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Assessing current and global-change driven behaviour of the semi-arid Onkaparinga catchment by means of spatially-explicit simulations of flow and nutrient loads based on the modelling tool SWAT

This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Adelaide

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Bachelor of Technology in Environmental Engineering

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Assessing current and global-change driven behaviour of the semi-arid Onkaparinga catchment by means of spatially-explicit simulations of flow, sediment and nutrient loads based on the modelling tool SWAT

ABSTRACT:

The semi-arid rural Onkaparinga catchment in South Australia is vulnerable to future change in climate and land use because of its extreme rainfall patterns and periods of drought along with intensive horti-and viticulture. The catchment provides up to 40% of the drinking water supply to the metropolitan area of Adelaide and hence the risks of eutrophication in the downstream reservoirs are of great concern. Effective management of such catchment requires development of a robust model that sufficiently represents the diverse land use and climate system of the catchment and thus facilitate in improved understanding of spatial and seasonal flow and nutrient dynamics. Hence, to achieve this, the semi-distributed catchment modelling tool SWAT (Soil and Water Assessment Tools) was utilised with following objectives: 1) to investigate different calibration approaches for enhancing model's validity, 2) to determine the combined effects of future climate and land use change on flow and water quality of the Onkaparinga catchment and 3) to better understand the spatial nutrient dynamics in the Cox Creek catchment by combining site-specific monitoring and spatially-explicit modelling.

The models developed by means of SWAT resulted in realistic simulations of the unique flow conditions of the semi-arid Onkaparinga catchment. Experiments with different calibration approaches have shown that multi-site calibration produced better simulation results for total nitrogen (TN) and phosphorus (TP) loads than single-site calibration, but had no significant effects on results for flow and total suspended sediments (TSS) loads. Further analysis revealed a high uncertainty in the simulation results of TSS pointing at the necessity of improving the sediment modules in SWAT.

The multi-sited calibrated model has been applied for future projections of climate and land use change to assess their effects on flow and water quality in the Onkaparinga catchment. The climate models suggested high uncertainty in terms of seasonally varying flow and nutrient loads, however a decreasing trend was observed. The effects of climate change were clearly dominating compared to effects of the projected land use change. Prospective simulations of combined effects for the period from 2046 to 2070 revealed highest decrease in water yield, TN and TP loads by -23.3%, -42.5% and -49.5%, respectively during the spring season. Results for summer months suggest the declines in flow and increase in nutrient concentration, mainly driven by land use changes, and hint at potential risks of algal blooms in downstream drinking water reservoir.

An approach that combines both monitoring and modelling for better understanding of nutrient dynamics was demonstrated in the Cox Creek catchment. Spatially intensive monitoring of flow and nutrients helped to identify the nutrient hotspots and established the strong link between market garden and TN and TP concentrations. Simulated nutrient export from different sub-basins matches well with field collected data for most of the sub-basins except at one, which is highly influenced by farm dam regulations. Hence future model efforts can be identified through combined monitoring and modelling.

In summary, this study has highlighted the benefit of utilising spatial data for improving the performance of catchment models and identifying model deficiencies. Resulting validated models can then serve as credible tools assessing effects of future scenarios on flow and water quality in catchments. Such approach provides scientific evidence to water resource policy-makers for making informed decisions.

DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Manoj Kumar Shrestha

June 2017

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in loving memory of my charming sister Anju…

A project has been delivered. This does not mean the quest of learning stops here.

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CHAPTER 1:

Introduction and Literature Review

Chapter 1: Introduction & Literature Review

1.1 Setting the scene

1.1.1 Water pollution problems and effects

The effects of human population growth are widespread in every aspect of our environment including water. Human activities such as intensification of agriculture, timber logging, industrialization and urbanization within a catchment are occurring at a rate that affects both water quantity and quality of adjacent water bodies. Whilst advances in water treatment technology and legislation have greatly reduced the effects from point source pollution such as industrial effluents on water bodies, diffuse source pollution such as agricultural and urban run-off, is relatively difficult to treat and largely counts for sediments and nutrients that have detrimental effects on fresh and marine water bodies worldwide (Ekholm et al., 2000; Lotze et al., 2006; Waterhouse et al., 2012).

Excess loads of nutrients, especially of nitrogen (N) and phosphorus (P), lead to eutrophication in fresh and marine ecosystems (Smith, 2003), which is a global problem. In Australia, severe cyanobacteria blooms occurred in the Murray-Darling River system in December 1991 and 2009. Australia's Great Barrier Reef is also at risk from eutrophication (Great Barrier Reef Marine Park Authority 2014). In all these cases eutrophication can be linked to land use changes, modified hydrologic regimes and extreme precipitation events (Young et al., 1996).

The economic and ecological costs from eutrophication are high as it affects not only water use for recreation, drinking, irrigation and aesthetic purposes but also aquatic biodiversity. As estimated by Dodds et al. (2009), approximately US$ 2.2 billion are annually spent in the US for losses on recreational and drinking water use, waterfront real estate, and for the recovery of threatened and endangered species. Similarly, algal bloom in Australian freshwater costs the community between AU$180 and 240 million every year (Atech, 2000). Hence, world-wide efforts focus on containment of nutrient sources in catchments in order to prevent economic and ecological losses, and protect critical water resources.

The study catchment, Onkaparinga catchment in South Australia, has an intensive mixed land uses and feeds into the Mount Bold Reservoir. Furthermore, it is supplemented with the pumped water from the River Murray. The water from the Mount Bold Reservoir is then transferred to the Happy Valley Reservoir, which is an off-stream reservoir that supplies raw water to the largest water treatment plant of South Australia. These reservoirs frequently experience seasonal episodes of algal bloom events causing a range of water quality challenges including taste and odour problems in recent decades (van der Linden and Burch, 2016).

1.1.2 Catchment management and models

Successful catchment management mitigates conflicts between ongoing human activities and the quantity and quality of water within and downstream of the catchment. Monitoring of stream flow and water quality is a key source of understanding hydrological as well as physical-chemical processes in catchments and are prerequisite for decision making. However, the size of catchments and associated costs typically exceed the capacity of water industries and catchment authorities to continuously maintain highly frequent and spatially-explicit stream monitoring.

In recent decades catchment modelling has evolved as a vital complementary approach to monitoring that enables integration of otherwise highly fragmented complex data and simulate past and future stream flow and nutrient loads across whole catchments. Process-based catchment models can determine site-specific hydrology and nutrient concentrations based on known causal and empirical relationships represented by mass balance equations. Such models are considered to be cost and time effective because of their ability to perform long-term simulations of the effects of catchment processes and management activities on water quantity and quality (Moriasi et al., 2007). Worldwide, different modelling tools are applied to assist programs for improving the water quality and ecosystem health at regional, national and continental scales. Examples include the EU Water Framework Directive (EU, 2016), the US Geological Survey's National Water Quality Assessment Program (USGS, 2002), and the Reef Water Quality Protection Plan in Australia (RWQPP, 2013).

Overall catchment models can facilitate informed decision-making by providing support to: (1) enhance scientific understanding of sources and processes that determine stream flow and contaminants, (2) predict long-term effects on stream flow and contaminants under the influence of future environmental, land use and climate changes and finally (3) design and adapt management strategies to achieve flow and water quality targets.

1.1.3 Catchment modelling tools

Several catchment models have been developed for the simulation of stream hydrology and water quality (Johnes, 1996) that are widely used for water resource planning and management. These models can be broadly classified as: lumped conceptual models or distributed process based models. Lumped hydrologic models simulate a spatially averaged hydrologic system, while distributed models rely on the spatial variability of model input parameters (Chow et al., 1988; Muttiah and Wurbs, 2002). Many studies have suggested that lumped models perform equally or better than distributed models. However, the later allows making spatially explicit predictions so that any effects from local events on catchments can be assessed at an individual site. Since, distributed models are data intensive and computationally complex, semi-distributed process based models are widely applied, because they have been shown to have prediction reliability even with limited data. These models divide catchments into sub-catchments that are further divided into non-spatial discrete hydrologic response units (HRU) based on a unique combination of topography, soil and land use. Popular semi-distributed process-based models include CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984), HSPF (Hydrological Simulation Program—FORTRAN)(Johansen et al., 1984), AGNPS (Agricultural Non-Point Source) (Young et al., 1989), HEC-HMS (Hydrologic Modelling System) (U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE-HEC), 2000) and SWAT (Soil and Water Assessment Tool) (Arnold et al., 2012; Arnold et al., 1998).

These models are driven by large numbers of equations and parameters that simulate the observed behaviour of complex catchment systems. The models' parameter complexity often exceeds the availability of measurable parameters. For example, in simulating flow, some parameters for soil and groundwater properties are represented conceptually or quantified by point scale observations, that do not match the scale that is required e.g. for soil hydraulic properties. Hence, these models need to be calibrated to identify the optimum parameter values. The goal function of the model calibration aims at the best match between predicted and measured outputs such as the daily outflow from the catchment. Before calibration, sensitivity analysis is usually carried out to identify the most sensitive parameters from the range of different parameters. The objective functions are usually statistical test such as minimization of relative error, average error or optimization of the Nash-Sutcliffe efficiency or coefficient of determination (Moriasi et al., 2007). After successful calibration, the evaluation or validation process follows in which the calibrated parameter values are used to determine if the objective function is satisfied for an independent validation dataset. If the objective function is not met, then the calibration and/or model assumptions may be revisited. Therefore, the calibration and validation process are often included to evaluate the ability of catchment models to reproduce certain catchment processes.

1.2 Current state-of-the-art and research gaps

1.2.1 Model calibration and uncertainty

Distributed models represent spatial variability of catchments related to land use, topography, soil, hydrology and weather information that require many parameters. This may cause an over-parametrization of models that reduces the models' robustness (Beven, 2001; Beven and Binley, 1992).

Appropriate parameter calibration is therefore key for reliable distributed models. Even though many studies on distributed models reported satisfactory results by calibrating parameters based on only one gauging station, it has been suggested that such 'single-site' approach may not account for the spatial variability of parameters particularly of large catchments with heterogeneous spatial properties, and cause inaccurate spatial predictions (Green and van Griensven, 2008; Jha et al., 2006).

The literature is currently divided whether multi-site or single-site parameter calibration produced more reliable simulations. Several authors have demonstrated the superiority of multi-site calibration over the single-site calibration (Chiang et al., 2014; Daggupati et al., 2015; Moussa et al., 2007; Qi and Grunwald, 2005; Wang et al., 2012), including applications of the SWAT for nested and non-nested catchments (Cao et al., 2006; White and Chaubey, 2005). In contrast, Khakbaz et al. (2012) and Reed et al. (2004) reported no significant improvements by multi-site compared to single-site model calibration.

Similar conclusions were drawn by Lerat et al. (2012) after applying four different calibration strategies including both single-and multi-site to 187 French catchments. They also suggested that future model application requires other sources of data such as use of remotely sensed data to constrain model predictions. These findings still raise the question whether multi-site calibration really outperforms the single-site calibration.

Model uncertainty is another lasting issue of catchment modelling. Even the most sophisticated models cannot represent comprehensively and realistically the complex processes of hydrological systems (Haan et al., 1995), but rely on simplified assumptions. Hence uncertainty is inherent to hydrological models and uncertainty analysis becomes increasingly part of model calibration (Montanari and Koutsoyiannis, 2012). Previous applications of uncertainty analysis studied solely the model parameter uncertainty (Beven and Binley, 1992; Duan Q et al., 1992; Gupta et al., 1998; Vrugt et al., 2003), without taking into account that uncertainty may also result from model structure as well as from measured input and output data such as precipitation and flow (Vrugt et al., 2005).

The following tools have been developed that assess different sources of model uncertainty: BATEA (Kavetski et al., 2006), SUFI-2 (Abbaspour et al., 2004) and GLUE (Beven and Binley, 1992). However, appropriate characterization and quantification of sources of uncertainty in model predictions is still a challenge (Bastola et al., 2011), and literature that links various calibration strategies to reduced uncertainty is limited. Hence, comparative analysis of different calibration approaches and their role in constraining uncertainty can be further investigated to develop a robust model.

1.2.2 Scenario analysis of future changes

Changes in climate and land uses greatly influence the catchment hydrology in many ways in different physiographic regions of the world. The changes in precipitation and temperature directly affect the surface water resulting in severe hydrologic events such as floods and droughts. Furthermore, there is growing evidence of link between water quality and climate variability (Aldous et al., 2011, Sahoo and Schladow, 2008). Schneider and Hook (2010) reported that surface water warmed at an average rate of 0.045 ± 0.011 °C yr^{-1} by increasing air temperatures during the period of 1985-2009.

Another study conducted in the River Kennet in UK (Wilby et al., 2006) indicated that increased temperature and climate variability may increase nitrate and ammonium concentrations.

A study on Prince Edward Island, Canada by De Jong et al. (2008) suggested an increase of nitrogen leaching by up to 30% under climate change scenario. The increment in temperature and nutrient concentration often results in eutrophication thus degrading the water quality (van Vliet and Zwolsman, 2008).

Similarly land use changes such as increased urbanization, intensive agriculture and afforestation and deforestation affects the amount of water, sediments and nutrients released from the catchment. Nielsen et al. (2012) demonstrated the significant relationship between agricultural land area and nutrient concentrations in adjacent lakes in Denmark. Increase in agricultural land could release more nutrients into the streams as Tong et al. (2012) found an increment of 4% and 3 % of daily TP and TN concentrations respectively.

Different studies analysed the relative effects of climate and land use change on flow and water quality to find variable results. For example, El-Khoury et al. (2015) argued that changed land uses may have a greater impact on nitrogen and phosphorus than climate change. Furthermore, a study conducted by Tu (2009) revealed the highest increase in nitrogen when the combined effects are considered.

The frequency, duration and intensity of extreme meteorological and hydrological events are predicted to increase in future, which affects water resources worldwide as suggested by IPCC (Intergovernmental Panel on Climate Change, 2007, 2014. Water limited catchments of Mediterranean climate are likely to be more vulnerable to these future uncertainties (Giorgi and Lionello, 2008; Piras et al., 2014). Furthermore, future changes in land uses driven by socio-economic and environment variability are likely to occur. Hence long term assessments of water quality and quantity are required as prerequisite for sustainable water resources management, especially in the context of future climate and land use change.

Many Global Climate Models (GCM) have been developed to project the future climatic drivers under different emission scenarios of greenhouse gases. Since data resolutions of GCM typically apply to 100 kms, their use for hydrological modelling at a catchment scale is limited and hence downscaling is often desired. Downscaled data using dynamic and statistical techniques are implemented successfully in different catchments as it enables projected climate scenarios to be applied at much smaller scale (Fowler et al., 2007; Fu et al., 2013; Nunez and McGregor, 2007).

Hydrological models run with the GCMs are widely used to assess possible future effects on water resources from different levels and forms of changes. After successful calibration and validation, these models can simulate responses of catchments to future drivers of environmental and climate changes. Simulation results are typically compared to baseline data and the relative change in flow and nutrients loads can be quantified for the future periods. Most of the studies concentrate on quantifying the effects on water quantity due to climate change only. A holistic approach that extends the impact assessment on both water quantity and quality under future climate and land use changes will help to prepare better for the future challenges.

1.2.3 Spatially intensive monitoring and modelling for better understanding of nutrient dynamics

Routine monitoring established at the main stream reflects environmental conditions of a larger area but fails to identify local sources of pollution (EPA, 1996). The spatial dynamics of flow and nutrients fluxes are observed within a catchment due to spatially heterogenic catchment characteristics (Gelbrecht et al., 2005; Hamilton and Miller, 2002; Kroon et al., 2012). Understanding of spatially explicit catchment behaviour are often desired by catchment managers and stakeholders for efficient management. However, installation of routine monitoring at different locations within a catchment is very expensive and often, simulations from models calibrated at one site is extrapolated in other sites for further assessment. As discussed earlier, such model simulation is not free from the inherent uncertainty. Hence, it is suggested that modelling simulation needs to be supported from spatial monitoring of flow and water quality (Davenport et al., 2008; Poudel et al., 2013).

Some studies have demonstrated the application of short term spatially intensive monitoring by sampling local sites such as tributaries for identifying local hotspots and revealing relationships between land use and nutrient dynamics (Eyre and Pepperell, 1999; Miles et al., 2013). Furthermore, these data can be used to identify the model discrepancies and recommend future modification for model enhancement (Baulch et at., 2013).

The Cox Creek catchment, one of the sub-catchments of the Onkaparinga catchment in the Adelaide Hills of South Australia, is considered to provide disproportionate amount of nutrients to the Onkaparinga River (Fisher, 2005). Identifying locations of critical loads of contaminants assists in targeting management effort rather than random placement of mitigation measures. Hence modelling supported by spatial monitoring may be prerequisite for efficient management of this catchment.

1.3 Research Objective and significance

In the context of the current changing environment, the need to address the research gaps as highlighted above are very pertinent to sustainable water resource management. This study is an attempt to contribute knowledge to improve the model robustness and its application in assessment of future effects of climate and land use changes in water resources of a Mediterranean catchment. For this research, the eco-hydrological model SWAT has been utilised in the Onkaparinga catchment of South Australia. The fundamental processes of SWAT and basic descriptions of the catchment regarding its location and characteristic are detailed in Chapter 2.

This PhD study in the Onkaparinga Catchment was carried out with the following aims and research outcomes:

1. To develop and calibrate a model of the Onkaparinga catchment that successfully predicts flow as well as loads of sediments and nutrients to the downstream Mt Bold reservoir using the SWAT modelling tool.

A review provided by Gassman et al. (2007) has highlighted that most SWAT applications are limited to modelling only catchment hydrology. Further studies on modelling related water quality parameters by SWAT can enhance the credibility of the model.

2. To determine calibration strategies that improve distributed catchment models.

Spatially distributed physical process based models are complex in nature with a large number of parameters and hence increased model uncertainty. Two calibration approaches for SWAT were tested to demonstrate whether considering internal measurements results in better model performance as well as uncertainty reduction in simulation of monthly flow and loads of total suspended sediments (TSS), total nitrogen (TN) and total phosphorus (TP).

3. To assess effects of future climate and land use changes on the Onkaparinga catchment within a Mediterranean climate zone.

Catchments in Mediterranean climate are particularly vulnerable to climate and land use changes. This study aims to improve knowledge on the response behaviour of Mediterranean catchments to ongoing changes driven by demographic and economic development. Resulting models and findings of this study will serve as computational tools and as a guide for local catchment managers to devise strategic management plans and policy.

4. To investigate the importance of complementary site-specific monitoring and modelling approaches in understanding the nutrient dynamics in the Cox Creek catchment.

The Cox Creek catchment is a mixed land use systems and is considered to be one of the impaired sub-catchment of the Onkaparinga catchment. Identification of nutrient hotspots in the mixed land use system is very difficult from the routine monitoring often situated at the catchment outlet. A short spatially intensive sampling was conducted to determine if any relationship exists between land use and nutrient concentrations. Furthermore, simulations from the SWAT model were evaluated against the field collected data to identify if both of them confirm the nutrient hotspots and to evaluate the reasons if disparities occur.

1.4 Thesis structure

This thesis is presented in five chapters. A general introduction highlighting the research aims and objectives is provided in the first chapter followed by discussions in the next three chapters. The final chapter sums up the general conclusion and provide recommends for future work.

Chapter 1: The current scientific knowledge of water quality problems and use of hydrological and water quality models to inform decisions are discussed in this chapter. Furthermore, the aims and objectives of the research are elaborated.

Chapter 2: Distributed catchment models suffer from over-parameterization and increased uncertainty in the model simulation. Single and multi-site calibration approaches for SWAT were investigated to determine better approach for increasing model performance as well as reducing uncertainty.

Chapter 3: The improved model was then used to assess the potential effects of climate and land-use change on flow and nutrient (TN and TP) loads of the Onkaparinga catchment in the next 50 years.

Chapter 4: This chapter highlights the results from spatially explicit monitoring and modelling in the Cox Creek catchment, one of the sub-catchments of the Onkaparinga catchment.

Chapter 5: The conclusion from these experiments are summarized with recommendations and directions for future modelling work in this basin.

CHAPTER 2:

Assessing SWAT models based on single- and multi-site calibration for the simulation of flow and nutrient loads in the semi-arid Onkaparinga catchment in South Australia

Statement of Authorship

Title of Paper	Assessing SWAT models based on single- and multi-site calibration for the simulation of flow and nutrient loads in the semi-arid Onkaparinga catchment in South Australia
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Name of Principal Author (Candidate)	Manoj Kumar Shrestha		
Contribution to the Paper	Conceived and designed the study. Prepared draft manuscript, incorporated reviewers comments and submitted for publication		
Overall percentage (%)	80 %		
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	31/01/2017

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		
Contribution to the Paper	Contributed to ideas, analyses and final editing of manuscript		
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Assessing SWAT models based on single and multi-site calibration for the simulation of flow and nutrient loads in the semi-arid Onkaparinga catchment in South Australia

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ABSTRACT

Distributed catchment models such as SWAT (Soil and Water Assessment Tool) are widely used to assess catchment characteristics and facilitate informed decisions for safeguarding water quantity and quality. This study applied SWAT to simulate monthly stream flow and loadings of total suspended sediment (TSS), total nitrogen (TN) and total phosphorus (TP) for five monitoring stations within the Onkaparinga catchment, and tested the models' performance based on single-site or multi-site calibration.

The results showed that multi-site calibration did not improve simulations of flow and sediments compared to single-site calibration. However, simulation results for TN and TP loads improved in both rural and urban sub-catchments of this catchment. Uncertainty analysis revealed that there is high uncertainty in model simulation of TSS by both strategies. The study has demonstrated: (1) the capability of SWAT to simulate realistically the extreme flow conditions of the semi-arid Onkaparinga catchment; (2) the benefit of local monitoring data for more realistic simulations of nutrient loads by means of the multi-site calibration of SWAT as pre-requisite for scenario analysis of spatially-explicit management options.

1. Introduction

Successful catchment management seeks compromises between conflicting land-uses and the quantity and quality of water received by downstream reservoirs. Process-based distributed catchment models such as SWAT prove to be useful tools for achieving this task (Daloğlu et al., 2012; Karamouz et al., 2010; Mateus et al., 2014; Nielsen et al., 2013).

The rural Onkaparinga catchment in South Australia feeds into the Mount Bold and Happy Valley reservoirs that contribute to the drinking water supply for the metropolitan area of Adelaide. It is not only affected by the arid climate of South Australia with high variability of rainfall and periods of drought but also by intensive horti- and viticulture. Since eutrophication of the reservoirs is a major concern for safe drinking water supply, improved understanding of spatial and seasonal nutrient dynamics within the catchment is prerequisite for preventative eutrophication management. This knowledge can be gained from application of distributed catchment models that take spatial heterogeneity explicitly into account.

Distributed catchment models require careful model calibration and validation procedure. Several authors have demonstrated the effectiveness of multi-site calibration over the single-site calibration centring solely on data of the catchment outlet (Chiang et al., 2014; Daggupati et al., 2015; Moussa et al., 2007; Qi and Grunwald, 2005; Wang et al., 2012) including successful applications of SWAT for nested and non-nested catchments (Cao et al., 2006; White and Chaubey, 2005). In contrast, some authors have reported no significant improvements by multi-site compared to single-site model calibration (Khakbaz et al., 2012; Reed et al., 2004). A similar conclusion was reached by Lerat et al. (2012) after applying four different calibration strategies including both single-and multi-site to 187 French catchments. Given these conclusions, it raises a question whether multi-site calibration really outperforms the single site calibration.

Hence this study aimed to identify if there is any significant improvement in SWAT model performance by multi-site calibration strategies at both watershed outlet and interior points. Compared to previous studies that focused on only stream flow comparisons, this study also highlights the comparison between

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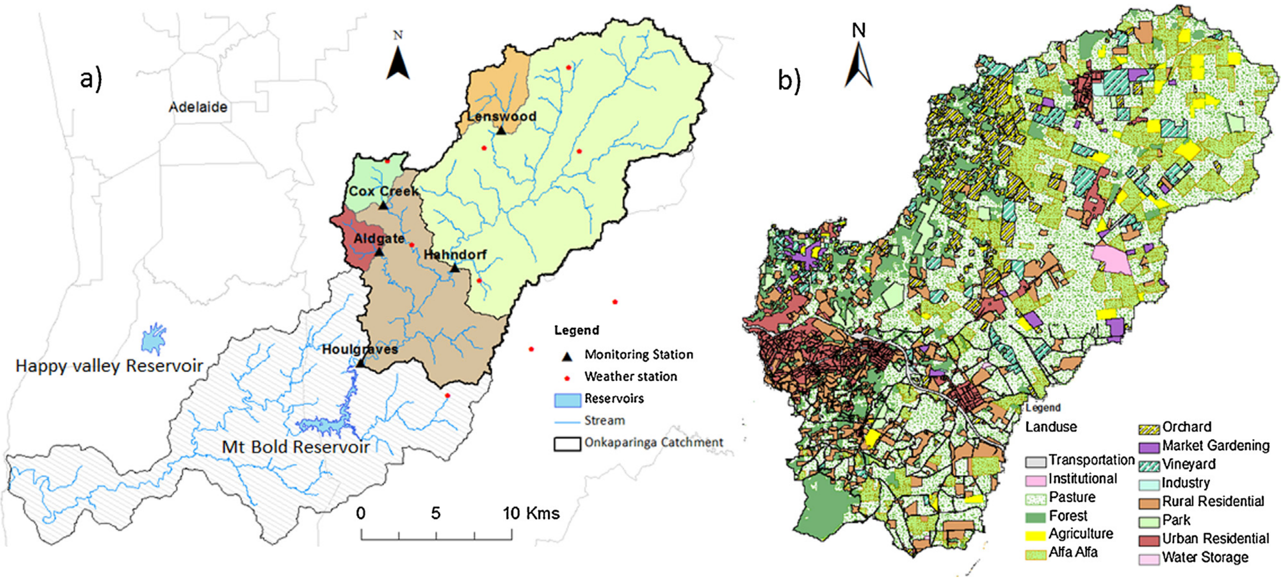

Fig. 1. The Onkaparinga Catchment. (a) Delineation map and monitoring stations. (b) Land use map.

the two calibration strategies for simulation of loadings of suspended solids, total nitrogen (TN) and total phosphorus (TP) of the Onkaparinga catchment by means of SWAT.

2. Materials and methods

2.1. Study area and data

The Onkaparinga catchment is situated east of Adelaide with an area of 535 km^2 and an elevation range from 10 to 700 m. This study applied to an area of 317 km^2 upstream of the Houlgraves gauging station of the Onkaparinga catchment (see Fig. 1a).

The Mediterranean climate of South Australia is characterized by dry summers and winter rainfall between 522 mm in the coastal and 1088 mm in upland areas (Westra et al., 2014). Mixed land uses of the catchment include horti-, viti- and agriculture, where farm dams typically serve for irrigation. A pipeline from the River Murray releases water into the Onkaparinga River downstream of Hahndorf (see Fig. 1a) that contributes approx. 87% (19952 ML) of the total flow during the dry season (Nov–April) and approx. 24% (45310 ML) during the wet season at Houlgraves.

The geological formation of the western part of the catchment consists of permeable sandstone and quartzite while the eastern part is underlain by less permeable siltstone and metasediments (Zulfic et al., 2002). The subsoil is clayey in texture on the lower slopes and flats of the catchment and may prevent water drainage. The hill slopes have clayey to sandy subsoils mainly utilized for horticulture and viticulture.

A Shuttle Radar Topography Mission (SRTM)- derived Digital Elevation Model (DEM) with a resolution of 30 × 30 m (Geoscience Austrlalia, 2011) was used to delineate the catchment and calculate important topographical parameters such as slope, channel dimensions and overland field length where a 1:100,000 land-use map of 2003 (see Fig. 1b) was used. The base data of the soil map of 2005 provided by the Department of Water, Soil and Natural Resources of South Australia has been compiled at scales of 1:50,000 or 1:100,000. The data attributes of the soil were extracted from the Australian Soil Resource Information System (ASRIS, 2013). Ten meteorological stations within and adjacent to the catchment were used. Since there were missing data for all the stations from the publicly available website of the Bureau of Meteorology, daily SILO

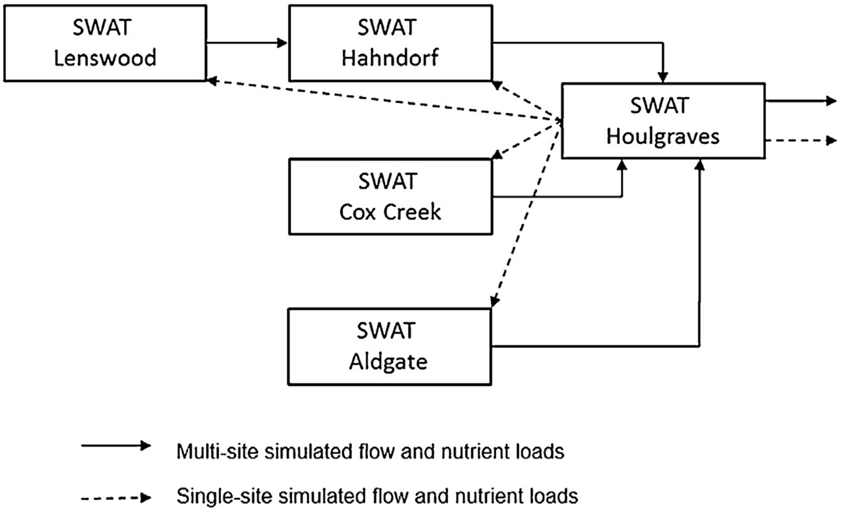

Fig. 2. Conceptual diagram of the multi-site and single-site approaches for modelling the Onkaparinga catchment by SWAT.

Table 1
Initial ranges and final calibrated SWAT's parameter values of single-site model and 5 individual models of the multi-site calibration.

No.	Parameters	Initial range	Single-site	Lens	Hahn	Cox	Ald	Houl
1	Curve number for mositure conditon II, r__CN2.mgt	(−0.2, 0.2)	−0.18	−0.05	−0.06	−0.07	−0.22	−0.065
2	Baseflow alpha factor, v__ALPHA_BF.gw	(0, 1)		0.72		0.44		
3	Ground water delay time, v__GW_DELAY.gw	(20, 450)	20.73	342.5		40.8	396	35.43
4	Threshold water depth in the shallow aquifer for return flow, v__GWQMN.gw	(0, 5000)	1283.5		3656	1644	1010	489.9
5	Groundwater 'revap' coefficient, v__GW_REVAP.gw	(0.02, 0.2)	0.17	0.15	0.08	0.11	0.17	0.15
6	Threshold depth of water in the shallow auifer for revap to occur, v__REVAPMN.gw	(0, 500)	156				80	217.05
7	Maximum canopy storage, r__CANMX.hru	(−0.3, 0.3)	0.07	0.2	−0.07			
8	Soil evaporation compensation factor, v__ESCO.hru	(0.72, 1)	0.88	0.93	0.76	0.8	0.85	0.91
9	Manning's n value for the main channel, v__CH_N2.rte	(0, 0.3)	0.23	0.12				0.13
10	Effective hydraulic conductivity in main channel, v__CH_K2.rte	(5, 130)		64	38.9	12.3	101	26.35
11	Baseflow alpha factor for bank storage, v__ALPHA_BNK.rte	(0, 1)	0.7	0.055	0.08	0.69	0.13	0.49
12	Soil available water capacity for first layer, r__SOL_AWC(1). sol	(−0.2, 0.2)	0.08		−0.016	0.05		−0.14
13	Saturated hydraulic conductivity for first layer, r__SOL_K(1). sol	(−0.1, 0.1)		−0.09				
14	Moist bulk density for first layer, r__SOL_BD(1). sol	(−0.15, 0.1)	−0.05	0.03	−0.07	−0.038		
15	Surface runoff lag time, v__SURLAG.bsn	(0, 12)			2.5		10.5	10.3
16	Deep aquifer percolation coefficient, v__RCHRG_DP.gw	(0, 1)	0.025	0.04	0.004	0.06	0.06	0.04
17	Plant water uptake compensation factor, v__EPCO.hru	(0.8, 1)				0.9	0.82	
18	Channel cover factor, v__CH_COV2.rte	(0, 1)		0.5				0.42
19	Channel erodobility factor, v__CH_COV1.rte	(0, 1)	0.2	0.25				
20	Linear parameter for sediment re-entrained in channel, v__SPCON.bsn	(0.0001, 0.001)			0.0004	0.0001		0.0003
21	Exponential parameter for sediment re-entrained in channel, v__SPEXP.bsn	(1, 2)			1.2		1.1	
22	USLE equation support practice factor, v__USLE_P.mgt	(0, 1)	0.028	0.027	0.03	0.006	0.002	0.002
23	USLE soil erodibility factor, r__USLE_K(1). sol	(−0.3, 0.3)	−0.06	−0.11	−0.07	0.15	−0.04	−0.1
24	Peak rate adjustment factor for sediment routing in main channel, v__PRF_BSN.bsn	(0, 2)	0.9					
25	Organic nitrogen enrichment ratio, v__ERORGN.hru	(0, 5)	3.9	4.4	4.17	4.8	4.8	4.3
26	Nitrogen percolation coefficient, v__NPERCO.bsn	(0, 1)	0.17		0.66	0.57	0.3	0.9
27	Denitrification exponential rate coefficient, v__CDN.bsn	(0, 3)	2	2.6	2.25	0.35	1.5	0.65
28	Denitrification threshold water content, v__SDNCO.bsn	(0, 1)	0.48	0.3	0.43	0.74	0.6	0.9
29	Phosphorus percolation coefficient, v__PPERCO.bsn	(10, 17)	16.4			13.4	15	10.9
30	Phosphorus soil partitioning coefficient, v__PHOSKD.bsn	(100, 200)	149.9	148	122.4	159.8	183	193
31	Organic phosphorus enrichment ratio, v__ERORGP.hru	(0, 5)	2.7	1.7	49	4.4	3.1	1.3
32	Phosphorus sorption coefficient, v__PSP.bsn	(0.01, 0.7)	0.62		0.08	0.22	0.35	0.14

r__ means the existing parameter value is multiplied by (1 + *a* given value); v__means the parameter is replaced by a given value. Blank represents that the parameter was not sensitive for that model and hence not considered during calibration. Parameters for flow (1–17), total suspended sediments (18–24), total nitrogen (25–28) and total phosphorus (29–32) are listed.

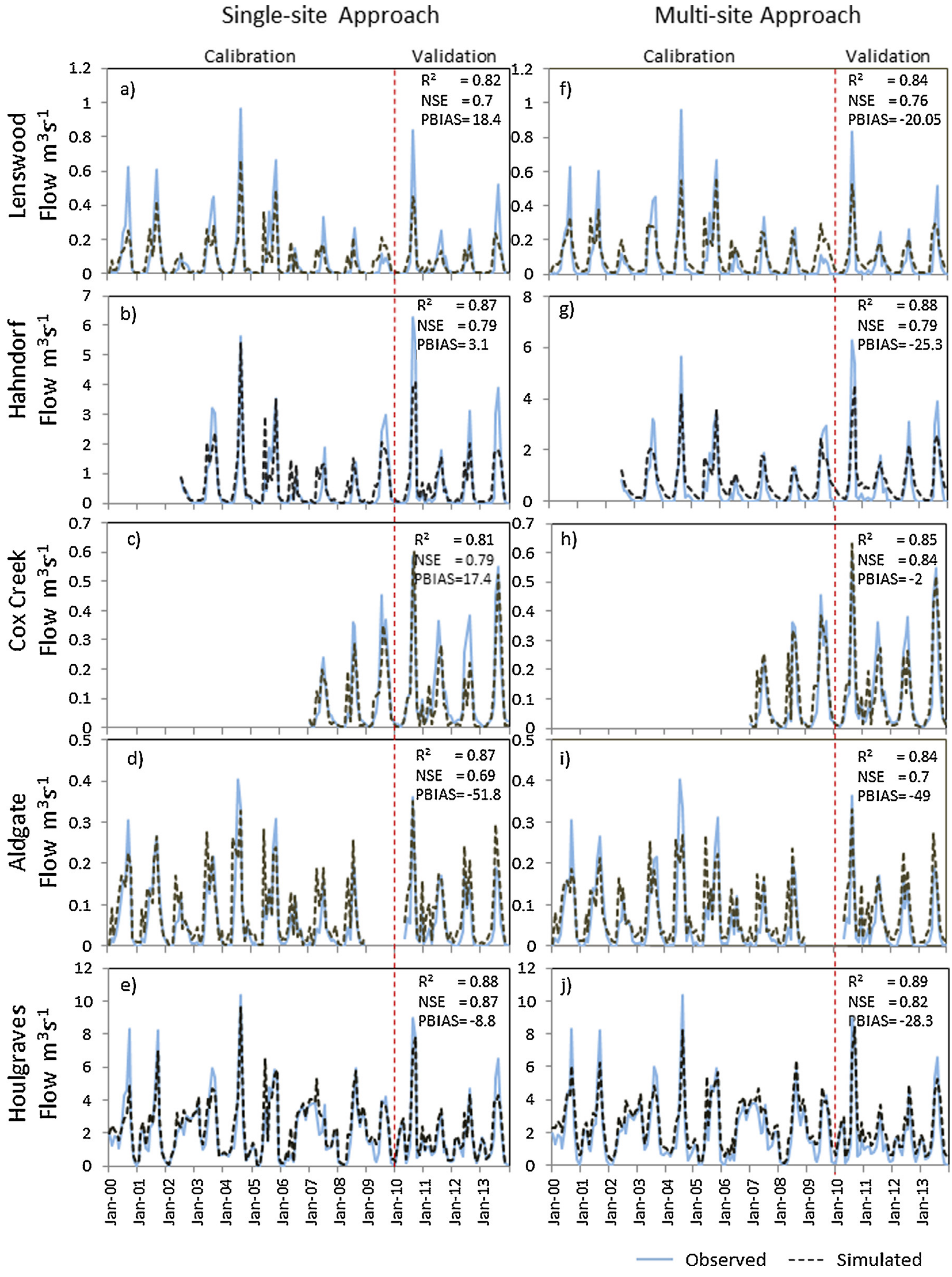

Fig. 3. Comparison of monthly flow simulation during calibration (2000–09) and validation (2010–13) for single-site and multi-site approach. (a–e) and (f–j) represents the results for single and multi-site approach respectively. Performance criteria results are provided for validation period only.

(Scientific Information for Land Owners, 2015) patched dataset were used.

The South Australian Water Corporation provided daily flow data and biweekly to monthly data of TN and TP from flow weighted composite samplers monitored at five gauging stations (see Fig. 1a) within the catchment. Flow data from the River Murray Pipeline were available on daily basis while grab sample data of water quality was available in weekly to monthly time steps. This contribution was treated as point source data.

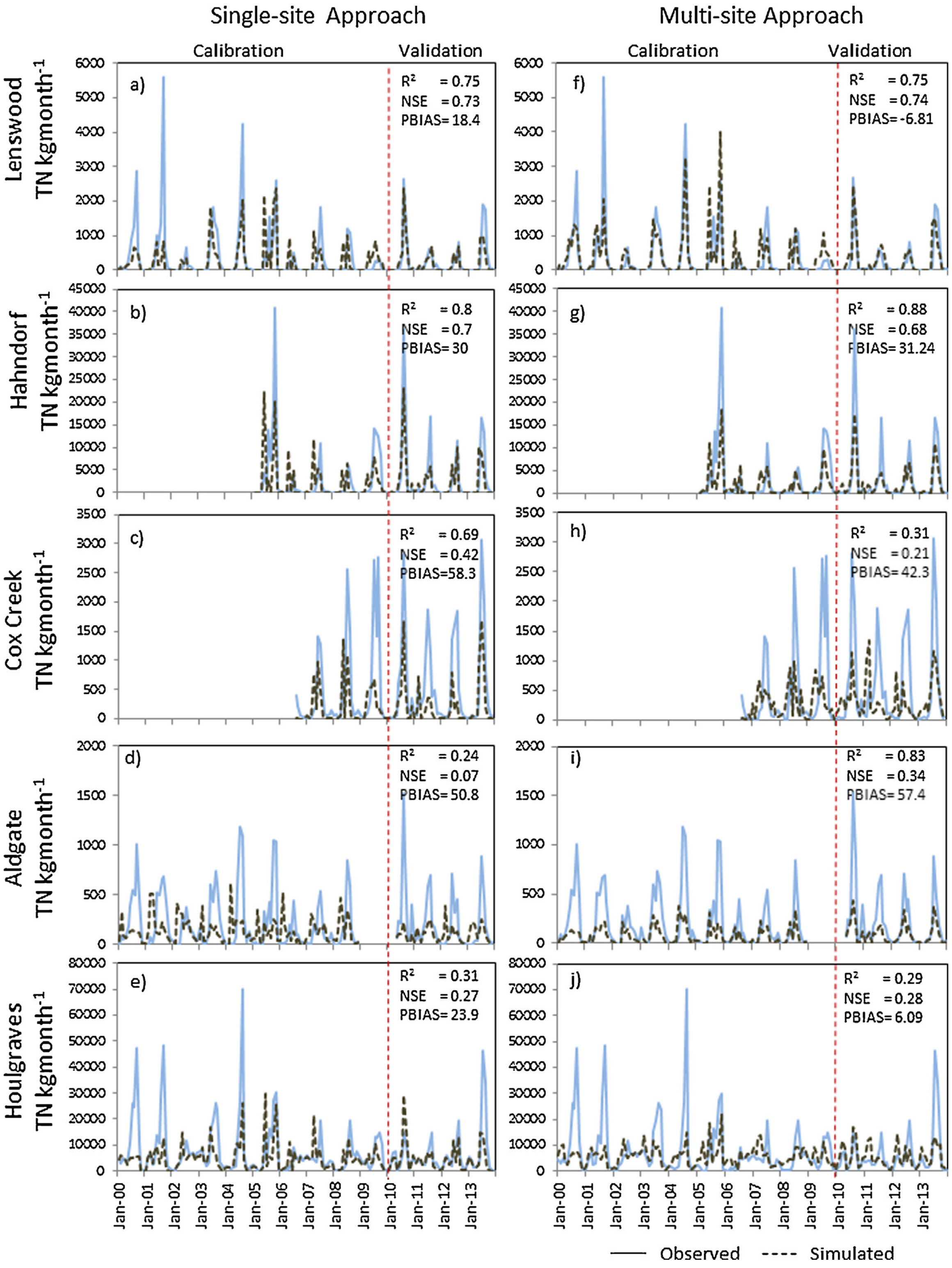

Fig. 4. Comparison of monthly total nitrogen (TN) simulation during calibration (2000–09) and validation (2010–13) for single and multi-site approach. (a–e) and (f–j) represents the results for single and multi-site approach respectively. Performance criteria results are provided for validation period only.

2.2. Application of SWAT

Arc SWAT 2012 (Winchell et al., 2013) was used for catchment modelling that is physically based and semi-distributed, and suits continuous, catchment-scale simulations. It operates on a daily time step and is designed to assess the impact of different management practices on water, sediment and nutrient transport in catchments (Arnold et al., 1998). It uses the SCS curve number (Soil Conservation Service, 1972) and the Penman-Monteith equation (Monteith, 1965) to estimate runoff and evapotranspiration respectively. For routing the flow, the variable storage routing method was applied. Planting and harvesting schemes were scheduled based on potential heat units. The harvest only operation was used for pasture, vineyard and orchard because these plants are not killed as

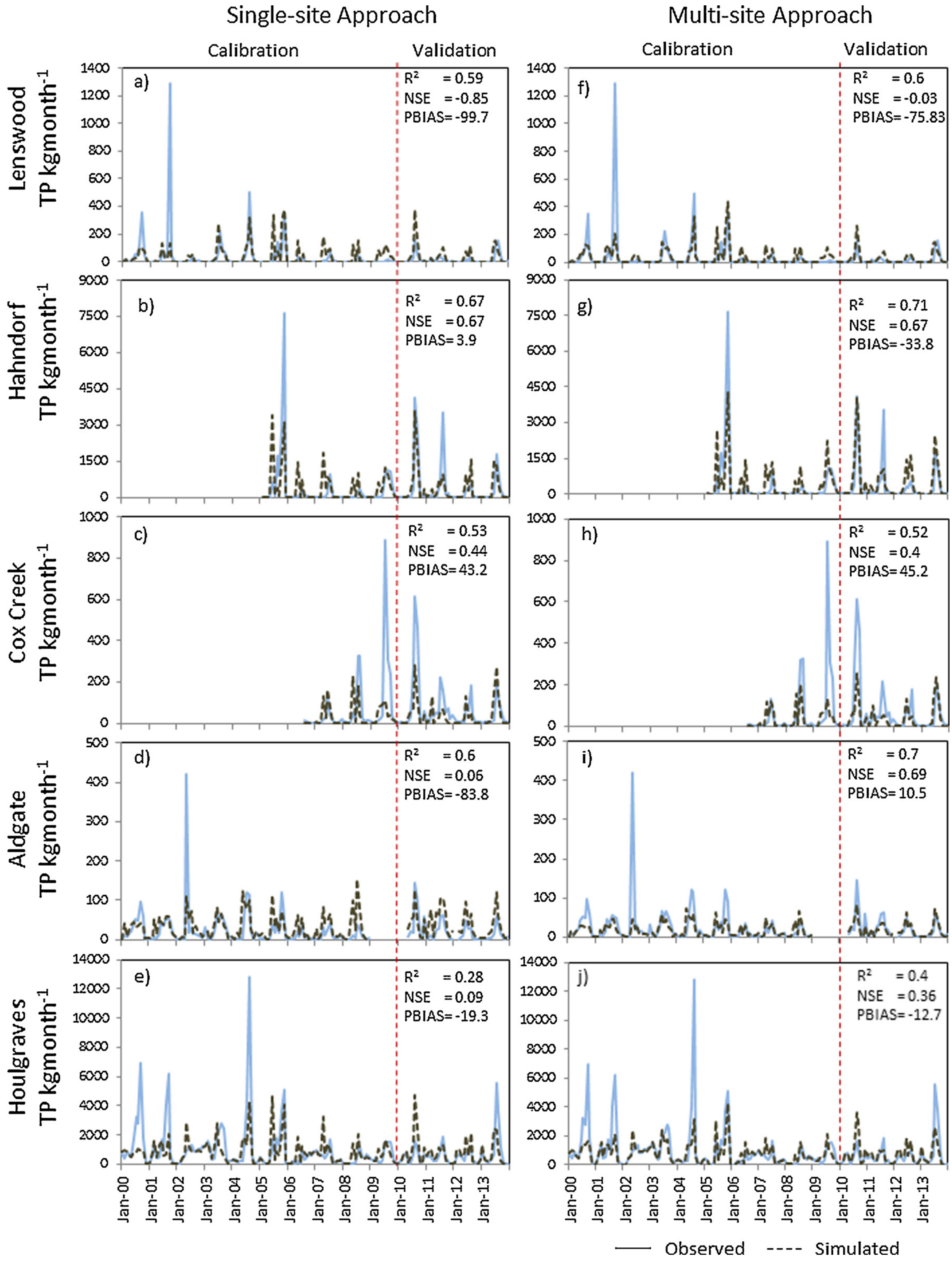

Fig. 5. Comparison of monthly total phosphorus (TP) simulation during calibration (2000–09) and validation (2010–13) for single and multi-site approach. (a–e) and (f–j) represents the results for single and multi-site approach respectively. Performance criteria results are provided for validation period only.

the crops. For the crops the 'harvest and kill' operation was used while for forest 'kill/end of growing season' was used. Fertilization and irrigation was set to be default.

The model has been designed for simulating monthly flow, total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP). A two year warm-up period was used which allowed enough time for the model to avoid the effects of the initial state conditions such as soil water content. Data from 2000 to 2009 was used for calibration and data from 2010 to 2013 was used for validation. All four years of validation data was available for each stations but only 3 years from 2007 to 2009 and 8 years from 2002 to 2009 of calibration data was available for the Cox Creek and the Hahndorf station respectively. It should be noted that the years 2000–2009 fall in the 'Millennium drought' period in Australia with prolonged

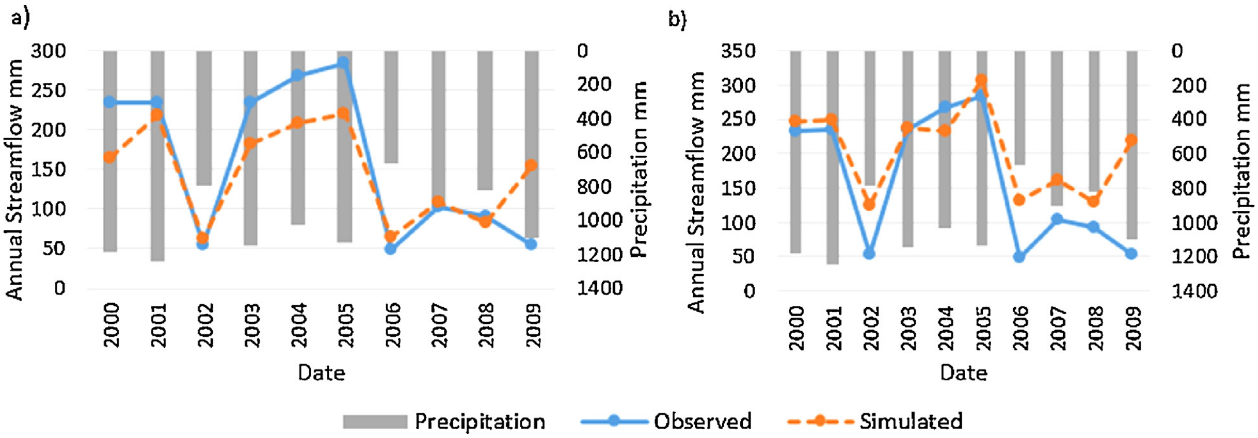

Fig. 6. Annual streamflow and precipitation for Lenswood (a) single-site calibration (b) multi-site calibration.

period of dry conditions (Bureau of Metorology, 2016). For all of the rainfall stations the year 2002, 2006–2008 and 2012 had below annual average rainfall.

2.3. Calibration and validation procedure

A single-site and a multi-site calibration approach has been applied to identify a model for the Onkaparinga Catchment that suits best for scenario analysis. The performance between these calibration approaches has been assessed by comparing simulated with observed output data. The single-site approach was solely calibrated by data from the outlet station of the catchment, i.e., at Houlgraves. The resulting model was further evaluated at four interior stations during the calibration and validation time periods as shown in Fig. 2.

The multi-site calibration according to Moussa et al. (2007) and Lerat et al. (2012) has been applied to four interior and the outlet station of the catchment. The model was first calibrated for the three head water catchments individually to obtain the parameter sets θ1, Θ2 and Θ3 for Lenswood, Cox Creek and Aldgate respectively. Next the model was calibrated for Hahndorf (θ4) keeping the parameter set Θ1 fixed. Finally the Houlgraves model (Θ5) was calibrated keeping all four parameter sets fixed for their respective sub-catchment. Hence multi-site calibration strategy used here gained benefits not only from the increased number of data but also the increased degree of parameter freedom compared to the single-site calibration. As such practices are common in hydrological modelling (Andersen et al., 2001; Lerat et al., 2012) comparative studies, effect of the number of parameters being varied is not considered in this study.

Parameters of SWAT models are varied at different spatial levels: HRUs, sub-basins and basin. Since sub-catchments may have different basin characteristics, assigning the same basin parameter values to the whole catchment may limit the calibration process. In order to allow each sub-catchment to have its specific basin parameter values and to avoid the limitation of calibration process, the above mentioned methodology has slightly been modified. Instead of fixing the parameter set as discussed above, we used the simulated flow and nutrient loadings obtained from that parameter set as input for the downstream station. For e.g., the output resulted from the parameter set Θ1 at Lenswood is used as an input for the downstream Hahndorf station and so on as shown in Fig. 2. In this way the basin parameter value obtained at the upstream station is not subjected to further modification while calibrating for the downstream station. Same number of initial parameter and their ranges were used to initiate the calibration at each of the station.

Model calibration and uncertainty analysis for both approaches were carried out by the semi-automated Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al., 2004) that uses a global search procedure through Latin Hypercube sampling. It estimated optimum parameter ranges and global sensitivity analysis for simulating the outputs: flow and loads of TSS, TP and TN for consecutive iterations. It was also used for estimating uncertainty in the model by means of the P-factor and the R-factor. The P-factor represents the percentage of observed data bracketed by 95% prediction uncertainty (95 PPU) and R-factor calculates the average width of the 95% uncertainty band divided by the standard deviation of corresponding observed data.

The sequential calibration of the variables suggested by Santhi et al. (2001) was performed wherein the flow was calibrated first and then followed by TSS, TN and TP. After successful calibration of flow, the flow parameter ranges were kept constant and subsequent calibration of TSS parameter was performed and so on. Finally a simultaneous calibration for the four variables were allowed using the parameter ranges obtained for each of the variable. Here, the best-fit parameter set that resulted in maximum objective function (Nash–Sutcliffe Efficiency in this case) was selected as the calibrated parameter set. Initial ranges of thirty two parameters that were used for calibrating the four output variables and the best-fit values are presented in Table 1.

The coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and percent bias (PBIAS) (Gupta et al., 1998) were used for evaluating the model performances as follows:

$$R^2 = \frac{\left|\sum_i (Y_{m,i} - Y_{\bar{m}})(Y_{s,i} - Y_{\bar{s}})\right|^2}{\sum_i (Y_{m,i} - Y_{\bar{m}})^2 \sum_i (Y_{s,i} - Y_{\bar{s}})^2} \quad (1)$$

$$\mathrm{NSE} = 1 - \frac{\sum_i \left(Y_{m,i} - Y_{s.,i}\right)^2}{\sum_i \left(Y_{m,i} - \bar{Y_m}\right)^2} \quad (2)$$

$$\mathrm{PBIAS} = 100 \times \frac{\sum_{i=1}^{n} \left(Y_{m,i} - Y_{s,i}\right)}{\sum_{i=1}^{n} Y_{m,i}} \quad (3)$$

Table 2
Calibration result of single-site and multi-site calibration approach for flow (m^3/s), total suspended sediment (TSS, tons/month), total nitrogen (TN, kg/month) and total phosphorus (TP, kg/month).

Gauging Stations	Area (km^2)	Performance criteria[a]	Calibration period							
			Single-site calibration				Multi-site calibration			
			Flow	TSS	TN	TP	Flow	TSS	TN	TP
Lenswood	16.9	R^2	0.73	0.07	0.37	0.21	0.73	0.12	0.56	0.35
		NSE	0.7	0.06	0.34	0.2	0.68	0.1	0.55	0.34
		PBIAS	8.1	39.3	32.4	−3.8	−25.8	−62.7	0	−1.7
Hahndorf	222.1	R^2	0.79	0.32	0.41	0.4	0.8	0.23	0.69	0.61
		NSE	0.78	0.3	0.39	0.4	0.74	0.15	0.55	0.6
		PBIAS	−14.7	−26.5	23.5	−0.9	−31.4	−119.6	35.5	−19
Cox Creek	10.4	R^2	0.77	0.17	0.33	0.17	0.81	0.27	0.19	0.32
		NSE	0.76	−2.54	0.2	0.13	0.78	0.16	0.13	0.22
		PBIAS	4.7	−221.9	55.9	49.2	−23.8	−46.9	39.5	49.3
Aldgate	8.17	R^2	0.7	0.38	0.04	0.29	0.65	0.37	0.6	0.3
		NSE	0.64	0.36	−0.1	0.25	0.62	0.25	0.2	0.2
		PBIAS	−27.3	−13.1	34.1	−30.1	−23	−27.8	63	31
Houlgraves	317.3	R^2	0.85	0.25	0.33	0.36	0.88	0.24	0.2	0.5
		NSE	0.84	0.2	0.25	0.33	0.82	0.01	0.2	0.4
		PBIAS	−8.9	−32.7	36.7	21.8	−19	−86.4	26	24

[a] Coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS) are model performance criteria.

where, Y is a variable (e.g., flow, TSS), m and s are measured and simulated value respectively, i is the ith measured or simulated data, n is the number of data points and $\bar{Y}$ represents the average value of the variable.R^2 indicates strength of linear relationship between the observed and simulated values. It ranges from 0 to 1 with 1 indicating the perfect model. NSE is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. It ranges between $-\infty$ and 1, with NSE = 1 being the optimal value. PBIAS indicates whether the simulated data is larger or smaller compared to observed counterparts. Positive values show model underestimation bias and negative values shows model overestimation bias with 0 being the optimal value.

The model performance was considered satisfactory when R^2 and NSE were greater than 0.5 and PBIAS ranged between ±25% for flow, ±55% and ±70% for sediments and nutrients respectively (Moriasi et al., 2007). These high ranges for the nutrients are due to the greater uncertainties in nutrient data associated with errors in stream flow measurements and sample collection, storage and analysis (Harmel and Smith, 2007).

3. Results and discussions

As the number of the gauging stations within the catchment increases, it is assumed that these additional data lead to improved models. Here we compared the single-site and multi-site calibration strategies to find out if this assumption is right.

3.1. Model performance for single-site calibration

The single-site approach was applied to calibrate the model for the outlet station at Houlgraves and to validate it for the 4 upstream stations. The performance statistics of this model for monthly flow, TSS, TN and TP during the calibration period are provided in Table 2. NSE of simulated flow at the outlet and upstream stations ranged from 0.64 to 0.84 and 0.69 to 0.87 which is well above the satisfactory criteria as recommended by Moriasi et al. (2007) during the calibration and validation periods, respectively. Similar results were achieved by Saha et al. (2014) using SWAT for flow simulation of the semi-arid Australian catchment. This suggests that the model can sufficiently take into account of hydrological characteristics at different spatial levels. Even though it achieved the criteria for satisfactory model performance, it underestimated most of the peak flows while low flows were well simulated for all stations except at the outlet where they were slightly overestimated (see Fig. 3a–e).

However, the model did not result in satisfactory simulation of sediment and nutrient loadings at the outlet during both calibration and validation period as represented by different quantitative statistics. Validation results at the interior stations were similar except for the Hahndorf station during the validation period. The unsatisfactory result for peak loadings (see Figs. 4 and 5a–e) may have been caused by the underestimated peak flows.

Table 3
Summary of the uncertainty analysis for two calibration strategies for validation period.

Stations	Performance Criteria	Single-site calibration				Multi-site calibration			
		Flow	TSS	TN	TP	Flow	TSS	TN	TP
Lenswood	P-factor	0.31	0.52	0.46	0.42	0.31	0.56	0.58	0.54
	R-factor	0.27	5.24	1.49	4.27	0.76	11.57	1.71	4.36
Hahndorf	P-factor	0.27	0.44	0.71	0.58	0.25	0.29	0.71	0.83
	R-factor	0.35	1.99	1.54	2.19	0.94	3.22	1.34	2.45
Cox	P-factor	0.58	0.71	0.48	0.46	0.42	0.54	0.58	0.38
	R-factor	0.39	4.35	1.21	1.46	0.25	1.82	1.08	1.04
Aldgate	P-factor	0.18	0.33	0.43	0.21	0.14	0.43	0.77	0.64
	R-factor	0.24	1.08	0.59	1.93	0.23	5.85	1.58	3.26
Houlgraves	P-factor	0.54	0.46	0.58	0.58	0.38	0.15	0.63	0.54
	R-factor	0.42	7.34	1.79	2.79	0.67	3.63	0.97	0.88

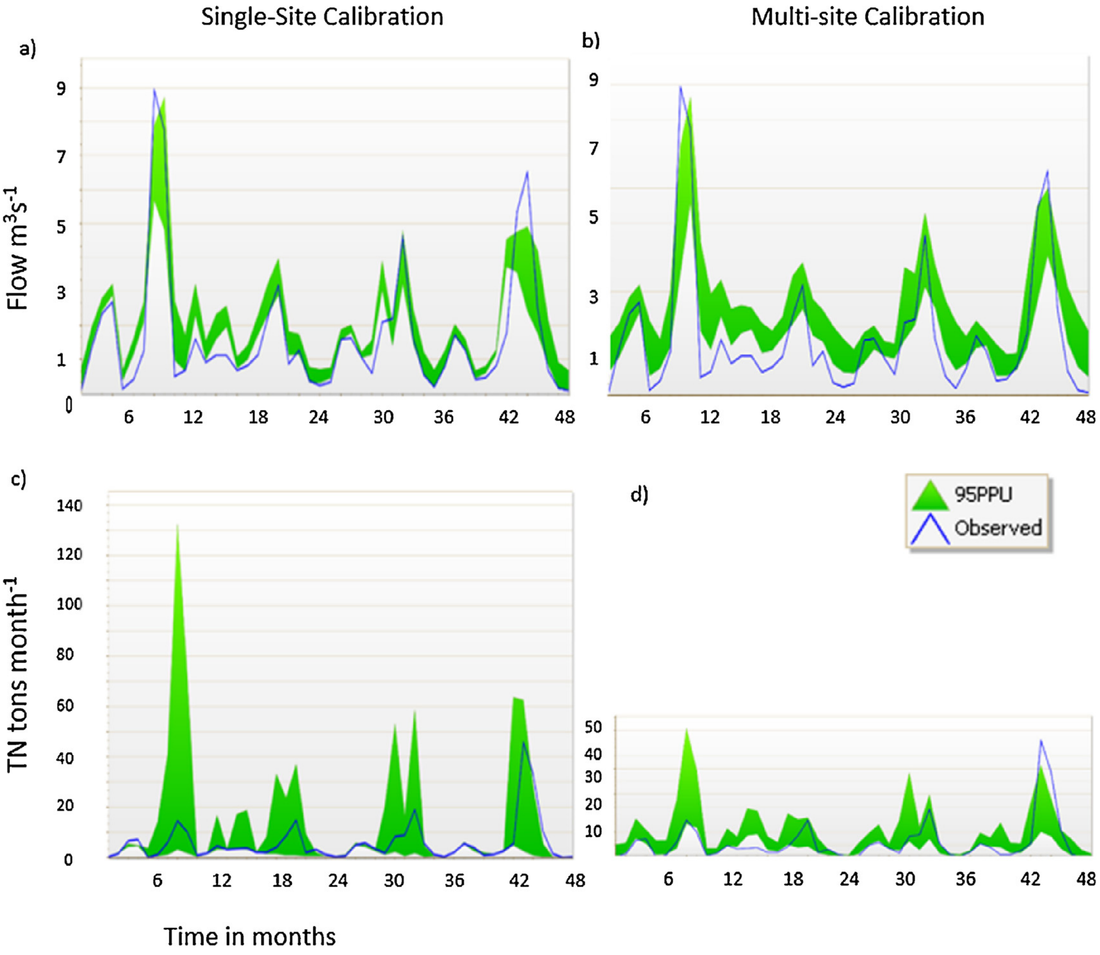

Fig. 7. Observed and 95% prediction uncertainty (95 PPU) of flow and TN loadings for validation period at Houlgraves.

The model performance did not meet the satisfactory criteria for simulation of TN and TP loadings at the Aldgate station. Graphical comparison shows unmatched timing of the event compared to the observed time series. Since most of the catchment is dominated by the pasture and rural settings, the urban characteristic of the Aldgate may not have been sufficiently reproduced. The underestimation of TN and TP loadings for the Cox Creek catchment may be explained by the market gardens known to have high nutrient losses. This sub-catchment loses 5.5 kg/ha and 0.77 kg/ha of TN and TP annually which is highest for any sub-catchments within the Onkaparinga catchment.

3.2. Model performance for multi-site calibration

As the single-site calibration did not perform well for sediment and nutrient loadings the multi-site calibration was deployed to investigate possible improvements. The performance statistics at the outlet and the interior stations are provided in Table 2 and represented in Figs. 3, 4 and 5f–j. Overall this approach led to improved nutrient simulation at both outlet and upstream stations compared to single-site calibration. Contrarily, the flow results were slightly lowered with NSE values ranging from 0.62 to 0.82 and 0.7 to 0.84 during calibration and validation period respectively. Results for the sediment loads improved only for the Cox Creek sub-catchment where the PBIAS from −221.9 was reduced to −46.9 which is within the range of a satisfactory criteria. This site has the lowest average annual TSS loading of 0.09 ton/ha and hence the overestimation was significantly reduced as indicated by the USLE practice factor (USLE_P) of 0.006 compared to 0.028 by the single-site calibration (Table 1). This value represents the ratio of soil loss with a specific support practice to the corresponding loss with up-and down slope culture. A sedimentation pond and a wetland system have been established at Cox Creek between 2004 and 2006 in order to reduce sediment and nutrient loads. This is reflected in the model by a decreased USLE_P value resulting in more realistic sediment loads during both calibration and validation. However, we could not reduce further the USLE-P value for Hahndorf as it decreased the performance of TN and TP simulation.

From the statistics summarised in Table 2 and results displayed in Figs. 3–5 it becomes obvious that TN and TP simulations have improved for the Lenswood, Hahndorf and Aldgate sub-catchments. The urban characteristics of the Aldgate is well represented by the multi-site calibration strategy, and hence the timing of measured nutrient loading matched well. Houlgraves which receives output from the calibrated upstream models also has improved nutrient simulations whereby the observed peak magnitude exceeding 2500 kg/month of TN was underestimated.

Even though model performance has improved compared to the single-site calibration, the quantitative statistics indicated that the nutrient loading simulations are poor. This poor result arose mainly from the underestimated loadings during the high flow events mainly for the Cox Creek and Aldgate. This suggests that improved data regarding nutrient management in these sub-catchments should be incorporated for future model improvement.

Flow simulation were satisfactory for both strategies but still we can see the model overestimation and underestimation throughout the flow time series in Fig. 3 for most of the sub-catchments. We analyzed how the rainfall-runoff translation occurs in reality and that simulated by the model. Fig. 6a and b for Lenswood station reveal that the same amount of rainfall did not translate into approximately same amount of observed stream flow as recorded in years 2003 and 2009. Both of these years had similar average annual precipitation and follow after the dry years 2002 and 2008. Contrarily the model translated almost similar stream flow for same amount of rainfall as shown in Fig. 6a and b. In semi-arid watersheds rainfall events are of short duration, high density and very local summer thunderstorms (Nie et al., 2011; Simanton et al., 1996). Since curve number method in SWAT uses averaged daily rainfall and does not consider the duration and intensity of rainfall, this may explain why peak flows were underestimated by the model in our catchment which agrees with other studies conducted in the semi-arid catchment (Niraula et al., 2012).

3.3. *Model uncertainty analysis*

Model simulation generally involves three sources of uncertainty: structural uncertainty, parameter uncertainty and input uncertainty. We used SUFI-2 to quantify the total uncertainty by estimating the P-factor and the R-factor. A P-factor should be close to 1 which means all observations are included by the prediction uncertainty, and an R-factor is generally desirable at a value of <1.5 (Abbaspour et al., 2015). These values were calculated for each of the station using the final calibrated parameter ranges obtained for the single-site and multi-site calibration strategy as provided in Table 3 for the validation period.

Comparatively the single-site calibration approach has narrower uncertainty for flow simulation as indicated by low R-factor and high P-factor (Table 3). On the other hand, multi-site calibration constricted the uncertainty of the model simulation of TN and TP. The 95 PPU band of TN and TP simulation by multi-site calibration brackets greater than 50% of observed data for most of the stations. Further a higher uncertainty during peak period of TN simulation is more evident for single-site calibration strategy as shown in Fig. 7c-d for the Houlgraves station. The TSS simulation by SWAT had high uncertainty for both strategies as reflected by high R-factors. As reported by Abbaspour et al. (2007), Chahinian et al. (2011) and Yesuf et al. (2015) model uncertainty can be attributed to poor data and model structure error. However, in this study we did not further investigate sources of uncertainties of our models.

4. Conclusions

(1) The model based on single-site calibration achieved better simulation results for flow while the models based on multi-site calibration performed better simulations for TN and TP loads. Even though the response of flow to precipitation is much unpredictable in this semi-arid catchment, the model performance for flow simulation is considered good.

(2) Simulation results for TSS loads were unsatisfactory and characterized by high uncertainty by models either with single-site or multi-site calibration. However, multi-site calibrated models reflected local catchment processes more realistic by utilizing site specific data and hence performed better, as demonstrated for the Cox Creek and Aldgate station.

(3) SWAT proved to be a suitable modelling tool for the arid rural Onkaparinga catchment for simulating flow and nutrient loadings. Model improvement by application of the multi-site calibration described here gives more confidence for further application in spatially-explicit scenario analyses of future land use changes and global warming.

Acknowledgments

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CHAPTER 3:

Future climate and land uses effects on flow and nutrient loads of a Mediterranean catchment in South Australia

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

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

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Future climate and land uses effects on flow and nutrient loads of a Mediterranean catchment in South Australia

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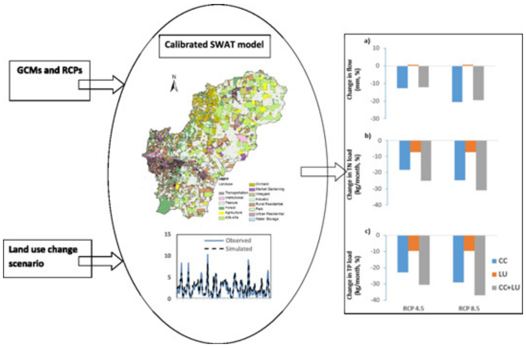
HIGHLIGHTS

- Temperature increases and average precipitation decreases under future climate.
- SWAT was applied to assess the effects of climate and land use change scenario.
- Stream flow and water quality were significantly altered by future climate change.
- Flow decline and nutrient enrichment were indicated for some summer months.

GRAPHICAL ABSTRACT



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ABSTRACT

Mediterranean catchments experience already high seasonal variability alternating between dry and wet periods, and are more vulnerable to future climate and land use changes. Quantification of catchment response under future changes is particularly crucial for better water resources management. This study assessed the combined effects of future climate and land use changes on water yield, total nitrogen (TN) and total phosphorus (TP) loads of the Mediterranean Onkaparinga catchment in South Australia by means of the eco-hydrological model SWAT. Six different global climate models (GCMs) under two representative concentration pathways (RCPs) and a hypothetical land use change were used for future simulations. The climate models suggested a high degree of uncertainty, varying seasonally, in both flow and nutrient loads; however, a decreasing trend was observed. Average monthly TN and TP load decreased up to −55% and −56% respectively and were found to be dependent on flow magnitude. The annual and seasonal water yield and nutrient loads may only slightly be affected by envisaged land uses, but significantly altered by intermediate and high emission scenarios, predominantly during the spring season. The combined scenarios indicated the possibility of declining flow in future but nutrient enrichment in summer months, originating mainly from the land use scenario, that may elevate the risk of algal blooms in downstream drinking water reservoir. Hence, careful planning of future water resources in a Mediterranean catchment requires the assessment of combined effects of multiple climate models and land use scenarios on both water quantity and quality.

1. Introduction

Projected changes of future climate are likely to affect the availability of global water resources in many ways. According to IPCC (2007, 2014),

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extreme meteorological and hydrological events can be expected in future resulting in more frequent droughts, storms and floods posing more uncertainty and risk on river catchments worldwide. Water limited catchments in Mediterranean climate regions experience already high seasonal variability alternating between dry and wet periods, and are particularly vulnerable to global climate change (Giorgi and Lionello, 2008; Piras et al., 2014). Climate projections for Mediterranean catchments in Southeast Australia suggest a decrease in runoff of up to 25% (Chiew and McMahon, 2002) with serious consequences for catchment management (Chiew et al., 2011; Charles and FU, 2015; Hope et al., 2015). Furthermore, future changes in land uses driven by socio-economic and environment variability are likely to occur. They can lead to changes in water availability and nutrient loadings in many different ways. Hence long term assessments of water quality and quantity are required as prerequisite for sustainable water resources management, especially in the context of future climate and land use change.

Previous studies on effects of climate and land use changes worldwide focused mainly on water availability, and only a few studies have addressed responses of nutrients to future changes (Dunn et al., 2012; Mehdi et al., 2015). There is growing evidence that surface water quality is directly affected by several climate related mechanisms (Aldous et al., 2011; Sahoo and Schladow, 2008). Molina-Navarro et al. (2014) found that decreasing runoff magnitudes diminished nitrogen export but increased total phosphorus (TP) loads in a Spanish catchment. Another study conducted in the River Kennet in UK (Wilby et al., 2006) indicated that increased temperature and climate variability may increase nitrate and ammonium concentrations. Moreover, episodic nitrogen peaks due to the "wash up" of accumulated soil nitrogen are likely as soon as the drought breaks. A study of two severe drought periods in the river Meuse, Belgium by van Vliet and Zwolsman (2008) showed, that water quality had been degraded by algal blooms favoured by changed water temperatures and nutrient concentrations. Schneider and Hook (2010) reported that surface water warmed at an average rate of 0.045 ± 0.011 °C year^{-1} by increasing air temperatures during the period of 1985–2009.

Similarly, studies conducted in several river basins of Scotland by Dunn et al. (2012) concluded that land use changes increased nitrate pollution. Another study on Prince Edward Island, Canada by De Jong et al. (2008) suggested an increase of nitrogen leaching by up to 30%. El-Khoury et al. (2015) argued that changed land uses may have a greater impact on nitrogen and phosphorus than climate change, and are crucial for determining adaptation strategies. Since these studies demonstrated that climate and land use changes differently affect nutrient release in catchments, the relative impact of these simultaneously occurring changes is of an interest to know.

Models such as the widely used process-based eco-hydrological model SWAT (Arnold et al., 1998) are generally used for investigating potential impacts of climate and land use changes on catchments. This study applies the SWAT model for the Onkaparinga catchment that has previously been developed by Shrestha et al. (2016) to carry out scenario analyses on flow, total nitrogen and total phosphorus loads affected by future climate and land uses. It combines data from six global climate models (GCM) for intermediate and high emission cases with likely land use changes simulated over a period of 25 years from 2046 to 2070, a time horizon that is relevant for planning restoration and adaptation strategies. It also analyses the uncertainty in predicted flow and nutrient loads caused by the choice of GCM and emission scenarios.

2. Materials and methods

2.1. Study area

The study was carried out within the Onkaparinga catchment situated 60 km east of Adelaide by modelling an area of 317 km^2 upstream of the Houlgraves gauging station (Fig. 1a). The elevation of this area ranges from 10 to 700 m and annual rainfall varies between 522 mm at the coast and 1088 mm in upland areas.

The Onkaparinga catchment is mostly dominated by pasture areas; however, intensive horticulture and viticulture are located in some of the western part of the catchment (Fig. 1b). The western part has hill slopes with clayey to sandy subsoils and has permeable sandstones suitable for orchard and vineyard. While, the eastern part consists of less permeable siltstone with lower slopes and flats that is clayey in texture (Zulfic et al., 2002).

2.2. Model set-up

The process-based semi-distributed catchment model SWAT was used, which can assess the effects of different management practises on water, sediment and nutrient transport in catchments (Arnold et al., 1998). A 30 m Digital Elevation model (DEM) was obtained from Shuttle Radar Topography Mission (SRTM). A 2003 land use and soil map of 2005 were sourced from Department of Water, Soil and Natural Resources of South Australia. Meteorological data were obtained from SILO (Scientific Information for Land Owners, 2015) patched dataset.

This study used the SWAT Onkaparinga catchment model developed by Shrestha et al. (2016) for simulation of monthly flow, TN and TP loadings. It was demonstrated that the multi-site calibration outperformed the single-site calibration in simulating nutrient loadings and hence this multi-site calibrated model was selected for this climate change effect study. However, it was observed that the organic N loading was not reproduced reasonably and the model was further calibrated which improved both organic N and TN loads. Performance during calibration (2000–2009) and validation (2010 − 2013) period for this improved model is provided in Table 1 and figure in Supplements. To understand the impacts of climate change on natural characteristic of the catchment only, the contribution of River Murray derived water was omitted from the calibrated Onkaparinga model. This model then was used for running climate change scenarios.

2.3. Future climate data and model simulation

Climate projection datasets for different regions of South Australia were produced by Task 3 of the Goyder Institute of Water Research Project (GIWR, 2015) and is available on SA Climate Ready portal at https://data.environment.sa.gov.au/Climate/SA-Climate-Ready. This projection used statistical downscaling techniques called Nonhomogenous Hidden Markov Model (NHMM) to simulate daily rainfall from global climate models (GCMS) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). These rainfalls were calibrated at multiple stations in different regions of South Australia. The GCM grid-scale output of non-rainfall variables were downscaled by using a weather generator conditional on the weather states and rainfall simulated by NHMM (Charles and Fu, 2015). Fifteen Coupled Model Intercomparison Project phase 5 (CMIP5) were chosen for the downscaling project for South Australia which were further studied to identify the six 'best' GCMS as provided in Table 2. Future emission scenarios representing two representative concentration pathways (RCP) from the IPCC AR5 were used to represent possible future greenhouse gas concentrations whereby RCP 4.5 and RCP 8.5 represents increases in radiative forcing in 2100 relative to preindustrial levels of 4.5 and 8.5 W/m^2 respectively or simply to put intermediate and high emission scenarios respectively.

Each of the downscaled GCMs produced 100 stochastic replicates (realisations) of future projected climate data until 2100 for rainfall and non-rainfall variables. However, only one realisation for each of the six climate models was used. The realisation that corresponds to the median of projected total precipitation amount for the period between 2006 and 2100 was selected for model simulation.

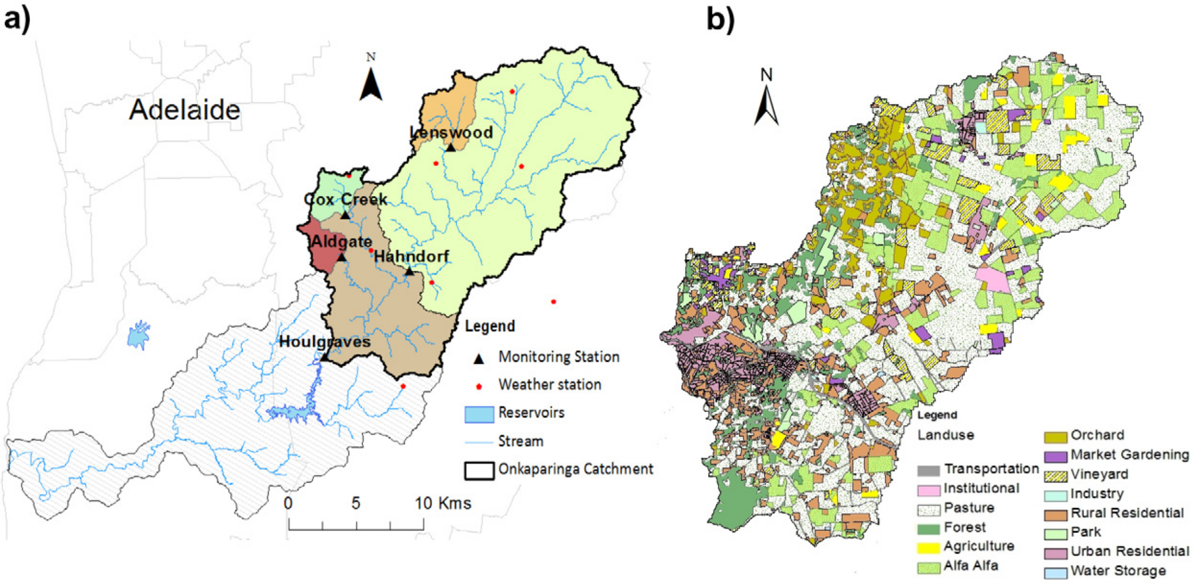

Fig. 1. The Onkaparinga catchment. (a) Location map and gauging stations. (b) Land use map.

2.4. Future land use change scenarios

The Onkaparinga catchment is important for the water supply of the metropolitan area of Adelaide and by its unique landscapes, only minor changes of its land uses are expected in future. As outlined in the Adelaide Hills Council Development Plan (2016) the current policy emphasises controlled development of the catchment by retaining its rural character. The here proposed land use scenarios consider these policies along with prospective population growth and hence three scenarios of land use were considered as shown in Table 3. The afforestation scenario consists of two land use changes with increase in forest cover by 40 and 70% respectively termed as frs-40 and frs-70 in expense of pasture. Similarly the urbanisation scenario included increase of urban area by 50 and 85% refereed as urb-50 and urb-85 respectively. Finally a combined land use scenario (LU) was devised that considers combination of frs-70 and urb-85 along with double extension of vineyard area. These changes were implemented by the land use change method of SWAT at the sub-basin scale. For example, the replacement of pasture by forest can be considered only if both land uses are present in the same sub-basin. The double extension of vineyards on agricultural land applies mainly to the Cox Creek sub catchment and corresponds with suggestions by Kunhert et al. (2015). The Table 3 summarises current and future land use percentages. To be consistent with climate change scenarios, the land use scenario has been designed for the period from 2046 to 2070, a time horizon that is relevant for planning restoration and adaptation strategies. Results from different land use change scenario reveals that urban area contributes to increase in annual flow and TN losses (see Fig. 2). However, afforestation resulted in small change in flows and higher losses of TN and TP loads. The LU scenario shows dominating effects on nutrients from afforestation compared to the urban areas because of relatively higher percentage of pasture being replaced to forest coverage.

2.5. Assessment of effects of different scenarios

Three scenarios were implemented to assess the combined effects of climate and land use on water yield, TN and TP load for the time period 2046–2070.

1) Future land use change with historical climate data from GCMs called "LU" scenario.
2) Projected climate data under two RCPs with historical land use map called "CC" scenario and
3) Future climate under two RCPs and future land use data combined called "CC + LU" scenario.

The calibrated model was run for the historical climate data (1981–2005) of six global climate models, considered as the reference scenario. This was compared against the flow, TN and TP loads resulting from model simulation of three future scenarios for a period of 25 years (2046–2070). The projected deviation (relative change in percentage between the reference and future scenario) of the three variables for each climate model was calculated and averaged to be considered as mean of the climate model ensemble in order to assess the relative

Table 1
SWAT calibration and validation result for flow (m^3/s), total nitrogen (TN, kg/month) and total phosphorus (TP, kg/month) loads.

	Performance criteria[a]	Calibration		
		Flow	TN	TP
Calibration	R^2	0.88	0.39	0.41
	NSE	0.82	0.37	0.35
	PBIAS	−17.5	15.1	−20.23
Validation	R^2	0.89	0.41	0.4
	NSE	0.82	0.37	0.36
	PBIAS	−24.57	−7.46	−12.7

[a] Coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS).

Table 2
Description of six "best" climate models used in study.

Climate model ID	Climate modelling group	Country
CanESM2	Canadian Centre for Climate Modelling and Analysis	Canada
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Foramtion Avancéeen Calcul Scientifique	France
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	USA
IPSL-CM5B-LR	Institut Pierre-Simon Laplace	France
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan
MRI-CGCM3	Meteorological Research Institute	Japan

Table 3
Current and future land use in percentage.

Land uses	Current area (%)	Environmental scenario		Development scenario		Combined scenario (LU) (%)
		Frs-40 (%)	Frs-70 (%)	Urb-50 (%)	Urb-85 (%)	
Forest	7.1	10.3	12.1	–	–	12.1
Pasture	57	53.7	51.9	55	54	47
Urban	4.1	–	–	6.1	7.8	7.8
Rural	8.6	–	–	–	7.9	7.9
Vineyard	1.9	–	–	–	–	3.9
Alfa-Alfa	14.9	–	–	–	–	14.9
Orchard	5.7	–	–	–	–	5.7
Agriculture	0.7	–	–	–	–	0.7

– indicates no change in initial cover for different proposed land use scenario.

impacts annually, seasonally and monthly. Furthermore, the uncertainty of climate projections from six GCMs was explored to evaluate the importance of multi-models in impact analysis.

3. Results and discussions

3.1. Future climate effects on precipitation and temperature

Table 4 shows the average annual and seasonal variability of both precipitation and temperature from multi-climate models in future periods relative to the baseline (1981–2005). It shows a general trend of increasing temperature and decreasing precipitation, with more pronounced effects for the later period (2046–2070) under RCP 8.5. Temperature increases in all seasons of both scenarios with the largest increases in spring and smallest in winter. Annual average daily temperature is expected to increase by 1.84 °C for 2046–2070 under the high emission scenario. On the other hand, average precipitation is expected to decrease both annually and seasonally except for a slight increment in autumn for 2021–2045 under RCP 4.5. The largest decrease is likely to occur during the spring up to a −20% change for the later period under RCP 8.5. The average annual precipitation change varies from −4.2% to −9.7% under different RCPs and future time periods.

3.2. Effects on water yield

3.2.1. Annual changes

The average annual water yield is projected to decrease under the CC scenarios, with stronger declines for RCP 8.5 as shown in Table 5. We also analysed the projections for 2021–2045 that estimates a decrease of the average annual water yield by −11.2% and −18.15% for RCP 4.5 and RCP 8.5 respectively (not shown in this paper). This is comparable to the findings from Westra et al. (2014) for the same catchment using a conceptual hydrological model GR4J that showed −11% and −16% decrease for the slightly elongated period 2016–2045. The average decrease for 2046–2070 is slightly higher than the 2021–2045 for both RCPs and hence only this period was assessed for future effects of climate (CC), land use (LU) and combined effects of both climate and land use change (CC + LU) scenarios.

Fig. 3a shows that the CC scenario alone has the largest effect on average annual water yield with a decrease of up to −20.5% for RCP 8.5. On the other hand, LU scenario shows a modest increment in water yield about 0.7% which is comparable to the changes as detected in the study by El-Khoury et al. (2015). The CC + LU scenario resulted in a slight decrease of water yield compared to CC scenario alone because of some increment produced by the future land use change. However, this decrease of up to −19.5% for RCP 8.5 may result in considerable concern around the management of water for drinking purposes.

3.2.2. Seasonal changes

The decrease in water yield under the CC scenarios are observed for all seasons with more pronounced changes in winter and spring that are, the main flow seasons (Table 5). Comparatively, spring has the largest reduction in water yield by −23.7% which is larger than the annual decrease. In contrast, the LU scenario shows increase in water yield for all seasons with the largest increase in autumn of 3.4%. This can be

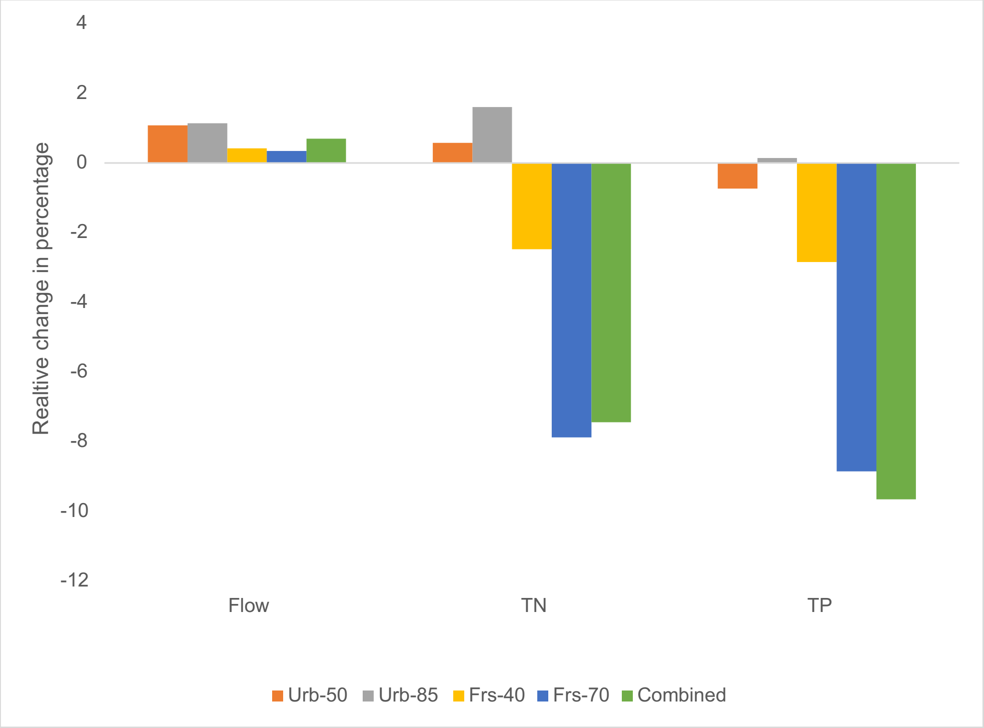

Fig. 2. Relative change in percentage on average annual water yield, total nitrogen (TN) and phosphorus (TP) load from different land use change scenarios. Urb represents urban area; Frs represents forest area; combined represents combination of Urb-85 and Frs-70. The number on the suffix represents percentage by which initial area is increased.

Table 4
Changes in precipitation and temperature under RCP 4.5 and RCP 8.5 scenario (Average of six GCMs ensemble), for 2021–2045 and 2046–2070.

	1981–2005		2021–2045 RCP4.5 (RCP8.5)[a]		2046–2070 RCP4.5 (RCP8.5)[a]	
	Average precipitation in mm	Average daily temperature in °C	% change in precipitation	Change in temperature °C	% change in precipitation	Change in temperature °C
Summer (DJF)	84.7	19.5	−9 (−2.5)	0.77 (0.95)	−5.8 (−8.8)	1.22 (1.75)
Autumn (MAM)	182	15.2	1.5 (−2.9)	0.85 (1.08)	−4.5 (−5.3)	1.29 (1.92)
Winter (JJA)	396.9	10	−0.8 (−3.7)	0.68 (0.87)	−5.3 (−6.4)	1.04 (1.57)
Spring (SON)	205	13.9	−13.6 (−12.6)	1 (1.2)	−16 (−20)	1.5 (2.14)
Annual	868.6	14.6	−4.2 (−7.8)	0.82 (1.26)	−5.5 (−9.7)	1.03 (1.84)

[a] Figure in brackets are the values for RCP 8.5.

attributed to the increased forest area coverage at the expense of pasture, which contributes more base flow during the summer and autumn season. The CC + LU scenario projects similar decreases of water yield as that of CC scenario.

The variability of change in water yield for two major seasons as projected by the average outputs of six GCMs is displayed in Fig. 4(a, b) under two RCPs. The CC scenario results in high variation of flow changes with stronger influence under RCP 8.5. Furthermore, some climate models result in increased flow represented by dots above the whisker and is considered outliers. It indicates that a high uncertainty stems from climate models and impact analysis studies should often consider ensemble approach as suggested by some authors (Feyen and Dankers, 2009; van Roosmalen et al., 2007). Similar variation as observed for CC + LU scenario can be attributed to dominance of climate change effect over land use.

3.2.3. Monthly changes

At monthly time step it is evident from the Fig. 5(a, b) that the LU scenario is likely to contribute an increase in flow during the period from December to May. The projected increase in forest coverage can increase the base flow, while the increase in urban area may increase the surface flow thus increasing overall flow during this period. However, decreases in flow due to CC effects results in decreased flow for the combined scenarios. It is likely that average monthly water yield decreases is higher under RCP 8.5 (Fig. 5b) for both CC and CC + LU scenario, which may put further stress on already water limited catchment.

3.3. Effects on nutrient loads

3.3.1. Annual changes

The three scenarios indicate a decline of average annual total nitrogen (TN) and phosphorus (TP) loads from the catchment and is most significant for RCP 8.5 (see Fig. 3b and c). Even though the model predicts a higher water yield by the proposed land use changes, there is a 7.4% decrease of TN loads and a 9.6% decrease of TP loads which can be attributed to the replacement of pasture areas by forest. Similarly, the CC scenario estimates up to 24.3% decreases of TN loads and 29% decrease of TP loads, a trend that has been further strengthened by the CC + LU scenario because of cumulative effects.

3.3.2. Seasonal changes

The LU scenario displays a seasonally varied response for nutrient loads. During winter, significant decreases by −10.7% and −10.6% for TN and TP respectively are likely to occur that are higher than the annual average loads. Interestingly, both TN and TP loads are projected to increase in the summer dry months which can be attributed to the increased flow. As with flow, the CC scenario results in an overall decrease of nutrient load for all seasons, with the greatest reduction in spring by −37.9% (TN) and −44.9% (TP) under RCP 8.5. The combined scenario shows a cumulative effect of decreasing nutrient loads.

The box plot in Fig. 4(c, d, e and f) all shows that there is a little variation in simulated change of nutrient loads among different GCMs for LU scenario. All GCMs result in a decreased nutrient load though considerable uncertainty exists in projections for both CC and CC + LU scenarios. However, the variation in TN and TP load has a similar trend, i.e., both nutrients have a high variation in winter under RCP 4.5 and small under RCP 8.5 and vice versa in spring. This again explains why multiple climate models are required for assessing the modelled responses.

3.3.3. Monthly changes

The monthly projections in Fig. 5(c, d, e and f) suggest increase in nutrient loading during dry months from January to February for TP and extending to April for TN load due to LU change which can be partially attributed to the increased flow. Both TN and TP loads are basically dominated by dissolved components than the organic components in summer. The model resulted in increase of mineral phosphorus loads by up to 10% in January and February. Nitrate being highly soluble can leach through the soil profile to appear as a ground water contribution as more forest area resulted in increment in base flow.

However, a significant reduction in nutrient loads up to −11% is observed for the wet months suggesting the decreasing effect of increase in less agricultural intensive practises such as forest plantations. Furthermore, analysis of sediments loss revealed decreases for all months which resulted in reduction of loss of sediment attached component of nutrients.

The effects of CC scenario on nutrient loads is much more dominant than the LU scenario with decreases up to −55% and −56% for TN and

Table 5
Average annual and seasonal changes in water yield (mm), total nitrogen (TN, kg) and phosphorus (TP, kg) load for future period (2046–2070) and emission scenarios RCP 4.5 (RCP 8.5)[a].

	Scenarios	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Spring (SON)	Annual
% change in water yield	LU	1.7	3.4	0.5	0.3	0.7
	CC	−11.6 (−15.6)	−9.3 (−15.1)	−11.9 (−19.7)	−14.3 (−23.7)	−12.7 (−20.5)
	CC + LU	−9.7 (−13.8)	−5.8 (−11.5)	−11.6 (−18.9)	−14.7 (−23.3)	−12.2 (−19.5)
% change in TN load	LU	10.2	0.4	−10.7	−7.6	−7.4
	CC	−1.5 (−11.5)	−9.8 (−17.7)	−16.7 (−22.5)	−34 (−37.9)	−18.4 (−24.3)
	CC + LU	10.9 (−2.1)	−11.9 (−20.1)	−25.9 (−32.1)	−38.9 (−42.5)	−24.6 (−30.9)
% change in TP load	LU	1.3	−9.6	−10.6	−7.7	−9.6
	CC	−23.3 (−21.3)	−9 (−18.4)	−19.2 (−25.8)	−41 (−44.9)	−22.9 (−29)
	CC + LU	−19.8 (−19.4)	−19.2 (−28.1)	−28 (−35.1)	−45.5 (−49.5)	−30.6 (−37.1)

[a] Figure in brackets are the values for RCP 8.5.

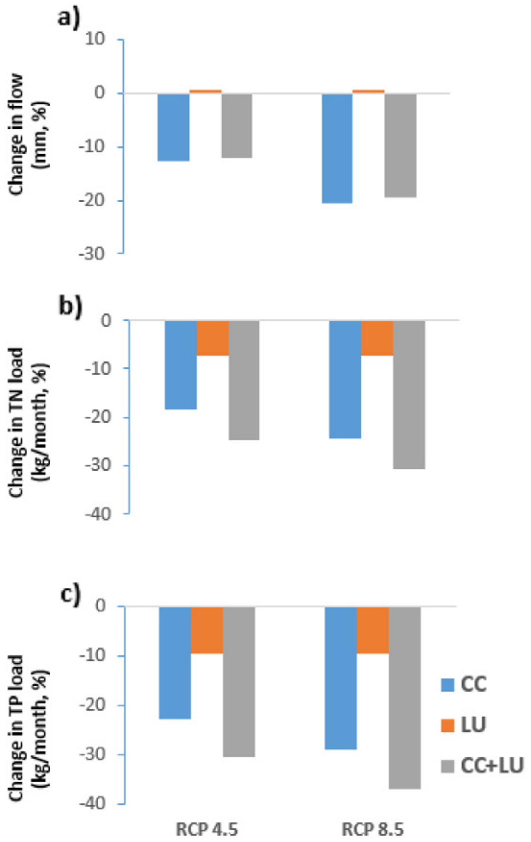

Fig. 3. Relative change on average annual water yield, total nitrogen (TN) and phosphorus (TP) load from impacts of Climate change (CC), land use (LU) and combination of climate and land use change (CC + LU) under RCP 4.5 and RCP 8.5.

TP loads respectively. However, it is to be noted that the change in percentage of land use is very minimal as can be seen in Table 3. Furthermore, Fig. 2 suggests clearly the effects of increasing forest area in reducing nutrient loads. Decreases in nutrient loading during most of the months can be attributed to decreases in flow and sediment yield which reduces transportation of the bulk of sediment attached particles from adjacent land uses to the streams. The impact is far more significant for RCP 8.5 compared to RCP 4.5. However, TN increases up to 14% (2.7%) for RCP 4.5 (RCP 8.5) while TP increases by 14% on April only under RCP 4.5 in dry months. The increase in TP is attributed to the increase in sediments loads on that particular month even though the monthly flow has decreased. It confirms with other studies for example, Molina-Navarro et al. (2014) that suggest the stronger relationship of sediments and TP loads.

TN increment in summer months despite flow and sediment yield reduction due to climate change indicates more losses of mineral components. This could result from the addition of more fertilisers in the future climate scenarios as the model triggered auto fertilisation of inorganic nitrogen increased to 96.37 kg/ha from baseline of 94.3 kg/ha per annum. Furthermore mineralisation of organic matter due to increase in soil temperature may accelerate in the future, which, however cannot be confirmed in this study on seasonal basis.

The combined scenarios show the cumulative effect of both climate and land use scenario ranging from +19% (+3%) to −57% (−57%) for TN (TP) under RCP 8.5. This increase is observed on January for TP while TN increases even in February.

A positive relationship was found between monthly nutrient load and flow ($R^2 = 0.5$ to 0.62 for both TN and TP under different RCPs; not reported here), hence decreasing flow can explain the decreasing nutrient loads as less organic materials could be transported from land to the surface water. Panagopoulos et al. (2011) reached a similar conclusion in a Mediterranean catchment in Greece where TN and TP was dependent on flow magnitude.

4. Conclusion

The models SWAT and GCM have been applied to the Mediterranean Onkaparinga catchment to quantify likely impacts of climate and land use changes on water flow and nutrient loads during the forecasting

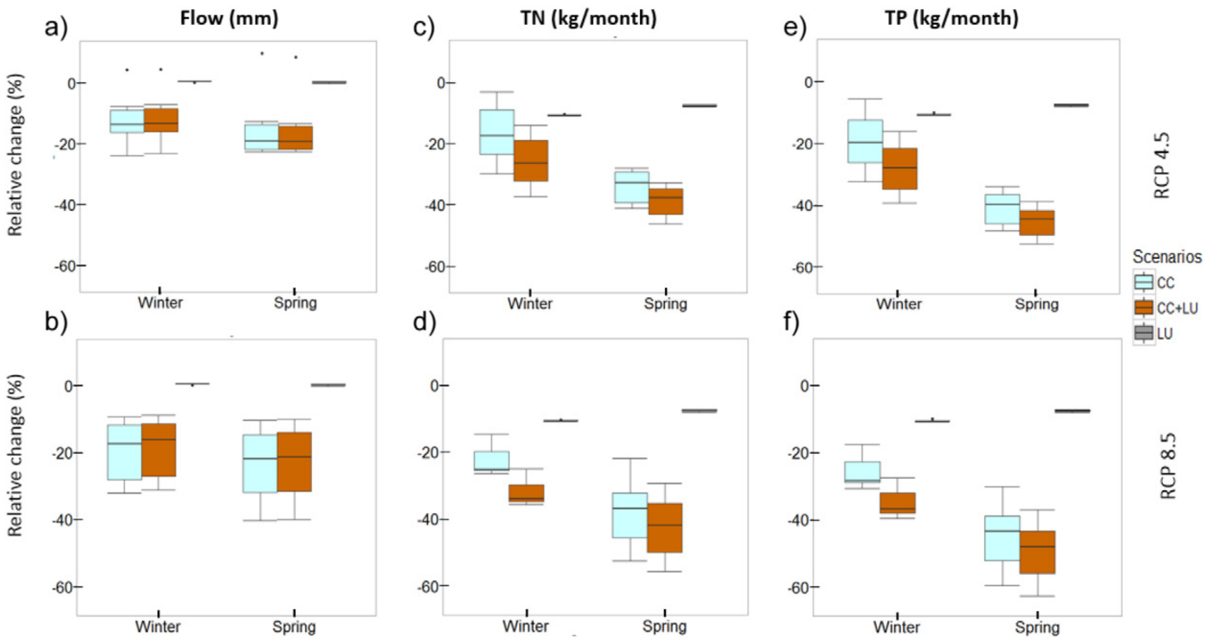

Fig. 4. Effects of future climate and land use change on winter and spring water yield (a, b), total nitrogen (c, d) and phosphorus (e, f) under two emission scenarios: RCP 4.5 (upper panel) and RCP 8.5 (Lower panel). Boxplot represents the relative change in percentage as observed from the ensemble of six global climate models for future climate (CC), land use (LU), and combination of future climate and land use change (CC + LU).

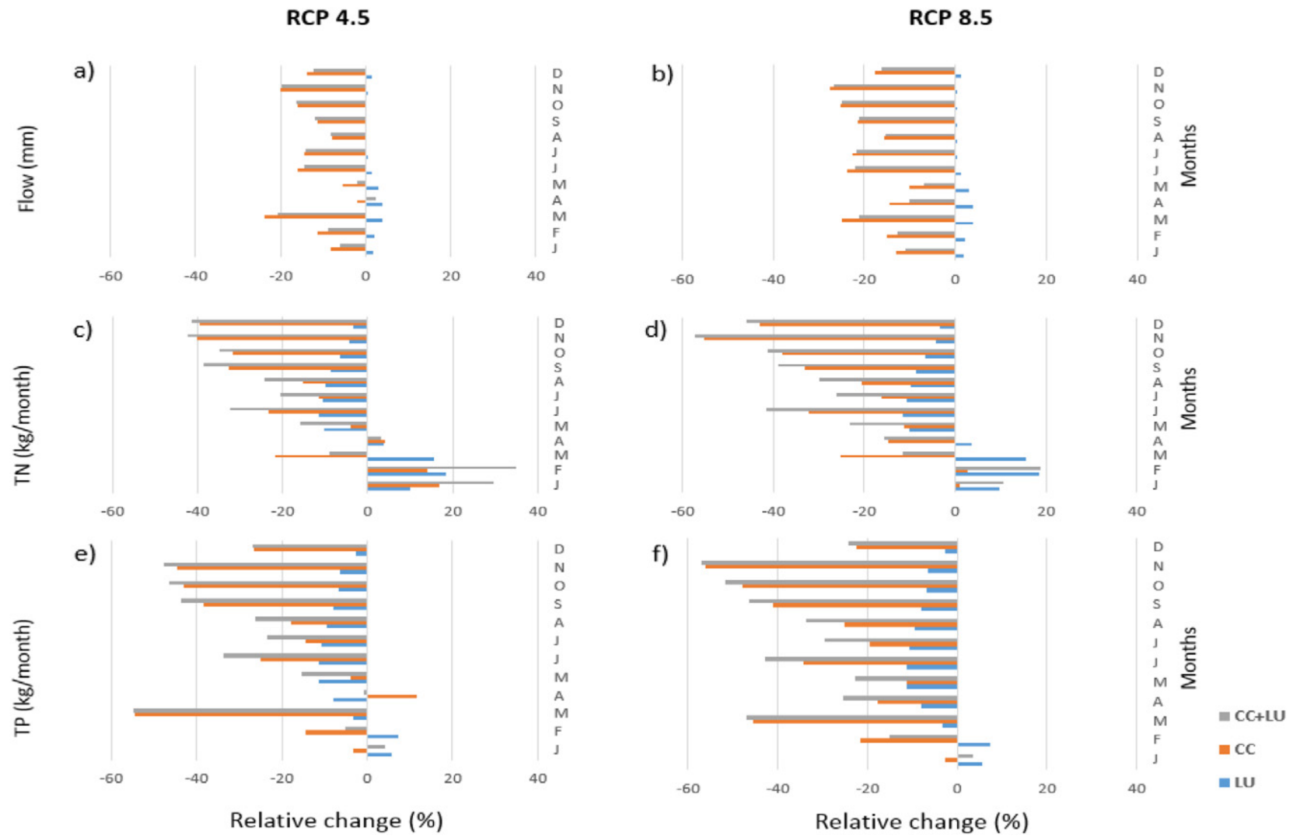

Fig. 5. Relative change in percentage on average monthly water yield, total nitrogen (TN) and phosphorus (TP) load from effects of climate change (CC), land use (LU) and combination of climate and land use change (CC + LU) under RCP 4.5 and RCP 8.5.

period from 2046 to 2070. Following conclusions can be drawn from the results:

1. Results from six GCM suggest that increasing temperature and decreasing precipitation in the period 2046 to 2070 will lead to declining water yield and nutrient loads at both annual and seasonal time scales. The largest decreases of water and nutrient yield have been projected for spring with pronounced effects by the high emission scenario RCP 8.5.
2. The land use scenario resulted in very small increases in flow, but decreased nutrient loadings coming from less erodible and lower nutrient input land management.
3. The combined scenario clearly showed that climate change can be expected to have more severe impacts on the ecohydrology of catchment than the proposed land uses, but displayed similar trends as the separately run scenarios.
4. The model predictions experienced significant uncertainty caused by the use of six different climate models. It proved right the ensemble approach by using six climate models in order to determine reliable adaptation strategies.
5. Monthly simulations forecasted declining flow and nutrient loadings for most of the months. In addition, decreased flow accompanied by nutrient enrichment during summer months may pose eutrophication risk to the downstream reservoir. This finding implies that future research should extend scenario analyses to the catchment-reservoir scale by linking outputs from the catchment models to a reservoir models that simulates consequences of catchment changes for water quality conditions in the downstream Mt. Bold reservoir.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.02.197.

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CHAPTER 4:

Understanding spatial pattern of nutrients across the Mediterranean catchment by means of spatially-explicit monitoring and modelling

Statement of Authorship

Title of Paper	Understanding spatial pattern of nutrients across the Mediterranean catchment by means of spatially-explicit monitoring and modelling
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
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Principal Author

Name of Principal Author (Candidate)	Manoj Kumar Shrestha		
Contribution to the Paper	Conceived and designed the study. Collected field data. Prepared draft manuscript and submitted for publication		
Overall percentage (%)	80 %		
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	31/01/2017

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	Identification of monitoring sites and collection of data. Contributed to ideas, analyses and editing of manuscript.		
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Contribution to the Paper	Contributed to ideas and final editing of manuscript		
Signature		Date	1/02/2017

Understanding spatial pattern of nutrients across the Mediterranean catchment by means of spatially-explicit monitoring and modelling.

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Abstract:

Understanding the spatial heterogeneity of nutrient dynamics in catchments is prerequisite for efficient management decisions. However, the option of site-specific monitoring by a network of automatic gauging stations within a catchment is very expensive. Another practice is the implementation of catchment models calibrated by data from a single gauging station, and the simulation of the spatially-variable catchment processes, which however may not represent the actual processes realistically. In this study, we demonstrate the applicability of spatially intensive monitoring and modelling to understand the nutrient dynamics and its relationship between local land uses in the Cox Creek catchment in South Australia. Flow, nitrate, phosphate, total Kjeldahl nitrogen (TKN), total nitrogen (TN) and phosphorus (TP) and dissolved organic carbon (DOC) concentrations were periodically monitored at both headwater tributaries and along the main stream for 2 years, complementing the long-term routine monitoring data at the main stream. The spatially distributed catchment model SWAT (Soil and Water Assessment Tool) was applied to simulate site specific flow and nutrient loads and further evaluated by the monitored data. The resulting spatial monitoring data revealed strong positive relationships between market garden area and nutrient dynamics. However, the relationship between DOC and land use could not be established. TN and TP export coefficient varied from 0.5 to 6.2 and 0.03 to 0.5 kg hectare^{-1} year^{-1} respectively within the catchment with the highest loads from one particular sub-basin dominated by market garden. Comparison between observed and simulated nutrient export coefficient showed similar trend, though the magnitudes were not always in agreement. However, the model highly overestimated for one of the sub-basins indicating the deficiency in current model structure being used. This suggested that the stream linked to huge farm dams, which significantly alters the flow regime and nutrient dynamics must be incorporated in the model structure for improvement in model performance.

Keywords: headwater; land use; nutrient hotspot; routine monitoring; South Australia; SWAT.

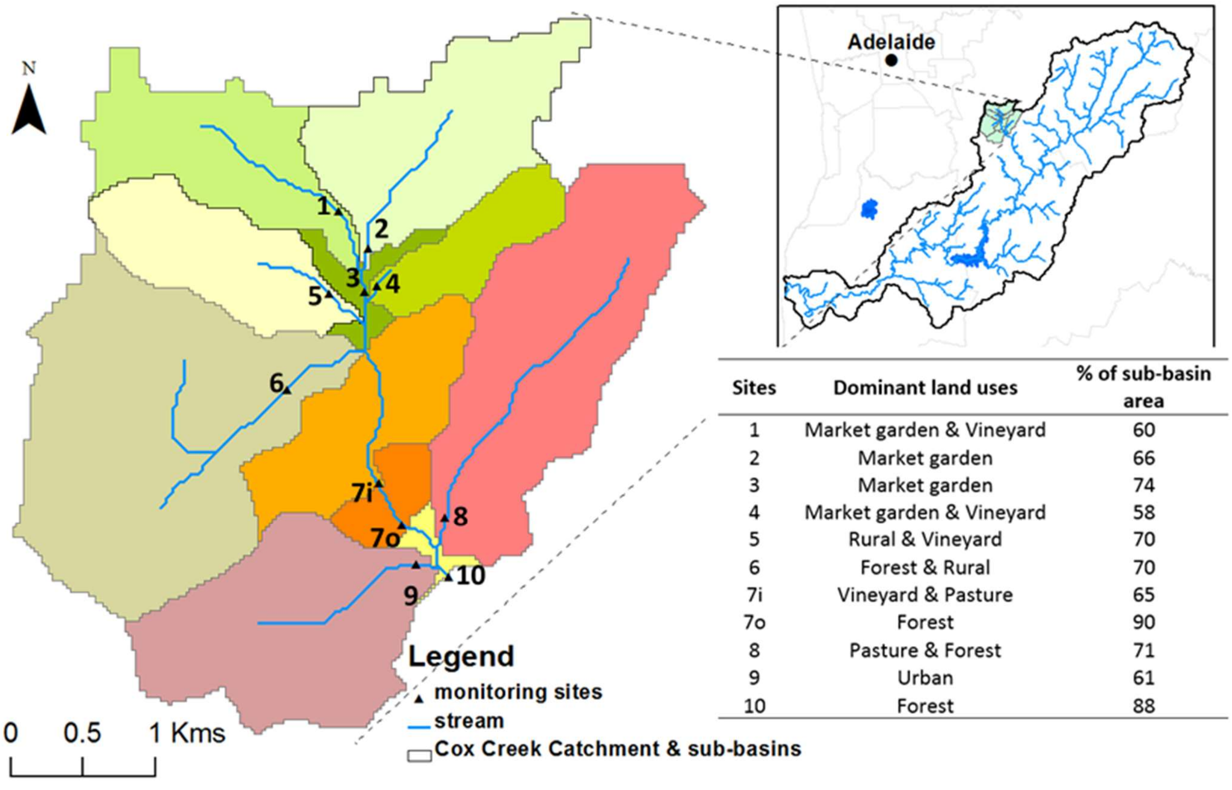
1. Introduction:

Effective management of non-point source pollution benefits from knowledge of current and prospective catchment condition. While hydrological and water quality monitoring is common practice to assess actual habitat conditions in catchments, modelling tools are available to simulate catchment properties retro- and prospectively. Hence a combination of both approaches promises improved decision making for sustainable catchment management.

Catchment properties are highly complex determined by soils, topography, climate and land use practices that cause distinct spatial variability of water quality conditions within a catchment (Gelbrecht et al., 2005; Hamilton and Miller, 2002; Kroon et al., 2012). Routine monitoring based on periodic measurements and samples, however, is costly and typically conducted at a few locations within the catchment. Resulting monitoring data therefore reflect environmental conditions of a larger area but fail to identify local sources of pollution (EPA, 1996). Spatially intensive monitoring by sampling local sites such as tributaries more frequently may provide information suitable for targeting management efforts (Eyre and Pepperell, 1999; Miles et al., 2013). At the same time it may reveal links between local land uses and stream contamination. Modelling tools are widely used to simulate the flow and water quality in catchments, and allow to predict effects of future management efforts (Karamouz et al., 2010; Mateus et al., 2014) as well as effects of future climate and land use changes (Dunn and Post, 2012; El-Khoury et al., 2015). The integration of monitoring and modelling has been suggested to better understand sources and processes of degrading stream water quality in catchments (Davenport et al., 2008; Poudel et al., 2013).

This study applied a combination of monitoring and modelling to the small rural Cox Creek catchment in South Australia. It aimed at to:

1) assess spatial variability of stream water quality within the catchment;
2) identify hot spots for high nutrient concentrations;
3) reveal relationship between local land uses and nutrient loads; and
4) identify mismatches between locally measured and simulated data as prerequisite for improving the implementation and calibration of the catchment model SWAT. A well-validated model SWAT can then be used as tool for scenario analysis on impacts of future climate and land use changes, and inform strategic catchment management.



Sites	Dominant land uses	% of sub-basin area
1	Market garden & Vineyard	60
2	Market garden	66
3	Market garden	74
4	Market garden & Vineyard	58
5	Rural & Vineyard	70
6	Forest & Rural	70
7i	Vineyard & Pasture	65
7o	Forest	90
8	Pasture & Forest	71
9	Urban	61
10	Forest	88

Fig.1: Locations of the 11 field monitoring sites and the dominant land uses of corresponding sub-basins in the Cox Creek catchment.

2. Materials and Methods:

2.1 Study area:

The study was carried out in the Cox Creek catchment (CCC), a sub-catchment of the Onkaparinga Catchment, covering an area of 14.80 km^2 as shown in Fig. 1. It has a Mediterranean climate of dry warm summers and wet winters. The annual average rainfall is 1055mm of which 80% occurs between April and October. The CCC has a mixed land use comprising of forest (26%), residential (27%), pasture (14%), vineyard (16%), market garden (14%) and others (3%). The soils are dominated by Chromosols and Kurosols which are the strong texture contrasting soils with high clay content in the subsoils. Since 2004 different mitigation measures including sedimentation pond (downstream of site 3) and a chain of wetlands (between 7i and 7o) were established in the catchment for nutrient retention (see Fig.1).

2.2 Field Monitoring and analysis:

A spatially intensive monitoring of the CCC was undertaken for a period of two years from 11/2013 to 10/2015. There are already four routine monitoring stations in the catchment, however all of them lie in the main stream. In order to capture the spatially heterogeneous properties of the basin characteristics, eleven monitoring sites (7 on headwaters and 4 on main reach) were established from headwaters to outlet, as shown in Fig. 1. Two of the monitoring sites 7i and 7o at the main stream lie close to the already established gauging stations. The snapshot of flow, nitrate, phosphate, total nitrogen (TN) and total phosphorus (TP) were captured to complement the data from long term monitoring stations. Additionally dissolved organic carbon (DOC) was sampled as monitoring of this parameter has not been conducted. Monthly and bi-weekly samplings were conducted during the dry and wet periods respectively within the standard working hours. TN, TP and DOC concentrations were analysed for one year from July 2014 to June 2015 with DOC sampled seasonally.

The OTT MF pro handheld electromagnetic flow meter was used for measuring the instantaneous discharge that has a flow velocity measurement range of 0-6m/s. The cross-section area of the stream flow is measured which then calculates the discharge of the stream. Nitrate and phosphate concentrations were estimated using the HACH DR 2800 spectrophotometer following the standard procedure in the lab, while, samples for analysis of TN and TP were sent to the Australian Water Quality Centre on the same sampling day. The samples were filtered using a 0.45 μm syringe filter which is then stored at 4 ^{0} C for subsequent lab analysis on the next day. Because of the high cost for DOC analysis we used true colour as surrogate for estimating DOC concentrations in the streams. A power function was identified between colour and DOC concentration (n=38, R^2=0.9) which is then used to convert the unit colour measurement to DOC concentrations.

29 field samplings were conducted to measure flow, nitrate and phosphate and true colour while only 11 samples for TKN, TN and TP. DOC samples were collected at four occasions to represent the seasonal fluctuation. Ranges of constituent concentration over the sampling period were compared between the sub-basins. As flow data were measured for each of the sub-basins a spatial flow-weighted constituent concentration was calculated to identify the impaired sub-basins. Furthermore, the relationship between particular land use and flow-weighted concentration were investigated at significant level of 0.05 ($p < 0.05$).

2.3 SWAT modelling:

SWAT is a physically based, semi distributed, catchment-scale simulation model that operates on a daily time step and is designed to assess the impact of different management practices on water, sediment and nutrient delivery from the watershed (Arnold et al., 1998). It requires various meteorological, topographical, soil and land use input data. A 30x30 meter resolution Digital Elevation Model (DEM) derived from a Shuttle Radar Topography Mission (SRTM) was used (Geoscience Australia, 2011). A 2007 Land use map of a scale 1:100,000 and soil map of 1:50,000 (ASRIS, 2013) was used. Relevant management practices such as planting, harvesting and fertilization use for grapes, pasture and market garden were collected from literature and Wayne Meyer (pers. com.).

Though there are four gauging stations, all of them lie in the main stream and hence the most downstream station data that is close to site 7o (See Fig. 1) was used for model calibration and evaluation in this study. Data from 2009 to 2015 for flow, nitrate, phosphate, TN and TP loads were collected. The alternate years 2009, 11, 13 and 15 served as calibration period and the rest for evaluation period. These alternate years were selected to represent the wet, average and dry period. Semi-automatic calibration algorithm Sequential Uncertainty Fitting (SUFI2) method (Abbaspour et al., 2004) was used to calibrate the model for simulation of flow and nutrient loads. The flow was calibrated first, which is then followed by nitrate, TN, phosphate and TP loads. The daily calibration result for flow is satisfactory with NSE values of 0.67 and 0.75 during calibration and validation period respectively. The percent bias (PBIAS) for the nutrient results are well under ± 75% (see Table 1) and hence considered to be satisfactory. However, nutrient simulations were underestimated as represented by positive PBIAS values.

3. Results and discussions:

3.1 Flow and nutrient concentration distribution:

The distribution of flow and nutrient concentrations in the headwater sub-basins and along the main stream during the sampling period is shown as a boxplot in Fig. 2 and tables in Appendix C. Sites 3, 7i, 7o and 10 are located at the main stream while other 7 sites are situated in the tributaries as shown in Fig. 1.

Table 1: Daily model calibration and validation results

	Performance Criteria[a]	Flow (m^3/s)	Nitrate (kg)	Phosphate (kg)	Total nitrogen(kg)	Total phosphorus(kg)
Calibration	R2	0.69	0.1	0.42	0.43	0.23
	NSE	0.67	0.01	0.38	0.4	0.2
	PBIAS	-25.1	54.2	53.3	41.7	57.1
Validation	R2	0.76	0.16	0.55	0.54	0.37
	NSE	0.75	0.12	0.53	0.52	0.33
	PBIAS	-25.4	50.6	47.5	36.2	57.2

[a] Coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS)

Flows in the tributaries show less fluctuation compared to that of main stream, however it is to be noted that flows at tributaries can increase to orders of magnitude in a single rainfall event. But after a day or two of the event the tributaries do not contribute much flow, while a reasonable flow can still be observed at the main stream. This can be partly attributed to the slow releasing sub-surface contributions along the main stream with higher contribution as the size of the catchment increases. Furthermore there is an active groundwater interaction revealed by studies from Green et al. (2010).

In case of nutrients some of the headwater sub-basins showed higher variability compared to that at the main stream for example at Site 2. The measurement at Site 2 (see Fig. 2b) ranged from 0.12-6.6 mg/l for nitrate (NO_3-N), 0.031 – 0.397 mg/l for phosphate (PO_4-P). The median values for the nutrients are also relatively higher at this location compared to other sites.

3.2 Temporal variation of water quality

The catchment is perennial while the headwater tributaries are found to be ephemeral during different seasons when there is no rainfall for prolonged period; Sub-basins 1 & 2 (Summer), 4 & 5 (Summer, Autumn and late Spring) and 6, 8 & 9 (Summer and Autumn). Stream flow at the main reach suggests that ground water storage may be an important contributor during the summer period. The average flow in the headwater basin varies from 0.001m^3/s (site 4) to 0.014 m^3/s (Site 6), while at the outlet (site 10) it was observed to be 0.1 m^3/s.

Nitrate concentrations were measured to be comparatively higher during the late autumn and winter season for all of the sub-basins. The maximum concentration observed for head water sub-basin at site 2 is 6.6 mg/l on May 20, 2015 with corresponding TN concentration of 7.54 mg/l. Phosphate and DOC did not follow any seasonal trend for most of the headwater sub-basin. Comparatively site 2 and Site 8 recorded highest and lowest concentration of phosphate concentration throughout the sampling period. While site 8 had the highest concentration of DOC for most of the samples.

3.3 Spatial variation of water quality

A flow-weighted concentration of nitrate, phosphate, TKN, TN, TP and DOC (see Fig. 3 a-f) was calculated for each of the site to compare the relative contribution and identify the impaired sub-basin. The site 2 was observed to have highest concentration of all the constituents except DOC. The concentration of nitrate, phosphate, TKN, TN and TP for site 2 is calculated to be 2.99, 0.15, 0.95, 4.15 and 0.34 mg/l respectively. Site 8 and 9 had the lowest concentration of these constituents while highest for DOC.

The concentration however decreases along the different sites in the main reach with lowest concentration at outlet of the catchment, which can be related to the dilution or nutrient attenuation processes of stream. Contrarily DOC does not follow this pattern. The constituent load contribution from head water tributaries to the load at the outlet revealed that highest load is attributed to site 2 which disproportionately releases 31 and 27% of the total load of nitrate and phosphate respectively.

Table 2: Correlation coefficients between proportion of land uses and flow weighted nutrient concentrations across the headwater sub-basins.

Land use	**Correlation coefficients r**					
	Nitrate	**Phosphate**	**TKN**	**TN**	**TP**	**DOC**
Pasture	-0.36	-0.73*	0.33	-0.39	-0.47	0.61
Market garden	0.91**	0.77*	0.45	0.9**	0.84**	-0.22
Forest	-0.33	-0.23	-0.08	-0.4	-0.34	0.18
Vineyard	-0.58	0	-0.58	-0.56	-0.36	-0.49
Rural residential	-0.72	-0.62	-0.32	-0.8	-0.7	0.43
Urban residential	0.34	-0.1	0.42	0.27	0.22	0.66
Transportation	-0.24	-0.53	0	-0.29	-0.33	0.62

** indicates significance at* $p < 0.05$. *** indicates significance at* $p < 0.01$.

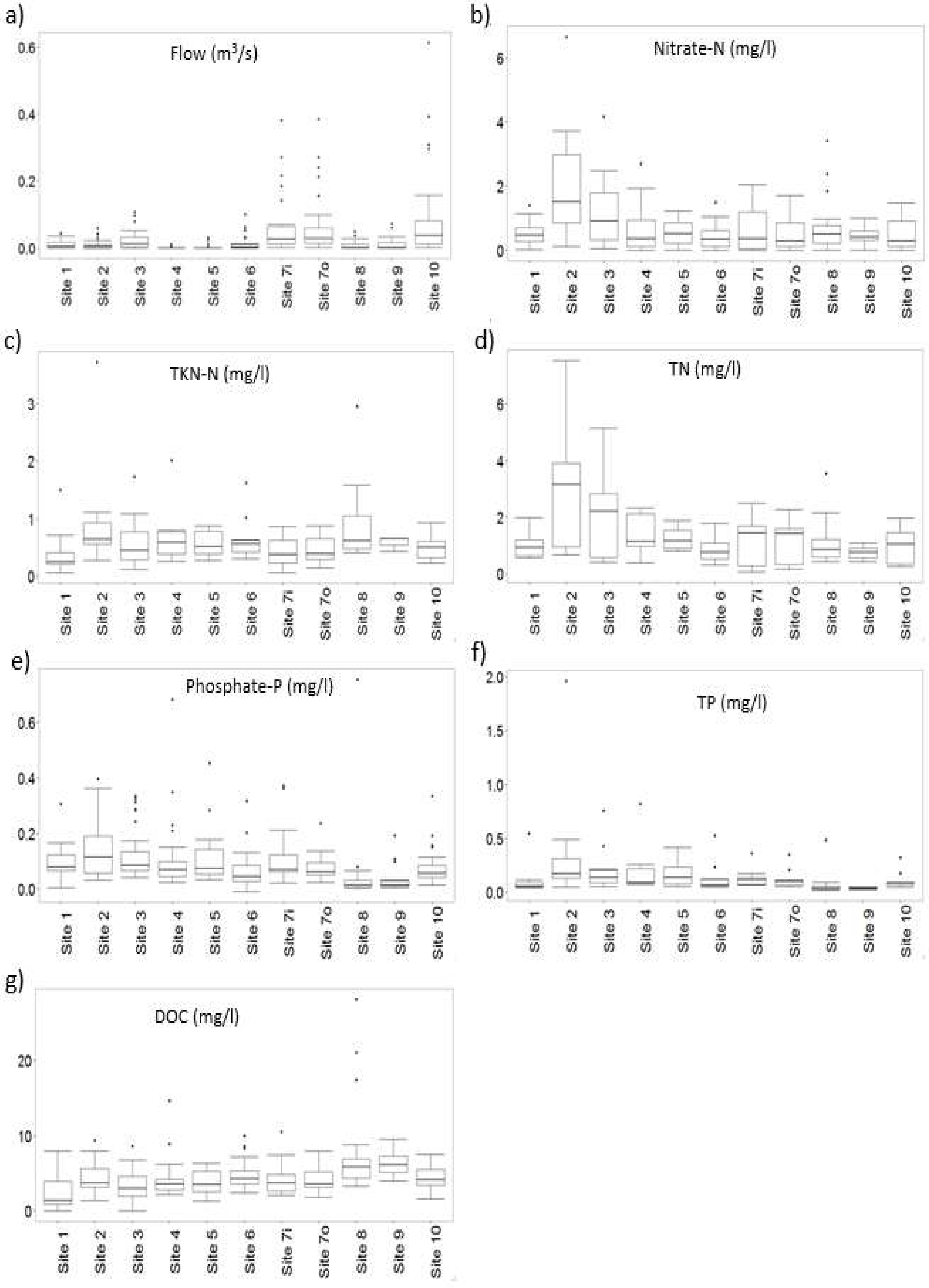


***Fig. 2**: Distribution of flow and nutrient concentration in the Cox Creek sub-catchment. Box plot of (a) flow, (b) Nitrate-N, (c) TKN-N, (d) TN, (e) Phosphate-P, (f) TP and (g) DOC.*

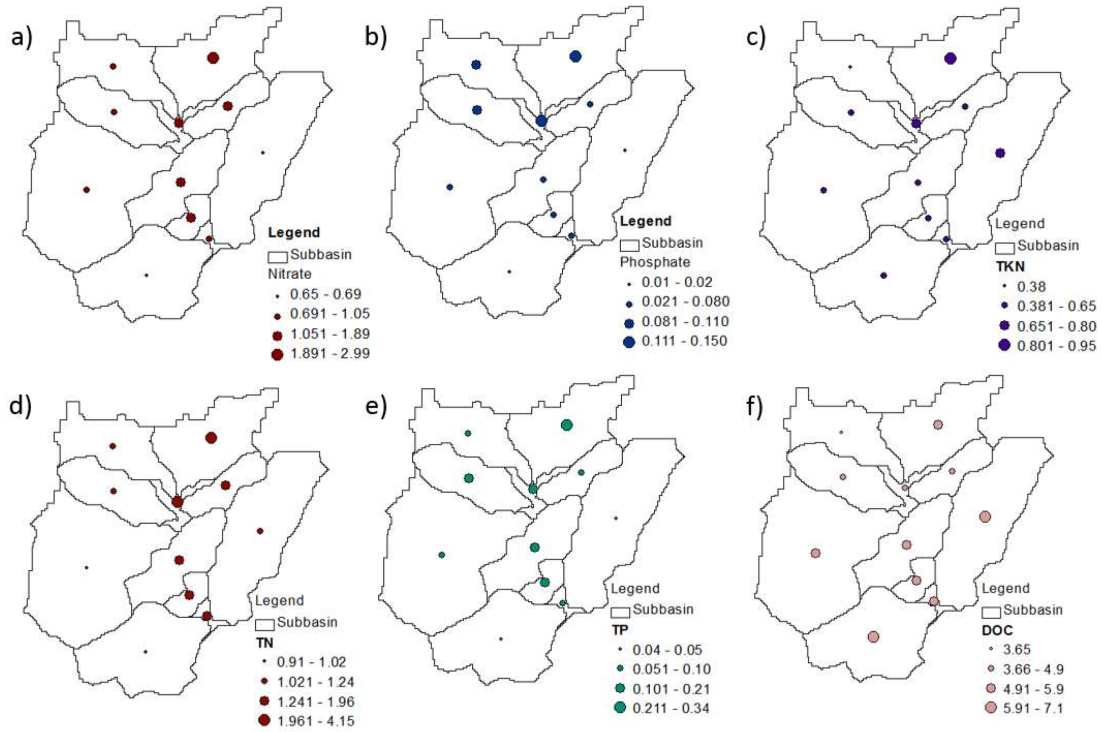


***Fig. 3**: Spatial flow-weighted concentration of (a) nitrate, (b) phosphate, (c) TKN, (d) TN, (e) TP and (f) DOC.*

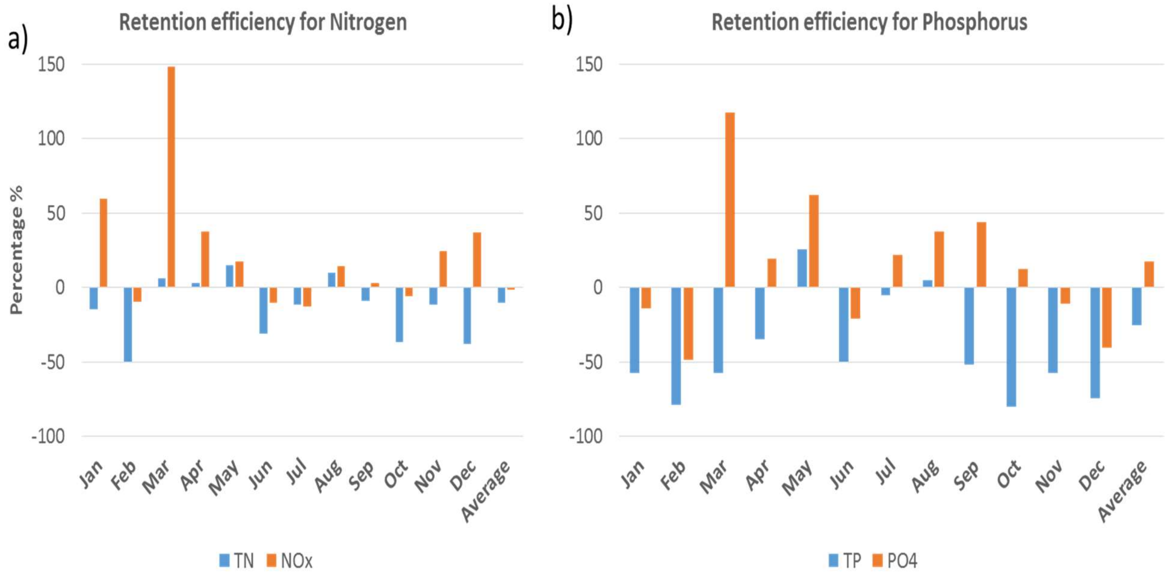


***Fig. 4:** Monthly and annual average nutrient load retention efficiency of sedimentation pond for a) Nitrogen and b) Phosphorus components.*

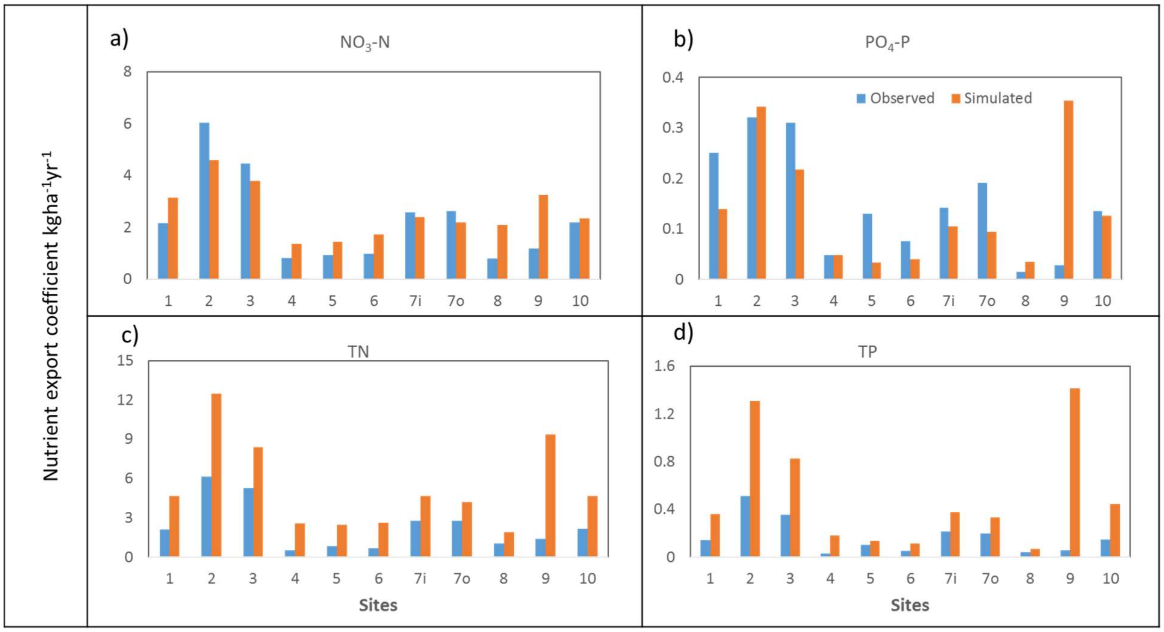


***Fig. 5**: Comparison between observed and simulated nutrient export coefficients of the sub-catchment areas related to the monitoring sites.*

3.4 Association between land use and nutrients

The relationship between land use and nutrient concentrations in the catchment were investigated for the head water sub-basin. For nitrate and TN, there is a highly significant positive correlation with the market garden as shown in Table 2. Also, a negative strong correlation was observed for the rural residential, however it is not statistically significant. For phosphate and TP, market garden showed a strong significant relationship while pasture had a significant negative relationship with phosphate only. This association reveals that market garden activity has a dominant role compared to other land uses in contributing significant amount of nutrients in the stream.

Furthermore, we assessed the efficiency of sedimentation pond (upstream of site 5) in retaining the nitrogen and phosphorus loads as the continuous flow and composite nutrient concentration data were available at the inlet and outlet of the pond. It was observed that the pond was efficient to retain annual average TN and TP loads with exceptions in some autumn and winter months (see Fig. 4 a,b). However, nitrate and phosphate retention were highly variable for different months with annual average suggesting that the pond even became the source of phosphate release while had very limited nitrate retention. It reveals that the pond is efficient in reducing the organic loads of nitrogen and phosphorus than the dissolved components. Hence a more targeted approach to reduce nitrate and phosphate concentrations from sub-basin 2 has to be explored further.

3.5 SWAT model results

Modelling results at the catchment outlet are satisfactory in simulation of flow and nutrient loads as described in section 2.3. Furthermore, the uncertainty in model simulation of spatial nutrient dynamics was evaluated by means of the spatially intensive sampling data. In general, the model simulated well the trend of nutrient export coefficient within the catchment though some overestimation and underestimation in magnitudes was seen (see Fig. 5 a-d). However, an out of trend simulation was observed particularly for sub-basin 9 with large overestimation.

Both modelled and observed data recognize sub-basin 2 as a nutrient hotspot for nitrate. Sub-basin 9 was also identified as the dominant hotspot by the model though in reality it produces a very marginal amount of loads in the catchment. Similarly, analysis of TN and TP export coefficient suggest that the model overestimated for all of the sites. However, the trend is reasonably matched for most of the time. Again, Site 2 and Site 9 have been shown to be a critical hotspot of nutrient as discussed for phosphate above. The model tends to produce high nutrient load at site 9 even when the stream was observed to be dry. The pond situated above the monitoring station seems to regulate the flow and hence any potential loads are not observed in the field collected data. It shows that the pond not being considered in model configuration may have resulted in model uncertainty. Enough information on flow retention and biogeochemical process of nutrient attenuation by the pond may be helpful in future model improvement for this catchment. Hence such study helps to identify where considerable model uncertainty exists and provide an opportunity to improve the process representation more reasonably.

4. Conclusions and Recommendations

The results from spatially intensive monitoring and modelling recognized the potential to identify the nutrient hotspots rapidly and cost-effectively within the catchment, which is often elusive in routine monitoring data. It revealed that one of the tributaries of the Cox Creek catchment may be contributing disproportionately significant amount of nutrient loads – 31 and 27% of the total load of nitrate and phosphate respectively. The statistical analysis established a strong relationship between market garden and the elevated nutrient concentration of nitrate, TN, phosphate and TP. However, no strong association of land use and DOC was achieved and hence future studies may require detailed investigation with high frequency sampling. This study suggests that a targeted management intervention in sub-basins dominated by market garden may help to reduce inorganic nitrogen and phosphorus loads. This was further strengthened by the inefficiency of the sedimentation pond to retain nitrate and phosphate loads, which is located downstream of the impaired sub-basin at the main stream. Likewise the importance of spatial monitoring data in identifying the model deficiences was highlighted, which suggests that one of the sub-basins require more data to improve model representaion more accurately. This may pave a way for robust model that could be confidently used for testing different water management scenarios.

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CHAPTER 5:

Conclusions and Recommendations

Chapter 5: Conclusions and Recommendations:

5.1 General Conclusion

Water resources planning and management will become more complex in future due to growing demands of the human population as well as climate change uncertainties. Semi-arid Mediterranean catchments are particularly vulnerable under these future changes which pose significant management challenges for water practitioners. Recent developments in computing have enabled water agencies throughout the world to adopt modelling tools to assist in making efficient decisions. However, modelling results are not free from different sources of uncertainty that may stem from the parameter, input and output uncertainty. This can greatly compromise our capability to plan effective strategies for improving water resources. Hence, there is a need for exploring different approaches to improve model performance so that future hydrological changes can be reliably projected under different climate and land use changes.

The first aim of this study (discussed in Chapter 2) was to test the applicability of the spatially distributed model SWAT (Soil and Water Assessment Tool) in the Onkaparinga catchment, a semi-arid Mediterranean catchment of South Australia. Although SWAT has been widely tested around the world, very limited applications have occurred in the Australian context. First, the capabilities of SWAT in simulation of flow, total suspended sediments (TSS), total nitrogen (TN) and phosphorus (TP) loads were investigated. Second, the question whether using data from more monitoring stations significantly improves the model performance, has been addressed by a comparative study between single- and multi-site calibration approaches. The main findings can be summarized as follows:

- SWAT can be used to simulate realistically the extreme flow conditions of the semi-arid Onkaparinga catchment.
- The results showed that multi-site calibration did not improve simulations of flow and sediments compared to single-site calibration. However, simulation results for TN and TP loads improved at both outlet and interior stations of the catchment.
- Uncertainty analysis revealed that multi-site calibration approach constrained the model uncertainty in simulation of nutrient loads. However, considerable

uncertainty in simulation of TSS loads persisted. Hence care should be taken while considering simulation results of TSS from the model.

The second aim of this study (discussed in Chapter 3) focused on assessing the combined effects of future climate and land use changes on flow and nutrient loads released from the catchment. Such study will provide valuable information for catchment managers to make efficient decisions for safeguarding future quantity and quality of water resources. Though climate and land use changes have long been recognized to alter water quality, yet most studies addressed effects on flow only. In order to make an assessment of both water quantity and quality in the Onkaparinga catchment, the improved SWAT model as discussed above and in Chapter 2 was used. The following findings were highlighted:

- Climate models suggested high uncertainty in terms of seasonally varying flow and nutrient loads. Overall, a decreasing trend in average monthly TN and TP loads by up to -55% and -56% respectively was found.
- The annual and seasonal water yield and nutrient loads appeared to be affected only slightly by envisaged land use changes, but have been significantly altered by intermediate and high emission scenarios, predominantly during the spring season.
- The combined scenarios indicated the possibility of declining flow in future but nutrient enrichment in summer months, originating mainly from the land use scenario that may elevate the risk of algal blooms in the downstream drinking water reservoir.

The final aim of this study (discussed in Chapter 4) was to explore the benefits of using short term spatially explicit monitoring combined with SWAT model to understand the spatial pattern of nutrient generation across the catchment. A two year field monitoring of flow and water quality measurements was conducted at 11 sites across the catchment, which supplements the routine monitoring at the main stream. Furthermore, these data were used to compare the model performance at different spatial locations and identify any model discrepancies and uncertainties. The monitoring and modelling results indicated:

- Spatial monitoring data aid in identifying the relationship between land use and nutrient concentrations. A strong positive link between market garden and nitrogen and phosphorus components was revealed.
- Both monitoring and modelling results suggested the same sub-basin as a nutrient hotspot where management intervention needs to be targeted.
- The model matched the spatial trend of observed nutrient export, but the size of observed and modelled responses did not always match. However, one of the sub-basins showed unusually high simulation of nutrient exports indicating model deficiencies in representation of actual processes in this sub-basin. This suggested that the farm dam upstream may be affecting the natural flow regime and nutrient dynamics and hence should be incorporated for future model improvement.

5.2 Recommendations for future work

Catchment models are very useful tools to make prudent decisions on managing valuable water resources. However, any catchment is a very complex system and hence models should accommodate the spatial heterogeneity that results from distinct soils, topography, climate and land use practices. This study recognized the value of site specific data for reducing uncertainty and ultimately improves the model reliability for testing future alternative management scenarios. Some success has been documented in the Onkaparinga catchment using the SWAT model; however, future studies must address various limitations of the current work, which are described below.

There is still considerable debate in utility of multi-site calibration approach for model improvement. This study has demonstrated that SWAT model performance can be enhanced using such an approach, however it is limited to only one catchment as described in Chapter 2. Hence it will be worthwhile to extend investigation in other catchments of Australia to verify our result, and if not, to examine the reasons for discrepancy. Such study can give valid reasons for a need to establish more gauging stations within the catchment and hence improve our understanding of spatial dynamics of flow and nutrient fluxes.

Though model improvement resulted from multi-site calibration approach, simulation of sediments and nutrient loads are still not entirely satisfactory. Hence future SWAT modelling in the Onkaparinga catchment can benefit from improved representation of the different land use management practices. Suspended sediment loads simulation on the other hand, was very uncertain mostly during the peak events as the erosion process may not be well represented by the empirical equations in SWAT.

This study underscored that future climate and land use change will affect the water quantity and quality of the Onkaparinga catchment. As it is an important source of drinking water to the metropolitan area of Adelaide, stakes are high for water management institutions due to these anticipated future changes. The Mount bold reservoir, a storage reservoir, receives water from the Onkaparinga catchment which is then transferred to a drinking water supply reservoir. The reservoir periodically suffers from algal bloom events and any change in catchment flow and nutrient dynamics may affect the already degraded water quality in the reservoir. Hence, the application of a coupled catchment and lake model could establish the sensitivities between these two systems and give better understanding of how the lake system behaves in response to catchment fluxes.

Routine monitoring stations at the main stream generally do not supply enough information to identify sub-basins nutrient hotspot areas. Complementary spatial monitoring approach as discussed in Chapter 4 would prove to be suitable for identifying nutrient hotspots in other catchments. In the Cox Creek catchment, a critical sub-basin was identified and performance of sedimentation pond downstream of the impaired sub-basin revealed the inefficacy of the pond to retain nitrate and phosphate loads. This study recommends that alternative management scenarios such as change in land use management practices or extension of sedimentation pond to wetland structure for retaining dissolved nutrients should be further evaluated in the catchment.

Also, this study highlighted some limitations of spatially intensive sampling. Even though the spatial trend of nutrient dynamics could be determined reasonably well, the true magnitude of nutrient export may be severely underestimated as it is limited by the frequency of data collected. The samplings were conducted randomly at least once in a month and are more representative of base flow conditions. As the catchment is observed to generate huge amount of flow and nutrients during peak event, future studies should focus on collecting frequent samples during such events, if this is practically possible. Such events frequently occurred overnight and automatic samplers may be required. However, it is expensive to install the samplers in all current monitoring sites. Studies such as this that use both monitoring and modelling approach helped to target a critical sub-basin where future monitoring can be conducted and management interventions can be determined thereafter.

While the model can certainly benefit from the multi-site data as discussed above, there are some challenges for the modelers. For example, multi-site calibrated model did not significantly improve the flow results compared to the single-site calibration approach in this study, though significant amount of resource was invested. It has long been recognized that the model output depends heavily on the model input data. It has to be ensured that there is an availability of good resolution of input data such as soil data and DEMs along with a spatial network of rain gauge station. Hence, the quality of input and output data must be weighed while making a judgement of the model outcome.

This study reiterates that modelling and monitoring should be integrated to improve scientific understanding of catchment dynamics, and ultimately to assist planning and decision making that when implemented facilitates to achieve the catchment management goals.

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APPENDICES:

Appendix A: Conference Paper A

Simulation of Nutrient Loadings from the Rural Cox Creek Watershed (South Australia) by SWAT as Prerequisite for Land use Specific Scenario Analysis

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Simulation of Nutrient Loadings from the Rural Cox Creek Watershed (South Australia) by SWAT as Prerequisite for Land-use Specific Scenario Analysis

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Written for presentation at the
21st Century Watershed Technology Conference and Workshop
The University of Waikato)
Hamilton, New Zealand)
(November 3-6, 2014)

Abstract. *The Cox Creek watershed has been identified as major source of nutrient loadings within the Onkaparinga catchment (OC) that contributes approximately 33 % of the drinking water supply for the Metropolitan area of Adelaide in South Australia. The Soil and Water Assessment Tool (SWAT) was applied to model daily flow, total nitrogen and total phosphorous loadings in the meso-scale Cox Creek watershed.*

Calibration and validation was performed at three gauging stations within the watershed to investigate the SWAT's ability to adequately simulate flow and nutrient loadings. Flow was successfully simulated at all stations while satisfactory results for nutrient loadings were achieved only for the most upstream site. Testing the downstream model for the two upstream sites proved to be successful only for flow simulation at all sites and nutrient loadings for the upstream site.

The study has shown that simulation results for nutrient loads of this watershed become more uncertain when drainage areas increase. Moreover, the model calibrated for the downstream site was not successful in representing the spatial heterogeneity of nutrient loadings within the watershed. In order to improve future applications of SWAT to the Cox Creek watershed, spatially-explicit data of nutrient loadings at tributary level are required as well as wetland processes need to be built into the models. This will be prerequisite for land-use specific scenario analysis.

Keywords. SWAT, Cox Creek watershed, nutrient loadings, Onkaparinga Catchment, scenario analysis.

Introduction

The quantification of both point- and non-point nutrient sources is prerequisite for estimating impacts of catchments with multiple land uses on eutrophication and cyanobacteria blooms in downstream lakes and reservoirs (Carpenter et al., 1998) and for determining management options. The Soil and Water Assessment Tool, SWAT (Arnold et al., 1998) has been designed for the simulation of flow and nutrient dynamics in catchments, and supports scenario analyses on best-practice management options (Daloğlu et al., 2012; Nielsen et al., 2013)

The Onkaparinga Catchment (OC) is the main source of water for the Happy Valley Reservoir that supplies 40% of Adelaide's metropolitan drinking water. Since P and N loadings to the Happy Valley Reservoir make it susceptible to cyanobacteria blooms causing high economic costs, the raw water quality that it receives from the OC is critical.

The Cox Creek Watershed (CCW) is one of the sub-catchments of the OC covering an area of 442 km^2. The upper part of the CCW dominated by viti- and horticultural makes only 1% of the total catchment area but contributes 24% or 1.35kg/ML of total phosphorus load and 34% or 4.2kg/ML of the total NOx-load of the Onkaparinga River (Fisher, 2005). To consider sustainable management options for the Cox-Creek sub-catchment is therefore of high priority for the reduction of overall nutrient loadings to the downstream Happy Valley Reservoir.

This study tested the applicability of the SWAT to better understand the nutrient sources and loading within the CCW as prerequisite for management decisions regarding the implementation of constructed wetlands or changed land uses. It utilised flow and nutrient measurements of three gauging stations operated in the CCW by the SA Water Corporation to test following hypotheses: (1) Using data from the most-downstream gauging station simulates less accurate flow and nutrient loadings for the two upstream gauging stations than running SWAT for individual sites. (2) To properly simulate impacts of constructed wetlands operated before the most-downstream gauging station requires a reconfigured SWAT model.

Materials and methods

Study Site

The Cox Creek watershed (CCW) is an important sub-catchment of the Onkaparinga Catchment providing surface water and groundwater for domestic, industrial and agricultural purposes locally, as well as for Adelaide's metropolitan water supply through the Happy Valley reservoir (South Australia). It is situated east of Adelaide as shown in figure 1. This modelling study was applied to an area of 10.4 km^2 of the CCW.

The CCW has a mixed landuse comprising of forest (23%), residential (22%), pasture (19%), vineyard (14%), market garden (14%), annual cropping (4.5%), and horticulture (3.5%). The soils are dominated by strong texture contrasting soils like Chromosols and Kurosols with high clay content in the subsoils. It has very steep slope along the ridges and forms a valley at the bottom of the hills. Its Mediterranean climate is characterized by dry warm summers and wet winters with an average annual rainfall of 1055mm occurring by 80% between April and October. Between 2004 and 2006 the SA Water Corporation has put mitigation measures for nutrient retention in the CCW in place by implementing a sedimentation pond upstream of gauging station 1, and a chain of wetlands including a reed bed between the gauging stations 2 and 3.

Model Background

SWAT is a physically based, semi distributed, long-term, continuous, catchment-scale simulation model that operates on a daily time step and is designed to assess the impact of different management practices on water, sediment and nutrient delivery from the watershed (Arnold et al., 1998). Major components of the model include weather, hydrology, erosion, plant growth, nutrients, pesticides, channel and reservoir routing.

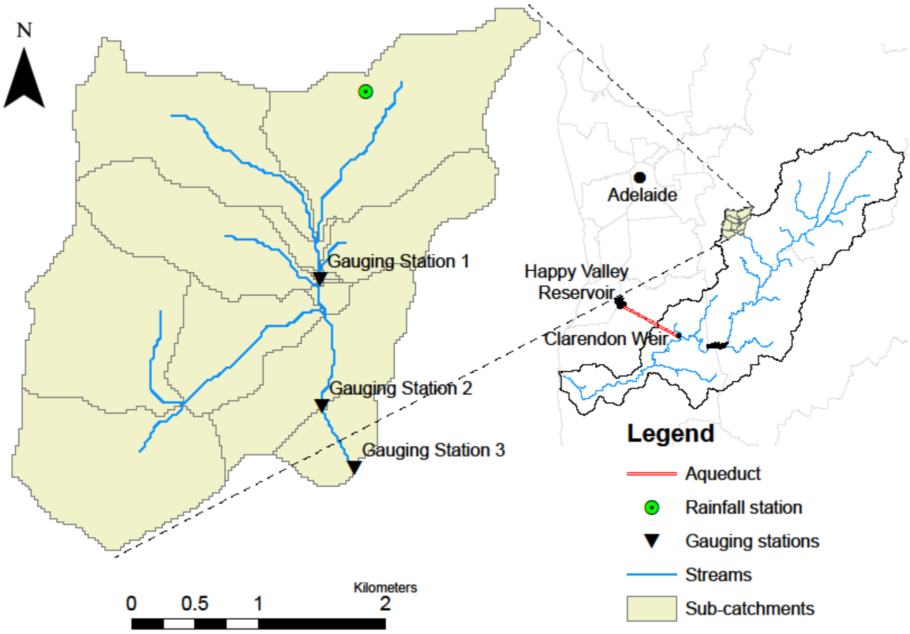

Figure 1: Location Map of Cox Creek Watershed within Onkaparinga Catchment

The modelling process in SWAT subdivides a catchment into multiple sub-catchments. These sub-catchments are further divided into Hydrologic Response Units (HRUs) which is a unique combination of homogeneous land use, soils, slope, and management (Gassman et al., 2007; Neitsch et al., 2011). Flow generation, sediment yield and pollutant loadings are summed across all HRUs in a sub-catchment, and the resulting flow and loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet

The water balance of each HRU in the catchment is represented by four storage volumes: snow, soil profile (0–2m), shallow aquifer (2–20m) and deep aquifer (>20m). SWAT models nitrogen and phosphorous cycles including transformation and movement processes in various organic and inorganic pools, where nutrient losses from soil occur through crop uptake, surface runoff and eroded sediment. It models movement of nutrients from soil surface to the streams and simulates in-stream nutrient processes by incorporating the QUAL2E model (Brown and Barnwell, 1987).

Input Datasets:

SWAT requires various input data related to weather, topography, soil and landuse, and various attributes which are collected from different sources as summarised in table 1. Flow and nutrient data were monitored at three gauging stations within the catchment by the SA Water Corporation. Daily nutrient loadings were derived from the biweekly to monthly concentrations of TN and TP sampled by flow weighted composite samplers.

Table 1.Data requirements, descriptions and sources

Data Requirements	**Data description**	**Data Sources**
DEM	25 m resolution	University of Adelaide
Observed flow and water quality parameters	3 gauging stations with data from 2009-2013 GS 1 (A5030526), GS 2 (A5031007) and GS 3 (A5031006)	SA Water
Weather data	Station number 23750 : Daily rainfall and solar radiation from 1991-2013	Bureau of Meteorology
	Station number 23842: Daily maximum and minimum temperature, long term average wind speed and relative humidity from 1990-2013	
Landuse map	2003 land-use map	University of Adelaide
Soil map	2005 soil map	ASRIS (Australian Soil Resource Information System)

Model Configuration:

The CCW was divided into 13 sub-basins and 175 HRUs based on land-use and soil heterogeneity using ArcSWAT 2009. The Soil Conservation Service (SCS) curve number (CN) method was used for simulating surface runoff, while variable storage coefficients were used for routing the flow in SWAT. Evapotranspiration was estimated by means of the Penman Montieth method. SWAT default values were chosen to simulate preliminary nutrient loadings.

After a warm-up period from 2006 to 2009 the model was run for 2009-2013. This warm-up period minimized uncertainties due to unknown initial conditions such as antecedent soil moisture conditions. Unlike other studies that focused mainly on monthly simulations, this study focused on daily simulations of flow, TN and TP loadings and compared the model performance for the three gauging stations within the catchment (see fig. 1).

The Sequential Uncertainty Fitting (SUFI2) method (Abbaspour et al., 2004) was used for the calibration and validation of the model. The flow was calibrated before the calibration of TN and TP. The parameter sensitivity was identified for each variable and parameter values were manually calibrated. Calibrated parameters were kept constant during subsequent calibration of other variables. Data of the years 2009 to 2011 was used for calibration and data of 2012 and 2013 was used for validation. To avoid bias in the calibration process (Migliaccio and Chaubey, 2007) a multi-site calibration was not performed since the gauging stations on the CCW are nested (see Fig. 1). The single-site calibration for the three gauging stations resulted in the three separate models SWAT GS-1, GS-2 and GS-3. Model performance of the three models was evaluated both qualitatively and quantitatively. The visual comparison of time series plots served as qualitative assessment while the quantitative assessment was based on the three statistical measures: coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE) (Nash et al 1970) and percent bias (PBIAS) (Gupta et al. 1998) whereby the model is considered satisfactory if R^2 and NSE is greater than 0.5 and PBIAS ranges between ± 25 % for flow and ±70 % for nutrients (Moriasi et al., 2007). These high ranges for the nutrients are due to the greater uncertainties in nutrient data associated with errors in streamflow measurements and sample collection, storage and analysis (Harmel and Smith, 2007).

Results and Discussions:

Individual Model Calibration and Validation:

All three models satisfied the model performance criteria for daily flow simulations for both the calibration and validation periods except the criteria PBIAS for the validation period of model GS-2 as summarised in table 2. Validations results are illustrated in figure 2. The slightly high positive PBIAS value is due to the underestimated flows during the second year for most of the days as can be seen in figure 2. However, the negative PBIAS value in the calibration period indicated an overestimated flow. The four most sensitive parameters for all three models were SCS Curve number CN2, main channel conductivity CH_K2, baseflow alpha factor for bank storage (ALPHA_BNK), and manning's n value for the main channel CH_N2.

Table 2.Calibration and validation results of the three SWAT models GS-1, GS-2 and GS-3 for daily Flow (m^3/s), Total Phosphorous (TP, kg/day) and Total Nitrogen (TN, kg/day)

Models	Drainage area (km2)	Performance Criteria [a]	Calibration 2009-2011			Validation 2012-2013		
			Flow	TP	TN	Flow	TP	TN
SWAT GS-1	4.1	R^2	0.7	0.49	0.62	0.7	0.63	0.67
		NSE	0.7	0.47	0.56	0.69	0.56	0.63
		PBIAS	3.6	0.5	59.9	0.7	40.9	53.3
SWAT GS-2	10	R^2	0.73	0.26	0.41	0.76	0.46	0.44
		NSE	0.72	0.18	0.34	0.69	0.34	0.32
		PBIAS	-11.7	78.3	50	32.2	76.3	68.1
SWAT GS-3	10.4	R^2	0.69	0.35	0.39	0.68	0.38	0.46
		NSE	0.69	0.32	0.33	0.67	-4.07	0.37
		PBIAS	10.8	39.3	2.7	15.7	-68.8	20.9

[a] Coefficient of determination (R2), Nash-Sutcliffe Efficiency (NSE), and percent bias (PBIAS) are model performance criteria.

Only the SWAT GS-1 model simulated daily TP and TN loadings satisfactorily. The models SWAT GS-2 and GS-3 with larger drainage areas did not perform as well whereby SWAT GS-2 performed better in the validation period while SWAT GS-3 overestimated TP loadings in the validation period indicating some model uncertainty. The parameter sensitivity for organic phosphorous enrichment ratio ERORGP and the phosphorous soil portioning coefficient PHOSKD ranked highest for the simulation of TP loadings. The three most sensitive parameters for TN loadings are organic nitrogen enrichment ratio ERORGN, threshold water content for denitrification SDNCO and nitrate percolation coefficient NPERCO. Sensitive parameters for flow and nutrients identified by this study were consistent with findings of similar studies in the literature (Abbaspour et al., 2007; Daloğlu et al., 2012).

Model Validation at upstream sites:

After the calibration of the SWAT GS-3 model by data of the gauging station 3 at the outlet of the catchment, its simulation results for the upstream gauging stations 1 and 2 have been tested for the calibration period. The simulated flows matched well with observed flows of the gauging station 1 and 2 (fig. 3) with high R^2 and NSE values and PBIAS values in a satisfactory range. The R^2 and NSE values for simulation results of TP and TN at gauging station 1 were also satisfactory even though magnitudes of peak events were not always matched well. However the simulation results of TP and TN for gauging station 2 were unacceptable as displayed by only negative NSE values.

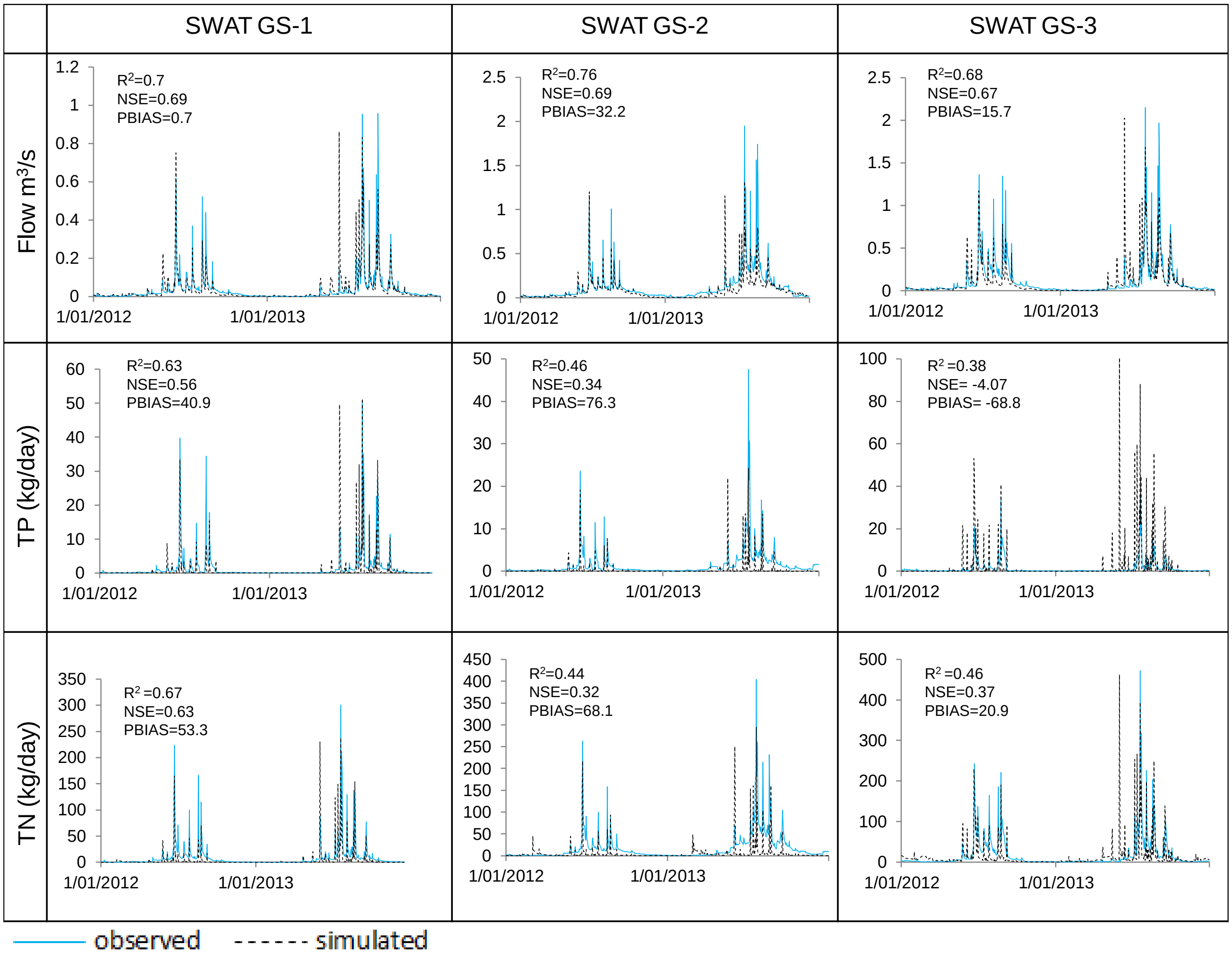

Figure 2. Validation of daily SWAT simulations of flow (top row), TP load (middle row) and TN load (bottom row) for the three gauging stations of the Cox Creek watershed.

It can be concluded from these results that SWAT GS3 still performed well for the upstream gauging station 1 but overestimated TN and TP loads for gauging station 2. Since the area between gauging stations 1 and 2 is largely covered by natural vegetation with little agricultural activities less transportation of nutrients is typical for this area but not properly simulated by SWAT GS-3. Grab sample data currently collected from stream sites between gauging station 1 and 2 support this finding by showing very low nutrient concentrations most likely causing dilution rather than enrichment.

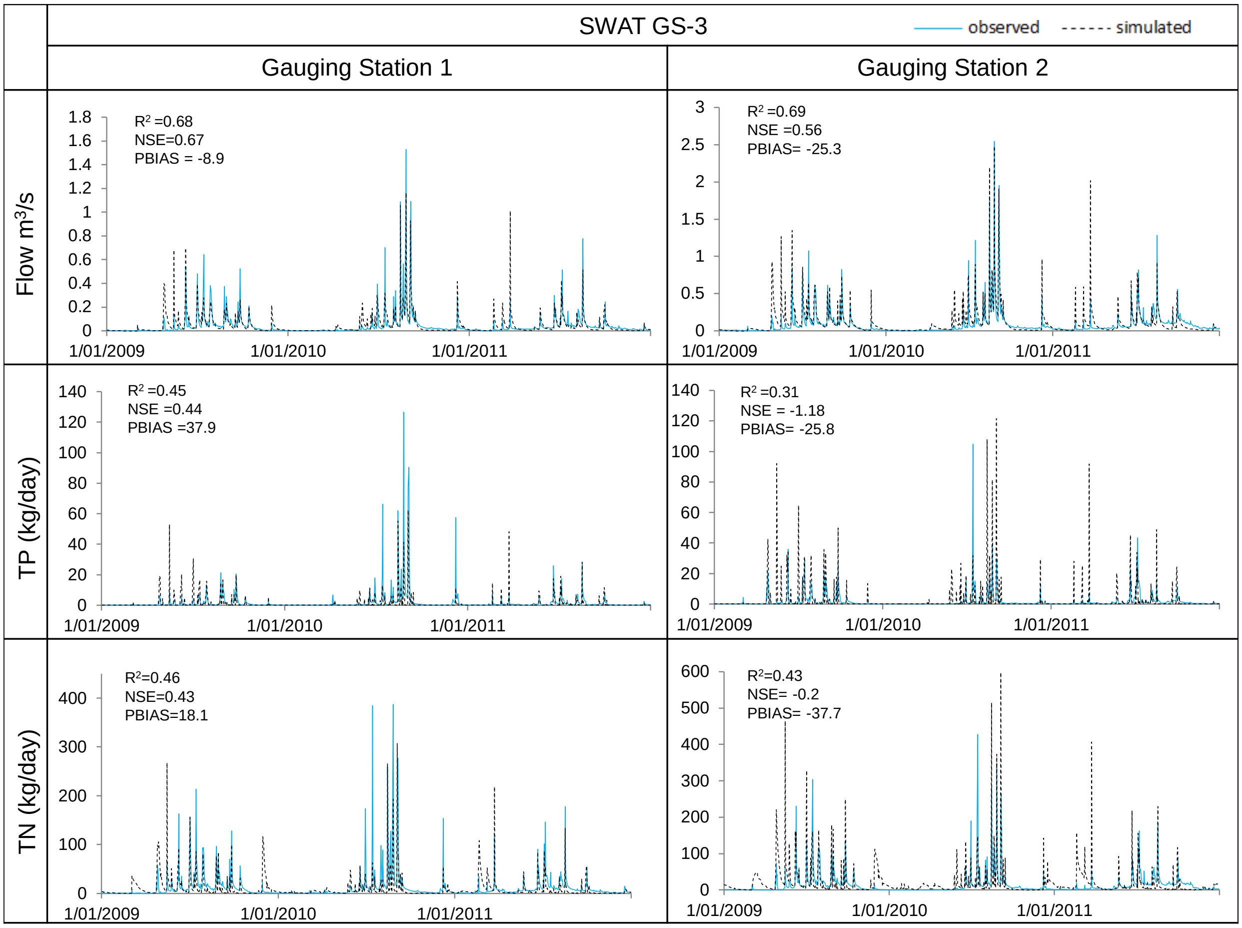

Figure 3. Simulation of Flow (top row), TP load (middle row) and TN load (bottom row) for the upstream gauging stations 1 and 2 of the Cox Creek watershed by running SWAT for downstream station 3

Conclusions:

SWAT models for the three gauging stations GS1, GS2 and GS3 simulated satisfactorily daily flows, TP and TN loadings in the Cox Creek Watershed. When applying SWAT GS3 to the upstream gauging stations 1 and 2 resulting flow simulations were still acceptable. However simulation results for TP and TN loads at gauging station 2 failed to match observed data suggesting that processes related to transportation or transformation of nutrients between sites GS1 to GS2 were not properly accounted for by the SWAT GS3 model. It clearly indicates the need for spatially-explicit monitoring of nutrient loadings at tributary level as prerequisite for improved catchment models that justify land-use related scenario analyses to identify suitable catchment management improvements. A two-year monitoring scheme for 11 stream sites within the CCW is currently underway with the intent to develop a data base that improves spatial resolution and accuracy of SWAT applications to this catchment.

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Appendix B: Conference Paper B

Scenario analysis on impacts of climate change on flow and nutrient loads in the Mediterranean Onkaparinga catchment, South Australia: Coupling global climate models with SWAT.

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Scenario analysis on impacts of climate change on flow and nutrient loads in the Mediterranean Onkaparinga catchment, South Australia: Coupling global climate models with SWAT

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ABSTRACT.
Water limited catchments of Mediterranean regions including South Australia experience already high seasonal variability alternating between dry and wet periods, and are particularly vulnerable to global climate change. Long-term assessments of water resources of South Australian catchments under the projected climate changes are required as a prerequisite for sustainable water resources management.

In this study, the SWAT (Soil and Water Assessment Tool) model is driven by meteorological forecasts of six global climate models (GCM) to assess impacts on flow, total nitrogen (TN) and phosphorus (TP) loads of the Mediterranean Onkaparinga catchment in South Australia for 50 years ahead. The GCM focus on two representative concentration pathways (RCPs) that describe possible future emission scenarios, RCP 4.5 (intermediate emission) and RCP 8.5 (high emission). Scenario results for flow and nutrient loads simulated by SWAT for the periods from 2021 to 2045 and from 2046 to 2070 are compared with baseline data from 1981 to 2005.

Results for RCP 4.5 indicate that the catchment is likely to experience a decrease in mean annual runoff mainly during the spring season with further decrease for RCP 8.5. Projected mean seasonal nutrient loads follow the trends of flow with even greater decrease in terms of percentage. However, uncertainties reflected by varying results for monthly flows and nutrient loads from different GCM projections suggest that results from a single climate model must be interpreted with caution.

Keywords. Climate change scenarios; flow and nutrient loads; GCM; Mediterranean catchment; SWAT.

1. Introduction:

Projected changes in future climate are likely to impact on the availability of global water resources in many ways.

According to IPCC (2007, 2014), extreme meteorological and hydrological events can be expected resulting in more frequent droughts, storms and floods posing more uncertainty and risk on river catchments worldwide. Water limited catchments in Mediterranean climates experience already high seasonal variability alternating between dry and wet periods, and are particularly vulnerable to global climate change (Giorgi and Lionello, 2008; Piras et al., 2014). Climate projections for Mediterranean catchments in South Australia suggest a decrease in runoff by 35% (Chiew and McMahon, 2002) with serious consequences for catchment management (Chiew et al., 2011; Charles and FU, 2015; Hope et al., 2015). Long-term assessments of the hydrology of South Australian catchments are required as prerequisite for sustainable water resources management.

Hydrological models are widely used to assess possible future impacts on water resources by utilising future climate data from specific emission scenarios simulated by global climate models (GCM).Impacts of climate scenarios are assessed by comparing predicted and historical runoffs. Since data resolutions of GCM typically apply to 100 kms, their use for hydrological modelling at catchment scale is limited. However downscaling the data to catchment scale using dynamic and statistical techniques allows to overcome this limitation (Fowler et al., 2007, Nunez and McGregor, 2007; Fu et al., 2013).

Many studies on impacts of climate change on catchment hydrology have been carried out in different parts of the world, including Mediterranean regions (Sellami et al., 2016, Lespinas et al., 2014). Even though climate change impacts both water quantity and quality in catchments, most of the published studies address effects on river flow only. However, there is growing evidence that surface water quality is directly affected by several climate related mechanisms (Aldous et al., 2011, Sahoo and Schladow, 2008). Molina-Navarro et al. (2014) found that decreasing runoff magnitudes caused reduced N exports but increased TP loads in a Spanish catchment. Another study conducted in the River Kennet in UK (Wilby et al., 2006) indicated that increased temperature and climate variability may increase nitrate and ammonium concentrations. Furthermore, episodic nitrogen peaks due to the wash up of accumulated soil nitrogen are likely as the drought breaks. A study of two severe historical drought periods in the river Meuse, Belgium by Vilet et al. (2008) revealed, that water quality was degraded by algal blooms favoured by changed water temperatures and nutrient concentrations. Schneider and Hook (2010) reported that surface waters warmed at an average rate of 0.045 ± 0.011 °C yr-1 by increasing air temperatures during the period of 1985-2009. Increased temperature and nutrient concentration of stream water can contribute to excessive algal bloom in downstream reservoirs increasing both economic and ecological costs.

This study applied the process-based eco-hydrological model SWAT (Arnold et al., 1998) driven by six climate models combined with two emission scenarios (intermediate and high emission) to predict impacts on flow, total nitrogen and phosphorus loads of the Mediterranean Onkaparinga catchment in South Australia for 50 years ahead. It also analysed the uncertainty in predicted river flow and quality indicators caused by the choice of GCM and emission scenarios.

2. Materials and methods

2.1 Study area:

The study was carried out within the Onkaparinga catchment situated 60 km east of Adelaide by modelling an area of 317 km^2 upstream of the Houlgraves gauging station (see Figure 1).The elevation of this area ranges from 10 to 700 metres and annual rainfall varies between 522 mm in coast and 1088 mm in upland areas.

The land uses of the Onkaparinga catchment include horti-,viti- and agriculture, where farm dams typically serve for irrigation. A pipeline from the River Murray releases water into the Onkaparinga River downstream of Hahndorf (see Figure 1)that contributes approx. 87 % (19952 ML) of the total flow during the dry season (Nov-April) and approx. 24 % (45310 ML) during the wet season at Houlgraves.

The geological formation of the western part of the catchment consists of permeable sandstone and quartzite while the eastern part is underlain by less permeable siltstone and metasediments (Zulfic et al., 2002). The subsoil is clayey in texture on the lower slopes and flats of the catchment and may prevent water drainage. The hill slopes have clayey to sandy subsoils mainly utilised for horticulture and viticulture.

The Digital Elevation Model (DEM) with a resolution of 30 × 30 m (Geoscience Australia, 2011) derived from a Shuttle Radar Topography Mission (SRTM) and a 1:100,000 land-use map of2003 was used. The base data of the soil map of 2005provided by the Department of Water, Soil and Natural Resources of South Australia has been compiled at scales of 1:50,000 or1:100,000. The data for soil attributes were extracted from the Australian Soil Resource Information System (ASRIS, 2013). Ten meteorological stations within and adjacent to the catchment were used. Since there were missing data for all stations from the publicly available website of the Bureau of Meteorology, daily SILO (Scientific Information for Land Owners, 2015) patched dataset were used.

The South Australian Water Corporation provided daily flow data and biweekly to monthly data of TN and TP concentrations from flow weighted composite samplers monitored at five gauging stations (see Figure 1) within the catchment. Flow data from the River Murray Pipeline were available on daily basis while grab sample data of water quality was available in weekly to monthly time steps. This contribution was treated as point source data.

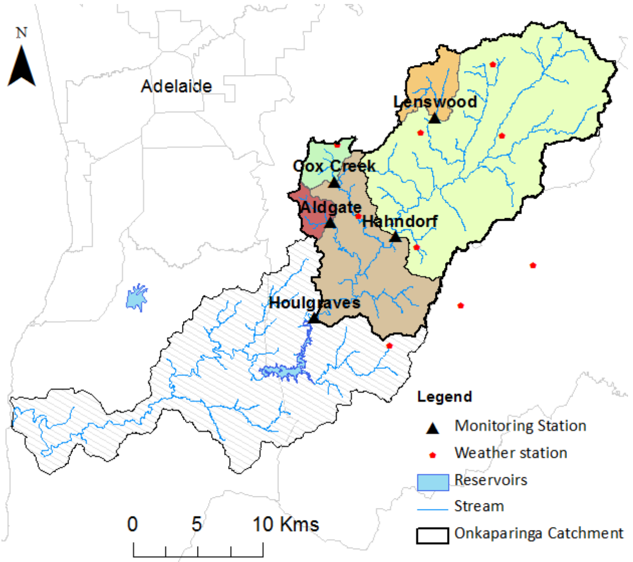

Figure 1: Onkaparinga Catchment and gauging stations

2.2 Model set-up

The process-based semi-distributed Arc SWAT 2012 (Winchell et al., 2013) was used for catchment modelling that supports continuous, catchment-scale simulations. It operates at daily time steps and is designed to assess the impacts of different management practices on water, sediment and nutrient transport in catchments (Arnold et al., 1998). SCS curve number (Soil Conservation Service, 1972)and the Pennman-Monteith equation (Monteith, 1965)was used to estimate runoff and evapotranspiration respectively. For routing the flow, the variable storage routing method was applied.

This study utilised the SWAT Onkaparinga catchment model developed by Shrestha et al. (2016) for simulation of monthly flow, total nitrogen (TN) and total phosphorus (TP) loadings. It was demonstrated that the multi-site calibration outperformed the single-site calibration in simulating nutrient loadings and hence this multi-site calibrated model was selected for climate change impact study. However, it was observed that the organic nitrogen loading was not reproduced reasonably and the model was further calibrated which improved both organic nitrogen and TN loads. Performance during calibration (2000-2009) and validation (2010-2013) period for this improved model is provided in table 1 and figure 2. To understand the impacts of climate change on natural characteristic of the catchment only, the contribution of River Murray was cut off from the calibrated Onkaparinga model. This model then was used for running climate change scenarios.

Table 1. SWAT calibration and validation result for flow (m3/s), total nitrogen (TN, kg/month) and total phosphorus (TP, kg/month) loads.

	Performance Criteria[a]	**Calibration**		
		Flow	TN	TP
Calibration	R^2	0.88	0.39	0.41
	NSE	0.82	0.37	0.35
	PBIAS	-17.5	15.1	-20.23
Validation	R^2	0.89	0.41	0.4
	NSE	0.82	0.37	0.36
	PBIAS	-24.57	-7.46	-12.7

[a] Coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS) are model performance criteria.

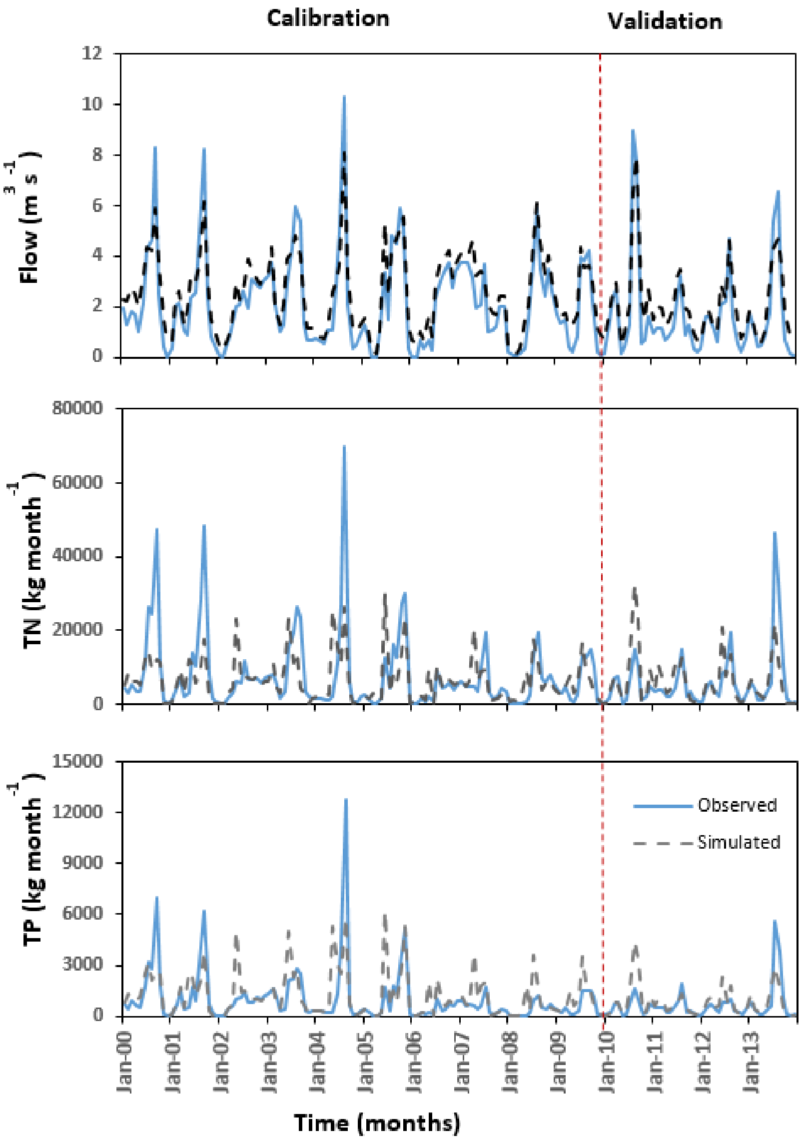

Figure 2. Simulated and observed time series, flow, TN and TP loads

2.3 Future climate data and model simulation:

Climate projection datasets for different regions of South Australia were produced by Task 3 of the Goyder Institute of Water Research Project (GIWR, 2015) and is available on SA Climate Ready portal at https://data.environment.sa.gov.au/Climate/SA-Climate-Ready. This projection used statistical downscaling techniques called Nonhomogenous Hidden Markov Model (NHMM) to simulate daily rainfall from global climate models (GCMS) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). These rainfall were calibrated at multiple stations in different regions of South Australia. The GCM grid-scale output of non-rainfall variables were downscaled by using a weather generator conditional on the weather states and rainfall simulated by NHMM (Charles and Fu, 2015). Fifteen Coupled Model Inter-comparison Project phase 5 (CMIP5)were chosen for the downscaling project for South Australia which were further studied to identify the six 'best' GCMS as provided in Table 2. Future emission scenarios representing two representative concentration pathways (RCP) from the IPCC AR5 were used to represent possible future greenhouse gas concentrations whereby RCP 4.5 and RCP 8.5 represents increases in radiative forcing in 2100 relative to preindustrial levels of 4.5 and 8.5 W/m^2 respectively or simply to put intermediate and high emission scenarios respectively.

Each of the downscaled GCMs produced 100 stochastic replicates (realisations) of future projected climate data until 2100 for rainfall and non-rainfall variables. However, only one realisation for each of the six climate models was used. The realisation that corresponds to the median of projected total precipitation amount for the period between 2006-2100 was selected for model simulation.

Table 2. Description of six "best" climate models used in study

Climate Model ID	Climate modelling group	Country
CanESM2	Canadian Centre for Climate Modelling and Analysis	Canada
CNRM-CM5	Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Foramtion Avancéeen Calcul Scientifique	France
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	USA
IPSL-CM5B-LR	Institut Pierre-Simon Laplace	France
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan
MRI-CGCM3	Meteorological Research Institute	Japan

2.4 Climate change impact assessment

The calibrated model was run for the historical climate data (1981-2005) of six global climate models, considered as reference scenario. This was compared against the flow, total nitrogen and phosphorus loads resulting from six best GCMs and two emission scenarios for a period of 50 years (2021-2070) with the time horizons 2021-2045 and 2046-2070. The projected deviation (relative change in percentage between the reference and future period) of the three variables for each climate model was calculated and averaged to be considered as mean of the climate model ensemble in order to assess the climate change impacts annually, seasonally and monthly. We also used the model ensemble approach to characterize the uncertainty of climate projections from six global climate models (GCMs).

3. Results and Discussions:

Climate related impacts for average flow and nutrient loadings at annual, seasonal and monthly time scales are discussed in this section. These impacts were assessed for the periods from 2021 to 2045 (FP1) and from 2046 to 2070 (FP2) in relation to the intermediate emission scenario (RCP 4.5) and the high emission scenario (RCP 8.5).

3.1 Future climate effects on precipitation and temperature:

Table 3 shows the annual and seasonal variability of both precipitation and temperature in future periods relative to the baseline. It shows a general trend of increasing temperature and decreasing precipitation, with more pronounced effects for FP2 under high emission scenario. Temperature is likely to increase in all seasons by both scenarios with highest increments in spring and lowest in winter. Annual average daily temperature is expected to increase by 1.84 ^{0}C for FP2. On the other hand, average precipitation is expected to decrease both annually and seasonally except in autumn for FP1 under RCP 4.5. The highest decrease is likely to occur during the spring upto -20 % for later period under RCP 8.5. The average annual precipitation change varies between -4.2 % and -9.7 % under different emission scenarios and future time periods.

3.2 Impacts of climate change on flow

The average annual water yield is likely to decrease with strongest effects for RCP 8.5 as shown in Table 4.Multi-model projections for FP1reveal a decrease of the average annual water yield by -11.2 % and -18.15% for RCP 4.5 and RCP 8.5 respectively, which corresponds with the study by Westra et al (2014) conducted for the same catchment using a conceptual hydrological model GR4J that showed 11 % and 16% decrease for slightly elongated period 2016-2045. The average decrease for FP2 for both scenarios is slightly higher than the FP1.

The box plot in figure 3 displays ranges of change for each of the seasons under different scenarios and time periods. Since the range of change is quite significant, the 25th and 75th percentile and median of seasonal flows are below zero suggesting a significant decreasing trend. Comparing the two flow seasons, the decrease is likely to be more significant in spring (SON) compared to winter (JJA) for both scenarios and time periods. The change in average spring flow is quite comparable for both time periods with -16.7% for RCP 4.5 and -23.8% for RCP 8.5. WhereasFP2 sees a further decrease in winter mean flow -11.9% (-19.7%) for RCP 4.5 (RCP 8.5).

Table 3. Changes in precipitation and temperature under RCP 4.5 and RCP 8.5 scenario (Average of six GCMs ensemble), for 2021-2045 and 2046-2070.

	1981-2005		2021-2045 RCP4.5 (RCP8.5)		2046-2070 RCP4.5 (RCP8.5)	
	Average precipitation in mm	Average daily temperature in ^{0}C	% change in precipitation	Change in temperature ^{0}C	% change in precipitation	Change in temperature ^{0}C
Summer (DJF)	84.7	19.5	-9 (-2.5)	0.77 (0.95)	-5.8 (-8.8)	1.22 (1.75)
Autumn (MAM)	182	15.2	1.5 (-2.9)	0.85 (1.08)	-4.5 (-5.3)	1.29 (1.92)
Winter(JJA)	396.9	10	-0.8 (-3.7)	0.68 (0.87)	-5.3 (-6.4)	1.04 (1.57)
Spring(SON)	205	13.9	-13.6 (-12.6)	1 (1.2)	-16 (-20)	1.5 (2.14)
Annual	868.6	14.6	-4.2 (-7.8)	0.82 (1.26)	-5.5 (-9.7)	1.03 (1.84)

*Figure in brackets represent the values for RCP 8.5

Table 4. Average annual and seasonal changes in water yield, total nitrogen (TN) and phosphorus (TP) load for two time periods and emission scenarios.

	2021-2045 RCP4.5 (RCP8.5)			2046-2070 RCP4.5 (RCP8.5)		
	% change in water Yield	% change in TN load	% change in TP load	% change in water Yield	% change in TN load	% change in TP load
Summer (DJF)	-13.7 (-14.3)	-7.4 (0.1)	-18.5 (-6.9)	-11.6 (-15.6)	-1.5 (-11.5)	-23.3 (-21.3)
Autumn(MAM)	-3 (-11.9)	2.5 (-16)	10.4 (-12.9)	-9.3 (-15.1)	-9.8 (-17.7)	-9 (-18.4)
Winter(JJA)	-7.9 (-15.5)	-5 (-12.1)	-5 (-12.5)	-11.9 (-19.7)	-16.7 (-22.5)	-19.2 (-25.8)
Spring(SON)	-16.7 (-23.8)	-27.2 (-23.5)	-30.3 (-26.9)	-14.3 (-23.7)	-34 (-37.9)	-41 (-44.9)
Annual	-11.2 (-18.15)	-8.4 (-14.7)	-8.9 (-16)	-12.7 (-20.5)	-18.4 (-24.3)	-22.9 (-29)

*Figure in brackets represent the values for RCP 8.5

Figure 4 a, b shows the range of average monthly water yield from six climate models simulated under different climate scenarios in two future periods. A high prediction uncertainty can be seen for monthly predictions, however, in general the decreasing trend is obvious. It is likely that average monthly water yield decreases in all months under high emission scenario during FP2 (figure 4b), which may put further stress on already water limited catchment.

3.3 Impacts of climate change on nutrient loads:

Similar to flow, both climate scenarios suggest a reduction of mean annual TN- and TP-loads by -24.3% and -29%respectively for RCP 8.5 for FP2. Whilst average annual TN loads change between -14.7% and -2.9% and -21.8% and -10.7% for RCP 4.5 and RCP 8.5 respectively for the first 25 years, it varies from -22.4% to -12% for RCP 4.5 and from -28.8% to -17.4% for RCP 8.5in the later period from 2046-2070. Similarly for TP, the average annual load changes for RCP 4.5 and RCP 8.5 ranges between -16.5% and -2.2% and -23.4% and -11.3% respectively for the first 25 years. In the later period from 2046-2070, it varies from -26.8% to -16.5% for RCP 4.5 and from -33.9% to -21.4% for RCP 8.5.

Seasonally, nutrient loads are predicted to decrease sharply for both winter and spring season in FP2 with higher reduction for RCP 8.5. Average spring TN load reduces by -34 % (-38%) while winter load decreases by -16.6% (-22.5%) for RCP 4.5 (RCP 8.5) in FP2. Similarly, for TP the decrease in average spring load is predicted to be -40.9% (-44.9%) and the winter load decrease is -19.2% (-25.8%).

The prediction range for nutrients as shown in figure 4 (c,d,e,f) is higher during the dry months suggesting higher uncertainty compared to the wet months. Nevertheless, average monthly nutrient loads from the ensemble of models shows a decreasing trend except in some months of autumn and summer under both scenarios and future periods (figure 4 c,d,e and f). This increase may be related to the increased temperature that can lead to enhanced nitrogen mineralisation (Wilby et al., 2006). Moreover, the decreasing water yield and increasing TN and TP loads during January, February and April may pose a significant management challenge as these conditions may be favourable for algal bloom.

A good positive relationship was found between monthly nutrient load and flow (R^2=0.5 to 0.62 for both TN and TP under different emission scenarios), hence decreasing flow can explain the decreasing nutrient loads as less organic materials could be transported from land to the surface water. Panagopoulos et al. (2011) found similar conclusion in a Mediterranean catchment in Greece where TN and TP was dependent on flow magnitude. Furthermore, Molina-Navarro et al. (2014) found similar conclusion for N exports, however, it contradicts to the TP load which was attributed to sediment load rather than flow magnitude.

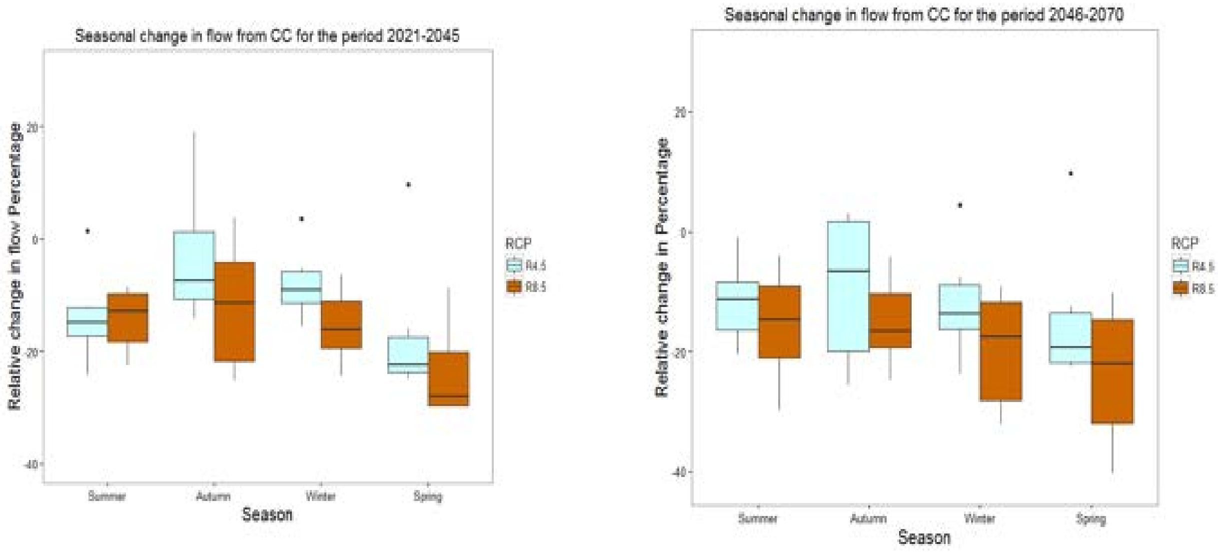

Figure 3. Box plot of percentage change in water yield relative to the baseline for two time periods and emission scenario.

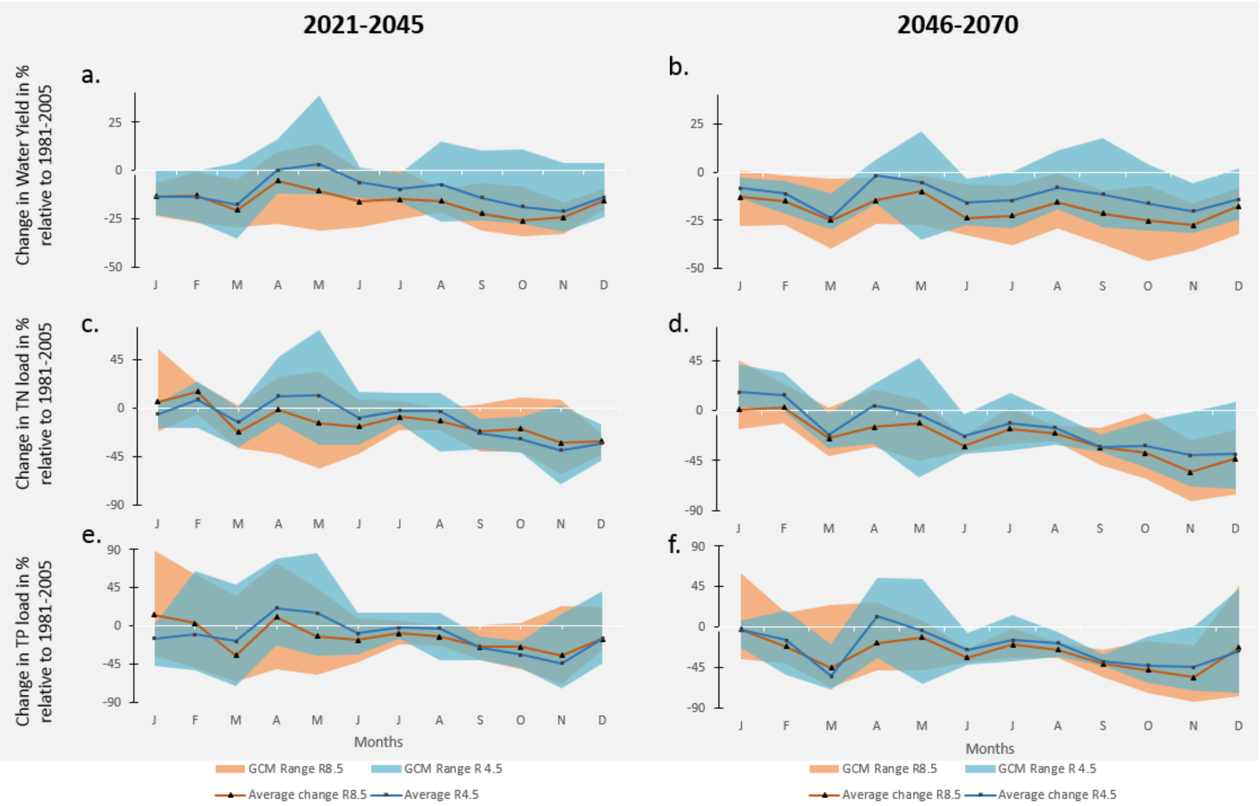

Figure 4. Projected range of change for water yield, TN and TP load for two future time periods and emission scenarios. The coloured band represents the range of change as calculated by the ensemble of six global climate models and lines representing the average of the ensemble models.

4. Conclusions:

During this study we investigated the impact of two emission scenarios RCP 4.5 and RCP 8.5 on the flow and nutrient loads of the Mediterranean Onkaparinga catchment. Climate data predicted for the 25-yearperiodsfrom2021 to 2045 and 2046 to 2070 by six global climate models were used as inputs for the SWAT model calibrated for the Onkaparinga catchment. Results suggest that:

1. increasing temperature and decreasing precipitation over the next 50 years will lead to declining water yield and nutrient loads at both annual and seasonal time scales,
2. highest changes can be expected by the high emission scenario RCP 8.5for the period from 2046 to 2071with reduction of the average annual water yield, TN- and TP-loads by -20.5%, -24.3% and -29% respectively.
3. declining effects on flow and nutrient loads are likely to be highest in spring whereby in some summer months increasing nutrient loads at declining flow have been predicted that pose the threat of eutrophication effects in the downstream reservoir.

Future research will focus on possible effects of changed flow and nutrient conditions in the Onkaparinga catchment on the downstream Mt Bold reservoir by feeding SWAT outputs of scenarios RCP 4.5 and RCP 8.5 as inputs into the lake ecosystem model SALMO.

5. Acknowledgement:

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Appendix C: Tables of Field collected data

Appendix C: Tables

Table 1: Field collected data for Site 1.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0004	0.52	0.004					22	2.8
12/13/2013	0							29	3.3
1/24/2014	0								
2/20/2014	0.004	0.12	0.14					0	0
3/13/2014	0.009	0.02	0.051					0	0
4/10/2014	0.021	0.12	0.164					0	0
5/1/2014	0.013	0.22	0.129					0	0
6/4/2014	0.005	0.12	0.167					0	0
6/25/2014	0.045	1.09	0.11					86	6.8
7/8/2014	0.024	1.14	0.123					50	4.8
7/31/2014	NA	0.93	0.308	1.5	1.98	0.545	7.4	108	7.9
8/18/2014	0.018	0.8	0.107	0.3	1.15	0.059		8	1.4
9/4/2014	0.011	0.68	0.072	0.52	1.23	0.101		36	3.9
10/20/2014	0.018	0.34	0.137	0.06	0.56	0.039		2	0.6
12/4/2014	0.001	0.38	0.123	0.22	0.63	0.05	1	5	1.1
1/9/2015	0.004	0.21	0.089					14	2.1
1/13/2015	0.003	0.38	0.079	0.23	0.77	0.058	1.5	12	1.9
2/26/2015	0								
3/26/2015	0.004	0.07	0.045	0.2	0.58	0.046		7	1.3
4/6/2015	0.003	0.33	0.072					6	1.2
4/17/2015	0.002	0.4	0.052	0.11	0.64	0.047	0.7	5	1.1
5/20/2015	0.012	0.67	0.075	0.28	1.1	0.072		18	2.5
6/30/2015	0.005	0.46	0.079					4	0.9
7/13/2015	0.029	1.41	0.096	0.71	1.98	0.116		70	6
8/4/2015	0.043	1.09	0.065					56	5.1
8/22/2015	0.01	0.61	0.065					38	4
9/9/2015	0.036	0.71	0.065					65	5.7
10/16/2015	0.005	0.7	0.062					4	0.9
11/5/2015	0.006	0.56	0.048					6	1.2

Appendix C: Tables

Table 2: Field collected data for Site 2.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP (mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.006	1.12	0.397			0		68	5.8
12/13/2013	0.009	0.92	0.329					63	5.6
1/24/2014	0	0.12	0.102					25	3
2/20/2014	0.001	1.22	0.311					33	3.6
3/13/2014	0.0006	0.82	0.148					55	5.1
4/10/2014	0.007	1.12	0.135					34	3.7
5/1/2014	0.011	1.82	0.042					14	2.1
6/4/2014	0.006	1.42	0.055					15	2.2
6/25/2014	0.06	3.62	0.246					141	9.4
7/8/2014	0.03	3.73	0.058					30	3.4
7/31/2014	NA	0.64	0.356	3.72	4.06	1.96	5.7	101	7.6
8/18/2014	0.007	2.77	0.072	0.46	3.76	0.046		13	2
9/4/2014	0.005	2.19	0.116	0.92	3.73	0.127		26	3.1
10/20/2014	0.001	0.87	0.179	0.28	1.18	0.099		8	1.4
12/4/2014	0	0.38	0.106	0.64	0.71	0.172	3.9	27	3.2
1/9/2015	0	0.46	0.19					52	4.9
1/13/2015	0.043	1.96	0.242	1.11	3.15	0.49	6.8	82	6.6
2/26/2015	0	0.22	0.099	0.65	0.72	0.188		45.5	4.5
3/26/2015	0.0005	0.2	0.065	0.58	0.69	0.133		32	3.6
4/6/2015	0.002	2.58	0.363					104	7.7
4/17/2015	0.004	1.88	0.127	0.54	1.61	0.169	4.7	59	5.3
5/20/2015	0.011	6.66	0.144	0.94	7.54	0.33		109	7.9
6/30/2015	0.009	3.04	0.031					11	1.8
7/13/2015	0.041	3.53	0.12	0.92	4.78	0.3		82	6.6
8/4/2015	0.024	3.68	0.048					42	4.3
8/22/2015	0.009	2.99	0.048					22	2.8
9/9/2015	0.02	3.03	0.058					49	4.7
10/16/2015	0.002	1.5	0.058					26	3.1
11/5/2015	0.007	1.52	0.062					32	3.6

Appendix C: Tables

Table 3: Field collected data for Site 3.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.012	0.62	0.066					17	2.4
12/13/2013	0.044	0.12	0.314					0	0
1/24/2014	0	0.12	0.325					37	3.9
2/20/2014	0.005	0.32	0.243					11	1.8
3/13/2014	0.013	0.12	0.083					0	0
4/10/2014	0.021	0.72	0.083					17	2.4
5/1/2014	0.015	0.82	0.069					13	2
6/4/2014	0.015	0.92	0.062					6	1.2
6/25/2014	0.108	2.48	0.175					122	8.6
7/8/2014	0.05	2.45	0.127					46	4.5
7/31/2014	NA	0.93	0.335	1.73	2.21	0.758	7.5	123	8.6
8/18/2014	0.025	1.8	0.042	0.3	2.4	0.051		14	2.1
9/4/2014	0.03	1.27	0.134	0.74	2.53	0.137		35	3.8
10/20/2014	0.005	0.41	0.116	0.12	0.6	0.061		6	1.2
12/4/2014	0.002	0.08	0.086	0.28	0.46	0.093	1.4	9	1.6
1/9/2015	0.002	0.27	0.089					16	2.3
1/13/2015	0.041	1.87	0.284	1.08	3.14	0.429	6.5	85	6.8
2/26/2015	0.001	0.12	0.079	0.45	0.57	0.163		32.5	3.6
3/26/2015	0.002	0.06	0.072	0.16	0.41	0.077		15	2.2
4/6/2015	0.004	1.4	0.288					72	6.1
4/17/2015	0.007	0.96	0.113	0.32	1.41	0.126	3.1	37	3.9
5/20/2015	0.028	4.17	0.123	0.73	5.15	0.212		74	6.2
6/30/2015	0.007	1.8	0.055					8	1.4
7/13/2015	0.098	2.47	0.103	0.81	3.33	0.205		82	6.6
8/4/2015	0.079	2.35	0.062					47	4.6
8/22/2015	0.019	1.58	0.065					29	3.3
9/9/2015	0.053	1.59	0.069					59	5.3
10/16/2015	0.004	0.84	0.045					13	2
11/5/2015	0.012	0.86	0.062					24	3

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Table 4: Field collected data for Site 4.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0007	0.22	0.23					29	3.3
12/13/2013	0.0004	0.02	0.21					22	2.8
1/24/2014	0								
2/20/2014	0.0001	0.001	0.1					22	2.8
3/13/2014	0	0.02	0.088					15	2.2
4/10/2014	0.0008	0.12	0.15					37	3.9
5/1/2014	0.0004	0.02	0.051					37	3.9
6/4/2014	0.0005	0.12	0.093					32	3.6
6/25/2014	0.012	1.15	0.068					70	6
7/8/2014	0.004	0.95	0.047					31	3.5
7/31/2014	NA	0.86	0.349	2.01	2.29	0.823	7	130	8.9
8/18/2014	0.001	0.7	0.042	0.34	0.98	0.085		26	3.1
9/4/2014	0.001	0.85	0.058	0.44	1.14	0.09		36	3.9
10/20/2014	0	0.26	0.127	0.26	0.48	0.082		17	2.4
12/4/2014	0	0.06	0.069	0.59	0.99	0.257	3.7	17	2.4
1/9/2015	0								
1/13/2015	0	0.8	0.095	0.77	1.21	0.22	7.7	71	6
2/26/2015	0								
3/26/2015	0								
4/6/2015	0	2.7	0.684					278	14.6
4/17/2015	0	0.1	0.041	0.39	0.39	0.073	5	35	3.8
5/20/2015	0.002	1.94	0.069	0.8	2.11	0.075		33	3.6
6/30/2015	0	0.15	0.024					18	2.5
7/13/2015	0.004	1.86	0.045	0.64	2.33	0.106		75	6.2
8/4/2015	0.005	1.31	0.062					41	4.2
8/22/2015	0.002	0.77	0.038					27	3.2
9/9/2015	0.006	1.26	0.069					44	4.4
10/16/2015	0	0.36	0.028					22	2.8
11/5/2015	0.001	0.36	0.045					32	3.6

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Table 5: Field collected data for Site 5.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0002	0.12	0.072					16	2.3
12/13/2013	0	0.02	0.148					7	1.3
1/24/2014	0								
2/20/2014	0								
3/13/2014	0								
4/10/2014	0								
5/1/2014	0								
6/4/2014	0.00002	0.22	0.034					30	3.4
6/25/2014	0.031	0.8	0.164					73	6.1
7/8/2014	0.013	1.07	0.069					33	3.6
7/31/2014	NA	0.5	0.284	0.88	1.07	0.412	6.1	70	6
8/18/2014	0.002	0.62	0.051	0.28	0.8	0.053		19	2.5
9/4/2014	0.001	0.58	0.062	0.37	0.83	0.07		21.5	2.8
10/20/2014	0								
12/4/2014	0								
1/9/2015	0								
1/13/2015	0	1.17	0.179	0.85	1.88	0.256	6.8	63	5.6
2/26/2015	0								
3/26/2015	0								
4/6/2015	0	1.23	0.455					76	6.3
4/17/2015	0								
5/20/2015	0.001	1.09	0.11	0.45	1.61	0.105		35	3.8
6/30/2015	0	0.23	0.062					14	2.1
7/13/2015	0.028	0.93	0.13	0.58	1.27	0.168		61	5.4
8/4/2015	0.014	0.75	0.075					39	4.1
8/22/2015	0.004	0.36	0.048					21	2.7
9/9/2015	0.026	0.52	0.082					51	4.8
10/16/2015	0	0.24	0.038					15	2.2
11/5/2015	0.001	0.18	0.045					27	3.2

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Table 6: Field collected data for Site 6.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0046	0.12	0.048					45	4.5
12/13/2013	0.0085	0.02	0.042					25	3
1/24/2014	0	0.32	0.13					29	3.3
2/20/2014	0.0025	0.001	0.021					36	3.9
3/13/2014	0	0.02	0.028					51	4.8
4/10/2014	0.0023	0.12	0.024					32	3.6
5/1/2014	0.0079	0.02	0.102					26	3.1
6/4/2014	0.0033	0.62	0.028					42	4.3
6/25/2014	0.101	1.5	0.093					116	8.3
7/8/2014	0.033	0.81	0.034					40	4.1
7/31/2014	NA	0.69	0.202	1.62	1.79	0.526	8.1	122	8.6
8/18/2014	0.01	0.71	0.055	0.56	1.1	0.052		58	5.3
9/4/2014	0.011	0.54	0.079	0.44	0.75	0.068		41.5	4.2
10/20/2014	0.002	0.31	0.085	0.4	0.66	0.051		25	3
12/4/2014	0.001	0.25	0.041	0.31	0.31	0.061	3.5	30	3.4
1/9/2015	0	0.5	0.106					59	5.3
1/13/2015	0.004	0.59	0.085	1.02	1.12	0.231	9.9	93	7.2
2/26/2015	0	0.05	0.01	0.62	0.62	0.129		36	3.9
3/26/2015	0	0.21	0.038	0.44	0.44	0.103		51	4.8
4/6/2015	0	1.05	0.318					154	10
4/17/2015	0	0.12	0.021	0.34	0.37	0.062	4.1	34	3.7
5/20/2015	0.03	0.45	0.048	0.62	1	0.047		43	4.3
6/30/2015	0.003	0.18	0.021					17	2.4
7/13/2015	0.052	0.77	0.058	0.64	1.09	0.085		79	6.4
8/4/2015	0.054	0.75	0.065					64	5.6
8/22/2015	0.014	0.38	0.028					54	5
9/9/2015	0.063	0.5	0.045					68	5.8
10/16/2015	0.002	0.34	0.007					25	3
11/5/2015	0.002	0.27	0.017					34	3.7

Appendix C: Tables

Table 7: Field collected data for Site 7i.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0189	0.001	0.075					20	2.6
12/13/2013	0.0444	0.001	0.069					18	2.5
1/24/2014	0.0025	0.001	0.373					17	2.4
2/20/2014	0.007	0.001	0.213					35	3.8
3/13/2014	0.0126	0.001	0.062					27	3.2
4/10/2014	0.0267	0.001	0.161					19	2.5
5/1/2014	0.0288	0.12	0.158					22	2.8
6/4/2014	0.0202	0.32	0.045					21	2.7
6/25/2014	0.37	1.54	0.123					97	7.4
7/8/2014	0.142	1.57	0.069					48	4.7
7/31/2014	0.151	1.2	0.069	0.53	1.67	0.115	5.2	51	4.8
8/18/2014	0.066	1.19	0.055	0.38	1.44	0.077		20	2.6
9/4/2014	0.064	0.73	0.083	0.74	1.46	0.174		47	4.6
10/20/2014	0.016	0.36	0.085	0.21	0.27	0.068		14	2.1
12/4/2014	0.006	0.02	0.089	0.19	0.22	0.071	2.5	16	2.3
1/9/2015	0.005	0.38	0.185					34	3.7
1/13/2015	0.037	1.1	0.2	0.87	1.7	0.358	7.6	85	6.8
2/26/2015	0.002	0.1	0.058	0.29	0.29	0.099		22.5	2.8
3/26/2015	0.005	0.14	0.045	0.06	0.06	0.07		29	3.3
4/6/2015	0.016	1.75	0.363					168	10.5
4/17/2015	0.013	0.06	0.106	0.25	0.32	0.132	3.4	38	4
5/20/2015	0.061	2.05	0.069	0.57	2.5	0.146		43	4.3
6/30/2015	0.026	0.76	0.021					20	2.6
7/13/2015	0.271	1.48	0.069	0.69	1.99	0.129		72	6.1
8/4/2015	0.186	1.42	0.096					57	5.2
8/22/2015	0.071	0.9	0.058					37	3.9
9/9/2015	0.216	1.05	0.069					60	5.4
10/16/2015	0.018	0.36	0.038					60	5.4
11/5/2015	0.032	0.31	0.069					34	3.7

Appendix C: Tables

Table 8: Field collected data for Site 7o.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC(mg/l)
11/14/2013	0.0233	0.02	0.034			0		19	2.5
12/13/2013	0.0392	0.02	0.237					11	1.8
1/24/2014	0.0055	0.02	0.066					15	2.2
2/20/2014	0.0103	0.12	0.083					48	4.7
3/13/2014	0.0187	0.001	0.048					31	3.5
4/10/2014	0.0158	0.17	0.096					36	3.9
5/1/2014	0.0295	0.22	0.127					48	4.7
6/4/2014	0.0382	0.12	0.055					28	3.3
6/25/2014	0.385	1.71	0.123					107	7.9
7/8/2014	0.156	1.46	0.079					51	4.8
7/31/2014	0.164	1.24	0.066	0.61	1.67	0.101	5.4	46	4.5
8/18/2014	0.049	0.97	0.045	0.37	1.42	0.073		23	2.9
9/4/2014	0.042	0.61	0.102	0.48	1.47	0.109		29	3.3
10/20/2014	0.015	0.14	0.053	0.22	0.28	0.049		14	2.1
12/4/2014	0.005	0.16	0.052	0.15	0.15	0.063	2.9	24	3
1/9/2015	0.004	0.33	0.053					30	3.4
1/13/2015	0.041	0.87	0.137	0.88	1.52	0.346	8.3	91	7.1
2/26/2015	0.001	0.1	0.045	0.39	0.4	0.087		30	3.4
3/26/2015	0.003	0.03	0.028	0.32	0.33	0.064		26	3.1
4/6/2015	0.048	0.6	0.106					65	5.7
4/17/2015	0.025	0.12	0.062	0.27	0.33	0.104	2.8	28	3.3
5/20/2015	0.093	1.68	0.106	0.74	2.19	0.209		64	5.6
6/30/2015	0.028	0.53	0.041					20	2.6
7/13/2015	0.241	1.57	0.075	0.7	2.27	0.113		66	5.7
8/4/2015	0.212	1.54	0.062					57	5.2
8/22/2015	0.099	0.85	0.052					41	4.2
9/9/2015	0.271	0.78	0.062					63	5.6
10/16/2015	0.016	0.23	0.024					63	5.6
11/5/2015	0.022	0.3	0.052					33	3.6

Appendix C: Tables

Table 9: Field collected data for Site 8.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0050	0.12	0.066					41	4.2
12/13/2013	0.0028	0.12	0.079					44	4.4
1/24/2014	0								
2/20/2014	0	0.001	0.031					28	3.3
3/13/2014	0								
4/10/2014	0.0005	0.12	0.002					74	6.2
5/1/2014	0.0003	0.22						35	3.8
6/4/2014	0.0010	0.22						62	5.5
6/25/2014	0.049	0.54	0.01					92	7.1
7/8/2014	0.023	0.74	0.001					78	6.4
7/31/2014	0.043	0.69	0.004	0.59	0.91	0.037	7.4	83	6.7
8/18/2014	0.01	0.47	0.034	0.45	0.61	0.023		61	5.4
9/4/2014	0.016	0.52	0.01	0.49	0.56	0.028		56	5.1
10/20/2014	0.001	0.31	0.032	0.41	0.43	0.016		41	4.2
12/4/2014	0	0.39	0.014	0.87	0.88	0.037	6	127	8.8
1/9/2015	0	3.42	0.011					753	28.1
1/13/2015	0	1.85	0.027	2.95	3.55	0.484	14.9	482	21
2/26/2015	0								
3/26/2015	0								
4/6/2015	0	2.38	0.756					363	17.4
4/17/2015	0								
5/20/2015	0.01	0.56	0.014	0.65	0.83	0.042		77	6.3
6/30/2015	0	0.09	0.004					40	4.1
7/13/2015	0.025	0.98	0.01	1.59	2.15	0.091		89	7
8/4/2015	0.028	0.88	0.017					87	6.9
8/22/2015	0.021	0.56	0.045					65	5.7
9/9/2015	0.037	0.91	0.007					71	6
10/16/2015	0.001	0.38						44	4.4
11/5/2015	0.001	0.32	0.004					42	4.3

Appendix C: Tables

Table 10: Field collected data for Site 9.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.0007	0.42	0.192					143	9.5
12/13/2013	0.0008	0.12	0.099					67	5.8
1/24/2014	0								
2/20/2014	0.0003	0.001	0.014					45	4.5
3/13/2014	0								
4/10/2014	0								
5/1/2014	0.0018	0.12	0.11					45	4.5
6/4/2014	0.0070							68	5.8
6/25/2014	0.074	0.51	0.004					106	7.8
7/8/2014	0.024	0.71	0.01					87	6.9
7/31/2014	0.037	0.67	0.004	0.67	0.9	0.032	9	95	7.3
8/18/2014	0.012	0.39	0.014	0.51	0.53	0.029		62	5.5
9/4/2014	0.017	0.4	0.021	0.66	0.66	0.047		54	5
10/20/2014	0	0.47	0.011	0.43	0.43	0.022		38	4
12/4/2014	0	0.36	0.03						
1/9/2015	0								
1/13/2015	0								
2/26/2015	0								
3/26/2015	0								
4/6/2015	0								
4/17/2015	0								
5/20/2015	0.016	0.51	0.017	0.65	0.86	0.041		79	6.4
6/30/2015	0.004	0.23	0.004					57	5.2
7/13/2015	0.061	0.91	0.028	0.67	1.08	0.038		95	7.3
8/4/2015	0.034	1	0.031					95	7.3
8/22/2015	0.016	0.39	0.014					73	6.1
9/9/2015	0.033	0.72	0.021					104	7.7
10/16/2015	0.0001	0.36	0.004					46	4.5
11/5/2015	0.004	0.58	0.014					110	8

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Table 11: Field collected data for Site 10.

Date	Flow(m^3/s)	Nitrate-N (mg/l)	Phosphate-P (mg/l)	TKN-N (mg/l)	TN (mg/l)	TP(mg/l)	DOC (mg/l)	True color	Estimated DOC (mg/l)
11/14/2013	0.055	0.12	0.024			0		30	3.4
12/13/2013	0.079	NA	NA						
1/24/2014	0.004	0.02	0.335					19	2.5
2/20/2014	0.008	0.001	0.083					73	6.1
3/13/2014	0.007	0.001	0.151					38	4
4/10/2014	0.063	0.001	0.158					31	3.5
5/1/2014	0.044	0.02	0.192					51	4.8
6/4/2014	0.034	0.12	0.045					36	3.9
6/25/2014	0.613	1.4	0.086					100	7.5
7/8/2014	0.157	1.2	0.069					65	5.7
7/31/2014	0.279	1.06	0.051	0.61	1.44	0.08	6.5	60	5.4
8/18/2014	0.074	0.88	0.031	0.47	1.28	0.059		30	3.4
9/4/2014	0.088	0.79	0.045	0.52	1.04	0.068		43	4.3
10/20/2014	0.018	0.18	0.074	0.23	0.26	0.045		9	1.6
12/4/2014	0.004	0.29	0.072	0.25	0.25	0.074	2.9	23	2.9
1/9/2015	0.006	0.23	0.083					34	3.7
1/13/2015	0.039	0.81	0.116	0.93	1.48	0.322	7.9	86	6.8
2/26/2015	0.001	0.19	0.024	0.51	0.51	0.097		21	2.7
3/26/2015	0.003	0.04	0.028	0.4	0.4	0.066		27	3.2
4/6/2015	0.037	0.3	0.096					60	5.4
4/17/2015	NA			0.25	0.29	0.095	3.1	30	3.4
5/20/2015	0.099	1.32	0.065	0.64	1.95	0.179		58	5.3
6/30/2015	0.022	0.48	0.014					26	3.1
7/13/2015	0.308	1.49	0.055	0.61	1.86	0.095		74	6.2
8/4/2015	0.296	1.36	0.058					65	5.7
8/22/2015	0.079	0.77	0.038					51	4.8
9/9/2015	0.392	0.96	0.055					65	5.7
10/16/2015	0.016	0.28	0.024					32	3.6
11/5/2015	0.023	0.24	0.045					42	4.3