



# Modeling the impacts of best management practices (BMPs) on pollution reduction in the Yarra River catchment, Australia

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## Abstract

Pollution of a watershed by different land uses and agricultural practices is becoming a major challenging factor that results in deterioration of water quality affecting human health and ecosystems. Sustainable use of available water resources warrants reduction of Non-Point Source (NPS) pollutants from receiving water bodies through best management practices (BMPs). A hydrologic model such as the Soil and Water Assessment Tool (SWAT) can be used for analyzing the impacts of various BMPs and implementing of different management plans for water quality improvement, which will help decision makers to determine the best combination of BMPs to maximize benefits. The objective of this study is to assess the potential reductions of sediments and nutrient loads by utilizing different BMPs on the Yarra River watershed using the SWAT model. The watershed is subdivided into 51 sub-watersheds where seven different BMPs were implemented. A SWAT model was developed and calibrated against a baseline period of 1998–2008. For calibration and validation of the model simulations for both the monthly and annual nutrients and sediments were assessed by using the Nash–Sutcliffe efficiency (NSE) statistical index. The values of the NSE were found more than 0.50 which indicates satisfactory model predictions. By utilizing different BMPs, the highest pollution reduction with minimal costs can be done by 32% targeted mixed-crop area. Furthermore, the combined effect of five BMPs imparts most sediments and nutrient reductions in the watershed. Overall, the selection of a BMP or combinations of BMPs should be set based on the goals set in a BMP application project.

**Keywords** BMPs · SWAT · Yarra River · Sediment · Nutrients

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## Introduction

Industrialisation and different changes in land use and agriculture practices have caused a huge impact on the shortage of water supply and the deterioration of water quality, resulting in a challenging issue for human health and ecosystems. The noteworthy effects on water and soil deterioration are caused by land use patterns modification from economic, demographic, cultural and political changes (Ingram et al. 1996). The change of tropical rain forests to agricultural fields decreases the porosity of the topsoil, which results in more nutrient leaching, runoff and erosion. The pollution management of Non-Point Source (NPS) from agricultural practices is very difficult as it is influenced by economic, social, climatic, and biological factors. As a result, to reduce water contamination from land use events and agricultural practices, watershed-scale management programs have been proven to be very effective (Guo et al. 2002).

The sustainable use of available resources and surrounding water system pollution control can be achieved by using improved agricultural cultivation systems. The governing agencies encourage applying best management practices (BMPs) to reduce environmental pollution. Watershed models are cost-efficient aids that can analyze the effects of several BMPs and create managing plans for the better quality of water (Wurbs 1998; Muttiah and Wurbs 2002). BMPs are structural, non-structural, practical, and effective practices that lessen the concentrations of pesticides, sediments, nutrients, and other contaminants in the catchment runoff which help to control the quality of water resources and reduce the harmful effect of land use. The study on the implementation of BMPs would help decision-makers to determine which BMP combination needs to be chosen to gain maximum benefit by doing cost/benefit ratio. The application of the BMPs is done by properly selecting them on the basis of environmental factors consisting of total nitrogen (TN), sediment and total phosphorus (TP) percentage reduction, financial factor consisting of social factor and overall cost consisting of the fondness of farmer. Identifying the highly polluted areas and treating them at the source will be the most efficient way to fulfill all the factors for the selection of BMPs (Tuppad et al. 2010a). However, in order to have proper water quality protection, the BMPs should be targeted at these highly polluted areas instead of random selection. A strategic targeting technique (built on simulated mean sub-watershed erosion rate) that lessens the watershed area by 2.2 times is recommended by Tuppad et al. (2010a) to maximize the water quality benefits from the applied BMPs. Many other researchers, for instance, Tripathi et al. (2003), Giri et al. (2014), Tesfahunegn et al. (2012), and Panagopoulos et al. (2011a, b), have discovered that the targeting methods are highly efficient and economical means for handling the quality of water by BMPs implementation practices.

The use of different BMPs such as reforestation, parallel terraces, and filter strips were implemented for handling the sediment in Ethiopia, particularly in the Blue Nile watershed and reduction of sediment loads was noticed in the outfalls of both watershed and sub-watershed of the above river (Schmidt and Zemadim 2015). Mbonimpa et al. (2012) studied the Upper Rock River watershed in Wisconsin, USA and found that using vegetative buffer strips over corn farms reduce the sediment load by 51–70% and 41–63% TP loss occurs. Many more studies were conducted by Vigiak et al. (2012), Tesfahunegn et al. (2012), Tuppad et al. (2010b), Panagopoulos et al. (2011b), Liu and Tong (2011) and Qi and Altinakar (2011) found out the reduction of sediment yields, TN and TP by using different BMPs. Particularly, the study of Vigiak et al. (2012) in the Avoca watershed of Victoria, Australia, by utilizing a combination of point and watershed scale model, CatchMODS found that the phosphorus load is reduced by 31% by using continuing meadows in the grazing process and zero-tillage in harvesting systems in comparison to present practices (yearly pastures and minimum tillage).

The distinctive hydrological setting of Australia has made the blooming of different water quality models for the Australian watershed, where very little information is available on soil properties, spatially referenced ecosystem or erosion and land use (Croke and Jakeman 2001; Kragt and Newham 2009). Because of this, lumped parameter conceptual hydrological models are often used for the simulation of runoff in Australian conditions (Potter et al. 2016; Vaze et al. 2011), such as the Australian Water Balance Model (AWBM) (Boughton 2004) and SIMHYD (Chiew et al. 2002) models. NPS pollution models for agricultural practice are mainly physics-associated models due to their diffuse and chronic nature (Borah and Bera 2003; Thorsen et al. 2001). Nguyen et al. (2017) utilized a class of supportive models called SWAT-SALMO to estimate the daily forms of nutrient flow in the Millbrook watershed basin systems of South Australia, and they found substantial eutrophication effects in the basin due to potential climate variation.

SWAT is a physics-associated models which best fit for the meticulous simulation of temporal and spatial assemble in chemicals, surface runoff, nutrients, sediment, and their connected flow alley, even though massive data and processing are required for modeling (Arnold et al. 1998; Borah and Bera 2003). It is a vigorous tool that identifies water quality problems and searches for solutions by BMPs (Borah and Bera 2004). The model has been used for several studies to evaluate the impacts of anthropogenic processes on water quality throughout the world (Chen et al. 2019; Nguyen et al. 2017; Parajuli et al. 2016; Rajib and Merwade 2017; Shrestha et al. 2017; Sunde et al. 2017; Tan et al. 2017). Especially in the Upper Mississippi River Basin, the

SWAT model is used to evaluate the impact of land use on a monthly period (Rajib and Merwade 2017).

BMPs are shown to be a successful approach to limit water contamination in various catchments across the world, including those in Spain (Puertes et al. 2021), China (Liyang et al. 2021; Ji et al. 2022), North Africa (Zettam et al. 2022), and Lithuania (Plunge et al. 2022). For instance, Zettam et al. (2022) discovered that the largest nitrate reduction would occur if parallel terraces were applied in a semi-arid agricultural catchment, while Plunge et al. (2022) found that in Lithuania, TN pollutant reduction can be maximized with BMP's implementation. These results show that the deployment of diverse BMPs can be used to reduce TN, TP and sediment pollution across regions with varying climatic conditions, as demonstrated by different simulations.

This study aims to assess the pollutants load reduction of sediment, TN and TP by using different BMPs on the Middle Yarra River watershed in Victoria, Australia. Using SWAT model, nutrients (TN and TP) and sediment (TSS) loads in the selected river section are calibrated from 1998 to 2004, and validated from 2005 to 2008, where all possible

variations in sediment and nutrient patterns are captured. In addition, manual tuning of the SWAT models in-stream and nutrient cycling factors is done for in-stream and nutrient cycling process calibration. This is the first time the effects of BMPs are simulated in the Middle Yarra River watershed and are found to be very suitable for developing watershed water quality management plans.

## Methodology

### Study area

The Yarra River of Victoria, Australia, comprising a watershed of 4000 km<sup>2</sup>, serves as a potential source of water for human consumption and maintains a huge supply of water for many agricultural industries. The river's watershed is separated into Lower, Middle and Upper segments as per land use activities.

The Middle Yarra portion having a 1511 km<sup>2</sup> area is selected for the research study (Fig. 1) and is denoted as the

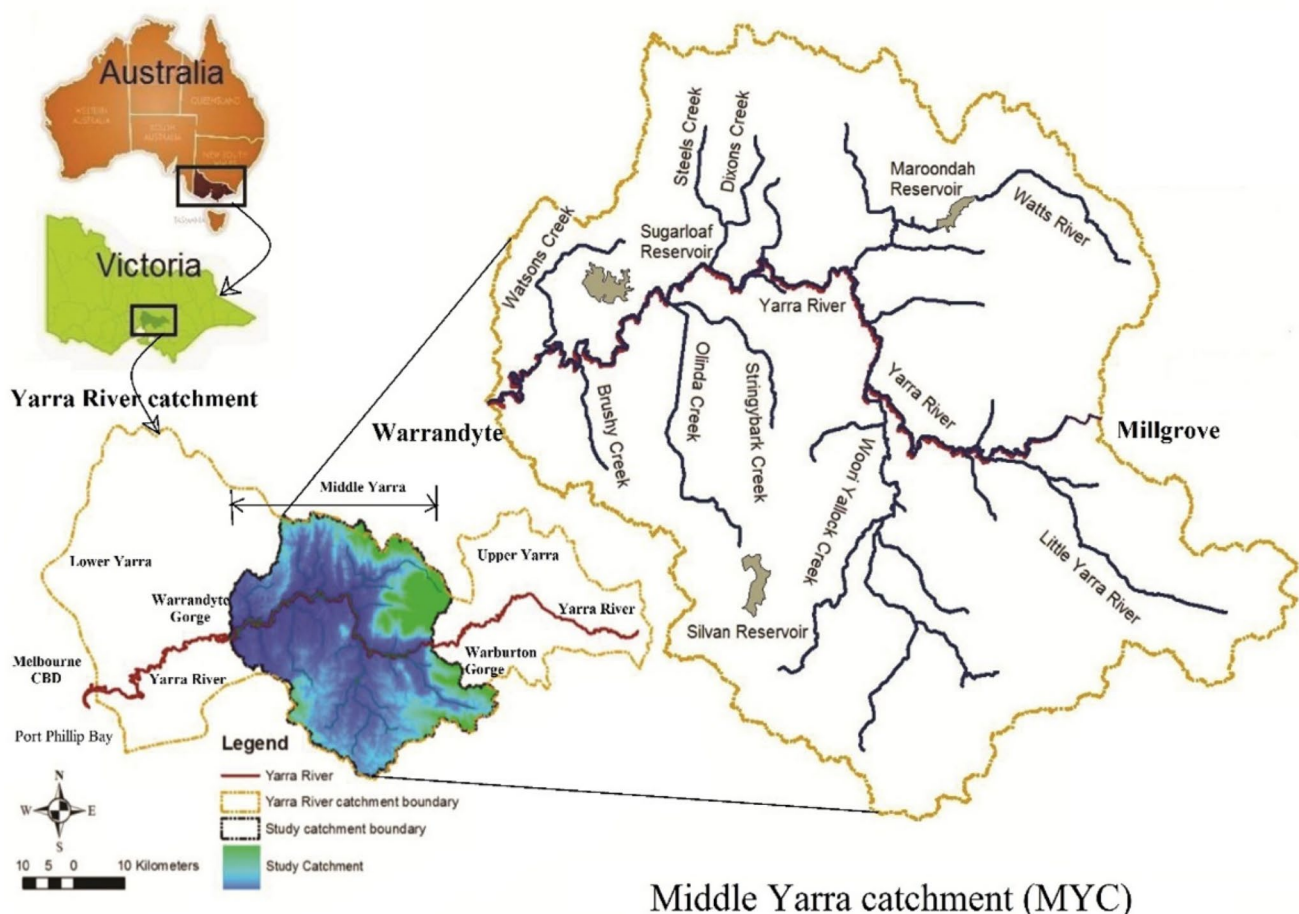


Fig. 1 The Middle Yarra Segment (MYS)

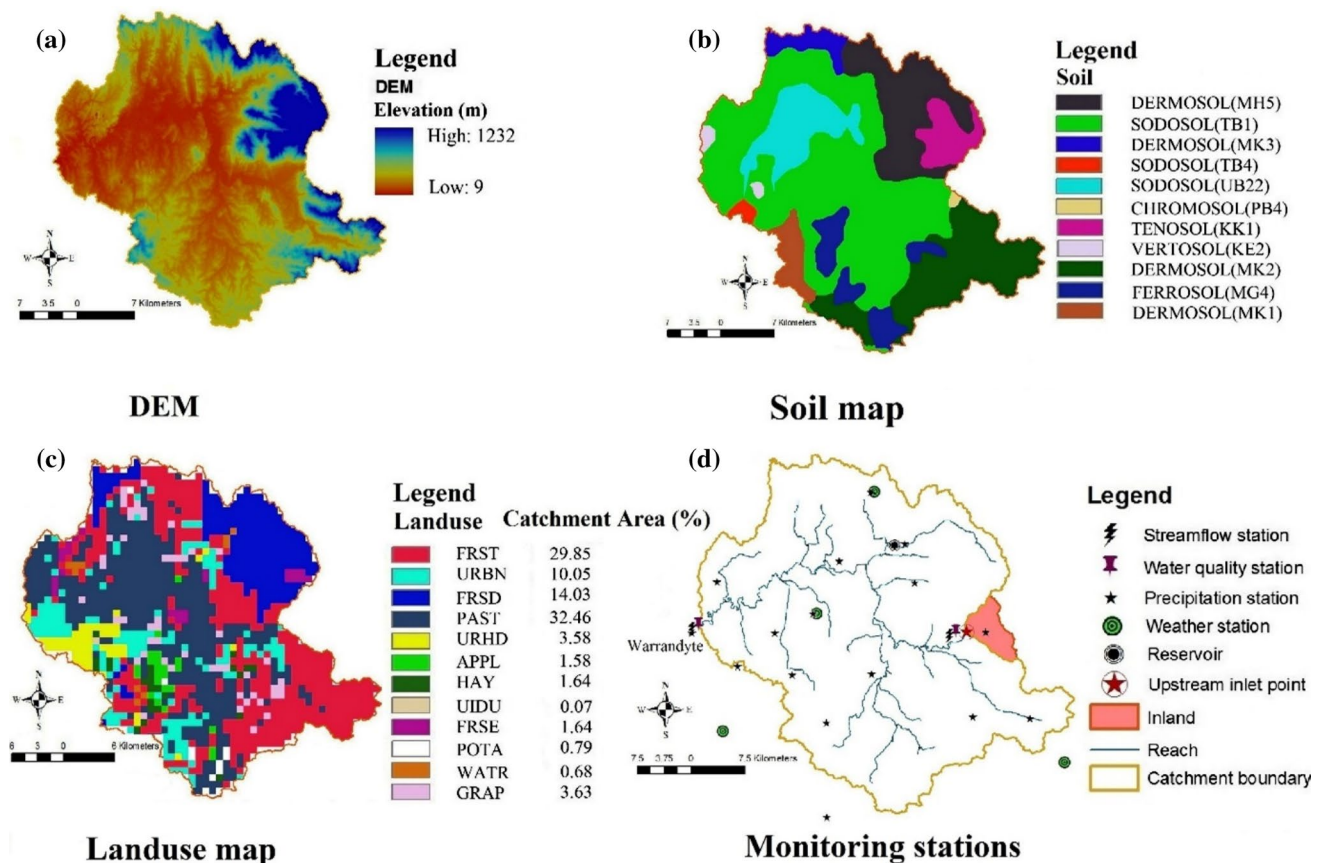
Middle Yarra Segment (MYS) throughout this paper. This is because the Yarra River watershed happens to be the largest contaminant discharge source of Port Phillip Bay territory in respect of total load and load/unit area (EPA Victoria 1999; Melbourne Water 2010).

### Input data in modeling

The ArcSWAT interface of the SWAT2005 model, which is a generic tool for watershed hydrology developed by the USDA-ARS is used in this study (Arnold et al. 1998; Winchell et al. 2009). The impact of a complex watershed on agriculture, water, and sediment yield of land use management over a long duration can be simulated by the SWAT model. Moreover, SWAT provides a powerful sensitivity and uncertainty and autocalibration analysis tool. Thus, the model is being widely recommended by many researchers for doing long-term simulations in the agricultural watershed (Borah and Bera 2004; Gassman et al. 2015). Table 6 (Appendix) shows the necessary input data for the model setup and calibration. The climate and streamflow monitoring data and digital input maps are depicted in Fig. 2.

The SWAT model utilizes the ASTER 30 m GDEM for this study, as illustrated in Fig. 2a. The soil types are shown in Fig. 2b with the major Principal Profile Form represented in brackets following the Factual Key of the Australian Soil Classification (Northcote 1979; Isbell 2002). In the watershed, 54% Sodosol and 35% Dermosol are the most common soil forms, and their various soil properties are available. In addition, 32% of the total area of the MYS is occupied by meadows, as shown in the detailed land use types in Fig. 2c. The SWAT model reclassifies land use classes compatible with the model guidelines for the MYS, though it has predefined land use forms, which makes a connection with the land use map (Winchell et al. 2009).

Daily climate data (precipitation and temperature, solar radiation, wind speed and relative humidity) from 1980 to 2008 are collected and their sources are shown in Table 6 (Appendix). Figure 3 depicts the MYS's average monthly precipitation and temperature. The maximum rainfall occurs in September, and the minimum occurs in February. As a result, the extreme temperature changes from 11.4 (July) to 25.3°C (February), while the least changes from 4.4 (July) to 12.3°C (February). In Fig. 4, it is observed that from 1997 onward, there is a swift declination in yearly mean rainfall



**Fig. 2** Soil properties, land use, digital elevation and monitoring stations map for the SWAT model at the MYS



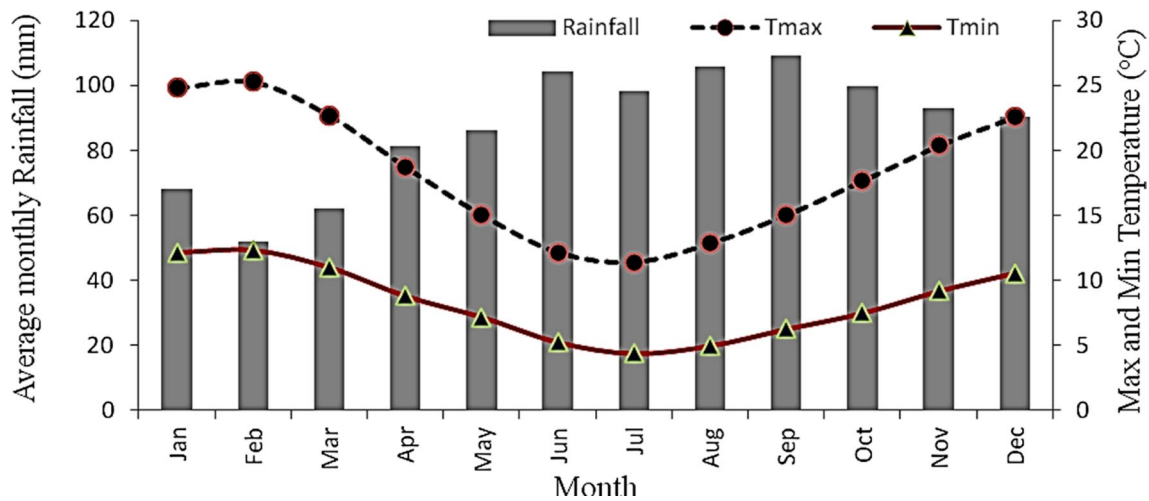


Fig. 3 Relation between monthly average temperature and precipitation (min and max) in the MYS

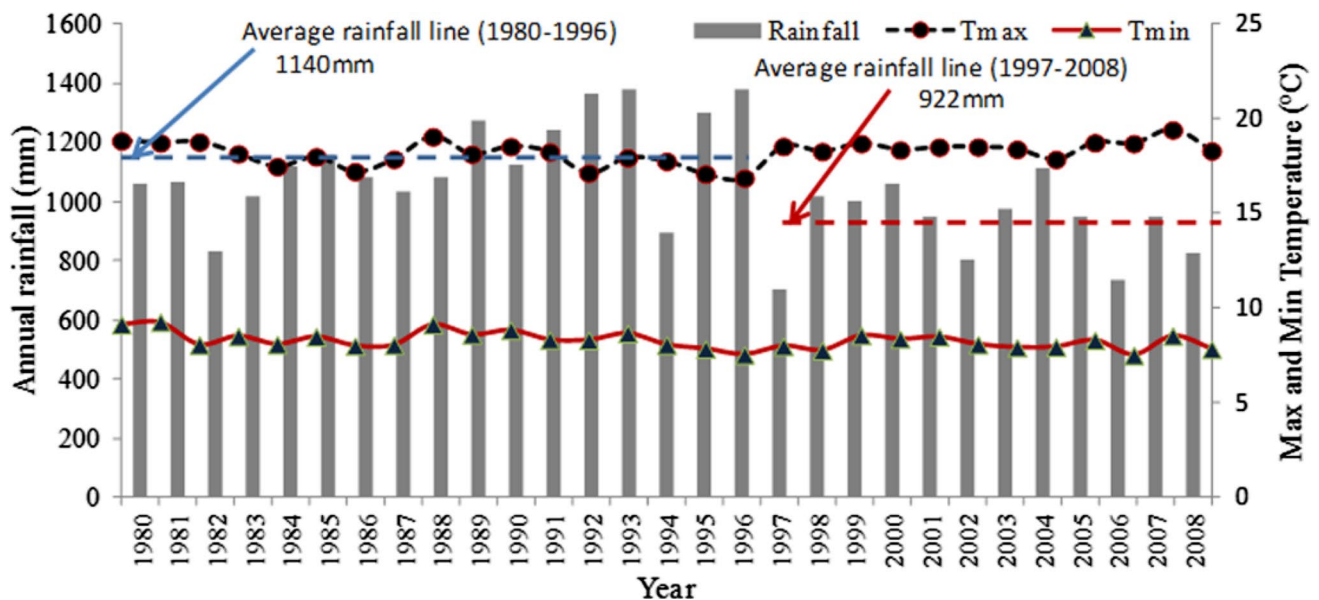


Fig. 4 Relation between yearly temperature and precipitation (min and max) in the MYS

(from 1140 to 922 mm), illustrating an extreme drought incident in the MYS, known as the millennium drought. Due to this disaster, a huge impact occurred on the agriculture, freshwater supply and industrial sectors in the watershed, which requires a methodical appraisal of future hydro-climatic studies for this watershed.

Baseflow, total streamflow, and surface runoff calibration need to be done to illustrate surface and subsurface hydrological processes accurately. "Baseflow Filter Program" (USDA-ARS 1999), which is an automated digital filter-based software, is used in this study to separate baseflow (Arnold et al. 1995). In the MYS, a maximum (75%) of the

total streamflow is provided by baseflow. Water quality data for sediment and nutrients were available from 1998 to 2008. By using the "upstream inlet point" operation in the SWAT model, the Upper segment streamflow, and sediment and nutrients from Yarra into the MYS are added by the Millgrove station data (Fig. 2d).

#### SWAT model: Structure, sensitivity analysis, calibration, and validation

The ArcSWAT interface of the SWAT 2005 version guideline is used to gather and arrange all the necessary datasets

and input database files for this study model (Winchell et al. 2009). The MYS is split into 51 sub-watersheds and 431 hydrological response sections (HRSs), with characteristic land use combinations, soil kind, and slope. The hydrological process modeling is done with Curve Number (C.N.), Penman–Monteith and Muskingum approach to estimate runoff, PET, and channel routing with NPK transformation.

At Warrandyte (MYS outlet), the sensitivity and calibration analysis of the model is performed with the auto-calibration and sensitivity tool of the SWAT. There are 26 streamflow parameters in the SWAT model. Details can be found in Das et al. (2022). Based on the sensitivity outcomes, the auto-calibration for the most sensitive streamflow factors is performed by the ParaSol (SCE-UA) (Van Griensven et al. 2006). Furthermore, in SWAT, manual tuning is made for baseflow and runoff related parameters in the runoff and baseflow calibration of the model. The ideal outcome of PBIAS and RSR is 0, and negative and positive PBIAS outcome reveals the underprediction and overprediction of the model, respectively. A simulated model can be assessed as acceptable if  $NSE > 0.50$  and  $RSR \leq 0.70$ , and if  $PBIAS \leq \pm 70\%$  for TN and TP and  $PBIAS \leq \pm 55\%$  for TSS for a monthly time frame as per Moriasi et al. (2007). Lastly, the coefficient of determination ( $R^2$ ) is also considered for the evaluation of the model outcome.

### Best management practices (BMPs)

BMPs are efficient and feasible conservation techniques that prevent or minimize nutrients and sediment from the land to groundwater or surface water or safeguard the quality of water from the potentially negative consequences of farming operations in a watershed. According to governing bodies such as USDA NRCS, BMPs can be structural and non-structural depending on capital and simple to more complicated practices. USDA NRCS (2012) mentioned that structured BMPs are grassed waterways, grad/streambank stabilization, acute area planting, cover crops, contour farming, parallel terraces, vegetative filter strips, and field buffer edges. On the other hand, they include tillage and residue management and manure or fertilizer management practices as BMPs that are non-structural (USDA NRCS 2012). The study area BMPs guidelines are collected from one of the Rural Land Program Water Sensitive Farm Design staff of Melbourne Water Corporation named Clinton Muller. On the basis of the BMPs guidelines and previous studies, seven BMPs were chosen to assess their effectiveness in the MYS, as illustrated in Table 1. Out of these 7 BMPs, the initial 2 BMPs are structural, and the rest are non-structural practices. Vegetative filter strips (VFS) are added to minimize the impact on the channel process along the edge of streams.

SWAT model already has inbuilt approaches for the simulation of non-structural BMPs, but it has no direct

approaches to apply structural practices. However, through the changes of input parameters, we can illustrate the structural practices in the model. Many researchers have implemented structural practices by changing the input parameters, and notable ones whose values are selected in this study are mentioned in Table 1.

BMPs are implemented in a similar targeting approach as were done by Tuppad et al. (2010a) discussed earlier. The selection of targeting sub-watershed is made by using the mean annual overland sediment load (ton/ha). The MYS is divided into 51 sub-watersheds, and the seven BMPs mentioned in Table 1 are implemented following the targeting methods. Firstly, the sub-watershed is ranked by the maximum sediment yield shown in Table 7 (Appendix), and the next maximum ranked sub-watershed is added successively till the aggregate area matches the targeted value of the overall mixed crop. In this study, 25, 50 and 100% targeted values are studied, and after implementation with an "all-or-nothing" basis, the simulated total mixed crop area's targeted value becomes 32, 50 and 100%. The consequences of the implemented BMPs on water quality are represented as percentage declination on mean yearly TP, TN, and Sediment loads/yields (mean from 1990 to 2008) at the HRS, sub-watershed, and watershed outfall levels. Watershed level declination includes aggregate load declination in view of routing and overland flow through the flow network. The calculation of the percentage reduction is done as per Tuppad et al. (2010b).

$$\text{reduction, \%} = \frac{y_1 - y_2}{y_1} \times 100 \quad (1)$$

where  $y_1$  and  $y_2$  average model outcomes prior to and later the implemented BMPs.

## Results and discussion

### Model sensitivity and suitability analysis

#### Streamflow

Details of the parametric selection can be found in Das et al. (2022). Table 2 shows that calibration of MYS performs very well for baseflow and streamflow (annual, monthly, and daily:  $R^2 > 0.75$ ,  $RSR < 0.50$ ,  $NSE > 0.75$  and  $PBIAS < 10\%$ ) as per the suggestion of Arnold et al. (2012) and Moriasi et al. (2007). Likewise, runoff calibration outcome is also acceptable with some exclusion ( $NSE: 0.42 < 0.50$  and  $RSR: 0.76 > 0.70$ ) of the daily and monthly time frames. In the calibration period, the model underpredicts the flow during the rainy season and overpredicts during the summer

**Table 1** Interpretation of different BMPs in the MYS management of water quality

| BMP                                       | Purpose   | Selection Criteria   | SWAT representing parameter |                           | Value when BMPs simulated                             | Reference   |
|---|---|--|-----------------------------|---------------------------|---|---|
|   |   |  | Parameter                   | Default/calibration value |   |   |
| (a) Fertilizer/manure reduced application | Reduce nutrient load  | Cropland   | –                           | Variable                  | Reduce by 30%   | Cho et al. (2010)<br>Panagopoulos et al. (2011b)  |
| (b) Conservation tillage                  | Facilitate sediment setting. Reduce velocity of flow<br>Reduce erosion            | Cropland   | OV_N                        | 0.14–0.15                 | 0.20  | Chow (1959)<br>Neitsch et al. (2004)<br>Neitsch et al. (2005)                           |
|   |   |  | CH_N1                       | 0.079                     | 0.14  |   |
|   |   |  | EFFMIX                      | 0.50–0.95                 | 0.25  |   |
|   |   |  | DEPTIL, mm                  | 125–150                   | 100   |   |
|   |   |  | CN2                         | 35–98                     | CN2 reduced by 2                                      |   |
| (c) Vegetative filter strips              | Reduce sediment, dissolved contaminants, and sediment adsorbed organics in runoff | Cropland   | FILTERW                     | 0.0 m                     | 14 m  | Cho et al. (2010)<br>Melbourne Water (2010)<br>Mbonimpa et al. (2012)                   |
|   |   |  |                             |                           | 20 m  |   |
| (d) Parallel terraces                     | Reduce surface runoff and peak runoff<br>Reduce sheet and rill erosion            | Cropland   | CN2                         | 35–98                     | CN2 reduced by 6                                      | Wischmeier and Smith (1978a, b)<br>Arabi et al. (2008)<br>Tuppad et al. (2010b)         |
|   |   |  | P-factor                    | 0.27–0.70                 | 0.10, if slope $\leq 10\%$<br>0.12, if slope $> 10\%$ |   |
| (e) Contour farming                       | Reduce surface runoff<br>Reduce sheet and rill erosion                            | Cropland   | CN2                         | Varies                    | CN2 reduced by 3                                      | Wischmeier and Smith (1978a, b)<br>Arabi et al. (2008)<br>Tuppad et al. (2010b)         |
|   |   |  | P-factor                    | 0.27–0.70                 | 0.5, if slope $\leq 10\%$<br>0.6, if slope $> 10\%$   |   |
| (f) Grassed waterways                     | Reduce peak flow rate   | Channel (1 <sup>st</sup> stream class)                     | CH_COV                      | 0.02–0.25                 | 0.001(completely protected)                           | Arabi et al. (2008)<br>Tesfahunegn et al. (2012)  |
|   | Reduce channel erodibility  |  | CH_EROD                     | 0.01–0.45                 | 0.001(completely protected)                           |   |
|   | Increase sediment trapping  |  | CH_N2                       | 0.01–0.031                | 0.001(completely protected)                           |   |
|   | Reduce gully erosion  |  |                             |                           | 0.24  |   |
| (g) Streambank stabilization              | Reduce sediment load  | Channel (2 <sup>nd</sup> and 3 <sup>rd</sup> stream class) | CH_COV                      | 0.02–0.25                 | 0.001(completely protected)                           | Chow (1959)<br>Narasimhan et al. (2007)<br>Arabi et al. (2008)<br>Tuppad et al. (2010b) |
|   | Maintain channel capacity   |  | CH_EROD                     | 0.01–0.45                 | 0.001(completely protected)                           |   |
|   |   |  | CH_N2                       | 0.01–0.031                | 0.05  |   |

CN2 initial SCS runoff curve number for moisture condition II, CH\_COV channel cover factor, CH\_EROD channel erodibility factor, OV\_N Manning's "n" value for overland flow, CH\_N1 Manning's "n" value for the tributary channel, CH\_N2 Manning's "n" value for the main channel, DEPTIL depth of mixing caused by the tillage operation (mm), EFFMIX mixing efficiency of tillage operation, FILTERW width of edge-of-filed filter strip (m), P-factor conservation support practice factor

**Table 2** Calibration of MYS streamflow with validation

|                  |             | Daily          |      |       |      | Monthly        |      |       |      | Annual         |      |       |      |
|------------------|-------------|----------------|------|-------|------|----------------|------|-------|------|----------------|------|-------|------|
|                  |             | R <sup>2</sup> | NSE  | PBIAS | RSR  | R <sup>2</sup> | NSE  | PBIAS | RSR  | R <sup>2</sup> | NSE  | PBIAS | RSR  |
| Total streamflow | Calibration | 0.78           | 0.77 | 10    | 0.48 | 0.93           | 0.89 | 10    | 0.34 | 0.96           | 0.87 | 10    | 0.36 |
|                  | Validation  | 0.74           | 0.72 | – 3   | 0.53 | 0.82           | 0.82 | – 3   | 0.43 | 0.87           | 0.81 | – 3   | 0.43 |
| Baseflow         | Calibration | 0.90           | 0.87 | 6     | 0.36 | 0.93           | 0.89 | 6     | 0.33 | 0.95           | 0.88 | 6     | 0.35 |
|                  | Validation  | 0.79           | 0.77 | – 11  | 0.48 | 0.81           | 0.79 | – 11  | 0.46 | 0.84           | 0.71 | – 11  | 0.54 |
| Runoff           | Calibration | 0.50           | 0.42 | 23    | 0.76 | 0.84           | 0.80 | 23    | 0.45 | 0.97           | 0.76 | 23    | 0.49 |
|                  | Validation  | 0.67           | 0.53 | 19    | 0.69 | 0.82           | 0.79 | 19    | 0.46 | 0.87           | 0.70 | 19    | 0.55 |

Positive and negative PBIAS values mean underprediction and overprediction respectively in percent

Monthly simulations are satisfactory if NSE  $> 0.50$  and RSR  $\leq 0.70$ , and if PBIAS  $\pm 25\%$  for streamflow as per Moriasi et al. (2007)

season in a monthly time frame. Moreover, the outcome of the model illustrates the underprediction of the streamflows.

In the validation period also, the streamflow performs very good ( $RSR < 0.50$ ,  $R^2 > 0.75$ ,  $NSE > 0.75$  and  $PBIAS < 10\%$ ), although some exclusions in the daily scale as per recommendation. Likewise, in the calibration period, the model overpredicts the flows in the summer season and underpredicts them in the winter season.

The simulation outcomes of the SWAT model from this study are found to be coherent with other SWAT findings, for instance, Kirsch et al. (2002) and Green and Griensven (2008). The overestimation and underestimation of the flows by the model is also found in the findings of Vervoort (2007) in the Mooki watershed in NSW and Watson et al. (2003) in the Woody Yaloak River watershed in Victoria.

### Sediment and nutrients

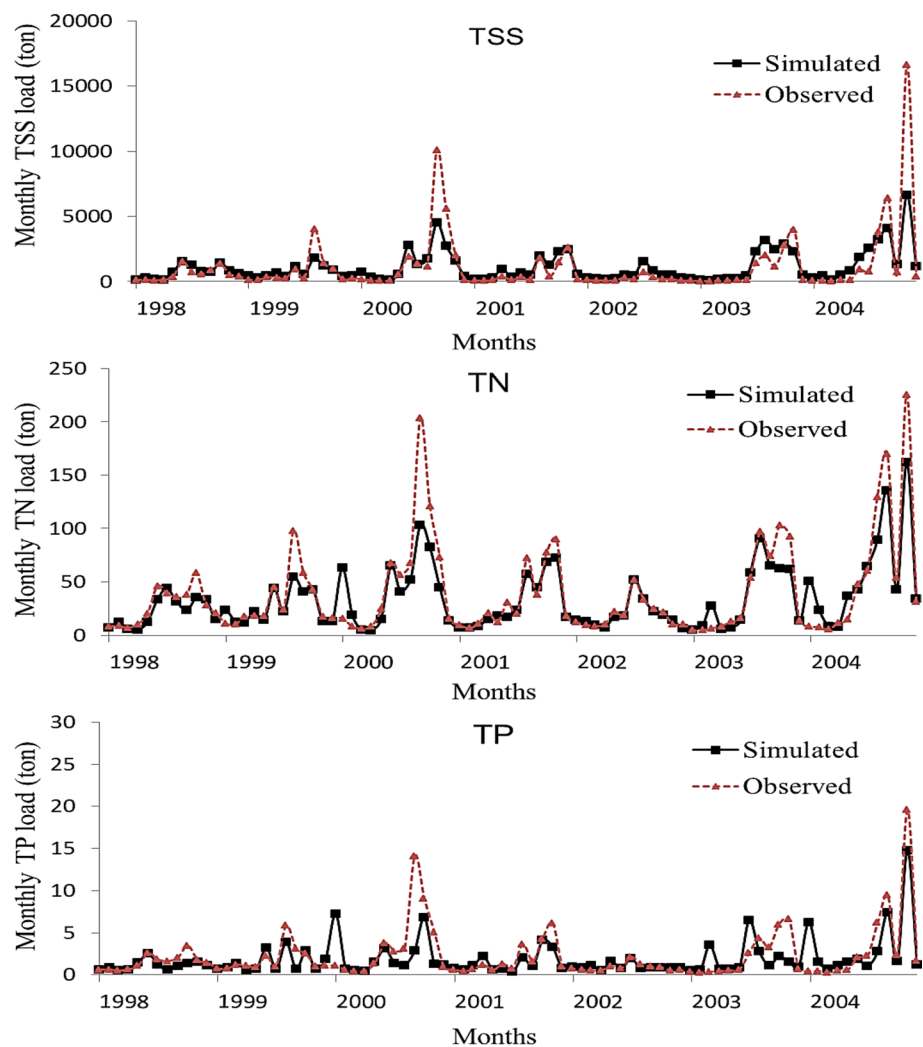
Based upon sensitivity analysis findings, 13 parameters are ranked as very significant and significant as per ranking

categorization by Van Griensven et al. (2006). These are CH\_EROD, CH\_COV, PHOSKD, NPERCO, RCHRG\_DP, PPERCO, SOL\_NO3, SOL\_LABP, SOL\_ORGP, SOL\_ORGN, SPEXP, SPCON and ULSE\_P from higher to lower rank respectively. ParaSol (SCE-UA) auto-calibration is performed at the MYS's outlet on the 13 most sensitive sediment (TSS) and nutrients (TN and TP) parameters.

Simulated nutrients (TP and TN) and sediment (TSS) values are calibrated with the data from 1998 to 2004 and validated with the data from 2005 to 2008, during which time all possible variations in sediments and nutrient patterns are captured. In addition, manual tuning of the SWAT models in-stream and nutrient cycling parameters is performed for in-stream and nutrient cycling process calibration.

The SWAT model worked very good through the calibration phase for the monthly and annual sediments as shown in Fig. 5 (TSS monthly:  $NSE > 0.50$ ,  $R^2 > 0.75$ ,  $RSR < 0.70$ , and  $PBIAS < 15\%$  and TSS annual:  $NSE > 0.75$ ,  $R^2 > 0.90$ ,  $RSR < 0.50$  and  $PBIAS < 15\%$ , as illustrated in Table 3). The calibration outcomes for the monthly and annual TP values

**Fig. 5** Calibration between simulated and observed monthly TSS, TN and TP in the MYS





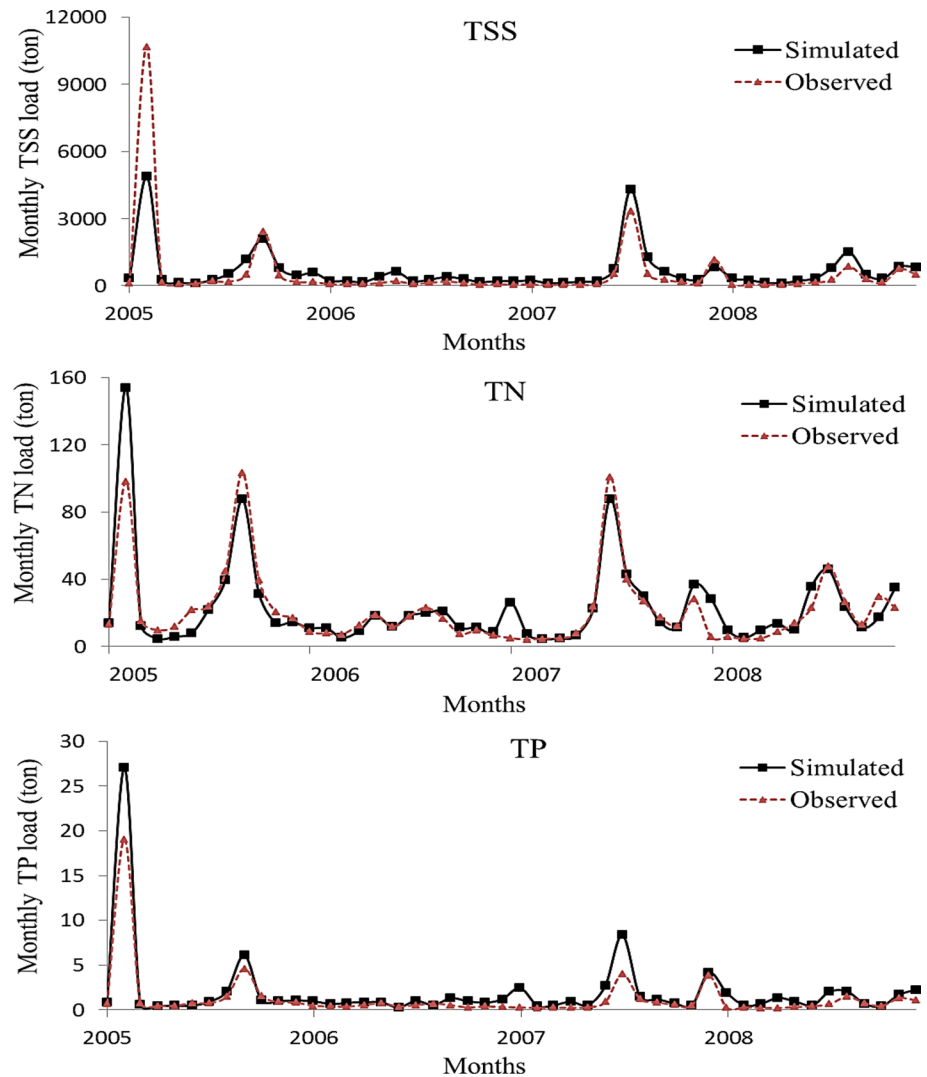
**Table 3** Statistical analysis of Sediment (TSS) and Nutrients (TN, TP) calibration (1998–2004) and validation (2005–2008)

|                        |             | Monthly |      |       |      | Annual |      |       |      |
|------------------------|-------------|---------|------|-------|------|--------|------|-------|------|
|                        |             | $R^2$   | NSE  | PBIAS | RSR  | $R^2$  | NSE  | PBIAS | RSR  |
| Sediment (TSS)         | Calibration | 0.77    | 0.62 | 2     | 0.61 | 0.91   | 0.78 | 2     | 0.47 |
|                        | Validation  | 0.78    | 0.68 | – 17  | 0.56 | 0.85   | 0.69 | – 17  | 0.55 |
| Total Nitrogen (TN)    | Calibration | 0.86    | 0.79 | 15    | 0.46 | 0.96   | 0.79 | 15    | 0.46 |
|                        | Validation  | 0.83    | 0.78 | – 5   | 0.47 | 0.98   | 0.95 | – 5   | 0.22 |
| Total Phosphorous (TP) | Calibration | 0.53    | 0.51 | 19    | 0.70 | 0.89   | 0.69 | 19    | 0.56 |
|                        | Validation  | 0.97    | 0.71 | – 56  | 0.54 | 0.97   | 0.35 | – 56  | 0.81 |

Positive and negative PBIAS values mean under prediction and over prediction respectively in percent

Monthly simulations are satisfactory if  $NSE > 0.50$  and  $RSR \leq 0.70$ , and if  $PBIAS \leq \pm 55\%$  for TSS and  $PBIAS \leq \pm 70\%$  for TP and TN as per Moriasi et al. (2007)

**Fig. 6** Validation between simulated and observed monthly TSS, TN and TP in the MYS



are very good as shown in Fig. 5 (TP monthly:  $NSE > 0.50$ ,  $R^2 > 0.50$ ,  $RSR \leq 0.70$ , and  $PBIAS < 25\%$  and TP annual:  $NSE > 0.65$ ,  $R^2 > 0.85$ ,  $RSR < 0.70$  and  $PBIAS < 25\%$ , as illustrated in Table 3). Similarly, annual, and monthly TN values are found satisfactory, as depicted in Table 3. The

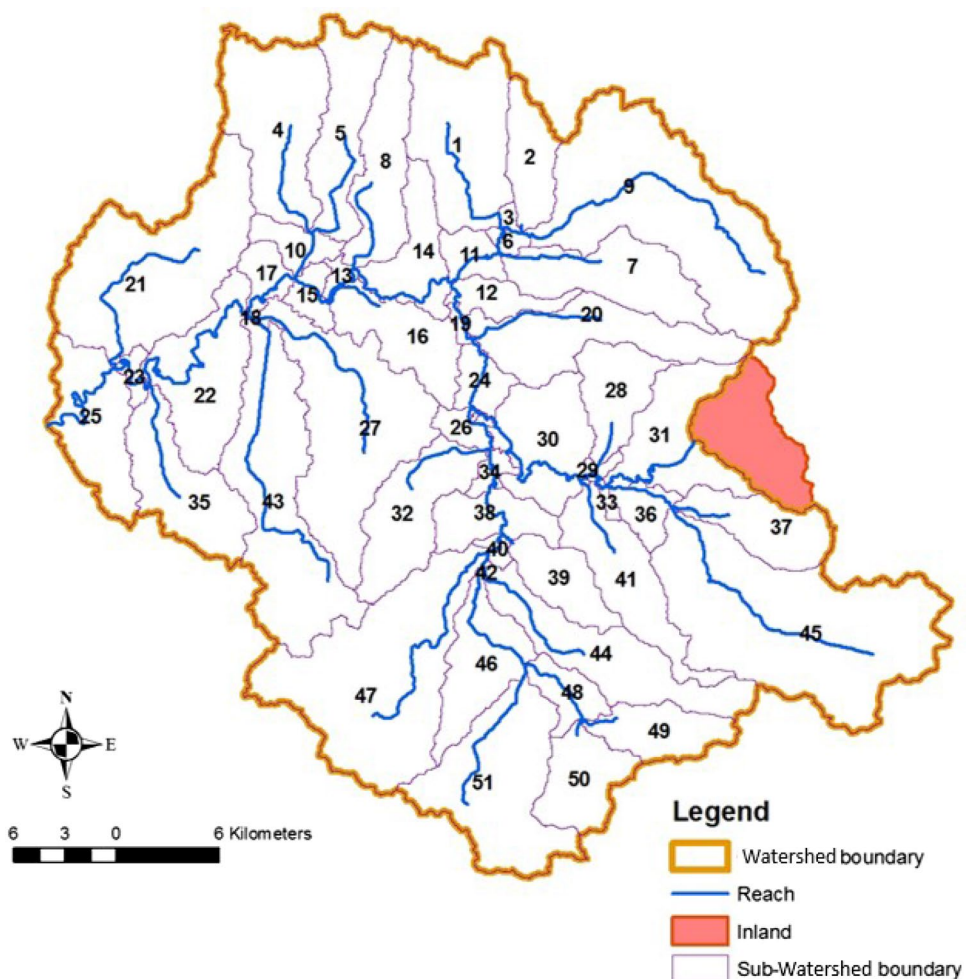
evaluation of the calibration of the model is done as per Moriasi et al. (2007) standards for the monthly and annual time steps. However, the SWAT model generally underpredicts the peak monthly and annual loads during calibration. Overall, during calibration, the sediments (TSS), TN and

TP (monthly and annual) values are underpredicted by the model, whereas the PBIAS product is positive, illustrating underestimation. Furthermore, the sediment (TSS) underestimation is much less than TP, whereas TP PBIAS values are much higher.

In the validation phase, the annual and monthly sediment (TSS) execution assessments are also very good as shown in Fig. 6 ( $NSE > 0.65$ ,  $R^2 > 0.75$ ,  $RSR < 0.60$ , and  $PBIAS \leq \pm 30\%$ , as illustrated in Table 3). Likewise, TN (monthly and annual) and TP (monthly) loads are satisfactory as shown in Fig. 6 (TN:  $NSE > 0.75$ ,  $R^2 > 0.80$ ,  $RSR < 0.50$ , and  $PBIAS \leq \pm 25\%$ ; TP:  $NSE > 0.65$ ,  $R^2 > 0.95$ ,  $RSR < 0.60$  but  $PBIAS \leq \pm 70\%$ , as illustrated in Table 3). Furthermore, the validation is unsatisfactory in annual TP loads ( $NSE < 0.50$  and  $RSR > 0.70$ ). However, the model overpredicts the apex monthly sediments (TSS), TP and TN values, where negative PBIAS output negative implies overestimation. Furthermore, the overestimation of TSS and TN is much lower than TP. The validation period overestimation of runoff events simulation during the winter seasons is expected because the validation duration is drier than the calibration.

The MYS SWAT model simulation results are consistent with other SWAT studies. SWAT overpredicts the load of nutrients in the validation period because of the deferred outcome of manure or fertilizer that occurred in the calibration period, according to Green and Griensven (2008). Furthermore, they also showed that the overprediction might occur because of the rainfall events that happened soon after manure or fertilizer was used. Likewise, Neitsch et al. (2002) discovered that for correct modeling, the exact report on the quantity and date of pesticide or manure or fertilizer usage is vital, and it does not present often. Moreover, overprediction of loads may happen with arbitrarily defined usage dates, which overlap with a rainy day. However, farmers do not the need use of manure or fertilizer on rainy days. As a result, Holvoet et al. (2005) recommended tackling this dilemma with a correct calibration using inverse modeling approaches and which case is used in this study (adjusting the usage and dates of fertilizers and manure during the calibration process). Furthermore, in the Nil catchment in Belgium, a sensitivity examination with SWAT on pesticide and hydrology found that the errors that may happen due to precipitation

**Fig. 7** Sub-watershed description in the MYS

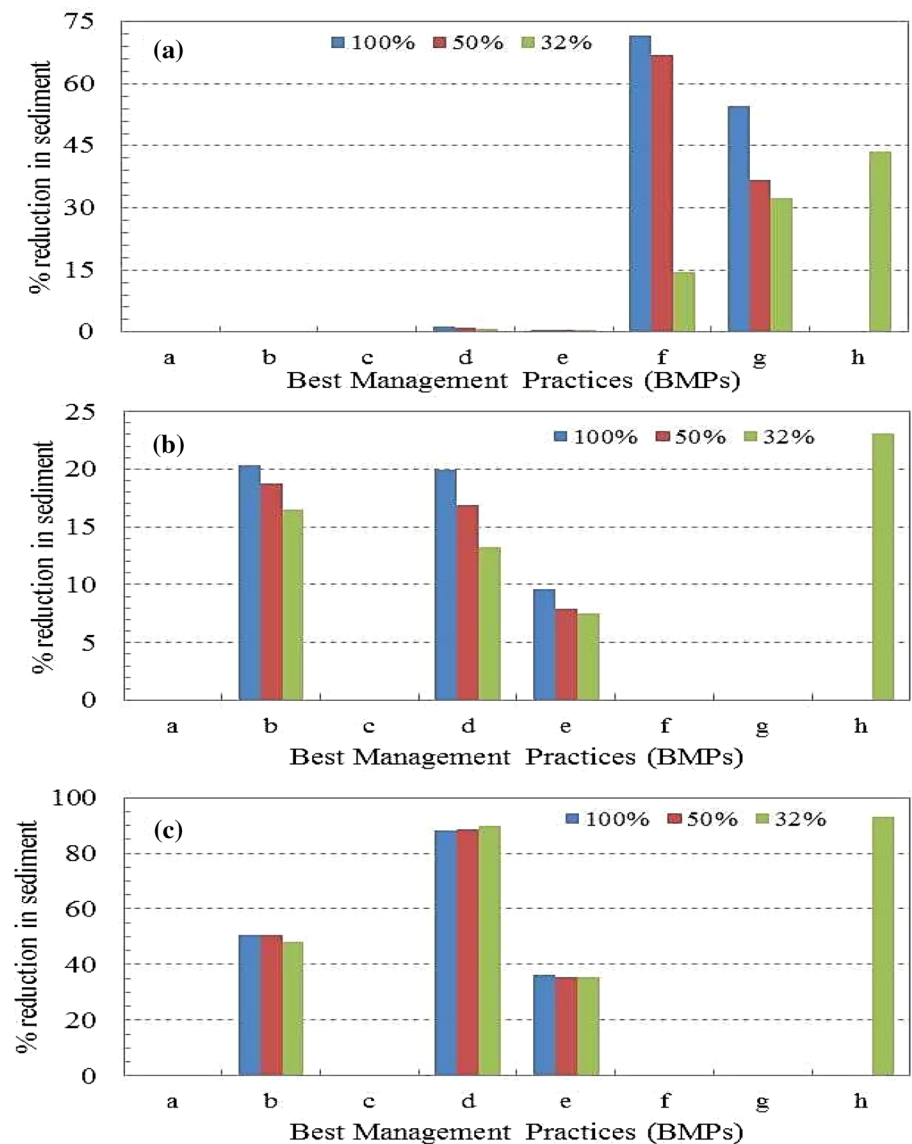


**Table 4** TN, Sediment, and TP percent declination loads/yields in the MYS for the chosen BMPs

| BMP   | Cumulative<br>Crop area (%) | Sediment reduction (%)  |                       |                | TN reductions (%)       |                       |                | TP reduction (%)        |                       |                |
|---|-----------------------------|-------------------------|-----------------------|----------------|-------------------------|-----------------------|----------------|-------------------------|-----------------------|----------------|
|   |                             | At water-<br>shed level | At sub-<br>shed level | At HRS level   | At water-<br>shed level | At sub-<br>shed level | At HRS level   | At water-<br>shed level | At sub-<br>shed level | At HRS level   |
| (a) Application of fertilizer/<br>manure at reduced rate            | 100<br>50<br>32             | 0<br>0<br>0             | 0<br>0<br>0           | 0<br>0<br>0    | 15<br>8<br>3            | 22<br>18<br>14        | 28<br>25<br>24 | 7<br>5<br>4             | 13<br>10<br>9         | 22<br>21<br>21 |
| (b) Conservative tillage  | 100<br>50<br>32             | 0<br>0<br>0             | 20<br>19<br>17        | 51<br>51<br>48 | − 14<br>− 11<br>− 9     | 6<br>6<br>6           | 6<br>8<br>7    | − 24<br>− 19<br>− 17    | 20<br>18<br>13        | 25<br>26<br>21 |
| (c) Vegetative filter strips  | 100<br>50<br>32             | −<br>−<br>−             | −<br>−<br>−           | −<br>−<br>−    | 12<br>6<br>2            | 15<br>12<br>8         | 18<br>15<br>14 | −<br>−<br>−             | −<br>−<br>−           | −<br>−<br>−    |
| (d) Parallel terraces   | 100<br>50<br>32             | 1<br>1<br>1             | 20<br>17<br>13        | 88<br>89<br>90 | 2<br>3<br>2             | 12<br>15<br>17        | 19<br>28<br>34 | 24<br>22<br>17          | 48<br>45<br>38        | 81<br>82<br>83 |
| (e) Contour farming   | 100<br>50<br>32             | 1<br>0<br>0             | 10<br>8<br>8          | 36<br>36<br>36 | 1<br>0<br>1             | 10<br>8<br>7          | 14<br>13<br>13 | 10<br>6<br>6            | 22<br>19<br>18        | 32<br>31<br>31 |
| (f) Grassed waterways   | 100<br>50<br>32             | 72<br>67<br>14          | −<br>−<br>−           | −<br>−<br>−    | 48<br>42<br>18          | −<br>−<br>−           | −<br>−<br>−    | 55<br>50<br>39          | −<br>−<br>−           | −<br>−<br>−    |
| (g) Streambank stabilization  | 100<br>50<br>32             | 55<br>37<br>32          | −<br>−<br>−           | −<br>−<br>−    | 0<br>0<br>0             | −<br>−<br>−           | −<br>−<br>−    | 0<br>0<br>0             | −<br>−<br>−           | −<br>−<br>−    |
| (h) Combination of above<br>(1), (2), (4), (6) and (7) type<br>BMPs | 32                          | 44                      | 23                    | 93             | 16                      | 30                    | 53             | 38                      | 43                    | 87             |

Figures are rounded up to the value of 0.50. Zero figures indicate very insignificant effect of a BMP on that level. Blank spaces in case of grassed waterways and streambank stabilization indicate that these BMPs are simulated as in-stream processes, which have no effects on the overland processes (at sub-watershed and HRS level). Blank spaces in case of vegetative filter strips indicate that it does not work on those cases in the MYS

**Fig. 8** Sediment declination in percent for various percentage of varied-crop region treated **a** at watershed level, **b** at sub-watershed level and **c** at HRS level



errors or usage rate are much less significant than the date of usage of pesticides (Holvoet et al. 2005).

### Evaluation of the BMPs

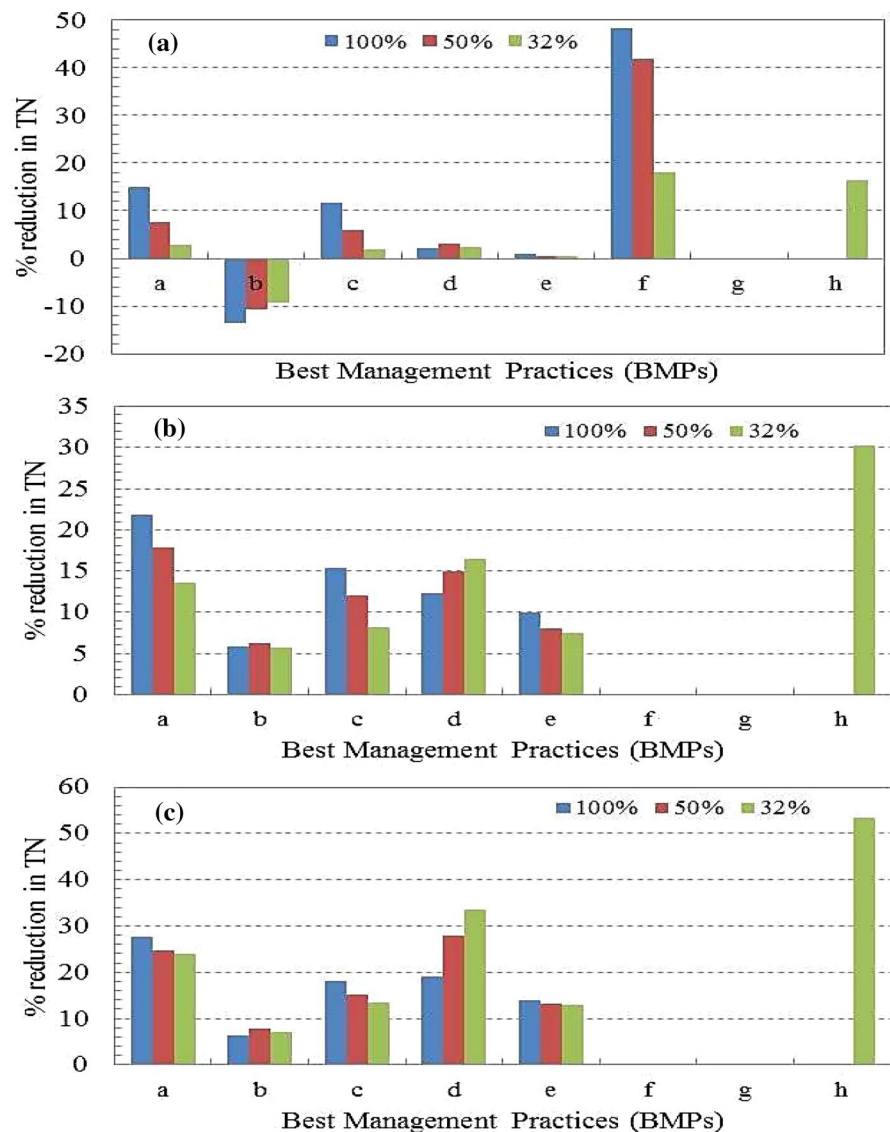
Figure 7 shows the 51 sub-watersheds where the seven BMPs have been implemented following the targeted methods. In Table 7 (Appendix), the implementation of the selected BMPs is done by choosing the 16 top-ranked sub-watersheds for 32% targeted value, for 50% targeted value for the top 26 ranked sub-watersheds and lastly, for 100% targeted value choosing all the sub-watersheds. The label "mixed-crop area" in Table 7 (Appendix) denoted the addition of the Hay, Potato, Pasture, Grape and Apple regions in a sub-watershed. Furthermore, the treated mixed-crop region of 32, 50 and 100% denoted about 13, 20 and 41% of the total watershed (1511 km<sup>2</sup>).

The three fractions of stream class in the MYS are shown in Table 8 (Appendix), where stream class 1 includes about 63% of the overall length of the stream and the other two classes include the remaining 37%. Moreover, in-stream class 1, the grassed waterways are applied, and in other stream classes, streambank stabilization is applied.

The implementation of the BMPs with respect to percentage declination of TN, TP and sediment in the MYS (Table 4). The percentage reduction is higher in the HRS level than at the sub-watershed level. It is due to the fact that at the HRS level, the yield reduction considers only regions with BMPs (mixed-crop region) and at the sub-watershed level, the yield reduction considers regions without BMPs (other land use forms) and with BMPs (mixed-crop region). Furthermore, since 13, 20 and 41% of the total watershed region (1511 km<sup>2</sup>) cover the 32, 50 and 100% of the treated varied-crop region, the reductions occur minimum at the



**Fig. 9** TN decline in percent for various percentage of varied-crop region treated **a** at watershed level, **b** at sub-watershed level and **c** at HRS level



watershed outlet level. Due to the same cause, the reductions are maximum for 100% of the treated mixed crop, then for 50% of the treated region except for parallel terraces where reductions are maximum in a reverse way at HRS level.

### Sediment load reduction

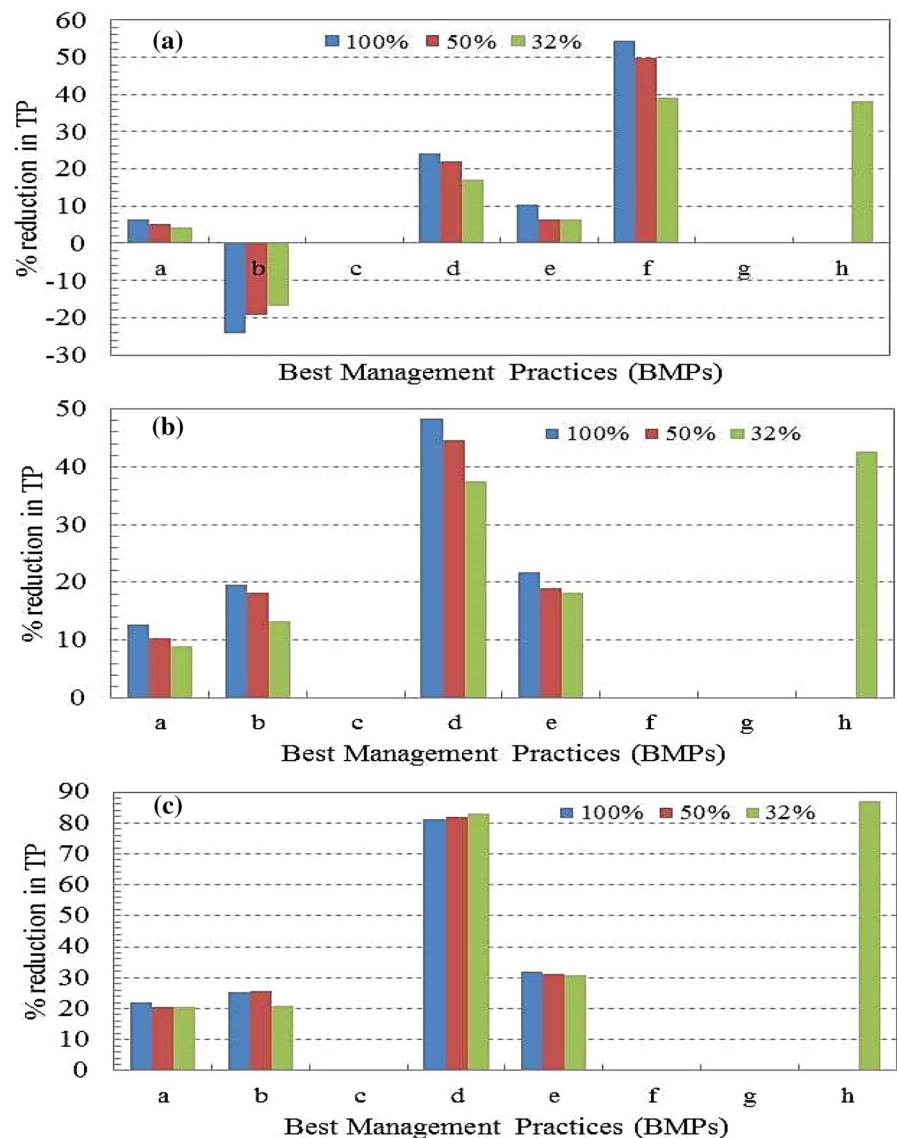
Figure 8a illustrates that at the watershed level, the percentage of sediment load reduction is higher within channel BMPs, and no significant impacts occur in upland BMPs. The changes in the application of fertilizer/manure or conservation tillage do not show any effect on the reduction of sediment. Furthermore, contour farming and parallel terraces show minor impacts. This could be due to the small application region being differentiated from the watershed region in upland BMPs. Conversely, the streambank stabilization shows a 32–55% reduction, and the maximum

reduction occurs in grassed waterways with 14–72% for the targeted 32, 50 and 100% of the treated crop region.

At the sub-watershed level, parallel terraces with 13–20%, contour farming with 8–10% and conservation tillage with 17–20% sediment yield reductions occurred for the three targeted proportions of the treated region illustrated in Fig. 8b and Table 4. Furthermore, it is seen that parallel terraces and conservative tillage simulations have nearly the same effects on sediment yield reductions at this level. There are zero effects on the sediment reduction for the case of fertilizer/manure reduced application as this BMP deals with the nutrient process only. Additionally, the within channel process BMPs like grassed waterways and streambank stabilization have no impact on the sub-watershed level as they affect the overland process.

At the HRS level, the maximum yield reduction of 90% occurred by parallel terraces, then conservation tillage of

**Fig. 10** TP decline in percent for various percentage of varied-crop region treated **a** at watershed level, **b** at sub-watershed level and **c** at HRS level



**Table 5** TN, TP, and Sediment percent reduction limit for the BMPs

| Pollutants | Cumulative mixed-crop region (%) | Scales of percent declination in the MYS |                        |              |
|------------|----------------------------------|--|------------------------|--------------|
|            |                                  | At watershed level                       | At sub-watershed level | At HRS level |
| Sediment   | 100                              | 1–72                                     | 10–20                  | 36–88        |
|            | 50                               | 1–67                                     | 8–19                   | 36–89        |
|            | 32                               | 1–32                                     | 8–17                   | 36–90        |
| TN         | 100                              | 1–48                                     | 6–22                   | 6–28         |
|            | 50                               | 3–42                                     | 6–18                   | 8–28         |
|            | 32                               | 1–18                                     | 6–17                   | 7–34         |
| TP         | 100                              | 7–55                                     | 13–48                  | 22–81        |
|            | 50                               | 5–50                                     | 10–45                  | 21–82        |
|            | 32                               | 4–39                                     | 9–38                   | 21–83        |

50% and contour farming of 36% occurred, as illustrated in Fig. 8c and Table 4. This is because, at the HRS level, yield reductions occurred considering only regions with BMPs. The sediment reductions in grassed waterways, streambank stabilization and fertilizer/manure reduced application have no effects at this level due to the same reason at the sub-watershed level.

#### Total nitrogen (TN) load reduction

In Fig. 9, the maximum mean annual TN load reduction of 18–48% occurs at the grassed waterways of the watershed level. However, there are no effects illustrated in Fig. 9 and Table 4 for the streambank stabilization within channel BMP. The cause of no effects is due to the in-stream algorithms in SWAT, QUAL2E, which eliminate erodibility and channel cover in the in-stream phosphorous and nitrogen

equations (Brown and Barnwell 1987; Tuppad et al. 2010b; Arabi et al. 2008).

The reduced fertilizer application rate, contour farming, and parallel terraces for the TN load reduction observed the very less effect. However, there is a notable increase of TN load in the conservation tillage, as shown in Fig. 9a and Table 4 (negative values). It is examined that although at the sub-watershed and HRS level, TN and TP are reduced, yet a rise of soluble phosphorous and soluble nitrogen is seen at this level. These soluble phosphorous and nitrogen are found to leach through the groundwater and lateral flow into the waterways, which outcome the rise of TP and TN at the watershed outlet (Table 4). Many studies like Tuppad et al. (2010b) also discovered similar outcomes (nutrient increment instead of declination) by the conservation tillage implementation. This increment is because of the rise of residue and the accumulation of easily available soluble phosphorous and nitrogen at the surface region for the short-age of soil conditioners (Tuppad et al. 2010b).

The streambank stabilization and grassed waterways have no impacts at the sub-watershed level as they are within channel process BMPs. On the other hand, in upland BMPs, reduced fertilizer application rate (14–22%) is more than parallel terraces (12–17%). The TN reduction of contour farming and conservation tillage is the outcome with the same varying from 6–10%.

At the HRS level, due to the overland process, the within channel process BMPs have no effect. The upland BMP “reduced fertilizer/manure application rate” causes a higher (24–28%) TN yield reduction than the parallel terraces (19–34%) as illustrated in Fig. 9c and Table 4. Also, the percentage of TN yield reduction by conservation tillage is the lowest (7%), similar to the sub-watershed level. Like sediment, the TN reductions at this level do not vary substantially for the targeted treated areas except for parallel terraces, as illustrated in Fig. 9c.

### Total phosphorus (TP) load reduction

Figure 10 shows that the mean annual TP load reduction at the grassed waterways is about 39–55% at the watershed level, which is similar to TN. For the within channel process, BMPs have no effects for the same reason as TN does not have. The parallel terraces have the maximum TP reductions with 17–24% at this level. Other upland BMPs, reduced rate fertilizer/manure application and contour farming, have a low TP reduction effect with a maximum of 10%. Furthermore, contour farming, and parallel terraces have substantial effects on TP reduction compared to TN and sediment which had almost no effects at this level (Table 4). Similarly, for the same reason as TN, conservation tillage of the TP load has negative effects, as illustrated in Fig. 10a.

At the sub-watershed level, for the same cause as TN, within the channel process, BMPs have no impact. The TP yield reductions of the parallel terraces have a maximum value of 38–48% at the watershed level. Among other upland BMPs, conservation tillage and contour farming have nearly similar effects on TP reduction whereas fertilizer/manure lessen application rate has lower effects as depicted in Fig. 10b and Table 4.

At the HRS level, the within channel process BMPs have no impact. As with the sub-watershed level, the parallel terraces with 81–83% TP yield reductions are found to be maximum. The second maximum is contour farming with 31–32%, and conservation tillage and fertilizer/manure reduced application rates also have similar effects varying from 21–26% as illustrated in Fig. 10c and Table 4.

### Synopsis of sediments (TSS), TP and TN loads

Table 5 illustrates the limits of sediment, TN and TP percentage reductions of the treated varied-crop region for the three targeted percentages. The findings show that at the sub-watershed and HRS level reduction values are nearly the same with minor deviation in TP at the sub-watershed level at 32% treated varied crop-region. Though, at the watershed level, the Sediment and TN treated region value of 32% target percentage limit is substantially different from 100 and 50% targeted percentage due to the small size of the treated area with respect to the whole watershed region. From Table 5, we also found that at the HRS level, the sediment, TN and TP percentage reduction for 32% treated area are nearly higher than 50% and 100% treated area. This is due to the higher-yielding HRSs in the 32% treated area. In the MYS watershed, the application of the BMPs shows that the treated mixed crop of 32% target percentage generated nearly similar declination efficiency in comparison to the other targeted percentage. Furthermore, the initial 16 high-ranking sub-watersheds comprising 13% of the total watershed region or 32% of the treated varied crop region provided about 84% of the total sediment loads in the MYS. Hence, the highest pollution reduction with minimal costs can be attained by utilizing BMPs on the 32% treated varied-crop region. It may be stated that among the BMPs, grassed waterways are found the most effective technique to reduce pollutant load (72% at watershed level).

A coherent impact of 5 BMPs applied on 32% of the treated varied-crop region is illustrated in Table 4. Table 4 also illustrates the inequal cumulative impacts of the distinct BMPs with the coherent impacts of the five BMPs, as a few BMP application parameters are common in some BMPs (Table 1). The combined impacts of five BMPs cause 23, 93 and 44% of sediment load reduction at the sub-watershed, HRS and watershed levels, respectively (Table 4 and Fig. 8). As discussed earlier in sediment yield reduction, grassed

waterways and streambank stabilization affect the overland process, so their reduction at the sub-watershed is comparatively less than others. The coherent impacts developed in 30, 53 and 16% of TN load lessening and 43, 87 and 38% of TP load lessening at the sub-watershed, HRS and watershed levels, respectively (Table 3 and Figs. 9 and 10). At the watershed level, the conservation tillage has adverse impacts on TP and TN load reductions. Overall, the coherent impacts are more suitable on TP load reduction and then sediment load reduction in the MYS (Table 3 and Figs. 8, 9 and 10).

In MYS water quality management, the simulations of BMPs illustrate that the choice of a BMP is grounded on the project objectives. For instance,

1. If the objective is to shield marine health at the mouth of the Yarra River (Port Phillip Bay), choosing a BMP that concentrates on contaminants load lessening at the outlet, i.e., grassed waterway is the best choice.
2. On the other hand, if the aim is to shield the marine health of the watercourses, choosing a BMP that concentrates on in-stream contaminants load is more suitable, i.e., parallel terrace is the best choice.

## Conclusions

In MYS, the application of BMPs shows significant reduction in the concentrations of the sediments and other contaminating parameters within channel and upland process of the watershed. The results showed that grassed waterway

practices generated the maximum percent reduction of sediment, TN and TP at the watershed outlet level. Conversely, at the sub-watershed and HRS levels, parallel terraces generated the maximum percent reductions of TN and TP. The application of reduced fertilizer has no effect on the reduction of sediments, whereas streambank stabilization has no effect on TP and TN percent reductions. At sub-watershed and HRS level, the application of fertilizer/ manure at a reduced rate of 30% or less caused a substantial reduction in TP and TN while the mean yield of various types of crops declined by about 15%. Furthermore, the adverse impacts of conservation tillage are found at the watershed level of TP and TN load reductions, and the vegetative filter strips only affect subsurface trapping efficiency. The combined impact of the five BMPs illustrated about 93, 44 and 23% reduction of sediment pollution at HRS level, watershed, and sub-watershed levels sequentially. The percent reduction value of the sub-watershed level is lower than the watershed level due to the no impacts of grassed waterways and streambank stabilization. Similarly, the combined impacts of 53, 30 and 16% of TN load reductions, and 87, 43 and 38% of TP load reductions are found at the HRS, sub-watershed and watershed levels, respectively. As a whole, the combined impacts of the five BMPs are more productive in sediment and TP load reductions in the MYS.

## Appendix

See Tables 6, 7, 8.

**Table 6** SWAT model data reference (Das et al. 2022)

| Data                          | Reference   |
|-------------------------------|---|
| Digital Elevation Model (DEM) | ASTER 30 m GDEM, jointly developed by The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA), ( <a href="http://asterweb.jpl.nasa.gov/gdem-wist.asp">http://asterweb.jpl.nasa.gov/gdem-wist.asp</a> )  |
| Soil                          | Atlas of Australian Soils from Australian Soil Resource Information System (ASRIS) developed by CSIRO and Department of Agriculture, Fisheries and Forestry (DAFF) ( <a href="http://www.asris.csiro.au">http://www.asris.csiro.au</a> )  |
| Land use                      | 50 m grid raster data for the period of 1997 to May 2006 collected from Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) ( <a href="http://adl.brs.gov.au/landuse">http://adl.brs.gov.au/landuse</a> )  |
| Climate                       | 16 rainfall stations, and 4 temperature (max and min), solar radiation, wind speed and relative humidity stations data from SILO climate database ( <a href="http://www.longpaddock.qld.gov.au/silo">http://www.longpaddock.qld.gov.au/silo</a> ) and Bureau of Meteorology (BoM) ( <a href="http://www.bom.gov.au/climate/data/">http://www.bom.gov.au/climate/data/</a> )   |
| Streamflow                    | Daily streamflow data for two stations at Warrandyte (outlet of the MYC) and Millgrove from Melbourne Water ( <a href="http://www.melbournewater.com.au/">http://www.melbournewater.com.au/</a> )   |
| Crop management practices     | Manure, fertilizer type and application rate, tillage practices, cropping seasons, and irrigation rate from Australian Bureau of Statistics ( <a href="http://www.abs.gov.au">http://www.abs.gov.au</a> ), Department of Environment and Primary Industries ( <a href="http://www.depi.vic.gov.au/">http://www.depi.vic.gov.au/</a> ) and Melbourne Water ( <a href="http://www.melbournewater.com.au/">http://www.melbournewater.com.au/</a> ) |



**Table 7** Ranking of targeted sub-watershed for the application of BMPs

| Rank | Sub-catchment number<br>(Related to Fig. 5) | Sediment yield<br>(ton/ha) | Mixed-crop area<br>(km <sup>2</sup> ) | Cumulative area<br>(km <sup>2</sup> ) | Percentage |
|------|---|----------------------------|---------------------------------------|---------------------------------------|------------|
| 1    | 11  | 8.73                       | 2.60                                  | 2.60                                  | 0          |
| 2    | 35  | 7.75                       | 5.70                                  | 8.30                                  | 1          |
| 3    | 6   | 7.56                       | 0.00                                  | 8.30                                  | 1          |
| 4    | 33  | 7.26                       | 0.43                                  | 8.73                                  | 1          |
| 5    | 43  | 6.07                       | 24.68                                 | 33.41                                 | 5          |
| 6    | 36  | 5.20                       | 2.46                                  | 35.86                                 | 6          |
| 7    | 5   | 4.83                       | 18.19                                 | 54.05                                 | 9          |
| 8    | 1   | 4.06                       | 3.11                                  | 57.16                                 | 9          |
| 9    | 25  | 3.52                       | 8.97                                  | 66.13                                 | 11         |
| 10   | 12  | 3.43                       | 5.45                                  | 71.58                                 | 12         |
| 11   | 8   | 3.20                       | 15.54                                 | 87.12                                 | 14         |
| 12   | 7   | 2.47                       | 0.00                                  | 87.12                                 | 14         |
| 13   | 22  | 2.46                       | 35.03                                 | 122.15                                | 20         |
| 14   | 23  | 2.23                       | 0.67                                  | 122.82                                | 20         |
| 15   | 10  | 1.47                       | 7.22                                  | 130.05                                | 21         |
| 16   | 27  | 1.24                       | 64.02                                 | 194.06                                | 32         |
| 17   | 30  | 1.17                       | 21.09                                 | 215.15                                | 35         |
| 18   | 24  | 1.16                       | 10.11                                 | 225.26                                | 37         |
| 19   | 41  | 0.69                       | 12.95                                 | 238.21                                | 39         |
| 20   | 32  | 0.69                       | 32.76                                 | 270.98                                | 44         |
| 21   | 20  | 0.66                       | 6.81                                  | 277.79                                | 45         |
| 22   | 31  | 0.66                       | 9.51                                  | 287.30                                | 47         |
| 23   | 37  | 0.59                       | 0.00                                  | 287.30                                | 47         |
| 24   | 3   | 0.58                       | 0.00                                  | 287.30                                | 47         |
| 25   | 15  | 0.56                       | 7.28                                  | 294.57                                | 48         |
| 26   | 45  | 0.55                       | 14.50                                 | 309.07                                | 50         |
| 27   | 46  | 0.52                       | 17.49                                 | 326.56                                | 53         |
| 28   | 17  | 0.47                       | 7.48                                  | 334.04                                | 55         |
| 29   | 13  | 0.44                       | 2.85                                  | 336.89                                | 55         |
| 30   | 14  | 0.44                       | 17.27                                 | 354.15                                | 58         |
| 31   | 4   | 0.42                       | 19.45                                 | 373.60                                | 61         |
| 32   | 47  | 0.38                       | 48.27                                 | 421.87                                | 69         |
| 33   | 51  | 0.37                       | 36.87                                 | 458.74                                | 75         |
| 34   | 21  | 0.36                       | 42.04                                 | 500.78                                | 82         |
| 35   | 18  | 0.32                       | 0.08                                  | 500.86                                | 82         |
| 36   | 40  | 0.28                       | 1.73                                  | 502.58                                | 82         |
| 37   | 28  | 0.27                       | 2.08                                  | 504.66                                | 82         |
| 38   | 2   | 0.26                       | 0.00                                  | 504.66                                | 82         |
| 39   | 38  | 0.25                       | 16.13                                 | 520.79                                | 85         |
| 40   | 50  | 0.25                       | 12.37                                 | 533.17                                | 87         |
| 41   | 19  | 0.24                       | 1.35                                  | 534.52                                | 87         |
| 42   | 34  | 0.24                       | 4.39                                  | 538.91                                | 88         |
| 43   | 39  | 0.23                       | 13.44                                 | 552.35                                | 90         |
| 44   | 9   | 0.21                       | 0.00                                  | 552.35                                | 90         |
| 45   | 16  | 0.20                       | 28.51                                 | 580.86                                | 95         |
| 46   | 48  | 0.15                       | 5.45                                  | 586.31                                | 96         |
| 47   | 26  | 0.12                       | 3.23                                  | 589.54                                | 96         |
| 48   | 29  | 0.12                       | 0.73                                  | 590.27                                | 96         |
| 49   | 44  | 0.11                       | 22.25                                 | 612.52                                | 100        |
| 50   | 42  | 0.01                       | 0.24                                  | 612.76                                | 100        |

**Table 7** (continued)

| Rank | Sub-catchment number<br>(Related to Fig. 5) | Sediment yield<br>(ton/ha) | Mixed-crop area<br>(km <sup>2</sup> ) | Cumulative area<br>(km <sup>2</sup> ) | Percentage |
|------|---|----------------------------|---------------------------------------|---------------------------------------|------------|
| 51   | 49  | 0.00                       | 0.00                                  | 612.76                                | 100        |

**Table 8** Element of stream classes in the MYS

| Stream class | Number of segments | Length (m) | Element of total stream length (%) |
|--------------|--------------------|------------|------------------------------------|
| 1            | 25                 | 212,605    | 63                                 |
| 2            | 16                 | 60,293     | 18                                 |
| 3            | 10                 | 62,752     | 19                                 |
| Total        | 51                 | 335,650    | 100                                |

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**Author contribution** SKD and AWMN designed the experiments and carried them out. SKD, AWMN, AA, NAA and MHRBK developed the model code, performed the simulations and presented in graphical forms. AA, MHRBK, NAA, SA, MI, MAURT and MS prepared the manuscript with contributions from all co-authors.

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**Data availability** The necessary data set is given in Appendix. Further information/data will be supplied upon request.

## Declarations

**Competing interests** The authors declare that they have no conflict of interest.

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