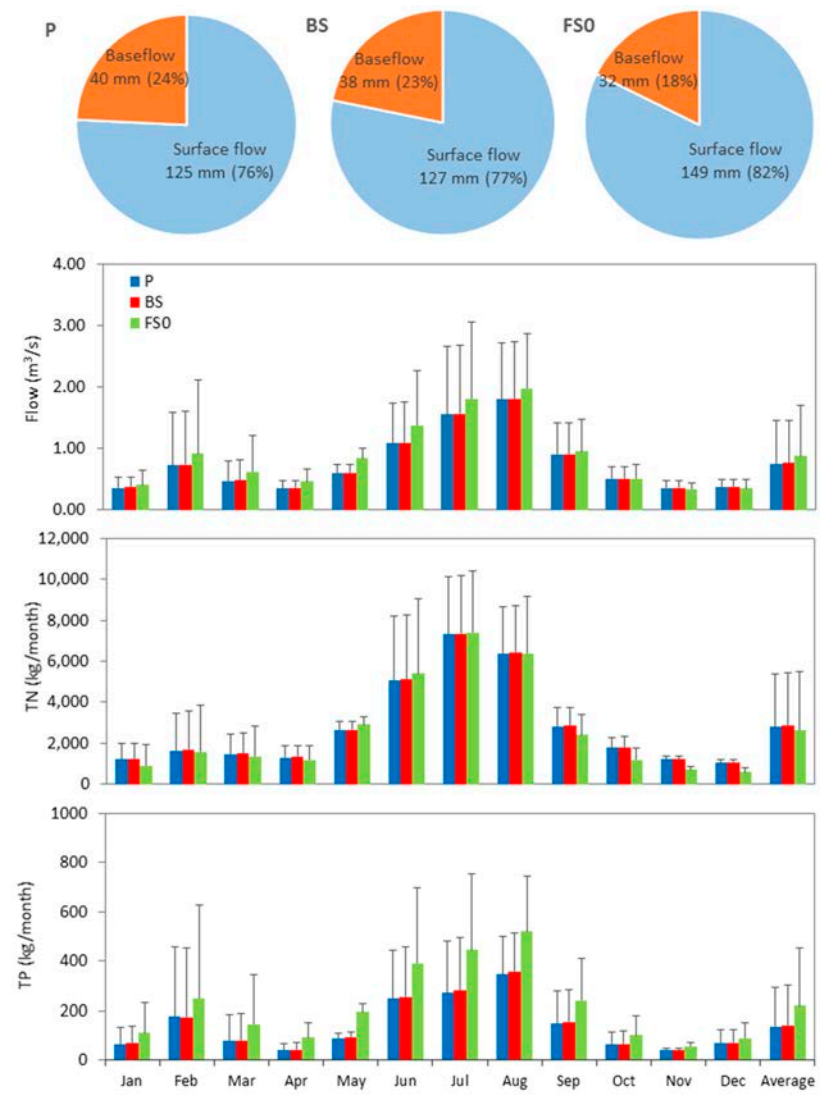

Figure 4. Streamflow, TN and TP responses to scenarios past urbanisation (P), present urbanisation (BS) and future urbanization (FS0). Pie charts show the relative proportion of different hydrological components. Bar graphs show the average streamflow, TN, and TP loads. Error bars show one standard deviation.

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.

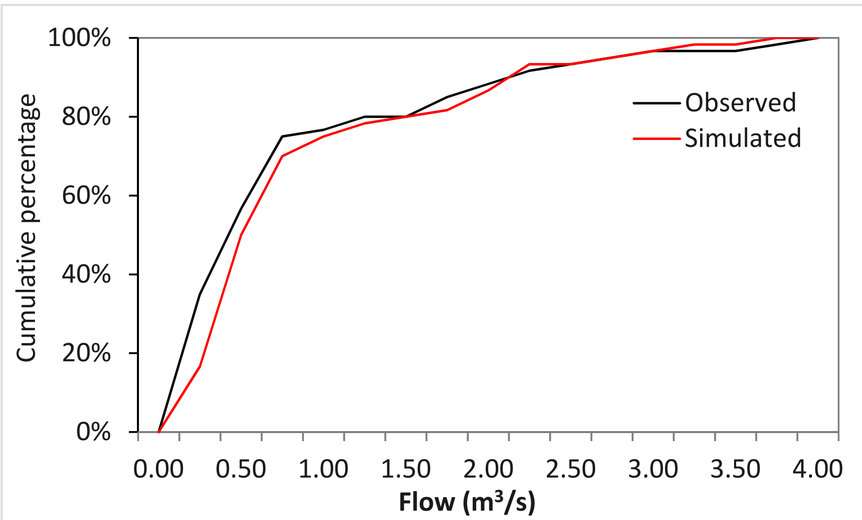

Figure 5. Flow duration curve of observed and simulated streamflow of the Urban Torrens catchment for the period from 2011 to 2015.

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 Tasdighi 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.

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References

1. United Nations. *Urban and Rural Areas 2007*; United Nations: New York, NY, USA, 2007. Available online: http://wwwunorg/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.; Wiliams, 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.; Borrman, 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]

Chapter 4. Effects of projected urbanisation and climate change on flow and nutrient loads of a Mediterranean-climate catchment in South Australia

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Principal Author

Name of Principal Author (Candidate)	Hanh Hong Nguyen		
Contribution to the Paper	Designed the study. Collected and analysed data. Prepared results and wrote the manuscript. Acted as the first and corresponding author. I hereby certify that the statement of the contribution is accurate.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Friedrich Recknagel		
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Contribution to the Paper	Helped to evaluate the results of the manuscript. Helped to review and edit the manuscript. I hereby certify that the statement of the contribution is accurate.		
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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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ABSTRACT

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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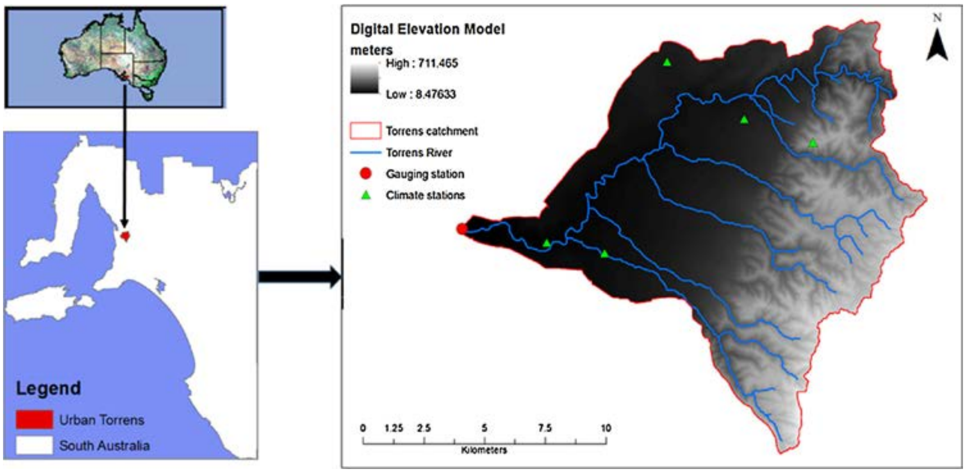

Fig. 1. Study area with topographic map and location of gauging and climate stations.

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

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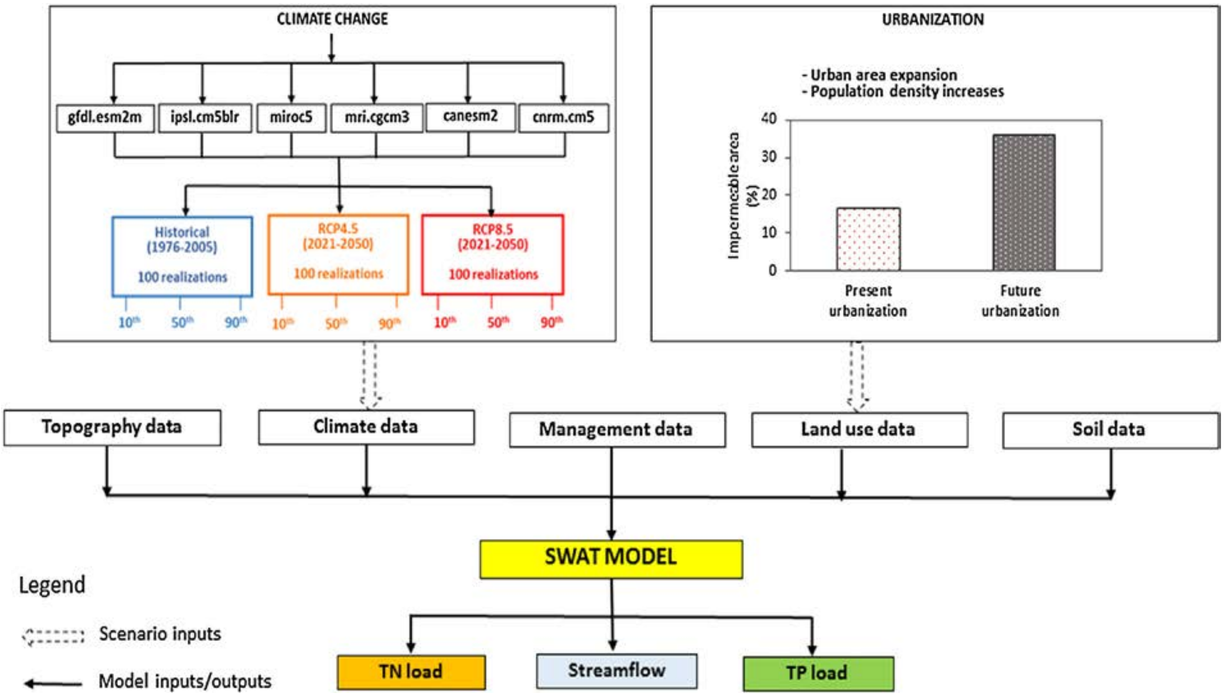

Fig. 2. Conceptual diagram of the study design.

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.

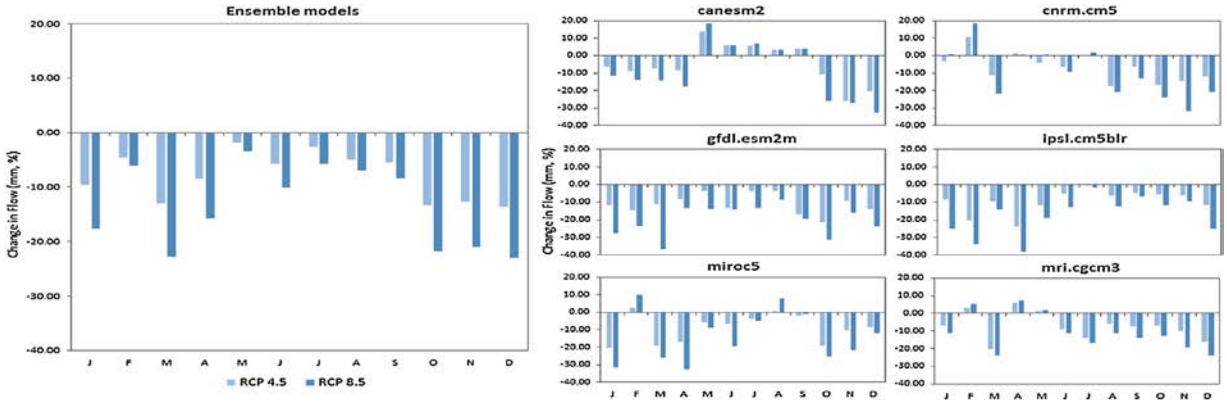

Fig. 3. Relative changes in monthly flow, showing the effects of different climate change projections for the period from 2021 to 2050.

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

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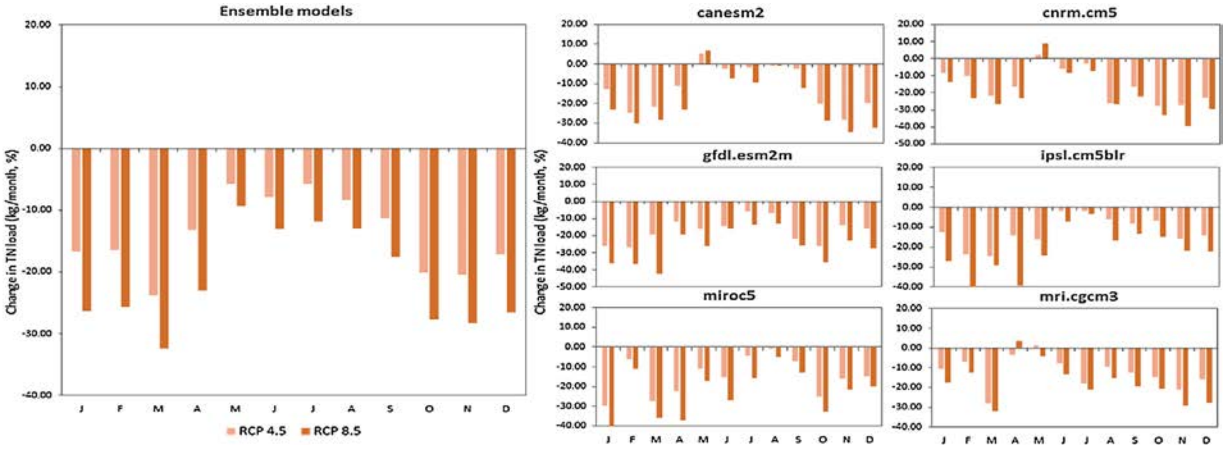

Fig. 4. Relative change of monthly TN deriving from the effects of different climate change projections for the period from 2021 to 2050.

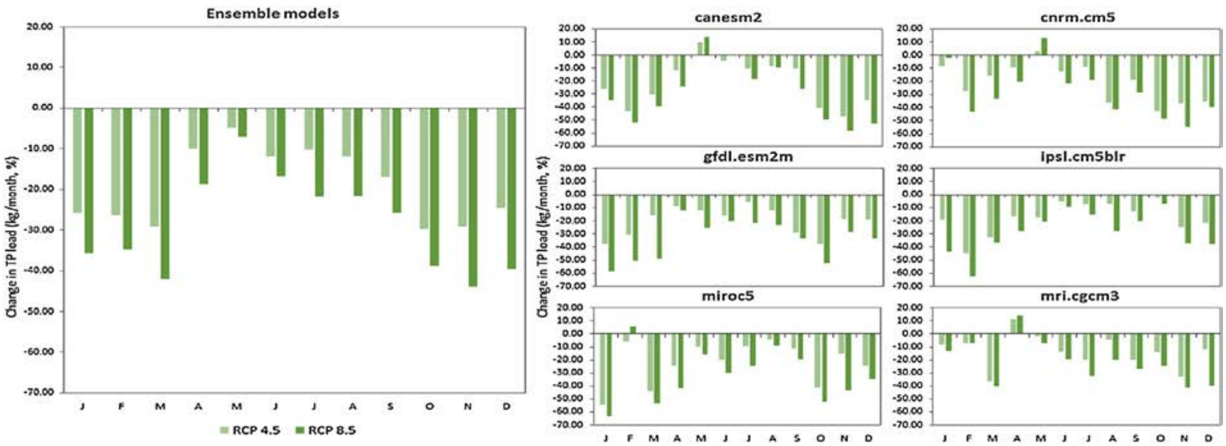

Fig. 5. Relative change of monthly TP deriving from the effects of different climate change projections for the period from 2021 to 2050.

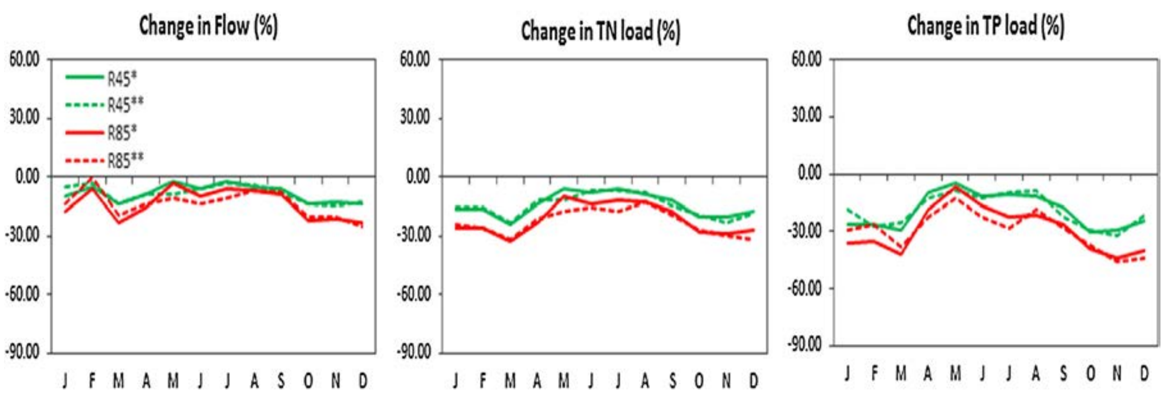

Fig. 6. Deviation of estimated average monthly flow, TN, and TP loads using median versus an ensemble of the 10th, 50th, and 90th percentile realizations of the climate projection data. *Note*: *Using climate data of 10th, 50th, and 90th realizations. **Using the climate data of the median realization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

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

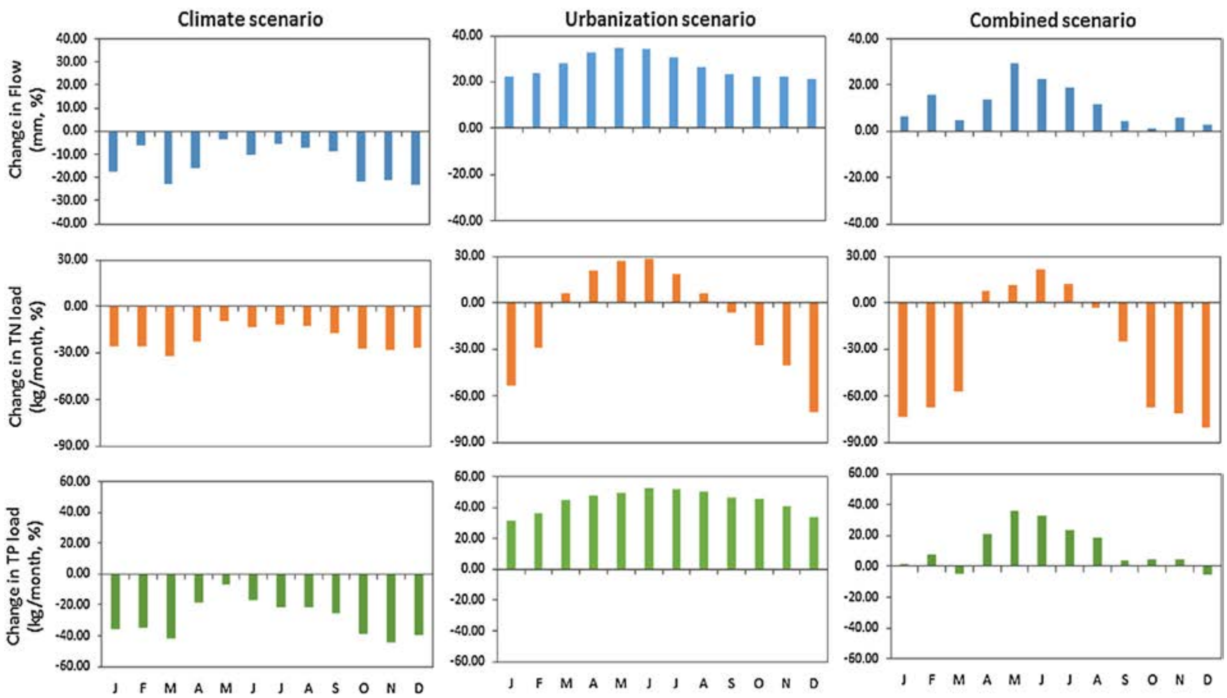

Fig. 7. Relative change of monthly flow, TN, and TP loads due to the effects of climate change, urbanization, and a combined scenario of climate change and urbanization under the high emission scenario RCP 8.5.

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.

Funding body

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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.

References

Abbaspour, K.C., Johnson, C., van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone J. 3, 1340–1352.
Arnold, J.G., Srinivason, R., Muttiah, R.R., Williams, J.R., 1998. Large area hydrologic modelling and assessment.Part I: Model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.
Barron, O., Silberstein, R., Ali, R., Donohue, R., McFarlane, D.J., Hodgson, G., Samrt, N., Donn, M., 2012. Climate change effects on water-dependent ecosystems in south-western Australia. J. Hydrol. 434-435, 95–109.
Brookes, J.D., 2012. River Torrens Water quality improvement trial – Summer 2011/12. Goyder Inst. Water Res. Tech. Rep. 12 (4), 116.
Bureau of Meteorology (BOM). Available online: http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml (accessed on 02.01.2016).
Cai, W., Santoso, A., Wang, G., Weller, E., Wu, L., Ashok, K., Masumoto, Y., Yamagata, T., 2014. Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. Nature 510 (7504), 254–258.
Chang, S.W., Nemec, K., Kalin, L., Clement, T.P., 2016. Impacts of climate change and urbanization on groundwater resources in a Barrier Island. J. Environ. Eng. 142 (12), 1–12.
Charles, S.P., Fu, G., 2015. Statistically downscaled projections for South AustraliaIn: Goyder Institute for Water Research Technical Report Series No. 15/1. , Adelaide, South Australia.
Clark, R., Gonzalez, D., Dilon, P., Charles, S., Cresswell, D., Naumann, B., 2015. Reliability of water supply from stormwater harvesting and managed aquifer recharge with a brackish aquifer in an urbanizing catchment and changing climate. Environ. Modell. Softw. 72, 117–125.
Clark, T., Humphrey, G., Frazer, A., Sanderson, A., Maier, H., 2002. Effectiveness of flow management in reducing the risk of cyanobacterial blooms in rivers. In: Hydrology and Water Resources Symposium, 20–23 May 2002. Institution of Engineers, p. 8.
DPLG, 2010. The 30-Year Plan for Greater Adelaide. A Volume of the South Australian Planning Strategy. Department of Planning and Local Government, In: https://livingadelaide.sa.gov.au/__data/assets/pdf_file/0007/278332/The_30_Year_Plan_for_Greater_Adelaide_2010_compressed.pd (accessed 10.01.2017).
Feyen, L., Dankers, R., 2009. Impact of global warming on streamflow drought in Europe. J. Geophys. Res. 114, 1–17.
Frost, A.J., Charles, S.P., Timbal, B., Chiew, F.H.S., Mehrotra, R., Nguyen, K.C., Chandler, R.E., McGregor, J.L., Fu, G., Kirono, D.G.C., Fernandez, E., Kent, D.M., 2011. A comparison of multi-site daily rainfall downscaling techniques under Australian conditions. J. Hydrol. 408 (1–2), 1–18.
Gale, R.J.B., Gale, S.J., Winchester, H.P.M., 2006. Inorganic pollution of the sediments of the River Torrens, South Australia. Environ. Geol. 50, 62–75.
García-Ruiz, J.M., López-Moreno, J.I., Serrano-Vicente, S.M., Beguería, S., Lasanta, T., 2011. Mediterranean water resources in a global change scenario. Earth Sci. Rev. 105, 121–129.
GIWR, 2015. SA climate ready data for South Australia – a user guideIn: Goyder Institute for Water Research Occasional Paper No. 15/1. , Adelaide, South Australia.
Grimmond, S., 2007. Urbanization and global environmental change: local effects of urban warming. Geogr. J. 173 (1), 83–88.
Hovenga, P.A., Wang, D., Medeiros, S.C., Hagen, S.C., Alizad, K., 2016. The response of runoff and sediment loading in the Apalachicola River, Florida to climate and land use land cover change. 'Earth' Future 4, 124–142.
Ilman, M.A., Gell, P.A., 1998. 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, , pp. 10–53.
Jordan, Y.C., Ghulam, A., Hartling, S., 2014. Traits of surface water pollution under climate and land use changes: a remote sensing and hydrological modelling approach. Earth Sci. Rev. 128, 181–196.
Martinez-Mena, M., Albaladejo, J., Castillo, V.M., 1998. Factors influencing surface runoff generation in a Mediterranean semi-arid environment: Chicamo watershed, SE Spain. Hydrol. Process. 12, 741–754.
Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50 (3), 885–900.
Nassif, S.H., Wilson, E.M., 1975. The influence of slope and rain intensity on runoff and infiltration. Hydrol. Sci. J. 20 (4), 539–553, http://dx.doi.org/10.1080/02626667509491586.
Neitsch, S.L., Arnold, J.G., Kinir, J.R., Wiliams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation 2009. Texas Water Resources Institute-Texas A&M University, College Station (Technical Report No. 406 edn).
Nguyen, H.H., Recknagel, F., Meyer, W., Frizenschaf, J., Shrestha, M.K., 2017. 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. Manage. 202, 1–11.
Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D., Zaehle, S., 2007. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. Proc. Natl. Acad. Sci. U.S.A. 104, 15242–15247.
Qiu, Z., Wang, L., 2014. Hydrological and water quality assessment in a suburban watershed with mixed land uses using the SWAT model. J. Hydrol. Eng. 19 (4), 816–828.
Rebbeck, M., Dwyer, E., Bartetzko, M., Williams, A., 2007. A Guide to Climate Change and Adaptation in Agriculture in South Australia. South Australian Research and Development Institute, Primary Industries and Resources SA and Rural Solutions SA, Urrbrae, Australia, pp. 12–22.
Reside, A.E., VanDerWal, J., Moran, C., 2017. Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. Biol. Conserv. 207, 9–16.
Richards, C.E., Munster, C.L., Vietor, D.M., Arnold, J.G., White, R., 2008. Assessment of a turfgrass sod best management practice on water quality in a suburban watershed. J. Environ. Manage. 86 (1), 229–245.
Schütte, S., Schulze, R.E., 2017. Projected impacts of urbanization on hydrological resource flows: a case study within the uMngeni Catchment, South Africa. J. Environ. Manage. 196, 527–543.
Shread, M.J., Borrman, G.M., 1994. Soils, stratigraphy and engineering geology of near surface materials of the Adelaide Plains Report Book 94/9, vol. 1. , pp. 492.
Shrestha, M.K., Recknagel, F., Frizenschaf, J., Meyer, W., 2017. Future climate and land uses effects on flow and nutrient loads of a Mediterranean catchment in South Australia. Sci. Total Environ. 590–591, 186–193.
Teshager, A.D., Gassman, P.W., Schoof, J.T., Secchi, S., 2016. Assessment of impacts of agricultural and climate change scenarios on watershed water quantity and quality, and crop production. Hydrol. Earth Syst. Sci. 20, 3325–3342.
United Nations, 2007. Urban and Rural areas 2007. United Nations, New York, USA. , In: http://www.un.org/esa/population/publications/wup2007/2007_urban_rural_chart.pdf (accessed 01.05.2017).

Vanderkruk, K., Owen, K., Grace, M., Thompson, R., 2010. Review of existing nutrient, suspended solid and metal modelsIn: Scientific review for Victorian Department of Sustainability and Environment, In: https://ensym.dse.vic.gov.au/docs/DSE_EnSym_WQ_Review_RT051009_final_correction.pdf (accessed 6 January 2017).

Wagner, P.D., Bhallamudi, S.M., Narasimhan, B., Kantakumar, L.N., Sudheer, K.P., Kumar, S., Schneider, K., Fiener, P., 2016. Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment. Sci. Total Environ. 539, 153–164.

Wang, R., Kalin, L., 2018. Combined and synergistic effects of climate change and urbanization on water quality in the Wolf Bay watershed, southern Alabama. J. Environ. Sci. 64, 107–121.

Wang, R., Kalin, L., Kuang, W., Tian, H., 2014. Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. Hydrol. Process. 28, 5530–5546.

Westra, S., Thyer, M., Leonard, M., Kavetski, D., Lambert, M., 2014. Impacts of climate change on surface water in the Onkaparinga catchment. In: Final Report Volume 1: Hydrological Model Development and Sources of UncertaintyGoyder Institute for Water Research, Adelaide, South Australia.

Whitehead, P.G., Lapworth, D.J., Skeffington, R.A., Wade, A., 2002. 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. 6 (3), 455–466.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 54 (1), 101–123.

Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2013. ArcSWAT Interface for SWAT 2012. User's Guide, USDA, Agricultural Research Service, , pp. 464.

Zhang, Y., Xia, J., Shao, Q., Zhai, X., 2013. Water quantity and quality simulation by improved SWAT in highly regulated Huai River Basin of China. Stoch. Environ. Res. Risk Assess. 27, 11–27.

Zoppou, C., 2001. Review of urban storm water models. Environ. Modell. Softw. 16, 195–231.

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Chapter 5. Modelling the impacts of altered management practices and land-use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia

Statement of Authorship

Title of Paper	Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia
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Name of Principal Author (Candidate)	Hanh Hong Nguyen
Contribution to the Paper	Designed the study. Collected and analysed data. Prepared results and wrote the manuscript. Acted as the first and corresponding author. I hereby certify that the statement of the contribution is accurate.
Overall percentage (%)	85%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 10/12/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Contributed to ideas and helped to review the final version of the manuscript. I hereby certify that the statement of the contribution is accurate.
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Contribution to the Paper	Contributed to input data processing and helped to review the results of the manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	11/12/2018

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Research article

Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia

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ABSTRACT

Sustainable management of drinking water reservoirs requires taking into account the potential effects of their catchments' development. This study is an attempt to estimate the daily patterns of nutrients transport in the catchment – reservoir systems through the application of the ensemble of complementary models SWAT-SALMO. SWAT quantifies flow, nitrate and phosphate loadings originating in catchments before entering downstream reservoirs meanwhile SALMO determines phosphate, nitrate, and chlorophyll-a concentrations within the reservoirs. The study applies to the semi-arid Millbrook catchment-reservoir system that supplies drinking water to north-eastern suburbs of Adelaide, South Australia. The catchment hosts viti- and horticultural land uses. The warm-monomictic, mesotrophic reservoir is artificially aerated in summer. After validating the simulation results for both Millbrook catchment and reservoir, a comprehensive scenario analysis has been conducted to reveal cascading effects of altered management practices, land uses and climate conditions on water quality in the reservoir. Results suggest that the effect on reservoir condition in summer would be severe, most likely resulting in chlorophyll-a concentrations of greater than 40 μg/l if the artificial destratification was not applied from early summer. A 50% curbing of water diversion from an external pipeline to the catchment will slightly limit chlorophyll-a concentrations by 1.22% as an effect of reduced inflow phosphate loads. The simulation of prospective land use scenarios converting 50% of present pasture in the Millbrook catchment into residential and orchards areas indicates an increase of summer chlorophyll-a concentrations by 9.5–107.9%, respectively in the reservoir. Global warming scenarios based on the high emission simulated by SWAT-SALMO did result in earlier growth of chlorophyll-a but overall the effects on water quality in the Millbrook reservoir was not significant. However scenarios combining global warming and land use changes resulted in significant eutrophication effects in the reservoir, especially in the unmanaged condition with stratification in summer. This study has demonstrated that complementary model ensembles like SWAT–SALMO allow to comprehend more realistically cascading effects of distinct catchment processes on internal reservoir's processes, and facilitate integrated management scenarios.

1. Introduction

Sustainable catchment management aims at compromises between catchment development and low pollution of drinking water reservoirs. Since the pioneering work by Vollenweider (1975) and Sakamoto (1966), external nutrient loads are accepted as key driving forces for eutrophication in reservoirs. It is also evident that global warming makes lakes and reservoirs more vulnerable to

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eutrophication effects (e.g. Schindler, 1997; Paerl and Huisman, 2009).

A quantitative assessment of effects of land use changes and global warming on catchments and drinking water reservoirs proved to be a challenging task because of the complexity of processes and impact sources. As addressed by Whitehead et al. (2009), the estimation of impacts of climate change solely on the nutrients release and accumulation in catchments owned huge uncertainty due to its natural extreme climatic variability that could cause opposite responses in flow and nutrient dynamics. Impacts on eutrophication in reservoirs is also not straightforward as it is the result of complex interactions of inflow, weather, soil and land use conditions, and is directly affected by the upstream catchment activities (Jeppesen et al., 2005). While numerous studies have been applied through an isolated approach either to stream systems in catchments to indicate potential significant effects on downstream reservoirs or to reservoirs solely through theoretic estimation of potential loads of pollutant from their catchments (e.g. Mehdi et al., 2015; Karlsson et al., 2016; Cianfani et al., 2015), there is a need for a more accurate estimation of cumulative effects on the catchment-reservoir systems in tandem (Kundzewicz et al., 2007; Whitehead et al., 2009). Analyzing such complex scenarios exceeds the scope of a single specific model.

To make such assessment relevant and credible, ensembles of catchment and reservoir models are required that reflect both key processes in catchments as well as in reservoirs (e.g. Arnold and Fohrer, 2005; White et al., 2010; Lerner and Zheng, 2011). The integration of catchment and reservoir models was tested successfully in the study of Debele et al. (2006) but none applications were developed on the externally coupled models of SWAT and CE-QUAL-W2. In a study coupling the catchment model SWAT with a simple empirical equation of phosphate concentration estimation, the ensemble modelling indicated that external nutrient loads from catchment contributed huge contamination, and a successful control of this critical source can help to significantly improve the water quality of the downstream reservoir (Nielsen et al., 2013). However, results from this study were related only to average annual nutrient concentrations, and did not consider consecutive eutrophication effects on phyto- and zooplankton. In another study, White et al. (2010) also combined the SWAT model to simulate the catchment, and the CE-Qual-W2 model to simulate the reservoir. Results from this study confirmed that the target to maintain chlorophyll-a (chl-a) below a defined threshold can only be achieved by controlling the nutrient loads from the upstream catchment by transferring agricultural land into rangeland. Similar to the White et al. (2010) approach, the study of Liu et al. (2015) agreed on the important influence of inflow runoff and nitrogen loads on the reservoir water quality. While the studies provided a variety of scenarios for management practice, effects of global warming and how it might interfere with other impact sources are totally neglected.

The Millbrook catchment-reservoir system covers an area of 36,100 ha and contributes approximately 16% of the drinking water supply for Adelaide, the capital of South Australia (Heneker, 2003). Its semi-arid climate causes already periods of low flow to dry conditions in the streams driven by sporadic heat waves and moderate rainfall (BOM, 2016). It is therefore of great importance to the local water industry to be informed about prospective impacts of future land use and climate changes at catchment-reservoir scale. The ensemble of complementary models SWAT-SALMO aims to suit this purpose by integrating simulation results for flow and nutrient loads of the Millbrook catchment by SWAT (Soil and Water Assessment Tool) with the simulation of nutrient and chl-a concentrations in the Millbrook reservoir by SALMO. The process-based catchment model SWAT (Arnold et al., 1998) simulates flow and in-stream pollutants, and allows to analyze alternative management scenarios of climate and land use changes in catchments (Arnold and Fohrer, 2005; Gassman et al., 2007; Douglas-Mankin et al., 2010; Krysanova and Srinivasan, 2015). The process-based lake model SALMO (Benndorf and Recknagel, 1982; Recknagel and Benndorf, 1982) simulates nutrient and plankton dynamics in lakes and proved to be suitable for scenario analyses of lakes with different environmental and climate conditions (e.g. Recknagel et al., 1995, 2008; Walter et al., 2001; Chen et al., 2014).

Overall this study focused on following objectives: (1) to estimate the daily catchment runoff and nutrient loads to the Millbrook reservoir; (2) to identify daily dynamics of phosphate (PO_4), nitrate (NO_3), and chl-a concentrations within the reservoir; (3) to estimate singular and combined impacts of altered management practices, land uses and warmer climate on the water quality of the Millbrook reservoir by means of scenario analyses. This will support better strategies for the integrated catchment management which considers both effects of the catchment development and environmental aspects of the reservoir protection for drinking water purposes.

2. Materials and methods

2.1. Study area

Millbrook reservoir (−34°49′ S - 138°47′ E) is one of ten drinking water reservoirs of SA (See Fig. 1). The reservoir has a storage capacity of 16,000 ML (Heneker, 2003). The reservoir receives water primarily from its water limited catchment (Nguyen et al., 2017). The average annual temperature is approximately 18 °C with the highest annual temperatures ranging from 27 °C to 29 °C (SILO, 2015). The period of this study coincided with the prolonged drought in SA with the lowest annual rainfall availability of 579 mm (BOM, 2016; Nguyen et al., 2017). During drought periods, water is diverted by pipelines from the river Murray into the reservoir to support the drinking water supply system. Besides, the reservoir is exposed to high nutrients entering from the livestock grazing in the upstream area (EPA, 2007). Aeration is often applied during summer seasons to avoid the risk of algal bloom.

2.2. Data

2.2.1. Input data for SWAT and SALMO

The input data required by the models SWAT and SALMO include the Digital Elevation Model (DEM), land use and soil maps, as well as meteorological, hydrological, and water quality data of the catchment and reservoir. The details of DEM, land use and soil maps required by SWAT are documented in Nguyen et al. (2017). The DEM was prepared using the 10 × 10 m contour interpolation while land use and soil maps were provided at the resolution of 1:100,000. The watershed climate condition was simulated using patched point dataset from the Scientific Information for Land owners which included the daily records of rainfall, maximum and minimum temperature, solar radiation, and relative humidity parameters (SILO, 2015). The wind speed data was simulated using the SWAT weather generator. The map in Fig. 1 illustrates current land uses of the Millbrook catchment including native Eucalyptus and pine tree forests (43.51%), pasture (41.98%), orchards (2.96%), urban land (6.26%) and water bodies such as farm dams (5.29%). Hydrological and water quality data were obtained from three gauging stations (Fig. 1). Data from the Australian Bureau of Statistics (ABS, 2015) and expert knowledge on irrigation and fertilization activities were also incorporated in the SWAT model. No irrigation was applied for Eucalyptus and pasture land uses while vineyards and orchards

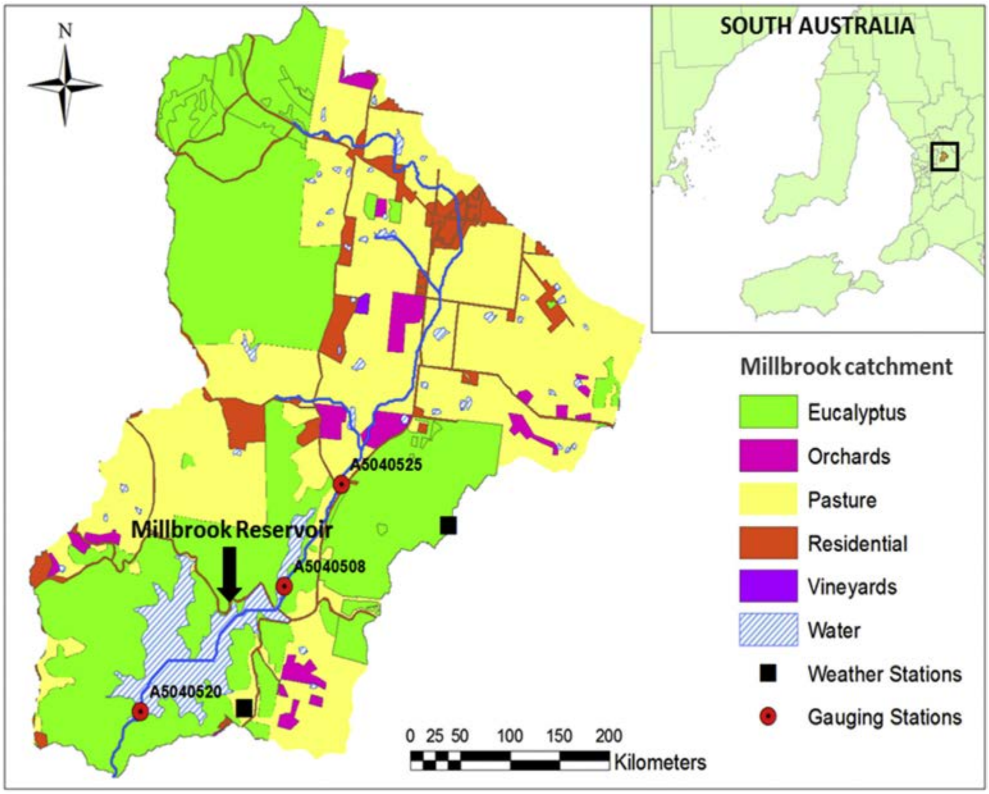

Fig. 1. Map of the study area.

were irrigated with rates of 106 and 509 mm respectively from November until March next year. Fertilizer was applied with the amount of 20 kg N and 5 kg P per ha on pasture and 50 kg N and 15 kg P per ha on orchards.

2.2.2. Projected climate data

Inputs for global warming scenario was extracted from the Goyder Institute Water Research project on development of SA Climate (GIWR, 2015). In this project, the CMIP5 Global Climate Models (GCMs) from IPCC Assessment Report (AR) 5 were selected because they incorporate all climate variables necessary for the downscaling approach (GIWR, 2015). Further, an ensemble of six better performing GCMs were identified, including CanESM2, CNRM-CM5, GFDL-ESM2M, IPSL-CM5B-LR, MIROC5, and MRI-CGCM3. The selection of the six "best" GCMs was based on their ability to reproduce important drivers, including the Indian Ocean Dipole and the El Niño Southern Oscillation (Cai et al., 2014). GCMs are tested using the lower and upper bounds of Representative Concentration Pathways (RCPs) 4.5 and 8.5, respectively, which are comparable to the intermediate B1 and high A1Fl emission scenarios in IPCC AR 4.

The Nonhomogeneous Hidden Markov Modeling (NHMM) technique was used for downscaling the GCM projections following the successful applications across southern Australia territories (e.g. Frost et al., 2011; Charles and Fu, 2014). The NHMM calibrates rainfall at a daily time step at multiple stations as a function of a discrete set of 'weather states' which represents the rainfall spatial patterns across the network of available weather stations. 100 realisations of projected rainfall are the stochastic replicates generated by repeating the statistical downscaling process NHMM 100 times for each GCM/emissions scenario combination. For non-rainfall variables, the downscaling was performed using a weather generator with the projected changes to 2100 obtained from GCM grid-scale output for these variables.

Since only a limited number of simulations could be run with the approach of the ensemble complementary models, this study calculated the projected annual rainfall of each GCM projection and selected the median realization of 100 realizations from the six GCMs suggested by GIWR (2015). For other variables, data from the same selected realization of rainfall variable was selected. The 'observed' records of 2007–2011 from SILO (2015) was used as a 'reference' baseline period for the study.

Due to the fact that the observed available records of the reservoir model fell within the future 'projected' climate period (2006–2100) and were not available for the 'historical' climate period (1961–2006), the study alternatively selected a number of 'projected' climate years that showed a pattern of global warming in SA, i.e. decreased precipitation and increased air temperature, in comparison to the baseline scenario. For this task, the difference in percentage between the 'projected' and 'historical' annual rainfall data, averaged for the thirty years' time slices of 1976–2005 and 2016–2045, was used as standard interval for the selection of specific years of 'projected' data that fell within the calculated range of rainfall decrease. To ensure that not only precipitation but also temperature met the assumption for the scenario, the same approach was used on the daily mean air temperature of six GCMs to filter the years with satisfactory data of both rainfall and temperature for the five years of the global warming scenario (Fig. 2a, b).

As the next step in the SWAT scenario run, the observed 'reference' data were replaced by 'projected' data which incorporated five climate variables, namely rainfall, maximum and minimum temperature, solar radiation, and relative humidity. The study used the Hargreaves PET method for calibration and validation, hence wind speed was not a critical variable and was estimated using a weather generator tool embedded in SWAT.

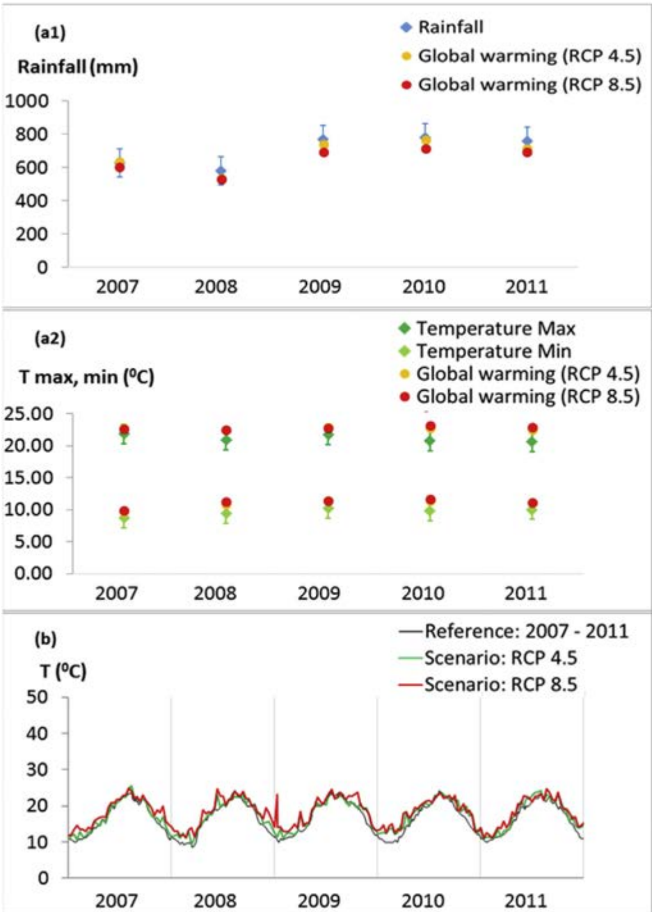

Fig. 2. Results projected by the GCMs for: (a_1) rainfall, (a_2) maximum and minimum air temperature, and (b) water temperature under the scenario of global warming. Error bars show one standard deviation.

Projected daily water temperatures of the Millbrook reservoir have been estimated from the selected daily air temperatures for five years by means of a linear regression between the observed data of air temperature and water temperature from 2000 to 2014. Observed water temperature was collected on a daily to weekly time steps from the three depth of the Millbrook reservoir, i.e. surface, 10 and 20 m depth. The ratio of air and water temperature was used to estimate the 'projected' water temperature of Millbrook reservoir which suggested an increase by 0.75 and 1.3 °C under the global warming of RCP 4.5 and 8.5, respectively (Fig. 2b). That result corresponds with the predicted rise of the global average surface water temperatures by 0.3–4.8 °C reported by O'Reilly et al. (2015).

2.3. Ensemble of complementary models SWAT - SALMO

The conceptual diagram for the models SWAT-SALMO in Fig. 3 illustrates that daily flow and nutrient concentrations in the catchment are simulated by SWAT before being used as inputs for the simulation of daily nutrient and chl-a concentrations in the reservoir by SALMO.

2.3.1. Calibration and validation of the model SWAT

The SWAT model (ArcSWAT version 2012) has been calibrated and validated by measured data from the gauging station A5040525 (see Fig. 1) located approximately 5 km upstream of the Millbrook reservoir. The model delineates the catchment into smaller sub-basins based on topography by means of the DEM, divides the sub-basins into hydrologic response units (HRUs) with unique landscape slopes by means of DEM as well as the specific land uses and soils, calculates hydrological balances, sediment loads and nutrient losses for each HRU aggregated for each sub-basin, and routes each variable through the stream network to the catchment outlet (Neitsch et al., 2011; Arnold et al., 2012).

In this study the surface runoff was calculated using a modification of the Soil Conservation Service (SCS) curve number technique, and water quality parameters were routed in streams using the QUAL2E model (Winchell et al., 2013). The model optimization was conducted by SWAT-CUP using the SUFI2 (Sequential Uncertainty Fitting version 2) (Abbaspour, 2015). The model was calibrated for data from 2007 to 2011 while data from 2012 to 2014 was used for validation. Simulation results for daily flow were evaluated according to Moriasi et al. (2007) by the criteria: $R^2 > 0.5$, Nash-Sutcliffe (NS) > 0.5 and Percent Bias (PBIAS) ± 25%. Results for daily TN and TP loads were examined graphically for matching observed data and by a PBIAS in a range ±70% (Lee et al., 2015).

2.3.2. Calibration of the model SALMO

The daily phosphate and nitrate loads from the catchment simulated by SWAT as well as calculated daily volumes and mixing depths, measured detritus, solar radiation, and water temperatures of the reservoir were used as inputs for the modelling of the Millbrook reservoir by SALMO. The model SALMO is a one-dimensional process-based lake model that allows to simulate concentrations of PO_4, NO_3, DO, detritus, the functional phytoplankton groups as well as herbivorous zooplankton for the mixed water body, and for the epi- and hypolimnion during thermal stratification (See Fig. 3). In this study SALMO was calibrated utilizing flow and nutrient loads from SWAT whereby PO_4 and NO_3 concentrations have been converted from simulated TN and TP concentrations using a monthly conversion factor of PO_4/TP and NO_3/TN from limited weekly to bi-monthly observed PO_4 and weekly observed NO_3 concentrations available in the period from 2007 to 2012. The calibration was performed for the five years of data including the dry years 2007/08 and 2008/09, the wet years 2010/11 and 2011/12, and the average year 2009/10 starting from July until June of the following year. The goodness of fit of the model was evaluated on the basis of the Root Mean Square Error (RMSE) for the state variables X calculated as follows:

$$\text{RMSE (X)} = \sqrt{\frac{\sum_{i=1}^{m}\left(\widehat{X}_i - X_i\right)^2}{m}},$$

where m is the total day number, X_i and $\widehat{X}_i$ are the measured and simulated values of X on the ith day respectively.

2.3.3. Scenario analysis

The calibrated SWAT and SALMO models were applied to simulate the scenarios defined in Table 1. The simulation results for all scenarios were assessed by the 'dry' 12 months from 07/2008 to 06/2009 and the 'wet' 12 months from 07/2010 to 06/2011. The scenario 1 aimed to reveal water quality conditions under natural thermal stratification of the Millbrook reservoir, to inform about the effect of artificial destratification on water quality operated in the reservoir. Since the following scenarios were applied to data of the destratified reservoir, its effect on water quality needs to be taken into account. The scenario 2 aimed to identify the impact of seasonally imported water from the River Murray to the catchment on the water quality of the reservoir, by reducing the imported water volume by 50%. The scenario 3 and 4 simulated effects of

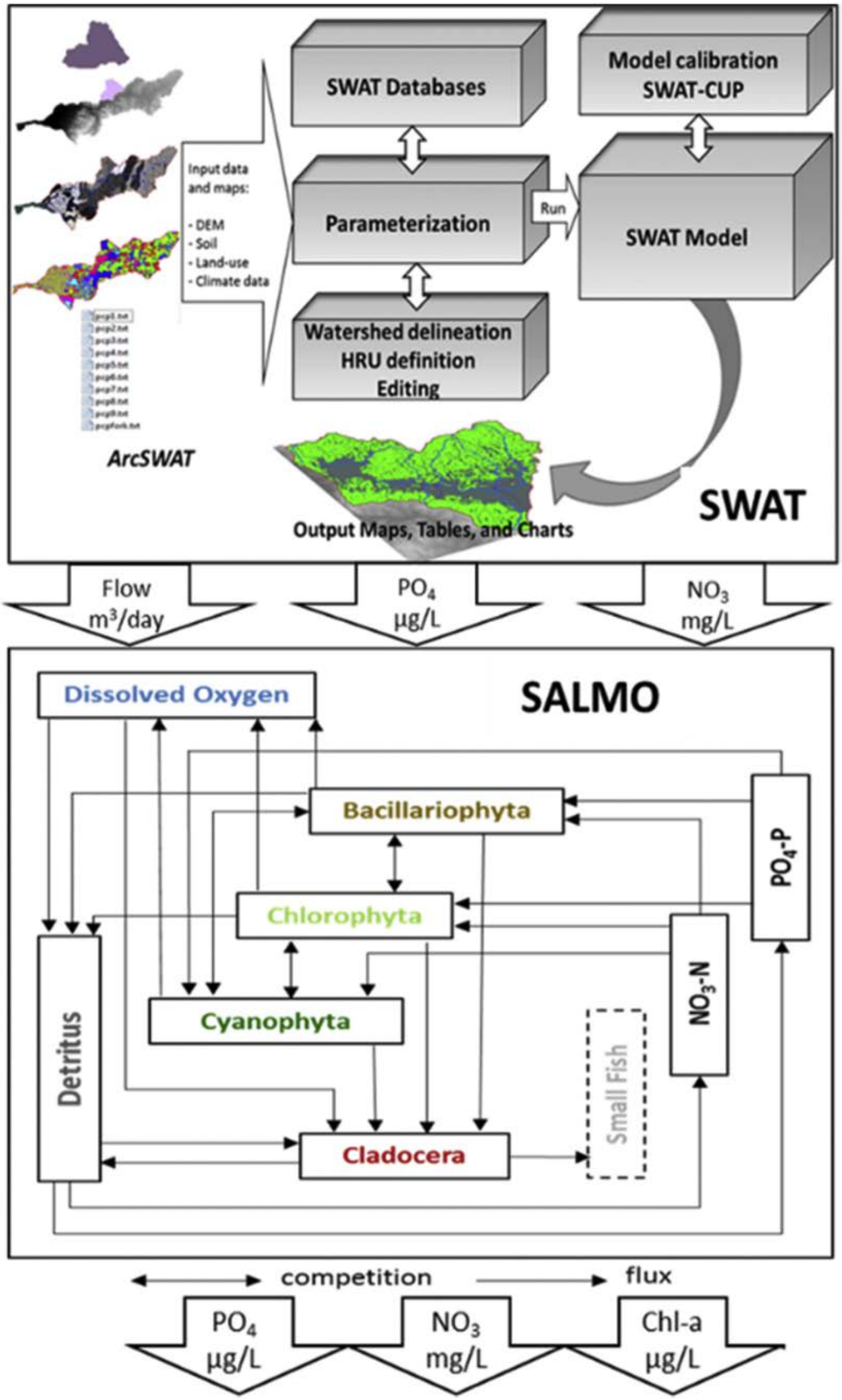

Fig. 3. Conceptual diagram of the models SWAT-SALMO.

Table 1
Summary of scenarios simulated by SWAT-SALMO for the Millbrook catchment-reservoir system.

Scenarios	Scenario Control by SWAT	Scenario Control by SALMO
1 Thermal stratification of the reservoir during summer		Providing separate input data for epi- and hypolimnion
2 Restricting import of external river water to the catchment by 50%	Simulating flow and nutrient loads in the catchment by reducing the pipeline contribution by 50%	Providing input data for altered flow and nutrient loads from SWAT
3 Converting 50% of pasture of the catchment into residential areas	Simulating flow and nutrient loads in the catchment by changing the land use map accordingly	Providing input data for altered flow and nutrient loads from SWAT
4 Converting 50% of pasture of the catchment into orchards	Simulating flow and nutrient loads in the catchment by changing the land use map accordingly	Providing input data for altered flow and nutrient loads from SWAT
5 Impact of global warming on water quality of the reservoir		Providing projected input data for water temperature (and solar radiation)
6 Impact of global warming al high emission (RCP 8.5) on flow and nutrient load in the catchment and on water quality of the reservoir Combination of scenarios	Simulating flow and nutrient loads in the catchment by utilising projected rainfall and air temperature data	Providing input data for altered flow and nutrient loads from SWAT, and projected input data for water temperature (and solar radiation)

replacing 50% of the pasture areas which are located upstream of the reservoir by residential areas or orchards on the water quality of the reservoir. This corresponds with an increase of approximately three times of residential and orchard land areas, i.e. of 537 ha and 544 ha, respectively. The scenarios 5 and 6 analyzed possible effects of global warming under high emission scenarios on the water quality of the reservoir only, and on both the nutrient loads from the catchment and the water quality of the reservoir, projected for a five years period in the coming 30 years. On the basis of outputs from single scenarios, the combined scenario of global warming under high emission scenario was performed with scenarios 1 to 4 to further reveal potential extreme effects that might happen in the upcoming 30 years span.

3. Results

3.1. Calibration and validation of SWAT-SALMO models

SWAT has been calibrated consecutively for flow, and loads of TN and TP. Before using auto-calibration, manual adjustment of parameters related to plant and urban data proved to be advantageous also recommended by Abbaspour et al. (2007, 2015), Neitsch et al. (2011) and Arnold et al. (2012). The resulting daily flow simulations achieved satisfactory statistics both for calibration and validation periods, with NS (0.59 and 0.63), R^2 (0.60 and 0.67), PBIAS ($-1.2 \div 1.5$), and the uncertainty band (p-factor = 0.25 and 0.34, r-factor = 0.42 and 0.52). The simulated TN loads achieved a very good PBIAS between −4.7 and −9.9 according to recommendations by Moriasi et al. (2007). However, the simulated TP load slightly overestimated the observed magnitudes as reflected by the PBIAS values of −71.4 for calibration, most likely as the result of missing data during dry months.

In order to optimize SALMO, the model inputs of flow and nutrient concentrations simulated by SWAT were firstly compared with measured data recorded at the station A5040525 (see Fig. 4a). The simulated flows and nutrient concentrations matched well the observed data as indicated by a PBIAS of 11.30, 11.58, and − 0.8 for flow, nitrate and phosphate concentrations, respectively. This justified the use of SWAT outputs as inputs for the SALMO simulations.

The nutrient and chl-a concentrations in the Millbrook reservoir simulated by SALMO matched well with the seasonal dynamics of observed data, as reflected by Fig. 4b and the R^2 values of 0.46 and 0.47 for PO_4 and NO_3 concentrations, respectively. Highest R^2 values were achieved for PO_4 in 2009 with 0.95 and for NO_3 in 2008 with 0.82. For chl-a, the average R^2 was 0.06 and the highest value was 0.15 simulated for 2010. The low R^2 values of chl-a calibration might be explained by the fact that the observed data was recorded from the surface water at the dam wall of the reservoir while SALMO simulates the average chl-a across the water column. Overall, the calibration results met the satisfactory criteria but differed significantly year by year.

3.2. Scenario analysis

The scenario 1 suggested that thermal stratification during summer has a significant effect on the water quality of the Millbrook reservoir (Fig. 5a). Whilst the PO_4 and NO_3 concentrations elevated in the hypolimnion layer of the reservoir during summers of both ‘dry’ and ‘wet’ years, the simulated chl-a concentrations in the epilimnion doubled compared to the reference data under mixed conditions. These results confirm the risk of eutrophication caused by the high nutrients runoff from the pasture lands in the Millbrook catchment as reported by EPA (2007).

The second scenario showed no significant effects of 50% reduced import of external river water on the water quality of the Millbrook reservoir in the ‘dry’ year (Fig. 5b). By contrast, the ‘wet’ year responded to the reduced inflow by lowering concentrations of PO_4 by 10.1% and of NO_3 by 5.2% in the Millbrook reservoir, resulting in a chl-a concentration decrease by 1.22% in summer (Fig. 5b). However, whilst limiting the intake of external river water might not be viable for sustained drinking water supply under the semi-arid climate of the catchment, the scenario highlights concerns regarding the additional nutrient loads carried by the river water.

Outcomes of the scenarios 3 and 4 revealed that an extension of orchards had a much higher impact on water quality of the Millbrook reservoir than new residential areas (see Fig. 6). The introduction of orchards and residential areas on pasture land by less than 10% showed minor effects while it became most notable at land use changes greater than 50%. At 50% replacement rate, the scenario 3 resulted in a 3.21% increase of runoff with approximately 10% lower PO_4 and 5% lower NO_3 concentrations from the catchment to the reservoir (Table A, Supplementary data) showing only a minor increase of summer chl-a concentrations by 0.11% (Fig. 6a). These findings suggests that soil imperviousness by growing urbanization is increasing the surface runoff that carries less nutrients (e.g. Groffman et al., 2003; Fleming et al., 2010). The scenario 4 resulted in elevated concentration of PO_4, NO_3 and chl-a in the Millbrook reservoir increasing from 44.2 to 113.67 μg/L, 0.84 to 1.27 mg/L, and 21.87 to 121.51 μg/L, respectively. These effects can be explained by the use of inorganic fertilizers that is a common

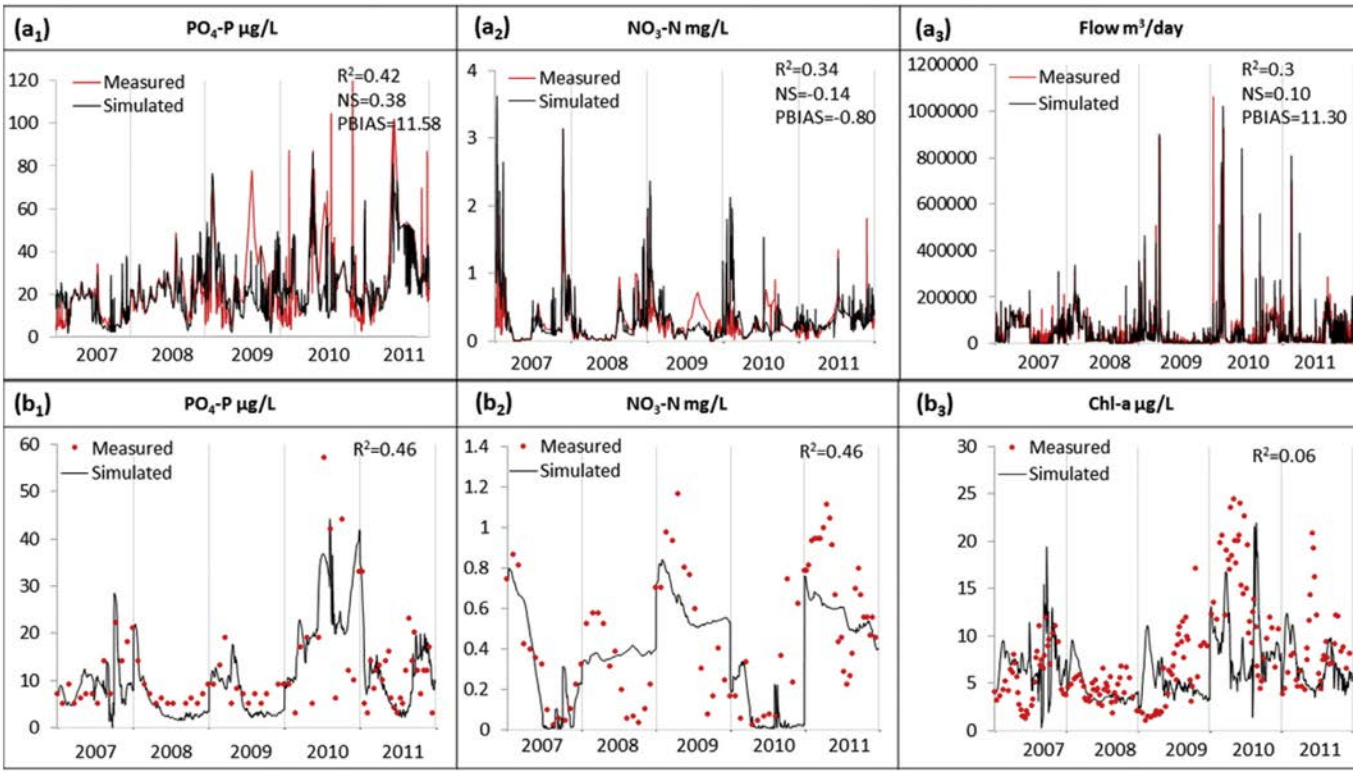

Fig. 4. Results of SALMO inputs simulated by SWAT (a_1, a_2, a_3) and SALMO outputs (b_1, b_2, b_3) for the Millbrook reservoir from 2007 to 2011.

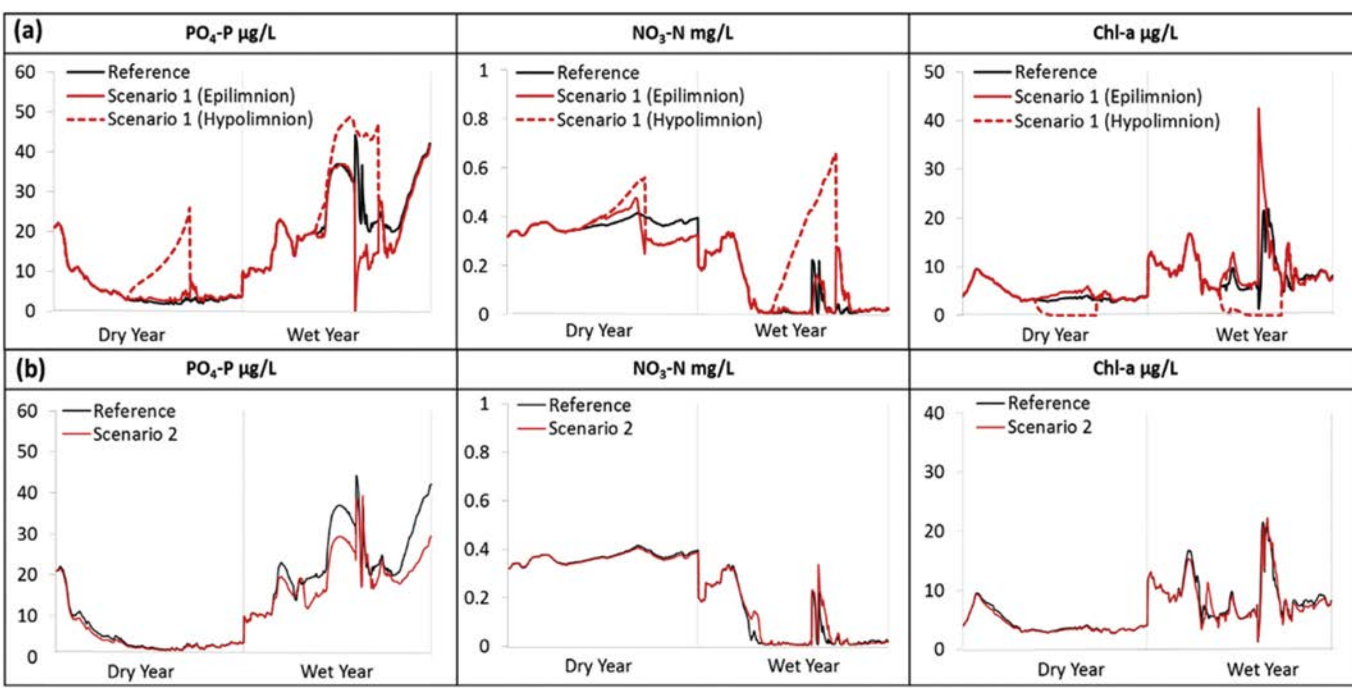

Fig. 5. Comparison of measured reference data of PO_4, NO_3 and chl-a of the Millbrook reservoir with simulated data for: (a) stratification and (b) 50% reduced import of external river water to the Millbrook catchment.

practice in horticulture (e.g. Fleming et al., 2010). However, considering the semi-arid condition in the region and the general global warming trend, the expansion of orchards is less likely to happen since horticulture production is limited during dry years (ABS, 2015; Nguyen et al., 2017). Similar to the first two scenarios, the land use change scenarios showed higher effects on the reservoir water quality during the 'wet' year than during the 'dry' year.

The global warming data projected by the GCM for the RCP 8.5 in Fig. 2a display a decrease of rainfall by 9.2% and an increase of maximum air temperatures by 5.8%, respectively. When

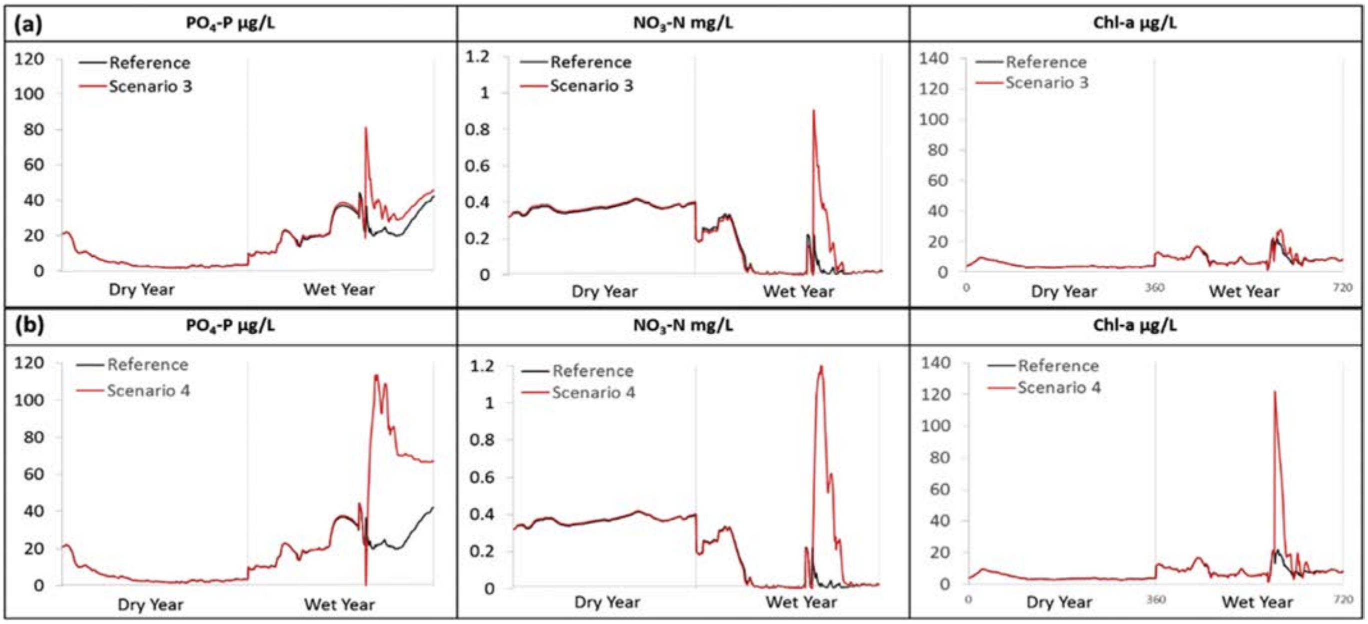

Fig. 6. Comparison of measured reference data of PO_4, NO_3 and chl-a in the Millbrook reservoir with simulated data after replacing 50% of pasture in the Millbrook catchment by: (a) residential areas and (b) orchards.

transformed into water temperatures, it yielded in an average increase by 1.3 °C (see Fig. 2b). Even though accelerated evaporation rates and bio-chemical processes under such altered conditions would be expected to effect the water quality of the reservoir, the scenario 5 revealed a 2.3% increase in PO_4 but only a 0.02% increase in the chl-a concentration occurring earlier in summer (Fig. 7a). As already indicated by scenario 1, this result confirms that artificial destratification of the Millbrook reservoir may successfully prevent high algal growth under the influence of future climate change.

The scenario 6 simulated combined effects of global warming under high emission (RCP 8.5) on the Millbrook reservoir taking into account higher surface water temperatures and altered water runoff from the catchment that resulted in a 13.59% higher chl-a concentration in summer. Even though simulation results indicated a decrease in the water runoff from the catchment, phosphate concentration increased most likely driven by more intense microbial and photochemical decomposition of organic matter.

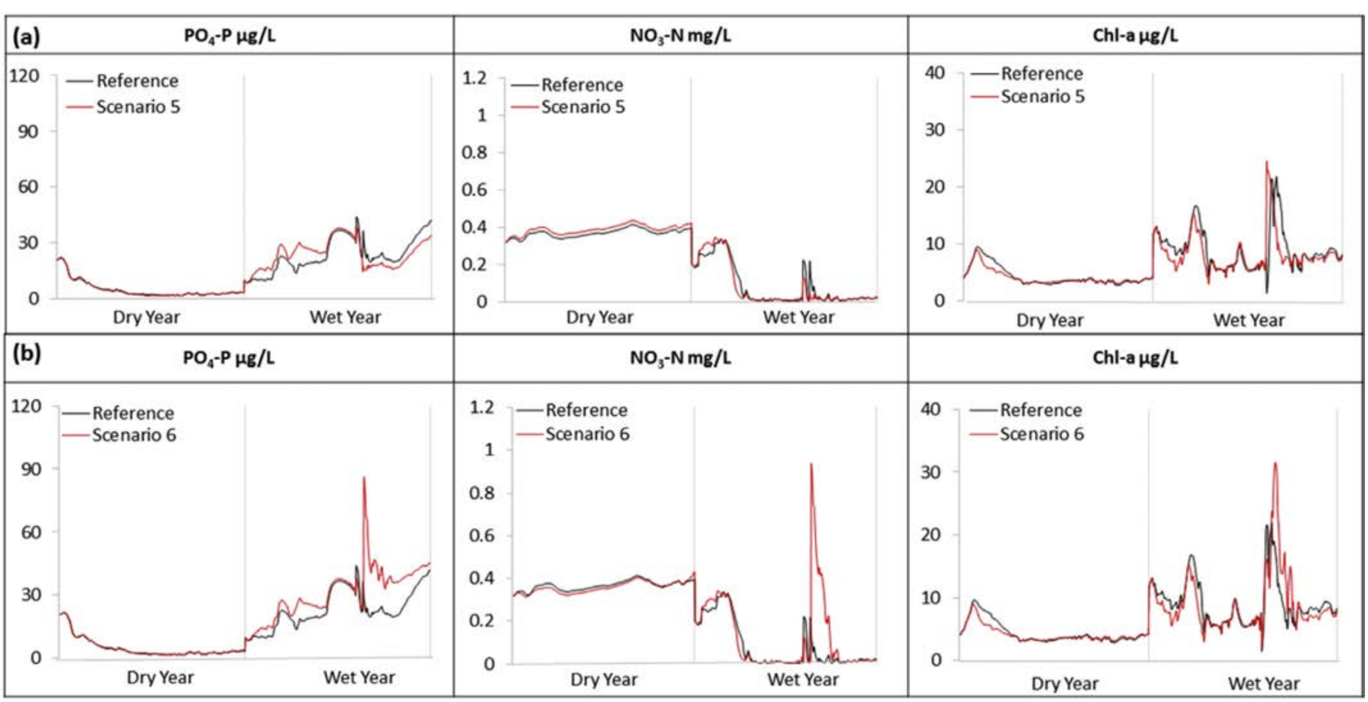

Fig. 7. Comparison of measured reference data of PO_4, NO_3 and chl-a of the Millbrook reservoir with simulated data for global warming at RCP 8.5 affecting: (a) the reservoir only and (b) both the catchment and the reservoir.

Table 2
Summary of the simulation results for the singular and mixed scenarios of the Millbrook catchment (*Note: Bars in red indicate highest while in green indicate lowest values*).

Model variables		Single scenarios				Combined scenarios	
		1	2	3	6	3+6	1+3+6
Inputs							
Change in Inflow	10.00%, 0.00%, -10.00%, -20.00%, -30.00%	0.00%	-19.49%	3.21%	-0.51%	4.23%	4.23%
Change in Inflow Phosphate concentration	10.00%, 0.00%, -10.00%, -20.00%	0.00%	-10.12%	-9.34%	8.18%	0.25%	0.25%
Change in Inflow Nitrate concentration	4.00%, 2.00%, 0.00%, -2.00%, -4.00%, -6.00%	0.00%	-5.17%	-4.72%	2.84%	1.36%	1.36%
Change in Water temperature	15.00%, 10.00%, 5.00%, 0.00%	0.00%	0.00%	0.00%	9.99%	9.99%	9.99%
Outputs							
Change in Chl-a (Summer Months)	60.00%, 40.00%, 20.00%, 0.00%, -20.00%	31.70%	-1.22%	9.52%	13.59%	8.06%	52.43%

4. Discussion

Processes in drinking water reservoirs can't be studied in isolation but must take into account dynamics of complex processes occurring in upstream catchments. This is of growing importance in view of the fact that global warming and population growth not only alter the hydrology and land uses in catchments but also biochemical processes in soils and water bodies. In this study the potential of the complementary model ensemble SWAT-SALMO has been tested to reveal single and combined effects of changing hydrology, land uses, and climate within the Millbrook catchment-reservoir system.

The Millbrook system experiences semi-arid climate that suffices only seasonal flow in the streams and thermally stratifies the reservoir favoring cyanobacteria blooms. To overcome these threads for sustainable water supply, the South Australian Water Corporation took the precautionary measures to seasonally divert water from the River Murray to the catchment, and prevent thermal stratification of the reservoir during summer by artificial mixing. Addressing these two measures, the scenarios 1 asked the question what would happen if the reservoir would remain thermally stratified, and scenario 2 what would happen if only 50% of the current volume of river water would be imported. The scenario 1 proved that artificial mixing is efficient by constraining the algal biomass in the reservoir by approximately 40%. The scenario 2 revealed that regardless of the reduced flow, the reservoir receives lower phosphate concentrations resulting in slightly lower chl-a concentrations. This finding hints at the fact that the imported river water carries higher phosphate concentrations than the catchment streams, possibly manageable by constructed wetlands to treat the imported river water before it is released to the catchment.

The Millbrook catchment is traditionally used for some fruit growing and viticulture, but increasingly attracts residents with a sense for rural life. Even though prospective extensions of residential areas may increase the catchment runoff by 2.3%, it doesn't cause a noticeable effect on chl-a concentrations as shown by scenario 3 (Fig. 6a; Table 2). Future extensions of land uses by orchards seem to cause severe impacts on eutrophication processes in the reservoir reflected by a peak concentrations of chl-a of 121.51 μg/L for the wet year by scenario 4 (Fig. 6b).

Forecasts suggest that global warming causes higher air and water temperatures as well as more frequent storm and drought events (e.g. IPCC, 2013), affecting terrestrial and freshwater systems through multiple pathways. To forecast likely impacts of global warming on a drinking water reservoir, it is therefore essential to consider both direct effects on its water quality and indirect effects from its catchment. The scenario 5 indicates that increased water temperatures under the impact of the global warming at RCP 8.5 don't alter nutrient and chl-a concentrations significantly. However, when additionally indirect effects from the catchment have been taken into account in scenario 6, an increase of phosphate by 8.2% and of chl-a by 13.6% can be expected in a wet year as an effect of increased nutrient loads into the reservoir as simulated by the

SWAT scenario (Table 2).

The likely coincidence of growing residential areas and global warming over the coming 30 years had been considered by combining assumptions of scenarios 3 and 6. Results in Table 2 indicate that reduced nutrient loads from extended residential areas would result in a slightly lower chl-a concentration compared to scenario 6, even though 10% higher water temperatures would occur. By contrast, severe eutrophication effects could be expected when assuming that growing residential areas and global warming apply to a thermally stratified Millbrook reservoir. It is expected to most likely resulting in a 50% increase of chl-a. Results from the combined scenarios 1, 3, and 6 again justify measures to artificially destratify the reservoir during summer.

5. Conclusions

This study has demonstrated that single lake models can't comprehend complex direct and indirect effects of changing environmental and climate conditions on lake eutrophication, and that complementary model ensembles such as SWAT-SALMO are vitally important to not only consider complex processes within but also between catchments and reservoirs. Such model ensembles are prerequisite for studying cascading effects of future scenarios between catchment and reservoir.

After calibrating and validating SWAT and SALMO separately, scenarios simulated by the model ensemble resulted in following findings:

(1) The current artificial mixing of the Millbrook reservoir in summer is successfully preventing possible excessive algal growth.
(2) The external river water imported to the Millbrook catchment carries higher phosphorus loads than its local stream water rising the risk of higher algal growth.
(3) The extension of orchards at current pasture areas in the Millbrook catchment most likely increases nutrient loads to the reservoir whilst extended residential areas increase the flow but slightly lower nutrient loads.
(4) Global warming at RCP 8.5 applied solely to the reservoir increases water temperatures with little effect on algal growth in the destratified reservoir. However, when applied to both systems, the combination of intensified nutrient release from the catchment and increased water temperatures resulted in significantly higher chl-a concentrations in the reservoir.
(5) The possible scenario for the upcoming 30 years for the Millbrook system of global warming at RCP 8.5 and extended residential areas suggests little eutrophication effects in the destratified reservoir but may pose the risk of harmful algal blooms in a thermally stratified Millbrook reservoir.

The global warming scenario in this study was simplified on the basis of extracting a part of downscaled GCMs provided by GIWR (2015). The uncertainty of SWAT to SALMO model was not considered either. Future research will build on outcomes of this study by taking advantage of improved seasonal management of the river pipeline and searching for most sustainable land use developments in the Millbrook catchment. Also, the accuracy of simulation results by the models SWAT-SALMO can be further improved by monitoring the reservoir and stream sites in the catchment more frequently. This is important because of the significant uncertainty that is currently inherent to the inputs of both models and causes not fully satisfying calibration results. The outputs of the global warming single and combined scenarios can also further be refined based on the ensemble of climate projections and the uncertainty bound of both models. This requires comprehensive uncertainty analyses of SWAT and SALMO.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.07.014.

References

Abbaspour, K.C., 2015. SWAT-CUP: SWAT Calibration and Uncertainty Programs – A User Manual. Eawag, 2015. 100pp.
Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Boger, K., Mieletner, J., Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. Hydrol. 333, 413–430.
Arnold, J.G., Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrol. Process. 19 (3), 563–572.
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., Kannan, N., Jha, M.K., 2012. SWAT: model use, calibration, validation. Trans. ASABE Am. Soc. Agric. Eng. 55 (4), 1491–1508.
Arnold, J.G., Srinivason, R., Muttiah, R.R., Williams, J.R., 1998. Large area hydrologic modelling and assessment. Part I: model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.
Australian Bureau of Statistics (ABS) (2015) Available: http://www.abs.gov.au/AUSSTATS/abs@.nsf/allprimarymainfeatures/A5A4DA2DF9F997A0CA2571AD007DDFD4?opendocument. Accessed October, 2015.
Benndorf, J., Recknagel, F., 1982. Problems of application of the ecological model SALMO to lakes and reservoirs having various trophic states. Ecol. Model. 17, 129–145.
Bureau of Meteorology (BOM), 2016. State of the Climate 2016. Report. 23 pp. Available: http://www.bom.gov.au/state-of-the-climate/. Accessed September, 2016.
Cai, W., Santoso, A., Wang, G., Weller, E., Wu, L., Ashok, K., Masumoto, Y., Yamagata, T., 2014. Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. Nature 510 (7504), 254–258. http://dx.doi.org/10.1038/nature13327.
Charles, S.P., Fu, G., 2014. Statistically Downscaled Projections for South Australia – Task 3 CSIRO Final Report. Goyder Institute for Water Research Technical Report Series No. 15/1, Adelaide, South Australia.
Chen, Q., Zang, C., Recknagel, F., Guo, J., Banckaert, K., 2014. Adaptation and multiple parameter optimization of the simulation model SALMO as prerequisite for scenario analysis on a shallow eutrophic lake. Ecol. Model. 273, 109–116.
Cianfani, C., Satizábal, H.F., Randin, C., 2015. A spatial modelling framework for assessing climate change impacts on freshwater ecosystems: response of brown trout *(Salmo trutta L.)* biomass to warming water temperature. Ecol. Model. 313, 1–12.
Debele, B., Srinivasan, R., Parlange, J.Y., 2006. Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins. Environ. Model Assess. http://dx.doi.org/10.1007/s10666-006-9075-1, 19pp.
Douglas-Mankin, K.R., Srinivasan, R., Arnold, J.G., 2010. Soil and water assessment tool (SWAT) model: current developments and applications. Trans. Am. Soc. Agric. Biol. Eng. (ASABE) 53, 1423–1431.
EPA, 2007. Protecting Drinking Water Quality into the Future—priority Areas and Land Use Compatibility in Adelaide's Mount Lofty Ranges Watershed. Report. SA Water, Catchment Research Centre for Water Quality and Treatment and Environment Protection Authority. ISBN 978-1-921125-06-5.
Fleming, N., Cox, J., He, Y., Thomas, S., Frizenschaf, J., 2010. Analysis of Constituent Concentrations in the Mount Lofty Ranges for Modelling Purposes eWater Cooperative Research Centre Technical Report. 37pp.
Frost, A.J., Charles, S.P., Timbal, B., Chiew, F.H.S., Mehrotra, R., Nguyen, K.C., Chandler, R.E., McGregor, J.L., Fu, G., Kirono, D.G.C., Fernandez, E., Kent, D.M., 2011. A comparison of multi-site daily rainfall downscaling techniques under Australian conditions. J. Hydrol. 408 (1–2), 1–18. http://dx.doi.org/10.1016/j.jhydrol.2011.06.021.
Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The Soil and Water Assessment Tool: historical development, applications and future research directions. Trans. Am. Soc. Agric. Biol. Eng. (ASABE) 50 (4), 1211–1250.
Goyder Institute for Water Research, (GIWR), 2015. SA climate ready data for South Australia - a user guide. Goyder Inst. Water Res. Occas. Pap. 15 (1), 1–22.
Groffman, P.M., Bain, D.J., Band, L.E., Belt, K.T., Brush, G.S., Grove, J.M., Pouyat, R.V.,

Yesilonis, I.C., Zipperer, W.C., 2003. Down by the riverside: urban riparian ecology. Front. Ecol. Environ. 6 (1), 315–321.
Heneker, T.M., 2003. Surface Water Assessment of the Upper River Torrens Catchment. The Department of Water, Land and Biodiversity Conservation. Report DWLBC 2003/2004.178pp.
IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, New York, 1535pp.
Jeppesen, E., Sondergaard, M., Jensen, J.P., Havens, K.E., Anneville, O., Carvalho, L., Coveney, M.F., Deneke, R., Dokulil, M.T., Foy, B., Gerdeaux, D., Hampton, S.E., Hilt, S., Kangur, K., Kohler, J., Lammens, E.H.H.R., Lauridsen, T.L., Manca, M., Miracle, M.R., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R., Romo, S., Schelske, C.L., Straile, D., Tatrai, I., Willen, E., Winder, M., 2005. Lake responses to reduced nutrient loading—an analysis of contemporary long-term data from 35 case studies. Freshw. Biol. 50, 1747–1771.
Karlsson, I.B., Sonnenborg, T.O., Refsgaard, J.C., Trolle, D., Børgesen, C.D., Olesen, J.E., Jeppesen, E., Jensen, K.H., 2016. Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change. J. Hydrol. 535, 301–317.
Krysanova, V., Srinivasan, R., 2015. Assessment of climate and land use change impacts with SWAT. Reg. Environ. Change 15, 431–434.
Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., Shiklomanov, I.A., 2007. Freshwater resources and their management. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 173–210.
Lee, T., Wang, X., White, M., Tuppad, M., Srinivasan, R., Narasimhan, B., Andrews, D., 2015. Modeling water-quality loads to the reservoirs of the upper trinity river basin, Texas, USA. Water 7, 5689–5704. http://dx.doi.org/10.3390/w7105689.
Lerner, D.N., Zheng, C., 2011. Integrated catchment management: path to enlightenment. Hydrol. Process. 25, 2635–2640. http://dx.doi.org/10.1002/HYP.8064.
Liu, M., Chen, X., Yao, H., Chen, Y., 2015. A coupled modelling approach to evaluate nitrogen retention within the Shanmei Reservoir watershed, China. Estuar. Coast. Shelf Sci. 166, 189–198.
Mehdi, B., Lehner, B., Gombault, C., Michaud, A., Beaudin, I., Sottile, M.F., Blondlot, A., 2015. Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. Agric. Ecosyst. Environ. 213, 47–60.
Moriasi, D.N., Arnold, J., Van Liew, M., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASAE Am. Soc. Agric. Eng. 50, 885–900.
Neitsch, S.L., Arnold, J.G., Kinir, J.R., Wiliams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation 2009. Technical report no. 406 edn. Texas Water Resources Institute-Texas A&M University, College Station.
Nguyen, H.H., Recknagel, F., Meyer, W., Frizenschaf, J., 2017. Analysing the effects of Forest cover and Irrigation farm dams on streamflows of water-scarce catchments in South Australia through the SWAT model. Water 33 (9), 1–16. http://dx.doi.org/10.3390/w9010033.
Nielsen, A., Trolle, D., Me, W., Luo, L., Han, B.P., Liu, Z., Olesen, J.E., Jeppesen, E., 2013. Assessing ways to combat eutrophication in a Chinese drinking water reservoir using SWAT. Mar. Freshw. Res. 64, 475–492.
O'Reilly, C.M., Sharma, S., Gay, D.K., Hapton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., et al., 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. 42 (24), 10,773–10,781. http://dx.doi.org/10.1002/2015GL066235.
Paerl, H., Huisman, J., 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. Environ. Microbiol. Rep. 1 (1), 27–37.
Recknagel, F., Benndorf, J., 1982. Validation of the ecological simulation model SALMO. Int. Revue Hydrobiol. 67, 113–125.
Recknagel, F., Hosomi, M., Fukushima, T., Kong, D.S., 1995. Short and long-term control of external and internal phosphorus loads in lakes—a scenario analysis. Water Res. 29 (7), 1767–1779.
Recknagel, F., Van Ginkel, K., Cao, H., Cetin, L., Zhang, B., 2008. Generic limnological models on the touchstone: testing the lake simulation library SALMO-OO and the rule-based Microcystis agent for warm-monomictic hypertrophic lakes in South Africa. Ecol. Model. 215, 144–158.
Sakamoto, M., 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Fundam. Appl. Limnol. 62 (1).
Schindler, D.W., 1997. Widespread effects of climate warming on freshwater ecosystems in North America. Hydrol. Process. 11, 1043–1067.
Scientific Information for Land Owners (SILO) (2015) Available at: http://www.longpaddock.qld.gov.au/silo/ppd/index.php.
Vollenweider, R.A., 1975. Input – output models. With special reference to the phosphorous load concept in limnology. Schweiz. Z. fur Hydrol. 37, 53–84.
Walter, M., Recknagel, F., Carpenter, C., Bormans, M., 2001. Predicting eutrophication effects in the Burrinjuck Reservoir (Australia) by means of the deterministic model SALMO and the recurrent neural network model ANNA. Ecol. Model. 146 (1), 97–113.
White, J.D., Prochnow, S.J., Fistrup, C.T., Byars, B.W., 2010. A combined watershed–water quality modelling analysis of the Lake Waco reservoir: II. Watershed and reservoir management options and outcomes. Lake Reserv. Manag. 26 (2), 159–167.
Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 54 (1), 101–123. http://dx.doi.org/10.1623/hysj.54.1.101.
Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2013. ArcSWAT Interface for SWAT 2012. User's Guide. USDA Agricultural Research Service, 464pp.

Chapter 6. Comparison of alternative models SOURCE and SWAT for predicting catchment streamflow and sediment and nutrient loads under the effect of land-use changes

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Principal Author

Name of Principal Author (Candidate)	Hanh Hong Nguyen
Contribution to the Paper	Designed the study. Collected and analysed data. Prepared results and wrote the manuscript. Acted as the first and corresponding author. I hereby certify that the statement of the contribution is accurate.
Overall percentage (%)	85%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 10/12/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Signature	Date 11/12/2018

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Contribution to the Paper	Contributed to ideas and helped to review the final version of the manuscript. I hereby certify that the statement of the contribution is accurate.
Signature	Date 14/12/2018

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Contribution to the Paper	Contributed input data and primary version of one model. Helped to evaluate the results of the manuscript. Helped to review and edit the manuscript. I hereby certify that the statement of the contribution is accurate.
Signature	Date 13/12/2018

Name of Co-Author	Matthew S. Gibbs
Contribution to the Paper	Helped to evaluate the results of the manuscript. Helped to review and edit the manuscript. I hereby certify that the statement of the contribution is accurate.
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Comparison of the alternative models SOURCE and SWAT for predicting catchment streamflow, sediment and nutrient loads under the effect of land use changes

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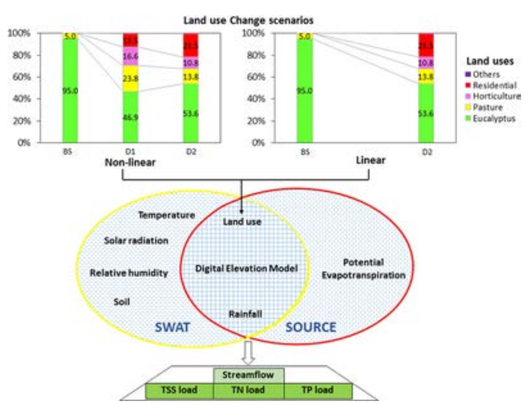
HIGHLIGHTS

- The less complex model SOURCE provided a quick and robust estimation of streamflow.
- The more complex model SWAT simulated nutrient loads more realistically.
- Both models predict plausible trends of flow and pollutants under land use changes.
- Static representation of non-linear change causes overestimation of pollution loads.

GRAPHICAL ABSTRACT



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ABSTRACT

Quantifying the water quantity and quality variations resulting from human induced activities is important for policy makers in view of increasing water scarcity and water pollution. Simple models can be robust tools in estimating the runoff from catchments, but do they also sufficiently reflect complex physio-chemical processes required for spatially-explicit simulation of soil-water interactions, and the resulting pollutant responses in catchments? Do these models respond sensitive to the impacts of different land use change representations? These questions are considered by applying the semi-distributed process-based catchment models SWAT and SOURCE to the Sixth Creek catchment in South Australia. Both models used similar data whereas inputs for SOURCE were generated from land-use based Functional Units (FUs), while FUs for SWAT were based on land use, soil and slope combinations. After satisfying calibration of both models for the outlet station of the catchment, the simulated flow by SOURCE produced high goodness of fit metrics, while nutrient loads simulated by SWAT were more realistic. Both models benefitted from using locally available Potential Evapotranspiration

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Streamflow
Pollution loads
Potential evapotranspiration

data for calibrating the hydrology. Scenarios of intensified land uses by two models showed more credible results for sediment and nutrient loads with the static approach when simulating the linear rather than the non-linear land use changes. The study has shown that informing decisions on the hydrology at catchment scale is well suited to less-complex models, whereas decisions on impact of land use change on water quality in catchments are better suited by models with process descriptions for soil-water interactions.

1. Introduction

Catchment models serves as powerful decision-making tools for sustainable management of water resources (e.g. Wellen et al., 2015). They allow the user to estimate, predict, and explain various catchment processes whereas direct observations are either scarce, not available, or timely and economically inefficient to monitor (Parajuli et al., 2009; Baffaut et al., 2014) or to consider "if-then" type scenarios. Since no catchment model can comprehend all relevant information to simulate every process realistically, modelling focuses on the description of key aspects by omitting or simplifying less important processes in the model structure (Lambin et al., 2003). As a result, models with various complexities have been developed worldwide to support decisions about alternative management strategies in the field of pollution control, best management practice, and land use and climate changes (Rode et al., 2010; Wellen et al., 2015). Model structures vary from simple lumped models (e.g. Boughton, 1988; Perrin et al., 2003) to complex process-based models such as the Integrated Nitrogen model for Catchments INCA (Whitehead et al., 2002), the Hydrological Simulation Program Fortran HSPF (Bicknell et al., 1997), or the Soil and Water assessment tool SWAT (Arnold et al., 1998).

While the number and complexity of models are increasing, decision making relies on models that best suit the purpose. While simple models are often easy to use with less effort in data preparation, have fewer calibration parameters and faster computer run time, more complex structured models may allow more diverse issues in water resources management to be considered (Krysanova and Srinivasan, 2015; Kim et al., 2012). In some cases, the decision in favor of a model may be based on the availability or accessibility of resources, i.e. time and money, the level of expertise, or the nature of input data (Illman and Gell, 1998). To address this issue, some studies have evaluated the robustness and accuracy of models in estimating the observed pollutant loads (e.g. Santhi et al., 2001; Liu et al., 2017; Krysanova and Srinivasan, 2015). The study by Kim et al. (2012) demonstrated that an ANN model provided a better estimation of sediment and phosphorous loading as shown by a lower value of error factors. Singh et al. (2012) also suggested that a multilayer perception NLM model performed better than the SWAT model based on calibration results for streamflow and sediment. While these data driven approaches are very good fit reproducing patterns in historical data, they are not as well suited to consider future changes not represented in the data, for example future land use changes. Tuppad et al. (2011) found that SWAT performed better than other catchment models in predicting nutrient losses. Similarly, the comparison of a series of catchment models by Liu et al. (2017), including STEPL-Purdue, SWAT, HIT, L-THIA, PLOAD, STEM-P, and Region 5, and based on their performance during uncalibrated, calibrated, and validated processes, concluded that SWAT results were superior but more time consuming to achieve. Sediment yield predicted by the SWAT and Annualized Agricultural Non-Point Source AnnAGNPS models were comparable to each other and agreed with the results of other models for Europe (Abdelwahab et al., 2018). However, none of the studies extended the comparison to address the 'fit-for-purpose' compatibility of certain models that is particularly true in the area of assessment of future stressors.

Land use change is considered one of the main stressors altering the quality and quantity of water resources worldwide (Foley et al., 2005; Wang et al., 2014). Changes in land use directly affect water yield of catchments due to altered topographic characteristics, interception and soil conditions within the modified land use areas (e.g. Molina-Navarro et al., 2014; Kidane and Bogale, 2017). Land use intensification by expansions of cropland, pasture land, and residential areas at the expense of native forest are projected to cause a significant increase in nutrient loads and sediment yields from upstream catchments, which ultimately creates negative impact on both terrestrial and aquatic ecosystems (Zhang et al., 2012; Molina-Navarro et al., 2014; Whitehead et al., 2002). Land use change is also affecting climate change though vegetation clearance and changes in carbon storage and sequestration (Lambin et al., 2003), and its impact might be more severe than those of climate change in some regions with already extreme dry climate (e.g. Nguyen et al., 2017a). Consequently, studies on impacts of land use change on catchment water resources address a major research concern in this century (Stonestrom et al., 2009; Wagner et al., 2017).

Previous studies have demonstrated that patterns of land use change, as well as the representation of these patterns, in models significantly affect predictions of catchment water quantity and quality (e.g. Fohrer et al., 2005; Wagner et al., 2017). Wagner et al. (2017) suggested that the static approach, with a constant land use over time, can result in satisfactory streamflow predictions when land use development is linear, while land use change is approximated more realistically by means of a dynamic representation for non-linear land use changes (Chiang et al., 2010; Wagner et al., 2016). The question arises how the difference in land use change representations may affect the prediction of water quality in catchments.

This study compares the performance of alternative catchment models in predicting the effects of land use changes on catchment streamflow, sediment, and nutrient loads for the Sixth Creek catchment in South Australia. Two models of different complexity have been trialled: the complex SWAT model has been used worldwide to simulate streamflow and non-point source pollutants (Neitsch et al., 2011; Wellen et al., 2015), and the more recently developed SOURCE model that can implement a less complex conceptual structure (Welsh et al., 2013). The SOURCE model has been tested throughout Australia and in some other countries such as China, Singapore, or Pakistan (https://ewater.org.au/casestudies/). This study aims at following research questions: (1) Do predictions of effects of land use change on streamflow, sediment, and nutrient loads differ between SWAT and SOURCE? (2) What is the impact of using a static approach for linear and non-linear land use changes in SWAT and SOURCE on the prediction of catchment streamflow, sediment, and nutrient loads?

2. Materials and methods

2.1. Study area

The study was applied to the Sixth Creek catchment in the western part of the Mount Lofty Ranges, South Australia (Fig. 1a). The catchment covers an area of 4300 ha and has an elevation range of 145 to 622 m above sea level. The climate of the region is Mediterranean, characterized by extreme dry summers and cool wet winters. Water is diverted from this catchment at the Gorge weir to the Hope Valley reservoir to contribute an important source of drinking water to the metropolitan region of the Adelaide city, South Australia. Due to the critical role for

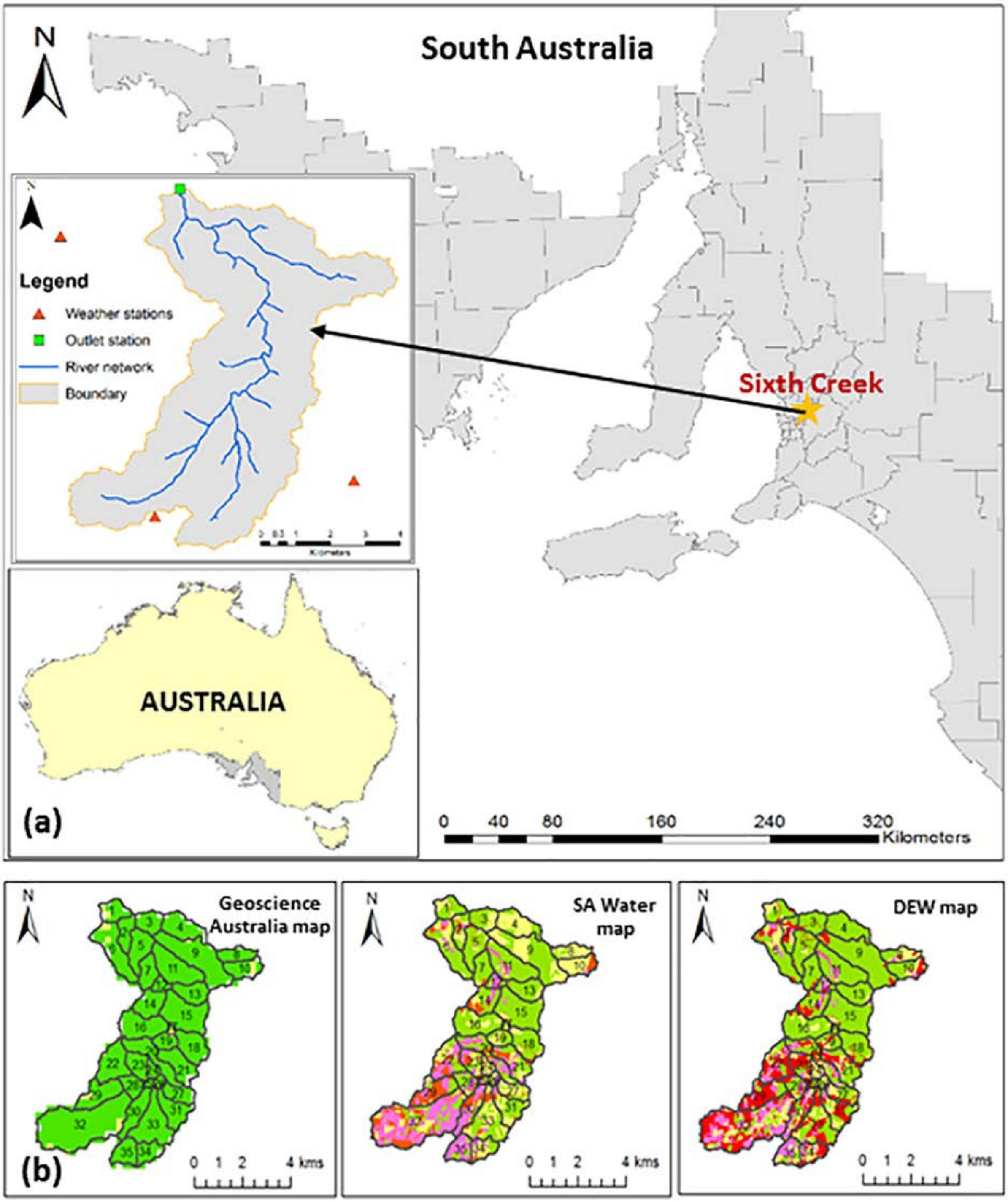

Fig. 1. Study area (a) and maps of consecutive land uses of the study area (b).

water supply of this catchment, land use development is allowed at certain upstream regions of the catchment, while forest remains as the major land use category of the catchment (Fig. 1b).

2.2. Input data

The basic dataset used in this study include: (i) digital elevation model (DEM); (ii) land use maps; (iii) soil map and properties; and (iv) meteorological data. The details of DEM, land uses, and soil maps are documented in Nguyen et al. (2017a). A 10 m DEM of the Upper Torrens region which covers the Sixth Creek catchment was used to generate the stream network and the catchment area. Soil map at the resolution of 1:100,000 was provided by the South Australian Water Corporation, while detailed soil database was collected from the Australian Soil Resource Information System (ASRIS, 2015). Three historical land use maps were available in this study region: the 250 m land cover map of Australia from Dynamic Land Cover Database (DLDC) of Geoscience Australia (Lymburner et al., 2010), the 10 m land use map from the South Australian Water Corporation (SA Water), and the recent 10 m land use map from the Department for Environment and Water (DEW). These maps represent different stages of catchment development from pre_European settlement (represented by 95% of native Eucalyptus forest and 5% of pasture lands) to an agricultural intensification stage (represented by 46.9% of native Eucalyptus

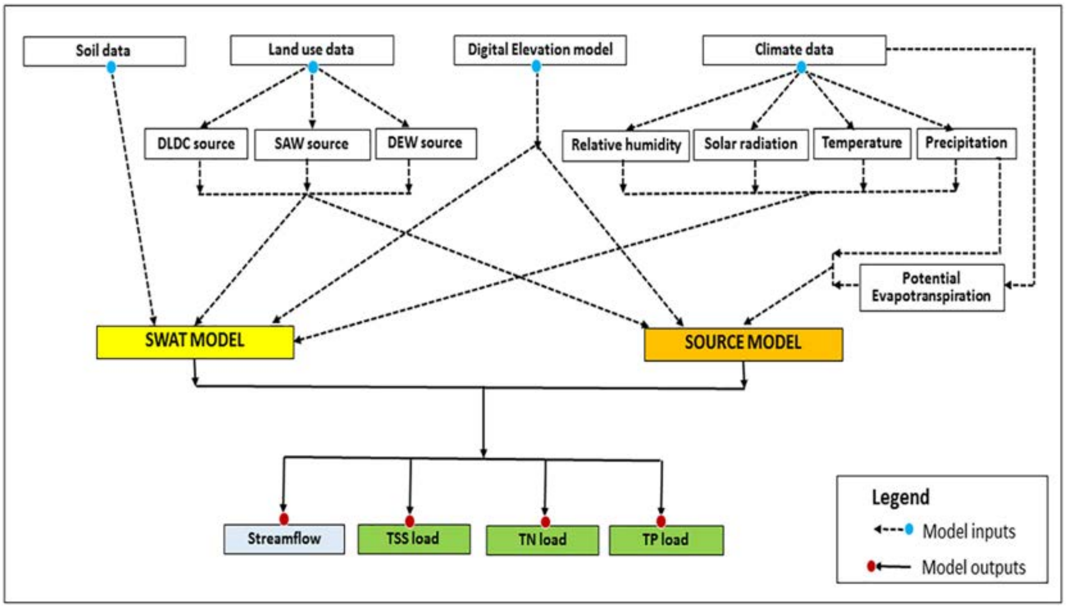

Fig. 2. Conceptual diagram of the SWAT and SOURCE models.

forest, 23.8% of pasture, 16.6% of horticulture, 12.5% of residential lands, and 0.2% of other land uses such as mining and water areas) and to the most recent land use advancement (represented by the 53.6% of native Eucalyptus forest, 13.8% of pasture, 10.8% of horticulture, 21.5% of residential, and 0.3% of other land uses). The models were calibrated using the most recent land use map of DEW source. The catchment climate condition was simulated using patched point data source of three weather stations provided by the Scientific Information for Land owners, which included daily data of rainfall, maximum and minimum temperature, solar radiation, relative humidity, and potential evapotranspiration parameters (SILO, 2015). For the SWAT model, the wind speed data was simulated using the in-built weather generator program. Daily data of streamflow, sediment and nutrient loads were obtained from the outlet gauging station of the catchment (Site number A5040523, https://amlr.waterdata.com.au/). No management practice was applied to derive the comparison of the most "pristine" version of the two models.

2.3. Alternative models SWAT and SOURCE

A conceptual diagram for the data sources for the SWAT and SOURCE models is provided in Fig. 2. Inputs into both models were kept as similar as possible to ensure that the divergence in parameter optimization and predictions were due to model structure rather than data. Simulation results for streamflow, sediment, total nitrogen (TN) and total phosphorous (TP) loads were used to compare the performance of the two models.

2.4. SWAT model calibration and validation

The SWAT model (ArcSWAT version 2012, revision 637) is a Hydrological Response Unit (HRU)-based and spatially explicit model (Arnold et al., 1998). The model simulates catchment processes such as evapotranspiration, runoff, nutrient and sediment transport on the basis of meteorological, soil, land use/land cover data and operational management practices (Neitsch et al., 2011). The model delineates a catchment into sub-basins based on DEM information and each sub-basin are further subdivided into a number of HRUs, each of which represents a unique combination of land use, soil type and slope. This process resulted in 35 sub-basins and 173 HRUs combination for the Sixth Creek catchment. In the hydrologic component, surface runoff is estimated separately for each HRU from daily rainfall using the modified Soil Conservation Service technique (SCS) and routed through the stream network to the catchment outlet to obtain the total streamflow of the catchment. Sediment yield is estimated from the Modified Universal Soil Loss Equation (MUSLE). TN and TP parameters are routed in streams using the QUAL2E model. Further details on the SWAT can be found in Neitsch et al. (2011).

The parameter optimization was conducted using the Sequential Uncertainty Fitting version 2 (SUFI2) in the SWAT Calibration and Uncertainty (SWAT-CUP) program (Abbaspour, 2015). The selection of sensitive parameters for model calibration was based on the experience of previous studies (e.g. Shrestha et al., 2016; Nguyen et al., 2017a) and verified with the Global sensitivity analysis method in SWAT-CUP program. The model was calibrated for data from 1997 to 2011 for streamflow and for data from 2007 to 2011 for sediment and nutrient loads, while data from 2012 to 2015 was used for validation of all four model variables. Three years of warm-up period was preserved prior to the defined calibration and validation stages to allow the stable performance of the model. Three primary evaluation statistics of simulated streamflow versus observed values were used in this study: correlation of determination (R^2), Nash–Sutcliffe efficiency coefficients (NSE), and Percent Bias (PBIAS). Satisfactory daily streamflows were evaluated according to Moriasi et al. (2007) by the criteria of R^2 and NSE above 0.5 and PBIAS in the range of ±25%, and supplemented by the results of uncertainty measures of p and r factors, which values close to 1 to give an indication of the confidence in the calibration. Daily TN and TP load optimizations were examined graphically for matching observed data and by the PBIAS value in the range of ±70% (Lee et al., 2015).

Table 1
Scenarios of land use change.

Land use representation	Land use maps	Scenario abbreviation
Static	Geoscience Australia map (2000)	BS
Static	SA Water map (2007/08)	D1
Static	DEW map (2015/16)	D2
Linear	SA Water and DEW maps	L
Non-linear	Geoscience Australia, SA Water, and DEW maps	NL

Table 2
SWAT calibrated parameters.

No.	Parameters	Description	Default	Fitted value	Sensitivity		
					Rank	t-Stat	p-Value
Streamflow							
1	CN2.mgt	Curve number for moisture condition II	[−0.3, 0.3]	−0.11[a]	1	−16.82	0
2	CH_K2.rte	Effective hydraulic conductivity in main channel	[0, 100]	66.30	2	9.89	0
3	CH_N2.rte	Manning's n value for the main channel	[0, 0.3]	0.14	3	6.94	0
4	ALPHA_BNK.rte	Baseflow alpha factor for bank storage	[0.1, 1]	0.96	4	−2.24	0.03
5	ESCO.hru	Soil evaporation compensation factor	[0.7, 1]	0.84	5	−1.97	0.05
6	SOL_AWC(1, 2).sol	Soil available water capacity for first and second layers	[−0.2, 0.2]	0.08[a]	6	1.95	0.05
7	REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur	[0, 500]	357.50	7	−1.91	0.06
8	GW_DELAY.gw	Ground water delay time	[0, 500]	472.50	8	−1.62	0.11
9	RCHRG_DP.gw	Deep aquifer percolation coefficient	[0, 0.4]	0.08	9	−1.56	0.12
10	SOL_K(1, 2).sol	Saturated hydraulic conductivity for first and second layers	[−0.2, 0.2]	−0.15[a]	10	1.51	0.13
11	GW_REVAP.gw	Groundwater 'revap' coefficient	[0.05, 0.2]	0.19	11	1.31	0.19
12	ALPHA_BF.gw	Baseflow alpha factor	[0.1, 1]	0.80	12	−0.95	0.34
13	GWQMN.gw	Threshold water depth in the shallow aquifer for return flow	[0, 5000]	745.00	13	0.47	0.64
14	HRU_SLP.hru	Average slope steepness	[−0.2, 0.2]	−0.14[a]	14	0.4	0.69
15	SOL_BD(1, 2).sol	Moist bulk density for first and second layers	[−0.2, 0.2]	−0.11[a]	15	−0.23	0.82
16	CANMX.hru	Maximum canopy storage	[−0.3, 0.3]	−0.10[a]	16	0.17	0.87
TSS load							
1	USLE_P.mgt	USLE equation support practice factor	[0, 1]	1.00	1	14.53	0.00
2	CH_COV1.rte	Channel erodibility factor	[0, 0.5]	0.20	2	0.19	0.85
3	CH_COV2.rte	Channel cover factor	[0.001, 0.01]	0.85	3	−0.09	0.93
4	SPEXP.bsn	Exponent parameter for calculating sediment re-entrained in channel sediment routing	[1, 1.2]	1.06	4	−0.05	0.96
5	SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	[0.0001, 0.001]	0.00	5	0.02	0.99
6	CH_ERODMO().rte	Jan. channel erodibility factor	[0, 1]	0.50	6	−0.01	1.00
TN and TP loads							
1	LAT_ORGN.gw	Organic N in the baseflow	[0, 30]	1.41	1	−17.59	0.00
2	RS5.swq	Organic phosphorus settling rate in the reach at 20 °C	[0.001, 0.1]	0.02	2	−0.63	0.53
3	PHOSKD.bsn	Phosphorus soil partitioning coefficient	[100, 200]	116.90	3	−0.38	0.70
4	CDN.bsn	Denitrification exponential rate coefficient	[0, 3]	1.58	4	−0.37	0.71
5	PERCOP.bsn	Pesticide percolation coefficient	[0, 1]	0.82	5	−0.20	0.84
6	BC4_BSN.bsn	Rate constant for decay of organic phosphorus to dissolved phosphorus	[0.03, 0.7]	0.64	6	−0.20	0.84
7	SDNCO.bsn	Denitrification threshold water content	[0, 1]	0.84	7	0.14	0.89
8	PSP.bsn	Phosphorus sorption coefficient	[0.01, 0.7]	0.24	8	0.08	0.93
9	NPERCO.bsn	Nitrogen percolation coefficient	[0, 1]	0.08	9	0.05	0.96
10	ERORGN.hru	Organic nitrogen enrichment ratio	[0, 5]	4.40	10	−0.01	0.99
11	ERORGP.hru	Organic phosphorus enrichment ratio	[0.05, 5]	2.50	11	0.00	1.00

[a] Indicated value refers to a relative change in the parameter.

2.5. SOURCE model calibration and validation

A SOURCE (version 4.1.1) catchment model is built upon a network of sub-basins and streams (which are represented by links and nodes). SOURCE divides a catchment into sub-basins based on the information from the hydrological DEM, which is a hydrologically conditioned and drainage enforced elevation model that provides a consistent representation of hydrological attributes of catchments (Dowling et al., 2011). Functional Units (FUs) are further defined within each sub-basin based on common hydrological response or land uses (eWater Ltd., 2013). In the case of the Sixth Creek model, the sub-basins and river networks generated by the SWAT model from DEM were imported into the SOURCE model as an alternative to the hydrological DEM input, meanwhile the FUs were defined using land use categories. Six rainfall-runoff models are available in the SOURCE, which generate streamflow basing on the information of rainfall and PET. For this study, the GR4J model (Perrin et al., 2003) built-in SOURCE platform was selected for the runoff generation due to its simplicity and has demonstrated good

Table 3.1
SOURCE calibrated parameters for streamflow.

No.	Parameters	Description	Default	Fitted value	
				Forested FU	Non-forested FU
1	x1	Capacity of the production soil store	[1, 1500]	596.62	213.41
2	x2	Water exchange coefficient	[−10.0, 5.0]	−3.74	−4.60
3	x3	Capacity of the routing store	[1, 500]	61.79	38.57
4	x4	Time parameter for unit hydrographs	[0.5, 4.0]	0.76	1.61
5	C	Baseflow filter - shape parameter	[0, 1]	0.68	0.61
6	k	Baseflow filter - parameter given by the recession constant	[0, 1]	0.13	0.40

Table 3.2
SOURCE calibrated parameters for TSS, TN, and TP loads.

No.	Land use	Default		Fitted value	
		EMC	DWC	EMC	DWC
TSS load					
1	Dense urban	61–140	14–16	15	1
2	Forest	40–66	6–23	10	0.5
3	Grazing	140–184	12–20	50	2
4	Horticulture	140–308	20–21	70	2
5	Rural living	90–131	10–14	20	1
6	Utilities	40–140	12–16	15	1
TP load					
1	Dense urban	0.1–0.25	0.08–0.14	0.13	0.02
2	Forest	0.08–0.16	0.03–0.11	0.16	0.005
3	Grazing	0.24–0.6	0.09–0.23	0.27	0.04
4	Horticulture	0.6–0.93	0.03–0.34	0.93	0.01
5	Rural living	0.13–0.22	0.04–0.06	0.13	0.015
6	Utilities	0.12–0.25	0.07–0.14	0.12	0.02
TN load					
1	Dense urban	1.8–2.0	1.3–1.5	3.1	1.2
2	Forest	0.9–2.1	0.3–1.0	3	0.2
3	Grazing	2.1–3.0	0.8–1.1	4.5	0.4
4	Horticulture	3.0–5.3	1.1–3.4	8	1
5	Rural living	1.6–2.0	0.7–0.9	3.5	0.4
6	Utilities	1.3–2.0	1.3–1.3	3.2	1.2

performance for Australian conditions (Coron et al., 2012; Gibbs et al., 2018). The Event Mean Concentration and Dry Weather Concentration (EMC/DMC) method was applied to simulate the constituent generation. For this small catchment, the pass-through routing method was selected based on expert knowledge. Further details on the SOURCE model are documented in Source User Guide 4.1 (https://wiki.ewater.org.au/display/SD41/).

The hydrology component in the SOURCE was calibrated by fitting the simulated to the observed streamflow with the Shuffled Complex Evolution then Rosenbrock algorithm (Duan et al., 1992; Rosenbrock, 1960). Similar to the SWAT model design, NSE was selected as an objective function and 500 iterations was run during the same periods of calibration and validation. Constituent loads in the SOURCE model were manually calibrated by fitting the observed and simulated graphs and achieving PBIAS in the range of ±70% using the recommended EMC/DMC values (Fleming et al., 2012; Fletcher et al., 2004) and consulting with local water quality model experts. Accuracy of streamflow calibration were evaluated basing on R^2, NSE, and PBIAS, while only PBIAS statistics was used to evaluate the daily calibration of constituent variables (Lee et al., 2015).

2.6. Land use scenarios

Three available historical land use data were used for scenarios. This information was considered in the modelling in a number of ways, with the different scenarios considered outlined in Table 1. Firstly, the calibrated models of SWAT and SOURCE were applied to run and to compare the results of land use change scenarios based on the commonly used delta approach, which compare models runs with different land use data for a certain time period (e.g. Niehoff et al., 2002; Huisman et al., 2009). This was done by simulating the time period considered, from 2000 to 2015, and comparing the results of three model runs with information of the three static land uses, i.e. land use map of the DLDC which represents the natural pre-European settlement (Scenario Baseline - BS), the SA Water map developed in 2007/08 (Scenario Development 1 - D1), and the most current 2015/16 map of DEW (Scenario Development 2 - D2). Secondly, in order to address the effects of using a static approach for linear and non-linear land use changes, the non-linear land use change pattern with a time step of eight years was calculated as the sum of two delta approach for periods which cover the transition from BS to D1 and from D1 to D2 (Scenario NL), and compared with the linear land use change pattern (Scenario L). The scenario L assumed the static land use development in-between the two land use phases over the 16 years' time scale and was estimated by the delta change between model runs using the BS and D2 land use data. The simplification in the scenarios NL and L was based on the availability of land use data and on the suggestion from the study of Wagner et al. (2017) which stated that land use updates at a coarse time step of five to eight years was acceptable for studies on effects of land use change. In all these scenarios, only land use map inputs were updated, while other model inputs were kept unchanged. The results of scenarios of

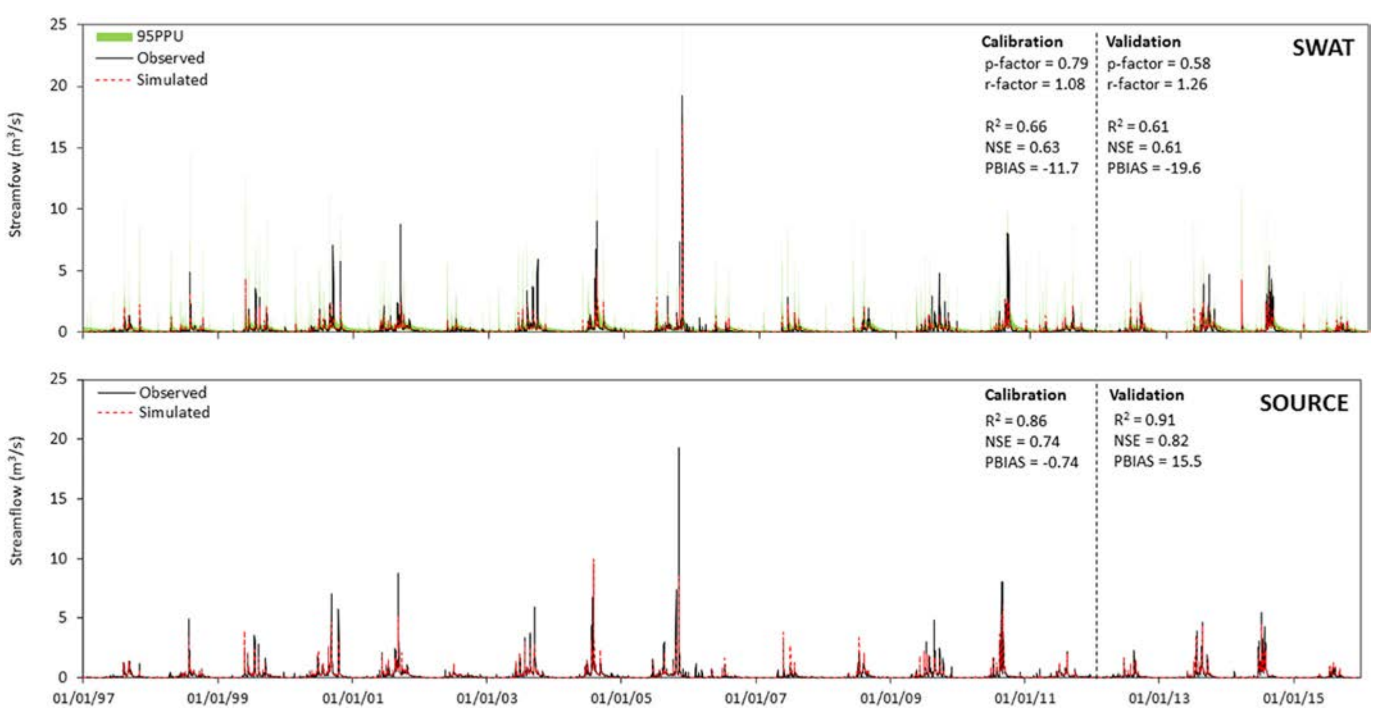

Fig. 3. Results of streamflow calibration (1997–2011) and validation (2012–2015) simulated by the SWAT and SOURCE models.

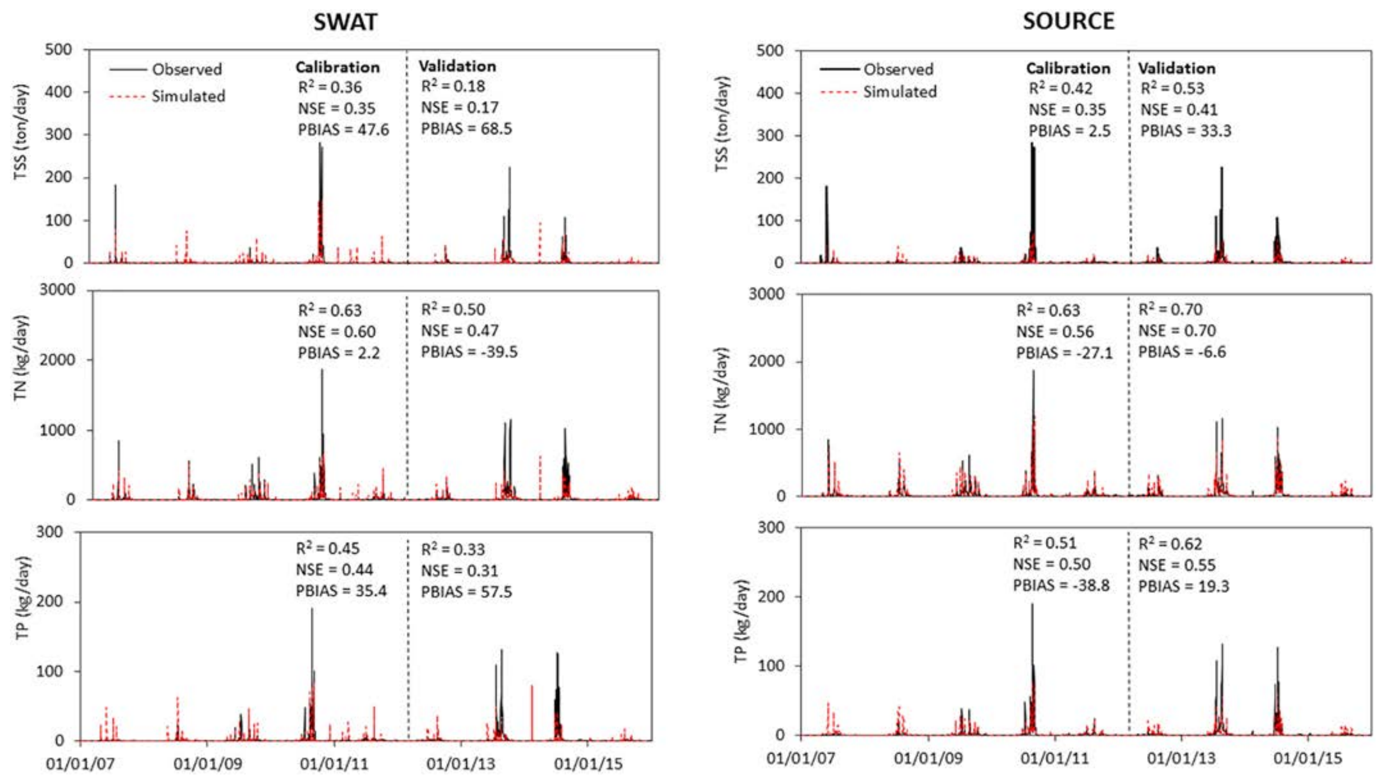

Fig. 4. Results of TSS, TN, and TP loads calibration (2007–2011) and validation (2012–2015) simulated by the SWAT and SOURCE models.

streamflow, sediment, and nutrient loads were interpreted on monthly, seasonal and annual time steps.

3. Results

3.1. Model sensitive parameters

The results of sensitive parameters defined through Global sensitivity analysis for streamflow, TSS, TN and TP calibrations by the SWAT is provided in Table 2. Overall, 16 parameters were defined sensitive for streamflow calibration, while 6 parameters were applied for sediment calibration and 11 parameters were used for TN and TP calibrations. Three most sensitive parameters for streamflow calibration were the Curve number for moisture condition II (CN2), the Effective hydraulic conductivity in main channel (CH_K2), and the Manning's n value for the main channel (CH_N2). For sediment calibration, the most sensitive parameters were the USLE equation support practice factor (USLE_P), the Channel erodibility factor (CH_COV1) and the Channel cover factor (CH_COV2). TN and TP loads optimizations were sensitive to the Organic N in the baseflow (LAT_ORGN), the Organic phosphorus settling rate in the reach at 20 °C (RS5), and the Phosphorus soil partitioning coefficient (PHOSKD) parameters.

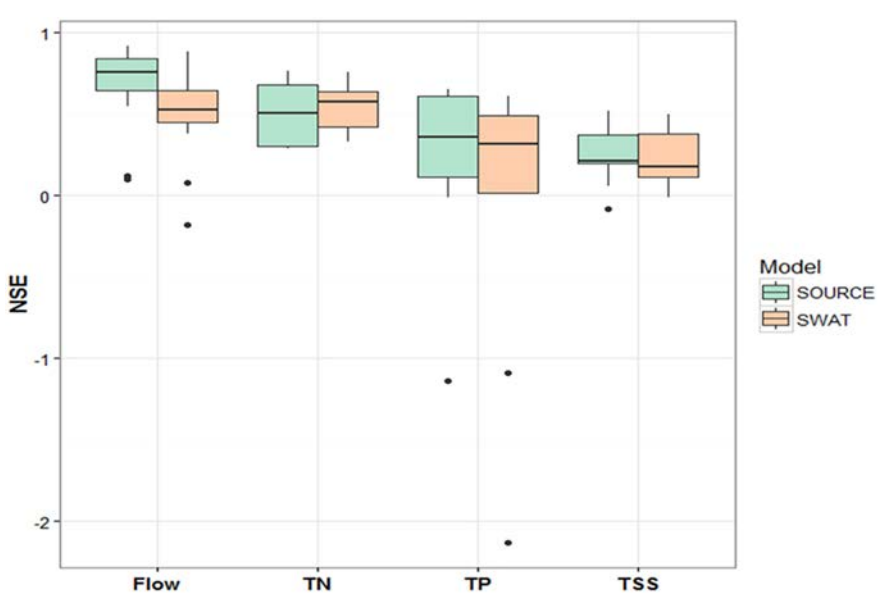

Fig. 5. Comparison of NSE goal achieved by the SWAT and SOURCE models for optimization of streamflow (19 years of data) and TSS, TN, and TP loads (nine years of data).

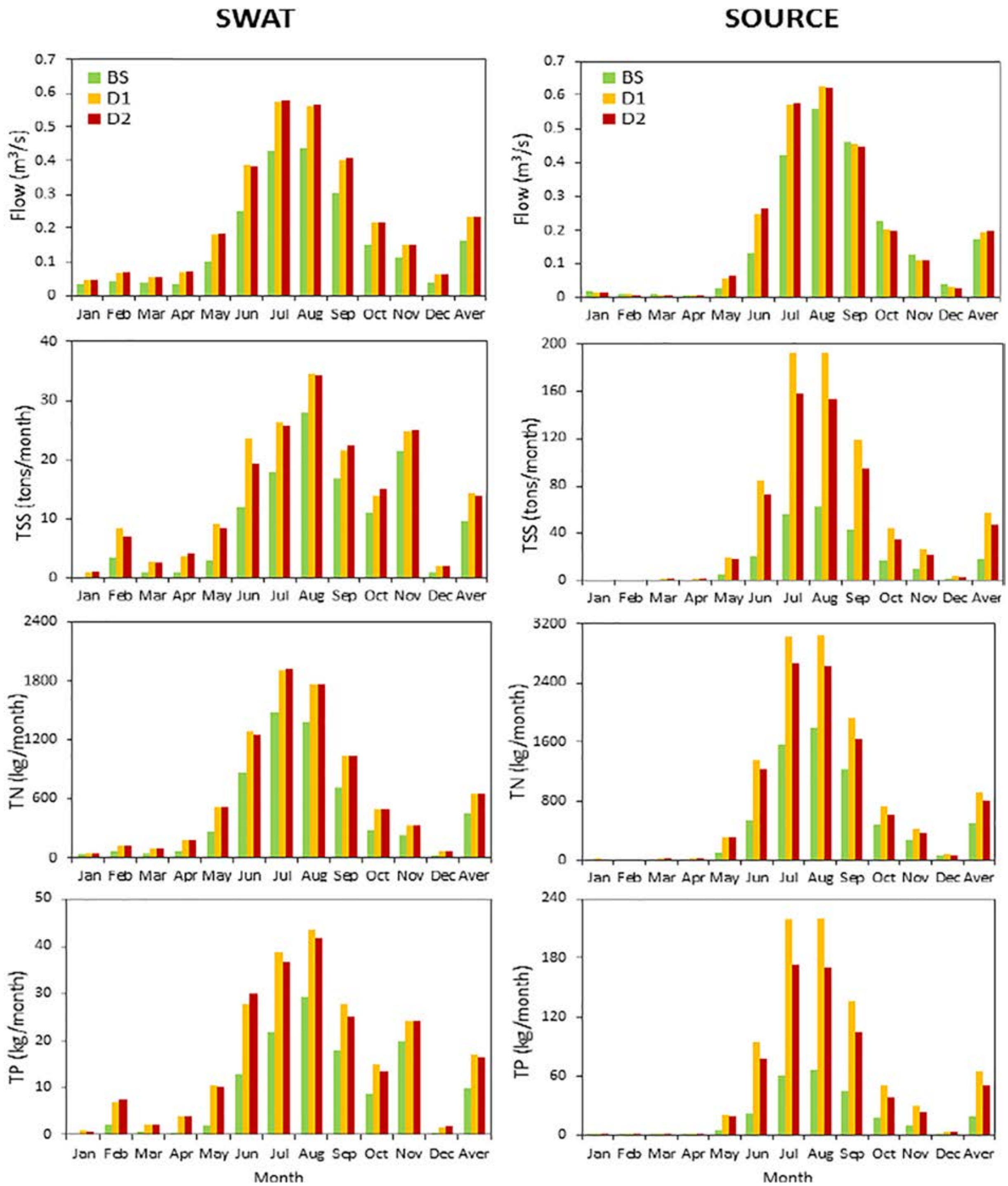

Fig. 6. Results of streamflow, TSS, TN, and TP loads on a daily aggregated to monthly time steps simulated by the SWAT and SOURCE using the three historical land use maps.

For the SOURCE model, no sensitivity analysis was performed, and it was assumed that all parameters influence the results. Streamflow calibration was carried out with four parameters of GR4J model, i.e. x1 to x4 parameters as shown in Table 3.1. Each of the land use functional units can have different values for these four parameters. To limit the number of additional parameters to calibrate, the land uses were grouped into two categories of Forested and Non-forested land uses to create two sets of meta-parameters, following the method of Westra et al. (2014). The two baseflow filter parameters k and C had no effects on total streamflow but were important for constituent simulation. Thus, prior to TSS, TN, and TP optimization step, the values of k and C defined through the automatic calibration of streamflow were further manually adjusted to 0.99 and 0.033, respectively, based on literature review values. For water quality variables, EMC and DWC parameter values were manually adjusted for each FU types (Table 3.2).

3.2. Model calibration and validation

The calibration results for streamflow, TSS, TN, and TP loads of the Sixth Creek catchment outlet using the SWAT and SOURCE models are shown in Figs. 3 and 4.

The parameter optimization for SWAT was performed consecutively for flow, TSS, then TN and TP loads. In order to increase the PET and ET ratio for this Mediterranean catchment, some parameters such as the

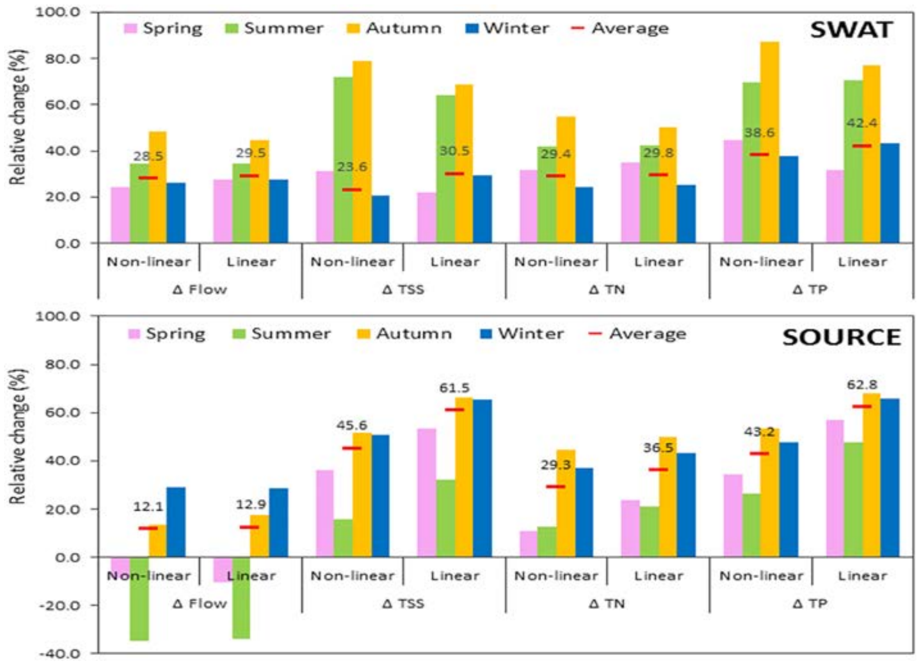

Fig. 7. Results of land use change scenarios with linear and non-linear representations by the SWAT and SOURCE models on streamflow, TSS, TN, and TP loads.

Maximum canopy storage (CANMX) and Groundwater 'revap' coefficient (GW_REVAP) had to be manually adjusted to values of 20 mm and 0.2 respectively, before automatic calibration of streamflow reached satisfactory results.. As a result, daily streamflow simulations achieved R^2 of 0.66 and 0.61, NSE of 0.63 and 0.61, and PBIAS of −11.7 and −19.6, and the uncertainty band of p-factor of 0.79 and 0.58 and r-factor of 1.08 and 1.26 for the calibration and validation, respectively. The simulated TSS, TN, and TP achieved satisfactory results with slightly better performance during calibration in comparison to validation as indicated by PBIAS values of 47.6 and 68.5 for TSS, 2.2 and −39.5 for TN, and 35.4 and 57.5 for TP during calibration and validation, respectively.

After the calibration of streamflow by the SOURCE model, the parameter optimization for TSS, TN, and TP loads was conducted. The streamflow simulation on a daily time step achieved very good results, as reflected by the well matched graphical representation of peak and base flows and of the following statistical metrics: R^2 of 0.86 and 0.91, NSE of 0.74 and 0.82, and PBIAS of −0.74 and 15.5 during calibration and validation, respectively. The PBIAS values of TSS, TN, and TP calibrations met the criteria suggested by Moriasi et al. (2007) with the absolute range varied from 2.5 to 38.8.

The calibration results when split to the calibration length of year by year for both models are shown in Fig. 5. Streamflow was better estimated by the SOURCE model, with 17 over 19 years achieved a better NSE values in comparison to SWAT. Meanwhile, average NSE values of TSS and TP were comparable between the SWAT and SOURCE. Though streamflow calibration results were achieved better, results of this study indicated that the SWAT resulted in a slightly better TN load simulation.

Table 4
SWAT and SOURCE models' calibration of streamflow using imported and estimated PET data input.

	Calibration		Validation	
	SWAT	SOURCE	SWAT	SOURCE
SILO imported PET				
R^2	0.66	0.86	0.69	0.91
NSE	0.66	0.74	0.66	0.82
PBIAS	−2.1	−0.74	−15.7	15.5
SWAT estimated PET				
R^2	0.66	0.87	0.61	0.91
NSE	0.63	0.74	0.61	0.78
PBIAS	−11.7	16.7	−19.6	36.5

3.3. Effects of land use change on model simulations

Fig. 6 shows monthly average simulation results for streamflow, TSS, TN and TP loads for the period from 2000/01 to 2015/16 based on the three historical land use data. The catchment experienced loss of forest due to expansions of pasture, horticulture, and residential lands under the scenario from BS to D1. The forest restoration along with a further increase of residential areas was observed by the scenario D1 to D2.

The scenario agricultural intensification D1 resulted in a remarkable increase in average monthly streamflow by 28.8% and 14.3% compared to BS, while the scenario urbanization and reforestation D2 displayed only a slight increase in average monthly streamflow by of 0.95% and 0.44% compared to D1 as estimated by the SWAT and SOURCE models, respectively. On monthly frequency, the trend of increases for streamflow was relatively similar for all months of the year as estimated by the SWAT. Meanwhile, minor changes are expected during dry months (December to May next year) and higher fluctuations are simulated during wet months (June to November) for streamflow by the SOURCE model. A similar overall pattern was observed for TSS, TN, and TP loads in the scenario D1, with higher loads simulated by the SOURCE in comparison to the SWAT. In particular, an increase of 218.7%, 79.7%, and 242.1% are estimated by the SOURCE and of 47.7%, 42.9%, and 73.7% are estimated by the SWAT for average monthly TSS, TN, and TP loads, respectively. In contrast, the land use change in the period of 2007/08 to 2015/16 resulted in the decreased pattern of TSS, TN, and TP of 18.5%, 12.4%, and 21.5% as modelled by the SOURCE and of 2.5%, 0.3%, and 1.0% as modelled by the SWAT. Sharper increase/decrease patterns were simulated by the SOURCE on monthly basis as compared to the SWAT, particularly for the rainy period in winter (June to August). Even though overall trends for the land use scenarios simulated by both models were conformable, more pronounced effects were simulated by the SOURCE model.

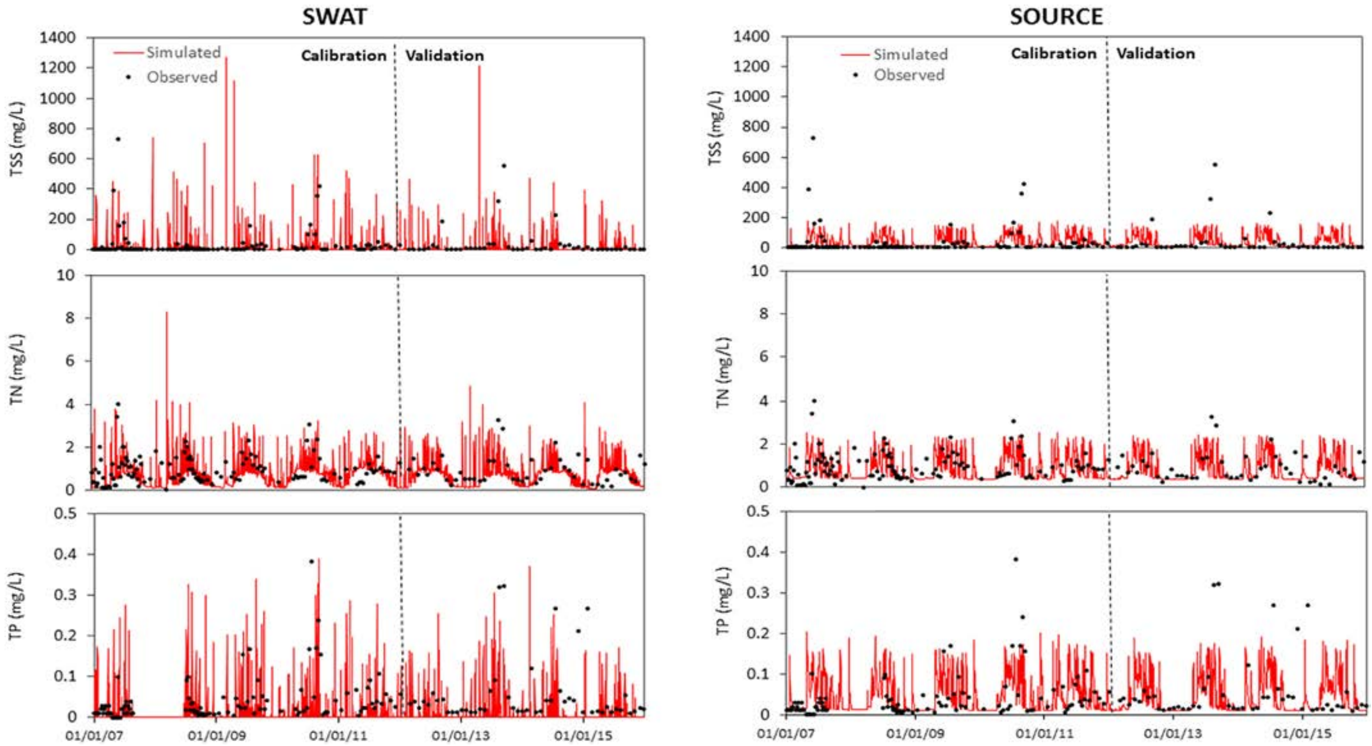

Fig. 8. Results of TSS, TN, and TP concentration estimations by means of the SWAT and SOURCE models at the Sixth Creek catchment, South Australia.

3.4. Effects of land use change representations on model simulations

Fig. 7 shows results of land use change scenarios either by linear static representation which ignores land use changes in-between the two time scales, or by the non-linear representation with a time step of eight years considering the land use shift in 2007/08.

The effects of land use change representation by the non-linear pattern did not affect the simulation of streamflow as compared to the simplified linear static method. The two land use estimation approaches L and NL resulted in the variation of 0.8% and 1% of average streamflow by the SOURCE and SWAT. The insignificant variation in streamflow results were also seen at the seasonal scale by both models when non-linear and linear land use changes were modelled. A similar pattern of low magnitude of increase was observed for TN load of 0.4%, when modelled by the SWAT. On the other hand, the difference in land use change representations showed notable effects on the simulations of TSS and TP loads by the SWAT, as shown by the difference of 6.9% for TSS and 3.8% for TP respectively. In case of the SOURCE model, the variations in estimation due to land use change representations were larger for all three constituents: 15.9% for TSS, 19.6% for TP, and 7.2% for TN loads. The fluctuation patterns among seasons remained unchanged when the non-linear and linear land use representations were applied in the SWAT and SOURCE.

4. Discussion

Complexity in time and space is inherent to river catchments, and therefore there is no single catchment model that can comprehend all processes specific for a real catchment (Krysanova et al., 1997; Rode et al., 2010). The challenge for catchment managers is thus to identify 'fit-for-purpose' forecasting tools by taking into account the complex nature of biophysical systems, data availability and the inherent uncertainties of the analysis methods (Liu et al., 2017). In this study the potential of the complex versus simple models for simulating and predicting the streamflow, TSS, TN and TP load responses has been tested by assessing impacts of land use changes on the Sixth Creek catchment. By keeping model inputs similar, the 'new' model SOURCE and the 'classical' model SWAT were tested regarding differences in their simulation results due to model structure.

Both models produced good validation results for daily streamflow and water quality loads as prerequisite for further scenario analysis. The results of parameter optimization for daily streamflow by the SWAT match criteria by Moriasi et al. (2007), and correspond with previous results for the same catchment (Nguyen et al., 2017b; Abiodun et al., 2017). The model SOURCE, however, achieved better results on streamflow calibration and validation compared to SWAT, by matching well with peak and base-flow levels, and showing better statistical metrics (Figs. 1 and 3).

In order to better understand these results, the same climate inputs using rainfall and PET were imported in both models. It showed that using estimated PET data from local source of SILO improved results compared to using the estimated PET data by SWAT (Table 4). Overall, results from the SOURCE model proved to be superior in both cases either with imported or with simulated PET inputs. These results confirmed that simple structure models like SOURCE can simulate reasonably well the core processes for streamflow estimation, as also shown in studies by Kim et al. (2012) and Singh et al. (2012). The reduced number of calibration parameters in the simpler Source model also allows more robust sets of parameter values to be identified, where in comparison the more complex SWAT model may suffer from parameter identifiability issues (e.g. Cibin et al., 2010; Shen et al., 2012). This result also suggests that locally developed hydrological models might suit better for estimating streamflow in catchments with locally specific characteristics such as semi-arid climate, which is typical for the Sixth Creek catchment. On the other hand, this result also finds the potential limitation of the SCS Curve number method for streamflow estimation in the SWAT model when applied to catchments with significant proportions of urban impermeable lands as pointed out by Tasdighi et al. (2018).

With regards to the simulation of water quality parameters such as TSS, TN, and TP, the result indicates that more complex models are required. While estimations of TSS and TP load compared well between the two models, SWAT achieved better results for the TN loads, despite the streamflow is the key driver for nutrient loads, and SOURCE achieved better streamflow results. An explanation for these findings can be seen in the calibrated concentrations of sediment and nutrient variables (Fig. 8). SWAT matched well the timing and magnitudes of sediment and nutrient concentrations, in particular for TN. In contrast, concentrations simulated by the EMC/DWC approach resulted in limited ranges of TSS, TN, and TP concentrations, without event specific responses. Results of this method did not differ the response behavior of TSS in comparison to TN and TP variables. The reason for this is that the EMC/DWC method used by SOURCE relies on fixed concentrations of EMC/DWC values of land uses, which are assumed to have similar hydrologic behavior and therefore generate similar rates of sediment and nutrient concentrations over time based on the manually calibrated values of EMC and DWC concentrations (e.g. Waters et al., 2014; Kuhnert et al., 2015; Rouse et al., 2016).

Predictive performance of a model is as good as its calibration as reflected in the outputs of the land use scenarios of the Sixth Creek catchment. In general, predicted patterns for catchment hydrology and water quality under the effect of land use change scenarios by both models corresponded reasonably well, regardless of the method of land use representations. However, the magnitudes of effects were quite different between the two models. The SWAT model suggested that streamflow increased in all months of the year, which caused an overestimation of the water yield under the scenarios D1 and D2 (Figs. 6 and 7). Meanwhile, the SOURCE model showed a lower water yield for the land use change scenarios of BS to D1 and D2 because the streamflow did not increase during dry seasons in spring and summer. In contrast, the underestimation of peak flows during calibration stage resulted in the underestimation of water yield under scenarios of land use change by the SWAT model in comparison to the SOURCE model. In case of water quality prediction, the overestimation of loads in the SOURCE model is affected by the limitation of EMC/DMC method. For instance, the high increase of TSS, TN, and TP loads of up to 242% under the D1 scenario was due to the increase in the horticultural (16.6%) and pasture (23.8%) lands which had remarkably higher EMC and DMC values in comparison to forest land use. SWAT estimated lower loads of TSS, TN, and TP since agricultural land uses were represented in the default settings without any management practices. A better estimation of scenarios can be achieved in both models by including the local operational management practices.

Differences between the SWAT and SOURCE models were also revealed when the non-linear and linear model land use representations were tested. Both models overestimated sediment and nutrient loads by the linear static approach with higher levels simulated by the SOURCE model that uses the EMC/DMC method. However, the difference in streamflow predictions was not significant complying with findings by Wagner et al. (2017). This can be explained due to the fact that most pronounced changes in land uses occurred in the period of 2000/01 to 2007/08 when approximately 50% of catchment area of forest was replaced by pasture, horticulture and residential lands whereas the period from 2007/08 to 2015/16 experienced a shift of pasture back to forest and further development of urban lands. These processes may either have caused trade-off in the catchment hydrology, or the overall changes of land uses by less than 10% were too small to create significant effects, as suggested by Brown et al. (2015).

5. Conclusions

This case study has shown that models with different complexity can give similar good results as long as the underlying key processes are covered by both models. Results show that the SOURCE model suits well as decision-making tool for the simulation and prediction of streamflow at catchment scale, particularly in regions with data scarce problems. However, fixing nutrient concentrations by the EMC/DWC model prevents SOURCE from simulating realistic key sediment and nutrient processes in time. In this study, the more complex model SWAT demonstrated to be superior for modelling and prediction of sediment and nutrient loads. This study has also demonstrated that outcomes of scenario analyses need to be interpreted carefully in the context of model design and underlying assumptions. Therefore, the results presented here of land use scenarios by SWAT and SOURCE in this paper are dependent on the assumptions set by their original configuration. Further studies will compare the SWAT and SOURCE in their later advanced versions, i.e. SWAT+ and SOURCE-Sednet, and incorporate management practices information.

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References

Abbaspour, K.C., 2015. SWAT-CUP: SWAT Calibration and Uncertainty Programs – A User Manual. Swiss Federal Institute of Aquatic Science and Technology, Eawag.

Abdelwahab, O.M.M., Ricci, G.F., De Girolamo, A.M., Gentile, F., 2018. Environ. Res. 166, 363–376. https://doi.org/10.1016/j.envres.2018.06.029.

Abiodun, O.O., Guan, H., Post, V.E.A., Batelaan, O., 2017. Comparison of MODIS and SWAT evapotranspiration over a complex terrain at different spatial scales. Hydrol. Earth Syst. Sci. Discuss., 1–36 https://doi.org/10.5194/hess-2017-599.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modelling and assessment part I: model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.

Australian Soil Resources Information System (ASRIS), 2015. Available at: http://www.asris.csiro.au/mapping/viewer.htm.

Baffaut, C., Dabney, S.M., Smolen, M.D., Youssef, M.A., Bonta, J.V., Chu, M.L., Guzman, J.A., Shedekar, V.S., Jha, M.K., Arnold, J.G., 2014. Hydrologic and water quality modeling: spatial and temporal considerations. Trans. ASABE 58 (6), 1661–1680.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigan, A.S., Johanson, R.C., 1997. Hydrologic Simulation Program—Fortran. User's Manual for Version 11 (EPA/600/R-97/080). US EPA, Ecosystems Research Division, Environmental Research Laboratory, Athens, GA (In Brun SE and Band LE 2000, 'Simulating runoff behaviour in an urbanizing watershed', Comput. Environ. Urban Syst. 24(1), 5–22).

Boughton, W.C., 1988. Modelling the rainfall-runoff process at the catchment scale. Civ. Eng. Trans. 30 (4), 153–162 Institution of Engineers, Australia, CE.

Brown, S.C., Versace, V.L., Lester, R.E., Walter, M.T., 2015. Assessing the impact of drought and forestry on streamflows in south-eastern Australia using a physically based hydrological model. Environ. Earth Sci. 74, 6047–6063.

Chiang, L., Chaubey, I., Gitau, M.W., Arnold, J.G., 2010. Differentiating impacts of land use changes from pasture management in a CEAP watershed using the SWAT model. Trans. ASABE 53 (5), 1569–1584.

Cibin, R., Sudheer, K.P., Chaubey, I., 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. Hydrol. Process. 24 (9), 1133–1148.

Coron, L., Andréassian, V., Perrin, C., Lerat, J., Vaze, J., Bourqui, M., Hendrickx, F., 2012. Crash testing hydrological models in contrasted climate conditions: an experiment on 216 Australian catchments. Water Resour. Res. 48 (5), 1–17. https://doi.org/10.1029/2011WR011721.

Dowling, T.I., Brooks, M., Read, A.M., 2011. Continental hydrologic assessment using the 1 second (30m) SRTM DEM of Australia. 19th International Congress on Modelling and Simulation, Perth, Australia, 2011.

Duan, Q.Y., Sorooshian, S., Gupta, V.K., 1992. Effective and efficient global optimization for conceptual rainfall–runoff models. Water Resour. Res. 28 (4), 1015–1031.

eWater Ltd., 2013. Source Scientific Reference Guide (v3.5.0). eWater Ltd, Canberra.

Fleming, N.K., Cox, J.W., He, Y., Thomas, S., 2012. Source Catchment Hydrological Calibration in the Mount Lofty Ranges Using PEST Parameter Optimisation Tool. eWater CRC, Canberra, Australia 978-1-921543-63-0, pp. 10–21.

Fletcher, T., Duncan, H., Poelsma, P., Lloyd, L., 2004. Stormwater flow and quality, and the effectiveness of non-proprietary stormwater treatment measures - a review and gap analysis. Technical Report 04/8. Cooperative Research Centre for Catchment Hydrology, Canberra.

Fohrer, N., Haverkamp, S., Frede, H.-G., 2005. Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas. Hydrol. Process. 19, 659–672.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309 (5734), 570–574. https://doi.org/10.1126/science.1111772.

Gibbs, M.S., McInerney, D., Humphrey, G., Thyer, M.A., Maier, H.R., Dandy, G.C., Kavetski, D., 2018. State updating and calibration period selection to improve dynamic monthly streamflow forecasts for an environmental flow management application. Hydrol. Earth Syst. Sci. 22, 871–887. https://doi.org/10.5194/hess-22-871-2018.

Huisman, J.A., Breuer, L., Bormann, H., Bronstert, A., Croke, B.F.W., Frede, H.-G., Gräff, T., Hubrechts, L., Jakeman, A.J., Kite, G., Lanini, J., Leavesley, G., Lettenmaier, D.P., Lindström, G., Seibert, J., Sivapalan, M., Viney, N.R., Willems, P., 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: scenario analysis. Adv. Water Resour. 32 (2), 159–170. https://doi.org/10.1016/j.advwatres.2008.06.009.

Illman, M.A., Gell, P.A., 1998. 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, p. 53.

Kidane, W., Bogale, G., 2017. Effect of land use land cover dynamics on hydrological response of watershed: case study of Tekeze Dam watershed, northern Ethiopia. Int. Soil Water Conserv. Res. 5, 1–6.

Kim, R.J., Loucks, D.P., Stedinger, J.R., 2012. Artificial Neural Network models of watershed nutrient loading. Water Resour. Manag. 26, 2781–2797.

Krysanova, V., Srinivasan, R., 2015. Assessment of climate and land use change impacts with SWAT. Reg. Environ. Chang. 15, 431–434.

Krysanova, V., Muller-wohfeil, D.I., Becker, A., 1997. Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. Ecol. Model. 106, 261–289.

Kuhnert, P.M., Pagendam, D., Cox, J., Fleming, N., He, Y., Thomas, S., Jenkins, C.L., van der Linden, L., 2015. An improved water quality model for the Onkaparinga catchment. Goyder Institute for Water Research Technical Report Series No. 15/6, Adelaide, South Australia.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annu. Rev. Environ. Resour. 28, 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459.

Lee, T., Wang, X., White, M., Tuppad, M., Srinivasan, R., Narasimhan, B., Andrews, D., 2015. Modeling water-quality loads to the reservoirs of the upper Trinity River basin, Texas, USA. Water 7, 5689–5704. https://doi.org/10.3390/w7105689.

Liu, Y., Li, S., Wallace, C.W., Chaubey, I., Flanagan, D.C., Theller, L.O., Engel, B.A., 2017. Comparison of computer models for estimating hydrology and water quality in an agricultural watershed. Water Resour. Manag. 31, 3641–3665. https://doi.org/10.1007/s11269-017-1691-9.

Lymburner, L., Tan, P., Mueller, N., Thackway, R., Lewis, A., Thankappan, M., Randall, L., Islam, A., Senarath, U., 2010. 250 Metre Dynamic Land Cover Dataset of Australia. Geoscience Australia, Canberra.

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A., Jeppesen, E., 2014. Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. J. Hydrol. 509, 354–366.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Neitsch, S.L., Arnold, J.G., Kinir, J.R., Wiliams, J.R., 2011. Soil and Water Assessment Tool: Theoretical Documentation 2009. Texas Water Resources Institute-Texas A&M University, College Station (Technical Report No. 406 edn).

Nguyen, H.H., Recknagel, F., Meyer, W., Frizenschaf, J., Shrestha, M.K., 2017a. 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. 202, 1–11.

Nguyen, H.H., Recknagel, F., Meyer, W., Frizenschaf, J., 2017b. Analysing the effects of forest cover and irrigation farm dams on streamflows of water-scarce catchments in South Australia through the SWAT model. Water 9 (33), 1–16.

Niehoff, D., Fritsch, U., Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. J. Hydrol. 267, 80–93.

Parajuli, P.B., Mankin, K.R., Barnes, P.L., 2009. Source specific fecal bacteria modelling using soil and water assessment tool model. Bioresour. Technol. 100 (2), 953–963.

Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a marsimonious model for streamflow simulation. J. Hydrol. 279 (1–4), 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7.

Rode, M., Arhonditsis, G., Balin, D., Kebede, T., Krysanova, V., van Griensven, A., van der Zee, S.E., 2010. New challenges in integrated water quality modelling. Hydrol. Process. 24, 3447–3461. https://doi.org/10.1002/hyp.7766.

Rosenbrock, H.H., 1960. An automatic method for finding the greatest or least value of a function. Comput. J. 7, 175–184.

Rouse, K., Gonzalez, D., Fernandes, M., Maheepala, S., Mirza, F., van Gils, J., He, Y., Cuddy, S.M., 2016. New modelling capability to target stormwater interventions that support seagrass health along Adelaide's coast. Goyder Institute for Water Research Technical Report Series No. 16/9, Adelaide, South Australia.

Santhi, C., Arnold, J.G., Williams, J.R., Gugas, W.A., Hauck, L., 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. Am. Water Resour. Assoc. 37 (5), 1169–1188.

Scientific Information for Land Owners (SILO), 2015. Available at: http://www.longpaddock.qld.gov.au/silo/ppd/index.php.

Shen, Z.Y., Chen, L., Chen, T., 2012. Analysis of parameter uncertainty in hydrological and sediment modeling using GLUE method: a case study of SWAT model applied to Three Gorges Reservoir Region, China. Hydrol. Earth Syst. Sci. 16, 121–132. https://doi.org/10.5194/hess-16-121-2012 (2012).

Shrestha, M.K., Recknagel, F., Frizenschaf, J., Meyer, W., 2016. 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. 175, 61–71.

Singh, A., Imtiyaz, M., Isaac, R.K., Denis, D.M., 2012. Comparison of soil and water assessment tool (SWAT) and multilayer perceptron (MLP) artificial neural network for predicting sediment yield in the Nagwa agricultural watershed in Jharkhand, India. Agric. Water Manag. 104, 113–120.

Stonestrom, D.A., Scanlon, B.R., Zhang, L., 2009. Introduction to special section on impacts of land use change on water resources. Water Resour. Res. 45, W00A00. https://doi.org/10.1029/2009WR007937.

Tasdighi, A., Arabi, M., Harmel, D., 2018. A probabilistic appraisal of rainfall-runoff modeling approaches within SWAT in mixed land use watersheds. J. Hydrol. 564, 476–489.

Tuppad, P., Douglas-Mankin, K.R., Lee, T., Srinivasan, R., Arnold, J.G., 2011. Soil and water assessment tool (SWAT) hydrologic/water quality model: extended capability and wider adoption. Trans. ASABE 54 (5), 1677–1684.

Wagner, P.D., Bhallamudi, S.M., Narasimhan, B., Kantakumar, L.N., Sudheer, K.P., Kumar, S., Schneider, K., Fiener, P., 2016. Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment. Sci. Total Environ. 539, 153–164.

Wagner, P.D., Bhallamudi, S.M., Narasimhan, B., Kumar, S., Fohrer, N., Fiener, P., 2017. Comparing the effects of dynamic versus static representations of land use change in hydrologic impact assessments. Environ. Model. Softw. 1-9. https://doi.org/10.1016/j.envsoft.2017.06.023.

Wang, R., Kalin, L., Kuang, W., Tian, H., 2014. Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. Hydrol. Process. 28, 5530–5546.

Waters, D.K., Carroll, C., Ellis, R., Hateley, L., McCloskey, G.L., Packett, R., Dougall, C., Fentie, 2014. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments. Whole of GBR. Technical Report. vol. 1. Queensland Department of Natural Resources and Mines, Toowoomba, Queensland (ISBN 978-1-7423-0999).

Wellen, C., Kamran-Disfani, A.R., Arhonditsis, G.B., 2015. Evaluation of the current state of distributed watershed nutrient water quality modelling. Environ. Sci. Technol. 49, 3278–3290.

Welsh, W.D., Vaze, J., Dutta, D., Rassam, D., Rahman, J.M., Jolly, I.D., Wallbrink, P., Podger, G.M., Bethune, M., Hardy, M.J., Teng, J., Lerat, J., 2013. An integrated modelling framework for regulated river systems. Environ. Model. Softw. 39, 81–102. https://doi.org/10.1016/j.envsoft.2012.02.022.

Westra, S., Thyer, M., Leonard, M., Kavetski, D., Lambert, M., 2014. Impacts of climate change on surface water in the Onkaparinga catchment – volume 1: hydrological model development and sources of uncertainty. Goyder Institute for Water Research Technical Report Series No. 14/22, Adelaide, South Australia.

Whitehead, P.G., Lapworth, D.J., Skeffington, R.A., Wade, A., 2002. 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. 6 (3), 455–466.

Zhang, W., Li, H., Sun, D., Zhou, L., 2012. A statistical assessment of the impact of agricultural land use intensity on regional surface water quality at multiple scales. Int. J. Environ. Res. Public Health 9, 4170–4186.

Chapter 7. Discussion, conclusions and future research

Mediterranean-climate catchments are particularly vulnerable to changing climate and environmental conditions, increasing the risks of both lasting droughts and extreme storm events. As a consequence, the quantity and quality of raw water for water usage downstream, for purposes such as for drinking water reservoirs, irrigation, hydropower and so forth, will be diminished. Adaptive management of these catchments therefore relies on a timely capacity to measure and foreshadow changes in catchment streamflow and water quality under the impact of possible land-use and climate changes.

This research focused on the development of predictive models for better understanding of how the suburban Torrens catchment and its Millbrook Reservoir in South Australia may respond to altered land use and climate conditions in the medium and long term. The models have been developed using SWAT, SOURCE and SALMO, and based on meteorological, hydrological, soil, land-use, flow and water-quality data for the catchment and reservoir. The validated models were used for analysing complex future scenarios. This final chapter concludes the thesis by summarising the main findings, limitations of the study and offering possible directions for future research.

7.1. Key outcomes and conclusions

Catchment hydrology is directly affected by local management practices

The first research question focused on streamflow prediction under the effects of local farm dams and forestry developments. These are critical issues of common interest in water-scarce catchments in Mediterranean climates and have been addressed before by application of the Water-Community Resource Evaluation and Simulation System (WaterCress), the Australian Water Balance Model (AWBM), or SOURCE (Alcorn et al., 2011; Fleming et al., 2012).

Application of the SWAT model indicated that the development of farm dams, irrigation practices and forestry can have mixed effects on catchment hydrology, which can be particularly significant during drought periods. Increases in forest plantations were predicted to cause a decrease in water yield, while the predicted effects of farm dams depended on their purpose rather than their volumetric capacities. Both plantations and dams require suitable control to sustain future drinking-water supply from this catchment. The results of this study corresponded well with previous modelling outcomes, and confirmed the suitability of the SWAT model as an alternative predictive tool for the Mediterranean-climate Torrens catchment.

Water quality control is required for managing the risk of water quality deterioration in rapidly urbanised catchments

Past and future impacts of urbanisation in the Torrens catchment were analysed in Chapter 3, with the results suggesting growing risks of flooding and rising phosphate loads. The magnitude of the effects of projected urbanisation in the next thirty years is expected to be greater than that of past urbanisation. The results also suggested that mitigation by combining buffer strips and restoring river banks and wetlands would be efficient in reducing projected increases in runoff and total phosphorus (TP) loads.

Streamflow and nutrient loads in Mediterranean-climate catchments are primarily driven by land-use change and only marginally affected by climate change

A scenario analysis of the combined effects of future urbanisation and climate change by means of SWAT revealed that more extreme drought conditions can be expected. In particular, reduced precipitation and higher evapotranspiration due to increased air temperature will be primary driving forces causing a decline in water availability in the already water-scarce catchment. In contrast, the model predicted an increase in monthly flow and TP loads resulting from extended impermeable areas due to urbanisation. The combination of both scenarios showed an offset of their effects on flow and TP loads, along with decreasing total nitrogen (TN) loads. In the long-term, urbanisation due to rapid population growth is of greater concern to the Torrens River catchment than the projected effects of climate change. However, sustainable management of the catchment needs to control the risk of both local and global changes.

Integrated catchment-reservoir modelling allows prediction of cascading effects between a catchment and a reservoir driven by land-use and climate changes

In one of the first applications of integrated catchment-to-reservoir modelling, the complementary models, SWAT and SALMO, simulated first the flow and nutrient loads from the Millbrook catchment using SWAT and secondly predicted nutrient and chlorophyll-*a* concentrations in Millbrook Reservoir using SALMO.

Chapter 5 highlighted that catchment development activities directly affect water quality of drinking-water reservoirs. The results of the SWAT-SALMO modelling suggested that development effects on the downstream reservoir would be most severe in summer if artificial mixing was not applied. Supplementing the source of water from the River Murray during dry periods was predicted to be effective since it helped to reduce the chlorophyll concentration as a result of reduced phosphate concentration in the inflow to the reservoir. Global warming was predicted to result in a shift to earlier growth of chlorophyll but the overall effects on reservoir water quality were not significant. Finally, land-use change, especially when combined with global warming, was projected to cause severe effects on the catchment-reservoir system.

Testing the credibility of alternative catchment models with different complexities for decision making

While the number of catchment models is increasing, the question arises of which model suits best for any given purpose. A review of the literature has revealed that there is no norm for application of catchment models. Representations of catchment processes by different model structures may be equally valid in terms of their ability to produce reasonably sound simulations in comparison with observed data, as has been shown in several studies (e.g. Arnold et al., 2012; Krysanova and Srinivasan, 2015). However, how the effects of equifinality in calibration of models with different structures affects model predictions is not well addressed.

Chapter 6 compared two process-based, spatially distributed catchment models of a case study at Sixth Creek, South Australia. The semi-distributed complexity of the SWAT model versus the lumped simple inputs of the SOURCE model were used to simulate the effects of land-use changes on catchment streamflow and sediment and nutrient loads. Results from this study showed that both SWAT and SOURCE can provide satisfactory calibration results at the outlet station of the catchment, with better validation of SOURCE hydrology and SWAT nutrient variables. Scenarios of intensified land uses with the two models were affected by the validation results, as is shown by the more credible results for streamflow variation when using SOURCE and for sediment and nutrient loads when land uses were represented by SWAT. Both models produced a similar pattern when comparing non-linear and linear land-use-change representations. Overall, this study showed that no single model can provide an optimum solution to every catchment issue, and that applying alternative models with different structures can provide more valuable information for decision making regarding long-term sustainable management of catchments. Simple rainfall-runoff models proved to be more suitable for studies of hydrology, whereas models such as SWAT with more process-based and spatially explicit descriptions may be required for estimation of water quality problems.

7.2. Research assumptions and limitations

There were several uncertainties in this study. First, the simulation results of the SWAT model for streamflow and water quality variables were restricted by use of the default ‘plant.dat’ database, which was developed outside of Australia, though some modifications were made in the case studies of the Torrens River catchment on the basis of local expert consultation. Second, limited availability of information on land-management practices such as irrigation, fertiliser application, and cropping seasons might explain the relatively low performance of sediment estimations in comparison with streamflow and nutrient variables. Third, in contrast with the results for climate-change scenarios, which were based on projected data from an ensemble of six GCMs, the urbanisation scenarios relied on the default configuration of 'urban.dat' in SWAT for the static representation of land-use changes. Other land-use scenarios were developed from either historical maps or the land-use update option available in SWAT. These representations ignored the non-linear nature of land-use changes, which might result in significant differences in the scenario analysis. Diverse scenarios of land-use and climate changes were tested by changing one factor at a time, such as land-use maps or climate data input, and fixing the other model inputs. Therefore, the simulation results represent 'if-then' responses focussed on certain pressures rather than a realistic picture of future changes. In addition, the uncertainty of the model inputs, model structure, and observed data were not analysed within the scope of this thesis, and future research is required in order to improve the credibility of the scenario outputs. However, the results of this study demonstrated the applicability of SWAT in combination and parallel with locally available modelling tools to support climate and land-use-change mitigation and adaptation efforts as well as to promote sustainable development of catchments.

7.3. Future research

My future research aims are: (1) to improve the SWAT model's performance by means of different case studies based on more available data and stepwise replacement of the default values in the SWAT database; and (2) to test the advanced model versions SWAT+ and SOURCE-Setnet, respectively, to improve the simulation of sediments in particular. The approach will also (3) be extended to other catchment models with a focus on water-quality estimation, to reveal the mechanism behind the relationships between climate change and land-use change in water-scarce catchments; and (4) to complement a preliminary study on modelling uncertainties in the catchment-reservoir model ensemble by using the Bayesian uncertainty approach.

References

- Alcorn, M.R. Hydrological Modelling of the Eastern Mount Lofty Ranges: Demand and Low Flow Bypass Scenarios. *Department for Water*, **2011**, Adelaide, Australia, 2–42, ISBN: 978-1-921923-02-9.
- Arnold, J.G.; Kiniry, J.R.; Srinivasan, R.; Williams, J.R.; Haney, E.B.; Neitsch, S.L. Input/Output Documentation Version 2012. *Texas Water Resources Institute* **2012**, TR-439, 63-650.

- Fleming, N.K.; Cox, J.W.; He, Y.; Thomas, S. Source Catchment Hydrological Calibration in the Mount Lofty Ranges Using PEST Parameter Optimisation Tool. *eWater CRC: Canberra, Australia*, **2012**, 10-21, ISBN: 978-1-921543-63-0.
- Krysanova, V.; Srinivasan, R. Assessment of climate and land use change impacts with SWAT. *Reg Environ Change* **2015**, *15*, 431-434.

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Uncertainty assessment of scenarios on climate and land use changes for the Millbrook catchment - reservoir system simulated by the model ensemble SWAT-SALMO

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ABSTRACT: In this study, we analyse the uncertainty of eutrophication effects of ongoing environmental and climate changes on the Millbrook reservoir simulated by the model ensemble SWAT-SALMO. The semi-arid Millbrook catchment-reservoir system provides drinking water to the north-eastern region of Adelaide, South Australia. The Soil and Water Assessment Tool (SWAT) simulated flow as well as nitrate and phosphate loadings originating from the catchment before entering the reservoir. The lake model SALMO received the simulated nitrate and phosphate loadings as input and determined daily phosphate, nitrate, and chlorophyll-a concentrations in the reservoir. This integrated modelling framework was key for simulating complex scenarios on impacts of future climate and land use changes on the whole catchment-reservoir system.

The uncertainty of simulation results has been taken into account by complex statistical algorithms, including the Sequential Uncertainty Fitting (SUFI2) of the SWAT calibration wizard, and multi-objective parameter optimisation of SALMO by means of the Hybrid Evolutionary Algorithm (HEA). In view of the large number of data processing steps required for the integrated simulations, the uncertainty assessment focused on the five best simulations results from the SWAT to be utilised for the parameter optimisation of SALMO.

The uncertainty of the model ensemble has been quantified as envelope of the fifty best iterations of nitrate, phosphate, and chlorophyll-a concentrations based on daily time steps for a typical "dry" and a typical "wet" year. The synergized envelop was further used to compare with the results of prediction of impacts of climate and land use changes on the Millbrook catchment - reservoir system. Overall, the estimation of uncertainty bound from the catchment-reservoir model ensemble may improve the credibility of the model predictions to be further considered in decision-making.

KEYWORDS: SWAT, SALMO, catchment-reservoir system, uncertainty, climate and land use change

CATEGORY: Uncertainty and Bayesian Inference Techniques

Comparative study of modelling sediment and nutrient loads of a small semi-arid catchment by the alternative models SWAT and SOURCE

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Abstract

Estimating sediment and nutrient loads derived from catchments is important for pollution control of downstream reservoirs. In this study, the well-established model SWAT and the newly developed model SOURCE have been applied to simulate the daily loads and concentrations of sediments (TSS) and nutrients (TN and TP) of a small (4,300 ha) mix land-uses catchment in South Australia. The land use of the catchment is dominated by forest (54%), residential (22%), and agriculture (25%). It drains into a drinking water reservoir which contributes water supply for the municipal region of the city of Adelaide. The two catchment models are process-based and semi-distributed. Inputs to SOURCE are generated by land-use based Functional Units (FUs), whilst FUs in SWAT are based on land use, soil and slope combinations. SWAT estimates the sediment yield rate (tones/day) by the Modified Universal Soil Loss Equation (MUSLE), and simulates the in-stream TN and TP loads (kg/day) by the Enhanced Stream Water Quality Model (QUAL2E) method. In contrast, SOURCE applies the Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) methods to calculate total TSS, TN, and TP loads as a product of concentration and streamflow. EMC and DMC methods rely on fixed concentrations of EMC/DMC values of land uses, which are assumed to have similar hydrologic behaviour and generates similar rates of sediment and nutrient concentrations over time.

Streamflow at the outlet station of the catchment has been simulated satisfactorily by both calibrated models. Both models simulated well the loads of TSS, TN and TP. Even though the validation statistics of SOURCE looked slightly better, the sediment and nutrient concentrations simulated by SWAT matched better the observed data in terms of peak and baseline values. This finding may suggest limitations of SOURCE by using fixed EMC/DMC values over time. Also, since the SOURCE sediment and nutrient loads result from concentrations and streamflow only, they might be less meaningful spatially. This aspect might be meaningful when in a next step the two models SWAT and SOURCE will be tested for their suitability to run scenarios on future land uses and climate change for policy-making.

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Modelling the runoff, nutrient and sediment loadings in the Torrens river catchment, South Australia using SWAT

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Abstract: Torrens River is situated in the most populated catchment of Adelaide, South Australia. Over the past several decades the lower part of the catchment has been heavily altered by urbanization that has impacted the water quality of Torrens streams. Recurrent algal blooms along the river are driven both by stormwater runoff and in-stream pollutants. This study aims to estimate the loadings of nutrients and sediments of the urban section of Torrens river catchment (also known as Karrawirra Parri Prescribed Watercourse) between 2007 and 2016. This part of the river initially receives water from the Gorge weir and its flow is swelling by urban tributaries downstream. The Soil and Water Assessment Tool (SWAT) has been applied to develop a comprehensive model by integrating all available data on weather, soil, land use, hydrology and water quality in the catchment. The data from 2007 to 2009 were used as a "warm-up" period. The model has been calibrated from 2010 to 2013 for the main stream and one creek site. The calibrated model has been validated for the main stream from 2014 to 2015 as well as for tributaries that have been spatially-explicit monitored from 2015 to 2016. The results indicate that the model simulates reasonably well the runoff and nutrient loadings whilst results for sediment loadings are less satisfactory. The reasons behind these shortcomings are analyzed, taking into account the length and quality of available data records. The results obtained from this case study suggest that SWAT is an effective tool for simulating the long-term characteristics of surface runoff of urbanized semi-arid catchments, and can assist in estimating nutrient loadings of the main stream and tributaries. The validated model is currently tested as a tool for simulating prospective effects of future land use and climate changes.

Keywords: *Catchment modelling, River Torrens, runoff, nutrients, sediment, SWAT*

Appendix 2. Monitoring results for the Torrens River Catchment, South Australia

Table 1. List of monitoring sites

ID	NAME	SITES	LATITUDE*	LONGTITUDE*	ELEVATION (m)
1	Tr_1	Kangaroo Reservoir	34°51'54.27"	138°45'31.91"	380
2	Tr_2	Sixth Creek	34°52'20.01"	138°45'16.56"	359
3	Tr_3	Gorge Weir	34°51'21.98"	138°43'52.67"	226
4	Tr_4	Linear Reserve	34°51'26.06"	138°42'36.54"	83
5	Tr_5	Fifth Creek	34°51'58.07"	138°41'21.29"	334
6	Tr_6	Lochiel Park	34°52'40.11"	138°38'54.87"	60
7	Tr_7	Fourth Creek	34°52'59.76"	138°39'7.82"	51
8	Tr_8	Third Creek	34°53'16.78"	138°38'25.59"	50
9	Tr_9	St Peters Billabong	34°54'20.54"	138°36'54.99"	34
10	Tr_10	Second Creek	34°54'24.20"	138°36'52.86"	29
11	Tr_11	First Creek	34°54'55.12"	138°36'23.90"	28
12	Tr_12	Adelaide Lake	34°55'2.87"	138°36'14.28"	<20

** Spatial reference: GDA_1994_MGA_Zone_54*

Storm-water collection and recycle systems at Lochiel Park

Upper Torrens in Spring – Summer – Autumn – Winter (pictures from left to right)

St-Peters Billabong pond

Torrens Lake

Gorge weir

Urban Creeks in summer (left picture) and winter (right picture)

Figure 1. Some images of monitoring sites

Table 2. Results of streamflow monitoring in the urban Torrens catchment

Unit: m^3/s

Date	**Monitoring sites**											
(mm/dd/yy)	**Tr_1**	**Tr_2**	**Tr_3**	**Tr_4**	**Tr_5**	**Tr_6**	**Tr_7**	**Tr_8**	**Tr_9**	**Tr_10**	**Tr_11**	**Tr_12**
07/07/15	0.870	0.115	0.000	0.000	0.033	0.202	0.052	0.042	0.200	0.850	0.200	NA
07/24/15	0.564	0.167	0.000	0.026	0.000	0.061	0.003	0.002	0.011	0.046	0.001	NA
08/11/15	0.004	0.203	0.000	0.015	0.022	0.094	0.040	0.028	0.420	0.812	0.346	NA
09/03/15	0.009	0.260	0.000	0.021	0.006	0.166	0.060	0.030	0.034	0.394	0.018	NA
09/23/15	0.268	0.104	0.000	0.017	0.012	0.049	0.004	0.018	0.006	0.135	0.001	NA
10/29/15	0.474	0.041	0.000	0.000	0.000	0.012	0.000	0.000	0.003	0.046	0.000	NA
11/20/15	1.025	0.027	0.000	0.000	0.000	0.007	0.000	0.000	0.002	0.024	0.001	NA
01/22/16	0.836	0.023	0.000	0.002	0.000	0.068	0.000	0.000	NA	NA	NA	NA
02/19/16	1.067	0.018	0.000	0.005	0.000	0.008	0.000	0.000	0.006	0.037	0.000	NA
04/21/16	0.010	0.030	0.000	0.001	0.000	0.011	0.000	0.000	0.006	0.024	0.000	NA
05/10/16	0.011	0.295	0.010	0.180	0.010	0.339	0.000	0.000	0.007	0.647	0.000	NA
06/09/16	1.357	0.282	0.000	0.017	0.041	0.614	0.086	0.070	0.003	1.127	0.105	NA
07/25/16	0.031	0.684	0.021	0.066	0.078	0.771	0.094	0.140	0.009	1.468	0.000	NA
08/19/16	0.015	0.684	0.000	0.059	0.078	0.771	0.175	0.065	0.011	1.350	0.000	NA
09/22/16	1.560	0.377	0.000	1.878	0.101	2.882	0.083	0.000	0.011	NA	0.000	NA
10/31/16	NA	0.231	0.996	0.575	0.031	1.617	0.017	0.031	0.022	NA	0.000	NA
11/24/16	1.600	0.108	0.180	0.180	0.007	0.190	0.000	0.000	0.050	NA	0.000	NA
12/21/16	1.681	0.125	0.000	0.014	0.000	0.050	0.000	0.000	0.012	0.130	0.000	NA
01/25/17	0.035	0.082	0.000	0.010	0.001	0.050	0.000	0.002	0.014	0.138	0.000	NA
02/22/17	0.016	0.058	0.000	0.001	0.000	0.013	0.000	0.000	0.024	0.054	0.000	NA
03/16/17	0.567	0.050	0.000	0.001	0.000	0.001	0.000	0.000	0.008	0.050	0.000	NA
04/27/17	0.700	0.170	0.000	0.009	0.001	0.115	0.001	0.001	0.008	0.438	0.001	NA
05/24/17	0.008	0.135	0.000	0.007	0.001	0.154	0.001	0.001	0.004	0.245	0.001	NA
06/04/17	0.000	0.075	0.000	0.021	0.000	0.038	0.000	0.000	0.007	0.087	0.000	NA
07/17/17	0.005	0.147	0.000	0.033	0.007	0.234	0.027	0.010	0.006	0.197	0.009	NA
08/23/17	1.289	0.711	0.000	2.472	0.124	2.594	0.045	0.069	0.017	1.542	0.072	NA
09/17/17	1.541	0.258	0.654	0.690	0.032	0.531	0.060	0.036	0.006	0.864	0.040	NA
10/22/17	0.002	0.062	0.000	0.007	0.002	0.041	NA	NA	0.008	0.108	NA	NA
11/19/17	0.953	0.036	0.000	0.006	NA	0.030	NA	NA	0.015	0.106	NA	NA
12/30/17	0.651	0.029	0.000	0.003	NA	0.025	NA	NA	0.049	0.005	NA	NA

Table 3. Results of TN monitoring in the urban Torrens catchment

Unit: mg/L

Date	Monitoring sites											
(mm/dd/yy)	Tr_1	Tr_2	Tr_3	Tr_4	Tr_5	Tr_6	Tr_7	Tr_8	Tr_9	Tr_10	Tr_11	Tr_12
07/07/15	1.14	0.3	0.3	0.72	0.62	1.08	0.36	0.43	1.06	1.55	0.64	NA
09/23/15	12.1	0.24	8.9	2.15	0.64	1.56	0.31	0.3	1.83	0.57	2.12	1.44
10/29/15	1.01	0.14	0.29	0.67	NA	2.62	NA	NA	1.4	2.38	2.47	1.49
11/20/15	1.09	0.19	0.58	0.54	NA	3.28	NA	NA	1.95	2.16	2.71	1.2
01/22/16	1.2	0.53	0.72	0.56	NA	1.82	NA	4.95	2.94	4.42	3.37	3.39
02/19/16	0.92	0.22	0.48	0.4	NA	3.15	NA	NA	2.39	2.99	NA	1.34
04/21/16	0.5	0.06	0.18	0.22	NA	2.12	NA	NA	4.11	3.51	NA	1.07
05/10/16	2.58	1.91	0.68	0.62	3.88	0.62	0.25	0.44	3.28	0.73	1.24	4.28
06/09/16	0.8	0.56	0.3	0.43	0.52	0.69	0.32	0.45	1.76	1.95	0.56	1.17
07/25/16	0.52	0.94	0.85	0.37	1.02	0.76	0.54	0.87	4.72	1.31	2.63	1.43
08/19/16	0.44	0.76	0.26	0.3	0.62	0.66	0.59	0.91	3.75	0.97	0.69	0.86
09/22/16	1.26	0.87	1.14	1.23	1.57	1.3	0.55	0.81	1.69	2.92	0.36	1.04
10/31/16	1.42	0.57	1.34	1.28	0.34	1.21	0.33	0.27	2.97	1.4	0.29	1.26
11/24/16	1.17	0.72	1.31	1.24	0.26	1.31	NA	NA	1.67	1.45	NA	1.35
12/21/16	1.42	0.34	0.89	0.68	NA	2.34	NA	NA	1.44	3.48	NA	1.76
01/25/17	0.73	0.38	0.97	0.5	0.41	1.76	NA	0.53	1.71	1.68	1.63	1.51
02/22/17	0.92	0.27	0.51	0.49	NA	3.22	NA	NA	2.43	3.26	NA	1.21
03/16/17	0.99	0.23	0.58	0.54	NA	2.48	NA	NA	2.44	1.88	NA	2.04
04/27/17	1.12	0.28	0.58	0.42	0.39	0.85	0.32	0.44	4.04	1.04	1.06	1.12
05/24/17	1.01	0.26	0.5	0.43	0.35	1.01	0.32	0.46	3.66	0.96	2.17	1.55
06/04/17	0.96	0.43	0.34	0.41	0.32	2.08	NA	NA	3.94	3.22	NA	1.35
07/17/17	1.4	0.75	0.18	0.57	0.32	0.98	0.1	0.75	3.95	0.87	0.45	0.84
08/23/17	1.36	0.84	1.19	1.14	1.35	1.22	0.8	0.77	2.79	1.19	1.86	1.09
09/17/17	1.31	0.41	1.06	0.86	0.27	0.94	0.36	0.24	2.67	1.47	0.27	1.26
10/22/17	0.93	0.66	0.88	0.51	0.3	3.01	NA	2.72	3.95	1.86	NA	2.13
11/19/17	1.28	0.12	0.31	0.37	NA	1.84	NA	NA	1.75	1.45	NA	1.44
12/30/17	1.1	0.2	0.52	0.52	NA	2.8	NA	NA	1.9	3.52	NA	1.98

Table 4. Results of TP monitoring in the urban Torrens catchment

Unit: mg/L

Date	Monitoring sites											
(mm/dd/yy)	Tr_1	Tr_2	Tr_3	Tr_4	Tr_5	Tr_6	Tr_7	Tr_8	Tr_9	Tr_10	Tr_11	Tr_12
07/07/15	0.057	0.015	0.026	0.028	0.07	0.062	0.038	0.065	0.101	0.087	0.111	NA
09/23/15	0.033	0.012	0.021	0.023	0.028	0.036	0.015	0.02	0.124	0.038	0.022	0.07
10/29/15	0.031	0.012	0.021	0.077	NA	0.079	NA	NA	0.193	0.088	0.108	0.182
11/20/15	0.042	0.013	0.063	0.088	NA	0.109	NA	NA	0.239	0.096	0.052	0.146
01/22/16	0.048	0.034	0.033	0.05	NA	0.188	NA	1.2	0.467	0.799	0.643	0.327
02/19/16	0.043	0.018	0.04	0.071	NA	0.049	NA	NA	0.312	0.066	NA	0.164
04/21/16	0.058	0.01	0.022	0.039	NA	0.044	NA	NA	0.34	0.042	NA	0.08
05/10/16	0.041	0.379	0.098	0.092	0.497	0.075	0.044	0.095	0.279	0.09	0.21	0.33
06/09/16	0.041	0.054	0.025	0.035	0.22	0.065	0.039	0.066	0.086	0.054	0.07	0.065
07/25/16	0.036	0.076	0.046	0.023	0.08	0.052	0.027	0.066	0.135	0.151	0.439	0.209
08/19/16	0.036	0.053	0.021	0.024	0.126	0.081	0.035	0.032	0.059	0.132	0.093	0.082
09/22/16	0.084	0.027	0.072	0.077	0.145	0.08	0.018	0.014	0.086	0.076	0.027	0.05
10/31/16	0.125	0.006	0.071	0.083	0.029	0.068	0.012	0.006	0.069	0.064	0.02	0.041
11/24/16	0.086	0.015	0.102	0.097	0.031	0.094	NA	NA	0.068	0.088	NA	0.085
12/21/16	0.108	0.009	0.074	0.053	NA	0.067	NA	NA	0.116	0.109	NA	0.125
01/25/17	0.047	0.015	0.042	0.056	0.096	0.08	NA	0.08	0.165	0.084	0.081	0.116
02/22/17	0.049	0.008	0.028	0.041	NA	0.054	NA	NA	0.145	0.051	NA	0.067
03/16/17	0.069	0.007	0.038	0.043	NA	0.056	NA	NA	0.105	0.09	NA	0.095
04/27/17	0.097	0.013	0.046	0.043	0.071	0.056	0.027	0.078	0.147	0.075	0.216	0.112
05/24/17	0.031	0.011	0.029	0.035	0.065	0.075	0.05	0.058	0.044	0.085	0.222	0.096
06/04/17	0.024	0.01	0.021	0.022	0.052	0.047	NA	NA	0.057	0.074	NA	0.173
07/17/17	0.016	0.036	0.013	0.025	0.06	0.042	0.01	0.035	0.048	0.044	0.147	0.054
08/23/17	0.072	0.029	0.065	0.056	0.087	0.065	0.046	0.061	0.057	0.062	0.263	0.074
09/17/17	0.076	0.008	0.042	0.031	0.013	0.031	0.012	0.006	0.031	0.038	0.013	0.034
10/22/17	0.036	0.014	0.059	0.043	0.035	0.058	NA	0.126	0.061	0.167	NA	0.168
11/19/17	0.079	0.011	0.029	0.04	NA	0.06	NA	NA	0.123	0.043	NA	0.103
12/30/17	0.085	0.007	0.045	0.037	NA	0.041	NA	NA	0.394	0.044	NA	0.25

Table 5. Results of TSS monitoring in the urban Torrens catchment

Unit: mg/L

Date (mm/dd/yy)	Monitoring sites											
	Tr_1	Tr_2	Tr_3	Tr_4	Tr_5	Tr_6	Tr_7	Tr_8	Tr_9	Tr_10	Tr_11	Tr_12
09/23/15	6	<1	2	2	1	3	1	<1	65	3	<1	6
10/29/15	12	<1	<1	3	NA	3	NA	NA	22	7	19	4
11/20/15	12	<1	8	42	NA	5	NA	NA	4	6	21	6
01/22/16	5	2	3	4	NA	8	NA	218	50	396	229	99
02/19/16	9	3	5	9	NA	5	NA		42	14	NA	27
04/21/16	8	1	1	8	NA	4	NA	NA	51	35	NA	8
05/10/16	8	344	37	21	157	14	13	2	1	19	19	38
06/09/16	8	5	1	4	15	42	12	21	3	19	14	14
07/25/16	7	21	25	2	5	9	9	27	5	<1	320	128
08/19/16	10	18	1	4	14	25	8	35	4	52	34	32
09/22/16	8	1	8	8	162	12	<1	3	6	12	4	12
10/31/16	11	1	13	14	6	17	1	<1	4	10	3	9
11/24/16	4	1	11	11	1	12	NA		12	12	NA	47
12/21/16	5	1	4	2		4	NA		10	8	NA	12
01/25/17	1	14	5	8	56	3	NA	145	28	3	5	12
02/22/17	4	4	2	7		6	NA		31	13	NA	21
03/16/17	2	1	2	8		2	NA		13	10	NA	14
04/27/17	7	1	5	55	3	7	5	2	37	10	11	17
05/24/17	16	14	3	4	6	12	2	2	3	16	11	14
06/04/17	2	1	4	4	2	4	NA	NA	2	3	NA	9
07/17/17	14	25	2	2	2	8	1	10	2	14	8	18
08/23/17	6	3	7	7	5	13	19	28	7	9	70	22
09/17/17	10	2	7	5	2	6	4	<1	1	5	1	6
10/22/17	2	2	7	5	1	3	NA	8	17	9	NA	15
11/19/17	6	<1	2	3	NA	5	NA	NA	3	6	NA	5
12/30/17	3	<1	6	3	NA	2	NA	NA	10	6	NA	3