BASINWIDE ANALYSIS OF WATER RESOURCES AND POLLUTE TRANSPORT USING A DISTRIBUTED PARAMETER MODEL

Amali Chathurika Dahanayake

158045C

Degree of Master of Philosophy

Department of Civil Engineering

University of Moratuwa
Sri Lanka

July 2019

BASINWIDE ANALYSIS OF WATER RESOURCES AND POLLUTE TRANSPORT USING A DISTRIBUTED PARAMETER MODEL

Amali Chathurika Dahanayake

158045C

Thesis submitted in partial fulfilment of the requirements for the degree of
Master of Philosophy

Department of Civil Engineering

University of Moratuwa
Sri Lanka

July 2019

Declaration of the Candidate and Supervisor

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature Date

The above candidate has carried out research for the MPhil thesis dissertation under my supervision.

Signature of the supervisor Date

Basinwide Analysis of Water Resources and Pollute Transport Using a Distributed Parameter Model

Abstract

The Nachchaduwa sub-catchment (598.74 km^2) of the Malwathu Oya basin is seasonally stressed in the dry periods and its downstream parts undergo intermittent floods during monsoon seasons while the fate and behaviour of excess Nitrogen (N) and Phosphorus (P) added to the waterways due to agricultural fertilizers used in the upstream areas remain unresolved. This study incorporated the Water and Energy Transfer Processes (WEP) model to assess the water resources and pollutant transport of the catchment concerning the present status and six possible future scenarios. The required data for the model runs including meteorological, geographical, hydrological, and data related to water quality and anthropogenic activities, were collected and processed identifying the suitable model parameter values. The amounts of N and P in fertilizers applied in this catchment exceeded the actual plant requirement. In both wet and dry seasons, the differences between the measured water quality parameters in upstream and downstream were not statistically significant. The model results of the hydrological component showed that the catchment response to the rainfall was highly regulated due to reservoir storage effect. The model results of the material transport component showed that, on average, the wet season had about 5~7 times the dry season value of the Total Suspended Solids (TSS) in the streams, and in both seasons, the modelled TSS, NO_3^- and PO_4^{3-} were within the ranges of the previously published results. Scenario analysis found almost all water quality parameters reduced with the reduction of fertilizer input (maximum 30.64% reduction) and with the increase in temperature (maximum 2.27% reduction), but they increased with the increase in rainfall (maximum 13.49% increase). The findings will be useful in identifying best water resources management practices and coping with the residual N and P in streams and water bodies in a more pragmatic manner.

Keywords: Hydrological and material transport models, Nachchaduwa, Nitrogen, Phosphorus, Process-based models

Acknowledgements

I would like to extend my sincere gratitude towards all the organisations and individuals who have contributed and supported to this research. This research was funded by University of Moratuwa Senate Research Council Grants; SRC/ST/2015/17, SRC/LT/2016/09 and SRC/ST/2017/33.

First, I would like to express my profound gratitude to the supervisor of this research, Dr. R. L. H. L. Rajapakse, Senior Lecturer, Department of Civil Engineering, University of Moratuwa, for his immense support, continuous supervision, valuable guidance, and cordial mentoring given throughout the study period, as well as for sharing his extensive knowledge and precious time on this study.

Then I would like to extend my appreciation towards the staff of the Department of Irrigation, in both Colombo and Anuradhapura divisions, for providing the necessary streamflow and reservoir operation data for this study, as well as for the patronage given in field visits to the Nachchaduwa reservoir. Then I would like to acknowledge the support given by the staff of the Fertilizer Division, Divisional Secretariat Division of Anuradhapura District, in collecting fertilizer issuing data. Thereafter, the staff of the Meteorological Department is acknowledged for their support given in collecting meteorological data for this study.

Further, my sincere acknowledgements are conveyed to Professor J. M. A. Manatunga, and to the staff of the laboratory of the division of Environmental Engineering, Department of Civil Engineering, University of Moratuwa, for their support and advices given during the water quality testing conducted in that laboratory.

The research would not have been possible without the support given by all the academic staff members of the Department of Civil Engineering, including Senior Professors, Professors, Senior Lecturers and Lecturers. All the non-academic and academic support staff of University of Moratuwa are greatly appreciated for their heterogeneous supports given throughout the study period.

Finally, I am greatly indebted to my family, colleagues, and friends who gave me an immense support to successfully complete this research study.

Table of Contents

List of Figures

List of Tables

List of Appendices

List of Abbreviations

Abbreviation	Description
APHA	American Public Health Association
ASC	Agrarian Services Centres
BMP	Best Management Practices
BOD	Biological Oxygen Demand
CEA	Central Environmental Authority
CCME	Canadian Council of Ministers of the Environment
CKDu	Chronic Kidney Disease of Unknown aetiology
COD	Chemical Oxygen Demand
DN	Dissolved Nitrogen
DP	Dissolved Phosphorus
DO	Dissolved Oxygen
DON	Dissolved Organic Nitrogen
DP	Dissolved Phosphorus
DSD	Divisional Secretariat Divisions
EC	Electrical Conductivity
FIMS	First Inter Monsoon Season
GCM	General Circulation Models
HERT	Hydrologic Engineering Research Team
HLMC	High Level Main Canal
HMIS	Hydro-meteorological Management Information System
HYV	High-Yielding Varieties
IGCI	International Global Change Institute

IN	Inorganic Nitrogen
IP	Inorganic Phosphorus
IPCC	Intergovernmental Panel on Climate Change
IPCC-TGCIA	Intergovernmental Panel on Climate Change - Task Group on Scenarios for Climate Impact Assessment
IWMI	International Water Management Institute
LB	Left Bank
LBHL	Left Bank High Level
LLMC	Low Level Main Canal
MCM	Million Cubic Meters (10^6 m^3)
MOP	Muriate of Potash
NCP	North Central Province
NEM	North East Monsoon
NGO	Non-Governmental Organizations
OFC	Other Field Crops
ON	Organic Nitrogen
OP	Organic Phosphorus
PBSD	Physically Based Spatial Distributed
PN	Particulate Nitrogen
PON	Particulate Organic Nitrogen
PP	Particulate Phosphorus
RB	Right Bank
RBHL	Right Bank High Level
RBLL	Right Bank Low Level
RSC	Residual Sodium Carbonate

SAR	Sodium Absorption Ratio
SCS	Soil Conservation Service
SLS	Sri Lanka Standards
SS	Suspended Solids
SIMS	Second Inter Monsoon Season
SRES	Special Report on Emission Scenarios
SWM	South West Monsoon
SWMS	South West Monsoon Season
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TSP	Triple Super Phosphate
USACE	United States Army Corps of Engineers
VBA	Visual Basic for Applications
WEP	Water and Energy transfer Processes
WHO	World Health Organisation
WQI	Water Quality Index

1 INTRODUCTION

1.1 Overview of the Study

Among the river basins in Sri Lanka Malwathu Oya basin is the second largest catchment (3284 km^2), and one of the most widely used sources of water for irrigation, water supply and other diversions in the North Central Province (Figure 1.1). It has now become a seasonally stressed river basin due to over exploitation and water pollution. The basin experiences water scarcity during the dry periods and the downstream areas of the catchment are flooded during the wet periods, whilst severe flooding was observed in 2011, 2014 and 2016 (Department of Irrigation, n.d.).

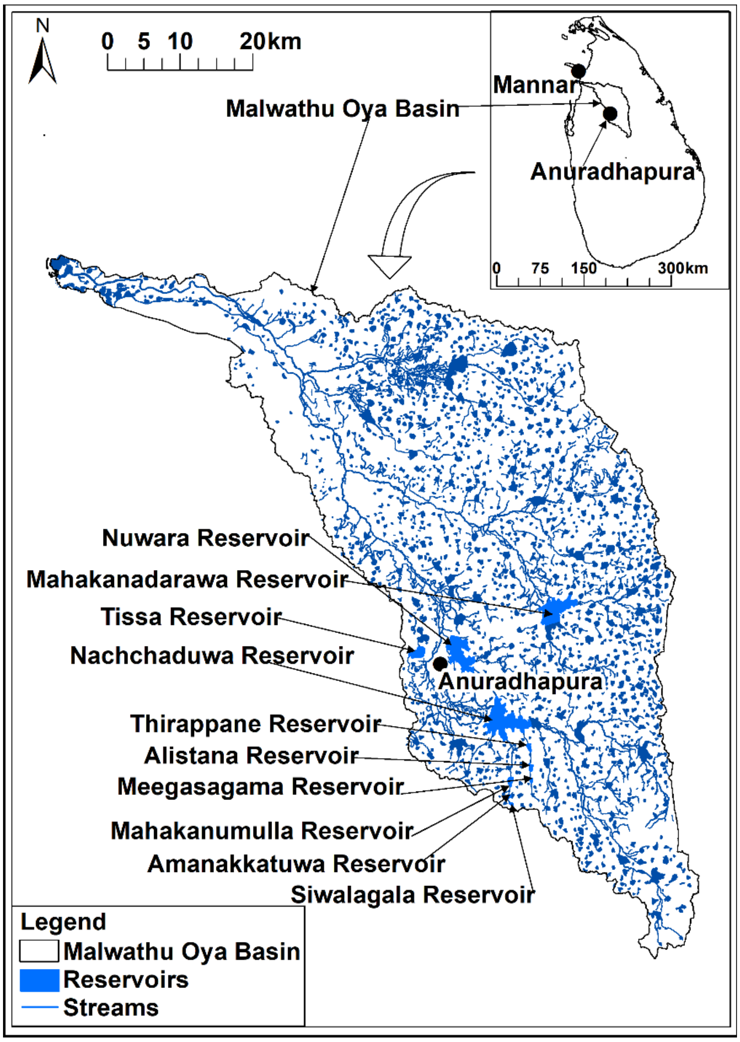


Figure 1.1: Malwathu Oya River Basin (original in colour)

The basin is augmented by adjacent Kala Oya basin from Kala wewa reservoir via Yoda Ela to feed Nachchaduwa, Tissa wewa and Basawakkulama reservoirs. The basin is distinct as it possesses a large number of tanks, from small size village tanks [average capacity 0.07 MCM (Million Cubic Meters) (60 Ac. ft)] to comparatively large working tanks [capacity ranging from 3.09 MCM (2 500 Ac. ft) (Tissa wewa) to 55.74 MCM (45 150 Ac. ft) (Nachchaduwa)], from which the rainfall runoff process is largely influenced. Up to a certain threshold, the river flow is more or less regulated and flood peaks are reduced (Department of Irrigation, n.d.). However, the water holding capacity of most of the tanks has been reduced significantly due to aquatic weeds, eutrophication and heavy siltation. Hence, most of the tanks are facilitating only for Maha season and lack of irrigation water has become a problem in Yala season (Gunarathna & Kumari, 2014).

The quality of water in Malwathu Oya is impaired by the stresses caused by anthropogenic activities (Perera, Sundarabarathy, Sivananthawerl, & Edirisinghe, 2014). With respect to irrigation-related water quality of the reservoirs, Nachchduwa has exceeded the threshold value of electrical conductivity (0.750 $mScm^{-1}$) and salinity (0.500 gl^{-1}) (Silva, 2004). Water of the nearby paddy lands is diverted to the river from different locations during cultivation seasons (Perera et al., 2014). Urban area waste has been discarded to the stream resulting pollution of water (De Alwis, 2006).

In the first inter-monsoon season (March - April), notably inflated concentrations of NO_3^-, PO_4^{3-}, Cl^- were observed in streams in the paddy cultivated areas of Malwathu Oya, while in the northeast monsoon season (December – February) the highest mean Dissolved Oxygen (DO) and turbidity values were observed. The statistically significant seasonal variations observed in the water quality concentrations are attributed to the application of chemical fertilizers in paddy cultivation (Perera et al., 2014). In addition, the outlet of the main stream from the Anuradhapura city and the canal flowing across the city, have shown higher values for pH, Total Dissolved Solids (TDS), PO_4^{3-} , electrical conductivity, DO level, and NO_3^-, confirming the impact of urban land use on water pollution in Malwathu Oya (Madushanka, Dissanayaka, & Amarasekara, 2015).

Therefore, it is evident that the Malwathu Oya river basin is seasonally stressed due mainly to over exploitation and water pollution in the dry periods and it is known to undergo intermittent flooding in the downstream areas during monsoon seasons. In addition, the fate and behaviour of nutrient elements (Nitrogen and Phosphorous) which are added to the waterways as a result of the excessive use of agrochemicals/chemical fertilizers in paddy lands and other crop areas in the upstream catchment area, remain unresolved.

Therefore, water resources management alternatives (to overcome issues occurring due to spatial and temporal variations, climate change impact, etc.) and measures to address issues related to degrading water quality (caused due to excessive use of agro-chemicals) in the basin should be studied, while the fate of pollutants including their conveyance and spatial and temporal accumulation patterns should also be investigated.

Nachchaduwa catchment (598.74 km^2) was selected as the study area since it is the uppermost sub-catchment in the Malwathu Oya basin, therefore no effect from previous catchments have to be considered, and because of the location of a major reservoir, hence the reservoir effect could also be modelled.

The temporal and spatial fluctuations of all variables included in mathematical equations of water flows in watersheds could be considered by mathematical distributed hydrological models. The employed parameters being physically measurable is another advantage. Hence, such models are able to provide a comprehensive and a more accurate depiction of the hydrological processes in a watershed than empirical and conceptual hydrological models. There are a number of omnipresent models of this type, like SHE, SWAT, IHDM, MIKE SHE (Jia, Ni, Kawahara, & Suetsugi (2001b) and Water and Energy Transfer Processes (WEP) model (Jia, Ni, Kawahara, & Suetsugi, 2001a).

A comprehensive energy balance analysis was incorporated in the hydrological modelling for the development of the WEP model (Jia & Tamai, 1998). Its main differences from other physics-based models involve; detailed consideration of energy transfer processes, use of sub grid heterogeneity of land use, application of generalized Green-Ampt model to save computation time and its potential use for various scenario analyses. As additional improvements to the WEP model, inclusion of the particle-bound pollutants by incorporating a soil erosion-transport model (Rajapakse, Inomata,

& Fukami, 2010), direct computation of groundwater outflow to rivers, simulation of multi-layered aquifers, as well as simulation of infiltration trenches, were developed. WEP model has been successfully applied to river basins in Japan, Korea and China (Cunwen et al., 2011; Jia et al., 2001a, 2001b; Jia, Niu, & Wang, 2007; Rajapakse et al., 2010). For the detailed description of model development, hydrologic and material transport modeling procedures and input/output data, one is referred to Jia et al. (2001a, 2001b, 2005) and Rajapakse et al., (2010).

Therefore, this study incorporated the Water and Energy Transfer Processes (WEP) model to assess the water resources and pollutant transport of the catchment concerning the present status and six possible future scenarios.

1.2 Identified Research Gap

1) Even though several studies have been undertaken on the water quality parameters in few locations of the water of the North Central Province of Sri Lanka, none have been conducted to quantitatively study and analyse the effects of particulate matter pollution in those waters. Most of the researches that have been completed thus far related to this topic are qualitative in nature. This study will set the baseline for commencing and continuing quantitative studies regarding the effects of particulate matter pollution in those waters.

2) No studies have been done to study the conveyance, spatial and temporal accumulation patterns of pollutants after they have been added to the waterways, in the North Central Province of Sri Lanka.

3) No distributed hydrological model analysis has previously been conducted on the Nachchaduwa watershed, to gain a better insight to the behaviour of the water quantity and quality.

4) Not enough studies have been accomplished, in order to regulate the over-usage of agrochemicals and fertilizers or to develop a guideline to the proper usage of fertilizers in that area.

5) Particulate matter pollution density maps for the waters in that region has not yet been developed. They could be used to find out whether the excessive usage of

agrochemicals has a correlation with the non-communicable diseases prevailing in those areas.

6) Based on the findings of the study, water resources management alternatives and measures to address issues related to the degrading water quality in the basin, due mainly to excessive use of agro-chemicals, can be recommended.

1.3 Problem Statement

The Nachchaduwa sub-catchment of the Malwathu Oya river basin is known to undergo intermittent floods in the downstream areas during monsoon seasons, and it is seasonally stressed due mainly to over exploitation and water pollution in the dry periods. In addition, the fate and behaviour of nutrient elements (Nitrogen and Phosphorous) which are added to the waterways as a result of the excessive use of agrochemicals/chemical fertilizers in paddy lands and other crop areas in the upstream catchment area, remain unresolved.

Therefore, water resources management alternatives (to overcome issues occurring due to spatial and temporal variations, climate change impact, etc.) and measures to address issues related to degrading water quality (caused due to excessive use of agro-chemicals) in the basin should be studied, while the fate of pollutants including their conveyance and spatial and temporal accumulation patterns should also be investigated.

1.4 Objectives

1.4.1 Overall objective

To study about the present status of water resources management and material (pollutant) transport in Malwathu Oya basin (Nachchaduwa sub catchment), the effects of impending climate change impacts on them, and the options for better water resources management and fertilizer usage (material transport), using the Water and Energy transfer Processes (WEP) model.

1.4.2 Specific objectives

1) Better understanding of the current status of the Nachchaduwa catchment by reviewing the water resources management and the material transport aspects of the catchment.

2) Get a better insight about the available distributed hydrological and material transport models and selecting a suitable model for the catchment, its applications, and its applicability to the present study.

3) Compiling a state-of-the-art database of the data relevant to the hydrological and material transport aspects of the catchment to identify model parameter values, and to prepare input files for the model runs.

4) Comprehend the present condition of the catchment by application of the model (analysis), including initial trial runs, calibration and validation.

5) Predict the probable future conditions by conducting scenario analyses using the model (considering water resources and fertilizer management options and impending climate change impacts) and obtaining results (considering the hydrological part and the material transport part).

The following scenarios will be analysed by using the developed (validated) model (more details of scenarios and how these numerical values are obtained have been described in the literature review).

(i) Fertilizer: Reducing the applied fertilizer inputs by 25%
(ii) Fertilizer: Reducing the applied fertilizer inputs by 50%
(iii) Fertilizer: Reducing the applied fertilizer inputs by 75%
(iv) Climate change: All rainfall values increased by 14%
(v) Climate change: Only extreme rainfall values increased/decreased by 5%
(vi) Climate change: All temperature values increased by 1.6 ˚C

6) Recommending and publishing suitable water resources management and fertilizer usage practices for the catchment (Best Management Practices) for the better awareness of the scientific community and the stakeholders involved.

1.5 Outline of the Thesis

Chapter One is the Introduction which describes the overview of the study, research gap, problem statement and the objectives of the study.

Chapter Two is the Literature Review which sheds light into the present status, water resources management, and water quality of the Malwathu Oya basin, followed by aspects of water quality monitoring, importance of physics based modelling for river basin management, fertilizer over usage of the basin as well as the climate change impacts.

Chapter Three is Materials and Methods which illustrates the methodology, data and data checking/data pre-processing procedures followed by the WEP model analysis in detail, which can further be categorised into three main analysis components of this study; developing the state-of-the-art database, experimental field analysis, and the distributed modelling analysis component.

Chapter Four is Results and Discussion, which elucidates the WEP model results for the present condition, sensitivity analysis results as well as the scenario analysis results, along with the discussion of the said results.

Chapter Five is Conclusions and Recommendations, which elaborates the conclusions obtained by this study, summarises the findings and gives recommendations for future studies.

2 LITERATURE REVIEW

Literature review sheds light into the present status, water resources management, and water quality of the Malwathu Oya basin, followed by aspects of water quality monitoring, importance of physics based modelling for river basin management, fertilizer over usage of the basin as well as the climate change impacts.

2.1 Overview and Present Status of the Malwathu Oya Basin

Malwathu Oya has the second largest catchment area (3284 km^2), among the river basins in Sri Lanka. Malwathu Oya originates at an elevation around 304.8 m MSL, east of Madatugama from Inamaluwa mountain range (Figure 2.1).

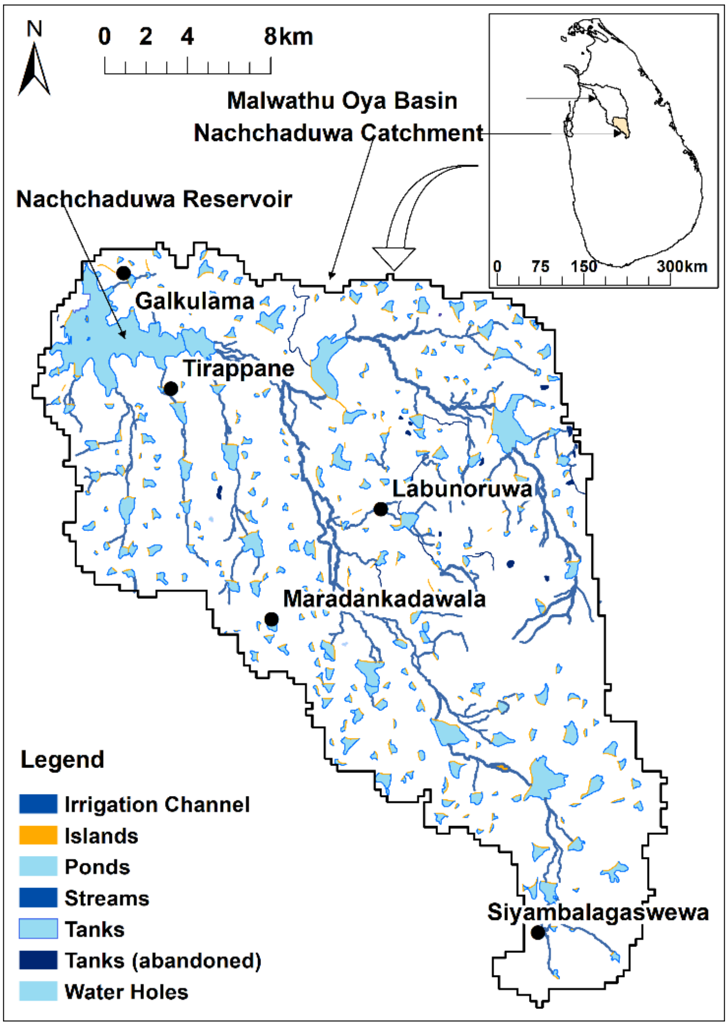


Figure 2.1: Nachchaduwa Catchment and the Malwathu Oya Basin (original in colour)

Except for the headwater area, the Malwathu Oya catchment is rather flat or slightly rolling with some isolated hills. Apart from paddy fields, the catchment area is covered with shrubs, some forests and non-irrigated plots. Malwathu Oya starts after confluencing Maminiya Oya and Horiwila Oya which are located on the Northern side and Southern side of Ritigala mountain respectively. Bellan Oya joins Horiwila Oya further up and it flows from the furthest end of Malwathu Oya. The major right bank tributary of the Malwathu Oya is the Kanadara Oya which confluences with Malwathu Oya after passing Anuradhapura at approximately 3.5 km upstream of the Kappachchi river gauging station. Kanadara Oya has its headwaters in the area of Weddakanda mountain and the chain of hills which forms Northern boundary of the Malwathu Oya basin closer to Vavuniya. Malwathu Oya is called as Aruvi Aru after it joins with Kal Aru and Nariwilli Aru which starts from Weddakanda and Medawachchiya area respectively. Further down along the Aruvi Aru, Tekkam Anicut is located and water is headed up by this structure to augment the Giants Tank and Akathimuruppu Tank which are located in minor coastal basins sandwitched between Malwathu Oya and adjacent major basins viz: Moderagam Aru in the south and Parangi Aru in the north (Department of Irrigation, n.d.).

2.2 Water Resources Management in Malwathu Oya

Majority of the upper catchment area which accounts to about 70% of the total basin area lies in the Anuradhapura district while lower catchment areas are in the Vavuniya and Mannar Districts in the Northern Province. Though upper catchment of Malwathu Oya is intercepted by major reservoirs (1) Nachchaduwa, (2) Mahakanadarawa, (3) Pavatkulam, (4) Nuwara wewa, and (5) Tissa wewa, the lower catchment is not regulated at all. However, the Tekkam anicut is located about 36 km upstream of the sea coast and augments reservoirs located in the adjacent coastal basins, namely, the Giants tank and the Akitamuruppu tank in the right bank and left bank, respectively. During dry weather period, base flow of Malwathu Oya is shared between the right bank and left bank main canals of the Tekkam Anicut and there is hardly any flow downstream along Malwathu Oya. However, during the rainy season, vast amount of water flows over the Tekkam anicut and discharges to sea while two irrigation areas located adjacently suffer due to inadequate irrigation water for cultivation during dry weather period specifically in Yala Season (Department of Irrigation, n.d.).

Irrigation Department has attempted to regulate the Malwathu Oya, upstream of Tekkam Anicut at Kappachchi, around 1958 through the technical assistance of United States of Soviet Republic. The objective of developing the proposed Malwathu Oya reservoir was to control floods in the downstream and provide irrigation water for 12 950 ha (32 000 acres) of lands which includes 8 094 ha (20 000 acres) of existing irrigation areas under Giants tank and Akitamuruppu tank (Department of Irrigation, n.d.).

Further, under Mahaweli Master Plan, in addition to augmenting the water resource in Malwathu Oya basin (System I) through North Central Province trans basin (NCP) canal, it was planned to develop the in-basin water resources through constructing the lower Malwathu Oya reservoir upstream of Tekkam Anicut to consolidate existing irrigation areas under Giants Tank and Akitamuruppu Tank together with the development of new irrigation areas (Department of Irrigation, n.d.).

In order to assess the hydrological characteristics of the Malwathu Oya cascade, Gunarathna and Kumari (2014) have conducted a detailed study, which found that there are around 180 cascade systems in Malwathu Oya basin which belongs to 15 sub catchments. Malwathu Oya main cascade, being a branched type large cascade has a form index of 3.6. The cascade has an area of 25.88 km^2 and a length of 7.1 km. Total water spread area of the tanks is 2.57 km^2 and the total commanding area of the tanks is 2.81 km^2. Even though the availability of water in this cascade is sufficient for the irrigation requirement of the command area, few individual tanks (Kudawewa, Palugaswewa and Sattambikulama) showed inadequacy of storage capacity due to siltation. This has resulted in these tanks facilitating only for the Maha season and having inadequate irrigation water in the Yala season has become a pressing concern. Hence, these tanks should be given prior attention on rehabilitation (Gunarathna & Kumari, 2014).

Anthropogenic activities such as using the reservation areas of the tanks for farming and building houses, municipal garbage disposal, illegal gravel and sand mining have contributed to the deterioration of the Malwathu Oya main cascade. Further, the majority of tanks faced eutrophication and aquatic weeds namely *Salvinia molesta* and *Eichornia crassipes* were prevalent. The adjacent paddy cultivated areas showed high salinity levels due to not maintaining the Kattakaduwa tank reservation area which was dedicated for salinity management (Gunarathna & Kumari, 2014).

The issues and conflicts regarding the water resources management in this basin can be discussed under two main areas, one being inter sectoral and the other being intra sectoral. There are issues related to irrigation, industries, water supply as well as sanitation. Numerous institutions govern the water resources management at present but they lack proper coordination between them. A single organisation which would have the complete authorisation is vital for the better management of water resources. A lot of legal acts and regulations with various institutions are available but the responsibility of executing them is disputed. Irrigation sector water resources development was mainly undertaken by the Irrigation Department. Proper objective oriented water resources development programmes are needed. Integrated management of water, land and other natural resources in the Malwathu Oya basin could be achieved by involving and empowering all stakeholders, such as the government organizations, non-governmental organizations (NGO), and the people (De Alwis, 2006).

2.3 Water Quality in Malwathu Oya Basin

2.3.1 Water quality in streams in Malwathu Oya basin

The seasonal variation of water quality parameters in the upper part of Malwathu Oya from Ritigala to Nachchaduwa was studied (Perera et al., 2014) and the mean concentrations of NO_3^-, PO_4^{3-}, Cl^-, Dissolved Oxygen (DO) and turbidity were found to range from 1.05~5.28 mg/l, 0.004~0.043 mg/l, 2.63~8.72 mg/l, 3.11~8.50 mg/l, 81.75~256.10 NTU, respectively. Notably inflated concentrations of NO_3^-, PO_4^{3-}, Cl^- were observed in streams in the paddy cultivated areas of Malwathu Oya, and the concentration levels followed a bimodal pattern which coincided with the cultivation pattern in the dry zone. In the northeast monsoon season (December – February) the highest mean Dissolved Oxygen (DO) and turbidity values were observed. With respect to DO and turbidity, the paddy and no-paddy areas did not show a significant difference. The chemical fertilizer application in the paddy cultivation was found to cause the statistically significant seasonal variations observed in the water quality parameters.

Higher values of Nitrogen were recorded in the First Inter Monsoon Season (FIMS) when the Yala cultivation season (April to September in dry season) begins and in the Second Inter Monsoon Season (SIMS) where the Maha cultivation season (October to March in rainy season) begins. However, the study found that the lowest NO_3^- values occurred in the South West Monsoon Season (SWMS) where there is lesser rainfall to the dry zone of the island, and the cultivation activities are minimum (Perera et al., 2014).

The study suggested that the rate of PO_4^{3-} movement could be affected by land preparation carried out for agricultural activities. The low values of PO_4^{3-} were attributed to the adsorption by clay particles or precipitation with calcium, as well as due to absorption by plants. According to Perera et al. (2014), none of the water samples of Malwathu Oya exceeded the World Health Organisation (WHO) recommended PO_4^{3-} level (2 mg/l) for drinking water (World Health Organisation [WHO], 2011). The higher Cl^- values were possibly due to high Cl^- containing water of Nachchaduwa and runoff water due to heavy rains. However, the NO_3^-, PO_4^{3-}, Cl^-, DO were within the threshold limits for drinking purposes, but the DO level in SWMS was unfavourable for most aquatic fauna including the fish.

According to Madushanka et al. (2015), Malwathu Oya had significantly different Electrical Conductivity (EC), NO_3^--N and PO_4^{3-}-P values, before and after passing the Anuradhapura city. The NO_3^--N level difference implied that a high dosage of N compounds were added to the river within the city area, mostly as fertilizers used on the agricultural areas nearby. The TDS values ranged between 255~731 mg/l and the outlet stream (Malwathu Oya after passing the city) showed poorer values than the inlet stream, for all the water quality parameters [Total Dissolved Solids (TDS), pH, EC, DO, PO_4^{3-}, NO_3^-, K^+, and faecal coliform colonies (total coliform and e-coli)], affirming the impact of urban land use and municipal/industrial effluents, on water pollution.

However, the pH values of all sampling points were within the recommended levels indicated by WHO (2011) and Central Environmental Authority (CEA) (2001). Madushanka et al. (2015) states that the maximum EC and TDS values acceptable for irrigation and agriculture are 0.7 $mScm^{-1}$ and 500 mg/l, respectively, according to CEA (2001). The standard value of PO_4^{3-}-P in municipal wastewaters is between 4~16 mg/l, according to Tchobanoglous, Burton, and Stensel (2003). Therefore, the water quality parameters of most of the samples were within the acceptable limits.

Zoysa and Weerasinghe (2016) found that the surface of Malwathu Oya was covered with higher plants, even in the dry seasons, establishing that the river water had high nutrient content, supporting the growth of plants. Further, this study stated that the river had reached eutrophic level. The river showed very high values of NO_3^- in April, June and August, with the highest NO_3^- concentration of 15 mg/l in August, compared to the reservoirs in the basin. According to the Sri Lanka Standards (SLS) tolerance limits for inland surface waters used as raw water for public water supply (Sri Lanka Standards [SLS] 722, 1985), the NO_3^--N concentration should be less than 10 mg/l. Therefore, Malwathu Oya water had exceeded the standard value for its water to be used as a water supply source. The river had significantly high concentrations of total coliforms, with the maximum value of 6 000 colonies/100 ml in June, exceeding the tolerance limit given in SLS 722 (1985) which is 5 000 colonies/100 ml. The WHO (2011) drinking water guideline specified that drinking water should not have total coliforms (0 mg/l), therefore, Malwathu Oya stream did not comply with the stipulated water quality standard values. In Anuradhapura area, the surface water had higher values for colour and turbidity than groundwater. Average turbidity and colour values increased by 50 NTU and 200 pt/Co units, respectively, during August (Zoysa & Weerasinghe, 2016).

2.3.2 Water quality in reservoirs in Malwathu Oya basin

The Malwathu Oya basin is distinct as it possesses a large number of tanks (irrigation reservoirs), from small size village tanks to comparatively fair-sized tanks, from which the rainfall runoff process is largely influenced. The main reservoirs in the basin are, Nachchaduwa (reservoir area 1781 ha), Nuwara wewa (reservoir area 1214 ha), Mahakanadarawa wewa (reservoir area 1457 ha) and Tissa wewa (reservoir area 182 ha), which are mainly used for irrigation purposes and drinking water supply. Reservoir water quality results of few studies have been summarised in Table 2.1.

Silva (2004) stated that the reservoirs in the Malwathu Oya basin had high Sodium Absorption Ratio (SAR) values and relatively high Cl^- and SO_4^{2-} concentrations. Analysis of long term trends of water quality found that the annual ranges of EC were relatively high in Nachchaduwa and Tissa wewa, compared to those of the other reservoirs studied. With respect to irrigation-related water quality of the reservoirs, Nachchaduwa and Nuwara wewa exceeded the threshold value of EC (0.750 mS/cm) and salinity (0.500 g/l). Although the reservoirs in the Malwathu Oya basin receive water from the Mahaweli river, the amount of water received may not be adequate to reduce the salt content to the acceptable range. These high values of salinity could affect the agriculture in the area in an adverse manner.

The spatial and temporal variation of NO_3^--N, PO_4^{3-}-P, K^+ and Cd^{2+} in Meegasagama, Alistana, Thirappane reservoirs (which belong to the Thirappane tank cascade of the Malwathu Oya basin) and Mahakanumulla, Amanakkatuwa, Siwalagala reservoirs (which belong to the Mahakanumulla tank cascade of the Malwathu Oya basin) (refer Figure 1.1), along with the drain channel of rice cultivated tracks between those reservoirs were studied (Wijesundara, Nandasena, & Jayakody, 2012, 2013). The two studies found that NO_3^--N, PO_4^{3-}-P, K^+ and Cd^{2+} gradually increased from the upper reservoir to the lower reservoir in both cascades, due to the gradual accumulation of nutrients from the applied fertilizers in paddy fields in the command areas of the reservoirs. The nutrients added to the reservoirs were adsorbed to sediments or washed with runoff. This trend was mainly observed during the rainy period resulting in higher runoff with the nutrients entering into the reservoirs. In the dry period, this trend was not observed due to the lesser runoff volume and due to being restrained by the plants in the river banks. All nutrient concentrations of these reservoirs and channels showed a bimodal pattern correlating with the bimodal rainfall pattern of the region. In both studies, the highest concentrations of all nutrients occurred in April and May in the Yala season, just after the application of chemical fertilizers, and then they gradually decreased.

Table 2.1: Water Quality in Reservoirs in Malwathu Oya Basin

Parameter	Nachchaduwa	Nuwara Wewa	Tissa Wewa	Mahakana--darawa	Thirappane Tank Cascade	Mahakanumulla Tank Cascade	Reference
pH	6.89~8.50	7.30~8.60	7.84~8.22	-	-	-	Silva (2004)
EC (µS/cm)	240~695	290~840	180~635	-	-	-	
Salinity (mg/l)	569	532	388	-	-	-	
Sodium Absorption Ratio (SAR) at high water level	1.144	1.229	1.245	-	-	-	
Sodium Absorption Ratio (SAR) at low water level	2.627	2.143	1.736	-	-	-	
Cl$^-$ (mg/l)	56~151	46~81	34~42	-	-	-	
SO$_4^{2-}$ (mg/l)	4.2~38.2	5.49~8.52	4.72~7.56	-	-	-	
NO$_3^-$-N (mg/l)	-	-	-	-	2.34~6.98	2.17~4.87	Wijesundara et al.(2012, 2013)
PO$_4^{3-}$-P (mg/l)	-	-	-	-	0.004~0.130	0.009~0.050	
K$^+$ (mg/l)	-	-	-	-	2.01~8.16	2.14~8.61	
Cd^{2+}	-	-	-	-	-	0.09~0.33	
Turbidity (highest value recorded) (NTU)	22	32	25	17	-	-	Zoysa and Weerasinghe (2016)
Chlorophyll-a concentration (highest value recorded) (µg/l)	less than 10	100	90	less than 10	-	-	
Algae population (highest value recorded) (colonies/ml)	less than 20,000	more than 20,000	more than 20,000	less than 20,000	-	-	

Since the lower parts of the cascade contained excessive amounts of nutrients, the fertilizer application of the area should be controlled, by considering the soil conditions and the washed-out amounts of nutrients in the irrigation (drain) water from the paddy fields (Wijesundara et al., 2012, 2013). Figure 2.2 illustrates the temporal variation of NO_3^- and PO_4^{3-} in all six reservoirs studied by Wijesundara et al. (2012, 2013), with the monthly rainfall (mm). Figure 2.3 illustrates the spatial variation of NO_3^- and PO_4^{3-} in each reservoir studied by Wijesundara et al. (2012, 2013). In Figure 2.2 and Figure 2.3, the boxes are bounded by 25th and 75th percentile values while whiskers represent minimum and maximums, and the horizontal line within the boxes denote the median of the data.

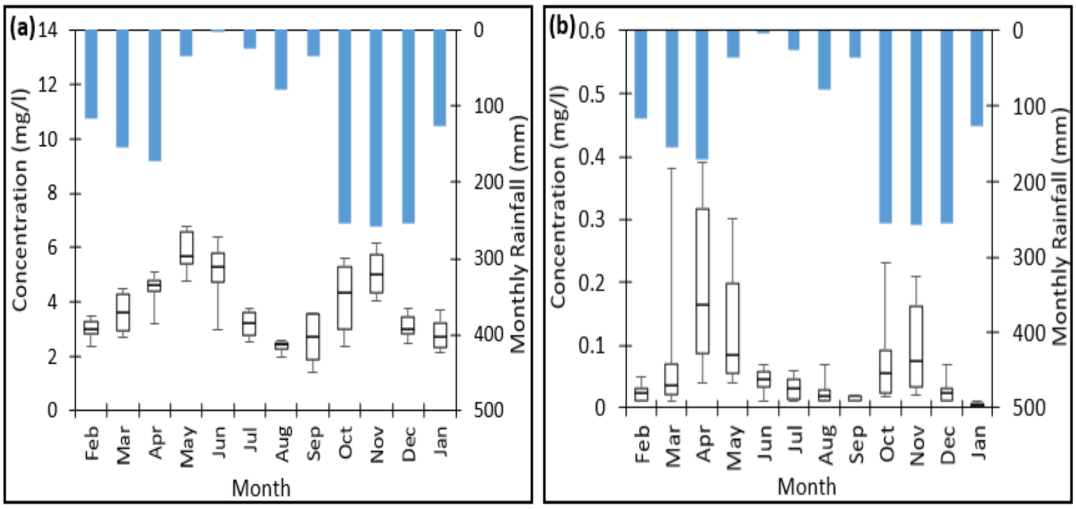


Figure 2.2: (a) The Temporal Variation of NO_3^- in all Six Reservoirs Studied by Wijesundara et al. (2012, 2013) (b) The Temporal Variation of PO_4^{3-} in all Six Reservoirs Studied by Wijesundara et al. (2012, 2013)

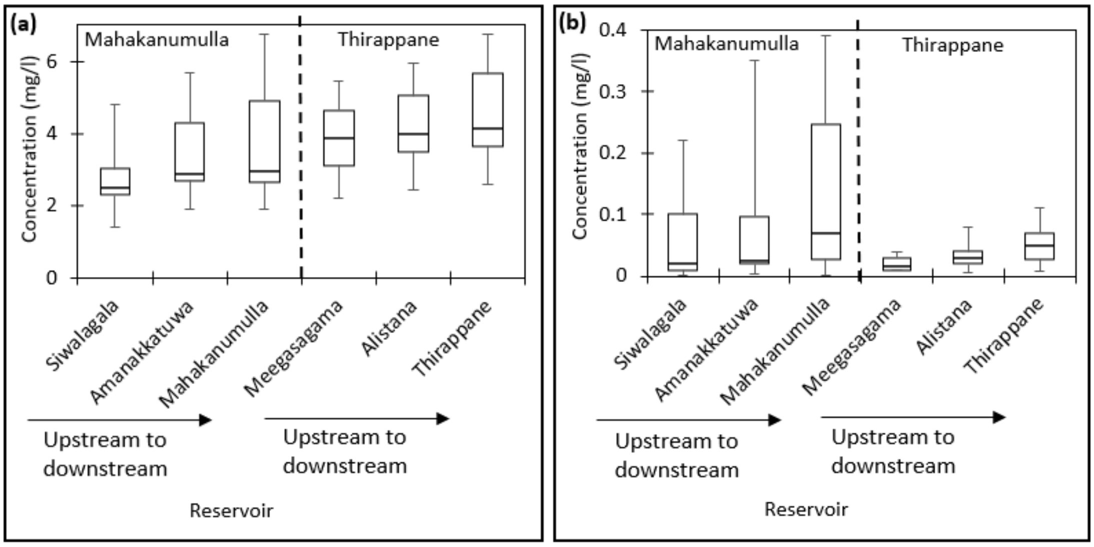


Figure 2.3: (a) The Spatial Variation of NO_3^- in Each Reservoir Studied by Wijesundara et al. (2012, 2013) (b) The Spatial Variation of PO_4^{3-} in Each Reservoir Studied by Wijesundara et al. (2012, 2013)

Zoysa and Weerasinghe (2016) conducted a study to evaluate water quality in Nuwara wewa, Tissa wewa, Nachchaduwa wewa and Mahakanadarawa wewa and stated that eutrophication caused by the nutrient accumulation in stagnant waters in these reservoirs was mainly due to the urbanisation and extensive use of agro-chemicals. Although Nuwara wewa and Tissa wewa showed high values for all water quality parameters [colour, turbidity, temperature, pH, alkalinity, NO_3^- and PO_4^{3-}, total coliforms, total algae population, chlorophyll-a content, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)] due to anthropogenic activities, Nachchaduwa and Mahakanadarawa reservoirs which are located far from the city with not much anthropogenic activities affecting their water quality remained within the safe limits.

In another study, ten small tanks in Malwathu Oya main cascade were analysed for DO, turbidity, pH, EC, NO_3^--N, PO_4^{3-} and Na^+. The Water Quality Index (WQI) developed by the Canadian Council of Ministers of the Environment (CCME) values of the dry and wet seasons showed that Malwathu Oya reservoir water quality was in ‘poor’ condition for drinking, fish & aquatic life, irrigation & agriculture, whereas it was in ‘marginal’ quality for recreational use (Gunarathna & Kumari 2016).

2.3.3 Groundwater quality in Malwathu Oya basin

Groundwater sources in Anuradhapura consist of natural springs, agro-wells, farm wells, domestic and home garden wells, etc. In a study conducted to analyse the water quality of 24 natural springs in the Anuradhapura district, it was found that the total hardness varied between 20~130 mg/l, not exceeding the maximum desirable value of 250 mg/l given in SLS Specification for Potable Water - Part 1: Physical and Chemical Requirement (SLS 614, 1983). Total alkalinity ranged from 10.7~240 mg/l, and more than 96% of the springs were below the maximum desirable value of 200 mg/l (SLS 614, 1983). The Mg^{2+} concentrations varied between 2.0~10.9 mg/l, and were well below the maximum permissible value of 30 mg/l (SLS 614, 1983). The NO_3^- and PO_4^{3-} concentrations were between 0~10 mg/l and 0~0.4 mg/l, respectively, which were below the maximum permissible values of 10 mg/l and 2 mg/l, respectively (SLS 614, 1983). The Fl^- varied within 0.01~0.40 mg/l and was below the maximum value 0.6 mg/l (SLS 614, 1983). In addition, the study confirmed that turbidity, pH, EC, TDS, Ca, Fe, Cl, SO_4^{2-} and Salinity were within the limits specified by SLS for drinking water. Since the rural areas of the district have limited access to pipe-borne water, water from natural springs could be recommended as an alternative source for drinking water (Ratnayake, Gonawela, & Wijekoon, 2012).

Kumari, Pathmarajah, Dayawansa, and Nirmanee (2016) analysed 20 shallow agricultural wells in the Malwathu Oya basin for their groundwater quality for irrigation. The pH values of the 20 agro-wells had high values in dry seasons and low values with the beginning of rainfall, in all land use patterns. The possible combination of rainwater with the atmospheric CO_2 in the rainy season would result in reducing the pH in groundwater which is being recharged from rain. All the wells were within the acceptable pH limits suitable for irrigation water in all months. With respect to NO_3^--N, 85% of wells had concentrations between 0~5mg/l [no restriction for irrigation according to Ayers and Westcot (1985)], where the remaining were between 5~30 mg/l [slight to moderate restriction for irrigation according to Ayers and Westcot (1985)], during pre-monsoon period. During post-monsoon period, NO_3^--N has increased in all wells. Further, the farm wells situated in highland paddy areas have recorded high NO_3^--N values than domestic wells. With respect to NH_4^+-N, 90% of wells had

0~5mg/l and the remaining had 15~20 mg/l in the pre-monsoon period. The concentrations increased with the rainy season, possibly due to waste from livestock, excessive fertilizer usage and leaching of rainfall. Two of the wells showed As concentration of 0.001 mg/l, not exceeding the threshold value for irrigation 0.1 mg/l (Ayers and Westcot, 1985). Cd or Pb were not detected in any of the wells. With respect to EC suitable for irrigation, 5% of wells had ‘excellent’ [100~250 µS/cm, Wilcox (1955)], 35% of wells had ‘good’ [250~750 µS/cm, Wilcox (1955)], and 60% of wells had ‘doubtful’ [750~2250 µS/cm, Wilcox (1955)] water quality, thus confirming the need for salinity control in groundwater.

Regarding average Na%, 35% of wells had ‘excellent’, 60% had ‘good’, and 5% had ‘permissible’ irrigation water quality. The Na% was higher in farm wells (paddy), than farm wells-upland and domestic and home garden well types. In the dry season, all wells had SAR between 0~4 except 3 wells. Further, 95% of wells had SAR below 4 and 5% of wells had SAR between 4~8, in the post-monsoon period. Hence, the groundwater is acceptable for irrigation, according to the classification given by Richards (1954), which states that SAR values between 0~10 as ‘excellent’. The average values of Residual Sodium Carbonate (RSC) were within the acceptable range for irrigation in the pre and post-monsoon periods [RSC<1.25 meq/l is classified as ‘safe’ and RSC 1.25~2.5 meq/l is classified as ‘marginal range’, Eaton (1950)]. Unlike all the other water quality parameters, RSC values showed a significant statistical difference between pre and post-monsoon seasons (Kumari et al., 2016).

The suitability of groundwater for irrigation according to the US salinity diagram was found and 5% of wells showed low salinity and low sodium (C1S1), 35% showed medium salinity and low sodium (C2S1), and 60% showed high salinity and low sodium (C3S1). Then, 35% of the wells were classified as ‘good’ for irrigation during the pre-monsoon season and 45% during the post-monsoon season (Kumari et al., 2016).

2.4 Review of the Current Status in Malwathu Oya Basin

According to the studies that were reviewed, the water quality in Malwathu Oya river basin is progressively deteriorating. The lack of continuous monitoring of the water quality and scarcity of comprehensive water quality data is severely affecting the studies of the water quality issues as well as in determining the preceding causes. Even the already available data are scattered and they are not systematised to be effectively used in decision making. Reliable, continuous and comprehensive data to determine the spatial and temporal variations of the water quality and the degree of pollution are not readily available. As a favourable improvement in river basin management efforts, several governmental organizations have recently established over 349 Hydro-meteorological Management Information System (HMIS) stations (automated weather monitoring stations) in few of the main river basins in Sri Lanka (Mahaweli, Kelani, Iranamadu and Kanakayaaru). Although the water quality data are monitored in the inlets of the drinking water sources by the National Water Supply and Drainage Board of Sri Lanka, most of the other water resources remain not monitored at all.

Further, the health risks associated with the pollution in river water is becoming a major concern in Sri Lanka (e.g. the CKDu prevailing in the North Central Province, where the consumption of water which has been polluted by the over usage of agro-chemicals and fertilizers in those areas is suspected to be a major cause). The already available water quality data are obtained via numerous different methods and they are inconsistent, making them futile in being used as a baseline information in studies. Hence, establishing monitoring programmes, at least for a set of selected water bodies which represent all types of aquatic ecosystems in Sri Lanka while developing meticulous methods to measure water quality, is of paramount importance (Silva, 1996).

Water quality related issues such as eutrophication, water logging and siltation, increase in organic residues, salination and exposure to hazardous chemicals generated by the untreated industrial effluents added to the surface water bodies are caused as a result of anthropogenic activities such as urbanization and related sewage/waste water discharge, land use modifications, excessive use of agrochemicals and fertilizers in agricultural practices, untreated industrial effluents being added to the waterways. In addition, the leachate of the municipal solid waste dumps might penetrate to the nearby water sources, further reducing the quality of the water.

2.5 Water Quality Monitoring for River Basin Management

According to Chapman (1996), water quality monitoring can be differentiated into long-term, short-term and continuous monitoring as follows.

1) Monitoring is the long-term, standardised measurement and observation of the aquatic environment in order to define status and trends.
2) Surveys are finite duration, intensive programmes to measure and observe the quality of the aquatic environment for a specific purpose.
3) Surveillance is continuous, specific measurement and observation for the purpose of water quality management and operational activities.

Physical, chemical and biological characteristics of data should be collected to the purpose of water quality management. The pollution of water, water usage and abstraction practices, and land use practices (agriculture etc.) must be included for proper water quality management. Water quality data will be useful not only for the pollution control, but also for identifying long term trends in pollution and for assessing the environmental impacts (Bartram and Ballance, 1996).

According to Strobl and Robillard (2007), a properly designed water quality monitoring network identifies water quality problems while establishing baseline values for short and long-term trend analysis. The need to evaluate observed water quality conditions and their suitability for the intended uses reflect a need for cost-effective and logistically practical water quality monitoring network. There are many variables that need to be included in a comprehensive and practical monitoring network including, a holistic appraisal of the monitoring objectives, representative sampling locations, suitable sampling frequencies, water quality variable selection, and budgetary and logistical constraints (Strobl and Robillard 2007).

2.6 Importance of Physics based Modelling for River Basin Management and Selection of the WEP (Water and Energy transfer Processes) Model for the Analysis

A hydrological and substance cycle analysis model is a collection of movement phenomena of water on the ground surface or the underground, expressed as equations or numerical values and provides response to rainfall or other types of input in that basin (Hydrologic Engineering Research Team [HERT], 2012).

The temporal and spatial fluctuations of all variables included in mathematical equations of water flows in watersheds could be considered by mathematical distributed hydrological models. The employed parameters being physically measurable is another advantage. Hence, such models are able to provide a comprehensive and a more accurate depiction of the hydrological processes in a watershed than empirical and conceptual hydrological models. There are a number of omnipresent models of this type, like SHE, SWAT, IHDM, MIKE SHE (Jia, Ni, Kawahara, & Suetsugi (2001b) and Water and Energy Transfer Processes (WEP) model (Jia, Ni, Kawahara, & Suetsugi, 2001a). Details of the three models; SWAT, ANSWERS and SHETRAN, which support almost the same analytical elements as the WEP model, are summarized hereafter.

The SWAT model is a time-series model which gives daily results related to the convection and accumulation of water, soil particles and chemical substances in large-area basins with no actual measurement data. The SWAT model has the following features:

1) The model is based on physical considerations.
2) It uses easily obtainable data
3) Its computational efficiency eradicates the need for a longer computational time, even for larger basins.
4) Simulations could be conducted over extended durations, making it possible to analyse the long-term effects of management changes.

The surface runoff and substances in a basin need to be defined by a certain number of elements. These settings include the path from a source of water to a water flow, a flow volume, monitoring data, and point source load, etc. The model computes on a day-to-day basis and can perform simulations for periods more than one year, in a relatively short length of time (HERT, 2012).

The ANSWERS-2000 model primarily focuses on assessing the effect of Best Management Practices (BMP) in urban and cultivated areas, while trying to reduce the transport of sediment and nutrients into waterways through surface runoff or nitrogen leaching through plant root layers. The model can be used on catchments where Physically Based Spatial Distributed (PBSD) calibration data cannot be used and monitoring has not been conducted. ANSWERS-2000 is a distributed (grid-based) model which has an area less than or equal to 1 ha, but it considers all parameters are uniform throughout each grid cell (eg. soil characteristics above and below the ground, vegetation, surface conditions, management of crops, and climate). The model computes that the runoff occurs in time steps of 30 seconds and it considers time steps of one day between runoff occurrences. It is capable of analysing interception, surface detention, infiltration, percolation, adsorption and conveyance of sediment containing particles of different sizes in small streams, areas between small streams, and water channels, growth of crops, uptake of nutrients by plants, dynamics of N and P in soil, nitric acid leaching, and loss of nitric acid, ammonium, total Kjeldahl nitrogen, and phosphorus in surface runoff affected by soil, nutrients, covers, and hydrological conditions. The model is equipped with a graphical user-friendly interface based on ArcView (HERT, 2012).

The SHETRAN model integrates a catchment’s water flows with the conveyance of pollutants in both the dissolved and particulate forms. It can simulate flows and material transport in three dimensions, in basins where the area is less than 5 000 km^2. The grid-based model uses 3D grids, and storage and movement of water, sediment, and dissolved substances are expressed as conservation equations of flows and transport by the difference approximation method. The model is capable of analysing rainfall interception by plants, evaporation and vapor, accumulation of snow and snowmelt, flow in land and water channels, differently saturated intermediate flows, and interaction between rivers and aquifers. The dynamics of N could be modelled in 3D with the integration of flows and transport of nitric acid. Further, the transport of nitric acid was modelled as a convection dispersion equation with terms for adsorption and 2 areas (dynamic area and dead space). Nitrogen changes that occur in the plant root layer or below could be modelled by NITS, which is a component of SHETRAN for nitric acid analysis (HERT, 2012).

A comprehensive energy balance was integrated in hydrological modelling for the WEP model, which was developed by Jia and Tamai (1998). Simulation of multi-layered aquifers and infiltration trenches, direct computation of groundwater outflow to rivers, were also added to the model later. The model uses meteorological, geographical, hydrological data and, data relevant to anthropogenic activities and water quality simulation processes, as inputs. The model is capable of providing time series values of water and heat balance as well as water quality/material transport results for each grid, as outputs. Its main differences from other physics-based models involve the following factors.

1) Apart from the hydrological processes a comprehensive energy balance analysis is also performed. This model augments the calculation of interception and evapotranspiration due to its detailed consideration of heat flux partitions on land surface. And the model could be easily coupled with atmospheric models.
2) The mosaic method, which is more reasonable especially in urbanized area with complex land covers, than the dominant land use method, is used to incorporate the sub grid heterogeneity of land use in the WEP model.
3) In order to save the calculation time, simulation of infiltration and infiltration excess during heavy rains is accounted by the generalized Green-Ampt model.
4) The effect of infiltration trenches on the hydrological cycle could be studied as they are simulated in the model.
5) Compared to the WEP model, many models are inadequate in consisting of mere conceptual models or take Nitrogen, Phosphorus, suspended solids, and some other substances into account but do not consider whether they are in a suspended state or in a dissolved state. The WEP model can therefore incorporate elements that many other models do not take into account.

Thus, the spatial and temporal variation of water and energy processes in watersheds with complex land covers could be modelled by the WEP model. The mathematical equations and methods used in the WEP model are tabulated in Table 2.2. In addition, anthropogenic components such as; water supply, groundwater lift, sewerage drainage and energy consumption, etc. are also taken into account (Jia et al., 2001a).

The WEP model was applied to the Ebi River watershed (27 km^2) with a grid size of 50 m and a time step of 1 h, where observed river discharges, groundwater levels and land surface temperatures were used for verification (Jia et al., 2001a). The model has also been successfully applied to the Haihe River Basin, China (Cunwen et al., 2011). This has also been used to simulate both hydrological processes and accompanied pollutant transfer processes in the Yellow River Basin, China (Jia et al., 2007) as well as the Yata River Basin, Japan (Rajapakse et al., 2010).

In order to analyse the particle-bound pollutants (N and P), the WEP model was enhanced by incorporating a soil erosion-transport model. In the study of Rajapakse et al. (2010) the model was used in the Yata River Basin, Japan, with the N and P components simulated by a discharge-based process. Land use, plant acreage, fertilizer loading, plant nutrient uptake and crop harvest in respective administrative units of the basin were used for validation purposes. The study found that the dissolved N (DN) component could be successfully modelled, however, the particulate N and P (PN, PP), and dissolved P (DP) components were not satisfactorily simulated. A process-based sediment erosion, transport, and deposition were introduced to integrate the particulate nutrient conveyance as soil-absorbed constituents. Results showed that the particulate nutrient conveyance was correlated with the suspended solids in the waterways (Rajapakse et al., 2010).

Table 2.2: Mathematical Equations and Methods used in the WEP Model

Process Type	Process	Mathematical Equation/Method Used for the Simulation
Hydrological Processes	Evapotranspiration	Penman–Monteith equation
	Infiltration excess during heavy rains	Generalized Green–Ampt model
	Saturation excess during the remaining periods	Balance analysis in unsaturated soil layers
	Groundwater flow	A two-dimensional simulation of multi-layered aquifers (a quasi-3D simulation)
	River flow routing	Conducted for every tributary and a main river by using the kinematic wave method
	Overland flow	Simplified as lateral inflow to rivers because the concentration time is estimated to be shorter than the simulation time interval
Energy processes	Short-wave radiation	Based on observation or deduced from sunshine duration
	Long-wave radiation	Calculated according to temperatures
	Latent and sensible fluxes	Aerodynamic method
	Surface temperature	Force–restore method

The composition of the WEP model inside a grid cell is illustrated in Figure 2.4. The mean flows in a grid cell is composed of the areal average of water and heat fluxes from all land uses in that cell. Land use is further divided into sub groups as follows;

(1) Water body group

(2) Soil-vegetation group

  (i) Bare soil

  (ii) Tall vegetation (forest of urban trees)

  (iii) Short vegetation (grass or crops)

(3) Impervious area group

  (i) Impervious urban cover

  (ii) Urban canopy

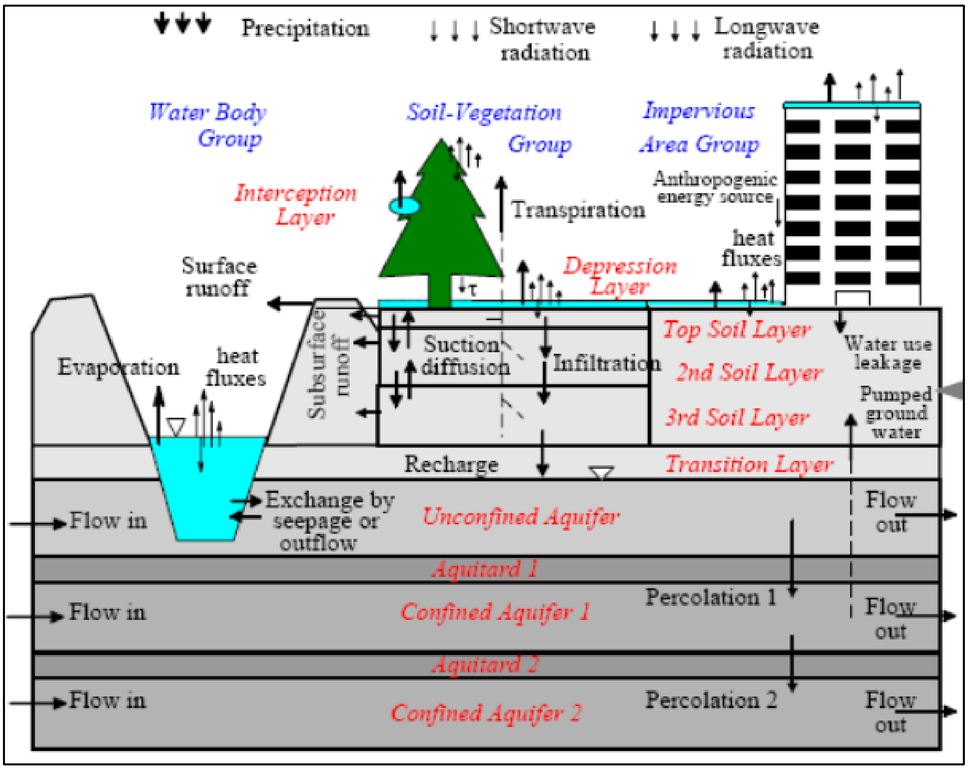


Figure 2.4: The Structure of the WEP Model - Vertical Structure within a Grid Cell (Rajapakse et al., 2010)

Nine vertical layers are incorporated in the WEP model for the soil-vegetation group which includes; an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer and two confined aquifers. The fraction of transmitted short-wave radiation of vegetation is used for the analysis of energy balance among soil and vegetation while the sky view factor of urban cover is used for the energy balancing of the urban cover and the urban canopy. The horizontal structure of the WEP model is shown in Figure 2.5 (Jia et al., 2001a).

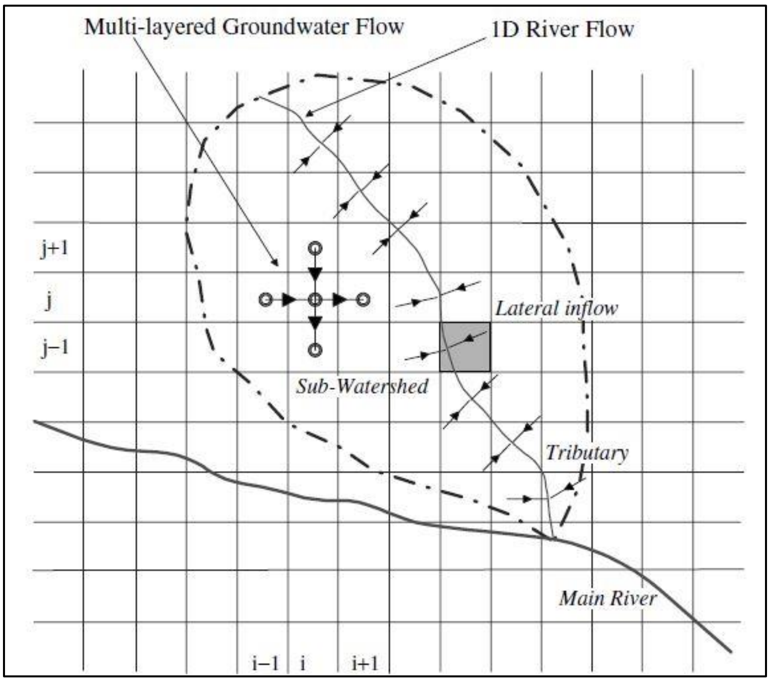


Figure 2.5: The Structure of the WEP Model - Horizontal Structure (Rajapakse et al., 2010)

2.7 Fertilizer Over Usage in the Basin

Sri Lanka has been a country which relied on agriculture as its main source of food, and agriculture has played a vital role in the country’s economy since ancient times. 1.7 million people in Sri Lanka are engaged in agriculture as their main livelihood. 37.4% of the land area which is suitable for cultivation has been used for agriculture. Agriculture accounts for 29% of the workforce and contributes about 10% of the country's gross national income (Central Bank of Sri Lanka, 2015). Majority of the people in the North Central Province still rely on agriculture as their main source of income. Excessive use of fertilizers for agricultural practices is causing the water resources of these areas to be heavily deteriorated.

According to the World Health Organisation representatives, the use of agrochemicals in Sri Lanka is 287 units per hectare. Accordingly, Sri Lanka has been named as the country that uses the largest amount of agrochemicals according to the country's land use ratios. The use of fertilizers and insecticides in Sri Lanka is reported to be high as well (Wijewardena, 2013). According to the reports of various social surveys, unfortunately, farmers actually use more than these recorded amounts of fertilizers, as well as they use even the banned types of agrochemicals (e.g. the Glyphosate usage in the era it was banned).

It has been found by the Government Analyst's Department of Sri Lanka that about 50% of the imported fruits in the general market have been contaminated by insecticides such as chlorpyrifos and profenofos which are both banned chemicals in Sri Lanka (Aloysius, 2018). Not only fruits but also 33% of vegetables have been found to be contaminated by agrochemicals of these types (Munasinghe, De Silva, Weerasinghe, Gunaratne, & Corke, 2015). Contamination of food by the over usage of agrochemicals, fertilizers and insecticides have led to an increased number of cancer patients and CKDu patients in the recent years, with the number of CKDu patients recorded from the Mahaweli Development Scheme areas alone increasing beyond 9000. The records indicate that the majority of CKDu patients are found in the North Central Province, Eastern Province, North Western Province and Uva Province where the paddy cultivation is prominent, confirming the relationship between the over usage of fertilizers and agrochemicals and the CKDu (Munasignhe et al., 2015). Additionally, an increasing number of cases of non-communicable diseases (such as diabetes and cardiovascular diseases) have been reported, being the cause of death in 75% of the total number of deaths recorded (Ministry of Health, Nutrition & Indigenous Medicine, 2015).

The over usage of fertilizers has badly affected the economy of the country, tarnishing the reputation and demand for Sri Lankan food products in the foreign market. The agrochemical amounts used by our farmers have exceeded the maximum permissible levels for food products. The reduction of the international trade demand for Ceylon tea could be stated as an instance for this. The harmful effects on the environment, especially on water resources, caused by the over usage of agrochemicals, fertilizers, insecticides, and weedicides have been reviewed in Sections 2.3 - 2.5.

In most occasions the poverty-stricken farmers are deprived of proper technical knowledge about the harmful effects of fertilizers and they are under the misconception that the over usage of agrochemicals would result in better yields. The fertilizer subsidy offered to the farmers by the government, and the absence of means to regulate the fertilizer usage are suspected to be major causes for the unplanned and excessive use of fertilizers. According to Weerahewa, Kodithuwakku, and Ariyawardana (2010), the fertilizer subsidy programme was implemented in 1962 mainly targeting to encourage farmers to start growing high-yielding varieties (HYVs) of rice which are readily responsive to chemical fertilizers, instead of growing traditional varieties of rice. The farmers generally expect the fertilizer subsidy to be continued by the successive governments, irrespective of the actual budgetary constraints (the subsidy costs 2.24% of total government expenditures in year 2009), hence making it a very sensitive issue in politics as well. The subsidy was facilitated for all Nitrogen (N), Phosphorus (P) and Potassium (K) types of fertilizers during 1962 to 1989, mainly aiming the paddy cultivation. The subsidy was stopped during 1990 to 1994, but was implemented again in 1995 for all N, P, K types of fertilizers. The subsidy was substantially curtailed in 1997 to 2004, allocating only for Urea fertilizers, whereas in 2005 it was reinstated for all three types of fertilizers. A fertilizer bag of 50 kg is set to a constant price irrespective of the price in the world market, and farmers cultivating paddy are eligible for claiming the subsidy if they have the legal rights to their paddy lands. However, continuation of the subsidy has caused several issues. The farmers tend to apply the fertilizers provided by the subsidy to the lands which they do not have legal rights and to other crop areas. Further the authorities such as Agrarian Services Centres (ASC) are frequently accused of their inefficiency in fertilizer distribution processes (Weerahewa et al., 2010).

According to Young, Pitawala, and Gunatilake (2010), banana, papaya and vegetables are also cultivated in the North Central Province, apart from the 40% of the province which has been used for paddy. The study states that the fertilizer application is 6 to 10 times in excess of the levels recommended by the government, according to the information received from government organisations and farmers. The quantity of urea fertilizer applied to paddies varies from 100 kg to 150 kg per acre, and triple super phosphate (TSP) applications range from 75 kg to 100 kg per acre. In banana and papaya plantations, 100 g of urea/TSP fertilizer per plant is added once every 3 months. The study suggests that the effect of fertilizer application on the water quality of the North Central Province should be studied since the fertilizer application rates are considerably high in the area. High values of Nitrate have been observed in groundwater wells after two weeks of fertilizer application, therefore, the study concludes that it takes about two weeks for leachates to reach the water table in the area. If the excessive usage of fertilizer is continued in the future the groundwater is at a risk of being contaminated by leachates (Young et al., 2010).

Young, Pitawala, and Gunatilake (2009) have conducted a study to evaluate the effect of agricultural practises on the chemical water quality in the Kala Oya basin (adjacent basin to the Malwathu Oya). It has been found that the fertilizer application in the basin is about 8 to 10 times in excess of the required amounts. The study further states that when agricultural waters consist of higher amounts of both Nitrates and Phosphates than natural waters, the accumulation of nutrients could be attributed to the application of fertilizers which is the only anthropogenic activity in the area. An abundant growth of nutrient absorbent plants in the riparian zones of the canals were observed and they in turn absorb a significant amount of Nitrate and Phosphate nutrients when the water flows through them, resulting considerably reduced values of nutrients in canal water despite the high rates of fertilizer application in the area. The study has observed high levels of Nitrate in water samples of wells taken within two weeks of application of fertilizer, as well as high levels of Phosphate and Potassium in lake water, confirming the impact of over usage of fertilizers on water resources. The study concludes that the recent intense agricultural practices used specially in vegetable cultivations cause high levels of cations and nutrients in agricultural wells, dug wells and lakes due to the recycling of same water throughout the year. It is further stated that some of the isolated lakes are highly adulterated which may result in the pollution of the groundwater by the groundwater recharge from those lakes.

Therefore, it is essential to regulate the amounts of fertilizers used to conserve the water quality of the water resources in the basin, hence scenario 1, 2 and 3 will be done to identify the effect of fertilizer regulation on the water quality. In scenario 1, 2 and 3, the present condition fertilizer input amounts would be reduced by 25%, 50% and 75%, respectively.

2.8 Climate Change Impacts

Climate change is inevitable with the various anthropogenic activities which are harmful for the environment. The increasing amounts of Carbon emissions and greenhouse gasses would increase the temperatures and would cause the glaciers to melt causing sea level rising and other various changes in the world climate. Further, the global warming is stated to cause changes in temperatures as well as rainfall patterns (Intergovernmental Panel on Climate Change - Task Group on Scenarios for Climate Impact Assessment [IPCC-TGCIA], 1999).

Sri Lanka has been collecting climate data from 1861 at 22 meteorological stations located in all districts of the country. The data on temperature and rainfall have been analysed by the Meteorological Department to determine their trends over the period 1901-2000, using data taken from 18 meteorological stations, excluding data from the stations in Northern and Eastern Provinces which were not functioning throughout (Ministry of Environment, 2011).

Analysis of climate data clearly indicates a change in the rainfall intensity, temporal and spatial distribution, and an increasing trend in air temperature. Most of the decrease in the annual rainfall is from the North East Monsoon (NEM) with no significant changes in the South West Monsoon (SWM) and the second inter-monsoon. The number of rainy days has also decreased prolonging the dry spells and increasing the intensity of rainfall. This change in rainfall distribution has caused a shift in the demarcation between the dry and wet-zones, with a reduction in the area of the wet-zone (Ministry of Environment, 2011).

As a part of a study in the coconut and tea sectors in the country (Ratnasiri, 2006), a detailed interpolation of Intergovernmental Panel on Climate Change (IPCC) temperature and rainfall projections applicable to Sri Lanka was carried out using software developed by the International Global Change Institute (IGCI) of University of Waikato, New Zealand (Warrick, et al., 1996). Under this project, temperature rise and rainfall change projections were developed corresponding to different IPCC emission scenarios and General Circulation Models (GCM models) for different time frames, for years 2050 and 2100 (Ministry of Environment, 2011).

The summer high temperature regions above 30 °C which is limited to a narrow region around Trincomalee Bay in the baseline scenario is seen to spread into the country covering the North-Eastern region by 2050 and over a greater part of the country by 2100. The temperature rise in the winter months is less prominent except in 2100 (Ministry of Environment, 2011).

The projections of rainfall change given for the two seasons - SWM and NEM - are more complex, though it is possible to identify some main features of the changes anticipated. For example, during the SWM, the South-West quadrant receives a maximum rainfall of about 2500 mm under baseline case, whereas in 2100, the maximum rainfall received is about 3500 mm over the same area. In the rest of the country too, there is an increase in the rainfall received during SWM period. During NEM, however, the maps do not show a significant change in the rainfall received, except for a slight increase in the eastern slopes of the central hills (Ministry of Environment, 2011).

In another study carried out using a regional model developed by the Hadley Centre, the rainfall received by 2050 in the Wet Zone during the SWM was found to increase by about 48% relative to the average rainfall received during 1961-1990, while during the NEM, the rainfall received in the Dry Zone, particularly in the Eastern Province, was found to decrease by 27-29% (De Silva, 2009). In other words, the wet zone is expected to become wetter and the dry zone drier with climate change (Ministry of Environment, 2011).

De Silva, Weatherhead, Knox, and Rodriguez-Diaz (2007) have developed a climate change dataset for Sri Lanka using selected outputs from the UK Hadley Centre for Climate Prediction and Research model (HadCM3) and selected IPCC Special Report on Emission Scenarios (SRES) A2 and B2 for 2050s. The study applied the proportional percentage changes given by that dataset to an existing baseline climatological dataset (baseline climatology dataset developed by the International Water Management Institute (IWMI)) covering Sri Lanka. The study states that the precise prediction of climate in the future is strenuous, as the predictions would cause changes in the human behaviour which would in turn affect the climate. Therefore, the climate change impacts are usually studied under various possible future scenarios which include the changes in the impetus of emissions such as Carbon intensity of energy supply, the income gap between developed and developing countries, and Sulphur emissions. For studying possible climate change, its impacts and alleviation schemes, the IPCC SRES have been used extensively. Climate change predictions for each scenario were developed by taking into account the expected concentrations of CO_2, mean sea level increase, global mean annual temperature and population (IPCC-TGCIA, 1999).

The developed future scenarios by the IPCC-TGCIA (1999) are; A1, A2, B1 and B2. Scenario A1 considers a future with swift inventions of more efficient technology, where the population growth is relatively low and the economic growth is very high. Scenario A2 considers a future which has high population growth, less involvement in making economic progress, and focussed on enforcing regional and cultural identities, with an emphasis on family values and local traditions. Scenario B1, on the other hand, would experience expeditious fluctuations in its economic structures, while adopting cleaner technological development. Environmentally and socially sustainable, collaborative, and local solutions would be adopted for; improving the equity, technological advancements, as well as for dematerialisation of the economy. This scenario accounts for a diverse world with slower but wider range of technological development, which enforces on community initiative and social innovation to find local, rather than global solutions.

De Silva et al. (2007) have used the IPCC SRES scenarios A2 and B2 for their derivation of climate change predictions for Sri Lanka for 2050s, because of the high population growth rates in the country. The estimated population in Sri Lanka by 2050 is 30 million, compared to the 16.4 million recorded in 1990, which exhibits a growth of 83% over the duration of those 60 years. Since this growth rate surpasses the projected global growth rates in all the IPCC SRES scenarios, scenarios A2 and B2 have been selected which have projected global increases of 64% and 53%, respectively, over these 60 years. Further, the HadCM3 model is a coupled atmospheric-ocean general circulation model which is more complicated than earlier versions (Hulme and Jenkins, 1998).

De Silva et al. (2007) found that there will be a decrease in rainfall in most parts of Sri Lanka in 2050, for the climate change scenarios of A2 and B2. Wet season average rainfall would decrease by 17% (in A2) and by 9% (in B2). However, the average annual rainfall would increase by 14% (A2) and 5% (B2). The maximum reductions in wet season rainfall (16% in A2, 12% in B2) are predicted to occur in Batticaloa. On the contrary, wet season rainfall would increase by 10% (A2) and 12% (B2) in Hambantota. It is predicted that in 20150, the average wet season temperature (the average of minimum and maximum air temperature) would increase by 1.6 °C (A2) and 1.3 °C (B2) and the average reference evapotranspiration would increase by 2% (A2) and 1% (B2). In the wet season in Batticaloa, the average temperature would increase by 1.4 °C (A2) and 1 °C (B2) and the average reference evapotranspiration would increase by 1.3% (A2) and 1.1% (B2), in 2050. The combined effect of the reduced rainfall and the high temperatures would require higher amounts of irrigation water in the wet season.

Therefore, the significance of climate change on the WEP model analysis should be taken into consideration, as the WEP model takes meteorological data as inputs in the analysis. Hence the impacts of the impending climate change would be analysed by using scenarios 4, 5 and 6, with respect to the present condition. In scenario 4, all rainfall values (in the present condition) would be increased by 14%. According to the results predicted by De Silva et al. (2007) for 2050s in Sri Lanka, the predicted increase of the average annual rainfall by 14% (A2) would be the worst-case scenario. On the other hand, the effect of the magnitude of extreme climate events would be studied by scenario 5, where only the extreme rainfall values would be increased/decreased by 5%. The impact of temperature changes would be studied by scenario 6, where all temperature values would be increased by 1.6 °C. According to the results predicted by De Silva et al. (2007) for 2050s in Sri Lanka, the average wet season temperature (the average of minimum and maximum air temperature) increases by 1.6 °C (A2) would be the worst-case scenario.

3 MATERIALS AND METHODS

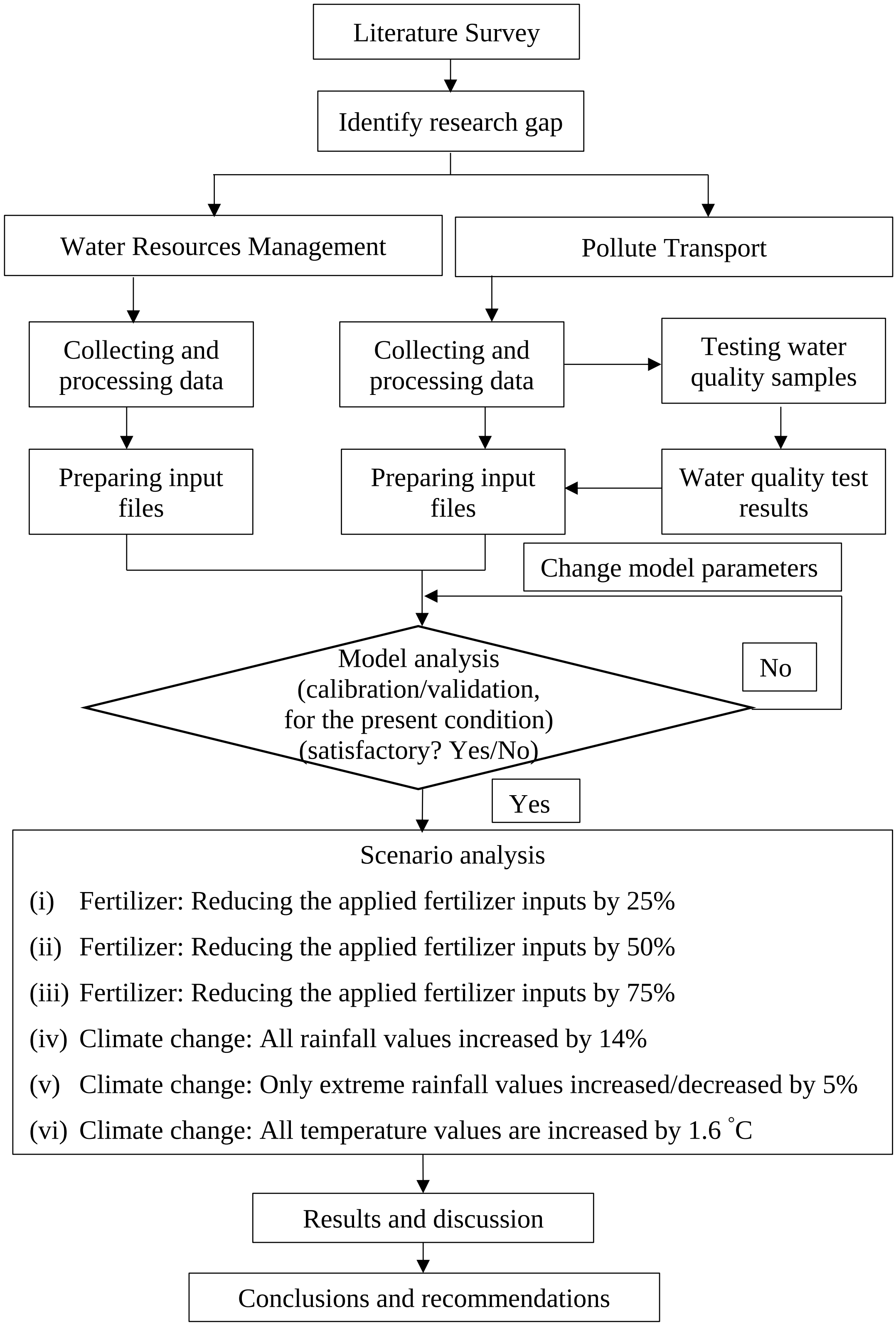
This Chapter illustrates the methodology, data and data checking/data pre-processing procedures followed by the WEP model analysis in detail, which can further be categorised into three main analysis components of this study; developing the state-of-the-art database, experimental field analysis, and the distributed modelling analysis component.

3.1 Methodology

The methodology flow chart is given in Figure 3.1. The research gap was identified by conducting an extensive literature survey. Nachchaduwa catchment was selected as the study area for this research since it is the uppermost sub catchment in the Malwathu Oya catchment and due to its presently stressed state Then the problem statement was developed. These were discussed in detail in Chapter 1 and Chapter 2.

Subsequently, the data related to the water resources management (hydrological component of the model) and the pollute transport (material transport component) of the catchment were collected and processed. The model parameter values were identified and the input files for the model runs were prepared. Simultaneously water quality sample testing was done in Yala and Maha seasons. Data and data pre-processing procedures are explained in detail under Section 3.2. After that, the application of the model (analysis), including initial trial runs, calibration/validation, for the present condition were performed. The validated model was used to analyse six possible future scenarios which were explained in detail in Section 2.8.

Suitable water resources management and fertilizer usage practices for the catchment (Best Management Practices) could be recommended based on the conclusions derived from the results and discussion. The results of this study were published in several indexed journals and international conferences to enlighten the scientific community and the general public. A detailed description of the methodology would be illustrated in Sections 3.2 and 3.3.



(i) Fertilizer: Reducing the applied fertilizer inputs by 25%

(ii) Fertilizer: Reducing the applied fertilizer inputs by 50%

(iii) Fertilizer: Reducing the applied fertilizer inputs by 75%

(iv) Climate change: All rainfall values increased by 14%

(v) Climate change: Only extreme rainfall values increased/decreased by 5%

(vi) Climate change: All temperature values are increased by 1.6 °C

Figure 3.1: Methodology Flow Chart

3.2 Data and Data Checking/Data Pre-Processing Procedures

3.2.1 Data Sources and Data Resolution

The data necessary for the hydrological component and the material transport component have been collected and processed. The data resolution and data sources are summarised in Table 3.1.

Table 3.1: Data Sources and Data Resolution

Index	Data Type	Resolution	Source
1	Malwathu Oya streamflow related data (Kappachchi gauging station) and Nachchaduwa reservoir operation data	Daily data	Department of Irrigation, Nachchaduwa and Colombo
2	Meteorological Data		Meteorological department, Colombo
2.1	Rainfall data (rainfall stations Anuradhapura, Kahatagasdigiliya, Kekirawa, Maha Illuppallama, Pelwehera)	Daily data	
2.2	Temperature data	Daily data	
2.3	Wind data	Daily data	
2.4	Relative humidity data	Daily data	
2.5	Sunshine data	Daily data	
3	Land use data	-	Survey Department
4	Soil/geology/elevation data	-	Survey Department and borehole reports
5	Water Quality data (Testing)	-	Collected water quality samples
6	Fertilizer data	ASC-wise	Anuradhapura DSD – Fertilizer Division
7	Population data	GND-wise	Census and Statistics Department
8	Water resources data	GND-wise	Census and Statistics Department

3.2.2 Study Area - Nachchaduwa Catchment Related Data

3.2.2.1 Nachchaduwa reservoir

Nachchaduwa catchment (Figure 2.1) (598.74 km^2) was selected as the study area since it is the uppermost sub-catchment in the Malwathu Oya basin, therefore no effect from previous catchments have to be considered, and because of the location of a major reservoir, hence the reservoir effect could also be modelled, and due to its presently stressed state as explained in previous chapters.

Malwathu Oya streamflow related data and Nachchaduwa reservoir operation data (sluice release data, spill release data, water issues, irrigation issues, etc.) were collected from the Department of Irrigation, from both Nachchaduwa Divisional Office and the Colombo Head Office. Nachchaduwa catchment area, reservoir and the command area were investigated by conducting several field visits, and photographs of important hydraulic structures were taken. Please refer Appendix A for more details regarding the Nachchaduwa reservoir related data.

3.2.2.2 Land use, soil types and delineation of sub catchments of the Nachchaduwa catchment

Land use and soil type details of the Nachchaduwa catchment were extracted using Esri ArcGIS software (version 10.3), from the GIS maps prepared by the Survey Department in year 2001. Geological details, soil layer details, etc. were obtained from the borehole data of the construction projects done in the vicinity of the catchment. Nachchaduwa catchment consists of several land use types, which include; chena, forests, home gardens/gardens, other cultivations, paddy, rock, scrub land, as well as the water bodies (Figure 3.2). The soil types of the catchment is mainly composed of; alluvial soils of variable texture and drainage (flat terrain) in the vicinity of the stream paths and, reddish brown earths and low humic gley soils in everywhere else (Figure 3.3). The entire catchment has been delineated into three sub catchments according to the terrain and stream path distribution (Figure 3.4).

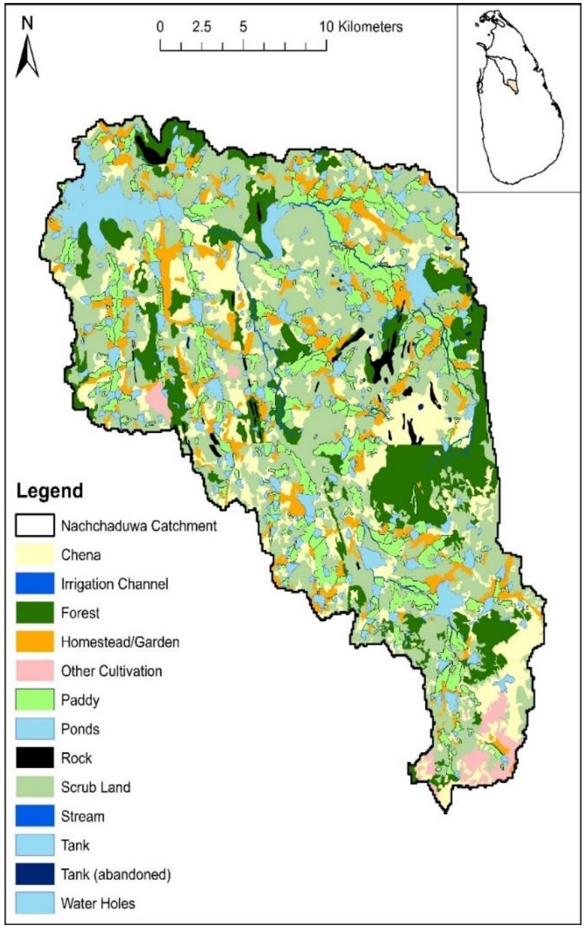


Figure 3.2: Land use of the Nachchaduwa Catchment (original in colour)

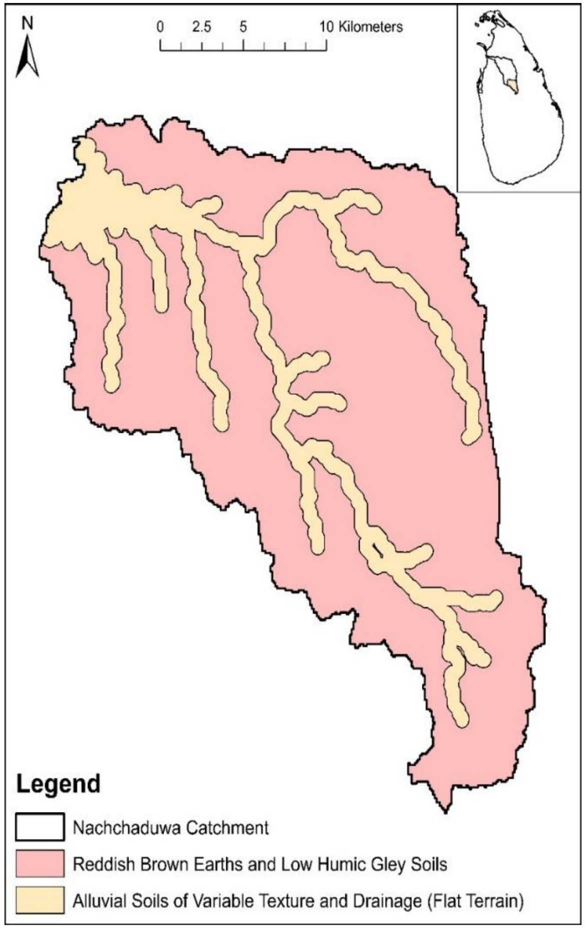


Figure 3.3: Soil Types of the Nachchaduwa Catchment (original in colour)

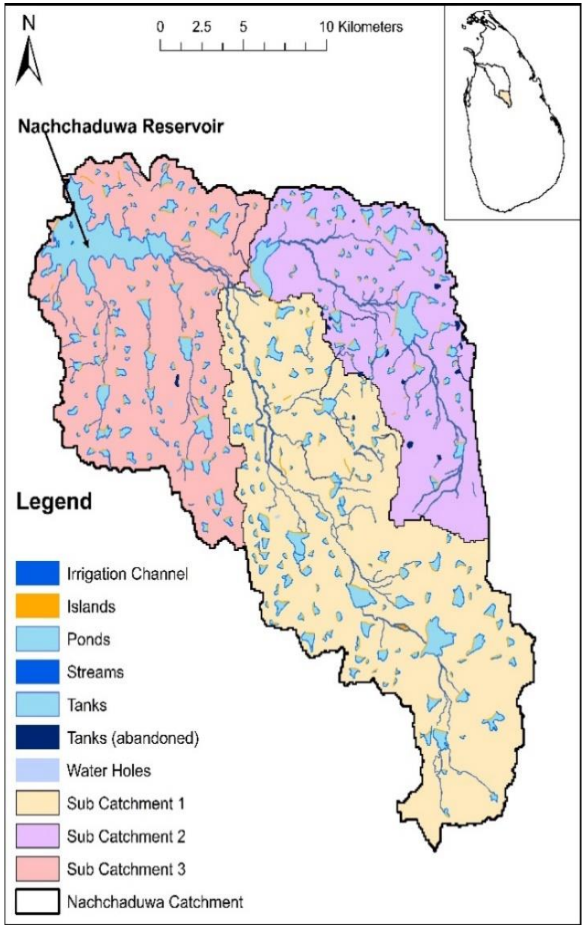


Figure 3.4: Delineation of Sub Catchments (original in colour)

3.2.3 Rainfall Data

Daily rainfall data for stations Anuradhapura, Kahatagasdigiliya, Kekirawa, Maha Illuppallama, Pelwehera were collected from the Meteorological Department for the years 2008 to 2015. The data were checked for outliers and missing data by using hydrological and statistical data checking procedures. Missing data were filled by plotting the single mass curves (by omitting the missing data points) for all these stations and by regression analysis. Please refer Appendix A for more details regarding the rainfall data.

The Thiessen average daily rainfall values were calculated for the catchment, and the Thiessen polygons were drawn for the catchment (Figure 3.5) (The polygon areas inside the grid are shown).

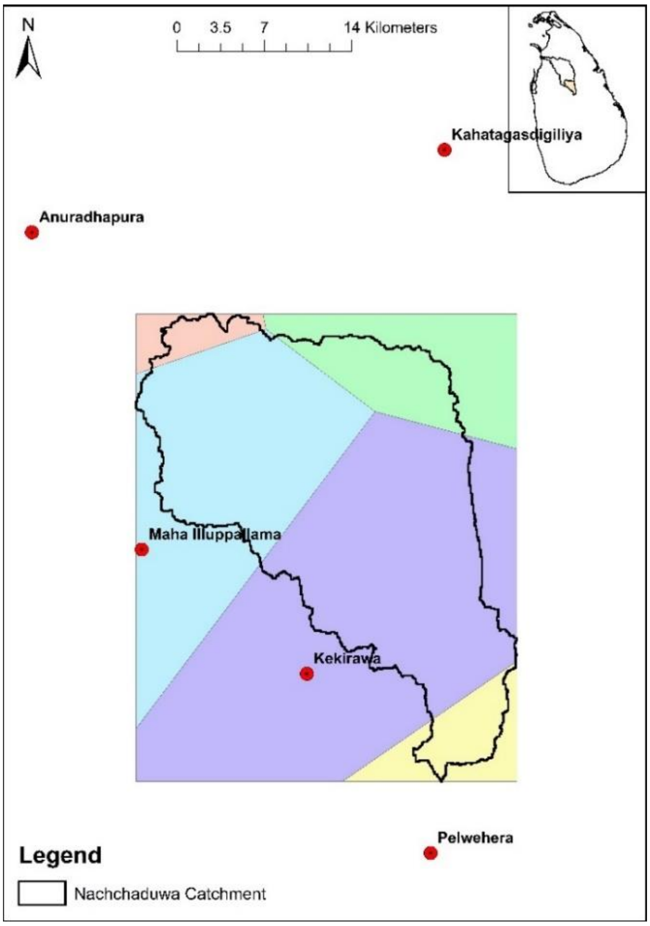


Figure 3.5: Thiessen Polygons for the Catchment (original in colour)

3.2.4 Streamflow Data

3.2.4.1 Initial data checking

The streamflow related data and reservoir operation data were collected from the Department of Irrigation (data were collected from both Nachchaduwa division and the Colombo divisions, but since only the Colombo division data showed some agreement with the rainfall values, Colombo division data has been used for this research) and were checked against the rainfall values. The monthly and annual runoff coefficients were also calculated using those data. The response of the catchment (the total daily outflow from the reservoir - included all the spill and sluice releases) with precipitation was checked and the resulting graph is shown in Figure 3.6. The response of the catchment (total outflow), on the day of precipitation, one day before the precipitation, one day after the precipitation, two days after the precipitation, three days after the precipitation, were checked. Further, the time of concentration for the catchment was found to be 25.8 hours following Ponrajah (1984). The annual runoff coefficient varied from 0.15 to 0.27 within the study period.

For more details of the streamflow data please refer Appendix A.

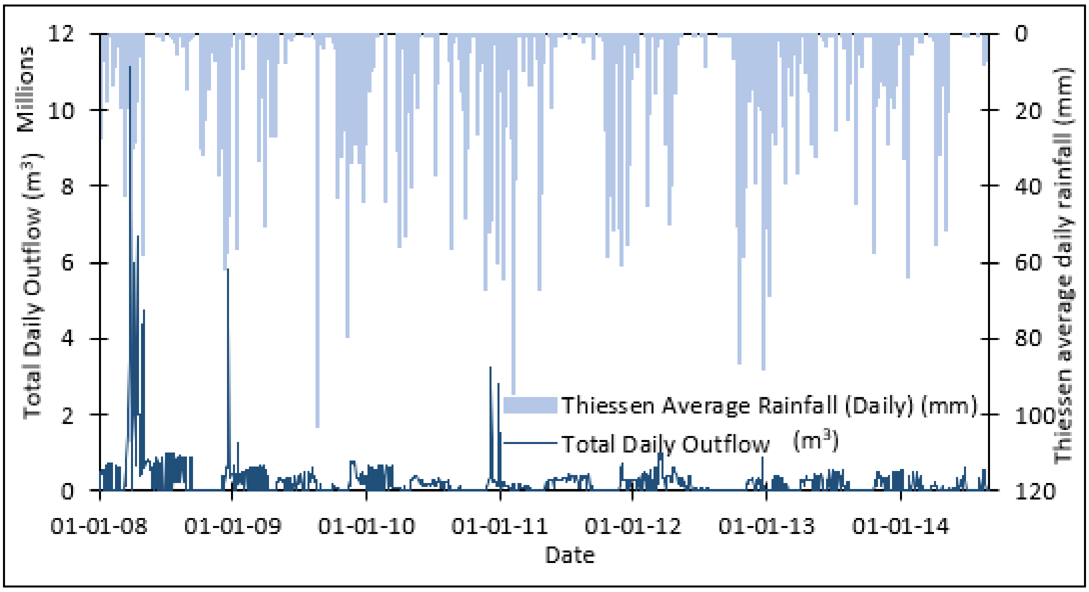


Figure 3.6: Thiessen Average Daily Rainfall (mm) and Total Daily Outflow (m^3) from the Reservoir (original in colour)

3.2.4.2 Developing a streamflow data series for the WEP model using HEC HMS

It was noted that during certain years, the rainfall and total outflow from the reservoir do not show a good correlation due to lack of reliable reservoir operation related data. The catchment response to the rainfall indicated that the measured spill and total release data are highly regulated due to reservoir storage effect (ungauged basin and regulated flows). Due to these reasons, a previously calibrated HEC-HMS model that was developed for this catchment was applied in the present study by incorporating the most suitable parameter values taken from previously published studies (Hettiarachchi, 2008; Kamran & Rajapakse, 2017). The outflow values from the total basin were obtained for a one-hour time interval from the HEC-HMS model and used as the streamflow data series for comparison with the WEP model. More details of the HEC HMS model are given in Appendix A.

Streamflow time series [outflow (discharge) values from the total basin] were obtained based on the pre-calibrated HEC-HMS model for the period of calibration (data from years 2008-2011 will be used for the calibration) and validation (data from years 2012-2015 will be used for the validation) separately, with 1 hour time interval. These data series would be used as the streamflow data series for comparison with the calibration and validation WEP model results.

3.2.5 Water Balance/Yield Analysis

A situation analysis was carried out by conducting a yield analysis to verify the current water scarce situation in Nachchaduwa sub-catchment. Irrigation requirement was calculated considering the current practice in the scheme; low land paddy (135 days) for Maha season and low land paddy (105 days) and Other Field Crops (OFC) for the Yala season. Subsequently a water balance study was carried out considering 75% probability rainfall values (Ponrajah, 1984), which were the design rainfall values for the reservoir operation study, and the Thiessen average daily rainfall values of collected data. The reservoir operation study model outputs were compared with actual operational data of the Nachchaduwa reservoir for verification. Then an alternative option was considered by using low land paddy (105 days) for Maha season and low land paddy (105 days) and Other Field Crops (OFC) for the Yala season, to determine whether an improvement is achievable for the water resources management.

According to the irrigation requirement calculated considering the current practice in the scheme [low land paddy (135 days) for Maha season and low land paddy (105 days) and Other Field Crops (OFC) for the Yala season], and the Nachchaduwa reservoir operation study, annual demand and supply varies in a pattern shown in Figure 3.7. Verification of the reservoir operation study model outputs with the actual operational data of the Nachchaduwa reservoir is shown in Figure 3.8. Yield analysis confirmed that there is water scarcity in the catchment, especially during the dry season extending from April to September. Results of the alternative option considered by using low land paddy (105 days) for Maha season and low land paddy (105 days) and Other Field Crops (OFC) for the Yala season, to determine whether an improvement is achievable for the water resources management, are given in Figure 3.9 and Figure 3.10. As seen from Figure 3.7 and Figure 3.9, the gap between the demand and supply of water has been reduced with the alternative cropping option, confirming an improvement is achievable for the water resources management. However, even with the alternative cropping option, still there is water scarcity prevalent in the catchment.

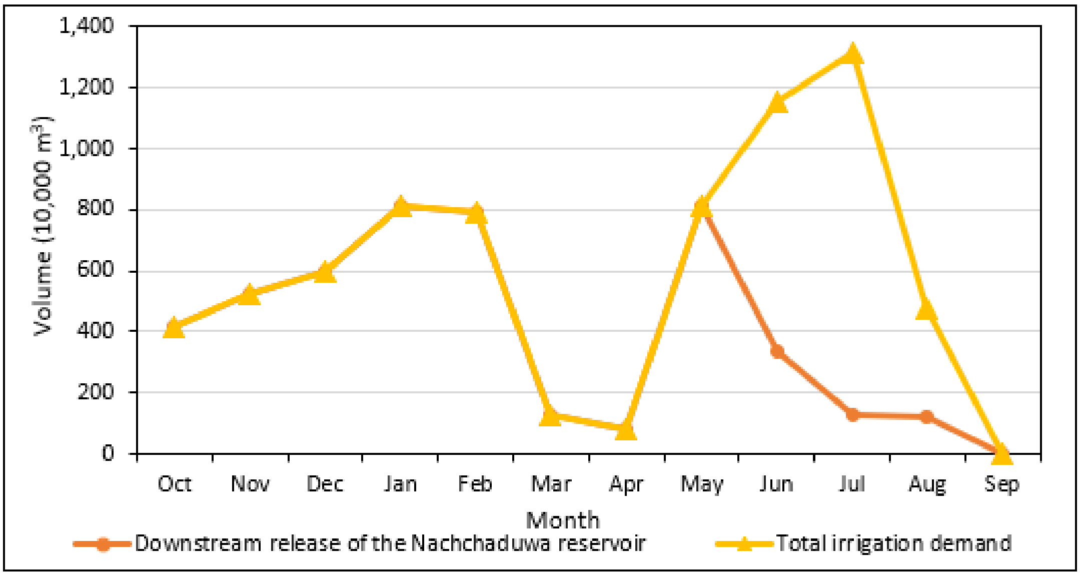


Figure 3.7: Annual Demand and Supply - Current Situation (original in colour)

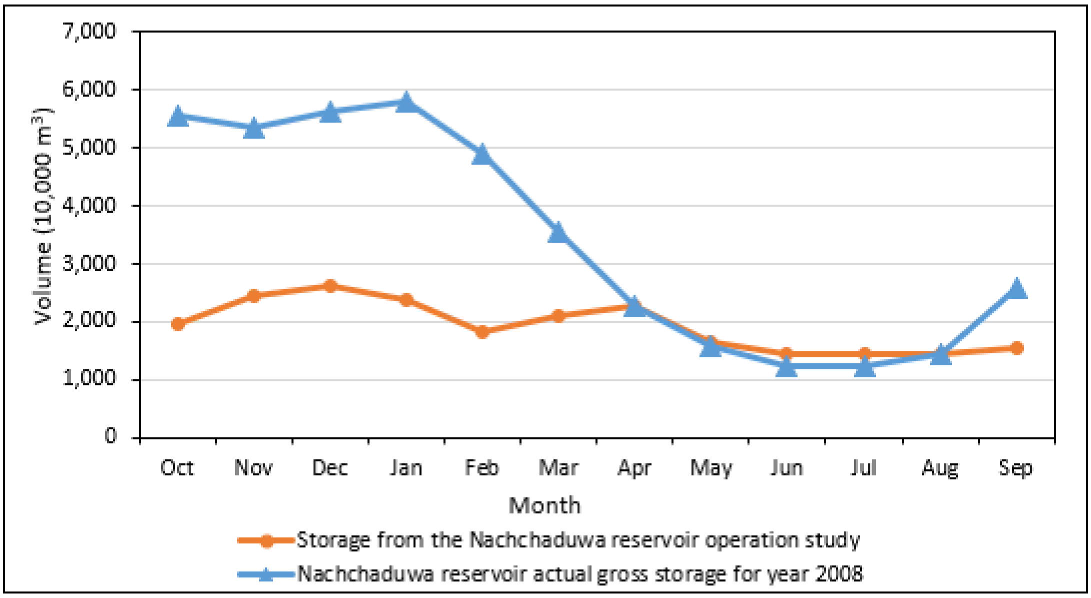


Figure 3.8: Verification of the Reservoir Operation Study Model Outputs with the Actual Operational Data - Current Situation (original in colour)

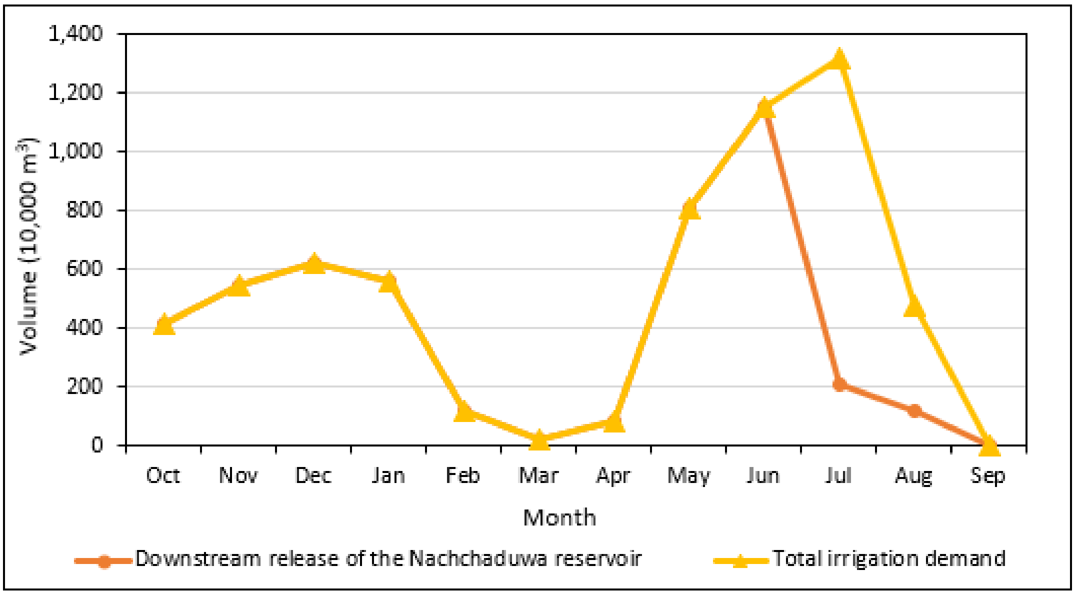


Figure 3.9: Annual Demand and Supply - Alternative Situation (original in colour)

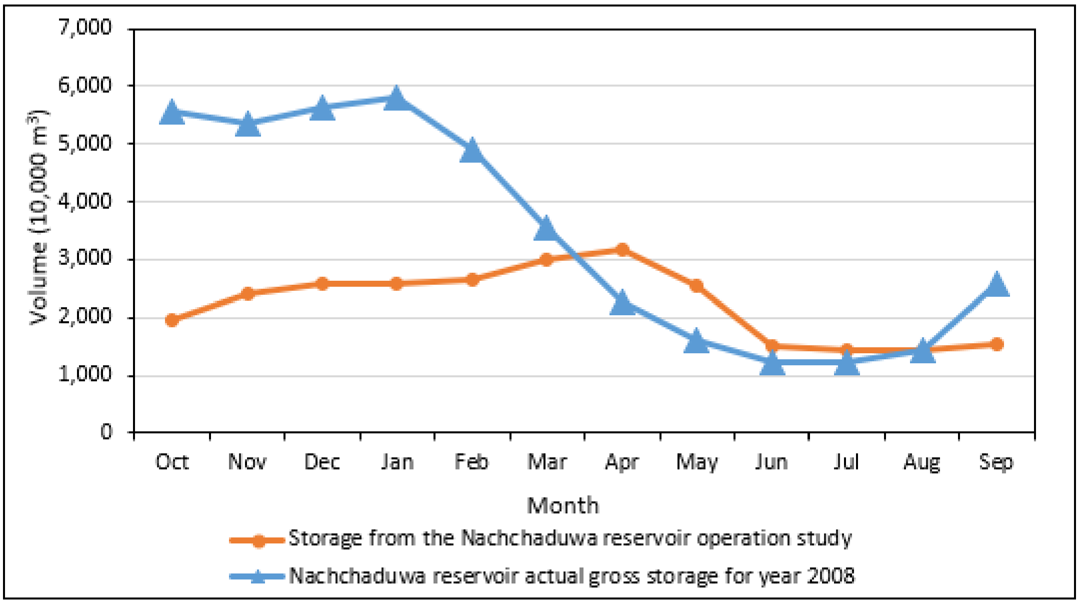


Figure 3.10: Verification of the Reservoir Operation Study Model Outputs with the Actual Operational Data - Alternative Situation (original in colour)

3.2.6 Meteorological Data

The WEP model has the capacity to simulate hourly data. Since hourly data were not available, it was checked whether an improvement could be made by using hourly data which was generated by daily data, following Bennett, Robertson, Ward, Hapuarachchi, and Wang (2015).

Meteorological data, including rainfall data, temperature data, wind data, relative humidity, sunshine data, have been collected from the Meteorological Department, and the data have been checked using the data checking procedures.

The checked data values have been used to prepare the input files. Excel Visual Basic for Applications (VBA) was used for data pre-processing and to prepare the input files necessary for the model runs. Hourly data series developed have been illustrated in Figure 3.11, Figure 3.12, Figure 3.13 and Figure 3.14 (only the developed data for 24 hour time period have been shown). Further, for the calibration of the model data from year 2008 to 2011 would be used, and for the validation of the model data from year 2011 to 2015 would be used.

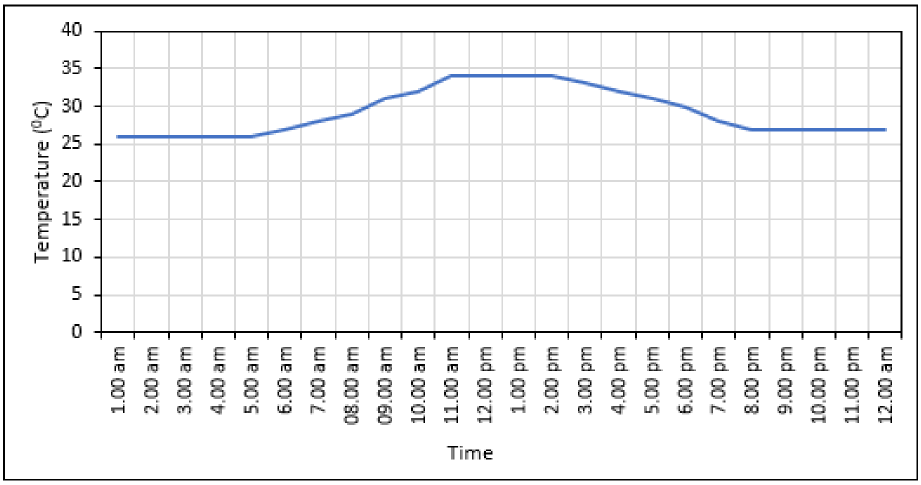


Figure 3.11: Hourly Temperature Data Series

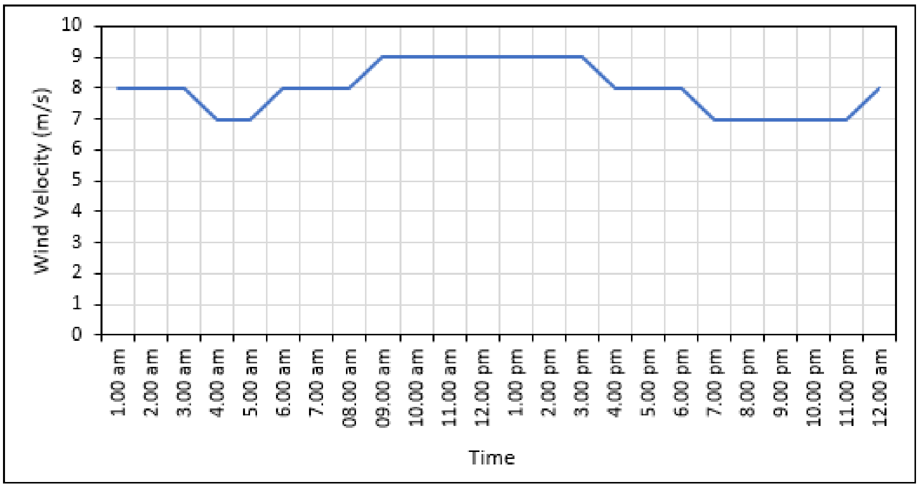


Figure 3.12: Hourly Wind Velocity Data Series

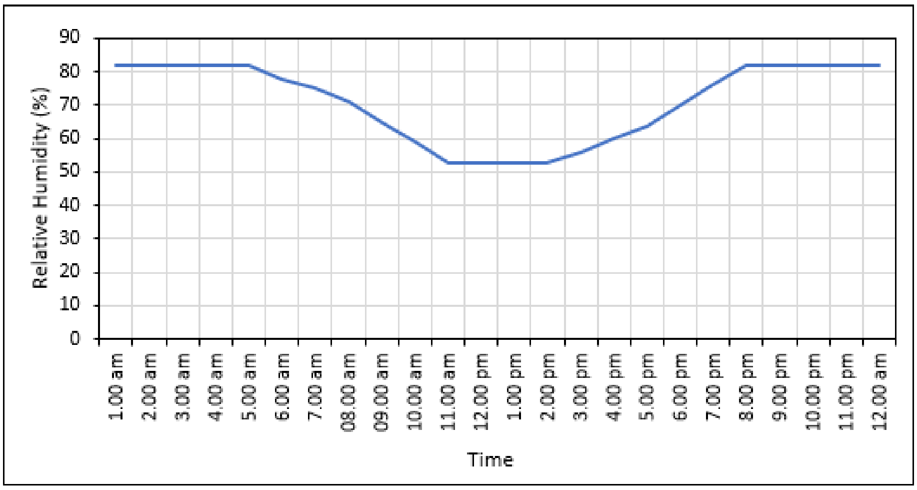


Figure 3.13: Hourly Relative Humidity Data Series

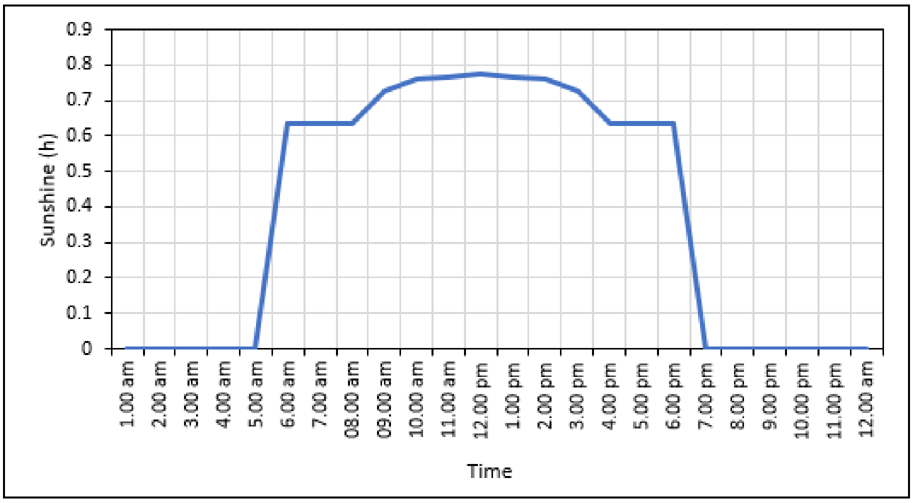


Figure 3.14: Hourly Sunshine Data Series

3.2.7 Reservoir/Streamflow Water Quality Data

Nitrogen and Phosphorus can be found in several different forms in water, mainly in dissolved and particulate forms (Hydrologic Engineering Research Team, 2012). Water quality samples were collected throughout the stream cascade covering both dry and wet seasons and they were tested for the water quality parameters (i.e. Nitrogen and Phosphorus), Total Suspended Solids (TSS), turbidity, temperature and pH value, following American Public Health Association [APHA] (2005). Four 500 ml samples per one location were collected from eight locations throughout the catchment considering reservoirs, stream segments, inlets and outlets of streams from paddy fields, etc. Half of the samples were preserved by adding 0.5 ml of concentrated Sulfuric (H_2SO_4) acid. One unfiltered and another filtered (using 0.45 µm syringe filters) sample each, were collected for all the locations. They were tested for N and P using the Persulfate Method for Simultaneous Determination of Total Nitrogen and Total Phosphorus (APHA, 2005). The samples were checked for the concentrations of anions (such as NO_3^-, NO_2^- and PO_4^{3-}) in ppm by using the 930 Compact IC Flex Ion Chromatography system (Metrohm AG, Switzerland). For checking the NH_4^+-N, the UDK 149 Automatic Kjeldahl Distillation Unit (VELP Scientifica Srl, Italy) was used.

The previous test results were confirmed by conducting colourimetric testing using the Palintest Photometer (Palintest Ltd., England). For determining PO_4^{3-}, NO_2^- and NO_3^-, the Palintest Phosphate, Palintest Nitrocol and the Palintest Nitratest methods were used. The colourimeter was used for determining NH_4^+ by Nessler's method. For more details about the reservoir/streamflow water quality data and the testing procedures adopted please refer Appendix A.

3.2.7.1 Reservoir/streamflow water quality - Yala season

The locations of the water quality samples that were collected throughout the stream cascade in the dry season (Yala season) are shown in Figure 3.15 to Figure 3.21.

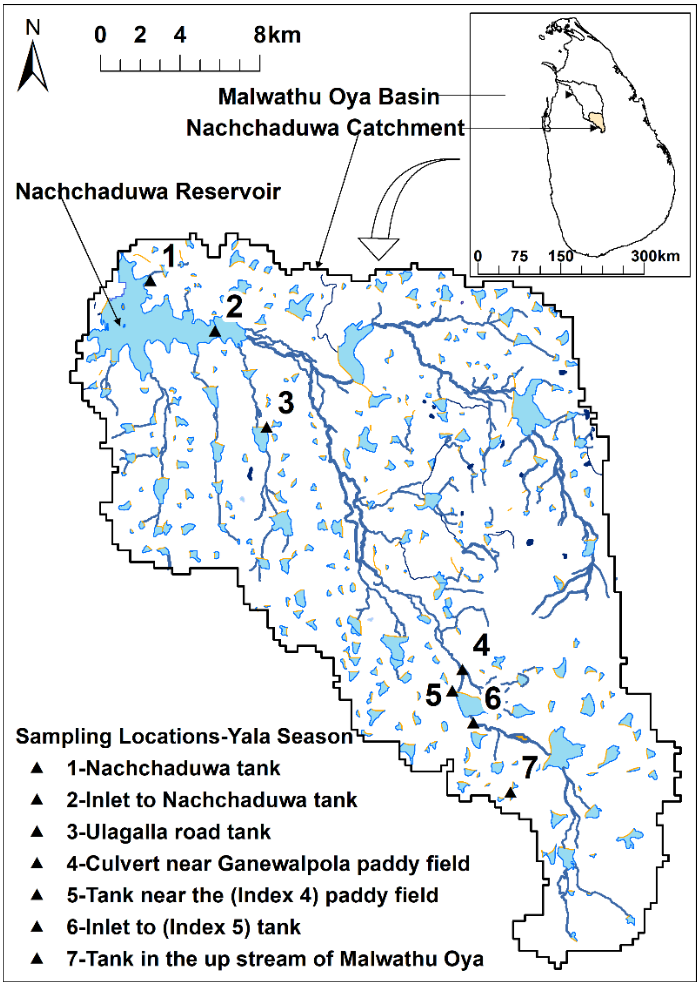


Figure 3.15: Water Quality Sampling Locations in the Yala (Dry) Season (original in colour)

Figure 3.16: Location 1 (original in colour)

Figure 3.17: Location 3 (original in colour)

Figure 3.18: Location 4 (original in colour)

Figure 3.19: Location 5 (original in colour)

Figure 3.20: Location 6 (original in colour)

Figure 3.21: Location 7 (original in colour)

Table 3.2 summarises the water quality sample details that were collected throughout the stream cascade in the dry season (Yala season) and Table 3.3 summarises the water quality test results of them.

Table 3.2: Water Quality Sample Details for Samples collected in Yala Season

Location ID	Location (in the map)	Coordinates (Latitude, Longitude in Decimal Degrees)	Time of Collection	Remarks (weather etc.)
1	Nachchaduwa Tank	(8.268254, 80.491571)	12.10pm	Sunny, no wind, shady area
2	Inlet to Nachchaduwa Tank	(8.245356, 80.521026)	12.44pm	Sunny, lot of vegetation in the water
3	Ulagalla road Tank	(8.201681, 80.544532)	1.17pm	Sunny, shaded by a tree, some vegetation in the water
4	Culvert near Ganewalpola Paddy Field	(8.0917695, 80.6336567)	2.40pm	Sunny, culvert, shaded by a tree
5	Tank near the (Index 4) Paddy Field	(8.0822030, 80.6291160)	3.00pm	Sunny, no wind, muddy water
6	Inlet to (Index 5) Tank	(8.067624, 80.638727)	3.50pm	Cloudy
7	Tank in the upstream of Malwathu Oya	(8.036215, 80.655543)	4.45pm	No wind, some vegetation

Table 3.3: Summary of Water Quality Test Results for the Samples Collected in Yala Season

Location ID	NO_3^- - N concentration (ppm)	NH_4^+ - N concentration (ppm)	NO_2^- - N concentration (ppm)	PO_4^{3-} - P concentration (ppm)
1	below 0.05	10	below 0.05	0.327
2	below 0.05	28	below 0.05	0.287
3	below 0.05	28	below 0.05	0.426
4	below 0.05	25	below 0.05	0.334
5	below 0.05	10	below 0.05	0.288
6	below 0.05	10	below 0.05	0.581
7	below 0.05	10	below 0.05	0.258

The mean and standard deviation of the upstream and downstream NH_4^+ - N concentrations determined from descriptive statistics are 13.75±7.50 ppm and

22.75±8.62 ppm, respectively. Single Factor ANOVA values for NH_4^+ - N concentrations are; F =2.483, P =0.166 and $F_{Critical}$ =5.987, respectively.

The mean and standard deviation of the upstream and downstream PO_4^{3-} - P concentrations determined from descriptive statistics are 0.37±0.15 ppm and 0.34±0.06 ppm, respectively. Single Factor ANOVA values for PO_4^{3-} - P concentrations are; F =0.076, P =0.792 and $F_{Crtical}$ =5.987, respectively.

Nevertheless, from these ANOVA results it can be concluded that the differences between the upstream and downstream concentration values of the water quality parameters are not statistically significant, despite the slightly increasing or decreasing trends shown from upstream to downstream sites.

The NO_3^- - N and NO_2^- - N concentrations were below the minimum measurable limit of the apparatus. Figure 3.22 represents a bubble diagram of the water quality test results, with the sampling locations.

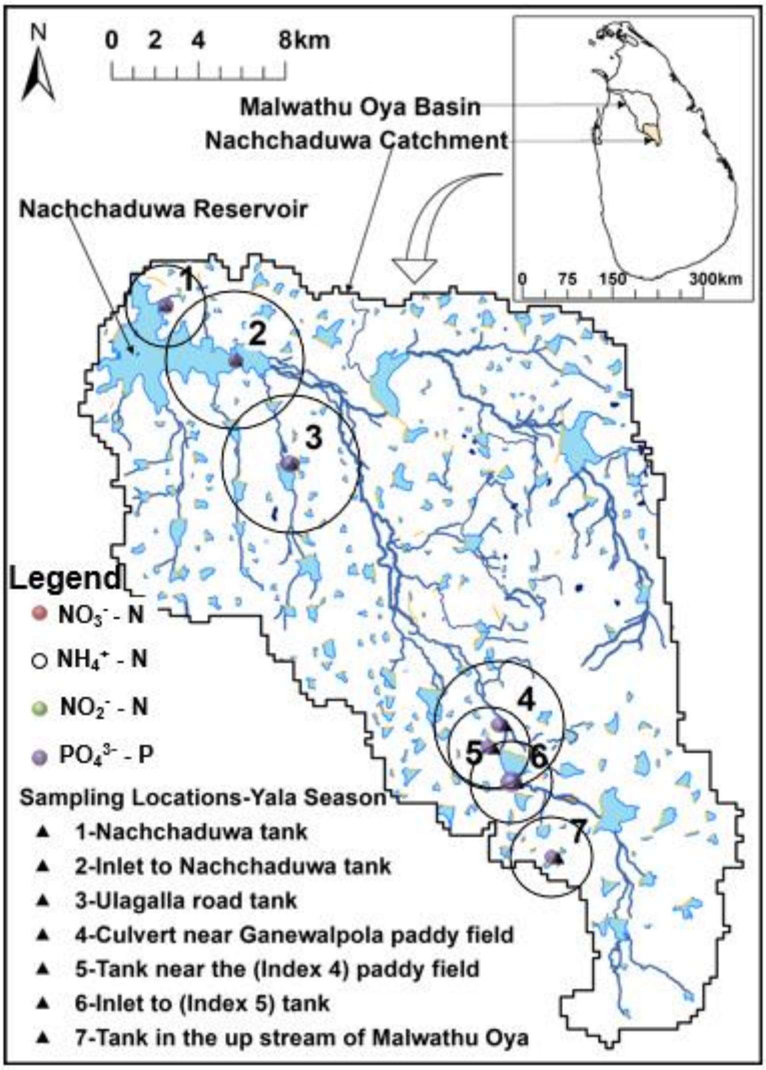


Figure 3.22: Water Quality Test Results with the Sampling Locations - Yala Season (original in colour)

3.2.7.2 Reservoir/streamflow water quality - Maha season

The locations of the water quality samples that were collected throughout the stream cascade in the wet season (Maha season) are shown in Figure 3.23 to Figure 3.27.

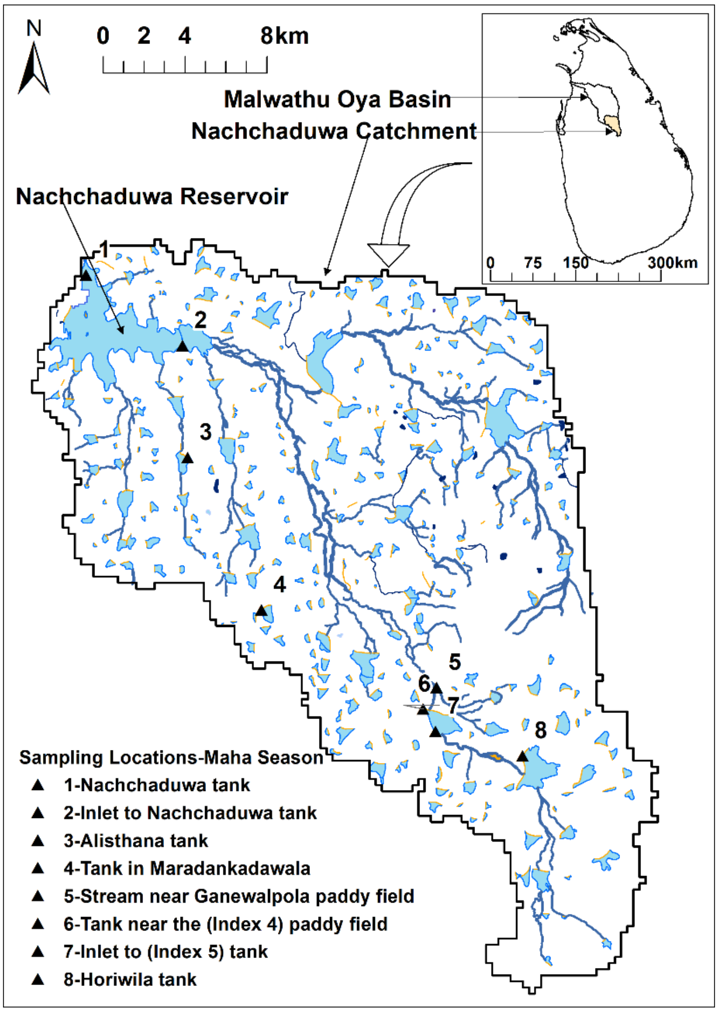


Figure 3.23: Water Quality Sampling Locations in the Maha (Wet) Season (original in colour)

Figure 3.24: Location 4 (original in colour)

Figure 3.25: Location 5 (original in colour)

Figure 3.26: Location 6 (original in colour)

Figure 3.27: Location 7 (original in colour)

Table 3.4 summarises the water quality sample details that were collected throughout the stream cascade in the wet season (Maha season). Figure 3.28 and Figure 3.29 show the water quality test results of Nitrogen components, and Figure 3.30 and Figure 3.31 show the water quality test results for Phosphorus components.

According to the water quality test results of the samples that were collected throughout the stream cascade in the wet season (Maha season), the single Factor ANOVA test P values for the upstream and downstream concentrations of Total Nitrogen (TN), Dissolved Nitrogen (DN), Particulate Nitrogen (PN), Total Phosphorus (TP), Dissolved Phosphorus (DP), Particulate Phosphorus (PP) are, 0.306, 0.204, 0.480, 0.170, 0.383, 0.307, respectively.

Therefore, in both seasons, the differences between the upstream and downstream concentration values of the water quality parameters are not statistically significant, despite the slightly increasing or decreasing trends shown from upstream to downstream sites, as graphically illustrated by the bubble diagrams in Figure 3.29 and Figure 3.31. A summary of all the measured water quality results for both seasons is given in Table 3.5.

Table 3.4: Water Quality Sample Details for Samples collected in Maha Season

Location ID	Location (in the map)	Coordinates (Latitude, Longitude in Decimal Degrees)	Time of Collection	Remarks (weather etc.)	pH	Temperature (^{0}C)
1	Nachchaduwa Tank	(8.273829, 80.479124)	9.04am	Cloudy, windy, open area	7	24.5
2	Inlet to Nachchaduwa Tank	(8.242692, 80.521927)	9.44am	Flowing water, nearby bridge, open area, sunny, slightly cloudy	7	25
3	Alisthana Tank	(8.193105, 80.524200)	10.15am	Sunny, slightly cloudy, vegetation (lotus plants), open area, upstream is a cattle-feeding ground	6	25
4	Tank in Maradankadawala	(8.125748, 80.557067)	10.47am	Sunny, vegetated area, nearby bridge	6	24
5	Stream near Ganewalpola Paddy Field	(8.091466, 80.634756)	11.25am	Slowly moving water, shaded place, cloudy, slightly sunny, windy	6	25
6	Tank near the (Index 4) Paddy Field	(8.081912, 80.628775)	11.50am	Sunny, slightly cloudy, windy, open area, some vegetation nearby	7	25
7	Inlet to (Index 5) Tank	(8.072062, 80.634266)	12.40pm	Cloudy, windy, open area, high vegetation (grass), there were some oil floating on the surface	6	25.5
8	Horiwila Tank	(8.061217, 80.672853)	1.50pm	Open area, under a tree, slightly sunny, cloudy, windy, vegetation (grass) nearby	6	25

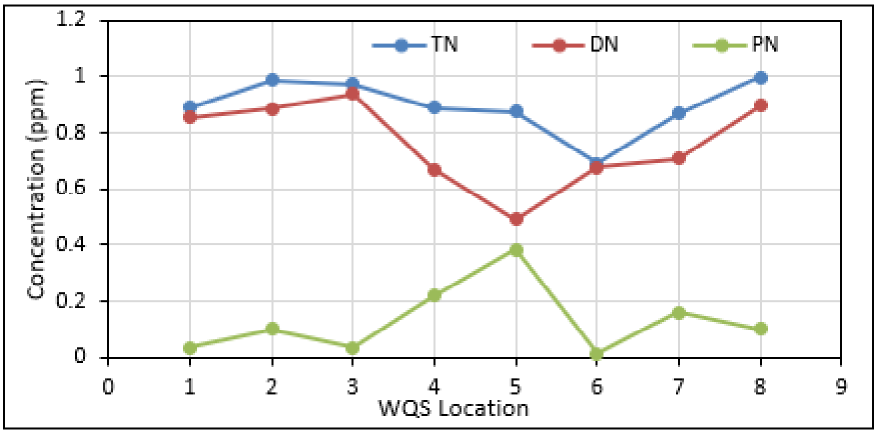


Figure 3.28: Water Quality Test Results for Nitrogen Components, for the Samples Collected in Maha Season (original in colour)

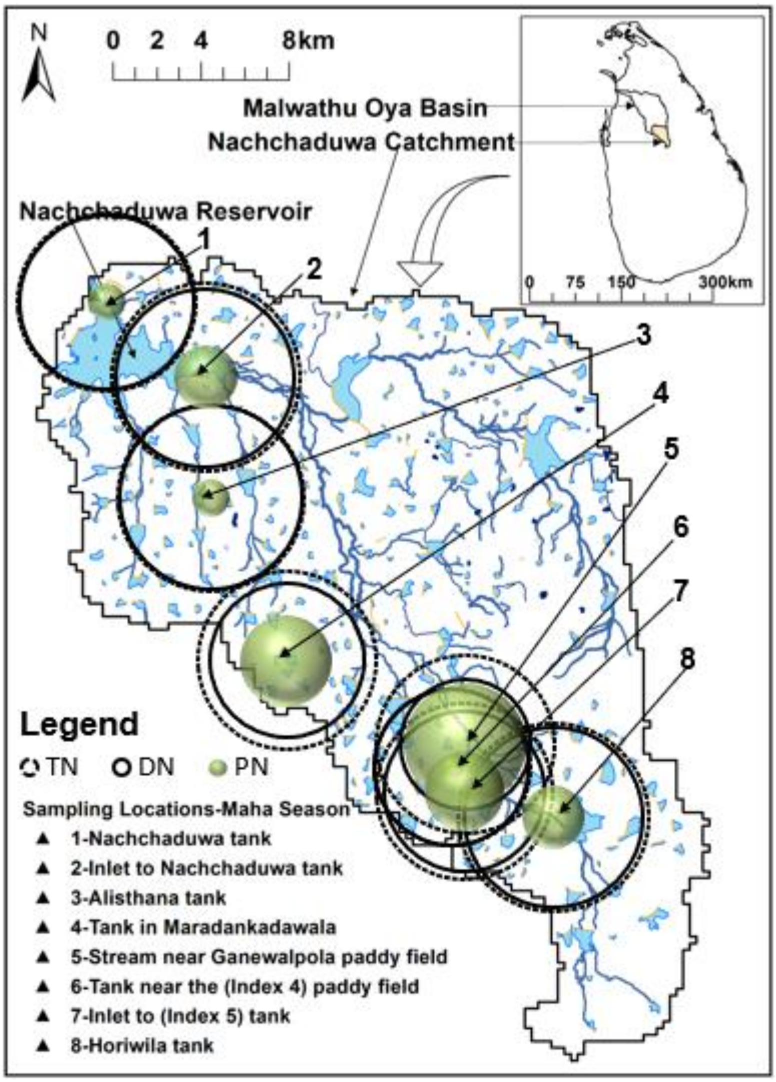


Figure 3.29: Water Quality Test Results (Nitrogen Components) with the Sampling Locations, for the Samples Collected in Maha Season (original in colour)

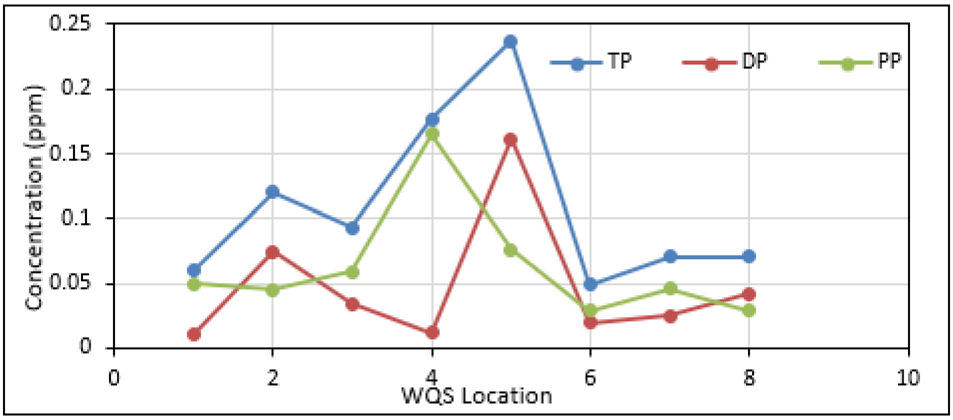


Figure 3.30: Water Quality Test Results for Phosphorus Components, for the Samples Collected in Maha Season (original in colour)

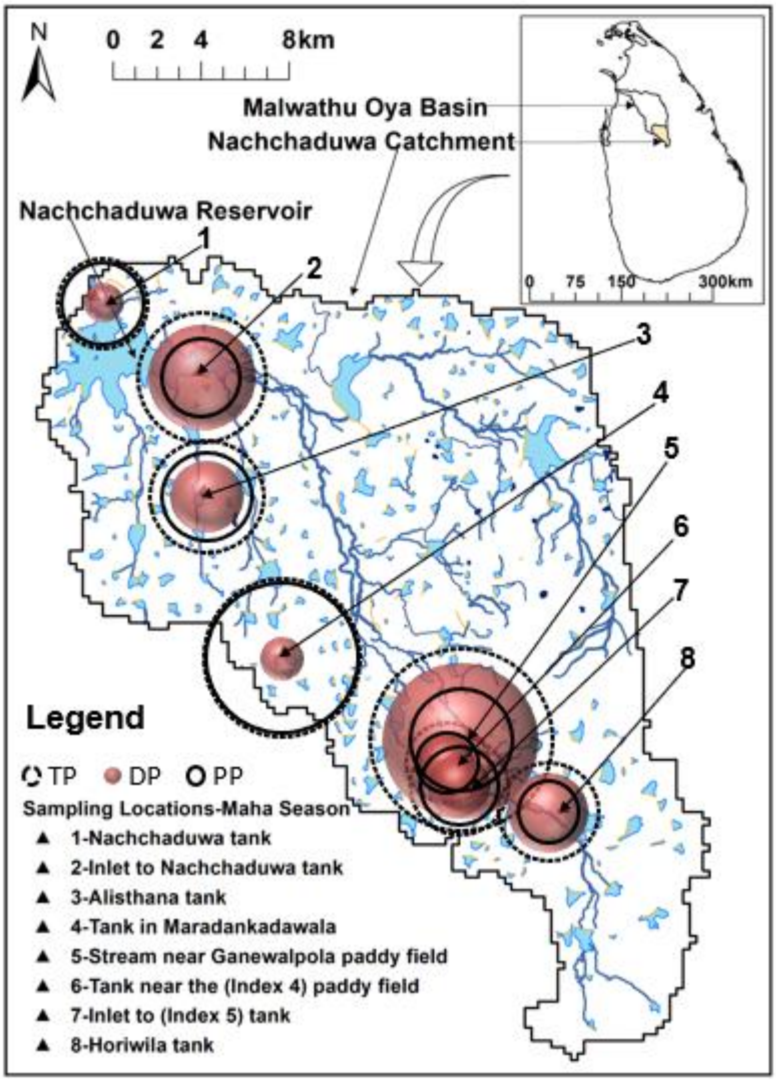


Figure 3.31: Water Quality Test Results (Phosphorus Components) with the Sampling Locations, for the Samples Collected in Maha Season (original in colour)

Table 3.5: Summary of the Water Quality Test Results (Concentrations in ppm)

Season	Water Quality Parameter	Upstream/ Downstream	Mean	Standard Deviation	P-value
Yala (dry)	NH_4^+-N	Upstream	13.750	7.500	0.166
		Downstream	22.750	8.620	
	PO_4^{3-}-P	Upstream	0.370	0.150	0.792
		Downstream	0.340	0.060	
	NO_3^--N	Below the minimum measurable limit of the apparatus			
	NO_2^--N	Below the minimum measurable limit of the apparatus			
Maha (wet)	TN	Upstream	0.859	0.016	0.306
		Downstream	0.935	0.003	
	DN	Upstream	0.694	0.028	0.204
		Downstream	0.838	0.014	
	PN	Upstream	0.165	0.025	0.480
		Downstream	0.097	0.008	
	TP	Upstream	0.016	0.000	0.170
		Downstream	0.060	0.003	
	DP	Upstream	0.062	0.004	0.383
		Downstream	0.027	0.001	
	PP	Upstream	0.045	0.000	0.307
		Downstream	0.079	0.003	

3.2.8 Fertilizer Related Data

Fertilizer issuance data for Urea [$CO(NH_2)_2$], Triple Super Phosphate (TSP) [$Ca(H_2PO_4)_2.H_2O$] and Muriate of Potash (MOP) [KCl] fertilizers, from 2011 Yala to 2015/2016 Maha seasons in the entire Anuradhapura district have been collected from the Anuradhapura Divisional Secretariat Division Office. The Divisional Secretariat Divisions (DSD) and their related Agrarian Service Centres (ASC), their total area, the area inside the catchment, paddy, other crops and homestead areas, required as model inputs have been estimated by the spatial maps using ArcGIS (Figure 3.32), and are summarised in Table 3.6.

All the fertilizer issued by the Anuradhapura DSD has been assumed to be applied for paddy. Missing data were filled by the seasonal average values (average of Yala and Maha seasons from 2011 to 2016), and the data set was developed from 2008 Yala to 2016 Yala season. Urea is composed of 46% Nitrogen and TSP is composed of 45% Phosphorus. It was assumed that 30% and 10% of the fertilizer amount applied for paddy is equal to the fertilizer amounts applied for other crops and homesteads, respectively. For paddy, other crops and homesteads, the monthly average values of applied Nitrogen and Phosphorus amounts (kg/ha) of each month have been calculated (considering the data for years 2008 Yala to 2016 Yala), according to the application patterns of fertilizers relevant to the current practices in the catchment. The applied amounts were compared with the required amounts of fertilizers which were found by literature (Table 3.7). It has been noted that in this sub-catchment, the applied Nitrogen and Phosphorus amounts (kg/ha) in almost all months for all three types of crops that were considered have exceeded the plant required amounts (refer Table 3.8 to Table 3.13). For a detailed description about the fertilizer related data pre-processing procedures please refer Annex A.

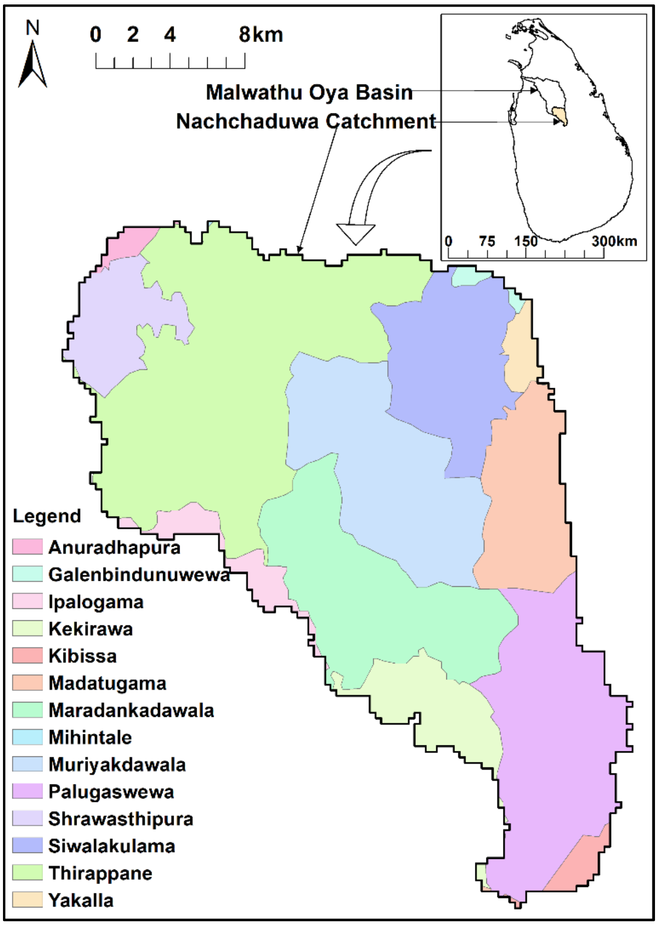


Figure 3.32: Agrarian Service Centres (ASC) inside the Nachchaduwa Catchment (original in colour)

Table 3.6: Crop area in every Agrarian Service Centres (ASC)

DSD	Relevant ASC Inside Catchment	Total ASC Area (km^2)	ASC Area Inside Catchment (km^2)	Paddy Area Inside ASC Inside Catchment (km^2)	Other Crops Area Inside ASC Inside Catchment (km^2)	Homesteads Area Inside ASC Inside Catchment (km^2)	ASC Number for ninout Input File
Galenbindunuwewa	Siwalakulama	55.17	54.96	14.58	0.00	5.66	1
	Yakalla	63.86	8.51	1.03	0.00	0.68	2
	Galenbindunuwewa	168.46	2.89	0.36	0.00	0.20	3
Ipalogama	Ipalogama	142.25	10.42	0.66	0.67	0.61	4
Kekirawa	Kekirawa	117.39	26.36	4.11	0.00	2.37	5
	Maradankadawala	79.51	78.06	13.04	0.00	6.94	6
	Madatugama	144.16	46.82	5.55	0.00	2.86	7
Mihintale	Mihintale	234.56	0.39	0.00	0.00	0.00	8
Nachchaduwa	Shrawasthipura	117.12	25.60	1.51	0.00	0.77	9
Nuwaragam Palatha East	Anuradhapura	88.16	3.46	0.27	0.00	0.74	10
Palugaswewa	Palugaswewa	198.22	90.37	9.80	4.68	5.40	11
Thirappane	Thirappane	200.82	165.31	21.38	1.53	17.77	12
	Muriyakadawala	78.24	78.24	13.09	0.00	6.86	13
Dambulla	Kibissa	152.24	6.77	0.34	3.24	0.49	14

Table 3.7: Required Amounts of Fertilizers for Crops

Crop Type	Growth Stage	Required Amount	Yala	Maha	Reference/ Remarks
Paddy	Day of transplanting (basal application)	40 kg/ha Phosphorus	April	October	United States Peace Corps (1980)
	Active tillering (first top dressing)	20 kg/ha Nitrogen	May, June	November, December	
		20 kg/ha Potassium			
	Panicle initiation (second top dressing)	20 kg/ ha Nitrogen	July, August, September	January, February, March	
		20 kg/ha Potassium			
Other Crops	Basal dressing (before sowing)	16.1 kg/ha Nitrogen	April	October	Mung beans (Field Crops Research and Development Institute, n.d.)
		45 kg/ha Phosphorus			
	Top dressing (at flowering)	13.8 kg/ha Nitrogen	May, June	November, December	
	No fertilizer required		July, August, September	January, February, March	
Homesteads	Basal dressing (before sowing)	3.22 kg/ha Nitrogen	April	October	Assumption: one fifth of the required amount for other crops (Field Crops Research and Development Institute, n.d.)
		9 kg/ha Phosphorus			
	Top dressing (at flowering)	2.76 kg/ha Nitrogen	May, June	November, December	
	No fertilizer required		July, August, September	January, February, March	

Table 3.8: Comparison of the Monthly Average Values of Applied Nitrogen Amounts (kg/ha) of Each Month, with the Required Amount, for Paddy (original in colour)

Required Value (kg/ha)	20	20	20	0	20	20	20	20	20	0	20	20
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama	0	0	7.23	10.84	7.23	3.61	0	0	21.81	33.49	22.32	11.16
Yakalla	0	0	25.16	37.74	25.16	12.58	0	0	46.56	71.10	47.40	23.70
Galenbindunuwewa	0	0	33.29	49.94	33.29	16.65	0	0	66.55	101.88	67.92	33.96
Ipalogama	0	0	69.03	103.54	69.03	34.51	0	0	115.28	175.80	117.20	58.60
Kekirawa	0	0	17.14	25.70	17.14	8.57	0	0	38.94	59.57	39.71	19.86
Maradankadawala	0	0	10.64	15.96	10.64	5.32	0	0	23.66	35.80	23.87	11.93
Madatugama	0	0	27.04	40.56	27.04	13.52	0	0	42.37	64.53	43.02	21.51
Mihintale												
Shrawasthipura	0	0	68.62	102.92	68.62	34.31	0	0	110.25	167.96	111.98	55.99
Anuradhapura	0	0	9.34	14.01	9.34	4.67	0	0	29.47	44.72	29.81	14.91
Palugaswewa	0	0	9.05	13.57	9.05	4.52	0	0	24.84	37.90	25.27	12.63
Thirappane	0	0	9.11	13.66	9.11	4.55	0	0	22.83	34.51	23.00	11.50
Muriyakadawala	0	0	9.17	13.76	9.17	4.59	0	0	25.72	38.93	25.95	12.98
Kibissa	0	0	25.31	37.96	25.31	12.65	0	0	69.48	106.00	70.67	35.33

Table 3.9: Comparison of the Monthly Average Values of Applied Phosphorus Amounts (kg/ha) of Each Month, with the Required Amount, for Paddy (original in colour)

Required Value (kg/ha)	0	0	0	40	0	0	0	0	0	40	0	0
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama	0	0	6.07	6.07	0	0	0	0	12.79	13.30	0	0
Yakalla	0	0	14.88	14.88	0	0	0	0	26.07	27.04	0	0
Galenbindunuwewa	0	0	19.64	19.64	0	0	0	0	37.93	39.48	0	0
Ipalogama	0	0	39.76	39.76	0	0	0	0	66.17	68.66	0	0
Kekirawa	0	0	9.51	9.51	0	0	0	0	22.50	23.37	0	0
Maradankadawala	0	0	6.33	6.33	0	0	0	0	13.84	14.21	0	0
Madatugama	0	0	14.48	14.48	0	0	0	0	23.96	24.86	0	0
Mihintale												
Shrawasthipura	0	0	36.73	36.73	0	0	0	0	62.11	64.35	0	0
Anuradhapura	0	0	5.74	5.74	0	0	0	0	16.37	16.89	0	0
Palugaswewa	0	0	5.52	5.52	0	0	0	0	14.51	15.01	0	0
Thirappane	0	0	5.86	5.86	0	0	0	0	13.34	13.66	0	0
Muriyakadawala	0	0	5.63	5.63	0	0	0	0	14.70	15.09	0	0
Kibissa	0	0	15.44	15.44	0	0	0	0	40.59	41.97	0	0

Table 3.10: Comparison of the Monthly Average Values of Applied Nitrogen Amounts (kg/ha) of Each Month, with the Required Amount, for Other Crops (original in colour)

Required Value (kg/ha)	0	0	0	16.1	13.8	13.8	0	0	0	16.1	13.8	13.8
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama												
Yakalla												
Galenbindunuwewa												
Ipalogama	11.65	11.65	11.65	27.44	27.44	6.86	6.86	6.86	6.86	46.60	46.60	11.65
Kekirawa												
Maradankadawala												
Madatugama												
Mihintale												
Shrawasthipura												
Anuradhapura												
Palugaswewa	5.29	5.29	5.29	7.58	7.58	1.90	1.90	1.90	1.90	21.18	21.18	5.29
Thirappane	32.09	32.09	32.09	50.81	50.81	12.70	12.70	12.70	12.70	128.35	128.35	32.09
Muriyakadawala												
Kibissa	0.74	0.74	0.74	1.07	1.07	0.27	0.27	0.27	0.27	2.98	2.98	0.74

Table 3.11: Comparison of the Monthly Average Values of Applied Phosphorus Amounts (kg/ha) of Each Month, with the Required Amount, for Other Crops (original in colour)

Required Value (kg/ha)	0	0	0	45	0	0	0	0	0	45	0	0
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama												
Yakalla												
Galenbindunuwewa												
Ipalogama	3.41	3.41	3.41	7.90	7.90	1.98	1.98	1.98	1.98	13.65	13.65	3.41
Kekirawa												
Maradankadawala												
Madatugama												
Mihintale												
Shrawasthipura												
Anuradhapura												
Palugaswewa	1.57	1.57	1.57	2.31	2.31	0.58	0.58	0.58	0.58	6.29	6.29	1.57
Thirappane	9.53	9.53	9.53	16.34	16.34	4.09	4.09	4.09	4.09	38.12	38.12	9.53
Muriyakadawala												
Kibissa	0.22	0.22	0.22	0.33	0.33	0.08	0.08	0.08	0.08	0.88	0.88	0.22

Table 3.12: Comparison of the Monthly Average Values of Applied Nitrogen Amounts (kg/ha) of Each Month, with the Required Amount, for Homesteads (original in colour)

Required Value (kg/ha)	0	0	0	3.22	2.76	2.76	0	0	0	3.22	2.76	2.76
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama	3.83	3.83	3.83	1.24	1.24	1.24	1.24	1.24	1.24	3.83	3.83	3.83
Yakalla	4.82	4.82	4.82	2.56	2.56	2.56	2.56	2.56	2.56	4.82	4.82	4.82
Galenbindunuwewa	8.32	8.32	8.32	4.08	4.08	4.08	4.08	4.08	4.08	8.32	8.32	8.32
Ipalogama	8.45	8.45	8.45	4.98	4.98	4.98	4.98	4.98	4.98	8.45	8.45	8.45
Kekirawa	4.59	4.59	4.59	1.98	1.98	1.98	1.98	1.98	1.98	4.59	4.59	4.59
Maradankadawala	2.99	2.99	2.99	1.33	1.33	1.33	1.33	1.33	1.33	2.99	2.99	2.99
Madatugama	5.57	5.57	5.57	3.50	3.50	3.50	3.50	3.50	3.50	5.57	5.57	5.57
Mihintale												
Shrawasthipura	14.69	14.69	14.69	9.00	9.00	9.00	9.00	9.00	9.00	14.69	14.69	14.69
Anuradhapura	0.73	0.73	0.73	0.23	0.23	0.23	0.23	0.23	0.23	0.73	0.73	0.73
Palugaswewa	3.06	3.06	3.06	1.09	1.09	1.09	1.09	1.09	1.09	3.06	3.06	3.06
Thirappane	1.85	1.85	1.85	0.73	0.73	0.73	0.73	0.73	0.73	1.85	1.85	1.85
Muriyakadawala	3.30	3.30	3.30	1.17	1.17	1.17	1.17	1.17	1.17	3.30	3.30	3.30
Kibissa	3.27	3.27	3.27	1.17	1.17	1.17	1.17	1.17	1.17	3.27	3.27	3.27

Table 3.13: Comparison of the Monthly Average Values of Applied Phosphorus Amounts (kg/ha) of Each Month, with the Required Amount, for Homesteads (original in colour)

Required Value (kg/ha)	0	0	0	9	0	0	0	0	0	9	0	0
Agr. Serv. Cen. (ASC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siwalakulama	1.14	1.14	1.14	0.52	0.52	0.52	0.52	0.52	0.52	1.14	1.14	1.14
Yakalla	1.37	1.37	1.37	0.76	0.76	0.76	0.76	0.76	0.76	1.37	1.37	1.37
Galenbindunuwewa	2.42	2.42	2.42	1.20	1.20	1.20	1.20	1.20	1.20	2.42	2.42	2.42
Ipalogama	2.47	2.47	2.47	1.43	1.43	1.43	1.43	1.43	1.43	2.47	2.47	2.47
Kekirawa	1.35	1.35	1.35	0.55	0.55	0.55	0.55	0.55	0.55	1.35	1.35	1.35
Maradankadawala	0.89	0.89	0.89	0.40	0.40	0.40	0.40	0.40	0.40	0.89	0.89	0.89
Madatugama	1.61	1.61	1.61	0.94	0.94	0.94	0.94	0.94	0.94	1.61	1.61	1.61
Mihintale												
Shrawasthipura	4.22	4.22	4.22	2.41	2.41	2.41	2.41	2.41	2.41	4.22	4.22	4.22
Anuradhapura	0.21	0.21	0.21	0.07	0.07	0.07	0.07	0.07	0.07	0.21	0.21	0.21
Palugaswewa	0.91	0.91	0.91	0.33	0.33	0.33	0.33	0.33	0.33	0.91	0.91	0.91
Thirappane	0.55	0.55	0.55	0.23	0.23	0.23	0.23	0.23	0.23	0.55	0.55	0.55
Muriyakadawala	0.96	0.96	0.96	0.36	0.36	0.36	0.36	0.36	0.36	0.96	0.96	0.96
Kibissa	0.97	0.97	0.97	0.36	0.36	0.36	0.36	0.36	0.36	0.97	0.97	0.97

3.3 WEP Model Analysis

3.3.1 Preparation of Input Files

There is a total of 43 hydrological component input files and 14 material transport component input files necessary for the WEP model run. The Digital Elevation Model (DEM) obtained by the Survey Department had a resolution of 90 m. It was reclassified using ArcGIS to obtain a 300 m by 300 m resolution grid for the catchment. The input files containing the elevation, slope, flow direction and flow accumulation of each grid cell were developed by using ArcGIS and Excel VBA macros. The stream was divided into 13 channel sections. For this study, 9 soil layers; interception layer, depression layer, three upper soil layers (thickness 0.2 m, 0.4 m, 1.4 m), transition layer (0.5 m), unconfined aquifer (12 m), aquitard 1 (12 m), confined aquifer 1 (12 m), aquitard 2 (12 m), confined aquifer 2 (12 m) were considered based on the actual formation of strata in the soil. Thickness of each layer and initial moisture content of each surface soil layer (3 layers) in each grid, were given as related input files. The Grama Niladari Division (GND) wise population and water supply data for the year 2012 were found from the statistical reports published (Department of Census and Statistics-Sri Lanka, 2012). The population density and the well density related to each cell was computed to prepare relevant input files. More details about preparation of input files are given in Appendix A.

Further, input files for the material transport component were prepared using the previously calculated fertilizer data for all crops, considering N and P. It was assumed that the total amount of nutrients a plant would absorb (kg) is equal to the required amount to the plant. Amount of N was presumed as the summation of the amount added by fertilizer and the amount produced in farmlands from N fixation [by lightning (Miyamoto, Ketterings, Cherney, & Kilcer, 2008), by combustion (Deacon, n.d.), and by plant N fixation (Cash, Melton, Gregory, & Cihacek, 1981; Walley, Tomm, Matus, Slinkard, & Van Kessel, 1996)]. De-nitrification was analysed by the model itself and for further details of the modelling approach of the non-point and point sources of pollution, one is referred to Rajapakse et al. (2010).

Apart from these, input files related to the controlling parameters, sub-catchment delineation, land use, meteorological data, soil parameters, river channel element details, aquifer details, initial groundwater levels, etc. have also been prepared for the model runs.

3.3.2 WEP Model Analysis

The input files prepared for the time period 2008 to 2011 were used for the calibration model runs, and the input files prepared for the time period 2012 to 2015 were used for the validation model runs. Since WEP is a hydrological and material transport model, initially the hydrological component was calibrated/validated and then the material transport component was calibrated/validated. The WEP model stream flow results were compared with the developed HEC-HMS model results and objective function values (error coefficients) such as Pearson Correlation Coefficient, R Squared Value, Root Mean Square Error, Nash-Sutcliffe Model Efficiency Coefficient, Mean Absolute Percentage Error were calculated for the calibration and validation periods. Further, the daily runoff coefficient for the HEC-HMS modelled values and the WEP model results were compared.

The TSS values obtained from the WEP model results were analysed for the wet season and dry season separately. Several water quality studies have been conducted focusing on the Nachchaduwa catchment (Perera et al., 2014; Wijesundara et al., 2012; Wijesundara et al., 2013) and the WEP model results were compared with the findings of those studies. In addition, the water quality test results were compared with the WEP model results.

3.3.3 Parameter Sensitivity Analysis

When comparing the WEP model results with the published water quality results, it has been identified that Phosphorus is the limiting factor. Therefore, the sensitivity of the WEP model results, with all the parameters governing the Phosphorus components in all the material transport component input files were analysed. The input files which have the maximum sensitivity to the model results were identified as “surfaceC.csv” (the input file which relates to material movement for the overland flow), “riverC.csv” (the input file which relates to material transport in the river channel) and “nonpointsource.csv” (the input file which relates to non-point source material transport in forest and urban area), and all the P related parameters in those input files were varied by ±25% to check the model sensitivity.

3.3.4 Scenario Analysis

As explained in Section 2.7 of the literature review, and according to the results of the fertilizer data analysis in Section 3.2.8, it is evident that there is an over usage of fertilizers and agro-chemicals in the catchment. Therefore, it is essential to regulate the amounts of fertilizers used to conserve the water quality of the water resources in the basin, hence Scenario 1, 2 and 3 will be done to identify the effect of fertilizer regulation on the water quality. In Scenario 1, 2 and 3, the present condition fertilizer input amounts would be reduced by 25%, 50% and 75%, respectively.

Furthermore, as explained in Section 2.8 literature review, the significance of climate change on the WEP model analysis should be taken into consideration, as the WEP model takes meteorological data as inputs in the analysis. Hence the impacts of the impending climate change would be analysed by using Scenarios 4, 5 and 6, with respect to the present condition. In Scenario 4, all rainfall values (in the present condition) would be increased by 14%. According to the results predicted by De Silva et al. (2007) for 2050s in Sri Lanka, the predicted increase of the average annual rainfall by 14% (A2) would be the worst-case scenario. On the other hand, the effect of the magnitude of extreme climate events would be studied by Scenario 5, where only the extreme rainfall values would be increased/decreased by 5%. The impact of temperature changes would be studied by Scenario 6, where all temperature values would be increased by 1.6 $^{\circ}$C. According to the results predicted by De Silva et al. (2007) for 2050s in Sri Lanka, the average wet season temperature (the average of minimum and maximum air temperature) increases by 1.6 $^{\circ}$C (A2) would be the worst-case scenario.

4 RESULTS AND DISCUSSION

This Chapter elucidates the WEP model results for the present condition, sensitivity analysis results as well as the scenario analysis results, along with the discussion of the said results.

4.1 WEP Model Results (for the Present Condition)

The WEP model is capable of providing time series values of water and heat balance as well as water quality/material transport results for each grid, as outputs. The results pertaining to the hydrological and material transport processes have been presented. Although the WEP model analysis produces a number of results files of various parameters, only the most important results have been presented here. The results which would be used to do the comparison of scenarios were given priority while presenting the results.

4.1.1 Streamflow comparison with HEC-HMS model results

The WEP model generated streamflow values have been compared with the streamflow timeseries obtained based on calibrated HEC-HMS model for both calibration and validation periods. The WEP model streamflow values are matching with the HEC-HMS model streamflow values (Figure 4.1 and Figure 4.2), and validation period showed better values for the error coefficients (Table 4.1).

Table 4.1: Error Coefficients for the Calibration and Validation Period

Error Coefficient	Calibration	Validation
Pearson Correlation Coefficient (PEARSON)	0.6439	0.6875
R Squared Value (RSQ)	0.4146	0.4727
Root Mean Square Error (RMSE)	9.3987	11.8675
Nash–Sutcliffe Model Efficiency Coefficient	0.3872	0.4274
Mean Absolute Percentage Error (MAPE)	0.2351	0.2351
Daily Runoff Coefficient (HEC-HMS)	0.2711	0.2734
Daily Runoff Coefficient (WEP)	0.3278	0.3293

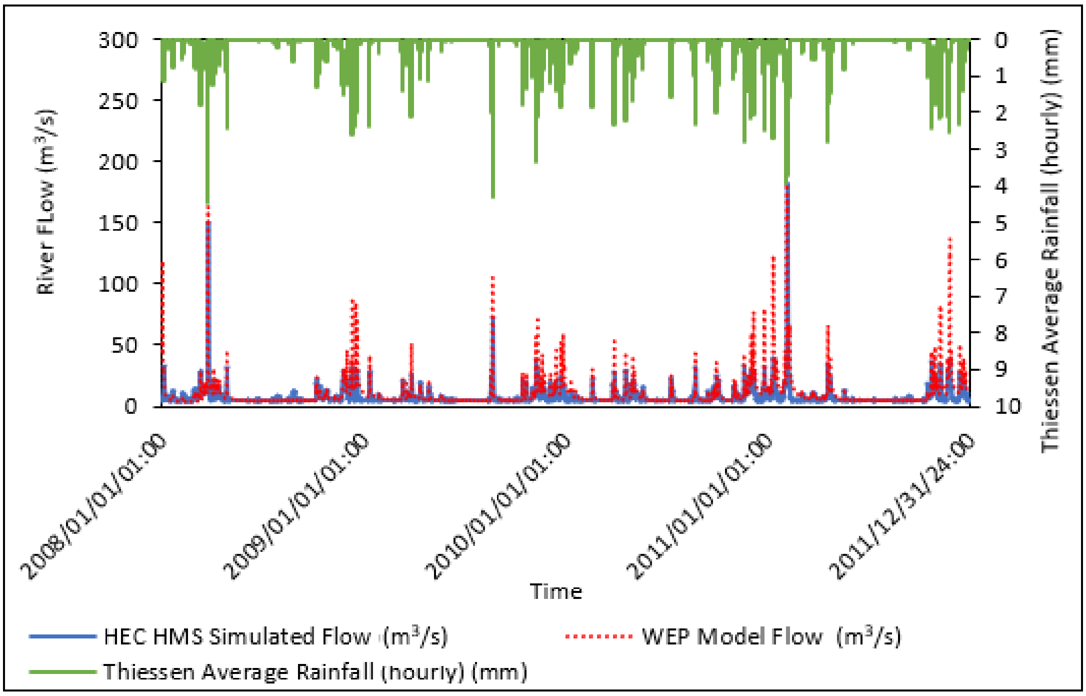


Figure 4.1: Streamflow Comparison with HEC-HMS Model Results for the Calibration Period

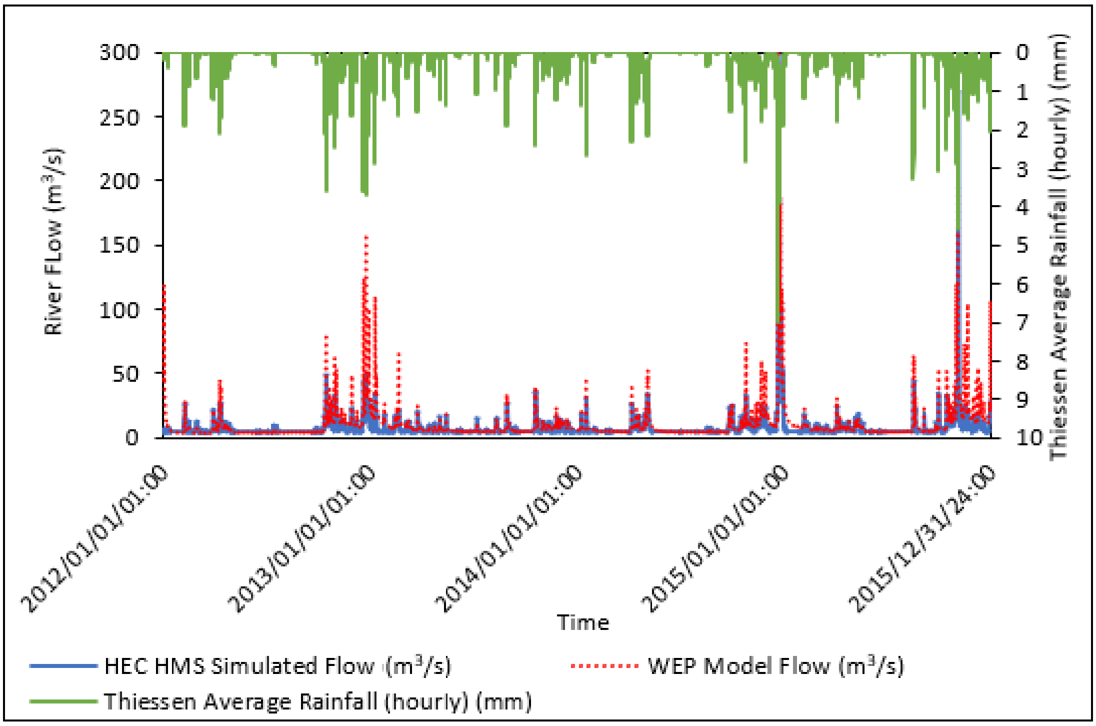


Figure 4.2: Streamflow Comparison with HEC-HMS Model Results for the Validation Period

4.1.2 Temporal variation of results

The “01river.csv” output file gives the results of river related parameters, including, the average value of the river flow, nutrient components (N and P), and suspended solids, in the rivers that have been specified (river numbers 11,12 and 13; refer Appendix A).

The temporal variation results [river flow, TSS, N components (PN - Particulate Nitrogen, DN - Dissolved Nitrogen, TN - Total Nitrogen), and P components (PP - Particulate Phosphorus, DP - Dissolved Phosphorus, TP - Total Phosphorus)] were classified under low flow (percentage exceedance flow rate of total river flow less than 10%), mid flow (percentage exceedance flow rate of total river flow between 45% and 55%), and high flow (percentage exceedance flow rate of total river flow greater than 90%), and have been compared with the three published results.

In addition, the temporal variation results of nutrient components of the WEP model analysis [N components (PN - Particulate Nitrogen, DN - Dissolved Nitrogen, TN - Total Nitrogen), and P components (PP - Particulate Phosphorus, DP - Dissolved Phosphorus, TP - Total Phosphorus)] were classified under the four seasons FIMS, SWMS, SIMS, and NEMS (described in detail under Section 2.3.1), in order to compare them with the three published results. For more details refer Appendix B.

A summary of these classified results is given in Table 4.2, but more detailed calculations of these classified results would be explained under Sections 4.1.2.2 and 4.1.2.3.

Table 4.2: Average Values of Nitrogen and Phosphorus Components, Classified for the Low Flow, Mid Flow, and High Flow, for the Calibration and Validation Periods

	Calibration Period							Validation Period						
	PN Total (mg/l)	DN Total (mg/l)	TN Total (mg/l)	PP Total (mg/l)	DP Total (mg/l)	TP Total (mg/l)	Total SS (mg/l)	PN Total (mg/l)	DN Total (mg/l)	TN Total (mg/l)	PP Total (mg/l)	DP Total (mg/l)	TP Total (mg/l)	Total SS (mg/l)
WEP-Average of values of dry/low flow days (flow<10%)	1.21	1.72	2.93	0.23	0.19	0.42	22.22	1.28	1.76	3.04	0.24	0.18	0.42	26.88
WEP-Average of values of mid-flow days (45%<flow<55%)	0.64	1.46	2.10	0.12	0.14	0.26	0.20	0.66	1.43	2.09	0.11	0.12	0.23	0.21
WEP-Average of values of wet/high flow days (flow>90%)	0.51	0.96	1.46	0.09	0.09	0.18	0.21	0.42	0.56	0.98	0.08	0.05	0.14	0.13

4.1.2.1 Total Suspended Solids (TSS) results

The temporal variation of TSS for the calibration and validation periods are shown in Figure 4.3 and Figure 4.4, respectively. The temporal variation of TSS showed a correlation with the Thiessen average rainfall values, implying that the rainfall would induce a washout of the solids, and hence adding them into the streams. The mean±standard deviation, minimum, maximum of values of TSS were; 0.90±4.56 mg/l, 0.11 mg/l, 87.40 mg/l in the calibration dry seasons, 4.79±14.88 mg/l, 0.13 mg/l, 148.57 mg/l in the calibration wet seasons, 0.76±3.45 mg/l, 0.09 mg/l, 49.94 mg/l in the validation dry seasons, 5.62±20.38 mg/l, 0.10 mg/l, 304.57 mg/l in the validation wet seasons (Table 4.3). Therefore, on average, the wet season has about five (calibration) to seven (validation) times the dry season value of the TSS in the streams. It has been found that the concentration of TSS in rivers increases as a function of flow. TSS concentrations have been shown to be strongly correlated with the streamflow with most of the sediment load transported during peak flow events (Silva, 2004; Wickramaarachchi, Ishidaira, Magome, & Wijayaratna, 2015; Wickramaarachchi, Ishidaira, & Wijayaratna, 2013). Since the streamflow is correlated to the rainfall in this catchment, the peaks and troughs in Figure 4.3 and Figure 4.4 could be justified.

Further, Wickramaarachchi et al. (2013) has found a linear regression relationship between the turbidity (NTU) value and TSS concentration (mg/l) value in a river as; TSS (mg/l) value is equal to 1.0457 times the turbidity (NTU) value. According to Zoysa and Weerasinghe (2016), the Nachchaduwa reservoir had a maximum recorded turbidity value of 22 NTU, which corresponds to a TSS value of 23 mg/l according to the previous relationship. Perera et al (2014) found that the mean turbidity values of the Malwathu Oya river ranged from 81.75 NTU (corresponds to TSS value of 85.49 mg/l) to 256.10 NTU (corresponds to TSS value of 267.80 mg/l). In addition, Gunaratna and Kumari (2016) found that the turbidity values of the Malwathu Oya river main cascade varied from 0.5 NTU (corresponds to TSS value of 0.52 mg/l) to 153 NTU (corresponds to TSS value of 159.99 mg/l). Furthermore, the TSS values of Gin river varied between 2.4 mg/l to 204 mg/l. Therefore, the TSS values obtained from the WEP model analysis are well within the previously published ranges.

Table 4.3: Total Suspended Solids (TSS) Values for the Calibration and Validation Period for the Wet and Dry Seasons

	Calibration Period (2008 - 2011)		Validation Period (2012 - 2015)	
Parameter	Dry	Wet	Dry	Wet
Mean	0.90	4.79	0.76	5.62
Standard Error	4.56	14.88	3.45	20.38
Minimum	0.11	0.13	0.09	0.10
Q1	0.16	0.18	0.11	0.17
Median	0.17	0.32	0.15	0.30
Q3	0.24	1.00	0.20	0.89
Maximum	87.40	148.57	49.94	304.57
Mean (wet)/Mean (dry)	5.33		7.40	

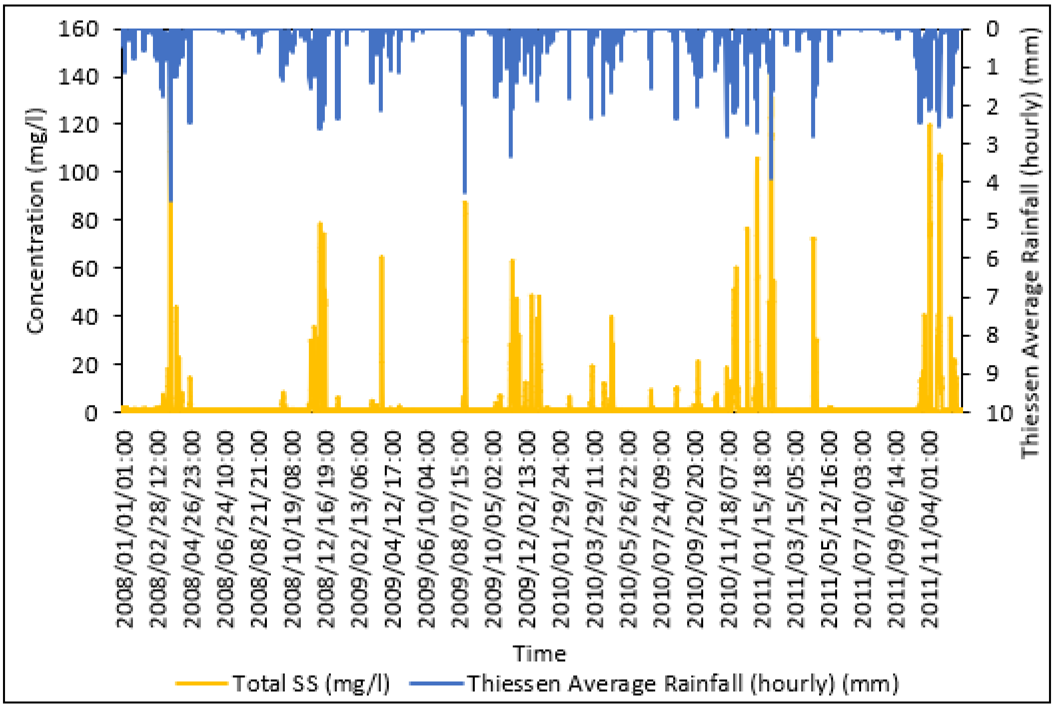


Figure 4.3: Temporal Variation of TSS with the Thiessen Average Rainfall, for the Calibration Period (original in colour)

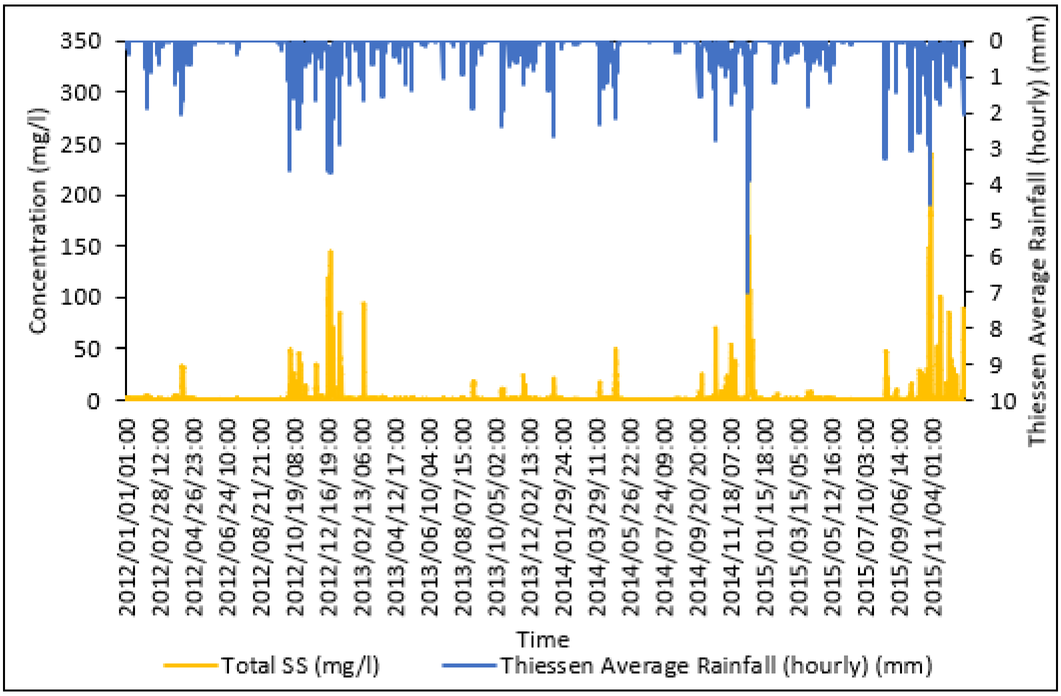


Figure 4.4: Temporal Variation of TSS with the Thiessen Average Rainfall, for the Validation Period (original in colour)

4.1.2.2 Results of Nitrogen components

The temporal variation of Nitrogen components, for the calibration and validation periods are illustrated in Figure 4.5 and Figure 4.6, respectively. The peaks in Figure 4.5 and Figure 4.6 are due to the combined effect from the increases in the input amounts of fertilizer as well as the increased streamflow peaks (due to rainfall). This is justifiable as it has been found that the municipal/industrial effluents as well as the excessive fertilizer usage in agriculture in the study area contribute to the increase in nutrient components in waterways (Madushanka et al., 2015; Perera et al., 2014; Kumari et al., 2016).

For the calibration period, the comparison of WEP model results for the low flows, mid flows, high flows, and for all flows, with the entire duration of the three published results, are illustrated in Figure 4.7, Figure 4.8, Figure 4.9, and Figure 4.10, respectively. Figure 4.11, Figure 4.12, Figure 4.13, and Figure 4.14 show the same for the validation period.

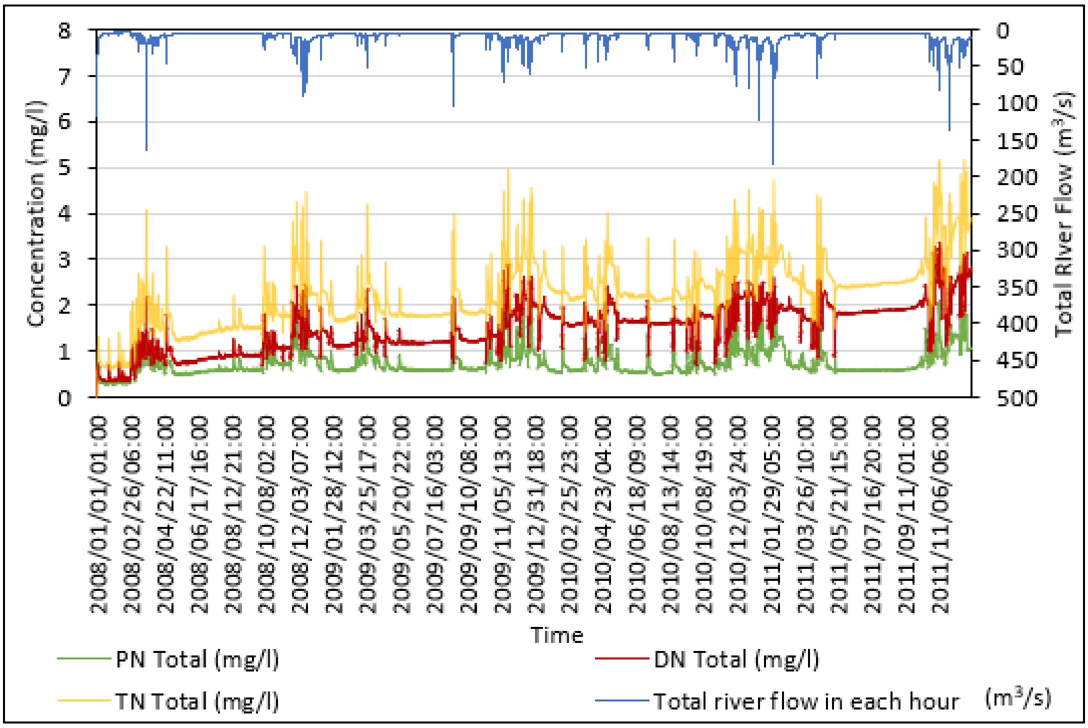


Figure 4.5: Temporal Variation of Nitrogen Components for the Calibration Period (original in colour)

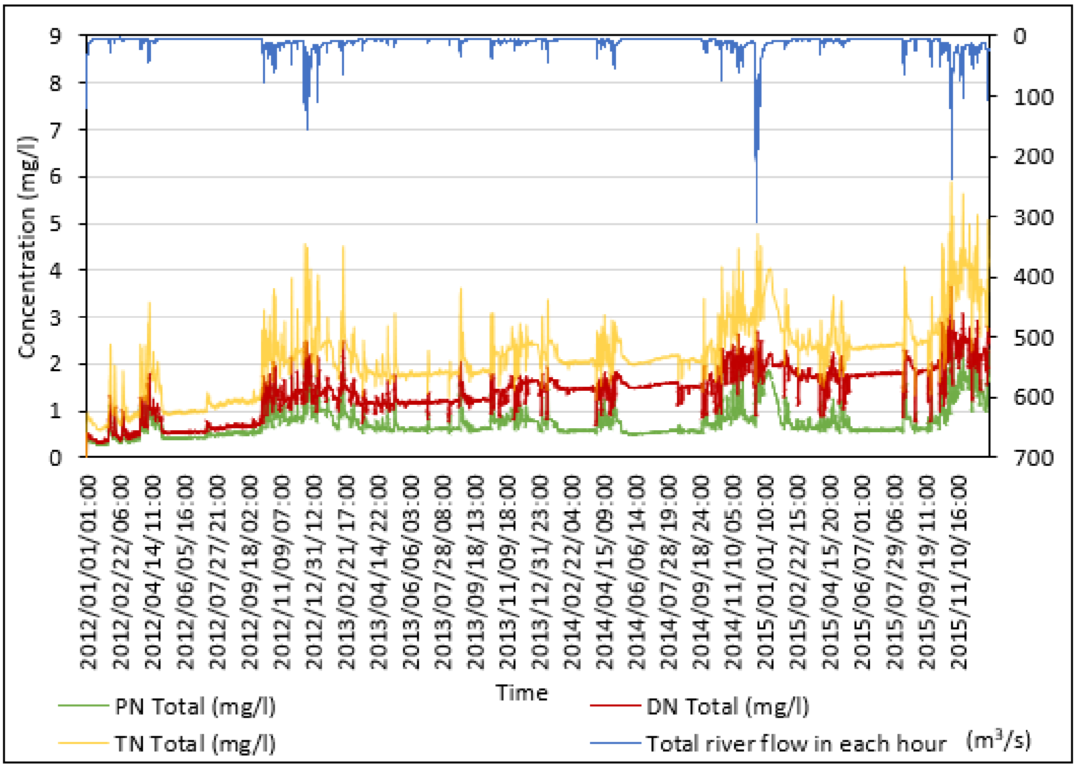


Figure 4.6: Temporal Variation of Nitrogen Components for the Validation Period (original in colour)

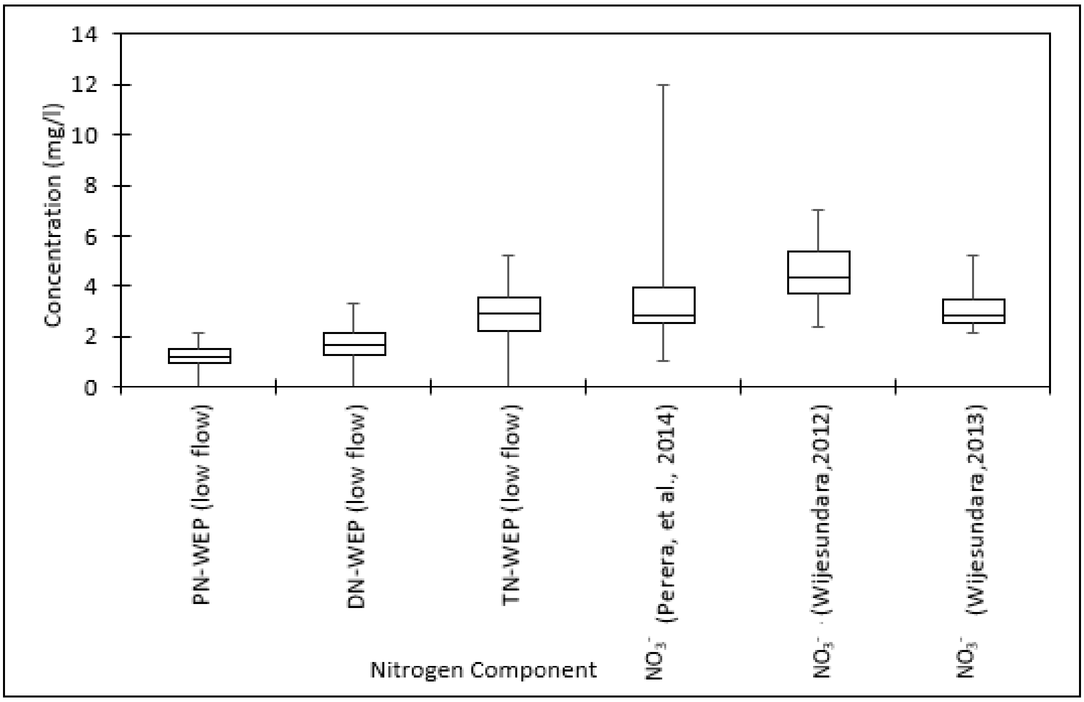


Figure 4.7: Comparison of WEP Model Results of Nitrogen Components for the Low Flows (Calibration Period) with the Entire Duration of the Three Published Results

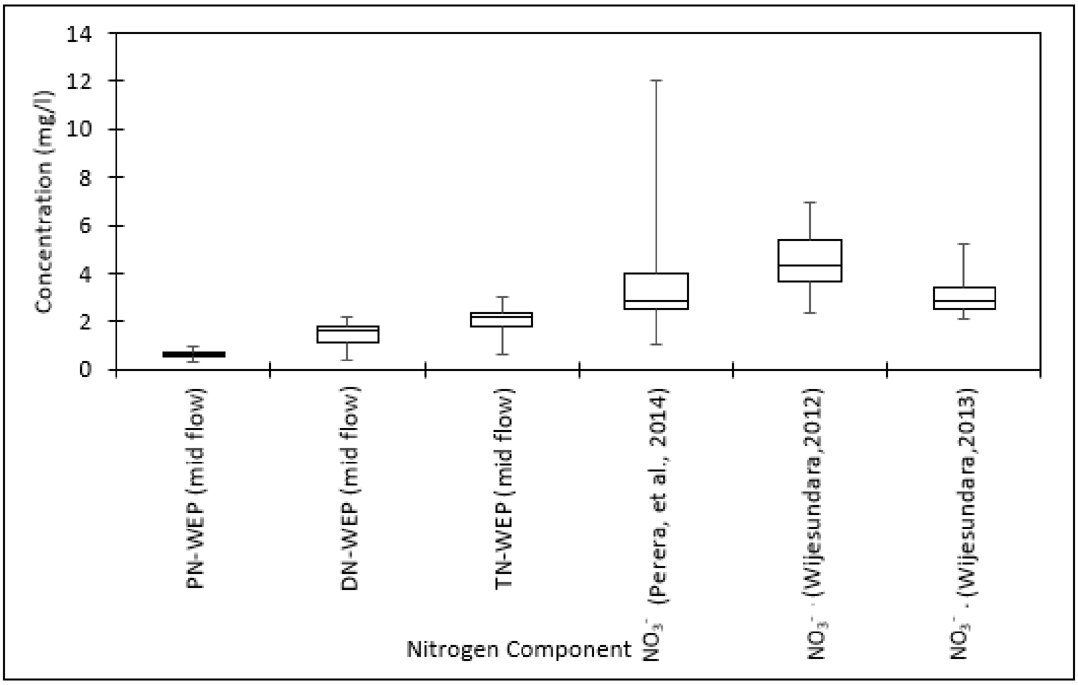


Figure 4.8: Comparison of WEP Model Results of Nitrogen Components for the Mid Flows (Calibration Period) with the Entire Duration of the Three Published Results

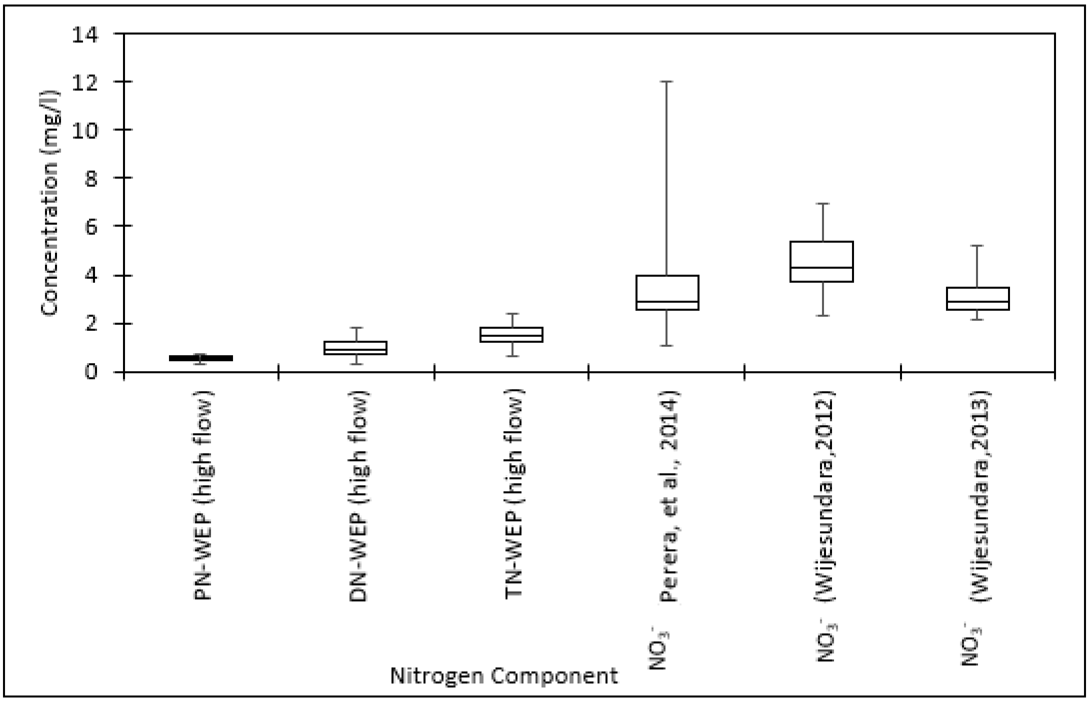


Figure 4.9: Comparison of WEP Model Results of Nitrogen Components for the High Flows (Calibration Period) with the Entire Duration of the Three Published Results

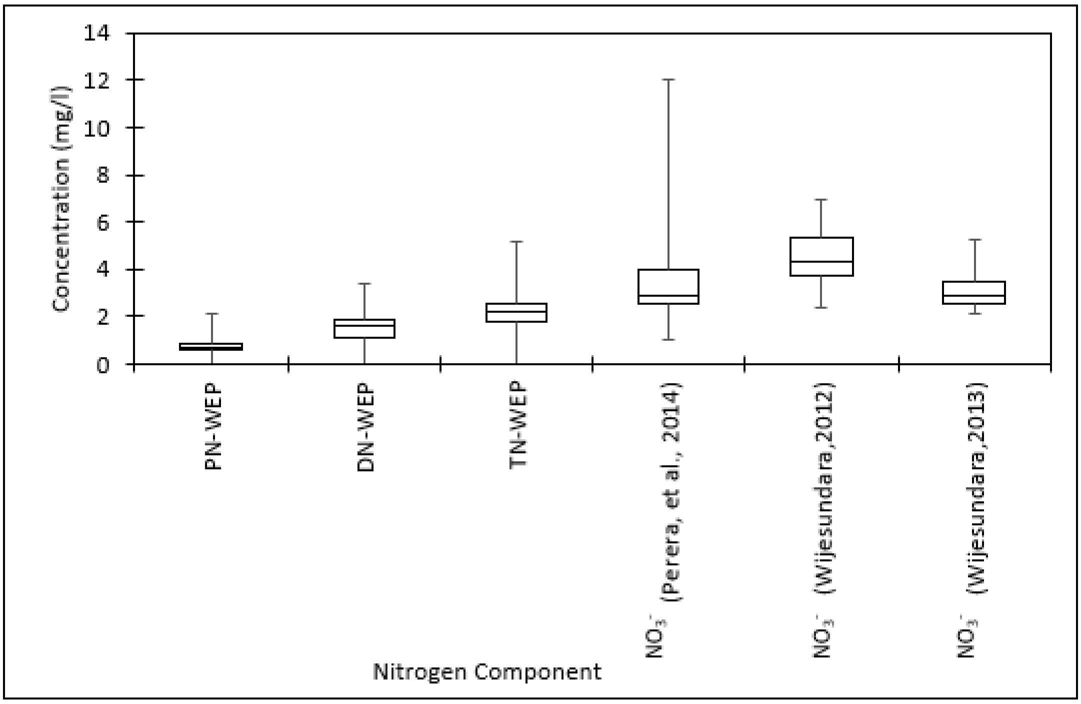


Figure 4.10: Comparison of WEP Model Results of Nitrogen Components for the All Flows (Calibration Period) with the Entire Duration of the Three Published Results

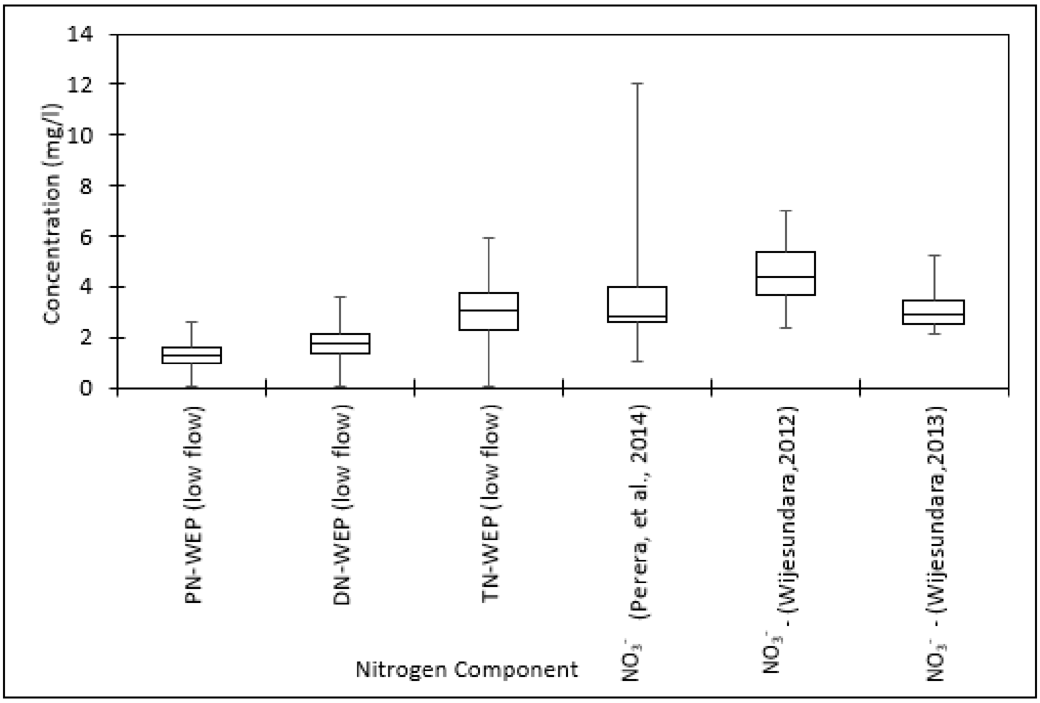


Figure 4.11: Comparison of WEP Model Results of Nitrogen Components for the Low Flows (Validation Period) with the Entire Duration of the Three Published Results

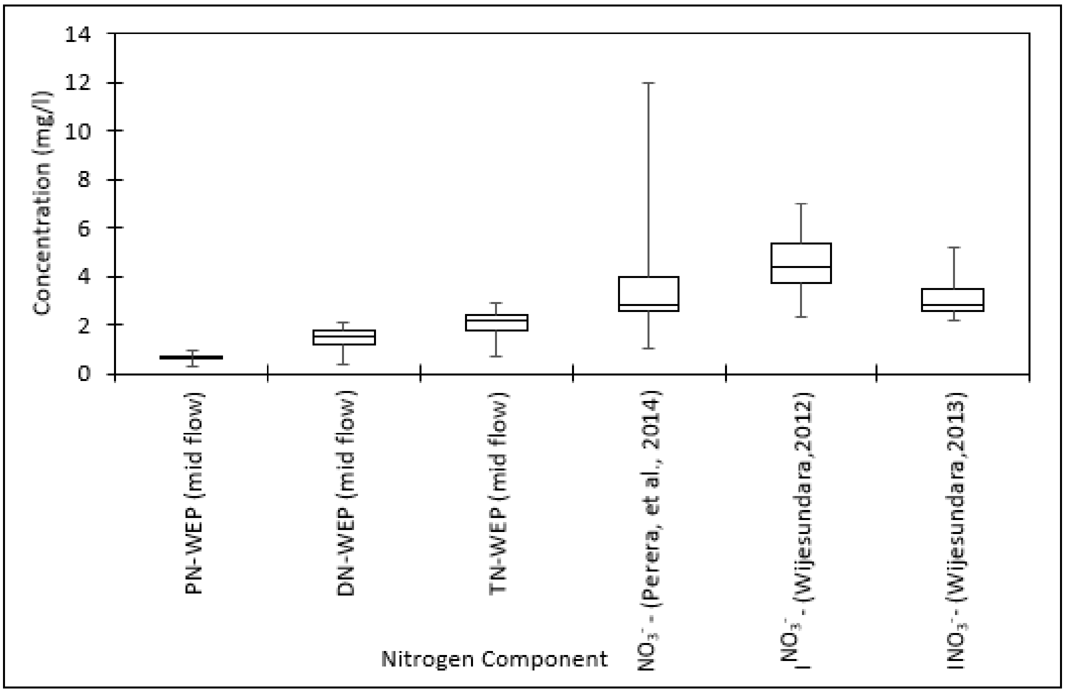


Figure 4.12: Comparison of WEP Model Results of Nitrogen Components for the Mid Flows (Validation Period) with the Entire Duration of the Three Published Results

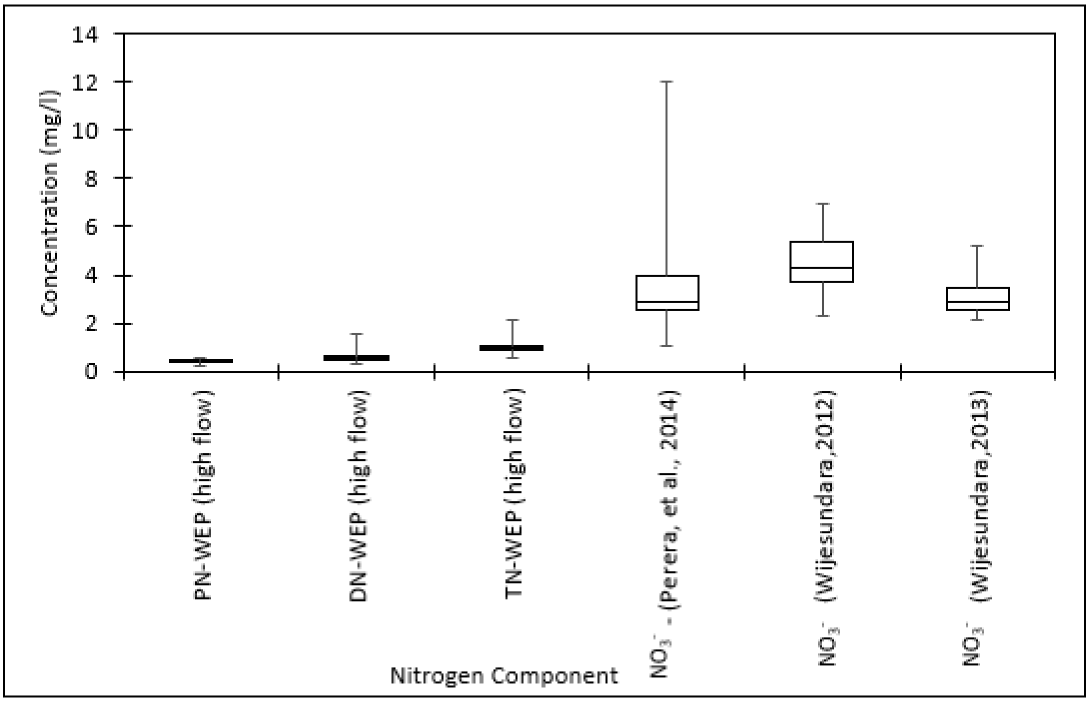


Figure 4.13: Comparison of WEP Model Results of Nitrogen Components for the High Flows (Validation Period) with the Entire Duration of the Three Published Results

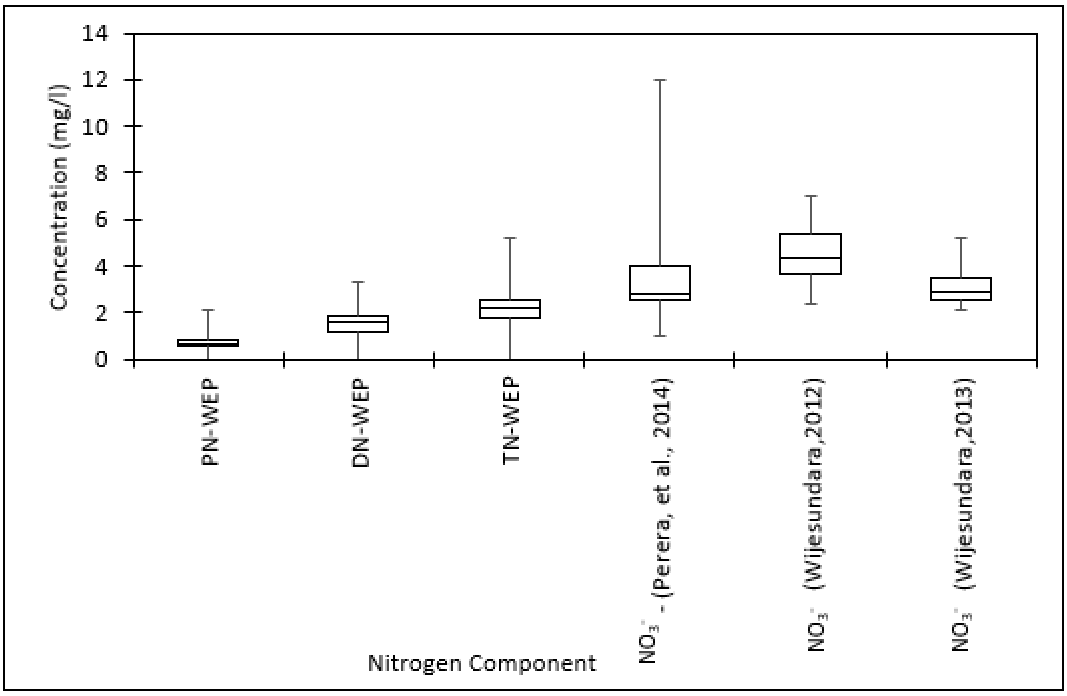


Figure 4.14: Comparison of WEP Model Results of Nitrogen Components for the All Flows (Validation Period) with the Entire Duration of the Three Published Results

It is evident from Figures 4.7 to 4.14 that for the Nitrogen components, for both the calibration period and the validation period, the WEP low flow values show the best match with the published results. The published values are given for NO_3^-, therefore, when comparing, the DN component from the WEP results should be considered. The DN in the WEP low flow conditions ranges from 0.0023 mg/l to 3.3177 mg/l in the calibration period, and in the validation period it ranges from 0.0035 mg/l to 3.6347 mg/l, whereas in the published values it ranges from 1.05 mg/l to 12.00 mg/l (Perera et al., 2014), hence the WEP results could be justified. Further, the three published studies have only measured the water quality as spontaneous measurements, for a shorter duration (only for one-year period), and the water quality parameters under all weather conditions have not been considered (as the sampling has been done once a month in all three studies). But the values of the WEP model results shown are the average of a longer time period (hourly values of all days for a period of four years), and therefore represent a wider and a more reasonable range of values of water quality parameters in the streams.

In addition, the maximum NO_3^- concentration in Malwathu Oya river has been found to be 15 mg/l in the month of August, by Zoysa and Weerasinghe (2016), therefore it could be stated that the WEP results are below the maximum value recorded in the basin and below the threshold value of 10 ppm for drinking water (WHO, 2011). Further, the canals and streams of the adjacent river basin Kala Oya have shown 0.0 mg/l – 10.7 mg/l, 0.0 – 23.4 mg/l of $[NO_3^-]$ and 0.02 mg/l – 2.60 mg/l, 0.22 – 0.66 mg/l of $[PO_4^{3-}]$, respectively (Young et al., 2009). Therefore, in both Yala and Maha seasons, the WEP model results of NO_3^- are within the ranges of the published results. For more details refer Appendix B.

4.1.2.3 Results of Phosphorus components

The temporal variation of Phosphorus components, for the calibration and validation periods are illustrated in Figure 4.15 and Figure 4.16, respectively. The peaks in Figure 4.15 and Figure 4.16 are due to the combined effect from the increases in the input amounts of fertilizer as well as the increased streamflow peaks (due to rainfall). This is justifiable as it has been found that the municipal/industrial effluents as well as the excessive fertilizer usage in agriculture in the study area contribute to the increase in nutrient components in waterways (Madushanka et al., 2015; Perera et al., 2014; Kumari et al., 2016).

For the calibration period, the comparison of WEP model results for the low flows, mid flows, high flows, and for all flows, with the entire duration of the three published results, are illustrated in Figure 4.17, Figure 4.18, Figure 4.19, and Figure 4.20, respectively. Figure 4.21, Figure 4.22, Figure 4.23, and Figure 4.24 show the same for the validation period.

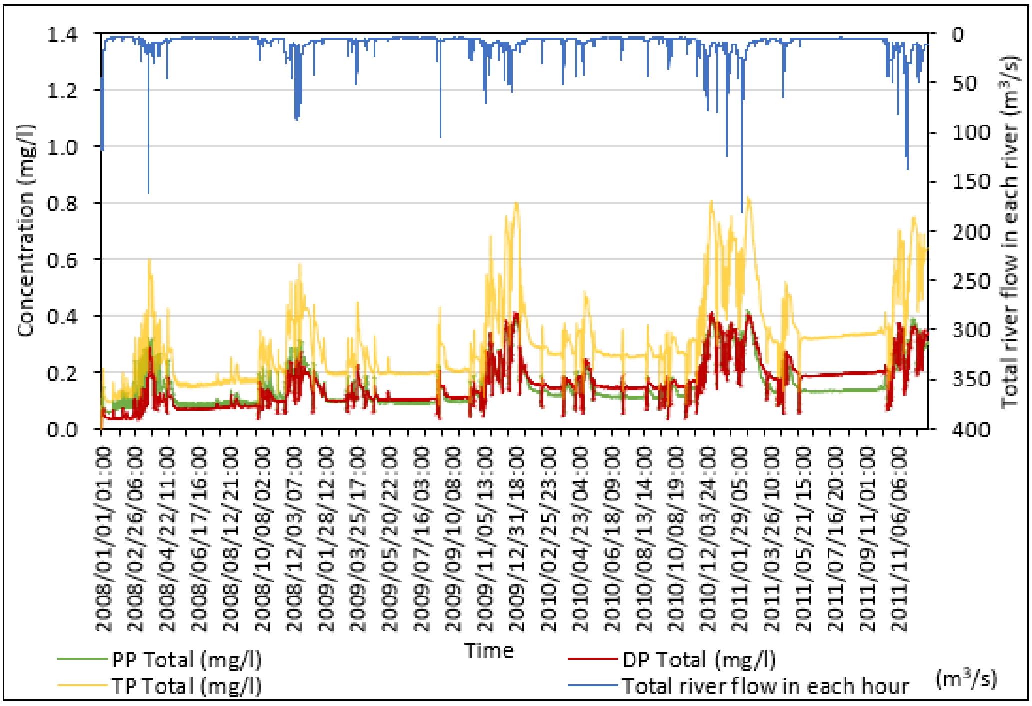


Figure 4.15: Temporal Variation of Phosphorus Components for the Calibration Period (original in colour)

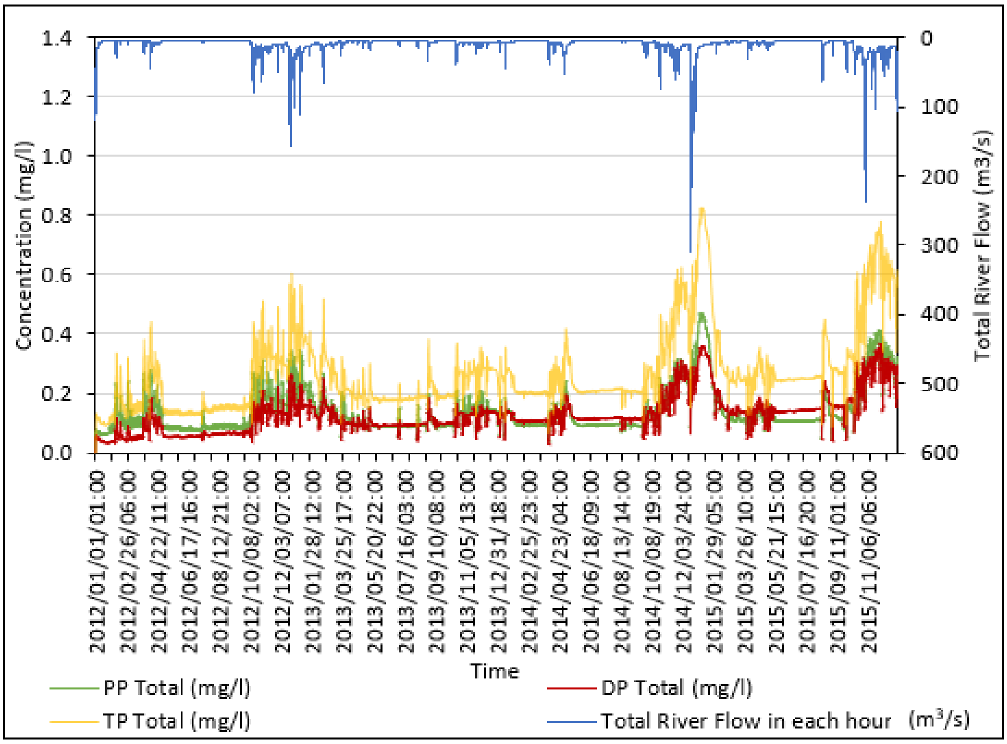


Figure 4.16: Temporal Variation of Phosphorus Components for the Validation Period (original in colour)

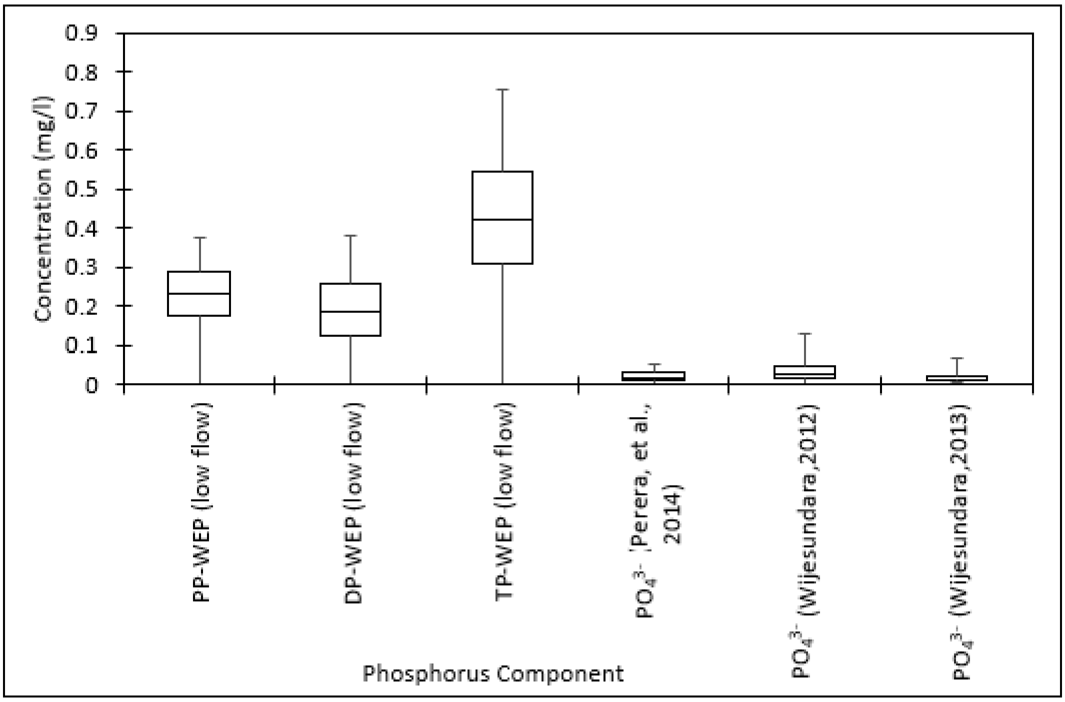


Figure 4.17: Comparison of WEP Model Results of Phosphorus Components for the Low Flows (Calibration Period) with the Entire Duration of the Three Published Results

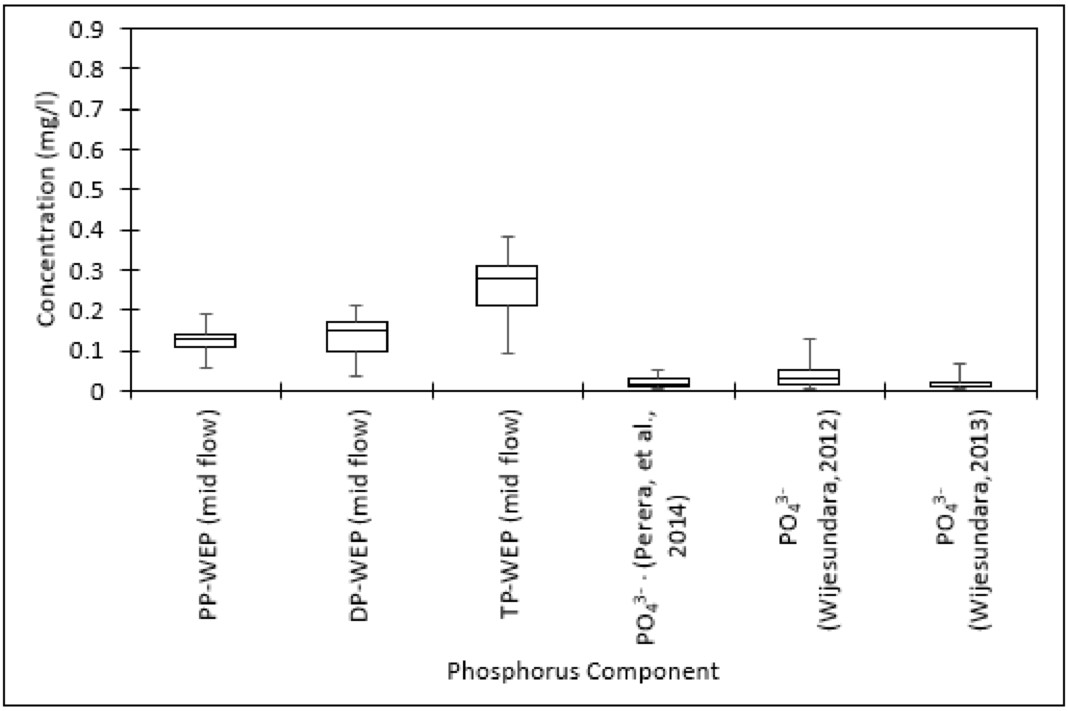


Figure 4.18: Comparison of WEP Model Results of Phosphorus Components for the Mid Flows (Calibration Period) with the Entire Duration of the Three Published Results

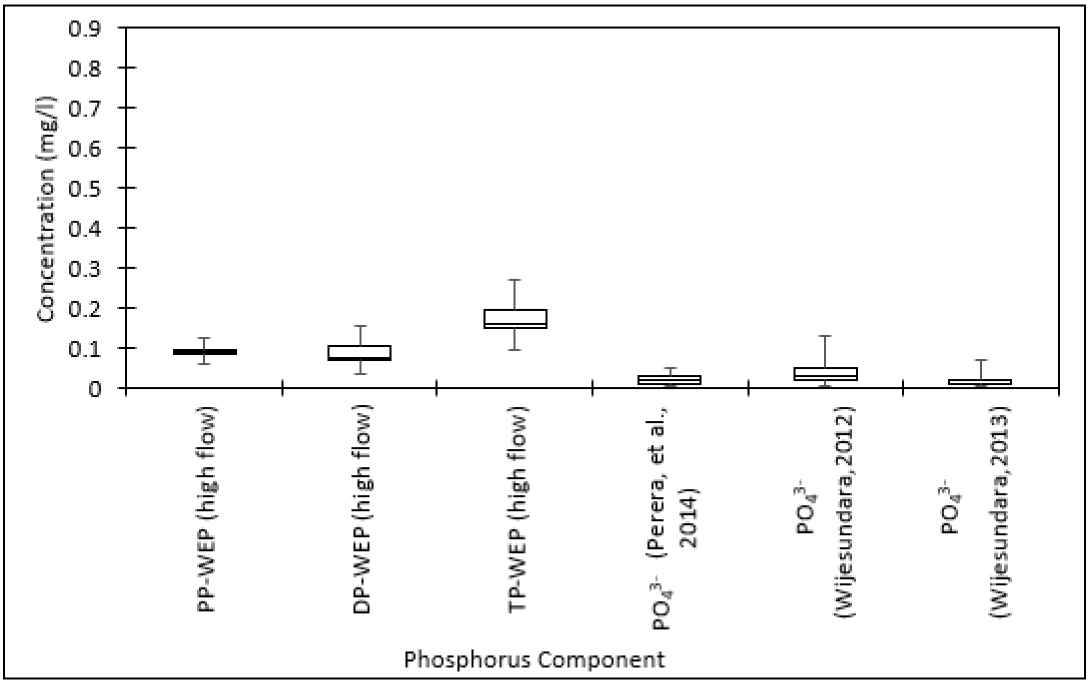


Figure 4.19: Comparison of WEP Model Results of Phosphorus Components for the High Flows (Calibration Period) with the Entire Duration of the Three Published Results

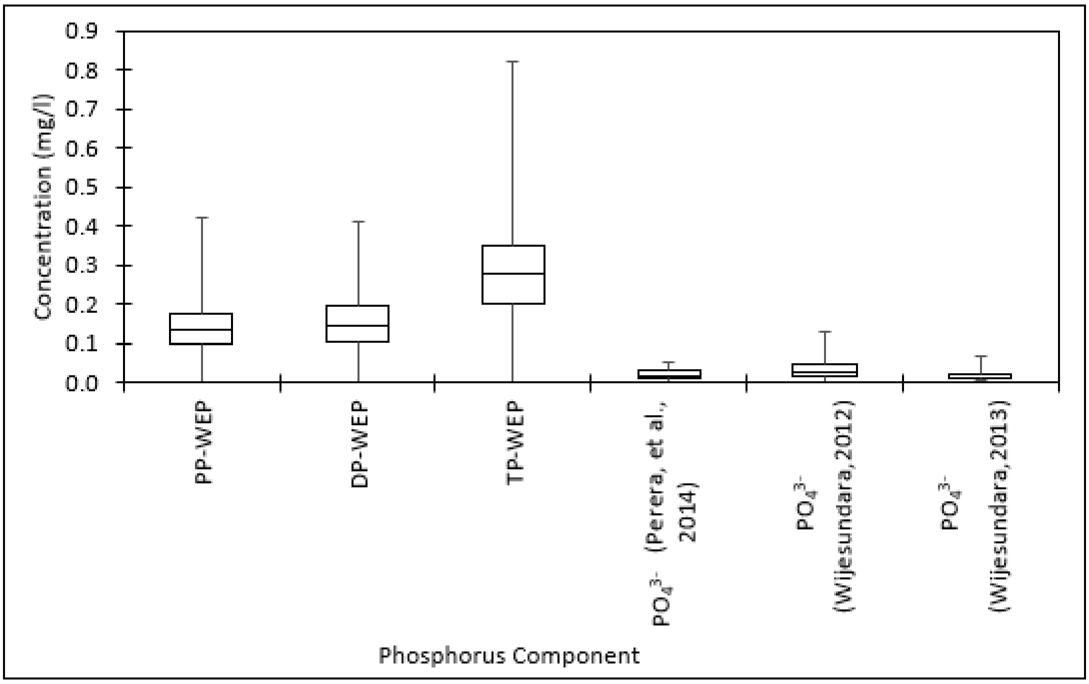


Figure 4.20: Comparison of WEP Model Results of Phosphorus Components for the All Flows (Calibration Period) with the Entire Duration of the Three Published Results

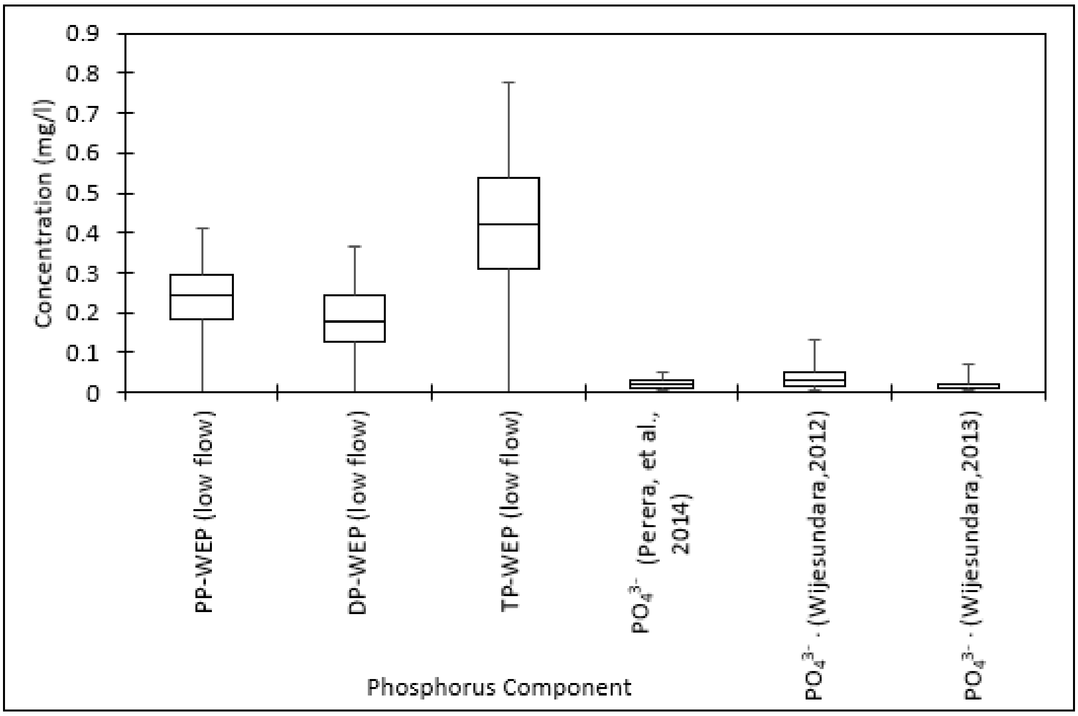


Figure 4.21: Comparison of WEP Model Results of Phosphorus Components for the Low Flows (Validation Period) with the Entire Duration of the Three Published Results

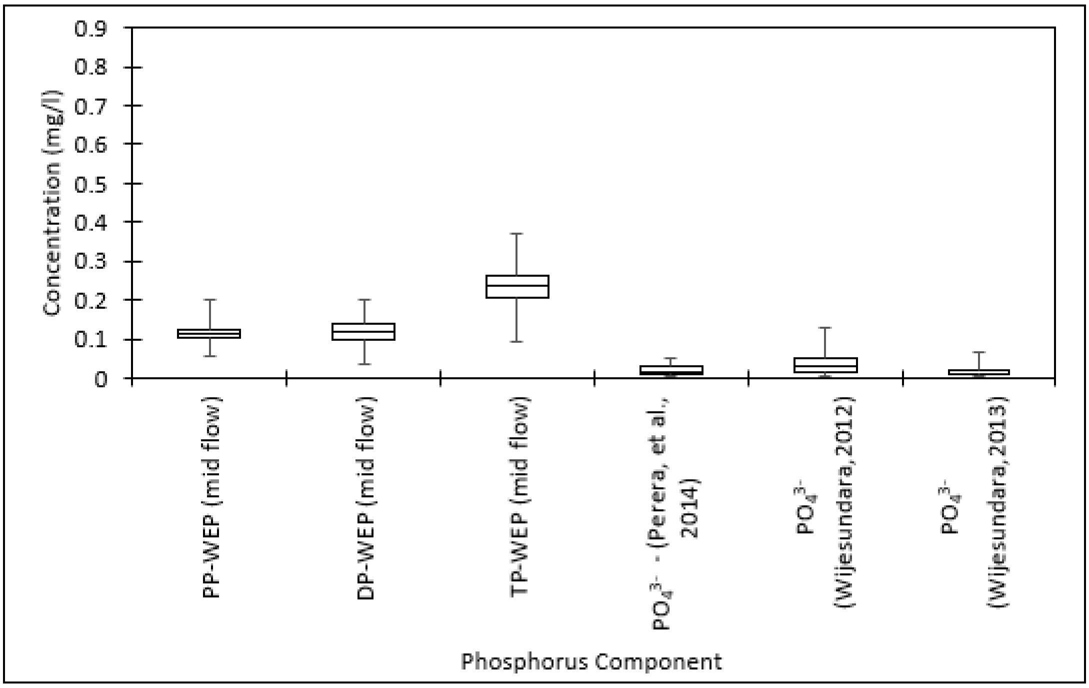


Figure 4.22: Comparison of WEP Model Results of Phosphorus Components for the Mid Flows (Validation Period) with the Entire Duration of the Three Published Results

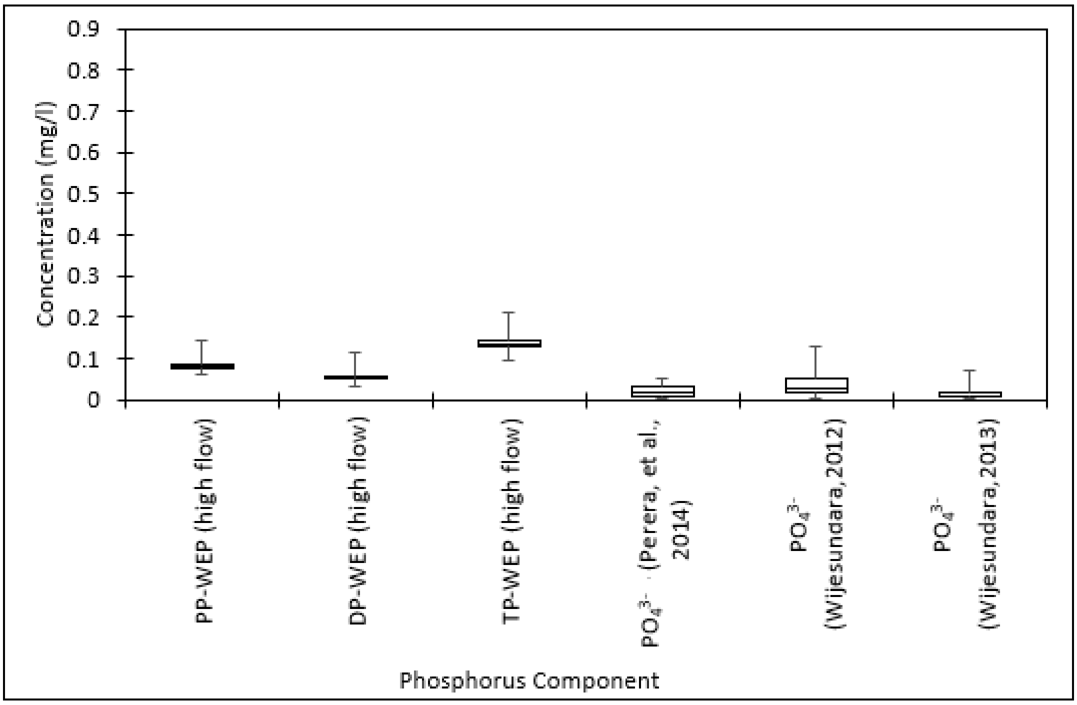


Figure 4.23: Comparison of WEP Model Results of Phosphorus Components for the High Flows (Validation Period) with the Entire Duration of the Three Published Results

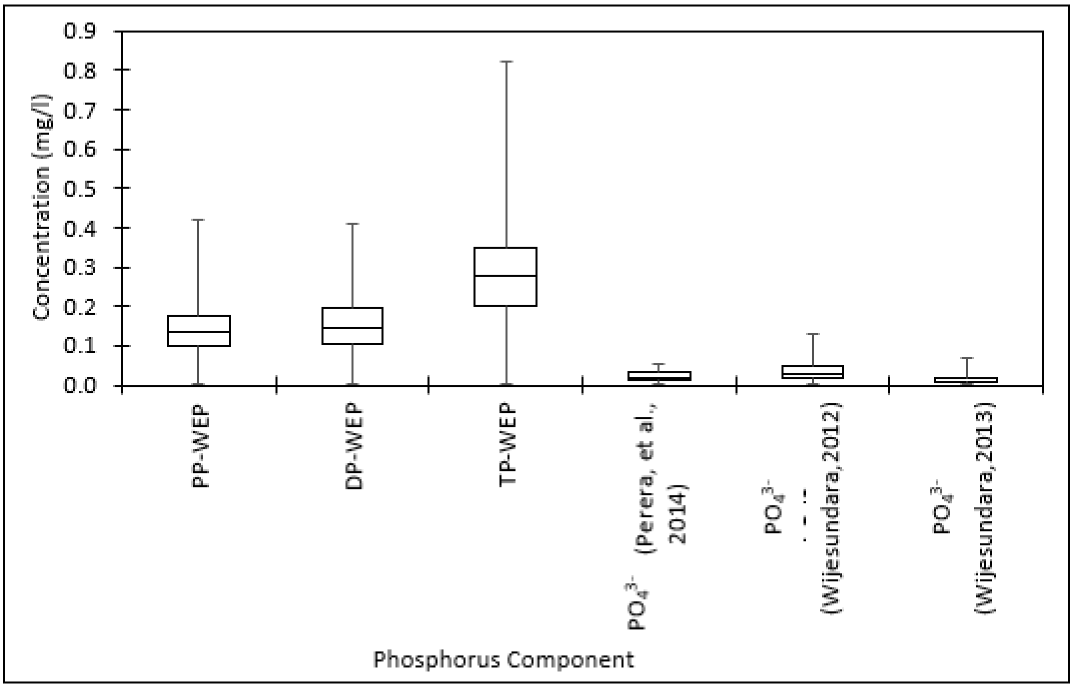


Figure 4.24: Comparison of WEP Model Results of Phosphorus Components for the All Flows (Validation Period) with the Entire Duration of the Three Published Results

It is evident from Figures 4.17 to 4.24 that for the Phosphorus components, for both the calibration period and the validation period, the WEP high flow values shows the best match with the published results. This could be attributed to the fact that, during high flow conditions the high streamflow would induce a washout of the solids, hence most of the particulate nutrients which were adsorbed to the sediments get washed away, adding them to the waterways (Wijesundara et al., 2012). The published values are given for PO_4^{3-}, therefore, when comparing, the DP component from the WEP results should be considered. The DP in the WEP high flow conditions ranges from 0.034 mg/l to 0.153 mg/l in the calibration period, and in the validation period it ranges from 0.032 mg/l to 0.116 mg/l, whereas in the published values it ranges from 0.004 mg/l to 0.130 mg/l (Wijesundara et al., 2012), hence the WEP results could be justified. Further, the three published studies have only measured the water quality as spontaneous measurements, for a shorter duration (only for one-year period), and the water quality parameters under all weather conditions have not been considered (as the sampling has been done once a month in all three studies). But the values of the WEP model results shown are the average of a longer time period (hourly values of all days for a period of four years), and therefore represent a wider and a more reasonable range of values of water quality parameters in the streams.

However, these modelled DP values are above the threshold value of 0.08 ppm of PO_4^{3-} for the occurrence of eutrophication (United States Environmental Protection Agency, 1976). Further, the values of WEP modelled DP were below the threshold of 2 mg/l of PO_4^{3-} for drinking and irrigation water (WHO, 2011).

Further, the canals and streams of the adjacent river basin Kala Oya have shown 0.0 mg/l – 10.7 mg/l, 0.0 – 23.4 mg/l of [NO_3^-] and 0.02 mg/l – 2.60 mg/l, 0.22 – 0.66 mg/l of [PO_4^{3-}], respectively (Young et al., 2009). Therefore, in both Yala and Maha seasons, the WEP model results of PO_4^{3-} are within the ranges of the published results. For more details refer Appendix B.

4.1.2.4 Results of other parameters

Apart from the results discussed before, the WEP model provides results for the temporal variation of daily and hourly groundwater levels of the three layers of aquifers for the specified grid cells that were defined in the "@cntrlpara.csv" input file. Further, the temporal variation of the rainfall at selected observation points, river flow at specified river locations, surface flow in specified grid cells, water depth at selected river locations, are given as results. In addition, the average evapotranspiration in paddy, evaporation from paddy and leaves, transpiration from paddy cultivated soil, in selected sub-catchments, are also given as results files. The average groundwater level of paddy in each sub catchment, average submerged depth in paddy in each sub catchment and river flow at the final day of each month, for each river segment, will also be given as results. The graphical representation of some these results for the calibration and validation periods are given in Appendix B.

Apart from these; the water budget, Nitrogen budget and Phosphorus budget, at the end of each year, for the cells containing paddy/all cells, for each sub-catchment and the developed area, soil wetness for each soil layer, surface temperature, groundwater flux (for X and Y directions), groundwater level at the end of each year, for all the cells, constitution of reclassified land uses in each cell, are given by the other temporal results files. These results could be useful for further model calibration and verification processes if the measured values of these parameters are available.

4.1.3 Spatial variation of results

Although the WEP model analysis produces a number of spatial variation results files of various parameters, only the most important results have been presented here. The results which would be used to do the comparison of scenarios were given priority while presenting the results. After plotting the variation of results given in the 82 spatial variation results files, the 7 files given in Table 4.4 were chosen for the comparison with the different scenarios. The critical month and the critical parameter were found after analysing the spatial variation given by each result file. Excel VBA macros were used for these procedures.

Table 4.4: Critical Months and Critical Parameters of the Selected Spatial Variation Results Files

File Name	File Definition	Critical Month(s)/ Critical Parameter (Present Condition)	
		Calibration	Validation
fort.108	Concentration of discharged DN from each farmland stratum (ANI1= layer 1, ANI2= layer 2 etc.)	October 2009, ANI1	September 2012, ANI1
n-andrn1.asc	DN: gravity drain/subsurface losses	November 2009	October 2012
p-apdrn1.asc	DP: gravity drain/subsurface losses	November 2009	October 2013
n-fxce.asc	Mesh influx DN quantity	November 2011	December 2014
n-fxpnce.asc	Mesh influx PN quantity	February 2011	December 2014
p-fxdpce.asc	Mesh influx DP quantity	February 2011	December 2014
p-fxppce.asc	Mesh influx PP quantity	February 2011	December 2014

The discharged nutrient concentrations (as represented in all the results files in Table 4.4), mainly depend on the washout rates due to streamflow which would be induced by rainfall. Therefore, the differences in the critical months during the calibration and the validation periods are attributed to the differences in the rainfall induced streamflow values.

4.1.3.1 Discharged DN from each layer ("fort.108" results file)

The fort.108 results file contains the concentration of discharged DN (g/m^2/hr) from each farmland stratum (each soil layer) (ANI1= layer 1, ANI2= layer 2, and ANI3= layer 3) at the end of each month for every cell. For the calibration period, the most critical month and critical parameter were found to be, October 2009 and ANI1, respectively. For the validation period, the most critical month and critical parameter were found to be, September 2012 and ANI1, respectively (refer Figure 4.25). In Figure 4.25, in the calibration period, the minimum, mean and maximum values of the ANI1 parameter were found to be 0.000 g/m^2/hr, 0.858 g/m^2/hr and 36.629 g/m^2/hr, respectively. In Figure 4.25, in the validation period, the minimum, mean and maximum values of the ANI1 parameter were found to be 0.000 g/m^2/hr, 0.646 g/m^2/hr and 24.198 g/m^2/hr, respectively.

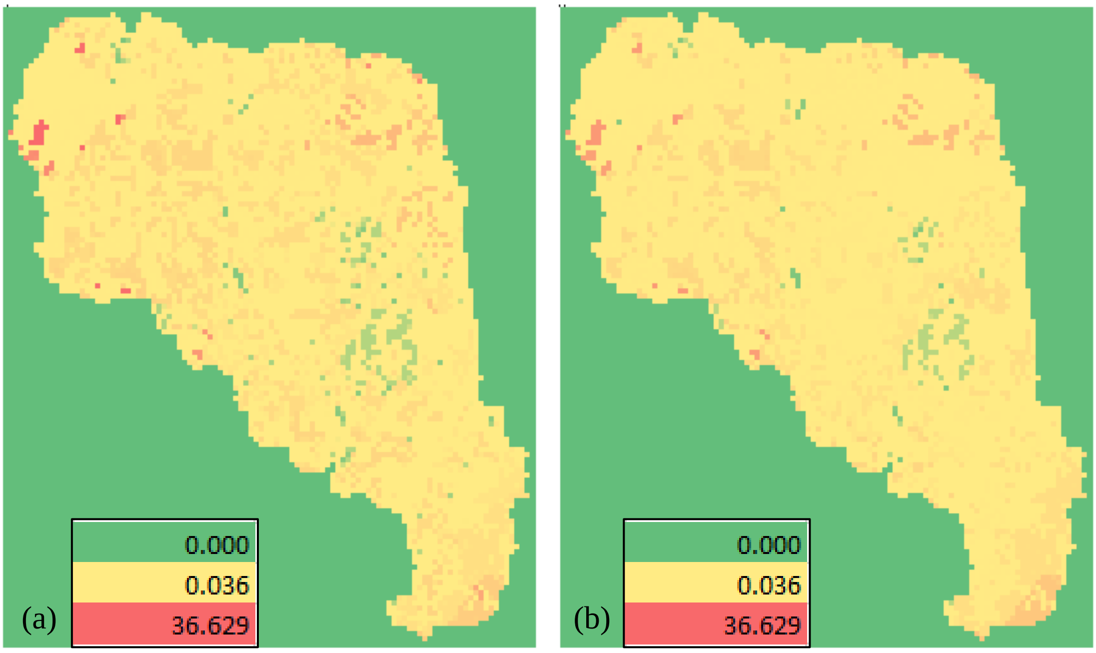


Figure 4.25: Critical Months and Critical Parameter of "fort.108" Results File; (a) Calibration Period (October 2009, ANI1) and (b) Validation Period (September 2012, ANI1) (original in colour)

4.1.3.2 DN in gravity drain/subsurface losses (“n-andrn1.asc” results file)

The n-andrn1.asc results file contains DN from gravity drain/subsurface losses at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, November 2009 and October 2012, respectively (refer Figure 4.26). In Figure 4.26, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 5.064 g/m^2/hr and 216.024 g/m^2/hr, respectively. In Figure 4.26, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 5.570 g/m^2/hr and 216.337 g/m^2/hr, respectively.

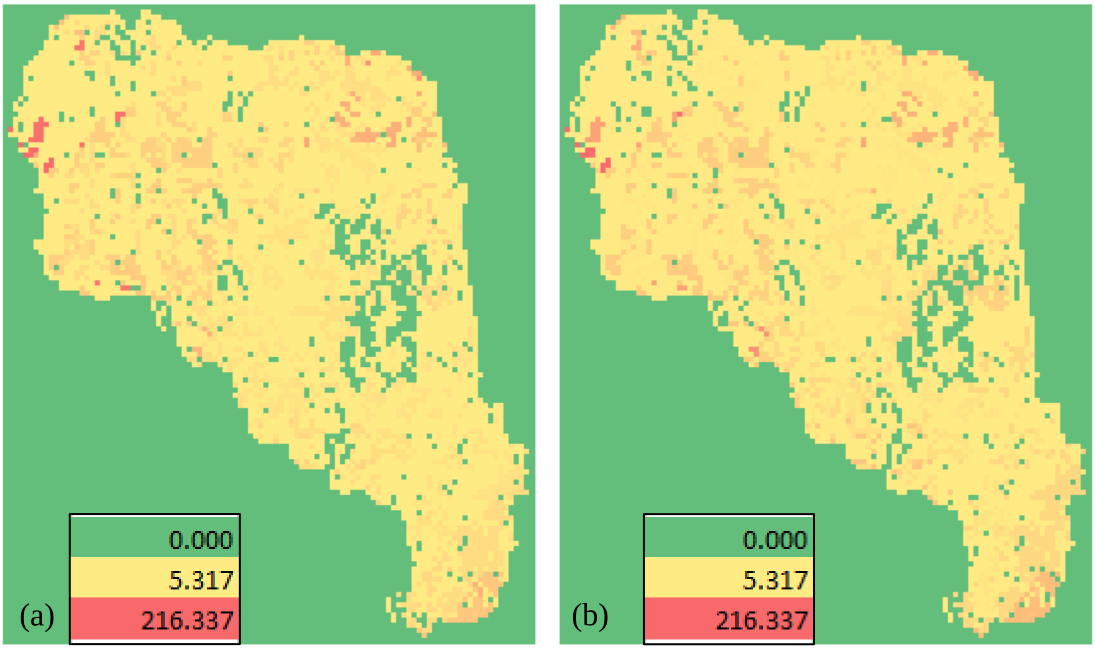


Figure 4.26: Critical Months of “n-andrn1.asc” Results File; (a) Calibration Period (November 2009) and (b) Validation Period (October 2012) (original in colour)

4.1.3.3 DP in gravity drain/subsurface losses (“p-apdrn1.asc” results file)

The p-apdrn1.asc results file contains DP from gravity drain/subsurface losses at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, November 2009 and October 2013, respectively (refer Figure 4.27). In Figure 4.27, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 0.670 g/m^2/hr and 104.436 g/m^2/hr, respectively. In Figure 4.27, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 0.572 g/m^2/hr and 84.346 g/m^2/hr, respectively.

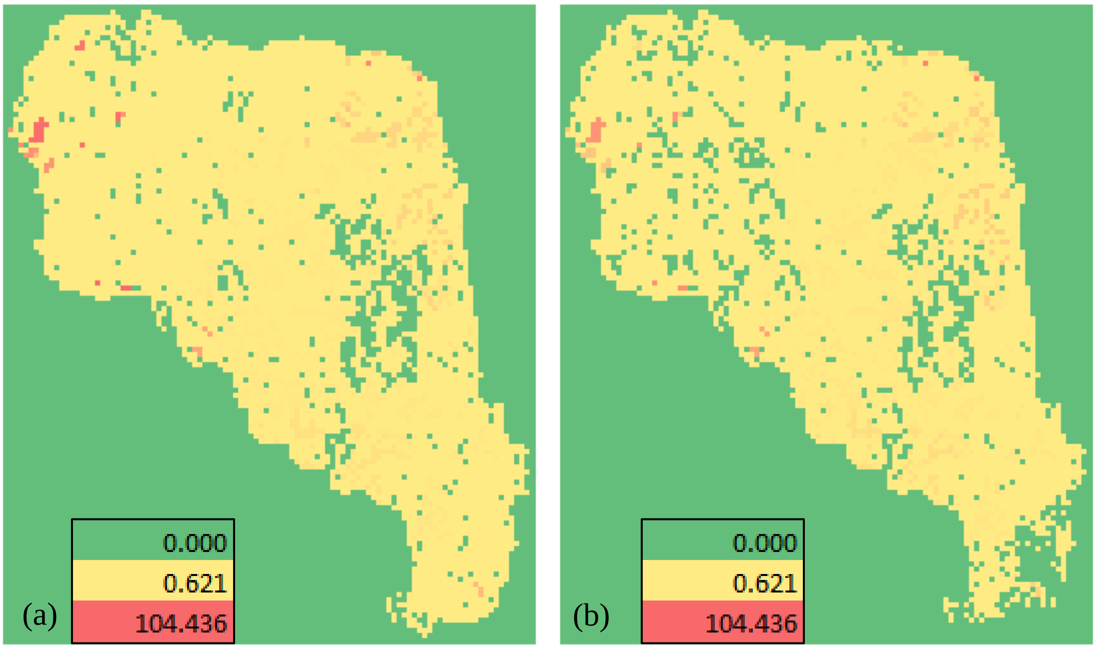


Figure 4.27: Critical Months of "p-apdrn1.asc" Results File; (a) Calibration Period (November 2009) and (b) Validation Period (October 2013) (original in colour)

4.1.3.4 Mesh influx DN quantity ("n-fxce.asc" results file)

The n-fxce.asc results file contains mesh influx DN quantity at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, November 2011 and December 2014, respectively (refer Figure 4.28). In Figure 4.28, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 28.180 g/m^2/hr and 11 292.281 g/m^2/hr, respectively. In Figure 4.28, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 42.707 g/m^2/hr and 14 663.427 g/m^2/hr, respectively.

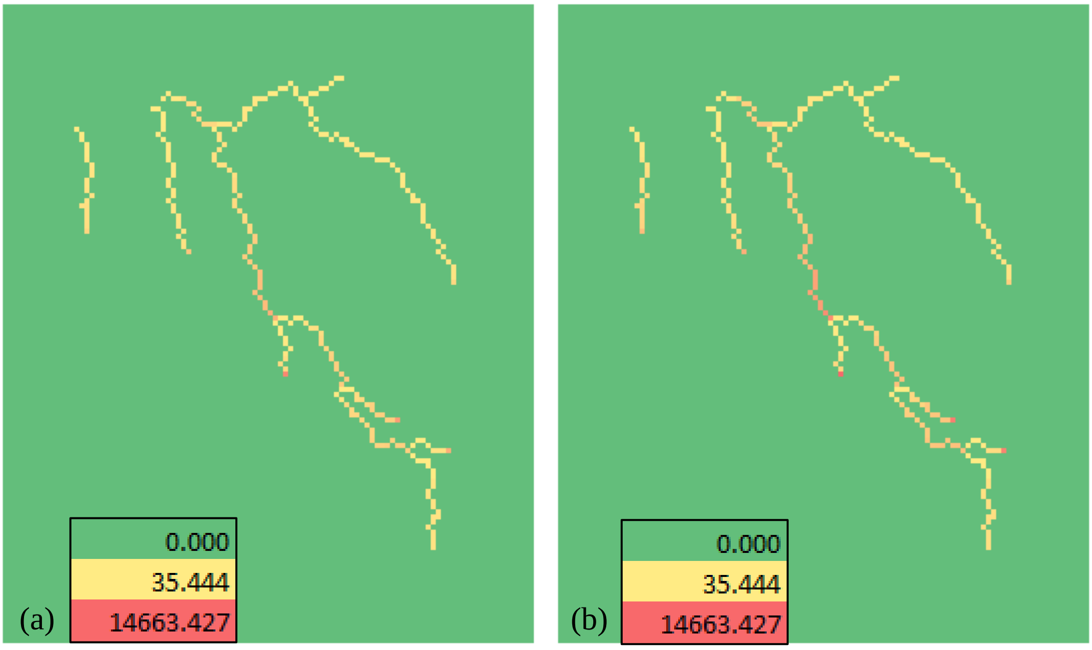


Figure 4.28: Critical Months of "n-fxce.asc" Results File; (a) Calibration Period (November 2011) and (b) Validation Period (December 2014) (original in colour)

4.1.3.5 Mesh influx PN quantity ("n-fxpnce.asc" results file)

The n-fxpnce.asc results file contains mesh influx PN quantity at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, February 2011 and December 2014, respectively (refer Figure 4.29). In Figure 4.29, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 15.920 g/m^2/hr and 5 098.138 g/m^2/hr, respectively. In Figure 4.29, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 28.847 g/m^2/hr and 8 974.121 g/m^2/hr, respectively.

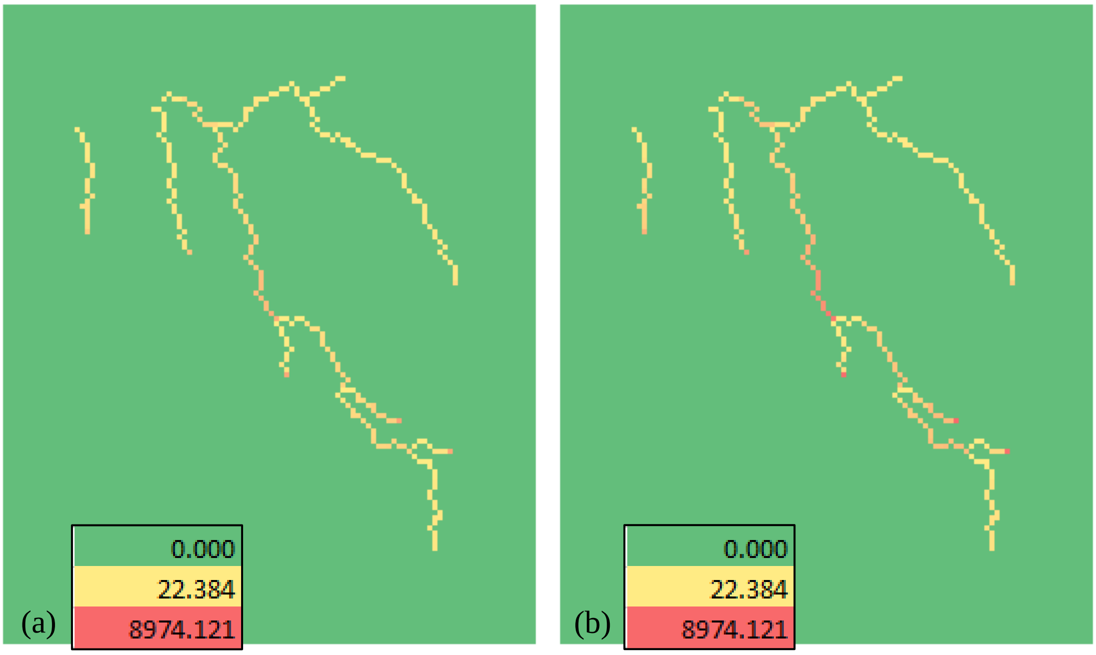


Figure 4.29: Critical Months of “n-fxpnce.asc” Results File; (a) Calibration Period (February 2011) and (b) Validation Period (December 2014) (original in colour)

4.1.3.6 Mesh influx DP quantity (“p-fxdpce.asc” results file)

The p-fxdpce.asc results file contains mesh influx DP quantity at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, February 2011 and December 2014, respectively (refer Figure 4.30). In Figure 4.30, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 6.004 g/m^2/hr and 1 657.521 g/m^2/hr, respectively. In Figure 4.30, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 8.146 g/m^2/hr and 2 390.457 g/m^2/hr, respectively.

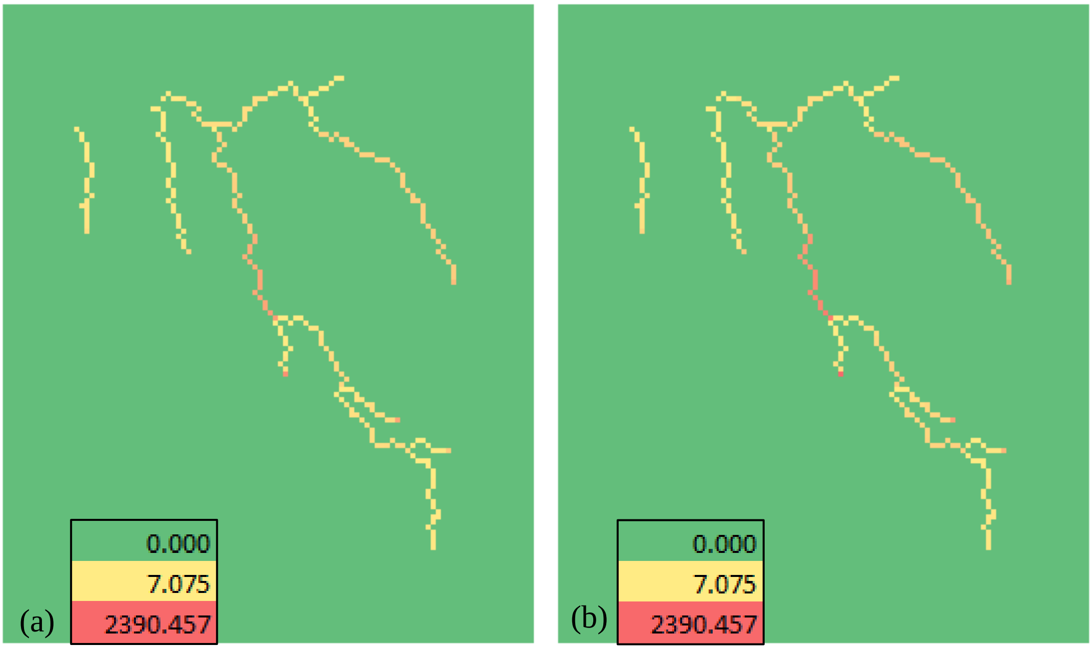


Figure 4.30: Critical Months of “p-fxdpce.asc” Results File; (a) Calibration Period (February 2011) and (b) Validation Period (December 2014) (original in colour)

4.1.3.7 Mesh influx PP quantity (“p-fxppce.asc” results file)

The p-fxppce.asc results file contains mesh influx PP quantity at the end of each month for every cell. The most critical month for the calibration and validation periods were found to be, February 2011 and December 2014, respectively (refer Figure 4.31). In Figure 4.31, in the calibration period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 6.258 g/m^2/hr and 1 650.272 g/m^2/hr, respectively. In Figure 4.31, in the validation period, the minimum, mean and maximum values were found to be 0.000 g/m^2/hr, 9.017 g/m^2/hr and 2 447.968 g/m^2/hr, respectively.

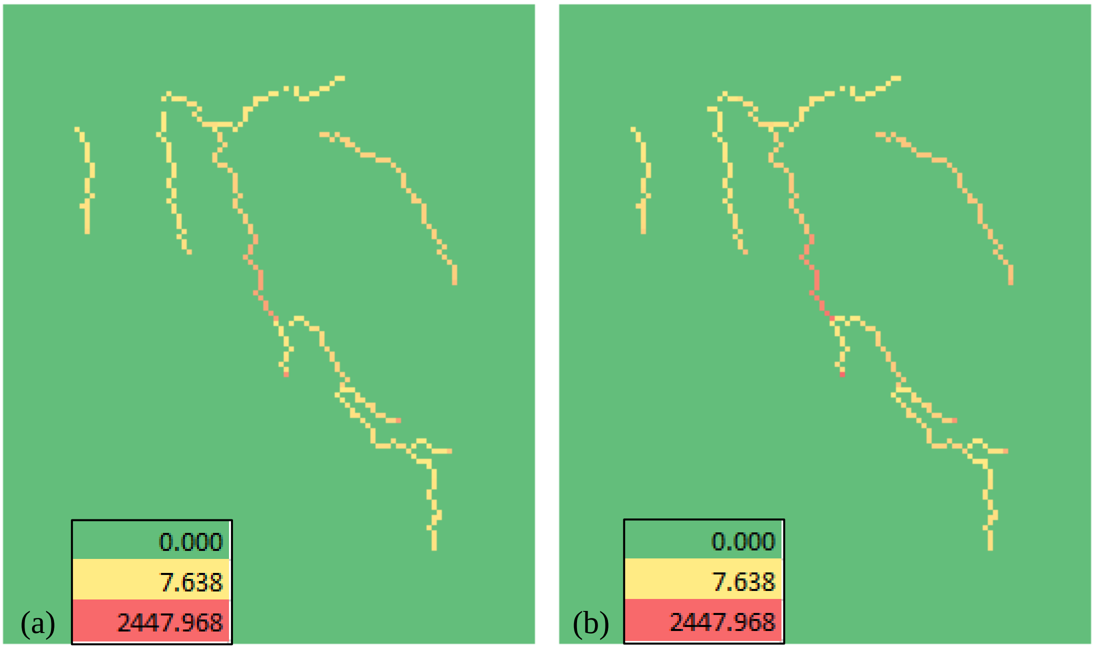


Figure 4.31: Critical Months of "p-fxppce.asc" Results File; (a) Calibration Period (February 2011) and (b) Validation Period (December 2014) (original in colour)

Apart from the 7 files which were described in detail above, N content in each soil layer at the end of each month for every cell (parameter ANF), fresh organic N content in paddy surface for each soil layer at the end of each month for every cell (parameter ANA) (g/m^2), refractory N content in paddy surface for each soil layer at the end of each month for every cell (parameter ANS), amount of inorganic condition Nitrogen outflow by surface runoff (and rainfall), at the end of each year, amount of organic (suspended) Nitrogen outflow by surface runoff (and rainfall), at the end of each year, are some of the other results which could be obtained as spatial variation results.

4.2 Sensitivity Analysis Results

4.2.1 Material movement for the overland flow ("surfaceC.csv" file)

The parameters governing the Phosphorus components in the input file which relates to material movement for the overland flow (surfaceC.csv file) are; RN (decomposition speed from suspended condition to dissolved power), KP (sedimentation coefficient), S_{max} (amount of the maximum deposit) and S_{ini} (amount of initial deposit). It was found that for Dissolved Phosphorus (DP), only parameter

RN had a significant impact and other parameters had no significant impact (Figure 4.32). For Particulate Phosphorus (PP), RN and S_{max} had a significant impact, while other parameters had no significant impact (Figure 4.33). For Total Phosphorus (TP), RN and S_{max} have a significant impact, while other parameters had no significant impact (Figure 4.34). In the legends of all figures in Section 4.2, the letter “I” denotes increase of that parameter and “D” denotes decrease of that parameter. Since it has been previously identified that the peaks and troughs of nutrient concentrations are correlated to the increases and decreases in the streamflow (due to rainfall), the streamflow has not been shown in Figures 4.32 to Figure 4.34 for clarity. Further, the models were run for a shorter duration instead of the entire four year duration, because the purpose of sensitivity analysis was to identify the sensitivity in model results with respect to the variation of parameter values.

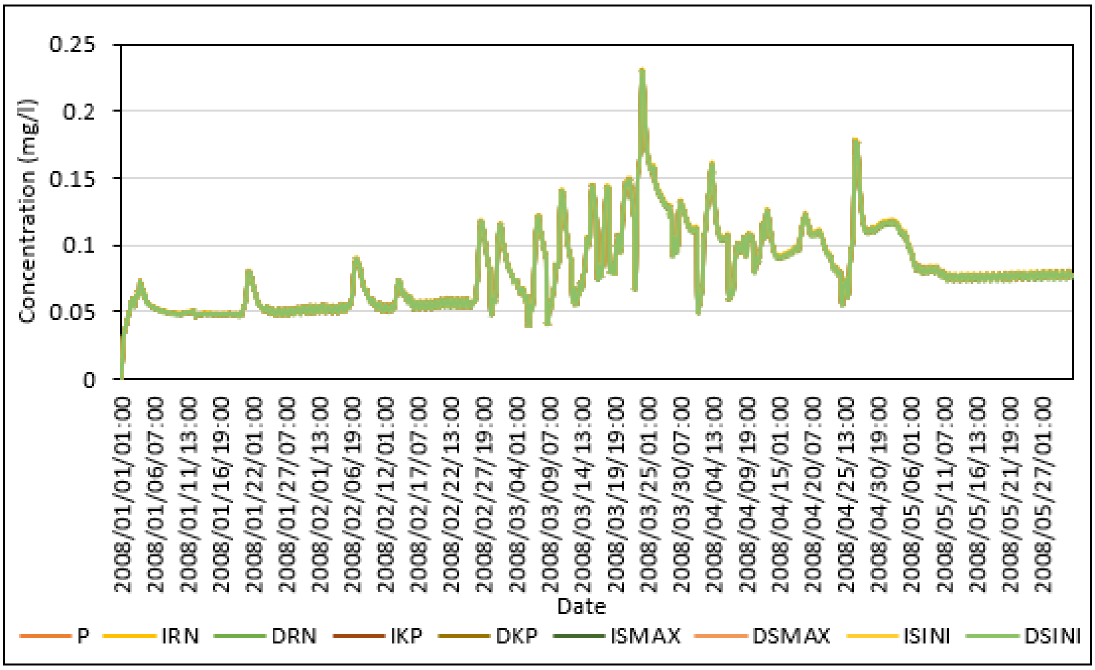


Figure 4.32: DP in Each Model Run (mg/l) in “surfaceC.csv” File (original in colour)

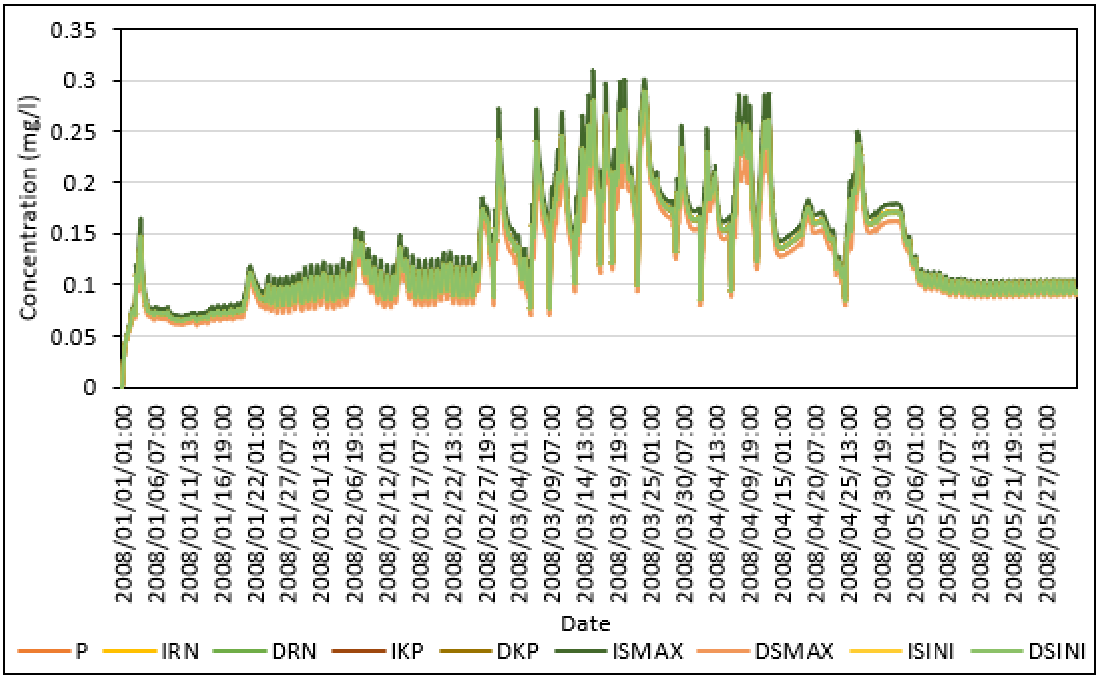


Figure 4.33: PP in Each Model Run (mg/l) in “surfaceC.csv” File (original in colour)

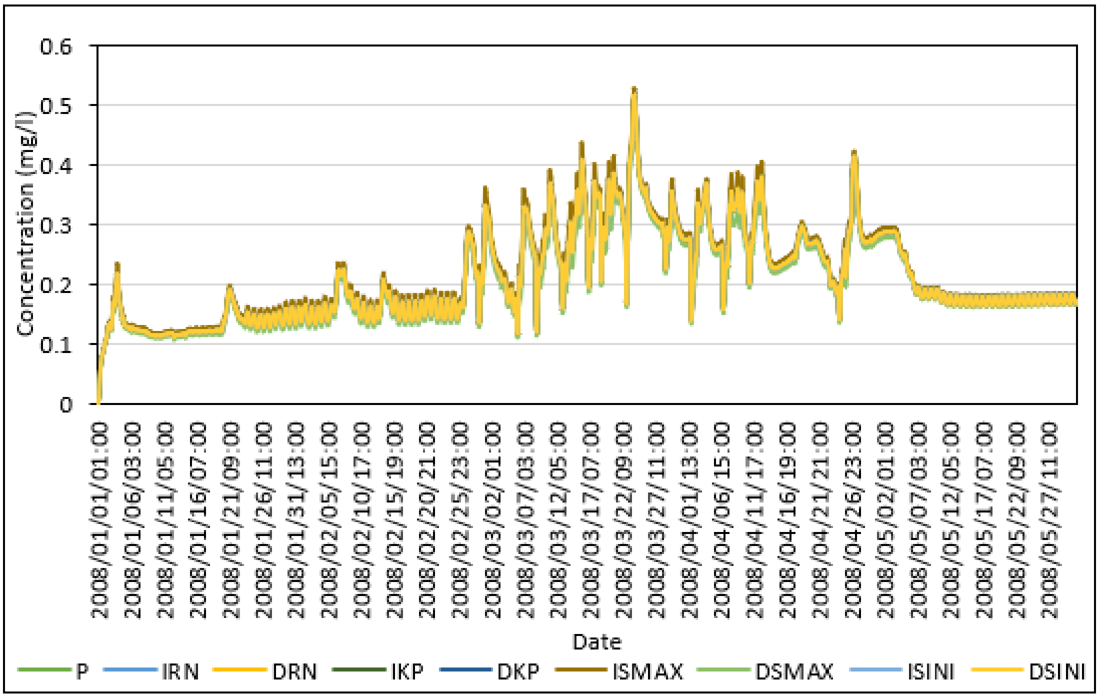


Figure 4.34: TP in Each Model Run (mg/l) in “surfaceC.csv” File (original in colour)

4.2.2 Material transport in the river channel ("riverC.csv" file)

The parameters governing the Phosphorus components in the input file which relates to material transport in the river channel (riverC.csv file) are; RN, KP, S_{max} (amount of the maximum riverbed deposit) and Sini (amount of initial riverbed deposit), µPP (suspended condition phosphorus diffusion coefficient), µDP (dissolved condition phosphorus diffusion coefficient). It was found that for DP, none of the parameters has any significant impact (Figure 4.35). For PP, KP had a significant impact while other parameters had no significant impact (Figure 4.36). For TP, KP have a significant impact, while other parameters had no significant impact (Figure 4.37).

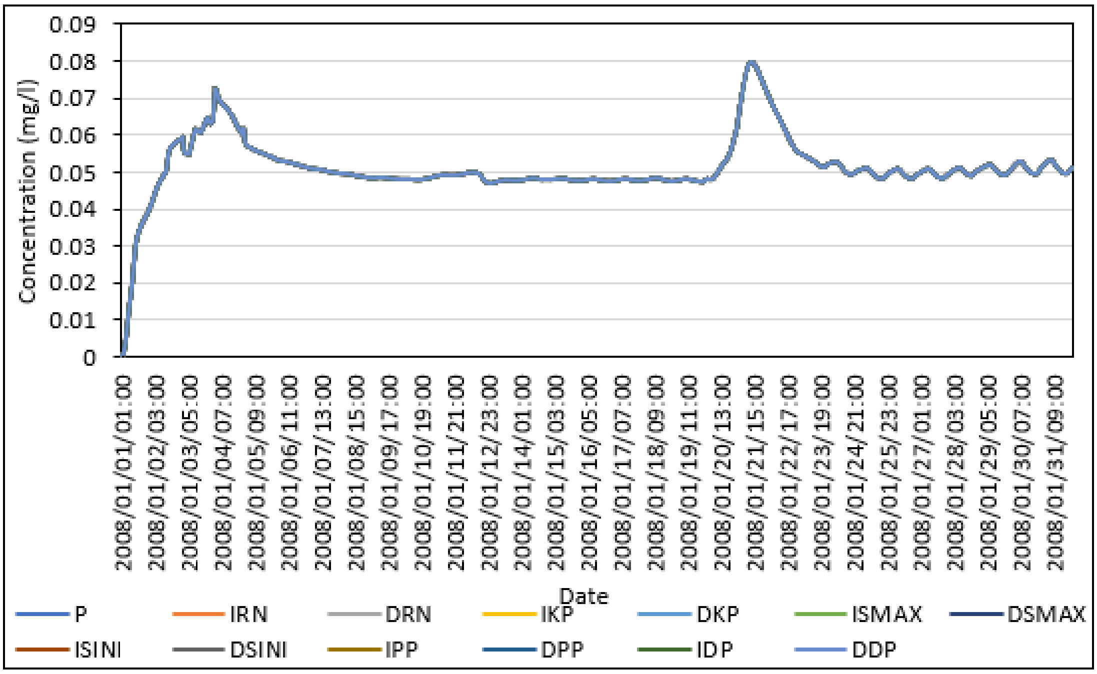


Figure 4.35: DP in Each Model Run (mg/l) in "riverC.csv" File (original in colour)

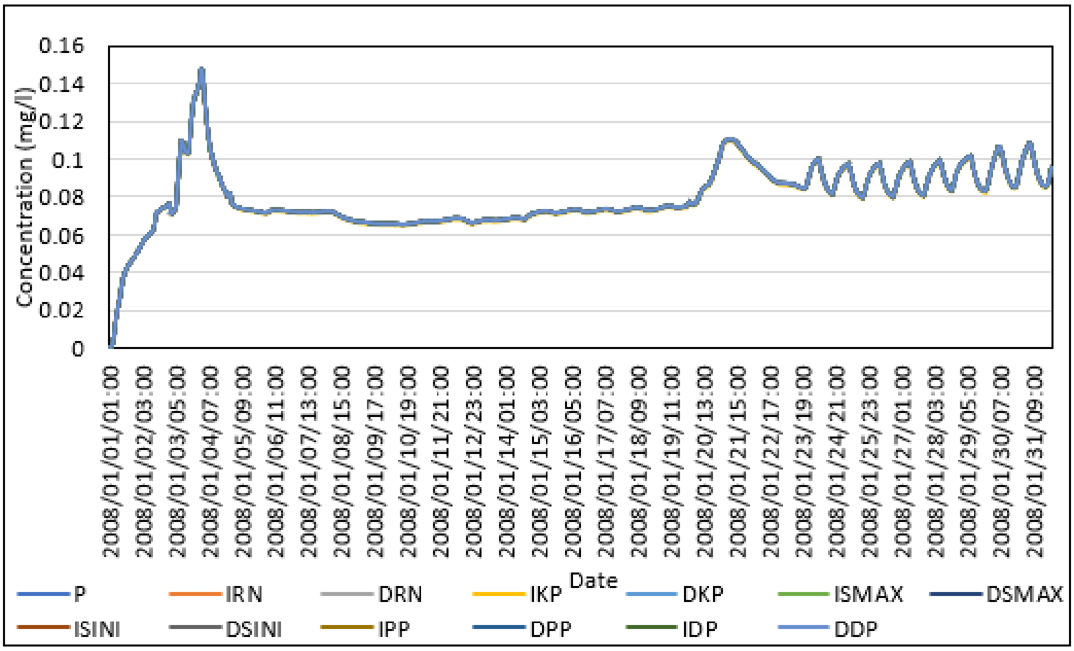


Figure 4.36: PP in Each Model Run (mg/l) in “riverC.csv” File (original in colour)

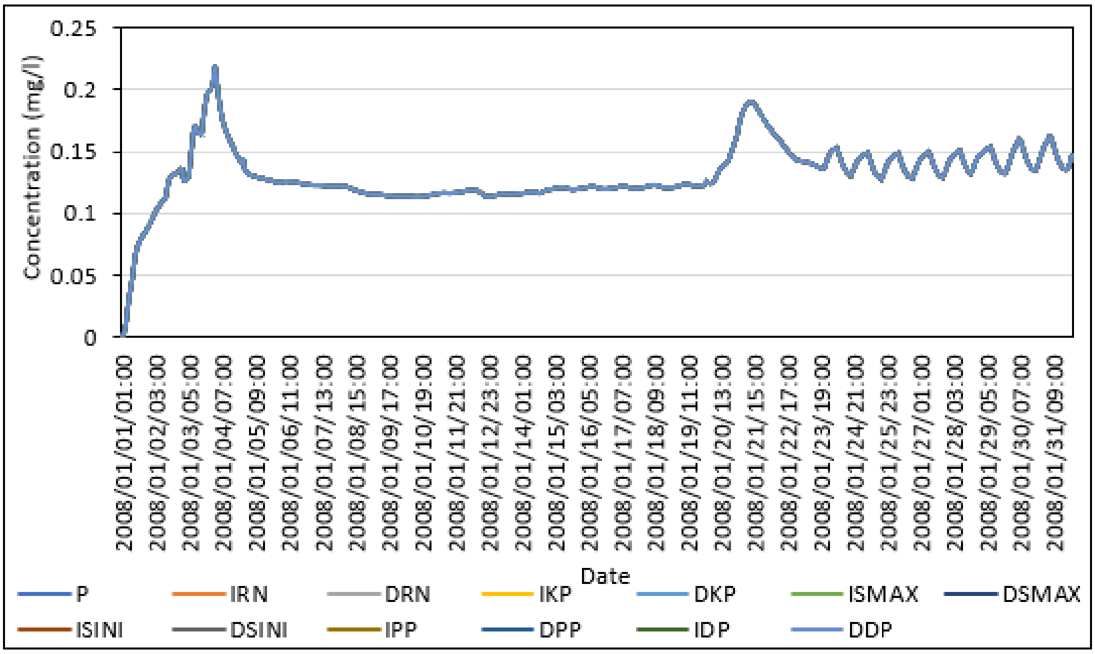


Figure 4.37: TP in Each Model Run (mg/l) in “riverC.csv” File (original in colour)

4.2.3 Non-point source material transport in forest and urban area ("nonpointsource.csv" file)

The parameters governing the Phosphorus components in the input file which relates to non-point source material transport in forest and urban area (nonpointsource.csv file) are; aDP [forest (infiltration region: high tree type a) generation load amount for DP] and aPP [forest (infiltration region: high tree type a) generation load amount for PP]. It was found that for DP, only aDP has a significant impact (Figure 4.38). For PP, aDP and aPP have a significant impact (Figure 4.39). For TP, aDP and aPP have a significant impact (Figure 4.40).

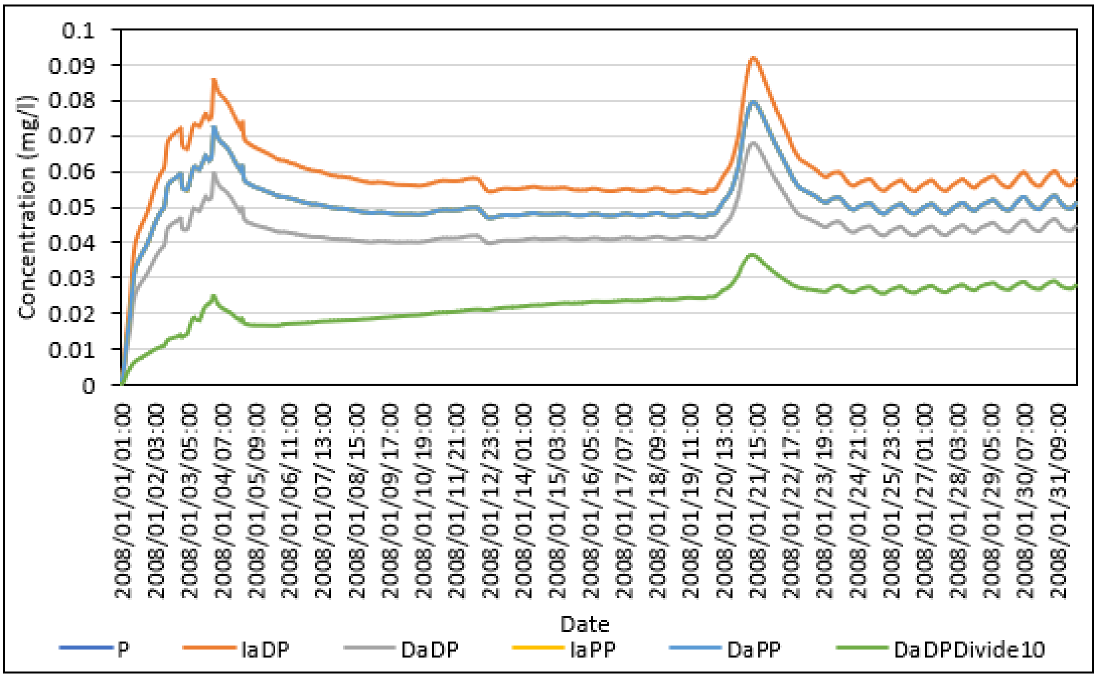


Figure 4.38: DP in Each Model Run (mg/l) in "nonpointsource.csv" File (original in colour)

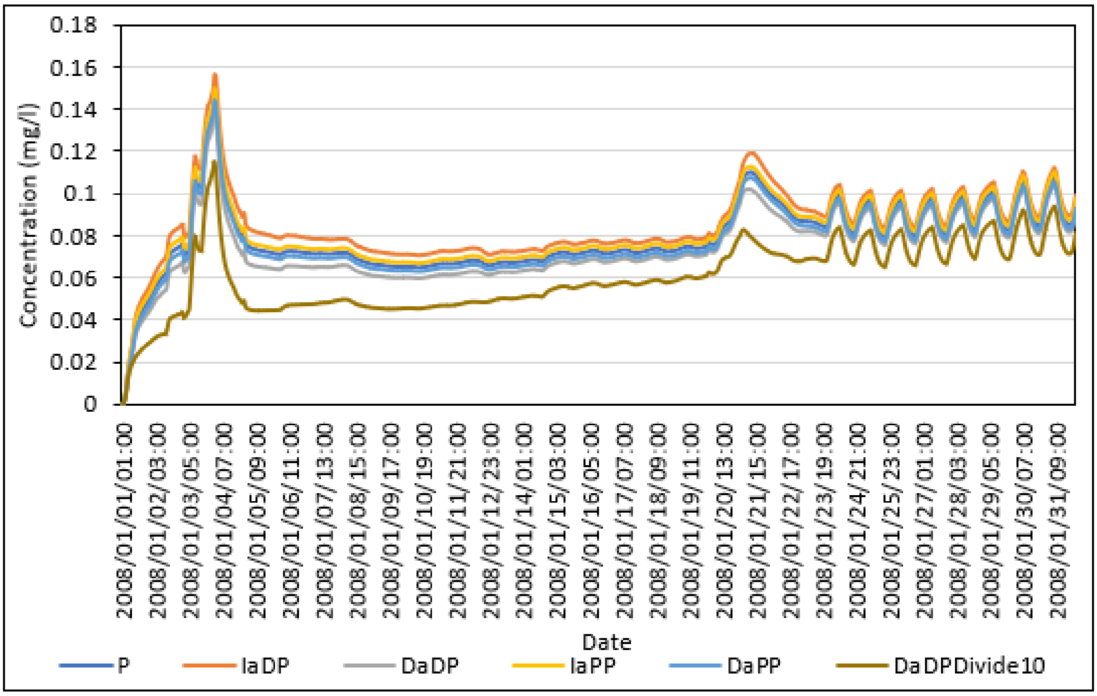


Figure 4.39: PP in Each Model Run (mg/l) in "nonpointsource.csv" File (original in colour)

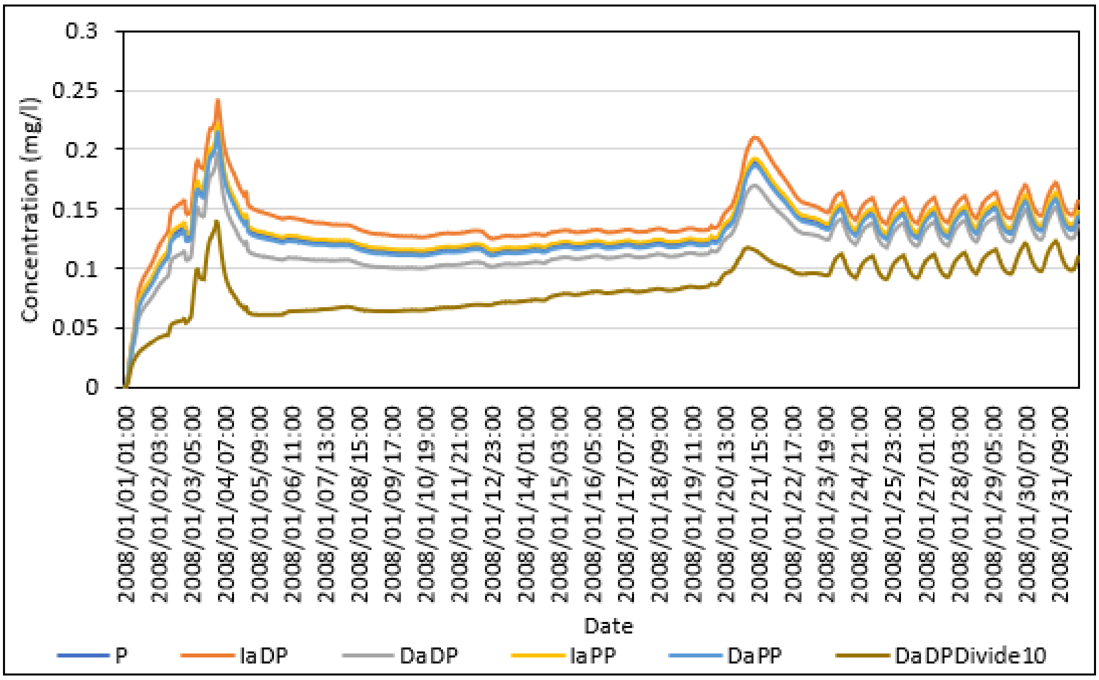


Figure 4.40: TP in Each Model Run (mg/l) in "nonpointsource.csv" File (original in colour)

Sensitivity analysis has shown the response characteristics of the WEP model results to all the parameters governing the Phosphorus components in the input files, and it was noted that different parameters have different sensitivity levels to the model results. Although it could be assumed that the pollutant loading due to the point sources in this catchment would be less than the non-point sources of pollutants since this catchment is not a highly urbanized and developed area, the results of the sensitivity analysis has shown that parameters governing both the point sources as well as non-point sources contribute to the variation of WEP model results.

4.3 Scenario Analysis Results

The validated model from the present condition was used for the comparison of scenarios.

4.3.1 Comparison of fertilizer related scenarios (Scenario 1, 2 and 3)

4.3.1.1 Comparison of temporal variation of results

a) Results of Nitrogen components

The variation of PN in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are graphically represented in Figure 4.41. The PN amounts of S1, S2, and S3 do not show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input does not have a significant impact on the accumulation and dispersal patterns of particulate Nitrogen in the water ways. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years. Since it has been previously identified that the peaks and troughs of nutrient concentrations are correlated to the increases and decreases in the streamflow (due to rainfall), the streamflow has not been shown in Figures 4.41 to Figure 4.43 for clarity.

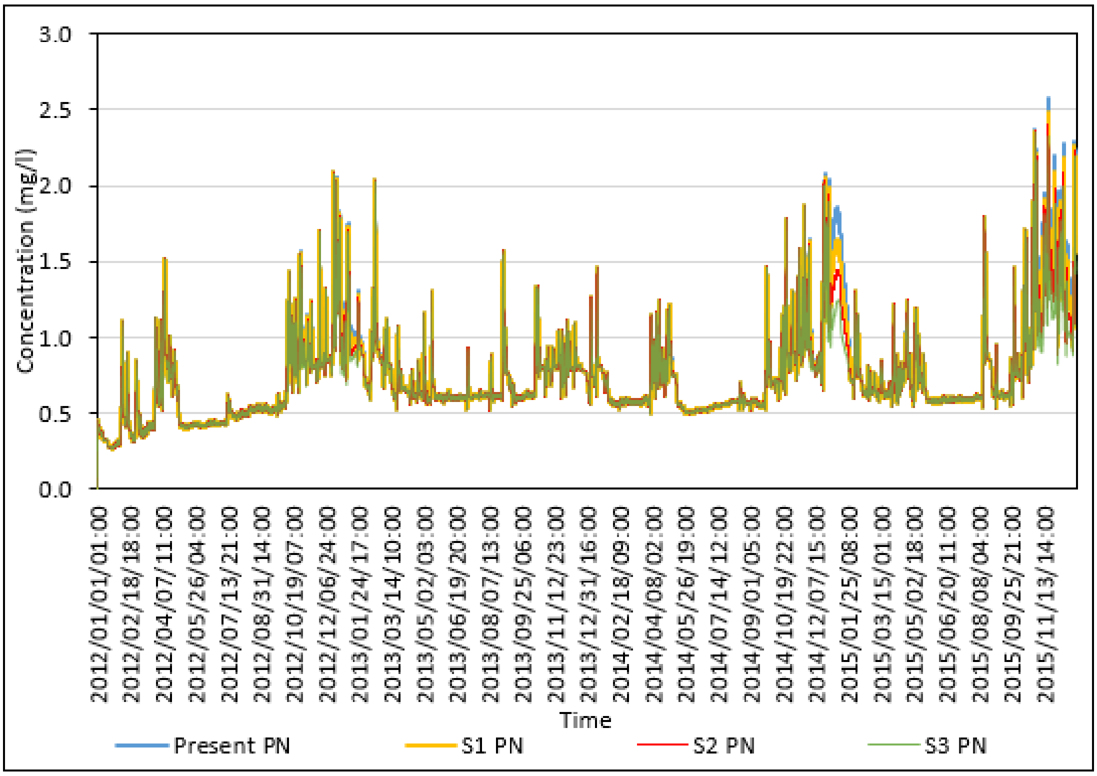


Figure 4.41: The Variation of PN in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

The variation of DN in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are illustrated in Figure 4.42. The DN amounts of S1, S2, and S3 show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input have a significant impact on the accumulation and dispersal patterns of dissolved Nitrogen in the water ways. The DN concentrations have decreased with the reduction of fertilizer input, when considering the present condition with S1, S2, and S3. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

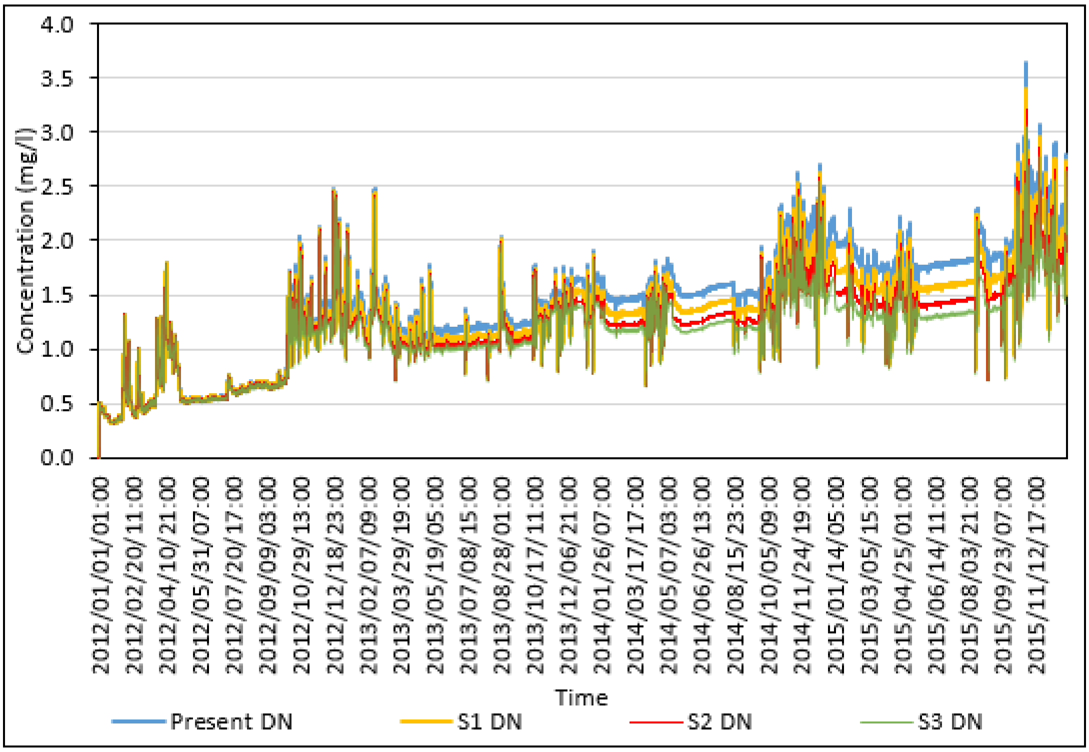


Figure 4.42: The Variation of DN in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

The variation of TN in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are illustrated in Figure 4.43. Since TN is the summation of PN and DN amounts, the TN amounts of S1, S2, and S3 show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input have a significant impact on the accumulation and dispersal patterns of total Nitrogen in the water ways. The TN concentrations have decreased with the reduction of fertilizer input, when considering the present condition with S1, S2, and S3. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

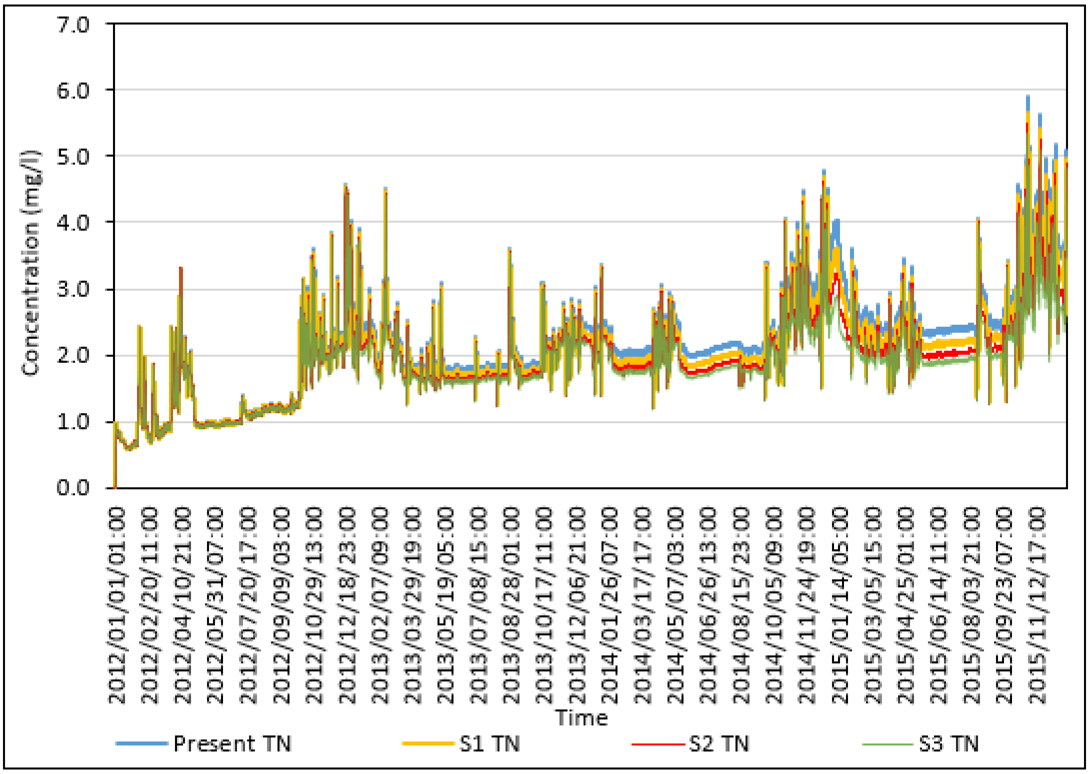


Figure 4.43: The Variation of TN in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

b) Results of Phosphorus components

The variation of PP in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are graphically represented in Figure 4.44. The PP amounts of S1, S2, and S3 show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input have a significant impact on the accumulation and dispersal patterns of particulate Phosphorus in the water ways. The PP concentrations have decreased with the reduction of fertilizer input, when considering the present condition with S1, S2, and S3. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

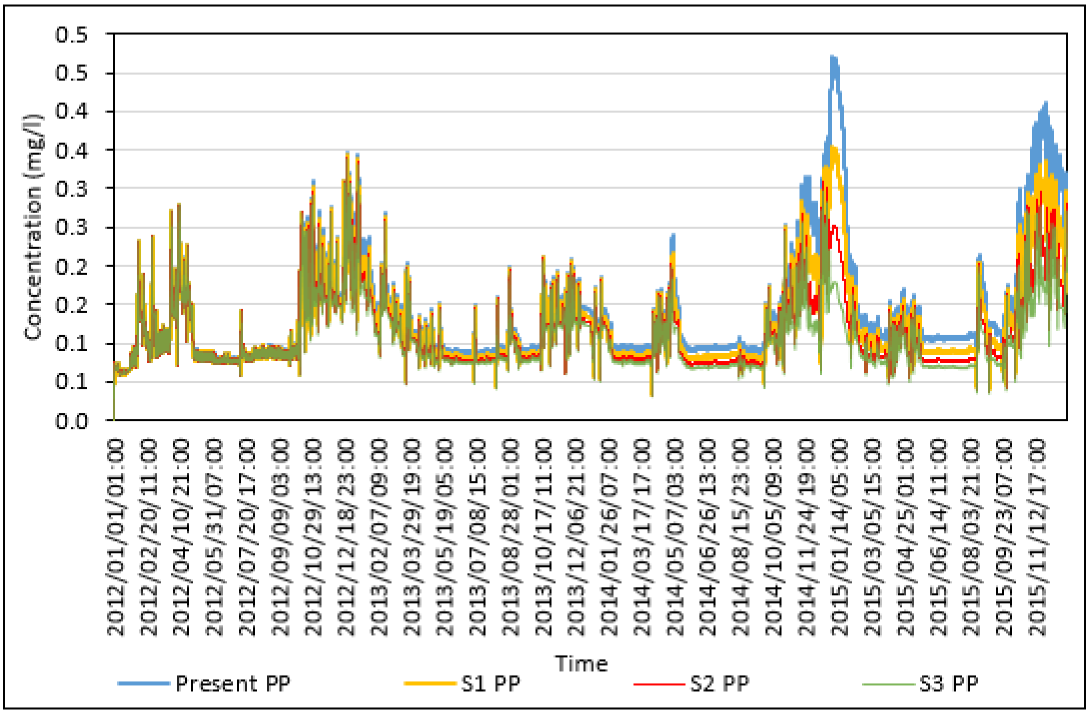


Figure 4.44: The Variation of PP in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

The variation of DP in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are illustrated in Figure 4.45. The DP amounts of S1, S2, and S3 show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input have a significant impact on the accumulation and dispersal patterns of dissolved Phosphorus in the water ways. The DP concentrations have decreased with the reduction of fertilizer input, when considering the present condition with S1, S2, and S3. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

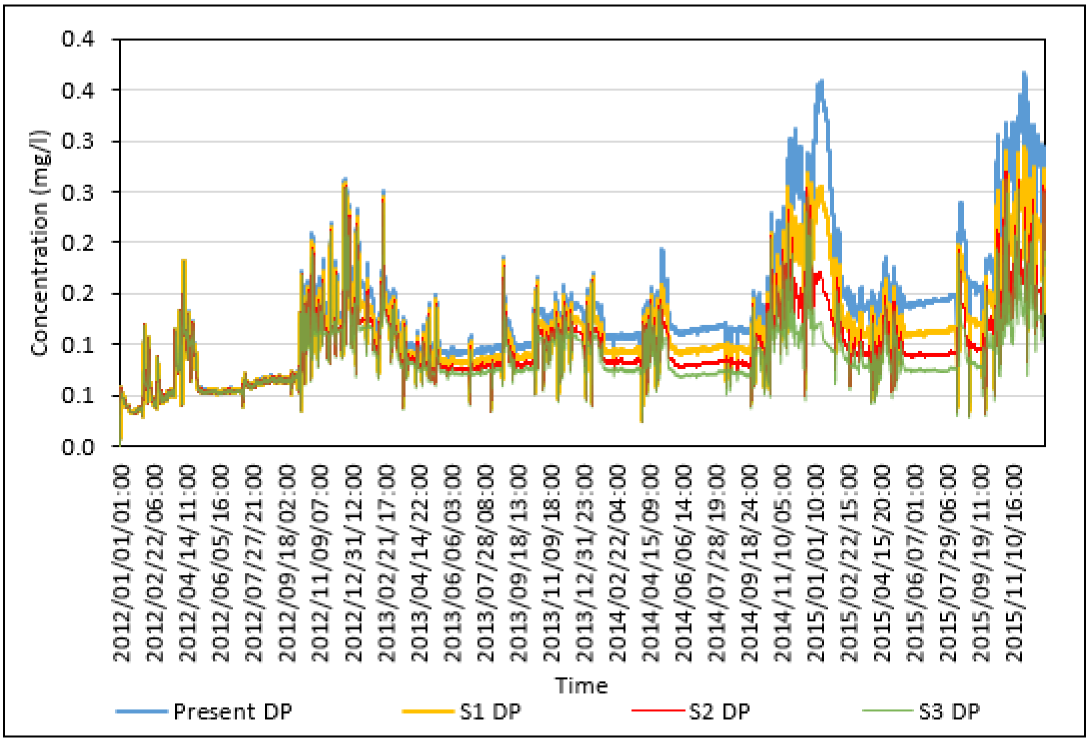


Figure 4.45: The Variation of DP in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

The variation of TP in the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) are illustrated in Figure 4.46. Since TP is the summation of PP and DP amounts, the TP amounts of S1, S2, and S3 show a significant deviation compared to the present condition, indicating that the reduction of fertilizer input have a significant impact on the accumulation and dispersal patterns of total Phosphorus in the water ways. The TP concentrations have decreased with the reduction of fertilizer input, when considering the present condition with S1, S2, and S3. The slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

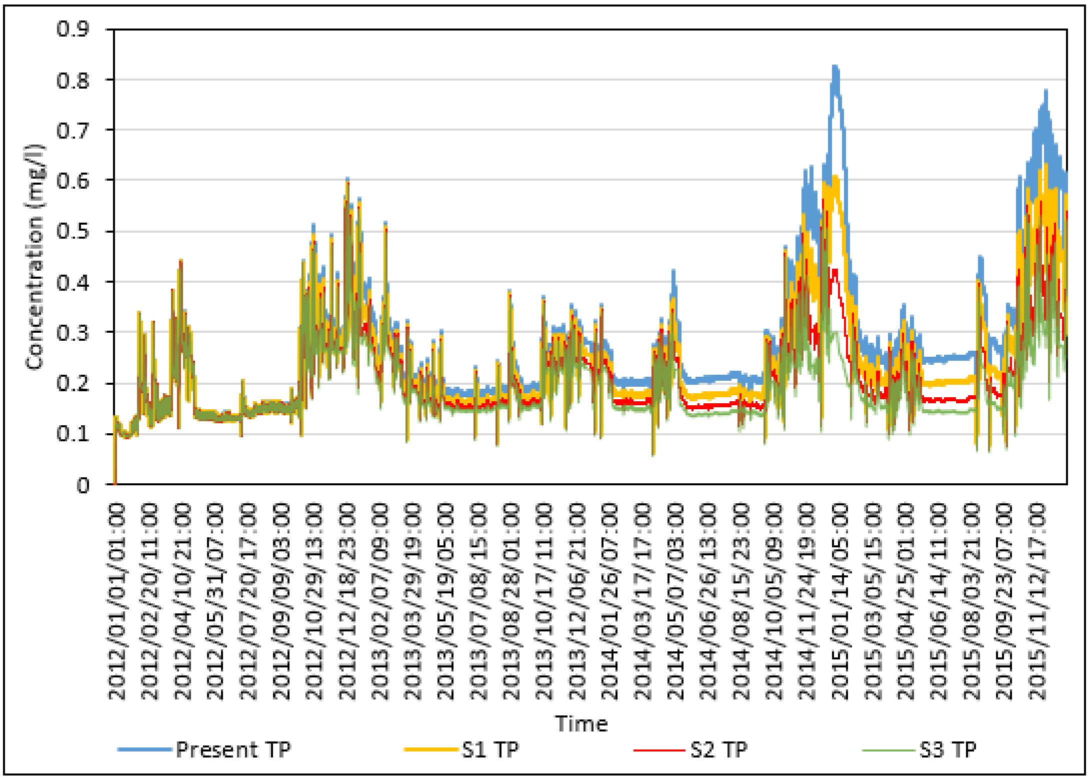


Figure 4.46: The Variation of TP in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

When considering the variation of Nitrogen components and the Phosphorus components, it is clearly evident that the Phosphorus components have shown much more significant deviation from their present condition values, when the fertilizer input amounts are reduced following S1, S2, and S3, than the Nitrogen components. This is because the parameters related to Phosphorus components have much more sensitivity to the WEP model results, as found from the sensitivity analysis. Therefore, the reduction in the fertilizer input has significantly affected in reducing the Phosphorus related components in the water ways.

c) Total Suspended Solids (TSS) variation

The TSS did not show a significant variation when comparing the present condition, Scenario 1 (S1), Scenario 2 (S2), Scenario 3 (S3) as illustrated in Figure 4.47. Therefore, the reduction of fertilizer input does not have a significant impact on the accumulation and dispersal patterns of Total Suspended Solids in the water ways.

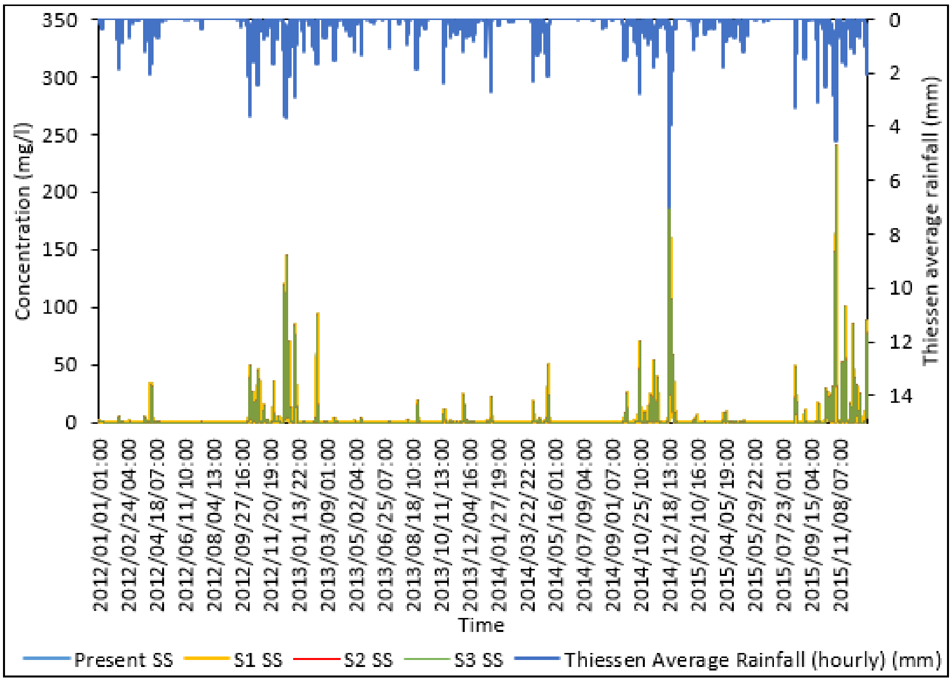


Figure 4.47: The Variation of TSS in Present Condition, Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3) (original in colour)

4.3.1.2 Comparison of nutrient concentrations with flow values

The results of all scenarios were classified under low flow, mid flow and high flow, similar to the present condition (refer Section 4.1.2), and they were compared with each other and with the previously published water quality values for the same basin.

a) Results of Nitrogen components

The mean±standard deviation of TN in different scenarios (concentrations in mg/l) have been tabulated in Table 4.5. Comparison of nutrient concentration values of all scenarios with the published results for the low flows, mid flows, high flows, and all flows conditions are shown in Figure 4.48, Figure 4.49, 4.50 and Figure 4.51, respectively.

Table 4.5: Comparison of TN in Different Flows (mean±standard deviation)

TN	Low flow	Mid Flow	High Flow	All Flows
Present	3.039 ± 0.940	2.087 ± 0.414	0.985 ± 0.255	2.155 ± 0.765
S1	2.935 ± 0.880	1.971 ± 0.361	0.977 ± 0.234	2.047 ± 0.703
S2	2.843 ± 0.832	1.882 ± 0.322	0.970 ± 0.218	1.960 ± 0.654
S3	2.766 ± 0.799	1.823 ± 0.293	0.965 ± 0.209	1.900 ± 0.617

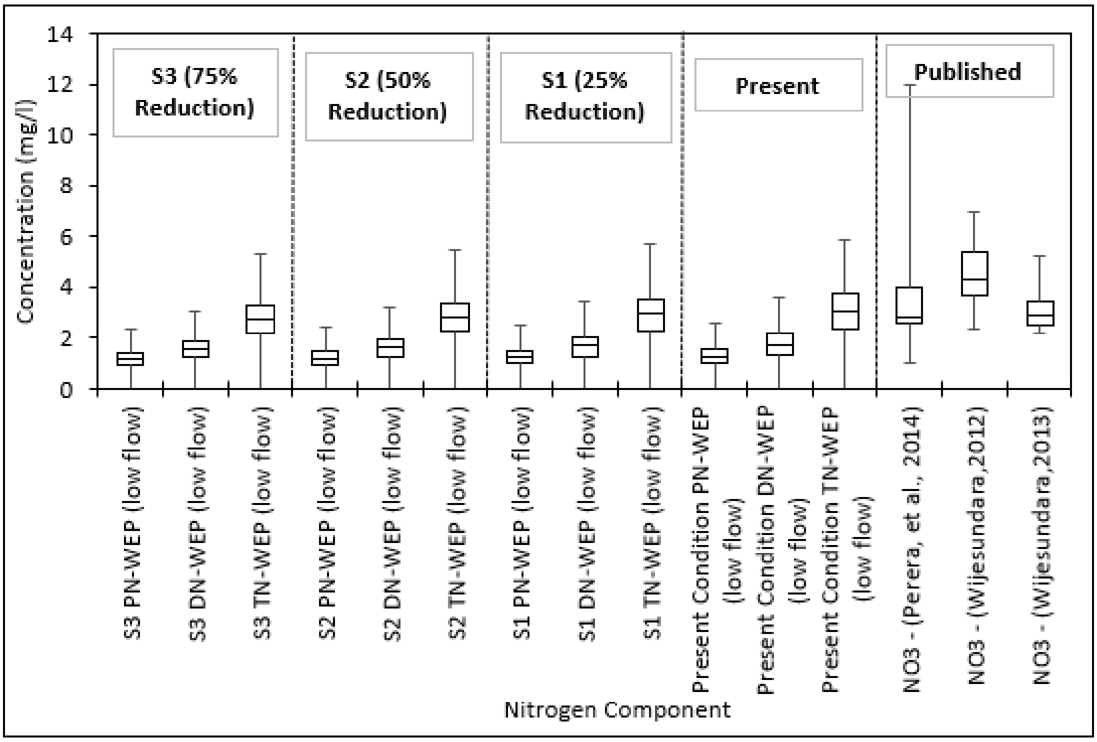


Figure 4.48: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the Low Flows

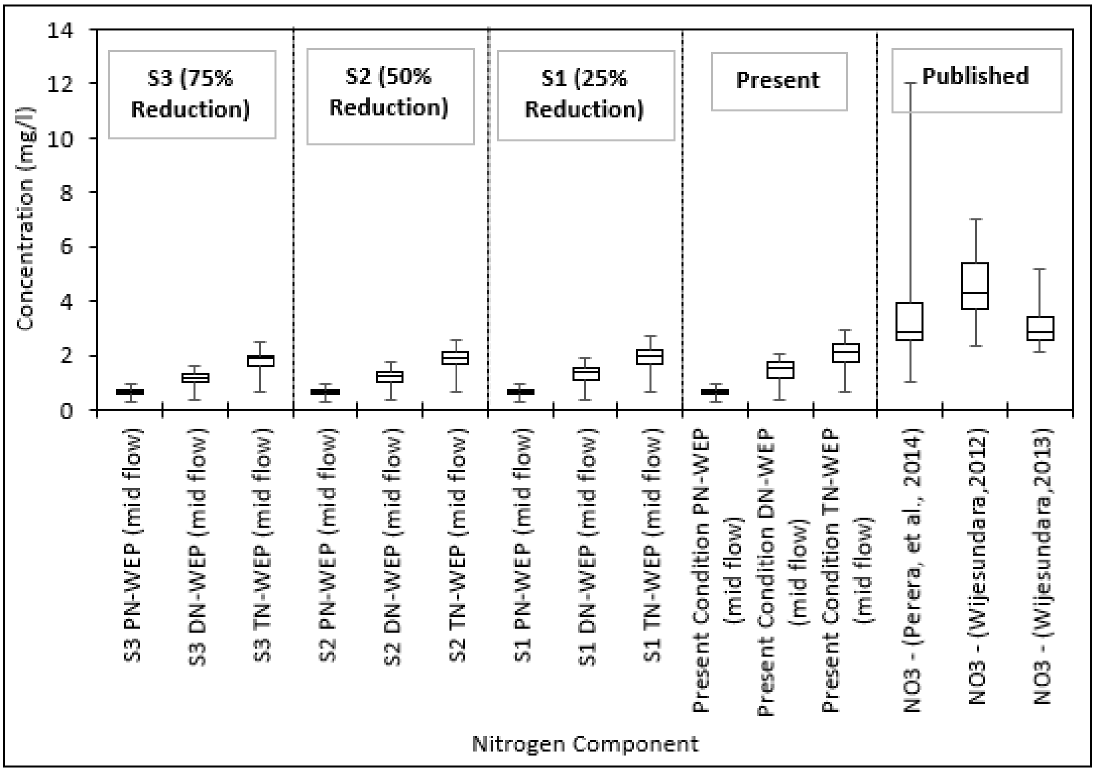


Figure 4.49: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the Mid Flows

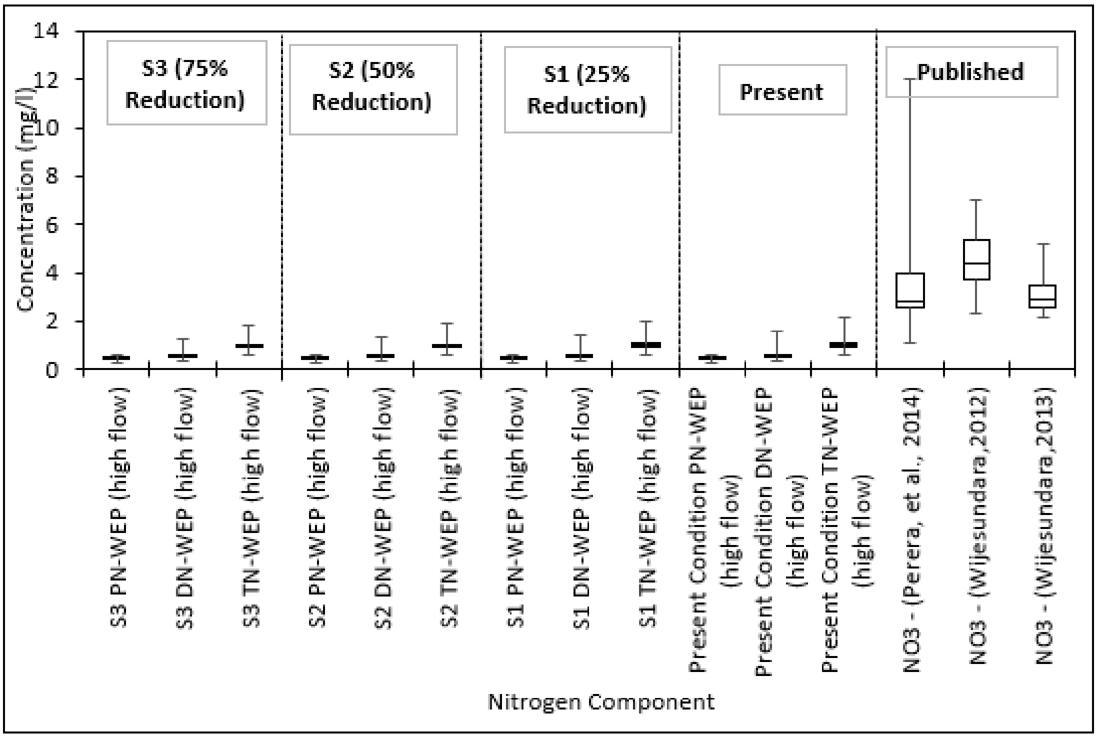


Figure 4.50: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the High Flows

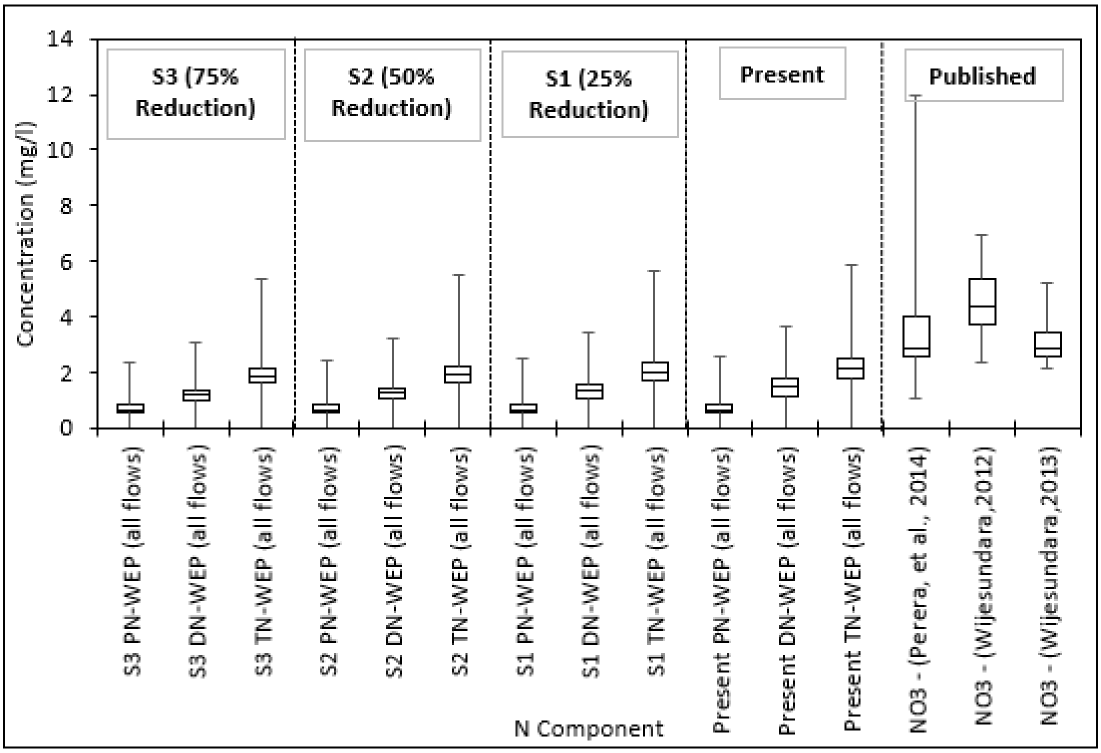


Figure 4.51: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the All Flows

According to the values given in Table 4.5 and after considering figures from Figure 4.48 to Figure 4.51, it could be stated that, the water quality results of all (Nitrogen) components have reduced with the reduction of the fertilizer input, and the low flow conditions showed better matching values with the published values.

b) Results of Phosphorus components

The mean±standard deviation of TP in different scenarios (concentrations in mg/l) have been tabulated in Table 4.6.

Table 4.6: Comparison of TP in Different Flows (mean±standard deviation)

TP	Low flow	Mid Flow	High Flow	All Flows
Present	0.418 ± 0.153	0.235 ± 0.045	0.139 ± 0.019	0.269 ± 0.133
S1	0.373 ± 0.120	0.207 ± 0.033	0.137 ± 0.016	0.237 ± 0.102
S2	0.337 ± 0.102	0.188 ± 0.028	0.136 ± 0.015	0.213 ± 0.080
S3	0.318 ± 0.098	0.175 ± 0.028	0.136 ± 0.014	0.198 ± 0.072

Comparison of nutrient concentration values of all scenarios with the published results for the low flows, mid flows, high flows, and all flows conditions are shown in Figure 4.52, Figure 4.53, 4.54 and Figure 4.55, respectively.

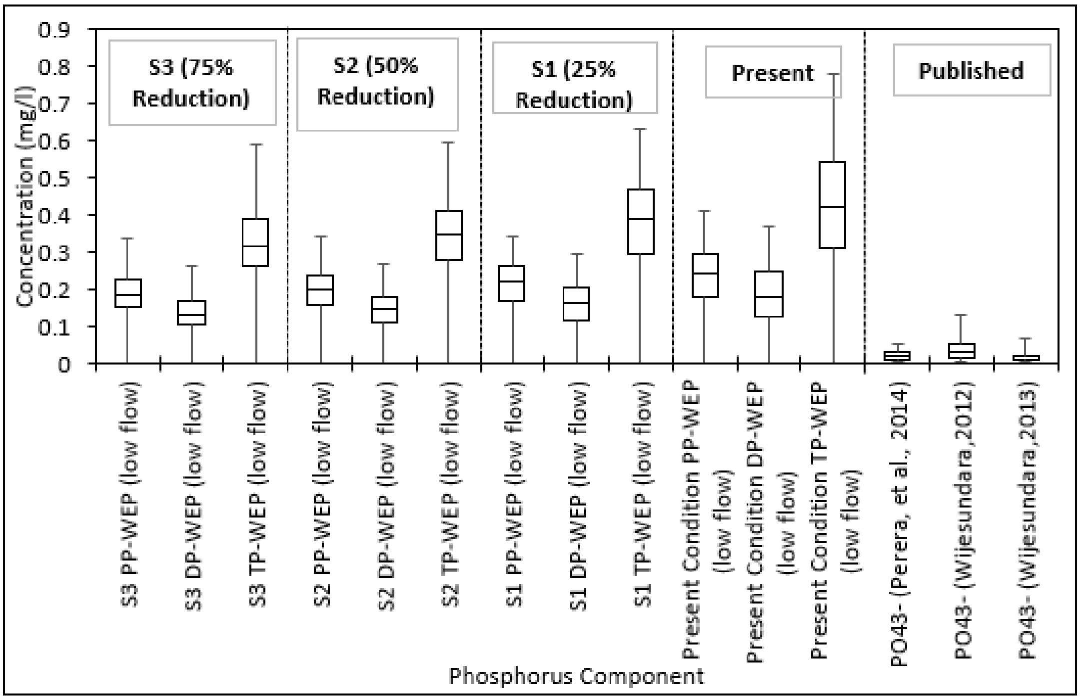


Figure 4.52: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the Low Flows

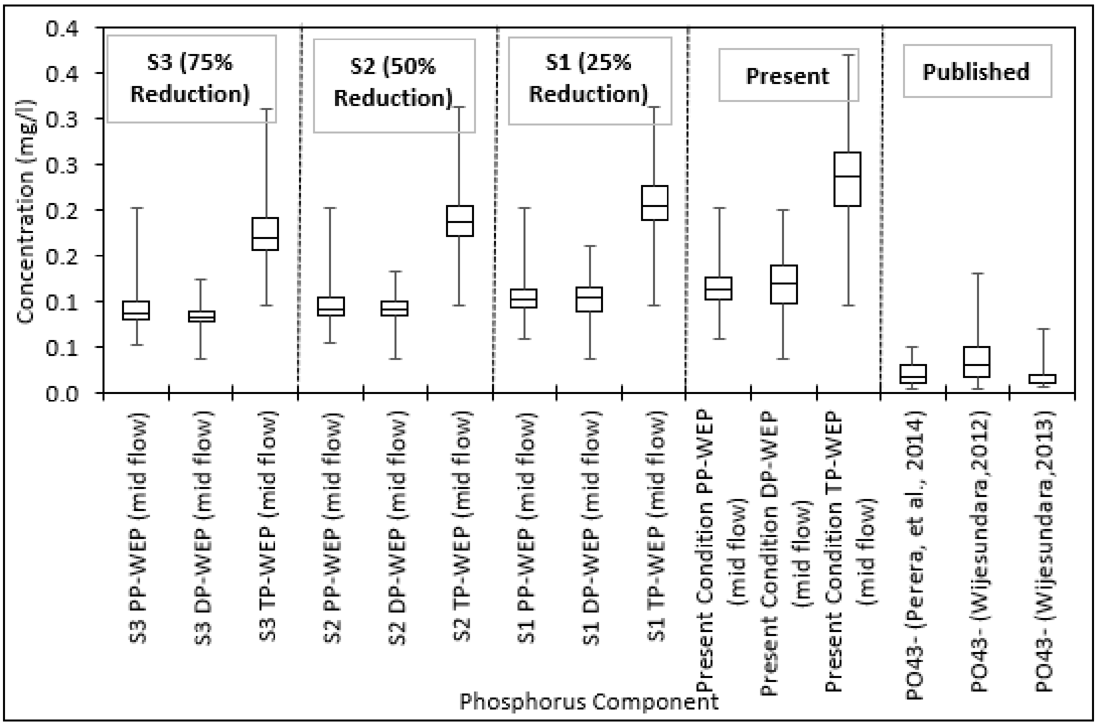


Figure 4.53: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the Mid Flows

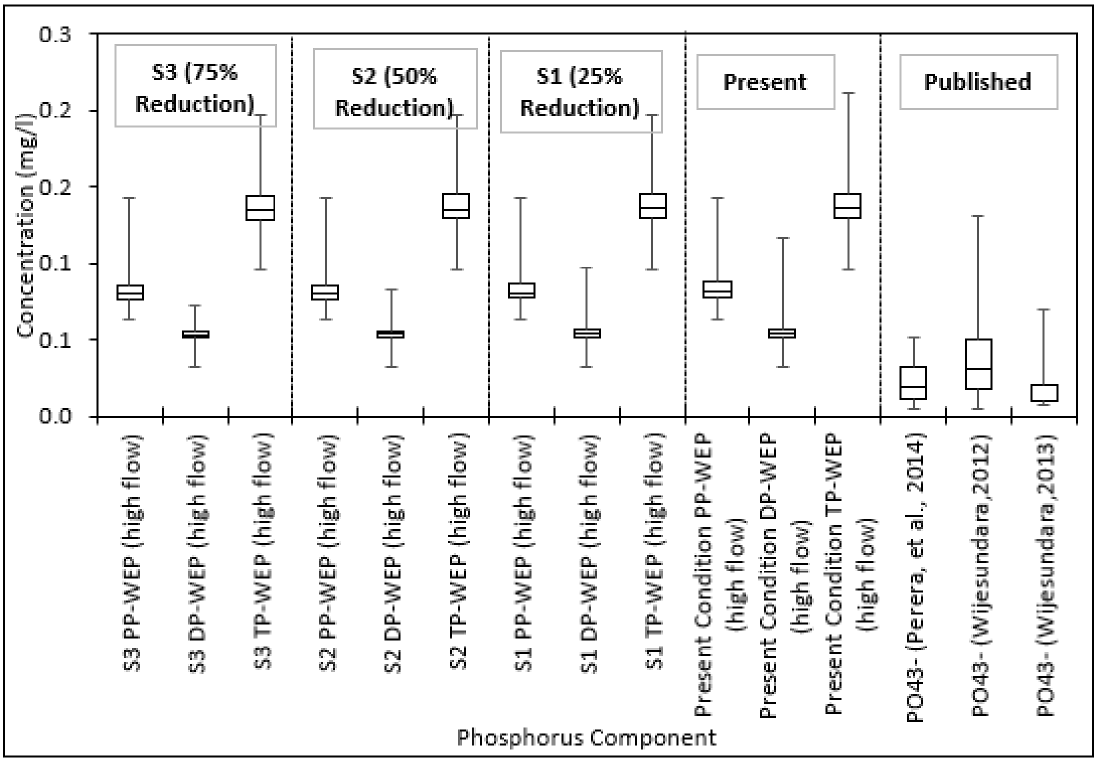


Figure 4.54: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the High Flows

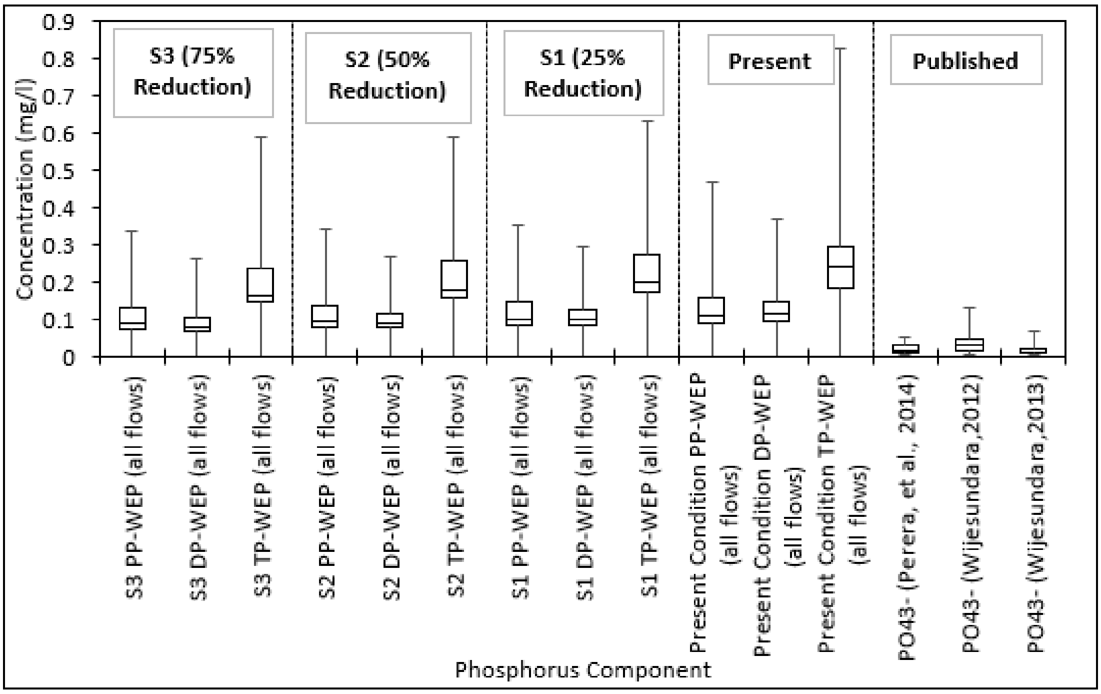


Figure 4.55: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the All Flows

According to the values given in Table 4.6 and after considering figures from Figure 4.52 to Figure 4.55, it could be stated that, the water quality results of all (Phosphorus) components have reduced with the reduction of the fertilizer input, and the high flow conditions showed better matching values with the published values.

c) Comparison of percentage difference

The percentage differences of the mean values of all water quality components, with respect to the present condition have been calculated. The comparison of values in Scenario 1, Scenario 2, and Scenario 3, have been tabulated in Table 4.7, Table 4.8, and Table 4.9, respectively.

Table 4.7: S1 Percentage Difference Compared to the Present Condition ((S 1 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	-2.240	-4.313	-3.437	-9.486	-12.234	-10.685	-42.396	-9.991	-32.405
Mid Flow	-0.004	-8.083	-5.545	-9.079	-13.888	-11.531	-48.129	-13.632	-34.498
High Flow	0.001	-1.385	-0.791	-0.663	-1.647	-1.051	-5.536	-2.175	-3.361

Table 4.8: S2 Percentage Difference Compared to the Present Condition ((S 2 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	-4.4497	-7.9269	-6.4583	-17.2754	-21.8912	-19.2902	-77.292	-18.835	-58.457
Mid Flow	-0.0075	-14.3000	-9.8107	-15.3629	-23.7932	-19.6617	-82.936	-24.118	-58.818
High Flow	0.0003	-2.5697	-1.4670	-1.1345	-2.8410	-1.8066	-9.818	-4.036	-5.782

Table 4.9: S3 Percentage Difference Compared to the Present Condition ((S 3 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	-6.672	-10.661	-8.976	-21.808	-26.391	-23.808	-98.317	-26.309	-72.007
Mid Flow	-0.011	-18.418	-12.636	-19.615	-30.644	-25.239	-106.564	-31.065	-75.499
High Flow	-0.001	-3.429	-1.958	-1.417	-3.584	-2.270	-12.659	-5.387	-7.272

Several conclusions could be made after taking into consideration of the percentage difference values tabulated in Table 4.7 to Table 4.9. Almost all the water quality parameter concentrations have been reduced with the reduction of fertilizer input (except only for PN in high flow conditions in S1 and S2). S3 shows the maximum amount of reduction in pollutant concentrations, when compared to the present condition. In addition, the Phosphorus components show higher amount of reduction, when compared with the reduction in Nitrogen components. Therefore, it could be presumed that the Phosphorus components are more sensitive to the fertilizer input to the WEP model.

When considering all scenarios, the maximum reduction in most of the water quality concentrations (DN, TN, DP, and TP) have been obtained in the mid flow values (this relationship is valid even if these N and P components are considered separately or as a summation). Therefore, it could be concluded that the accumulation and dispersal amounts of nutrients (especially in the dissolved condition) in the mid flow conditions are more sensitive to a reduction in fertilizer input.

However, when considering PN and PP, in all three scenarios, the maximum reduction has occurred during low flow conditions. This could be attributed to the fact that, during high flow conditions the high streamflow would induce a washout of the solids, and hence removing them quickly from the streams, therefore, most of the particulate nutrients get washed away. Therefore, during low flow conditions a more prominent reduction of the particulate nutrients could be expected, with the reduction of fertilizer input. Hence, during high flow conditions the reduction of particulate nutrient concentrations are less significant.

Although the fertilizer input has been reduced in S1, S2, and S3 with respect to the present condition, an increase of concentrations have occurred for PN in high flow conditions in S1 and S2. Since the Nitrogen input does not solely depend on the amount given by fertilizer alone [as it also depends on the amount given from N fixation (lightening, combustion, plant N fixation)], these concentration values could be justified.

4.3.1.3 Comparison of spatial variation of results

The seven spatial variation results files chosen for comparison (refer Section 4.1.3) in all scenarios were compared with each other and with the present condition results. The summary of the critical months and the percentage differences in the maximum values in the critical months have been tabulated in Tables 4.10 to Table 4.12. Further, the percentage difference in the maximum value was calculated as; ((Scenario max value)-(Present condition max value))*100)/(Present condition max value) .

Table 4.10: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S1

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 1 (25% reduction)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	-14.160
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	-13.674
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	October 2013	-40.089
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	-4.870
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	-2.919
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	-25.252
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	-21.536

Table 4.11: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S2

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 2 (50% reduction)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	-24.658
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	-25.388
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	September 2014	-69.126
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	-9.017
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	-5.689
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	-47.989
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	-41.238

Table 4.12: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S3

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 3 (75% reduction)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	-33.151
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	-35.976
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	September 2014	-85.952
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	-12.449
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	-8.544
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	-61.142
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	-53.574

According to Table 4.10 to Table 4.12, it is evident that the percentage difference (percentage reduction) in the maximum value (in the critical month), between the percent condition and the scenarios, have increased with the increase of the reduction of fertilizer input. The maximum reduction has occurred in S3 in the “p-fxdpce.asc” results file, which gives influx of DP quantity to grid cells. Almost all the water quality parameter concentrations have been reduced with the reduction of fertilizer input. S3 shows the maximum amount of reduction in pollutant concentrations, when compared to the present condition. In addition, the Phosphorus components show higher amount of reduction, when compared with the reduction in Nitrogen components. Therefore, it could be presumed that the Phosphorus components are more sensitive to the fertilizer input to the WEP model. The reduction of the critical values in the critical months of these results files which depict the spatial variation of various nutrient components, are further illustrated by Figures from Figure 4.56 to Figure 4.62. The practical importance of obtaining these spatial variation results files is that, after further refinement of data in the future, these could be used to identify the hotspots of pollutant concentrations. This would be very much helpful in isolating the areas where the fertilizer regulation must be carried out. On the other hand, it could be concluded that the accumulation and dispersal amounts of nutrients especially in the dissolved condition, are more sensitive to a reduction in fertilizer input.

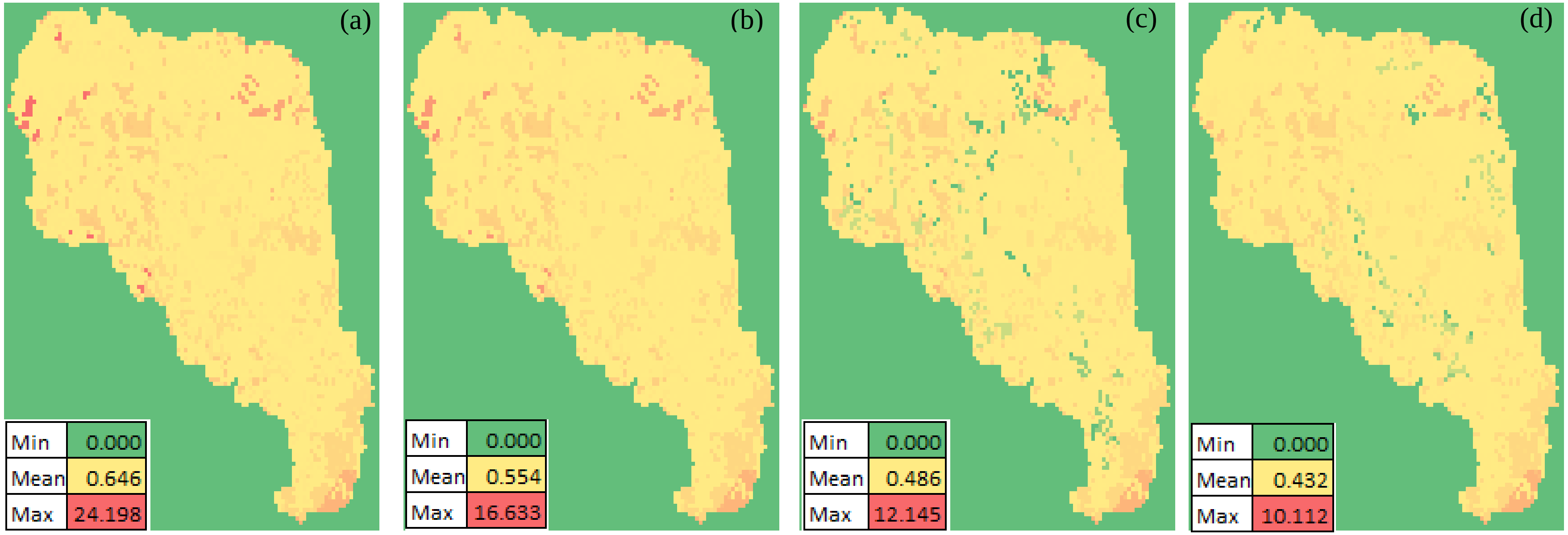


Figure 4.56: Comparison of Discharged DN from each layer ("fort.108" Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

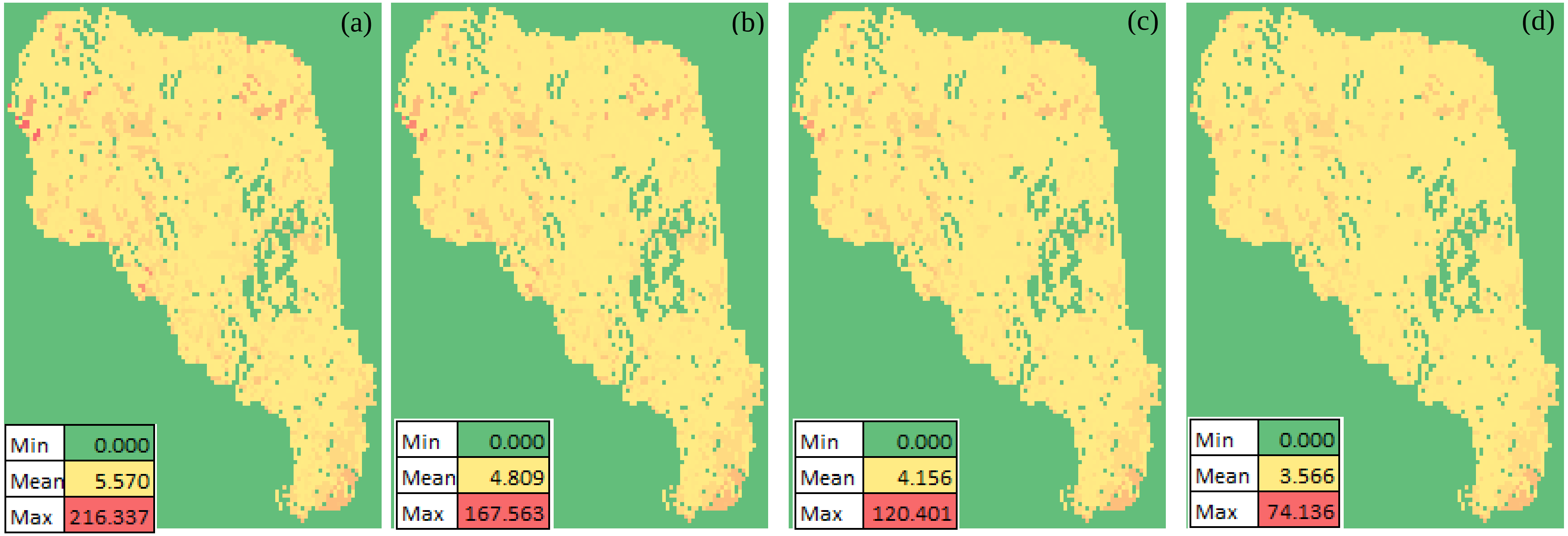


Figure 4.57: Comparison of DN in Gravity Drain/Subsurface Losses (“n-andrn1.asc” Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

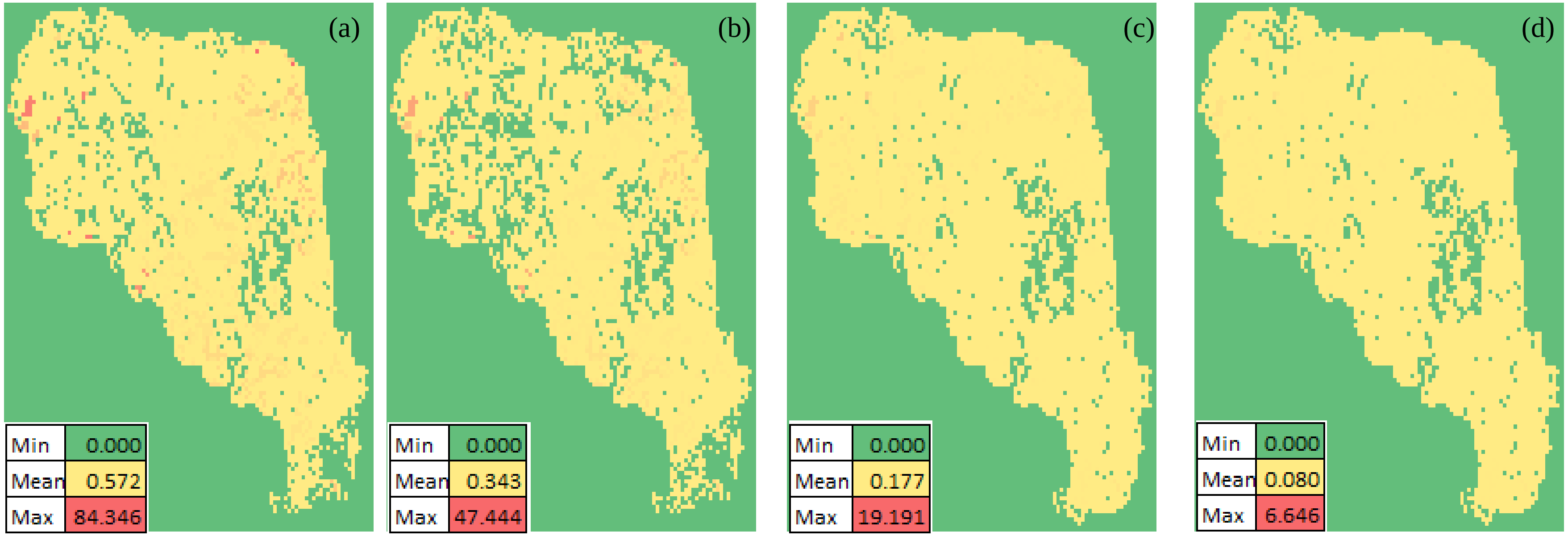


Figure 4.58: Comparison of DP in Gravity Drain/Subsurface Losses (“p-apdrn1.asc” Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

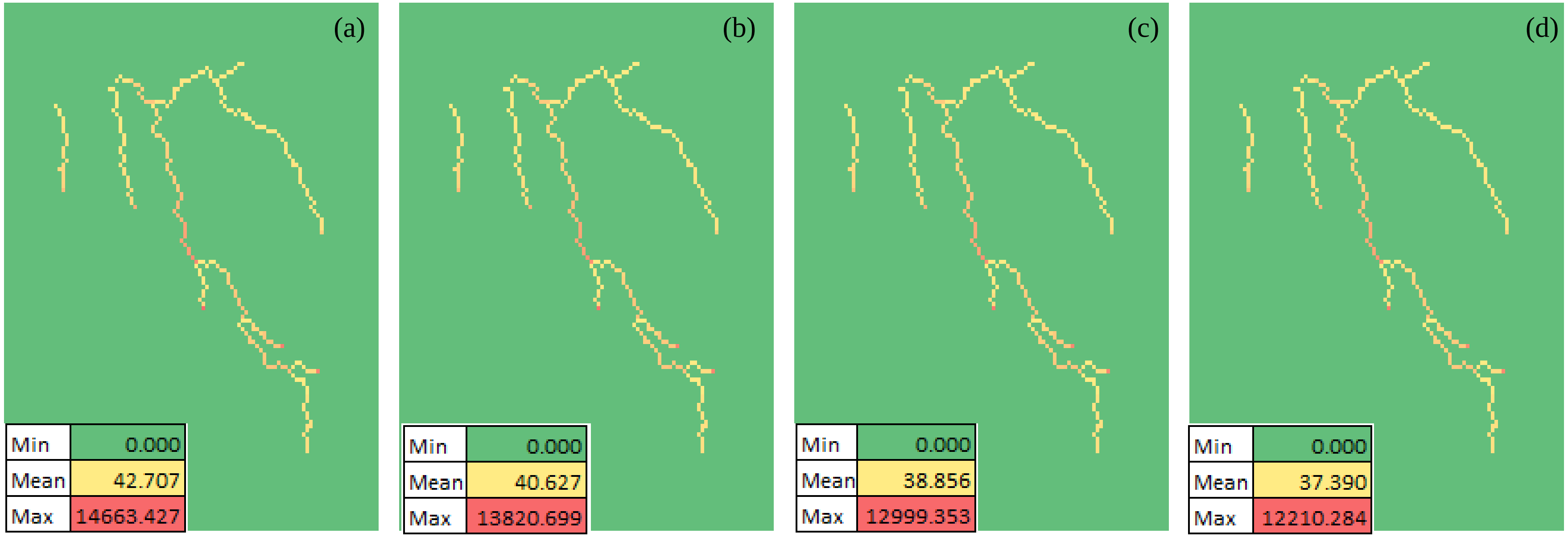


Figure 4.59: Comparison of Mesh Influx DN Quantity ("n-fxce.asc" Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

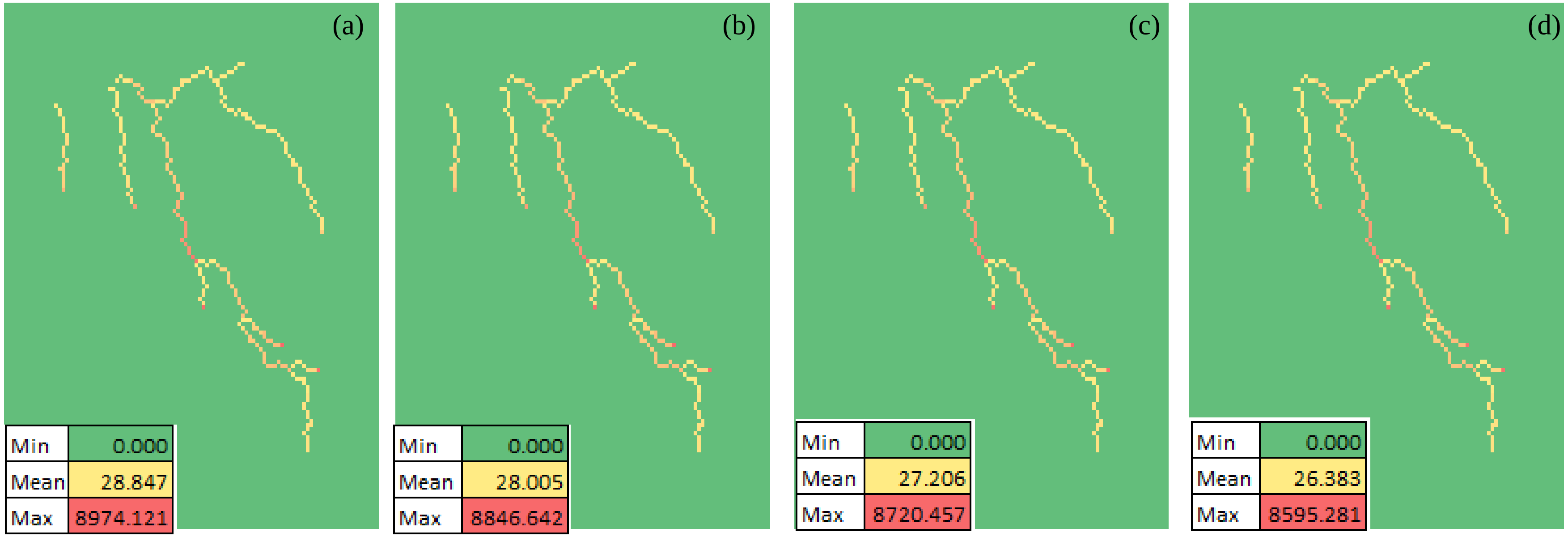


Figure 4.60: Comparison of Mesh Influx PN Quantity (“n-fxpnce.asc” Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

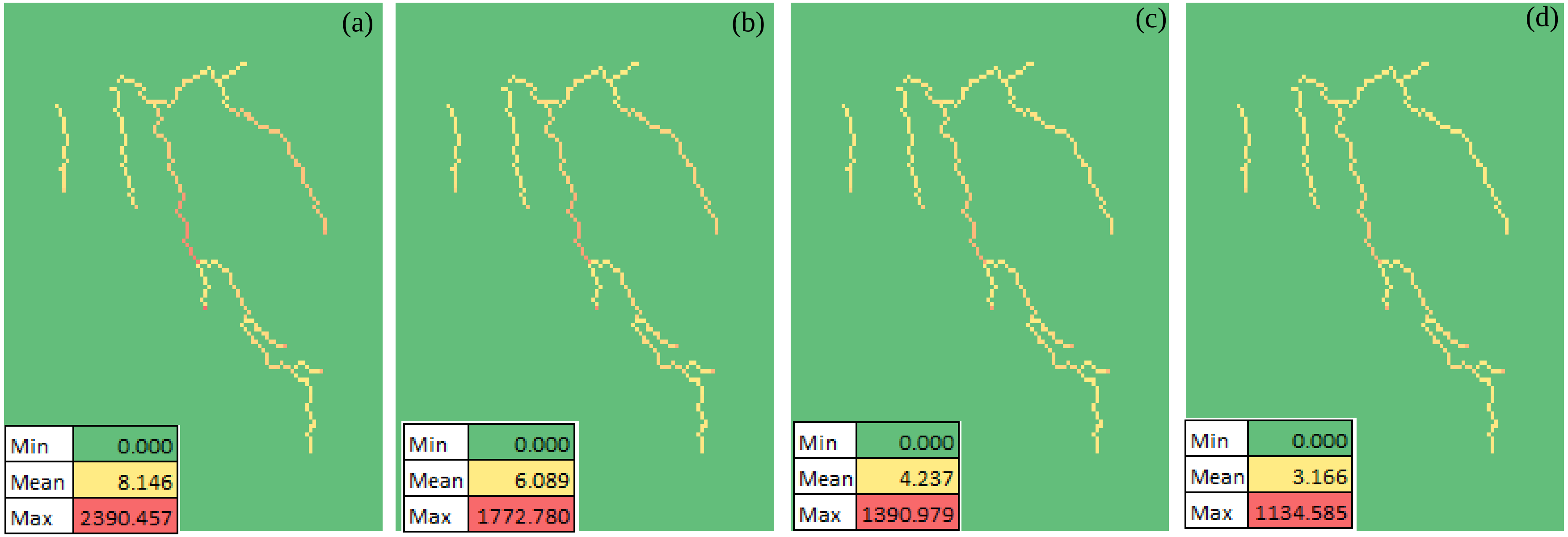


Figure 4.61: Comparison of Mesh Influx DP Quantity (“p-fxdpce.asc” Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

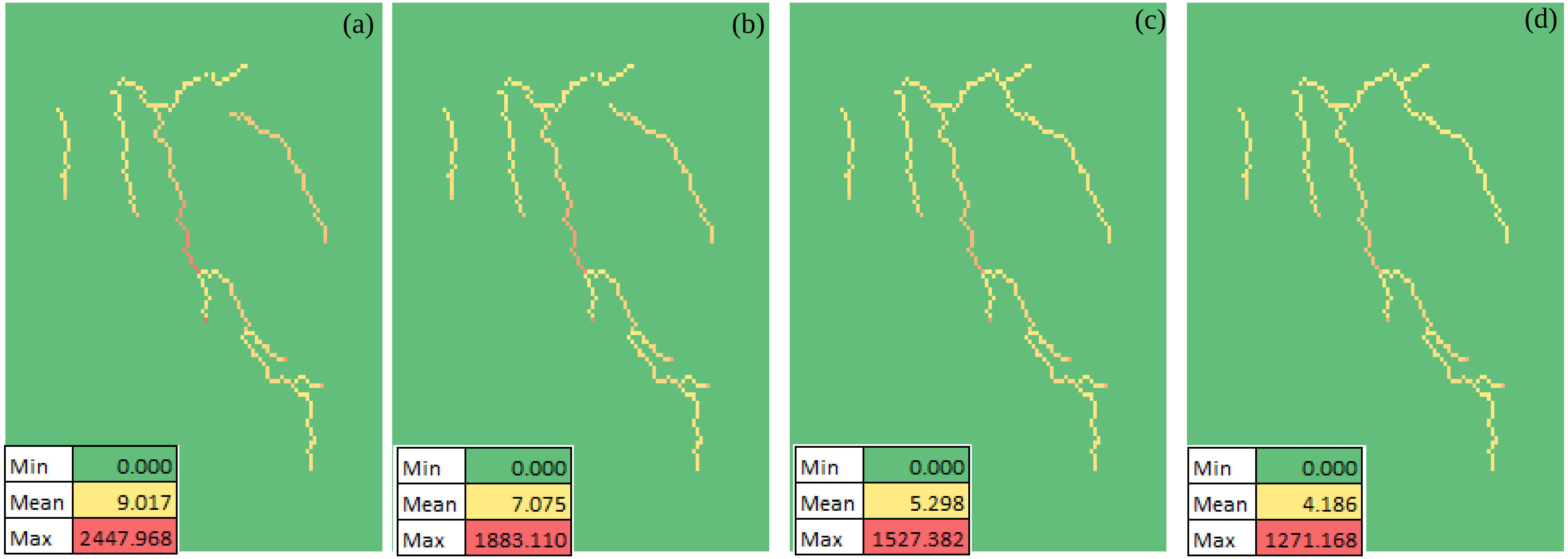


Figure 4.62: Comparison of Mesh Influx PP Quantity ("p-fxppce.asc" Results File); (a) Present Condition, (b) Scenario 1, (c) Scenario 2, (d) Scenario 3 (original in colour)

4.3.2 Comparison of climate change related scenarios (Scenario 4, 5 and 6)

4.3.2.1 Comparison of temporal variation of results

a) Results of Nitrogen components

The variation of PN in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are graphically represented in Figure 4.63. The PN amounts of S4, S5, and S6 do not show a significant deviation compared to the present condition, however, a slight deviation is noticeable. The PN of S4 and S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) as well as the increase in the magnitude of rainfall extreme events (S5), have an impact on the PN. In other words, the accumulation and dispersal patterns of particulate Nitrogen in the water ways are dependent on the amount of rainfall received. Further, PN values of S6 are lesser than the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of particulate Nitrogen in the water ways. In Figure 4.63 to Figure 4.65, the slightly increasing trend of concentrations occurring at the end of the study period (compared to the beginning) are due to the high amounts of fertilizer input in those years.

The variation of DN in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are illustrated in Figure 4.64. The DN amounts of S4, S5, and S6 do not show a significant deviation compared to the present condition, however, a slight deviation is noticeable. The DN of S4 and S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) as well as the increase in the magnitude of rainfall extreme events (S5), have an impact on the DN. In other words, the accumulation and dispersal patterns of dissolved Nitrogen in the water ways are dependent on the amount of rainfall received. Further, DN values of S6 has decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of dissolved Nitrogen in the water ways.

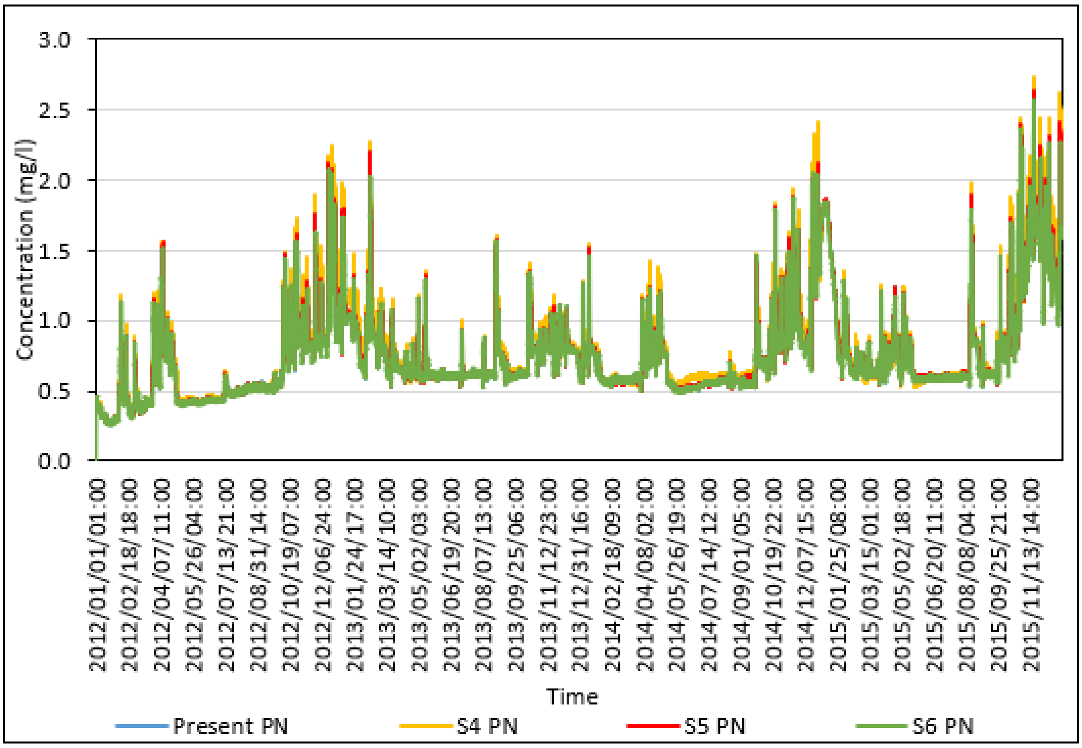


Figure 4.63: The Variation of PN in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

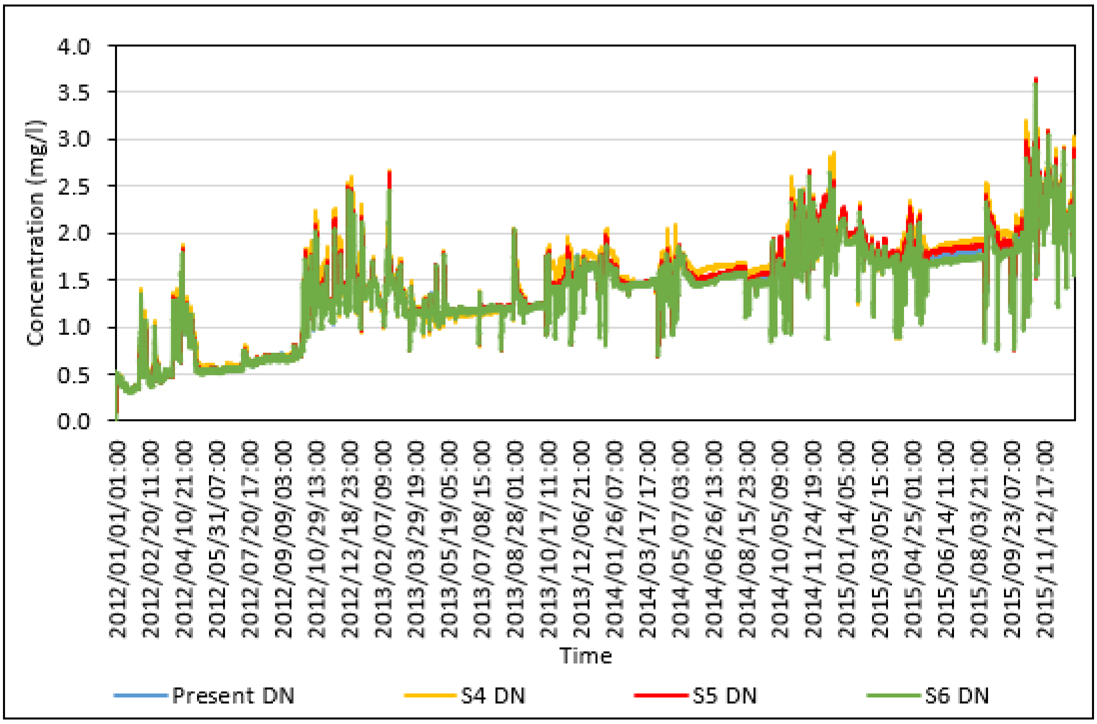


Figure 4.64: The Variation of DN in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

The variation of TN in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are illustrated in Figure 4.65. Since TN is the summation of PN and DN amounts, the TN amounts of S4, S5, and S6 do not show a significant deviation compared to the present condition, however, a slight deviation is noticeable. The TN of S4 and S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) as well as the increase in the magnitude of rainfall extreme events (S5), have an impact on the TN. In other words, the accumulation and dispersal patterns of total Nitrogen in the water ways are dependent on the amount of rainfall received. Further, TN values of S6 has decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of total Nitrogen in the water ways.

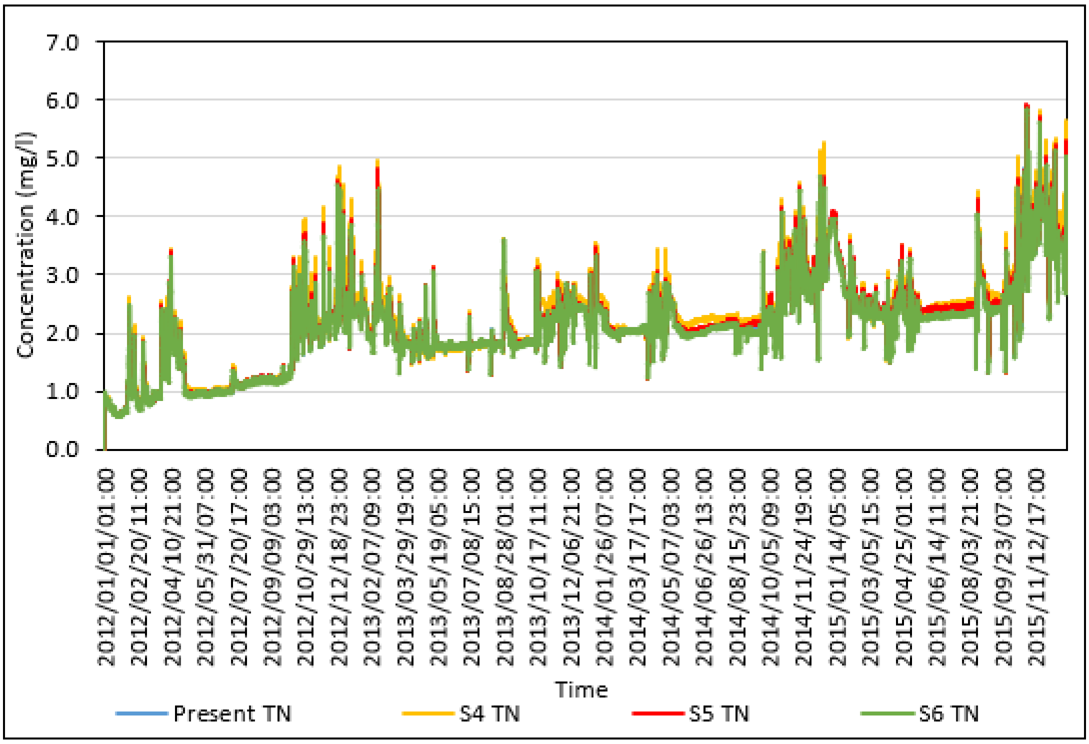


Figure 4.65: The Variation of TN in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

b) Results of Phosphorus components

The variation of PP in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are illustrated in Figure 4.66. The PP values of S4 have increased significantly with respect to the present condition, and the PP values of S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) has a significant impact on the amounts of PP and the increase in the magnitude of rainfall extreme events (S5) has a slight impact on the PP. In other words, the accumulation and dispersal patterns of particulate Phosphorus in the water ways are dependent on the amount of rainfall received. Further, PP values of S6 has decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of particulate Phosphorus in the water ways.

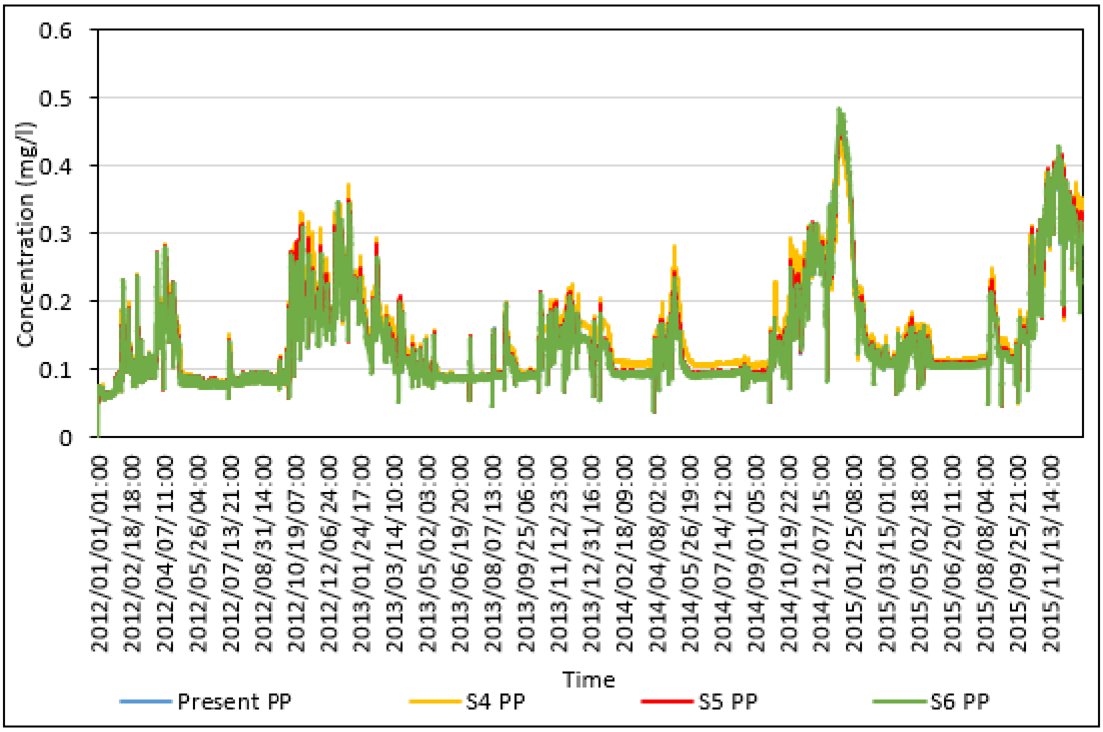


Figure 4.66: The Variation of PP in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

The variation of DP in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are illustrated in Figure 4.67. The DP values of S4 have increased significantly with respect to the present condition, and the DP values of S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) has a significant impact on the amounts of DP and the increase in the magnitude of rainfall extreme events (S5) has a slight impact on the DP. In other words, the accumulation and dispersal patterns of dissolved Phosphorus in the water ways are dependent on the amount of rainfall received. Further, DP values of S6 has decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of dissolved Phosphorus in the water ways.

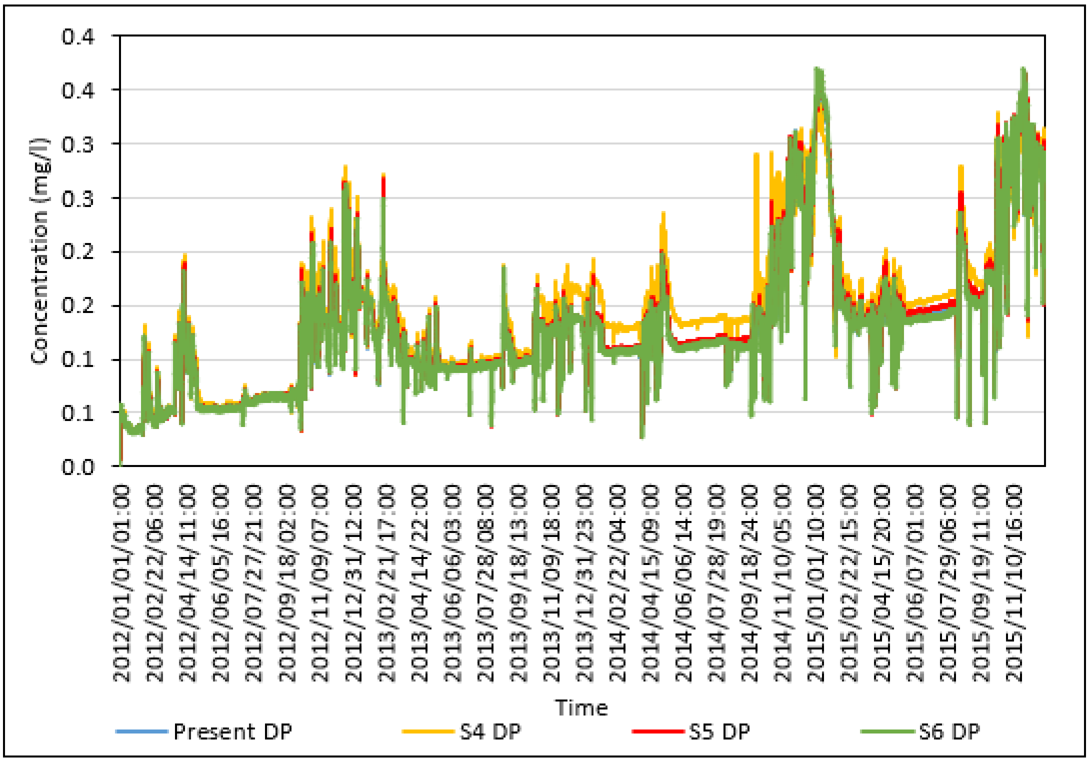


Figure 4.67: The Variation of DP in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

The variation of TP in the present condition, Scenario 4 (S4), Scenario 5 (S5), Scenario 6 (S6) are illustrated in Figure 4.68. Since TP is the summation of PP and DP amounts, the TP values of S4 have increased significantly with respect to the present condition, and the TP values of S5 have slightly increased with respect to the present condition, indicating that the increase in all rainfall values (S4) has a significant impact on the amounts of TP and the increase in the magnitude of rainfall extreme events (S5) has a slight impact on the TP. In other words, the accumulation and dispersal patterns of total Phosphorus in the water ways are dependent on the amount of rainfall received. Further, TP values of S6 has decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of total Phosphorus in the water ways.

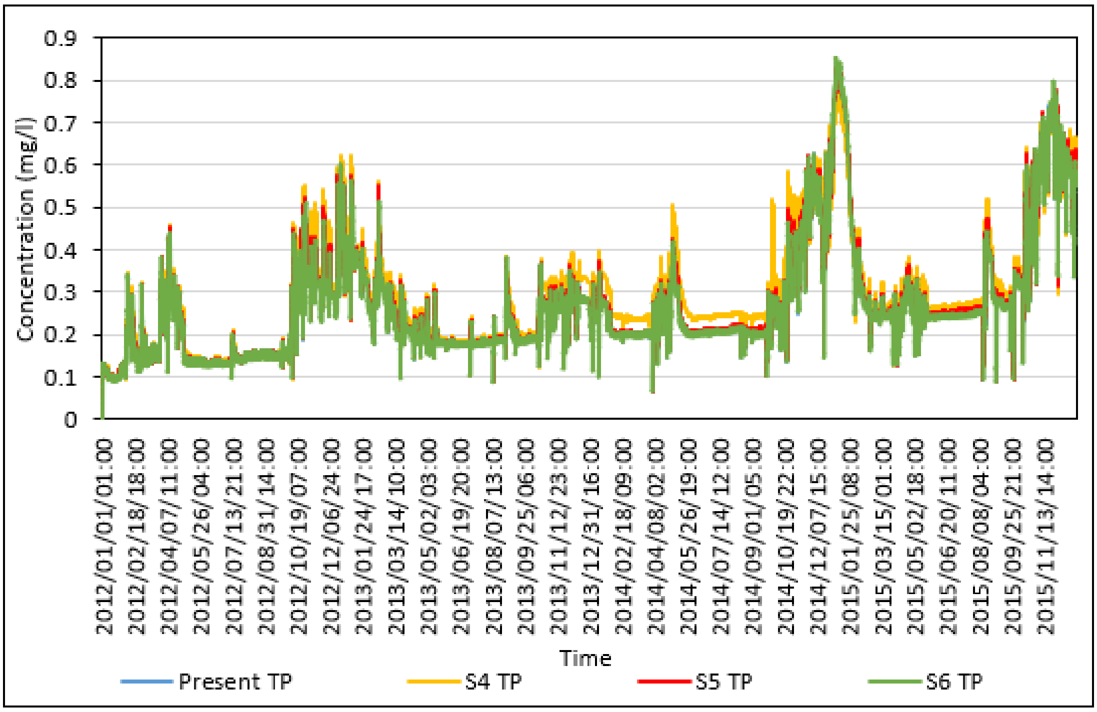


Figure 4.68: The Variation of TP in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

When considering the variation of Nitrogen components and the Phosphorus components, it was observed that in S4 and S5, the Phosphorus components have shown greater deviation from their present condition values, than the Nitrogen components. With respect to this difference (regarding N and P), S4 has shown greater values than S5. Therefore, it could be concluded that the parameters related to Phosphorus components have more sensitivity to the input rainfall values than the parameters related to the Nitrogen components, with the increase in all rainfall values (S4) having more effect than the increase in the magnitude of extreme events (S5).

However, in S6, the Nitrogen components have shown greater deviation from their present condition values than the Phosphorus components, hence implying that the parameters related to Nitrogen components have more sensitivity to the input temperature values than the parameters related to the Phosphorus components.

c) Total Suspended Solids (TSS) variation

The temporal variation of TSS in all scenarios is illustrated in Figure 4.69. TSS values of S4 have increased significantly with respect to the present condition, implying that the increase in rainfall resulting in a high streamflow that in turn would induce a washout of the solids, and hence the increase in TSS. In S5, with respect to the present condition, only the extreme values of TSS have been increased, as a result of increasing only the magnitude of extreme rainfall events in S5. Nevertheless, in S6, a distinct deviation from the present condition values of TSS was not observed, implying that the increase in temperature values does not have a significant impact on the accumulation and dispersal patterns of Total Suspended Solids in the water ways.

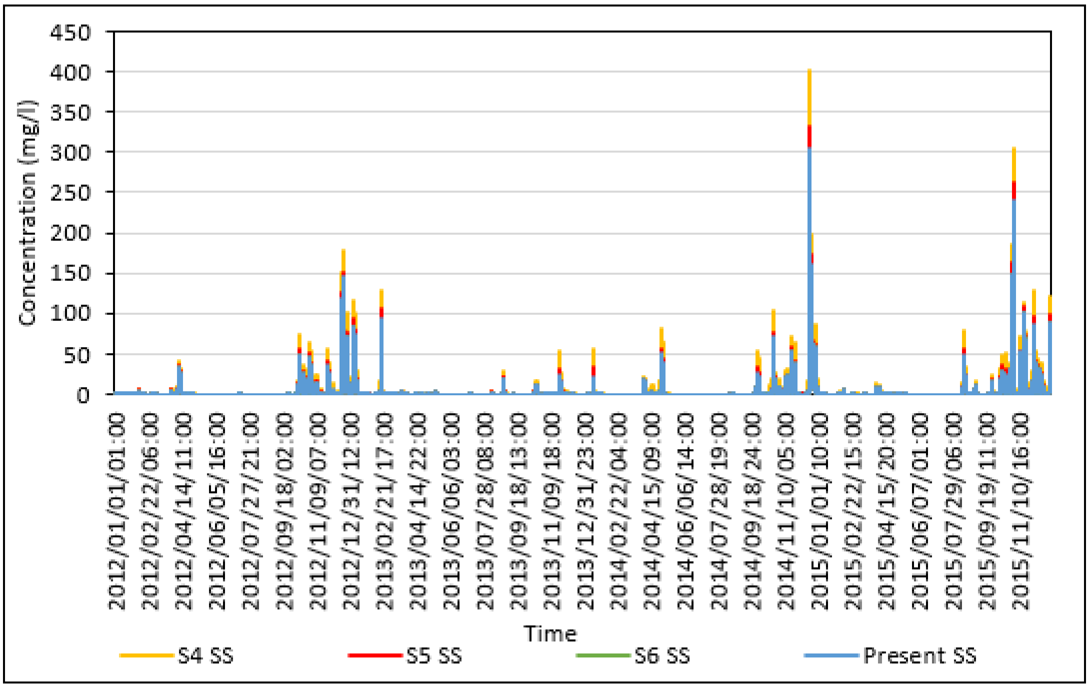


Figure 4.69: The Variation of TSS in Present Condition, Scenario 4 (S4), Scenario 5 (S5) and Scenario 6 (S6) (original in colour)

4.3.2.2 Comparison of nutrient concentrations with flow values

The results of all scenarios were classified under low flow, mid flow and high flow, similar to the present condition (refer Section 4.1.2), and they were compared with each other and with the previously published water quality values for the same basin.

a) Results of Nitrogen components

The mean±standard deviation of TN in different scenarios (concentrations in mg/l) have been tabulated in Table 4.13.

Table 4.13: Comparison of TN in Different Flows (mean±standard deviation)

TN	Low flow	Mid Flow	High Flow	All Flows
Present	3.039 ± 0.940	2.087 ± 0.414	0.985 ± 0.255	2.155 ± 0.765
S4	3.208 ± 0.988	2.164 ± 0.438	0.980 ± 0.164	2.047 ± 0.703
S5	3.077 ± 0.960	2.115 ± 0.433	0.976 ± 0.225	1.960 ± 0.654
S6	3.003 ± 0.930	2.051 ± 0.389	0.986 ± 0.264	1.900 ± 0.617

Comparison of nutrient concentration values of all scenarios with the published results for the low flows, mid flows, high flows, and all flows conditions are shown in Figure 4.70, Figure 4.71, 4.72 and Figure 4.73, respectively.

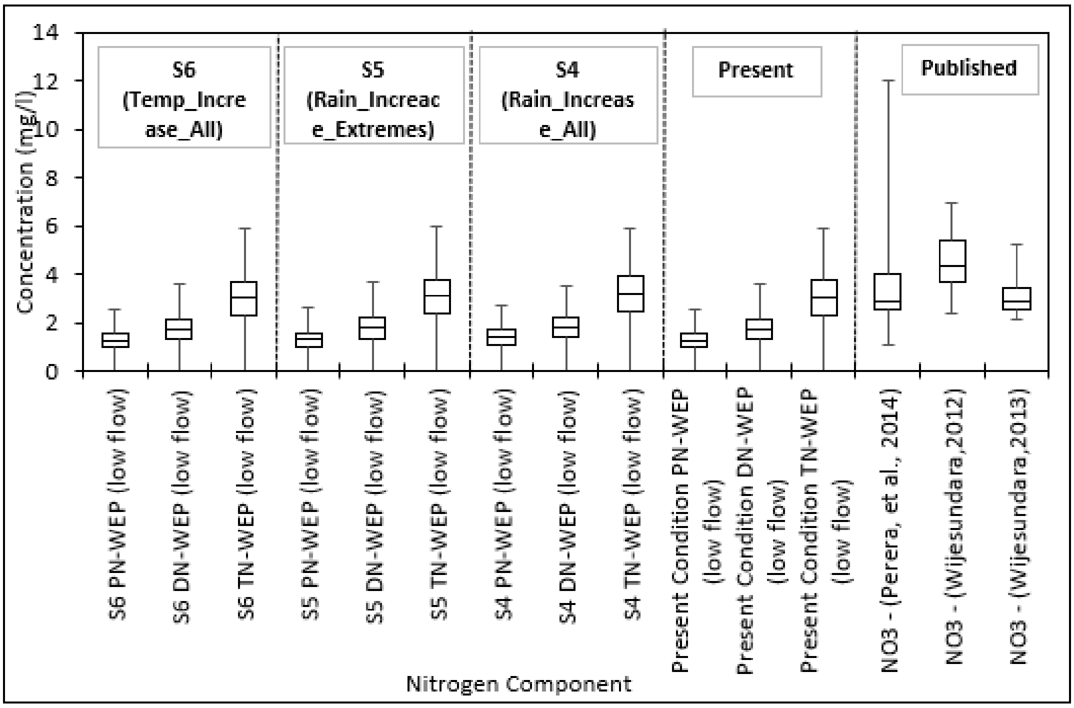


Figure 4.70: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the Low Flows

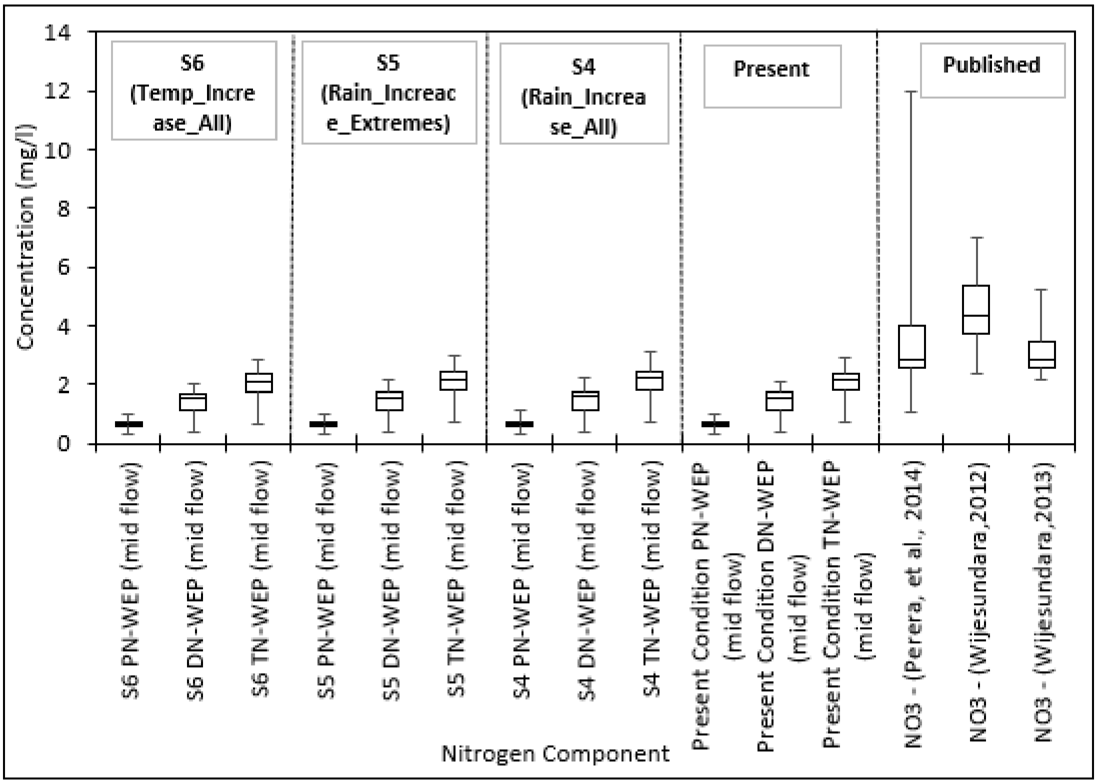


Figure 4.71: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the Mid Flows

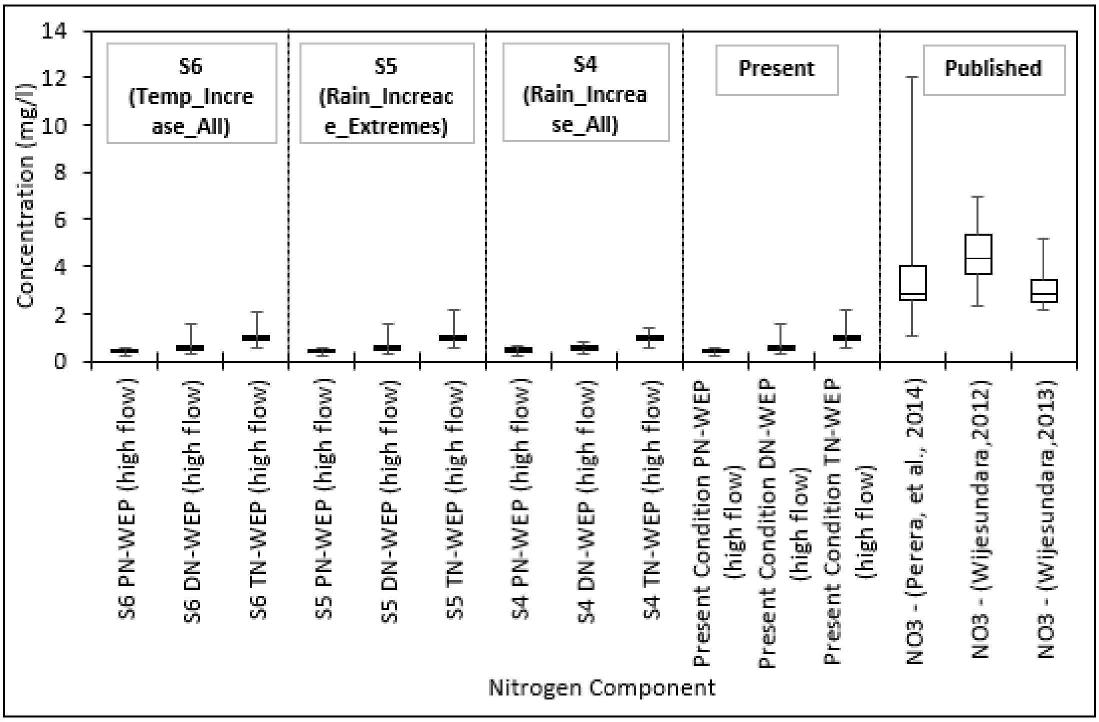


Figure 4.72: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the High Flows

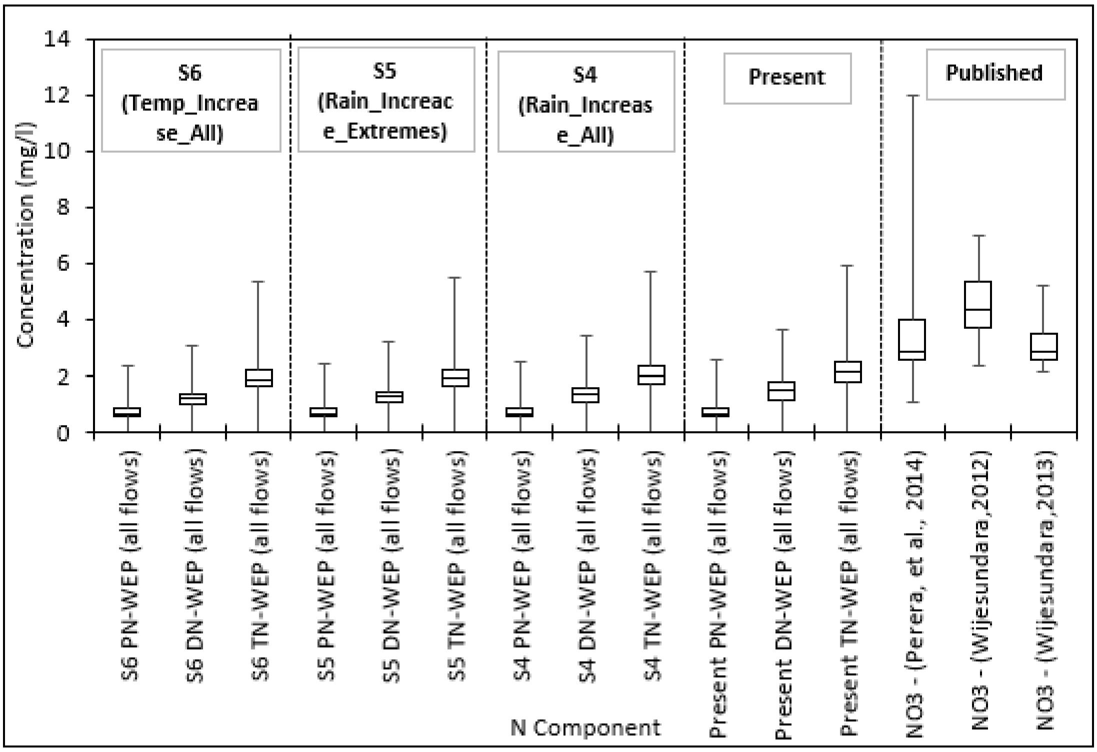


Figure 4.73: Comparison of Nutrient Concentration Values (Nitrogen Components) of All Scenarios with the Published Results for the All Flows

According to the values given in Table 4.13 and after considering figures from Figure 4.70 to Figure 4.73, it could be stated that the low flow conditions showed better matching values with the published values, with respect to the water quality results of all Nitrogen components.

b) Results of Phosphorus components

The mean±standard deviation of TP in different scenarios (concentrations in mg/l) have been tabulated in Table 4.14.

Table 4.14: Comparison of TP in Different Flows (mean±standard deviation)

TP	Low flow	Mid Flow	High Flow	All Flows
Present	0.418 ± 0.153	0.235 ± 0.045	0.139 ± 0.019	0.269 ± 0.133
S4	0.430 ± 0.144	0.264 ± 0.053	0.139 ± 0.015	0.237 ± 0.102
S5	0.421 ± 0.154	0.240 ± 0.047	0.138 ± 0.018	0.213 ± 0.080
S6	0.416 ± 0.155	0.231 ± 0.044	0.138 ± 0.020	0.198 ± 0.072

Comparison of nutrient concentration values of all scenarios with the published results for the low flows, mid flows, high flows, and all flows conditions are shown in Figure 4.74 Figure 4.75, 4.76 and Figure 4.77, respectively.

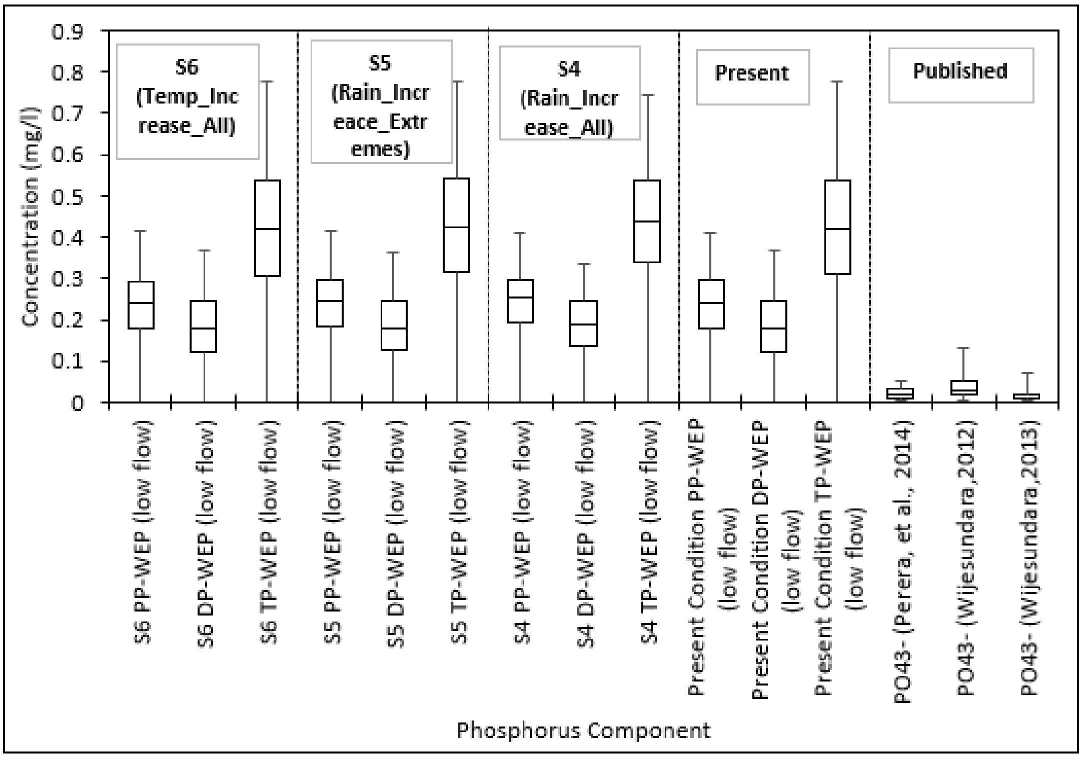


Figure 4.74: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the Low Flows

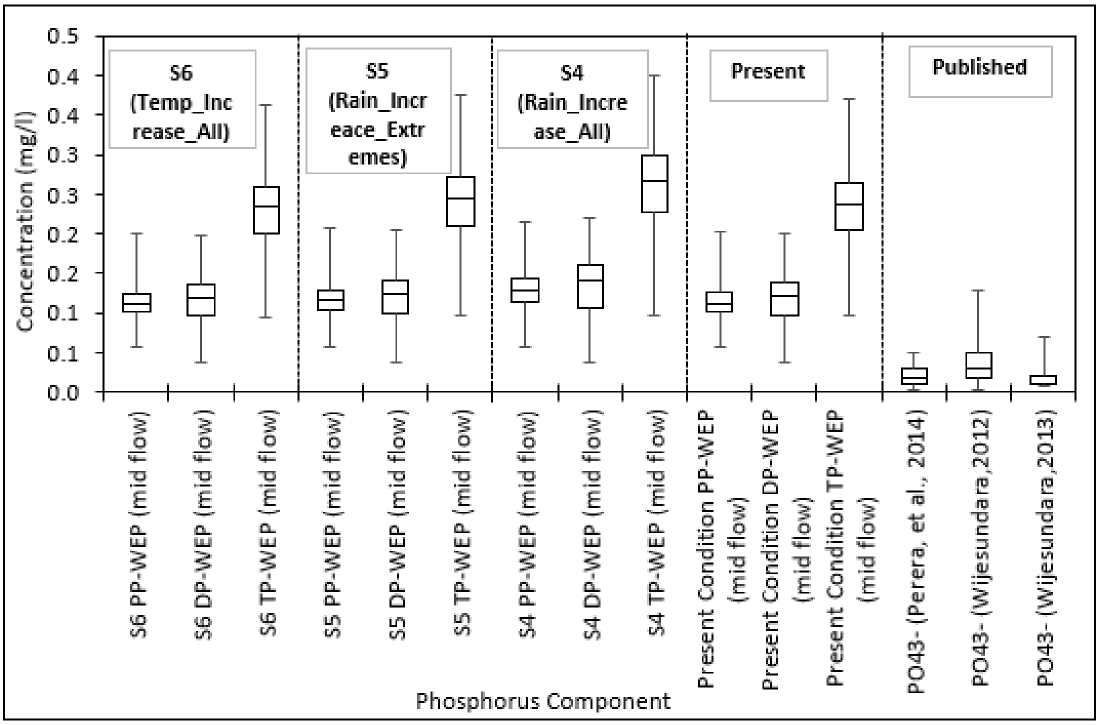


Figure 4.75: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the Mid Flows

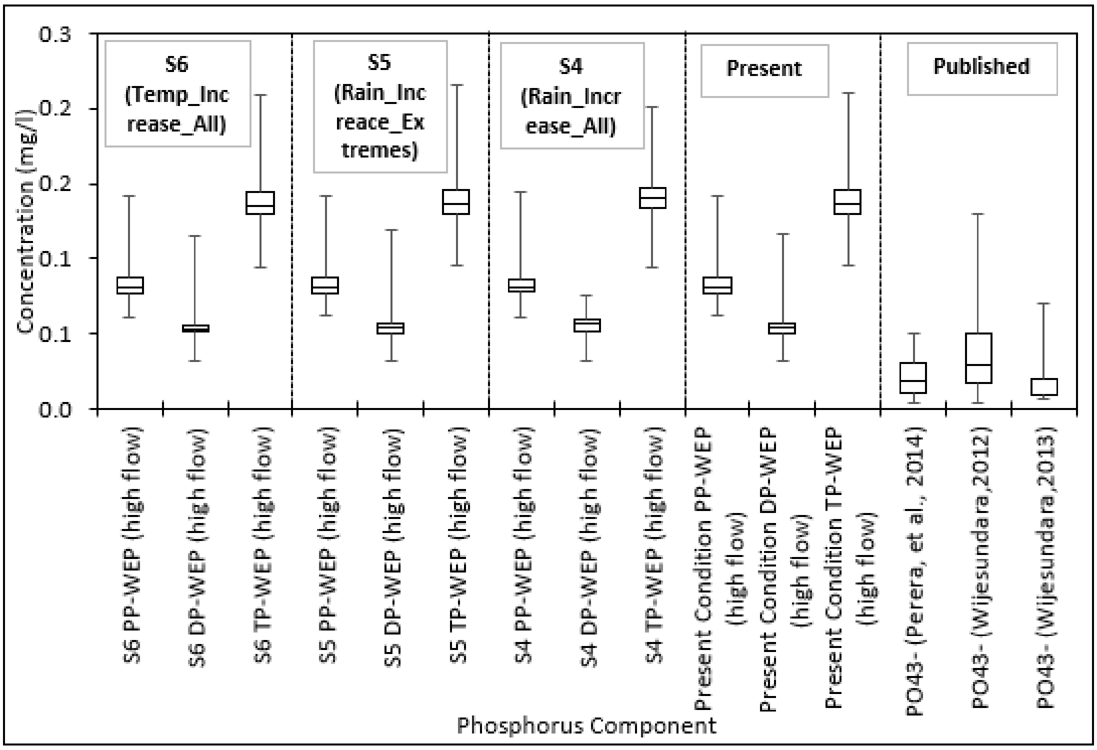


Figure 4.76: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the High Flows

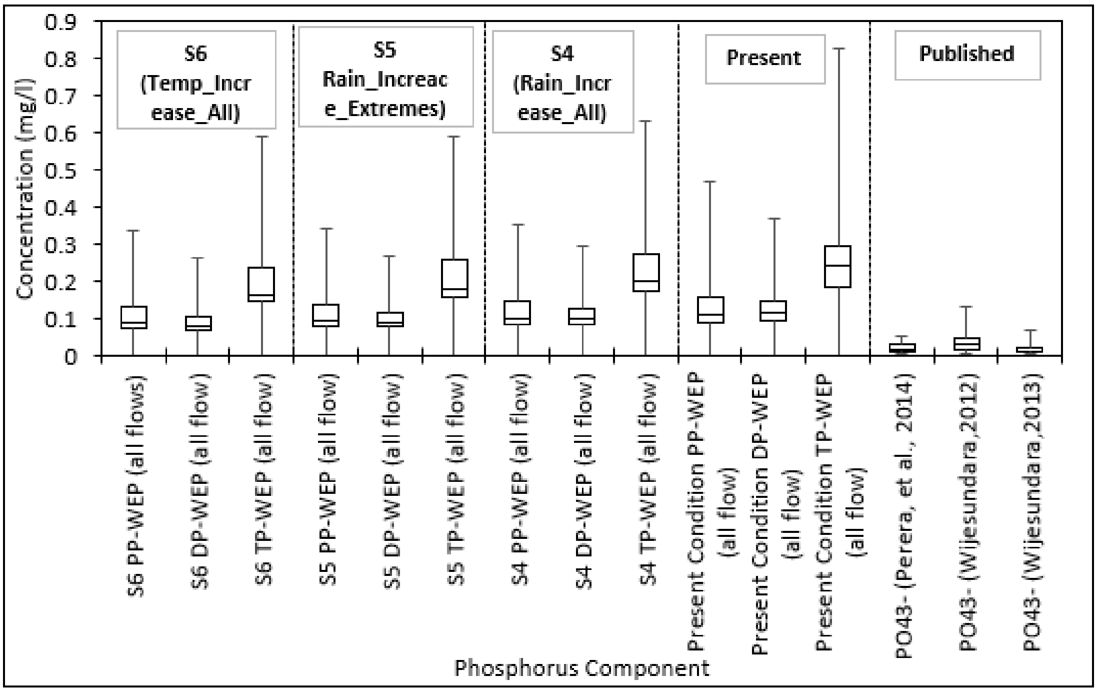


Figure 4.77: Comparison of Nutrient Concentration Values (Phosphorus Components) of All Scenarios with the Published Results for the All Flows

According to the values given in Table 4.14 and after considering figures from Figure 4.74 to Figure 4.77, it could be stated that, the high flow conditions showed better matching values with the published values, with respect to the water quality results of all Phosphorus components.

c) Comparison of percentage difference

The percentage differences of the mean values of all water quality components, with respect to the present condition have been calculated. The comparison of values in Scenario 4, Scenario 5, and Scenario 6, have been tabulated in Table 4.15, Table 4.16, and Table 4.17, respectively.

Table 4.15: S4 Percentage Difference Compared to the Present Condition ((S4 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	7.983	3.816	5.576	3.178	2.666	2.955	26.173	17.375	8.798
Mid Flow	3.726	3.664	3.683	11.295	13.494	12.416	48.279	11.073	37.206
High Flow	1.938	-2.352	-0.512	0.199	-0.138	0.067	-0.798	-0.927	0.128

Table 4.16: S5 Percentage Difference Compared to the Present Condition ((S5 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	1.581	1.019	1.257	0.859	0.651	0.768	6.136	3.857	2.279
Mid Flow	0.475	1.714	1.325	2.036	2.535	2.291	10.377	3.514	6.863
High Flow	0.154	-1.694	-0.902	-0.083	-0.897	-0.404	-3.827	-2.442	-1.385

Table 4.17: S6 Percentage Difference Compared to the Present Condition ((S6 Average - Present Condition Average)*100)/(Present Condition Average)

	PN	DN	TN	PP	DP	TP	Total	Total N	Total P
Low Flow	-0.757	-1.519	-1.197	-0.521	-0.318	-0.432	-4.743	-3.473	-1.271
Mid Flow	-0.508	-2.271	-1.718	-1.283	-1.529	-1.409	-8.718	-4.497	-4.221
High Flow	-0.204	0.367	0.122	-0.502	0.074	-0.275	-0.418	0.285	-0.703

Several conclusions could be made after taking into consideration the percentage difference values tabulated in Table 4.15 to Table 4.17.

Almost all the Nitrogen water quality parameter concentrations of S4 have increased with respect to the present condition (except only for DN and TN in high flow conditions), indicating that the increase in all rainfall values, have an impact on the concentrations of Nitrogen nutrients, which are increased accordingly. In other words, the accumulation and dispersal patterns of Nitrogen in the water ways are dependent on the amount of rainfall received. The maximum increase in all Nitrogen related water quality concentrations has been obtained in the low flow values in S4. Therefore, it could be concluded that the accumulation and dispersal amounts of Nitrogen nutrients in the low flow conditions are more sensitive to an increase in all rainfall values. This could be attributed to the fact that, during high flow conditions the high streamflow would induce a washout of the N related nutrients, and hence removing them quickly from the streams, therefore, most of the nutrients get washed away. Therefore, during low flow conditions a more prominent increase of the nutrients could be expected, with the increase in rainfall input. Hence, during high flow conditions the increase of N related nutrient concentrations are less significant. However, the DN and TN amounts have shown a decrease with respect to the present condition, during high flow conditions. This could be attributed to the fact that, since the high amount of dilution happening during the high flow conditions, the DN and TN nutrient concentrations have decreased even below their present condition values, with the increase in all rainfall values in S4.

On the other hand, the values of Phosphorus nutrient concentrations of S4 have increased significantly with respect to the present condition (except only for DP in high flow conditions), indicating that the increase in all rainfall values (S4) has a significant impact on the amounts of Phosphorus. In other words, the accumulation and dispersal patterns of Phosphorus nutrients in the water ways are dependent on the amount of rainfall received. Further, the maximum increase in all Phosphorus related water quality concentrations has been obtained in the mid flow values in S4. Therefore, it could be concluded that the accumulation and dispersal amounts of Phosphorus nutrients in the mid flow conditions are more sensitive to an increase in all rainfall values. However, the DP amounts have shown a decrease with respect to the present condition, during high flow conditions. This could be attributed to the fact that, since the high amount of dilution happening during the high flow conditions, the DP nutrient concentrations have decreased even below their present condition values, with the increase in all rainfall values in S4.

When S5 is considered, almost all the Nitrogen water quality parameter concentrations have increased with respect to the present condition (except only for DN and TN in high flow conditions), indicating that the increase in the magnitude of rainfall extreme events, have an impact on the concentrations of Nitrogen nutrients, which are increased accordingly. In other words, the accumulation and dispersal patterns of Nitrogen in the water ways are dependent on the amount of rainfall received. The maximum increase in almost all Nitrogen related water quality concentrations has been obtained in the mid flow values in S5 (except for PN where it was obtained in low flow conditions). Therefore, it could be concluded that the accumulation and dispersal amounts of Nitrogen nutrients in the mid flow conditions are more sensitive to an increase in the magnitude of rainfall extreme events. However, the DN and TN amounts have shown a decrease with respect to the present condition, during high flow conditions. This could be attributed to the fact that, since the high amount of dilution happening during the high flow conditions, the DN and TN nutrient concentrations have decreased even below their present condition values, with the increase in the magnitude of rainfall extreme events in S5.

On the other hand, the values of Phosphorus nutrient concentrations of S5 have increased with respect to the present condition (except for high flow conditions), indicating that the increase in the magnitude of rainfall extreme events (S5) has an impact on the amounts of Phosphorus. In other words, the accumulation and dispersal patterns of Phosphorus nutrients in the water ways are dependent on the amount of rainfall received. Further, the maximum increase in all Phosphorus related water quality concentrations has been obtained in the mid flow values in S5. Therefore, it could be concluded that the accumulation and dispersal amounts of Phosphorus nutrients in the mid flow conditions are more sensitive to an increase in the magnitude of rainfall extreme events. However, the nutrient amounts (PP, DP and TP) have shown a decrease with respect to the present condition, during high flow conditions. This could be attributed to the fact that, since the high amount of dilution happening during the high flow conditions, the nutrient concentrations have decreased even below their present condition values, with the increase in the magnitude of rainfall extreme events in S5.

Further, the N related nutrient concentration values of S6 have decreased with respect to the present condition (except for DN and TN in high flow conditions), implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of Nitrogen in the water ways. The maximum decrease in almost all Nitrogen related water quality concentrations has been obtained in the mid flow values in S6 (except for PN where it was obtained in low flow conditions). Therefore, it could be concluded that the accumulation and dispersal amounts of Nitrogen nutrients in the mid flow conditions are more sensitive to an increase in the temperature. However, the DN and TN amounts have shown an increase with respect to the present condition, during high flow conditions.

On the other hand, the P related nutrient concentration values of S6 have decreased with respect to the present condition (except for DP in high flow conditions), implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of Phosphorus in the water ways. The maximum decrease in all Phosphorus related water quality concentrations has been obtained in the mid flow values in S6. Therefore, it could be concluded that the accumulation and dispersal amounts of Phosphorus nutrients in the mid flow conditions are more sensitive to an increase in the temperature. However, the DP amounts have shown an increase with respect to the present condition, during high flow conditions.

When considering the variation of Nitrogen components and the Phosphorus components, it was observed that in S4 and S5, the Phosphorus components have shown greater deviation from their present condition values, than the Nitrogen components. With respect to this difference (regarding N and P), S4 has shown greater values than S5. Therefore, it could be concluded that the parameters related to Phosphorus components have more sensitivity to the input rainfall values than the parameters related to the Nitrogen components, with the increase in all rainfall values

(S4) having more effect than the increase in the magnitude of extreme rainfall events (S5).

However, in S6, the Nitrogen components have shown greater deviation from their present condition values than the Phosphorus components, hence implying that the parameters related to Nitrogen components have more sensitivity to the input temperature values than the parameters related to the Phosphorus components.

When considering all scenarios, and the summation of all Phosphorus components are considered as a whole (column “Total P”) the maximum reduction/increase in the water quality concentrations have been obtained in the mid flow values. Therefore, it could be concluded that the accumulation and dispersal amounts of Phosphorus nutrients in the mid flow conditions are more sensitive to a change in the climate.

However, when considering all scenarios, and the summation of all Nitrogen components are considered as a whole (column “Total N”), the maximum increase is found in low flow values in S4 and S5, but in mid flow values in S6. Therefore, it could be concluded that the accumulation and dispersal amounts of Nitrogen nutrients in the low flow conditions are more sensitive to a change in the rainfall, but mid flow conditions are more sensitive to a change in the temperature.

On the other hand, when considering all scenarios, and the summation of percentage differences in all N and P components are considered together (column “Total”) the maximum reduction/increase in the water quality concentrations have been obtained in the mid flow values. Therefore, it could be concluded that the accumulation and dispersal amounts of nutrients (when all nutrients are taken as a whole) in the mid flow conditions are more sensitive to a change in the climate.

4.3.2.3 Comparison of spatial variation of results

The seven spatial variation results files chosen for comparison (refer Section 4.1.3) in all scenarios were compared with each other and with the present condition results. The summary of the critical months and the percentage differences in the maximum values in the critical months have been tabulated in Tables 4.18 to Table 4.20. Further, the percentage difference in the maximum value was calculated as; ((Scenario max value)-(Present condition max value))*100)/(Present condition max value) .

Table 4.18: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S4

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 4 (Rain_Increase_ All)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	-5.169
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	-0.671
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	October 2013	24.237
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	34.843
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	43.871
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	16.835
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	19.497

Table 4.19: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S5

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 5 (Rain_Increace _Extremes)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	-0.508
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	0.414
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	October 2013	17.045
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	6.723
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	7.675
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	3.499
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	3.985

Table 4.20: Comparison of Critical Months and the Percentage Differences in the Maximum Values - Present and S6

File	Critical Month(s)		Percentage difference in the maximum value
	Present Condition	Scenario 6 (Temp_Increase _All)	
fort.108 (Discharged DN from each layer)	September 2012, ANI1	September 2012, ANI1	1.104
n-andrn1.asc (DN in gravity drain/subsurface losses)	October 2012	October 2012	-0.837
p-apdrn1.asc (DP in gravity drain/subsurface losses)	October 2013	October 2013	-5.708
n-fxce.asc (Mesh influx DN quantity)	December 2014	December 2014	-3.390
n-fxpnce.asc (Mesh influx PN quantity)	December 2014	December 2014	-2.264
p-fxdpce.asc (Mesh influx DP quantity)	December 2014	December 2014	-0.297
p-fxppce.asc (Mesh influx PP quantity)	December 2014	December 2014	-0.856

According to Table 4.18, in S4, it is evident that in almost all the parameters (which were chosen to represent the spatial variation of results) have increased with respect to the present condition, indicating that the increase in all rainfall values, have an impact on the concentrations of nutrients, which are increased accordingly. In other words, the accumulation and dispersal patterns of nutrients in the water ways are dependent on the amount of rainfall received. The maximum increase in S4 has been obtained in the “n-fxpnce.asc” results file, which gives influx of PN quantity to grid cells. Therefore, it could be concluded that the influx of PN quantity to grid cells is more sensitive to an increase in all rainfall values.

When S5 is considered, according to Table 4.19, it is evident that in almost all the parameters (which were chosen to represent the spatial variation of results) have increased with respect to the present condition, indicating that the increase in the magnitude of rainfall extreme events, have an impact on the concentrations of nutrients, which are increased accordingly. In other words, the accumulation and dispersal patterns of nutrients in the water ways are dependent on the amount of rainfall received. The maximum increase in S5 has been obtained in the “p-apdrn1.asc” results file, which gives the DP quantity in gravity drain/subsurface losses. Therefore, it could be concluded that the DP quantity in gravity drain/subsurface losses is more sensitive to an increase in the magnitude of rainfall extreme events.

According to Table 4.20, almost all the nutrient concentration values of S6 have decreased with respect to the present condition, implying that an increase in temperature would cause a decrease in the accumulation and dispersal patterns of nutrients in the water ways. The maximum decrease in S6 has been obtained in the “p-apdrn1.asc” results file, which gives the DP quantity in gravity drain/subsurface losses. Therefore, it could be concluded that the DP quantity in gravity drain/subsurface losses is more sensitive to an increase in the temperature.

The reduction/increase of the critical values in the critical months of these results files which depict the spatial variation of various nutrient components, are further illustrated by Figures from Figure 4.78 to Figure 4.84. The practical importance of obtaining these spatial variation results files is that, after further refinement of data in the future, these could be used to identify the hotspots of pollutant concentrations with respect to impending climate change. This would be very much helpful in isolating the areas where the remedial measures must be carried out. On the other hand, it could be concluded that the accumulation and dispersal amounts of nutrients are sensitive to a change in the climate.

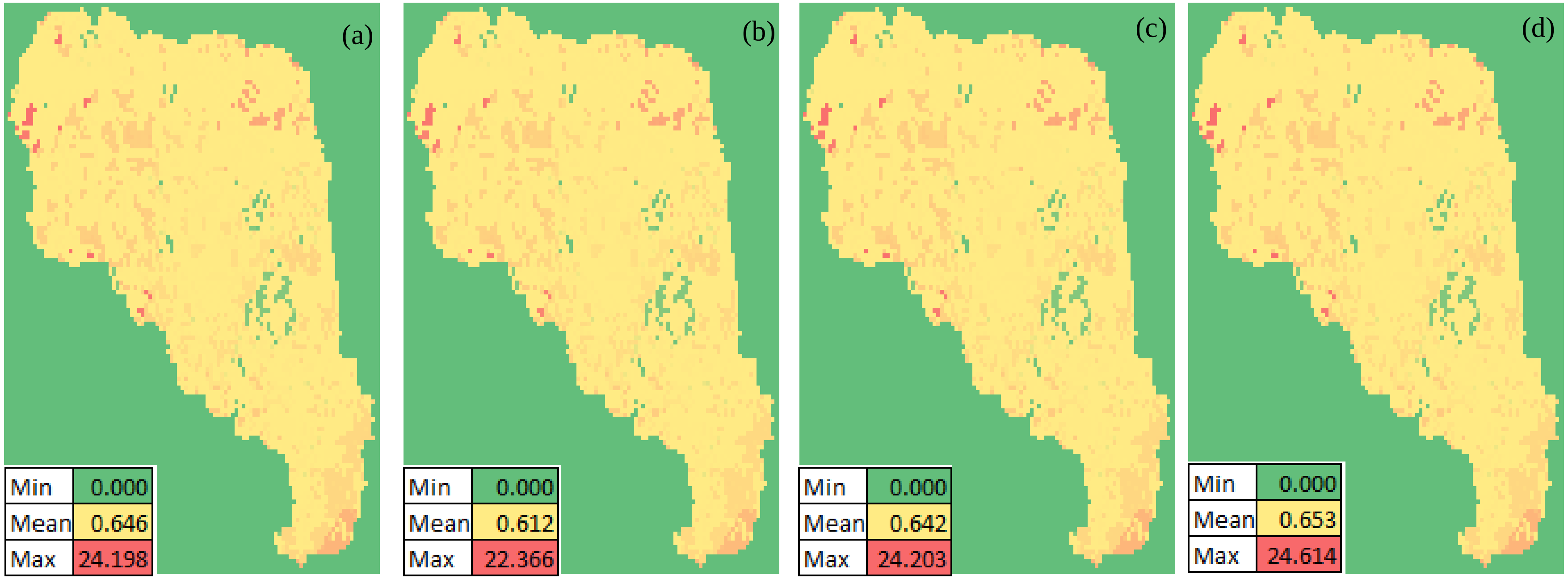


Figure 4.78: Comparison of Discharged DN from each layer ("fort.108" Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

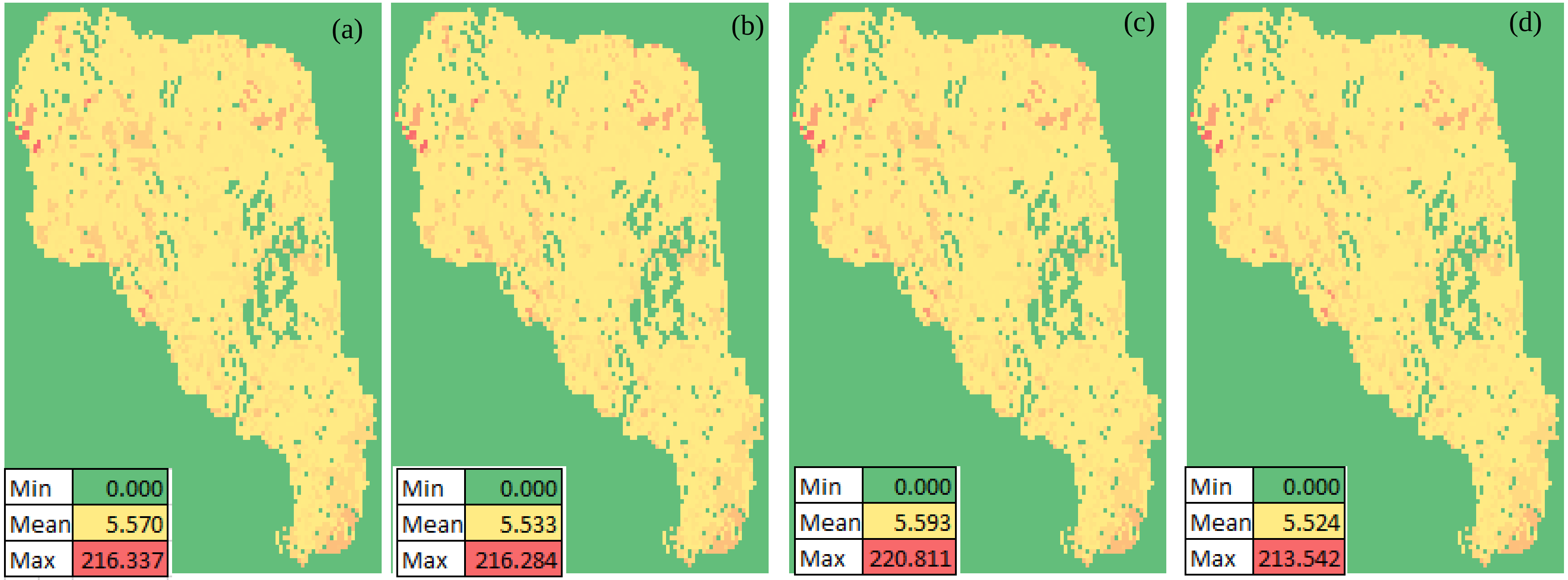


Figure 4.79: DN in Gravity Drain/Subsurface Losses (“n-andrn1.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

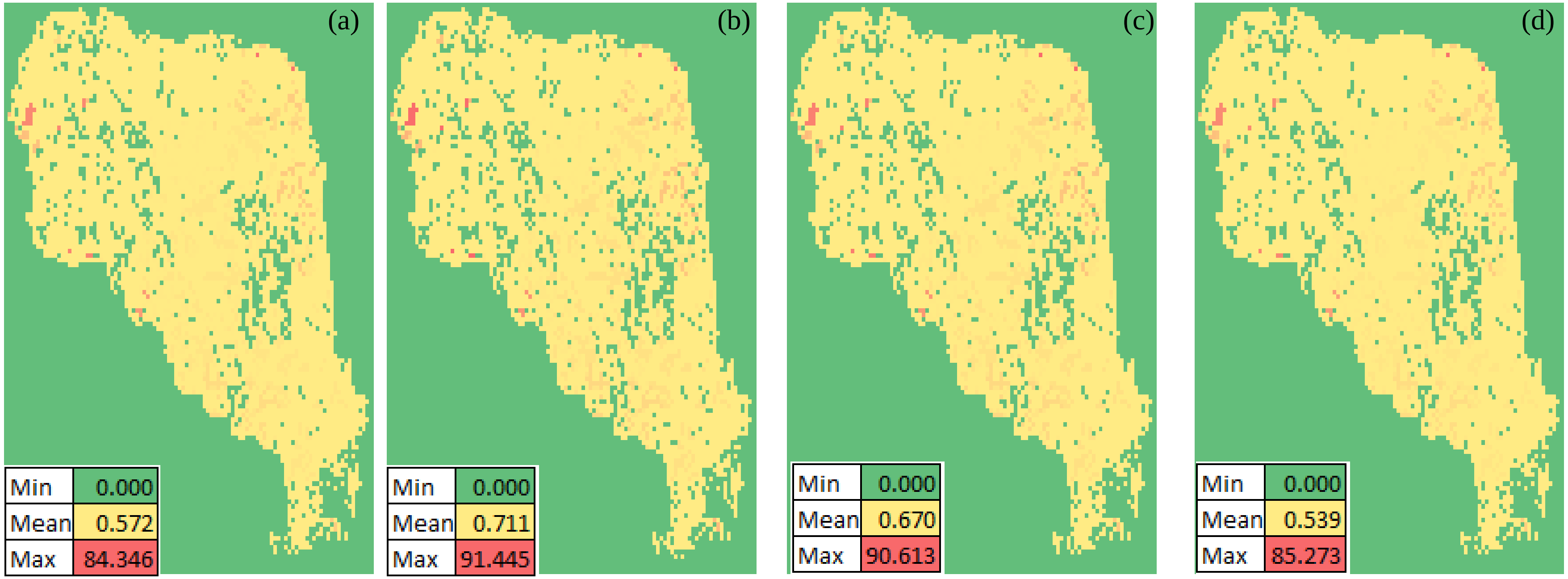


Figure 4.80: Comparison of DP in Gravity Drain/Subsurface Losses (“p-apdrn1.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

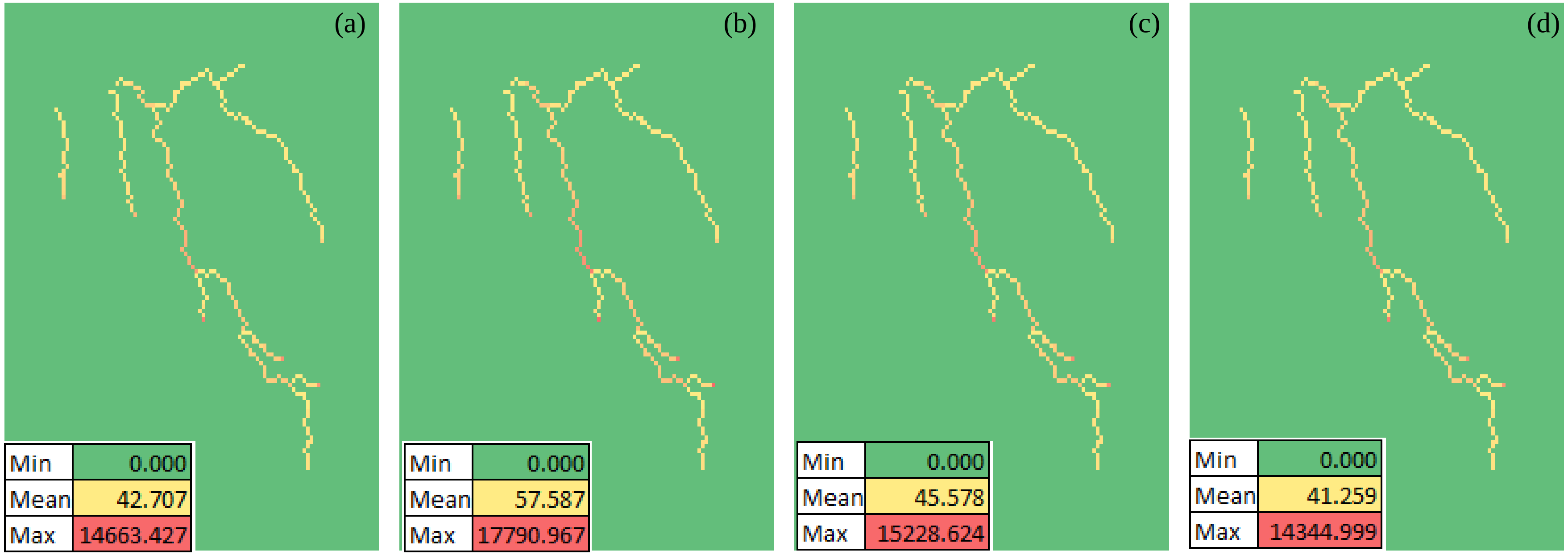


Figure 4.81: Comparison of Mesh Influx DN Quantity (“n-fxce.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

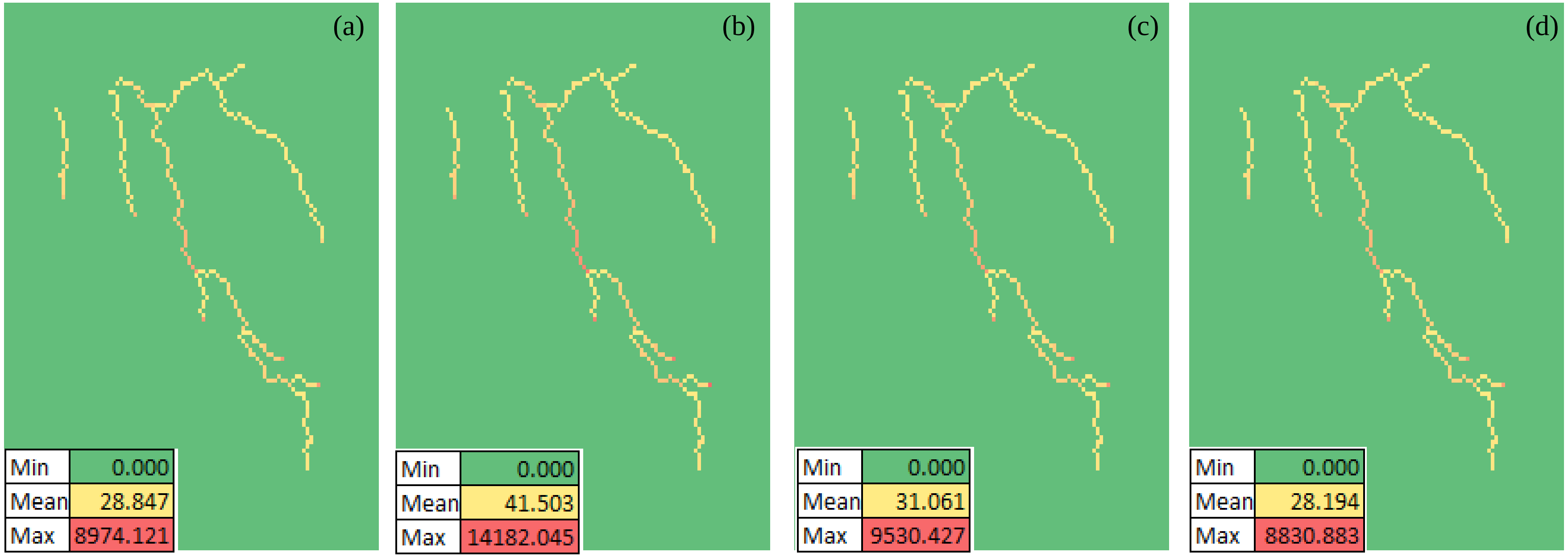


Figure 4.82: Comparison of Mesh Influx PN Quantity (“n-fxpnce.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

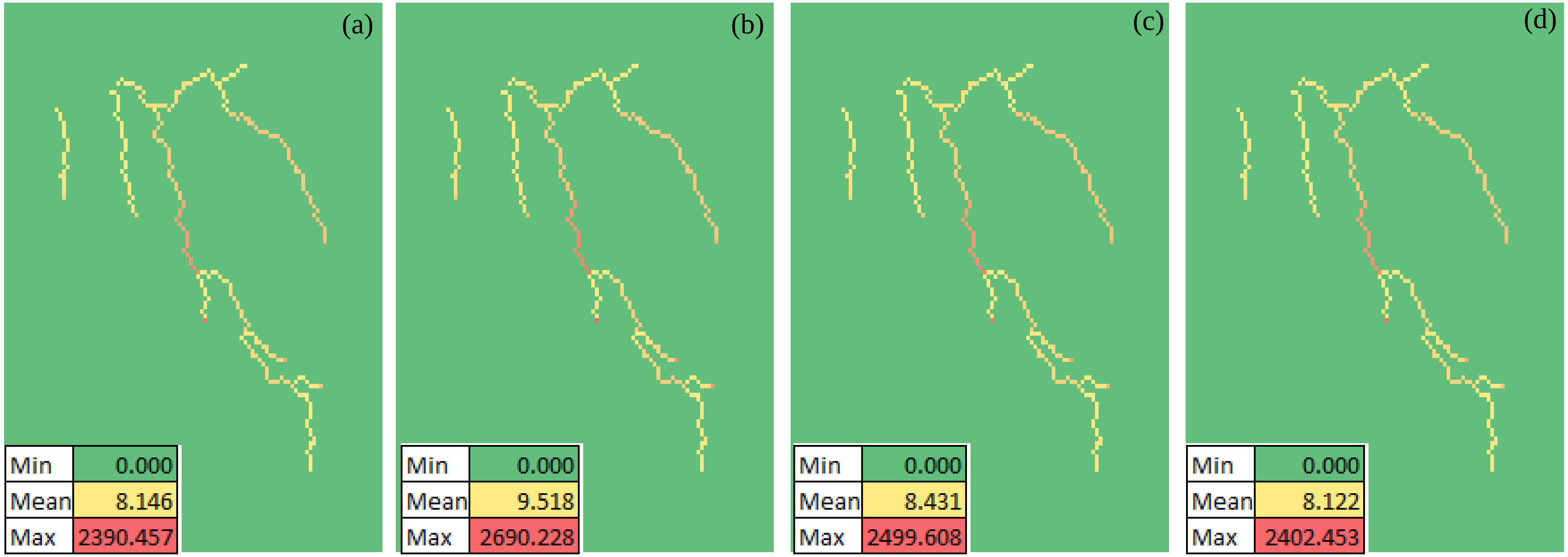


Figure 4.83: Comparison of Mesh Influx DP Quantity (“p-fxdpce.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

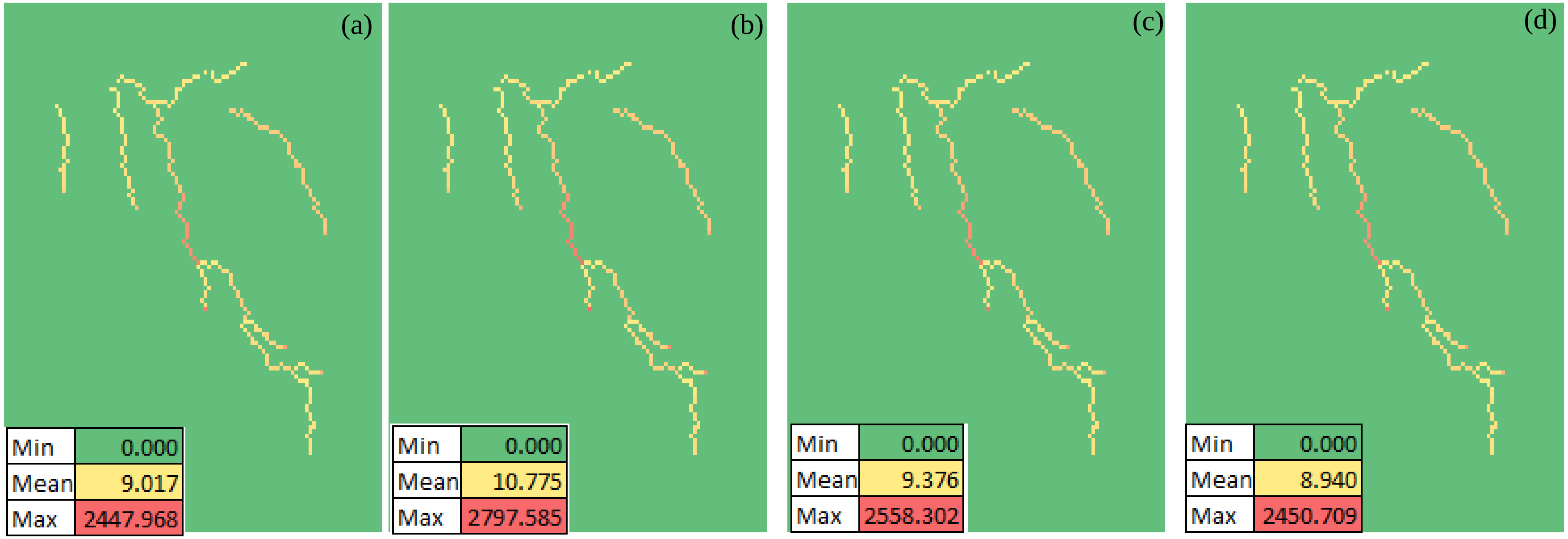


Figure 4.84: Comparison of Mesh Influx PP Quantity (“p-fxppce.asc” Results File); (a) Present Condition, (b) Scenario 4, (c) Scenario 5, (d) Scenario 6 (original in colour)

5 CONCLUSIONS AND RECOMMENDATIONS

This Chapter elaborates the conclusions obtained by this study, summarises the findings and gives recommendations for future studies.

5.1 Conclusions

1) The catchment response to the rainfall is highly regulated due to reservoir storage effect (ungauged basin with regulated/moderated flows).

2) The amounts of N and P in fertilizers applied have significantly exceeded the actual plant requirement for all crop types considered.

3) In both wet and dry seasons, the differences between the measured water quality parameters in upstream and downstream were not statistically significant.

4) The WEP model results showed that on average the wet season had about 5~7 times the dry season value of the Total Suspended Solids (TSS) in the streams, and in both seasons, the modelled TSS, NO_3^- and PO_4^{3-} were within the ranges of the previously published results.

5) Scenario analysis with respect to reduction of fertilizer input, increase in rainfall and temperature, has found that, almost all water quality parameters reduced with the reduction of fertilizer input and with the increase in temperature, but they increased with the increase in rainfall.

6) The maximum reduction/increase in most of the water quality concentrations were obtained in the mid flow values. Therefore, it could be concluded that the accumulation and dispersal amounts of nutrients in the mid flow conditions are more sensitive to a change in the fertilizer input and climate.

7) The parameters related to P have more sensitivity to the input rainfall values than the parameters related to the N, to the fertilizer and rainfall input to the WEP model, with the increase in all rainfall values having more effect than the increase in the magnitude of extreme rainfall events. However, the parameters related to N have more sensitivity to the input temperature values than the parameters related to P.

8) The reduction of fertilizer input does not have a significant impact on the accumulation and dispersal patterns of TSS in the water ways. However, with the

increase in rainfall the TSS has increased significantly with respect to the present condition, which was not observed with the increase in temperature.

9) The findings of this research study will be useful in identifying and for recommending the best management practices and for coping with the excess fertilizer/agrochemical usage of this catchment in a more pragmatic manner.

5.2 Summary of Findings

1) The catchment response to the rainfall indicated the measured spill and total release data are highly regulated due to reservoir storage effect, confirming that the catchment needs to be analysed as an ungauged basin with regulated flows and hence the use of a pre-calibrated HEC-HMS model for verification is justified.

2) The WEP model streamflow values were reasonably matching with the HEC-HMS model streamflow values and validation period showed better correlation coefficients (Pearson correlation coefficient of 0.6875), establishing the suitability of applying the WEP model for the analysis of water resources in this catchment.

3) Yield analysis confirmed that there is a water scarcity in the catchment, especially during the dry season (April-September), even after implementing the proposed alternative crop pattern. However, an improvement in water resources management is achievable by choosing alternative crop patterns for this catchment.

4) A distinct variation of the laboratory tested dry and wet season water quality parameters was observed in the catchment. In both seasons, the differences between the upstream and downstream concentration values of the water quality parameters are not statistically significant, despite the slightly increasing or decreasing trends shown from upstream to downstream sites.

5) For this catchment, the applied Nitrogen and Phosphorus amounts (kg/ha) of fertilizers in almost all months for all three types of crops that were considered have exceeded the actual plant requirement, confirming the necessity of regulation of fertilizer usage.

6) The temporal variation of WEP model simulated TSS showed that on average, the wet season has about five (calibration) to seven (validation) times the dry season

value of the TSS in the streams, establishing that the high washout of nutrients as suspended matter during the high streamflow values in the wet season causes an increase in the concentrations of nutrients in waterways.

7) For the Nitrogen components, the WEP low flow values and for the Phosphorus components, the WEP high flow values show the best match with the previously published results. In addition, the water quality values of the WEP model results shown are the average of a longer time period, and therefore represent a wider and a more reasonable range of values of water quality parameters in the streams. Nevertheless, in both Yala and Maha seasons, the WEP model results of NO_3^- and PO_4^{3-} are within the range of the previously published results.

8) Sensitivity analysis has shown that the WEP model results have a reasonable response to all the parameters governing the Phosphorus components in the input files, and different parameters have different sensitivity levels to the model results. Although it could be assumed that the pollutant loading due to the point sources in this catchment are less significant than the non-point sources of pollutants since this catchment is not a highly urbanized and developed area, the results of the sensitivity analysis have shown that the parameters governing both point sources as well as non-point sources contribute to the variation of WEP model results.

9) Scenario analysis with respect to reduction of fertilizer input (S1, S2, and S3) has found that, almost all the water quality parameter concentrations have been reduced with the reduction of fertilizer input (except only for PN in high flow conditions in S1 and S2). S3 shows the maximum amount of reduction in pollutant concentrations, when compared to the present condition. In addition, the Phosphorus components show higher amount of reduction, when compared with the reduction in Nitrogen components. Therefore, it could be presumed that the Phosphorus components are more sensitive to the fertilizer input to the WEP model.

10) When considering all scenarios (S1, S2, and S3), the maximum reduction in most of the water quality concentrations (DN, TN, DP, and TP) have been obtained in the mid flow values. Therefore, it could be concluded that the accumulation and

dispersal amounts of nutrients in the mid flow conditions are more sensitive to a reduction in fertilizer input.

11) When considering the spatial variation of results in S1, S2, and S3, with respect to the present condition, the percentage difference (percentage reduction) in the maximum value (in the critical month), between the percent condition and the scenarios, have increased with the increase of the reduction amount of fertilizer input. The maximum reduction has occurred in S3 in the "p-fxdpce.asc" results file, which gives influx of DP quantity to grid cells, suggesting that Phosphorus nutrients in the dissolved form are more sensitive to the fertilizer input.

12) The TSS values in S1, S2, and S3 did not show a significant variation with respect to the present condition, therefore, the reduction of fertilizer input does not have a significant impact on the accumulation and dispersal patterns of TSS in the water ways.

13) Scenario analysis with respect to climate change (S4, S5, and S6) has shown that, almost all the Nitrogen and Phosphorus water quality parameter concentrations increased with the increase in rainfall (S4 and S5), but they decreased with the increase in temperature (S6).

14) Parameters related to Phosphorus components have more sensitivity to the input rainfall values than the parameters related to the Nitrogen components, with the increase in all rainfall values (S4) having more effect than the increase in the magnitude of extreme rainfall events (S5). But parameters related to Nitrogen components have more sensitivity to the input temperature values (S6) than the parameters related to the Phosphorus components.

15) When considering all climate related scenarios, and the summation of percentage differences in all N and P components are considered together, the maximum reduction/increase in the water quality concentrations have been obtained in the mid flow values. Therefore, it could be concluded that the accumulation and dispersal amounts of nutrients (when all nutrients are taken as a whole) in the mid flow conditions are more sensitive to a change in the climate.

16) With respect to the spatial variation of results, the maximum increase in S4 has been obtained in the “n-fxpnce.asc” results file, which gives influx of PN quantity to grid cells. Therefore, it could be concluded that the influx of PN quantity to grid cells is more sensitive to an increase in all rainfall values. The maximum increase in S5 and S6 has been obtained in the “p-apdrn1.asc” results file, which gives the DP quantity in gravity drain/subsurface losses. Therefore, it could be concluded that the DP quantity in gravity drain/subsurface losses is more sensitive to an increase in the magnitude of rainfall extreme events, and to an increase in the temperature.

17) TSS values of S4 have increased significantly with respect to the present condition, implying that the increase in rainfall resulting in a high streamflow that in turn would induce a washout of the solids, and hence the increase in TSS. In S5, with respect to the present condition, only the extreme values of TSS have been increased, as a result of increasing only the magnitude of extreme rainfall events in S5. Nevertheless, in S6, a distinct deviation from the present condition values of TSS was not observed, implying that the increase in temperature values does not have a significant impact on the accumulation and dispersal patterns of Total Suspended Solids in the water ways.

5.3 Recommendations for Future Studies

1) It is recommended to conduct further studies and continuous water quality measurements which are essential when a water quality model is to be calibrated for river basins.

2) It is recommended to establish physics-based models, which could be used for all the river basins, as an alternative and remedial measure to address the scarcity of basin wide river water quality data in Sri Lanka.

3) Since the WEP model has been successfully applied in river basins in Japan, Korea and China in similar studies, the results of this study could also be generalised and are applicable to any similar ungauged basin in this region with regulated or unregulated flows.

REFERENCES

Aloysius, C. (2018). Are the fruits we eat poisoning us? *Sunday Observer*. Colombo: The Associated Newspapers of Ceylon Ltd. Retrieved 08 20, 2018, from http://www.sundayobserver.lk/2018/03/18/features/are-fruits-we-eat-poisoning-us

American Public Health Association, American Water Works Association, & Water Environment Federation. (2012). *Standard Methods for the Examination of Water and Wastewater* (22 ed.). American Public Health Association.

Ayers, R., & Westcot, D. (1985). *Water Quality for Agriculture - Irrigation and Drainage Paper 29.* Rome: Food and Agriculture Organization of the United Nations.

Bartram, J., & Ballance, R. (1996). Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes (1st ed.). London, UK: Chapman & Hall.

Bennett, J., Robertson, D., Ward, P., Hapuarachchi, H., & Wang, Q. (2015). Calibrating hourly rainfall-runoff models with daily forcings for streamflow forecasting applications in meso-scale catchments. *Environmental Modelling & Software, 76*(2016), 20 - 36.

Cash, D., Melton, B., Gregory, J., & Cihacek, L. (1981). *Rhizobium inoculants for alfalfa in New Mexico [Research Report 461].* Las Cruces: New Mexico State University Agricultural Experiment Station.

Central Bank of Sri Lanka. (2015). *Annual Report.* Colombo: Central Bank of Sri Lanka.

Central Environmental Authority. (2001). *Proposed Ambient Water Quality Standards for Inland Waters Sri Lanka.* Colombo, Sri Lanka: Central Environmental Authority.

Chapman, D. (1996). Water Quality Assessments - A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring (2nd ed.). London, UK: Chapman and Hall.

Cunwen, N., Yangwen, J., Hao, W., Zuhao, Z., Yaqin, Q., Shujun, B., & Caixia, L. (2011). Assessment of Water Quality under Changing Climate Conditions in the Haihe River Basin, China. In N. Peters (Ed.), *Water quality: Current Trends and Expected Cimate Change Impacts (Proceedings of symposium H04 held during IUGG2011 in Melbourne, Australia, July 2011)* (pp. 165-171). Melbourne: IAHS Press.

De Alwis, S. (2006). Competition for Water Demands, Management Conflicts and Inter-related Issues in Malwathu Oya Basin of Sri Lanka.

De Silva, C. (2009). Climate Change Effects on the North-East Monsoon and Dry Zone Agriculture in Sri Lanka. In S. Nissanka, & U. Sangakkara (Ed.), *Proceedings of the First National Conference on Global Climate Change and its Impacts on Agriculture, Forestry and Water in the Tropics*, (pp. 32-39). Kandy.

De Silva, C., Weatherhead, E., Knox, J., & Rodriguez-Diaz, J. (2007). Predicting the Impacts of Climate Change - A Case Study of Paddy Irrigation Water Requirements in Sri Lanka. *Agricultural Water Management, 93*, 19-29. doi:10.1016/j.agwat.2007.06.003

Deacon, J. (n.d.). *The Microbial World: The Nitrogen Cycle and Nitrogen Fixation*. Retrieved 02 25, 2017, from http://archive.bio.ed.ac.uk/jdeacon/microbes/nitrogen.htm

Department of Census and Statistics-Sri Lanka. (2012). Department of Census and Statistics-Sri Lanka.

Department of Irrigation. (2012). Dam Safety and Water Resources Planning Project (DSWRPP) Nachchaduwa Dam: Operation and Maintenance Manual. Department of Irrigation.

Department of Irrigation Sri Lanka. (n.d.). *Malawathu Oya Reservoir Project Feasibility Report.* Department of Irrigation Sri Lanka.

Eaton, F. (1950). Significance of Carbonates in Irrigation Waters. *Soil Science, 69*, 123-133.

Field Crops Research and Development Institute. (n.d.). *Mung Bean*. Retrieved February 07, 2017, from Field Crops Research and Development Institute (FCRDI) Mahailluppallama: https://www.doa.gov.lk/FCRDI/index.php/si/2015-09-23-04-45-47/35-mung-bean

Gunarathna, M., & Kumari, M. (2014). Sustainable Management of Malwathu Oya Cascade-I: Present Status and Future Needs. *GSTF Journal on Agricultural Engineering(JAE), Vol.1*(No.1), 81-85.

Gunarathna, M., & Kumari, M. (2016). Water Quality Assessment of a Tank Cascade System using CCME Water Quality Index. *International Journal of Research and Innovation in Applied Science (IJRIAS), I*(III), 1-6.

Hettiarachchi, I. (2008). Modelling Runoff Characteristics of the Minneriya and Nachchaduwa Catchments.

Hulme, M., & Jenkins, G. (1998). *Climate Change Scenarios for the UK - UKCIP Technical Report No. 1.* Norwich, UK: Climate Research Unit.

Hydrologic Engineering Research Team [HERT], I. C. (2012). *WEP Model Instruction Manual*. Hydrologic Engineering Research Team, International Center for Water Hazard and Risk Management, Public Works Research Institute.

Intergovernmental Panel on Climate Change - Task Group on Scenarios for Climate Impact Assessment [IPCC-TGCIA]. (1999). *Guidelines on the use of Scenario Data for Climate Impact and Adaptation Assessment* (Version 1 ed.). (T. Carter, M. Hulme, & M. Lal, Eds.) Intergovernmental Panel on Climate Change - Task Group on Scenarios for Climate Impact Assessment.

Jayakody, P., Raschid-Sally, L., Abayawardana, S., & Najim, M. (2006). Urban Growth and Wastewater Agriculture: A Study from Sri Lanka. *Proceedings of the 32nd WEDC International Conference, Colombo, Sri Lanka, 2006*, (pp. 105-111). Colombo.

Jia, Y. W. (2005). Distributed Hydrologic Modeling in a Partially Urbanized Agricultural Watershed using WEP Model. *Journal of Hydrologic Engineering, 10*, 253-263.

Jia, Y., & Tamai, N. (1998). Water and Heat Balances in the Middle-reach Catchment of Tama River and Sensitivity Analysis. *Annual Journal of Hydraulic Engineering, JSCE, 42*, 151–156.

Jia, Y., Ni, G., Kawahara, Y., & Suetsugi, T. (2001a). Development of WEP model and its application to an Urban Watershed. *Hydrological Processes, 15*, 2175–2194. doi:10.1002/hyp.275

Jia, Y., Ni, G., Kawahara, Y., & Suetsugi, T. (2001b). Simulation of Hydrological Cycle in an Urbanized Watershed and Effect Evaluation of Infiltration Facilities with WEP Model. *Journal of Hydroscience and Hydraulic Engineering, 19*(No.1), 43-52.

Jia, Y., Niu, C., & Wang, H. (2007). Integrated modeling and assessment of water resources and water environment in the Yellow River Basin. *Journal of Hydro-Environment Research 1*, 12-19. doi:10.1016/j.jher.2007.04.001

Kamran, M., & Rajapakse, R. (2017). The Effect of Watershed Subdivisions and Antecedent Moisture Condition on HEC-HMS Model Performance in the Maha Oya Basin, Sri Lanka. Phang: University of Phang.

Kumari, M., Pathmarajah, S., Dayawansa, N., & Nirmanee, K. (2016). Evaluation of Groundwater Quality for Irrigation in Malwathu Oya Cascade-I in Anuradhapura District of Sri Lanka. *Tropical Agricultural Research, 27*(4), 310-324.

Madushanka, R., Dissanayaka , D., & Amarasekara, M. (2015). Impact of Urban Land Use in Anuradhapura City on Water Quality of Upper Malwathu Oya Stream. *Proceedings of the Water Professionals' Day Symposium*, (pp. 137-143).

Ministry of Environment. (2011). *Sri Lanka's Second National Communication on Climate Change*. Colombo: Climate Change Secretariat, Ministry of Environment.

Ministry of Health,Nutrition & Indigenous Medicine. (2015). *Annual Health Bulletin.* Colombo: Medical Statistics Unit, Ministry of Health, Nutrition & Indigenous Medicine.

Miyamoto, C., Ketterings, Q., Cherney, J., & Kilcer, T. (2008). *Agronomy Fact Sheet Series - Fact Sheet 39*. Retrieved 08 20, 2018, from Cornell University Cooperative Extension: http://nmsp.cals.cornell.edu/publications/factsheets/factsheet39.pdf

Munasinghe, J., De Silva, A., Weerasinghe, G., Gunaratne, A., & Corke, H. (2015). Food safety in Sri Lanka: Problems and Solutions. *Quality Assurance and Safety of Crops & Foods - Special Issue: Food Safety in Asia, 7*(1), 37-44.

Perera, P., Sundarabarathy, T., Sivananthawerl, T., & Edirisinghe, U. (2014). Seasonal Variation of Water Quality Parameters in Different Geomorphic Channels of the Upper Malwathu Oya in Anuradhapura, Sri Lanka. *Tropical Agricultural Research, 25*(2), 158-170.

Ponrajah, A. J. (1984). *Design of Irrigation Systems for Small Catchments* (2nd ed.). Colombo, Sri Lanka: Irrigation Department.

Rajapakse, H., Inomata, H., & Fukami, K. (2010). Diffuse Source Particulate-matter Pollution Modelling in a Semi-Urbanized Agricultural Basin in Japan using Process-based WEP and an Erosion-transport Model. *Water Practice & Technology, Vol 5*(No 3). doi:10.2166/WPT.2010.051

Ratnasiri, J. (2006). Final Report of the GEF/UNEP Project on Assessment of Impacts of and Adaptation to Climate Change in the Coconut and Tea Plantations in Sri Lanka submitted to START International Secretariat, Washington, DC. Colombo: Sri Lanka Association for the Advancement of Science.

Ratnayake, R., Gonawela, J., & Wijekoon, D. (2012). *Natural Springs in the Anuradhapura District.* Colombo: Water Resources Board Sri Lanka.

Richards, L. (1954). Diagnosis and Improvement of Saline and Alkali Soils - Agricultural Handbook 60. Washington: United States Department of Agriculture.

Silva, E. (1996). *Water Quality of Sri Lanka: A Review on Twelve Water Bodies* (1st ed.). Kandy, Sri Lanka: Institute of Fundamental Studies.

Silva, E. (2004). Quality of Irrigation Water in Sri Lanka - Status and Trends. *Asian Journal of Water, Environment and Pollution, Vol. 1*(No. 1), 5-12.

Sri Lanka Standards. (1983). Sri Lanka Standards (SLS) Specification for Potable Water - Part 1: Physical and Chemical Requirement (SLS 614). Sri Lanka Standards.

Sri Lanka Standards. (1985). Sri Lanka Standards (SLS) Tolerance Limits for Inland Surface Waters used as Raw Water for Public Water Supply (SLS 722). Sri Lanka Standards.

Strobl, R., & Robillard, P. (2007). Network Design for Water Quality Monitoring of Surface Freshwaters: A Review. *Journal of Environmental Management, 87*, 639–648.

Tchobanoglous, G., Burton, F., & Stensel, H. (2003). *Wastewater Engineering Treatment and Reuse* (4th ed.). Metcalf & Eddy Inc.

United States Environmental Protection Agency. (1976). *Quality Criteria for Water*. Washington D.C.: United States Environmental Protection Agency.

United States Peace Corps. (1980). *United States Peace Corps Information Collection & Exchange*. (M. L. Morris, Editor) Retrieved February 07, 2017, from United States Peace Corps - Rice Production - A Training Manual and Field Guide to Small-Farm Irrigated Rice Production: http://www.nzdl.org/gsdlmod?e=d-00000-00---off-0cdl--00-0----0-10-0---0---0direct-10---4-------0-1l--11-en-50---20-about---00-0-1-00-0--4----0-0-11-10-0utfZz-8-00&a=d&cl=CL1.36&d=HASHd437e4577406c1595cde6e.12

Walley, F., Tomm, G., Matus, A., Slinkard, A., & van Kessel, C. (1996). Allocation and Cycling of Nitrogen in an Alfalfa-bromegrass Sward. *Agronomy Journal, 88*, 834–843.

Warrick, R., Kenny, G., Sims, G., Ericksen, N., Ahmad, Q., & Miria, M. (1996). Integrated Model System for National Assessment of Climate Change - Applications in New Zealand and Bangladesh. *Journal of Water, Air and Soil Pollution, 92*, 221-227.

Weerahewa, J., Kodithuwakku, S., & Ariyawardana, A. (2010). *The Fertilizer Subsidy Program in Sri Lanka*. Ithaca, New York: Cornell University.

Wickramaarachchi, T., Ishidaira, H., & Wijayaratna, T. (2013). Streamflow, Suspended Solids, and Turbidity Characteristics of the Gin River, Sri Lanka. *Engineer, XXXXVI*(04), 43-51.

Wickramaarachchi, T., Ishidaira, H., Magome, J., & Wijayaratna, T. (2015). Projecting Turbidity Levels in Future River Flow: A Mathematical Modelling Approach. *Engineer, XLVIII*(01), 61-70.

Wijesundara, W., Nandasena, K., & Jayakody, A. (2012). Spatial and Temporal Changes in Nitrogen, Phosphorus and Potassium Concentration in Water in the

Thirappane Tank Cascade in Dry Zone of Sri Lanka. *Journal of Environmental Professionals Sri Lanka, 1*(1), 70-81.

Wijesundara, W., Nandasena, K., & Jayakody, A. (2013). Seasonal and Spatial Variations of N, P, K and Cd Concentrations in Water of the Mahakanumulla Cascade in the Dry zone of Sri Lanka. *Tropical Agricultural Research, 24*(3), 279 - 288.

Wijewardena, D. (2013). Country Awash with Agro Chemicals - Lanka is World's Top User. *The Island - e paper*. Colombo: Upali Newspapers (Pvt) Ltd. Retrieved 08 20, 2018, from http://www.island.lk/index.php?page_cat=article-details&page=article-details&code_title=94148

Wilcox, L. (1955). Classification and use of Irrigation Waters - United States Department of Agriculture Circular 969. Washington: United States Department of Agriculture.

World Health Organization. (2011). *Guidelines for Drinking-water Quality* (4th ed.). Geneva: World Health Organization.

Young, S., Pitawala, A., & Gunatilake, J. (2009). Effect of Agricultural Practices on Chemical Quality of Water in Kala Oya River Basin. *Journal of Geological Society of Sri Lanka, 13,* 97-104.

Young, S., Pitawala, A., & Gunatilake, J. (2010). Fate of Phosphate and Nitrate in Waters of an Intensive Agricultural Area in the Dry Zone of Sri Lanka. *Paddy and Water Environment, 2010*(8), 71–79. doi:10.1007/s10333-009-0186-6

Zoysa, D., & Weerasinghe, T. (2016). Study on the Chemical and Biological Status of Malwathu Oya Basin Anuradhapura in Sri Lanka. *British Journal of Environmental Sciences, 4*(1), 1-10.

APPENDICES

APPENDIX A: ADDITIONAL DATA FOR MATERIALS AND METHODS

A.1 Data and Data Checking/Data Pre-Processing Procedures

A.1.1 Study Area - Nachchaduwa Catchment Related Data

A.1.1.1 Nachchaduwa reservoir

Inflows:-

(1) Inflow from Malwathu Oya

(2) Rainfall

(3) Feeder Canal

Outflows:-

(1) Ungated spill

(2) Gated spill

(3) Left Bank High Level (LBHL) spill

(4) Left Bank (LB) sluice - High Level Main Canal (HLMC)

(5) Left Bank (LB) sluice - Low Level Main Canal (LLMC)

(6) Right Bank High Level (RBHL) sluice

(7) Right Bank Low Level (RBLL) sluice

(8) Seepage

(9) Evaporation

Spill release = (1) + (2) + (3)

Irrigation release = (4) + (5)

To Nuwara Wewa = (6) + (7)

(1) + (2) ➔ Malwathu Oya

LBHL spill ➔ HLMC

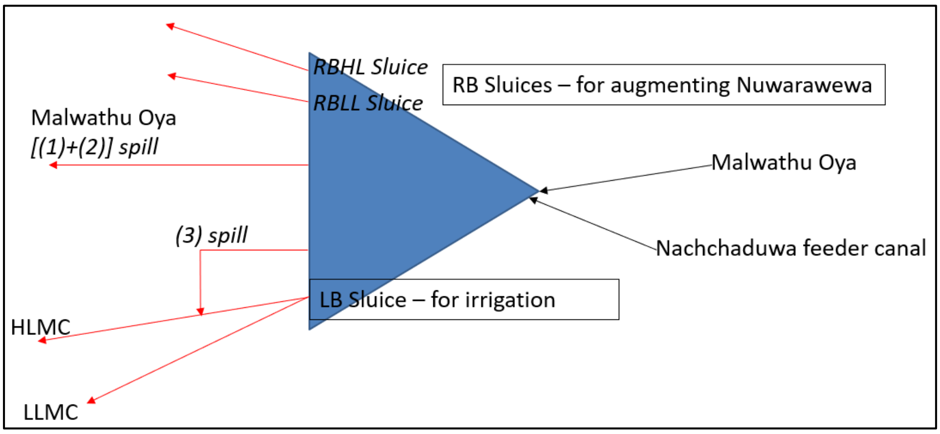


Figure A.1: Schematic Diagram of the Nachchaduwa Reservoir

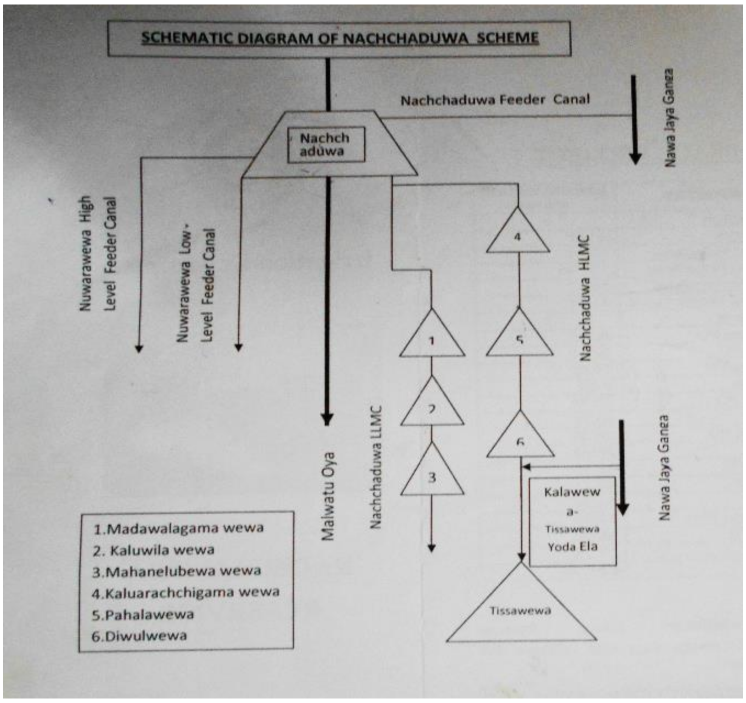


Figure A.2: Schematic Diagram of the Nachchaduwa Irrigation Scheme (Department of Irrigation, 2012)

Figure A.3: Un-gated spillway (original in colour)

Figure A.4: Gated Spillway (original in colour)

Figure A.5: LB High Level Spill (original in colour)

Figure A.6: LB Sluice (Old) (original in colour)

Figure A.7: LB Sluice (New) (LB Low Level Sluice) (original in colour)

Figure A.8: RB High Level Sluice (original in colour)

Figure A.9: RB Low Level Sluice (original in colour)

Figure A.10: HLMC and LLMC (original in colour)

A.1.2 Rainfall Data

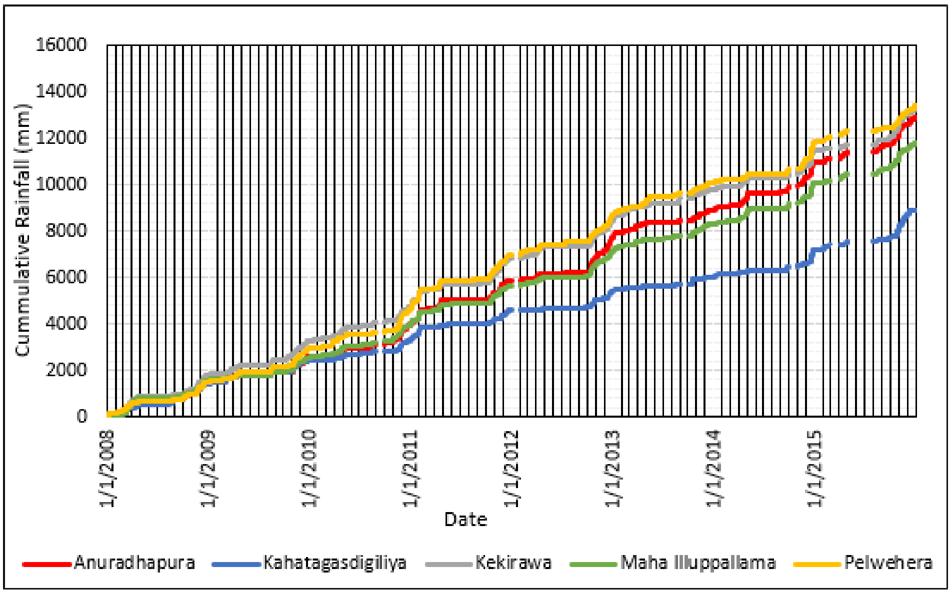


Figure A.11: Single Mass Curve (missing data points are omitted) (original in colour)

According to the single mass curve (Figure A.11),

(1) (01/01/10 - 02/01/10) Kekirawa corelates with Pelwehera.

(2) (01/09/10 - 30/09/10) Pelwehera corelates with Kekirawa.

(3) (01/01/12 - 31/01/12) Kahatagasdigiliya corelates with Maha Illuppallama.

(4) (01/09/13 - 30/09/13) Kahatagasdigiliya corelates with Maha Illuppallama.

(5) (01/10/14 - 31/10/14) Kahatagasdigiliya corelates with Maha Illuppallama.

(6) (01/03/15 - 31/03/15) Kekirawa corelates with Pelwehera.

(7) (01/05/15 - 31/05/15) Kahatagasdigiliya corelates with Maha Illuppallama.

(8) (01/06/15 - 31/07/15) Pelwehera corelates with Kekirawa.

Missing data in the above given periods were filled using those criteria. Subsequently, the double mass curves for each station were drawn (Figure A.12 to Figure A.16).

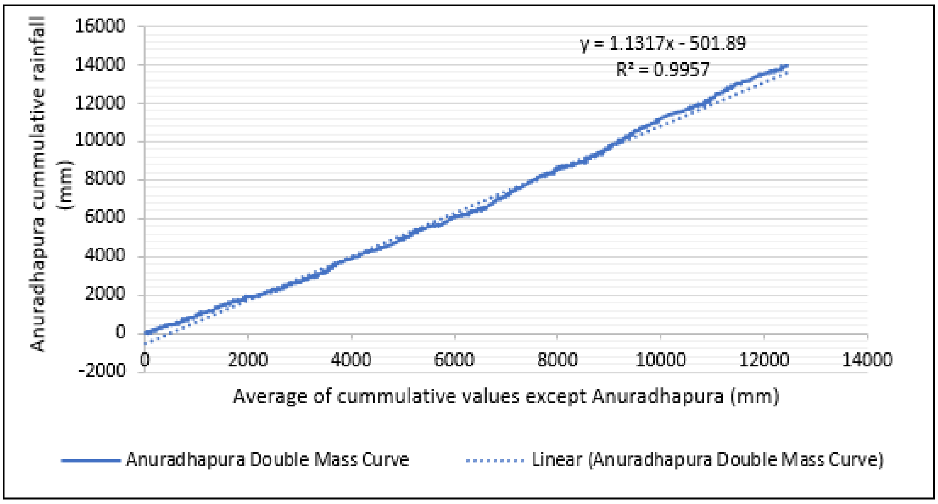


Figure A.12: Anuradhapura Double Mass Curve

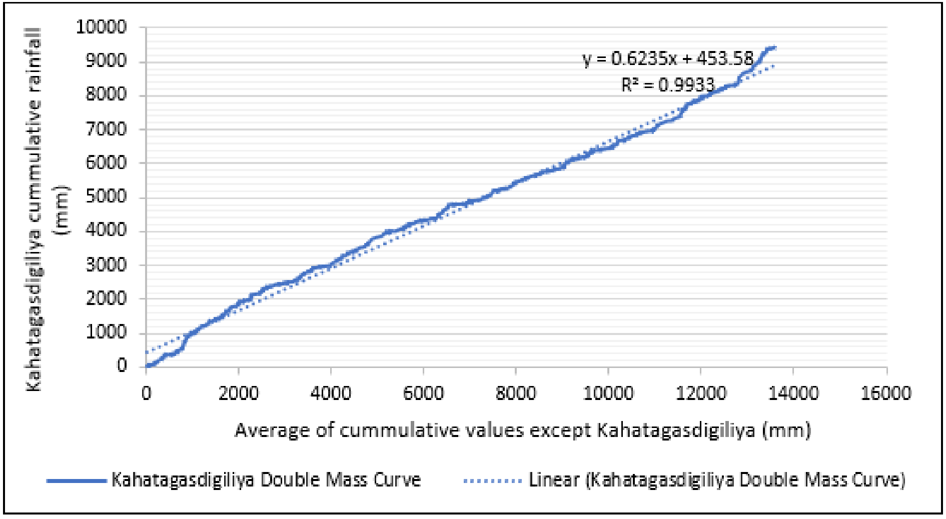


Figure A.13: Kahatagasdigiliya Double Mass Curve

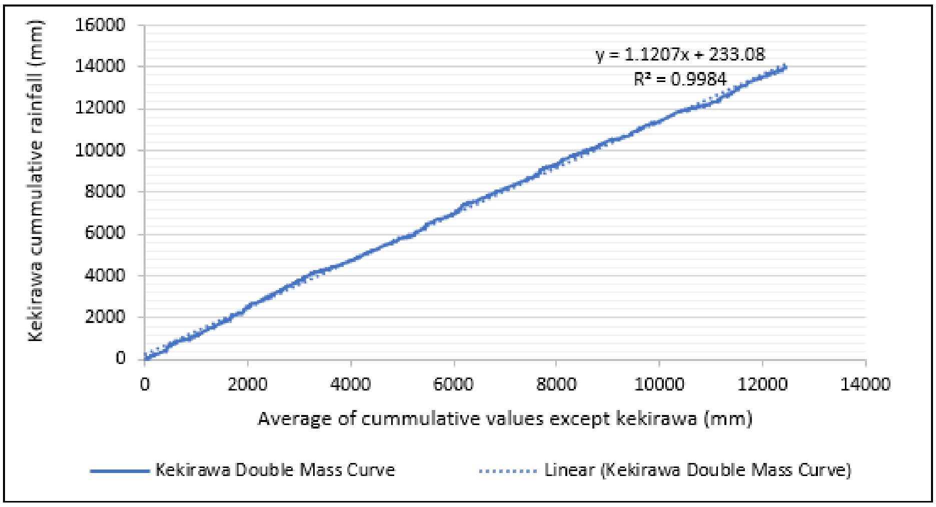


Figure A.14: Kekirawa Double Mass Curve

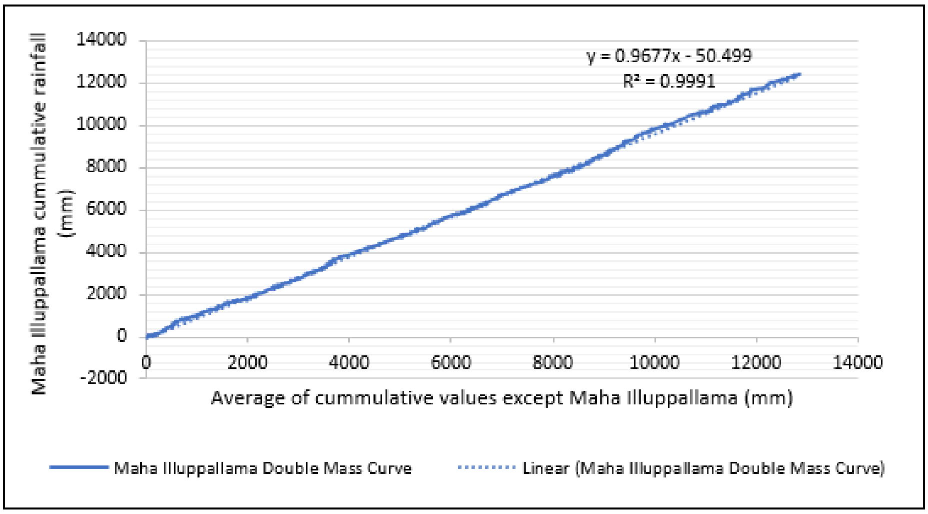


Figure A.15: Maha Illuppallama Double Mass Curve

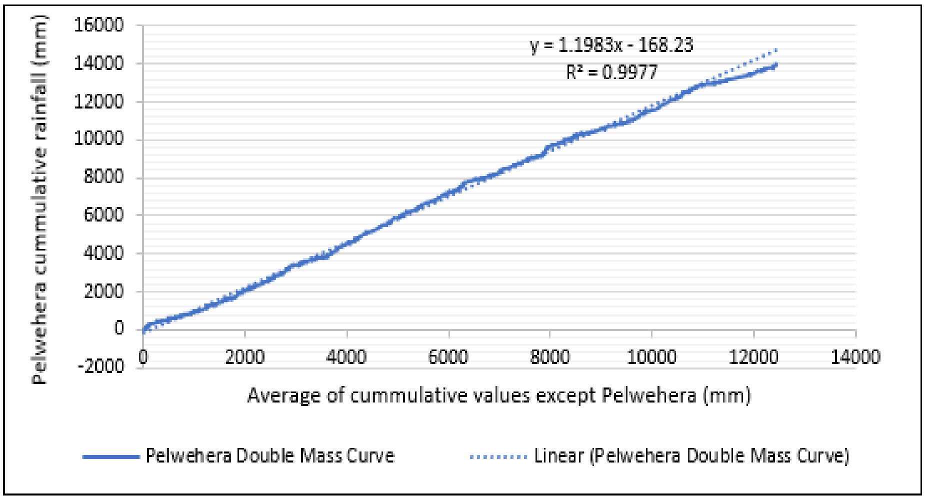


Figure A.16: Pelwehera Double Mass Curve

A.1.3 Streamflow Data

A.1.3.1 Initial data checking

Tank water balance:-

Inflow – Outflow = change in storage

Inflow to tank = change in storage of the tank + outflows from the tank (1)

$$\left\{\begin{matrix}\text{Inflow to}\\ \text{tank}\end{matrix}\right\} = \left\{\begin{matrix}\text{(Thiessen}\\ \text{rainfall) *}\\ \text{(total}\\ \text{catchment}\\ \text{area)}\end{matrix}\right\} + \left\{\begin{matrix}\text{Inflow from}\\ \text{Malwathu Oya}\\ \text{(return flows}\\ \text{after absorption}\\ \text{from upstream}\\ \text{tanks and paddy}\\ \text{fields)}\end{matrix}\right\} + \left\{\begin{matrix}\text{Inflow}\\ \text{from}\\ \text{Kala Oya}\end{matrix}\right\} \qquad (2)$$

From (1) and (2);

$$\left\{\begin{matrix}\text{Inflow}\\ \text{due to}\\ \text{rainfall}\end{matrix}\right\} = \left\{\begin{matrix}\text{Change}\\ \text{in}\\ \text{storage}\end{matrix}\right\} + \left\{\begin{matrix}\text{Outflows}\\ \text{from the}\\ \text{tank}\end{matrix}\right\} - \left\{\begin{matrix}\text{(Inflow from}\\ \text{Malwathu}\\ \text{Oya) +}\\ \text{(Inflow from}\\ \text{Kala Oya)}\end{matrix}\right\} = Q \qquad (3)$$

$$\text{Runoff coefficient} = \frac{Q}{\text{(Thiessen rainfall) * (Total catchment area)}} \qquad (4)$$

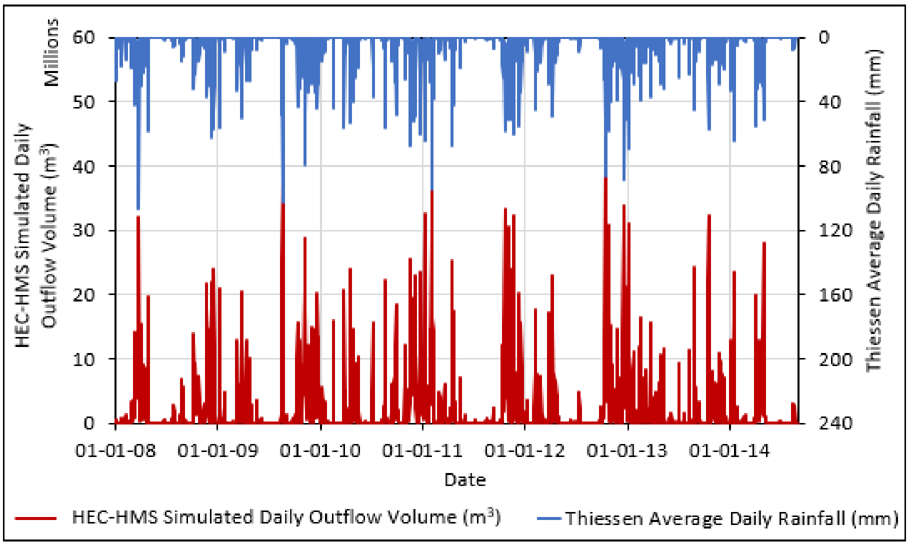


Figure A.17: Initial Data Checking: HEC-HMS Simulated Daily Outflow Volume (m^3) and Thiessen Average Daily Rainfall (mm) (original in colour)

A.1.3.2 Developing a streamflow data series for the WEP model

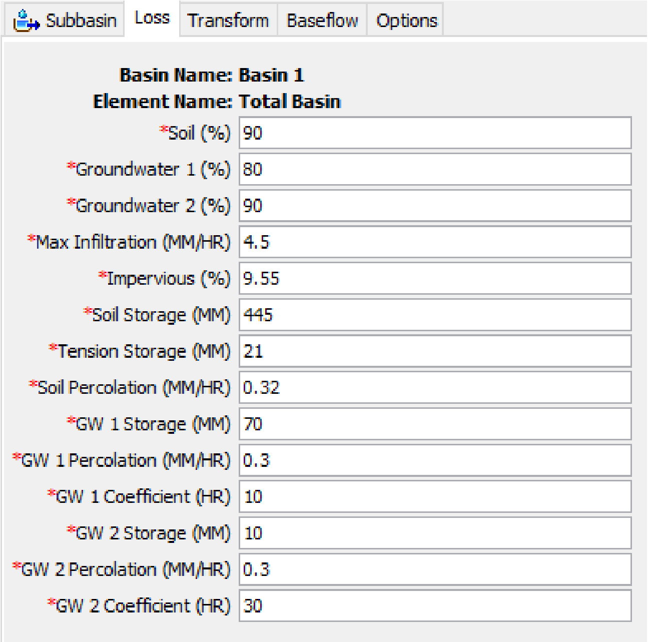
A preliminary analysis was done in order to develop a streamflow data series by using the envelope values of the following.

(1) Envelope of streamflow values from Kappachchi gauging station

(2) Envelope of streamflow data (Irrigation Department Colombo Division)

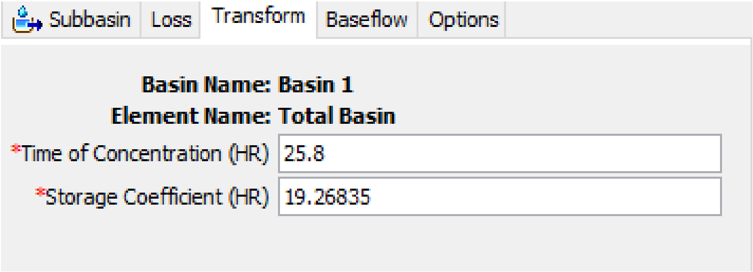
(3) Envelope of Thiessen average rainfall

(4) HEC-HMS model (related to Section 3.2.4.2)



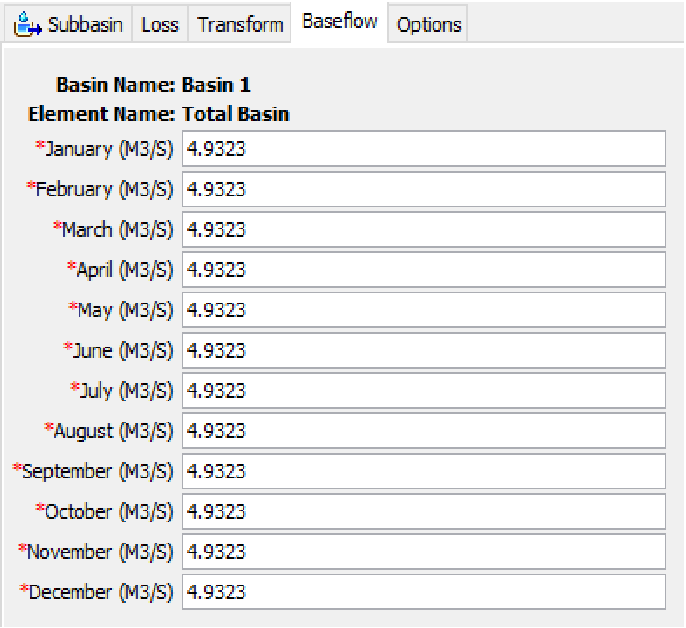
Basin Name: Basin 1
Element Name: Total Basin
*Soil (%) 90
*Groundwater 1 (%) 80
*Groundwater 2 (%) 90
*Max Infiltration (MM/HR) 4.5
*Impervious (%) 9.55
*Soil Storage (MM) 445
*Tension Storage (MM) 21
*Soil Percolation (MM/HR) 0.32
*GW 1 Storage (MM) 70
*GW 1 Percolation (MM/HR) 0.3
*GW 1 Coefficient (HR) 10
*GW 2 Storage (MM) 10
*GW 2 Percolation (MM/HR) 0.3
*GW 2 Coefficient (HR) 30

Figure A.18: Parameter Values used for the Loss Method of the HEC-HMS Model



Basin Name: Basin 1
Element Name: Total Basin
*Time of Concentration (HR) 25.8
*Storage Coefficient (HR) 19.26835

Figure A.19: Parameter Values used for the Transform Method of the HEC-HMS Model



Basin Name: Basin 1
Element Name: Total Basin

*January (M3/S)	4.9323
*February (M3/S)	4.9323
*March (M3/S)	4.9323
*April (M3/S)	4.9323
*May (M3/S)	4.9323
*June (M3/S)	4.9323
*July (M3/S)	4.9323
*August (M3/S)	4.9323
*September (M3/S)	4.9323
*October (M3/S)	4.9323
*November (M3/S)	4.9323
*December (M3/S)	4.9323

Figure A.20: Parameter Values used for the Baseflow Method of the HEC-HMS Model

The results of some of the developed envelope series of streamflow data values are compared in Figure A.21.

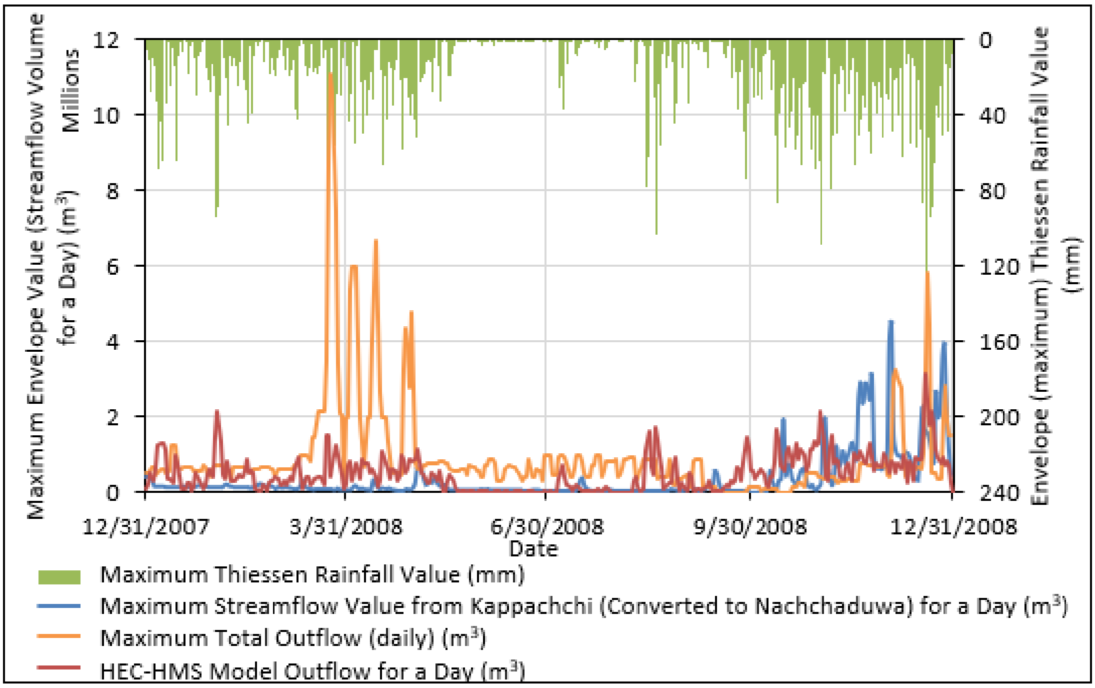


Figure A.21: Comparison of Various Streamflow Data Series (original in colour)

A.1.4 Reservoir/Streamflow Water Quality Data

Nitrogen and Phosphorus can be found in several different forms in water (Figure A.22 and Figure A.23).

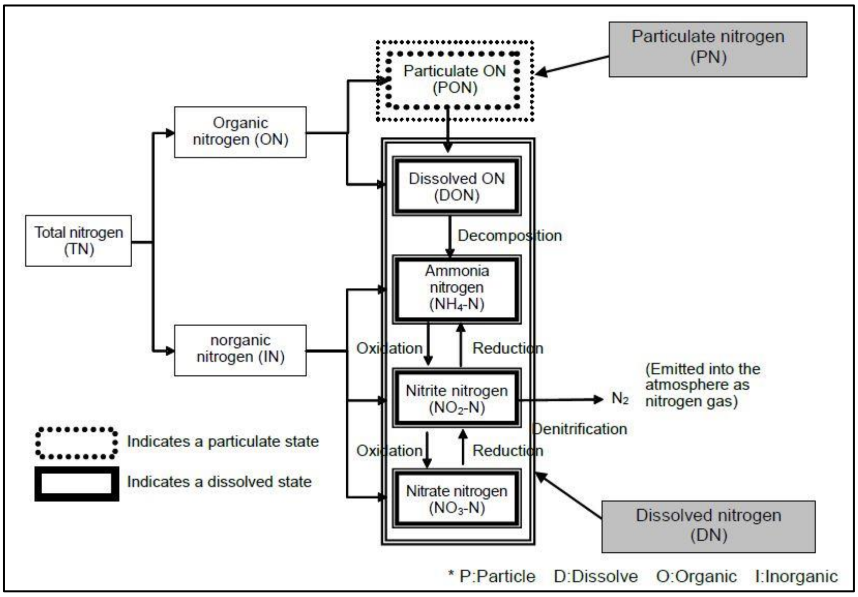


Figure A.22: Nitrogen Components (HERT, 2012)

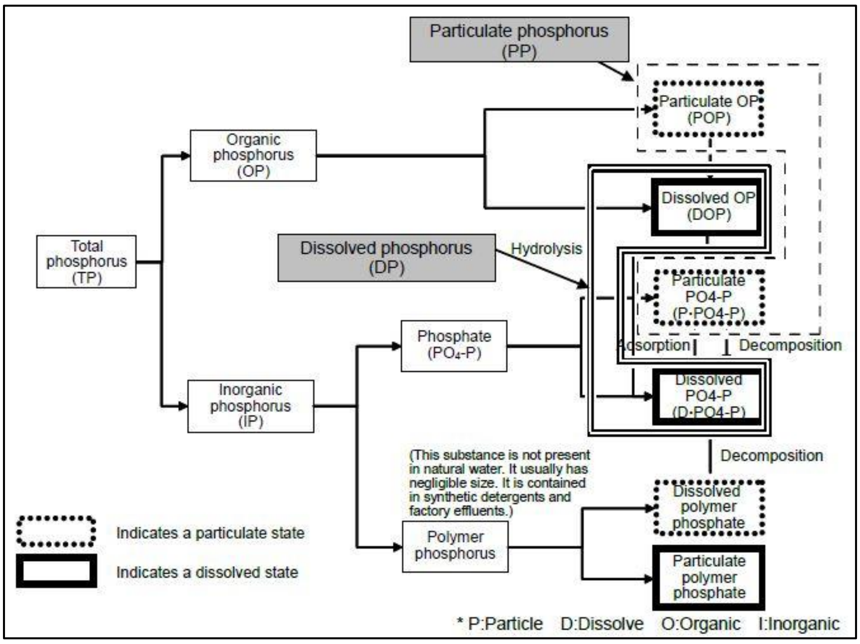


Figure A.23: Phosphorus Components (HERT, 2012)

A.1.4.1 Testing procedures

Testing was conducted according to APHA et al., (2005) (Figure A.24 to Figure A.27). For determining Nitrogen components;

TN = Total Nitrogen

PON = Particulate Organic Nitrogen

DON = Dissolved Organic Nitrogen

Check unfiltered sample for TN (using IC, after persulfate digestion) (5)

Check filtered sample for TN (using IC, after persulfate digestion) (6)

Check filtered sample for (without persulfate digestion);

NH_4^+ - N (using Kjeldahl instrument for distillation and back titration by H_2SO_4) (7)

NO_2^- - N (using IC) (8)

NO_3^- - N (using IC) (9)

Therefore,

(5) - (6) = PON

(6) - [(7) + (8) + (9)] = DON

(7) ➔ NH_4^+ - N

(8) ➔ NO_2^- - N

(9) ➔ NO_3^- - N

Figure A.24: Filtration by 0.45µm Syringe Filters (original in colour)

Figure A.25: Titration for Determining NH_4^+ - N (original in colour)

Figure A.26: “930 Compact IC Flex – MetroOhm” Ion Chromatography (IC) system (original in colour)

Figure A.27: “UDK 149 Automatic Distillation Unit – VELP” Kjeldahl Unit (original in colour)

Similarly, for determining the Phosphorus components,

TP = Total Phosphorus

PP = Particulate Phosphorus

P (OP) = Particulate Organic Phosphorus

P (PO_4^{3-} - P) = Particulate Phosphate Phosphorus

D (PO_4^{3-} - P) = Dissolved Phosphate Phosphorus

Check unfiltered sample for TP (using IC, after persulfate digestion) (10)

Check filtered sample for TP (using IC, after persulfate digestion) (11)

Check filtered sample for PO_4^{3-} (without persulfate digestion) (12)

Check unfiltered sample for PO_4^{3-} (without persulfate digestion) (13)

Therefore,

(10) - (11) = P (OP) + P (PO_4^{3-} - P) = PP

(13) - (12) = P (PO_4^{3-} - P)

(12) ➔ D (PO_4^{3-} - P)

Figure A.28: Vacuum Filtering by the Buchner Funnel to Determine TSS (original in colour)

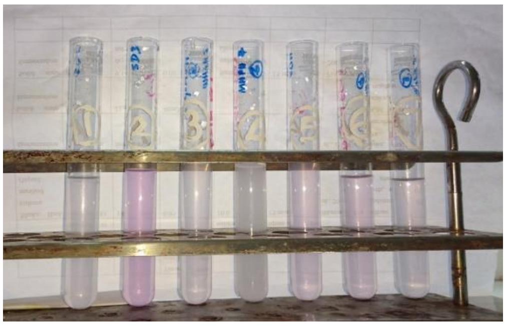


Figure A.29: Colourimetric Testing: Determining NO_3^- by the Palintest Nitratest Method (original in colour)

A.1.5 Fertilizer Related Data

A.1.5.1 Fertilizer related data for paddy

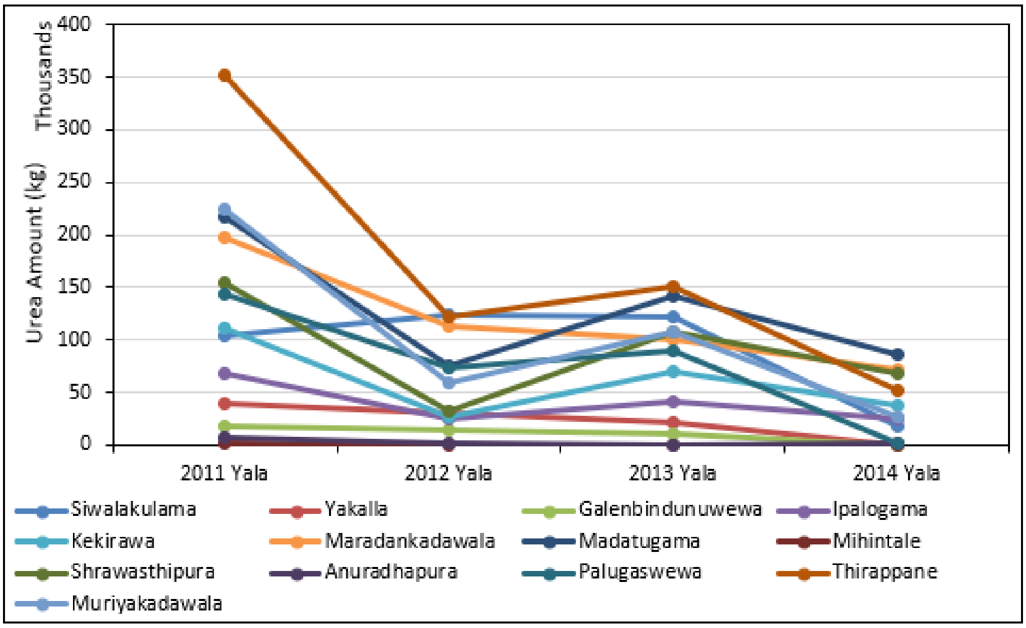


Figure A.30: The Temporal Variation of the Applied Urea Amount (kg) for Yala (original in colour)

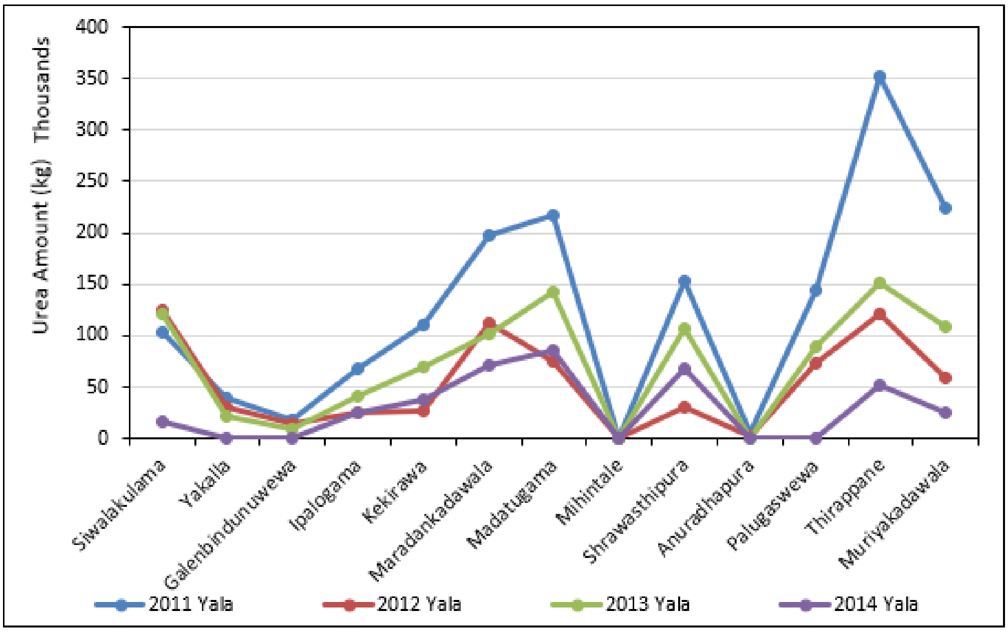


Figure A.31: The Spatial variation of the Applied Urea Amount (kg) for Yala (original in colour)

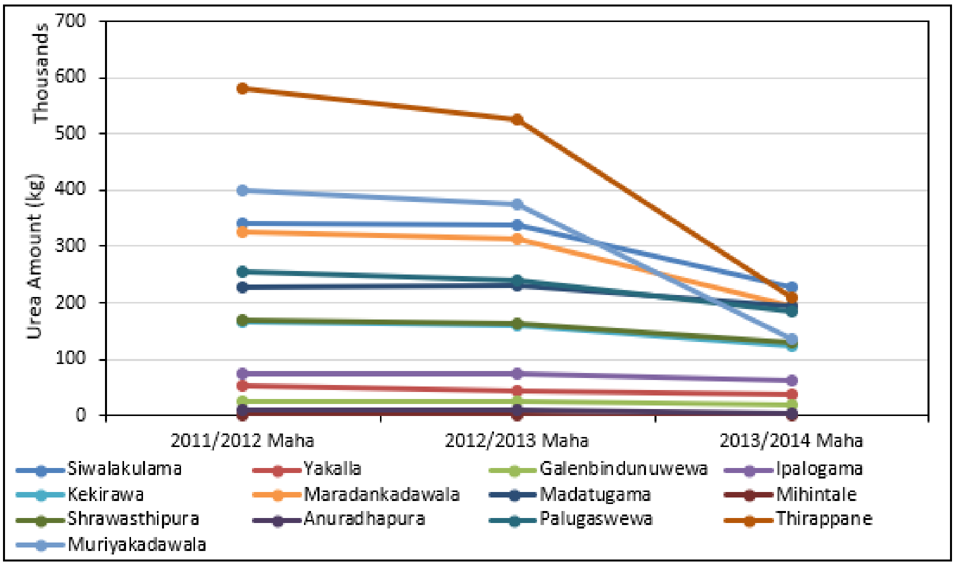


Figure A.32: The Temporal Variation of the Applied Urea Amount (kg) for Maha (original in colour)

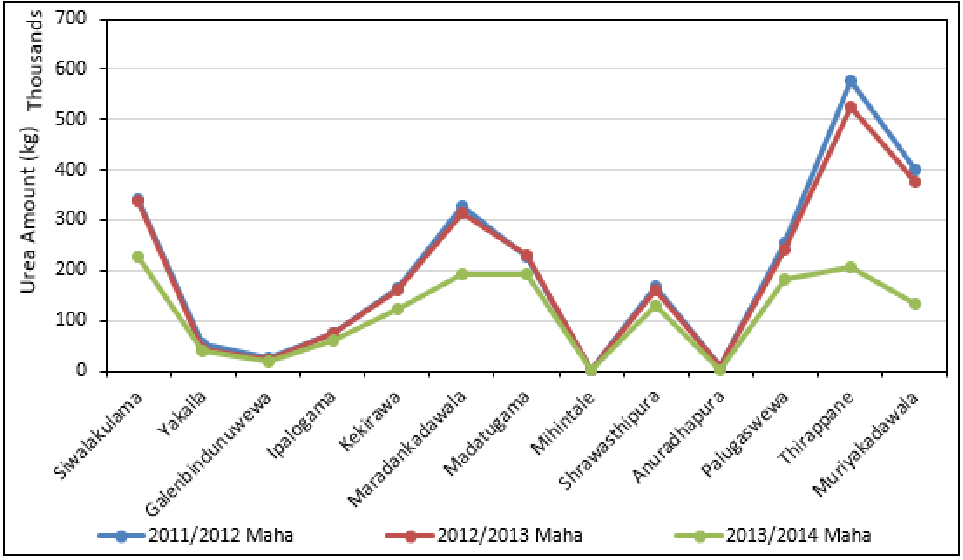


Figure A.33: The Spatial variation of the Applied Urea Amount (kg) for Maha (original in colour)

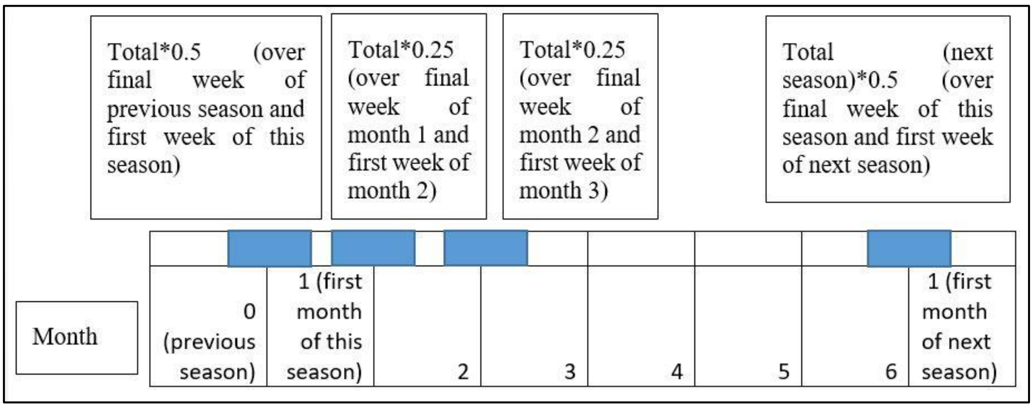


Figure A.34: The Application of Urea in Every Month for Paddy

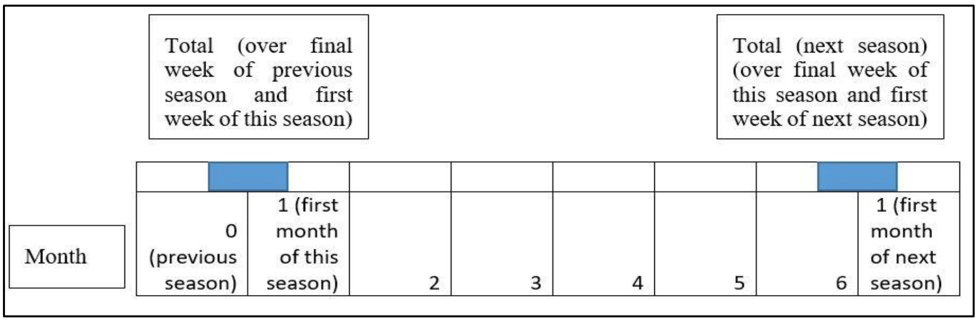


Figure A.35: The Application of TSP in Every Month for Paddy

A.1.5.2 Fertilizer related data for other crops

Figure A.36: The Application of Urea in Every Month for Other Crops (original in colour)

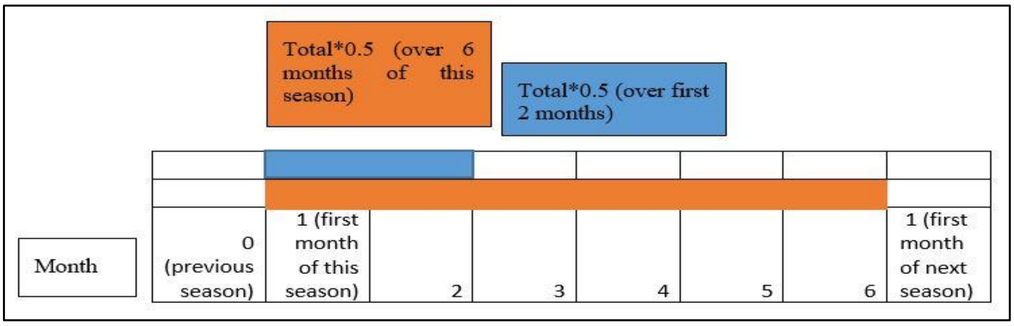


Figure A.37: The Application of TSP in Every Month for Other Crops (original in colour)

A.1.5.3 Fertilizer related data for homesteads

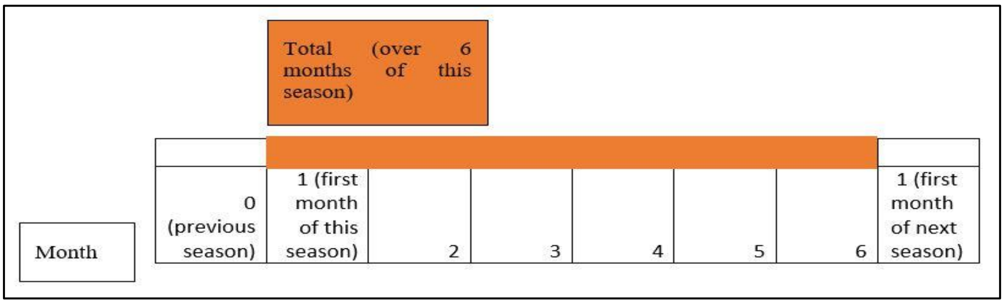


Figure A.38: The Application of Urea in Every Month for Homesteads (original in colour)

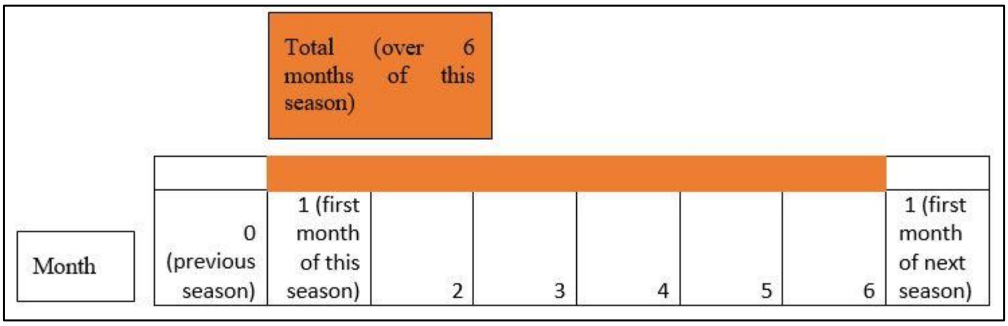


Figure A.39: The Application of TSP in Every Month for Homesteads (original in colour)

A.2 WEP Model Analysis

A.2.1 Preparation of Input Files

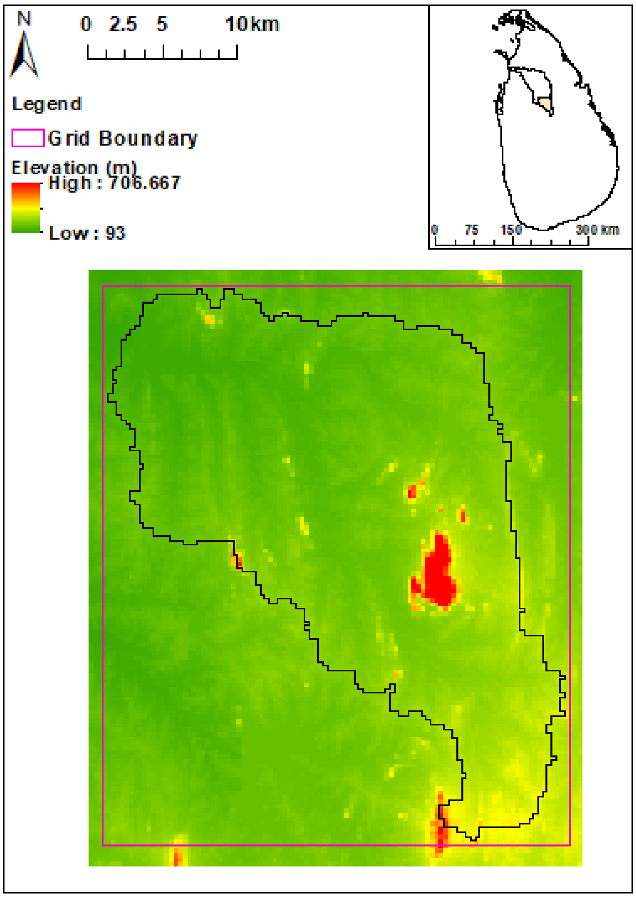


Figure A.40: Altitude of Each Grid Cell (original in colour)

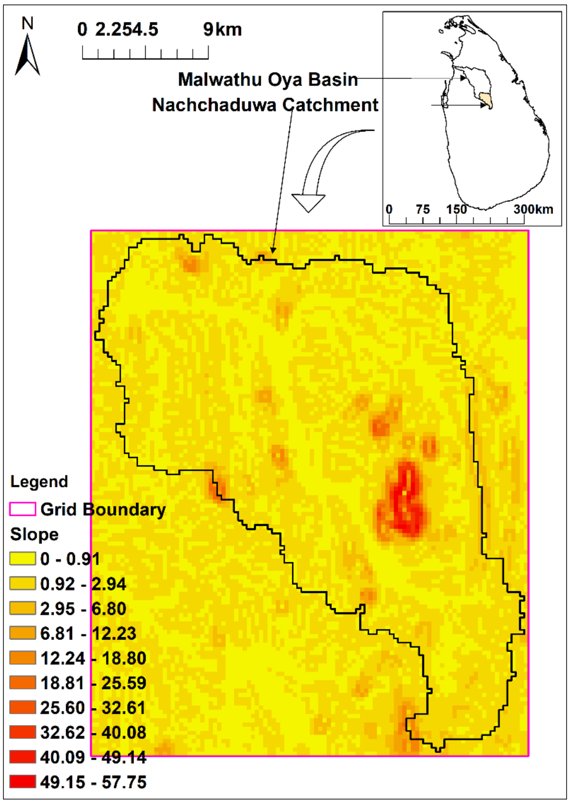


Figure A.41: Slope in Each Grid Cell (original in colour)

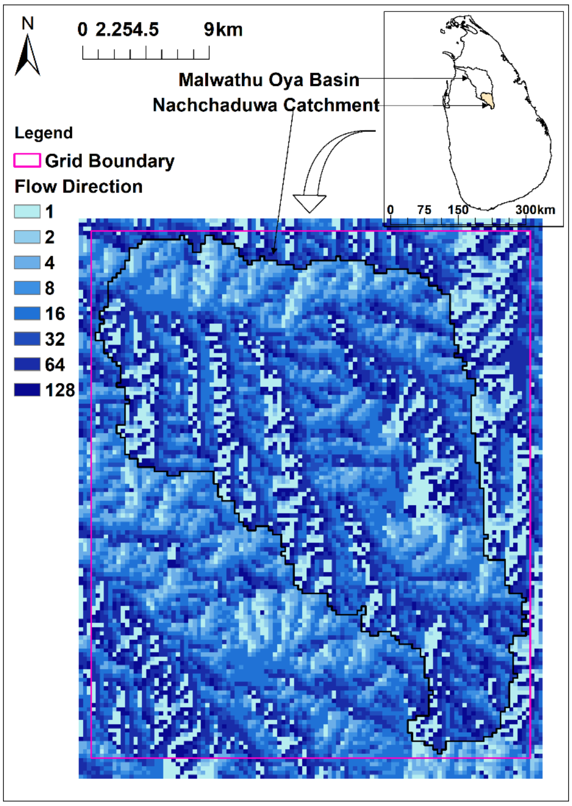


Figure A.42: Flow Direction in Each Grid Cell (original in colour)

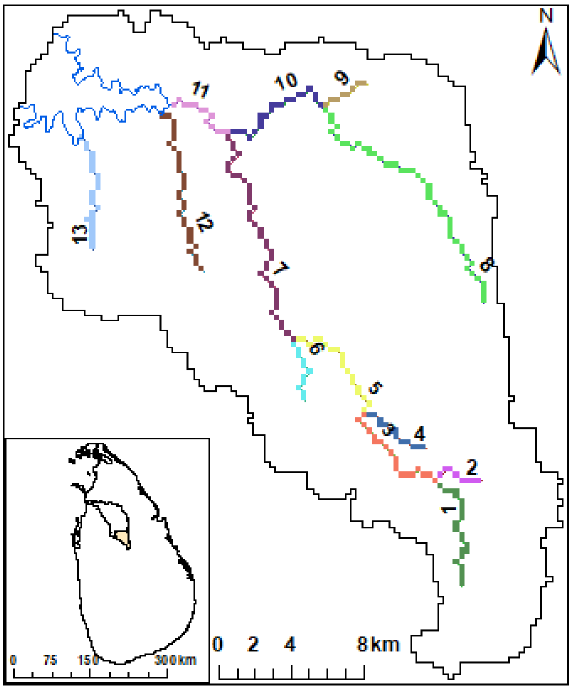


Figure A.43: River Network for the WEP Model Input Files (original in colour)

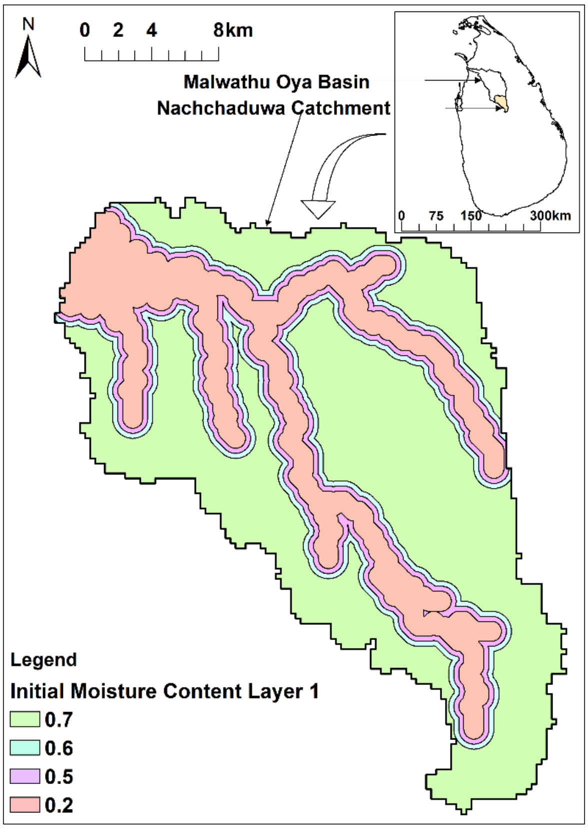


Figure A.44: Initial Moisture Content (original in colour)

Table A.1: Nitrogen Fixation Amounts

Crop Type	Method of N Input	Amount	Unit
Other Crops	From fertilizer	(refer Section 3.2.8)	
	Lightning	70.05	kg/km^2/month
	Plant N fixation	2335.10	kg/km^2/month
	Combustion	140.11	kg/km^2/month
	Total	**2545.26**	**kg/km^2/month**
Paddy	From fertilizer	(refer Section 3.2.8)	
	Lightning	70.05	kg/km^2/month
	Plant N fixation	0.00	kg/km^2/month
	Combustion	140.11	kg/km^2/month
	Total	**210.16**	**kg/km^2/month**
Homesteads	From fertilizer	(refer Section 3.2.8)	
	Lightning	70.05	kg/km^2/month
	Plant N fixation	467.02	kg/km^2/month
	Combustion	140.11	kg/km^2/month
	Total	**677.18**	**kg/km^2/month**

.

Table A.2: Variation of Total Input and Total Uptake of Nitrogen (kg) in Each Year in Each ASC

ASC	Total N input (kg)				Total N Output (Plant Uptake) (kg)			
	2008	2009	2010	2011	2008	2009	2010	2011
Siwalakulama	324,040	324,040	324,040	366,344	301,466	301,466	301,466	301,466
Yakalla	50,025	50,025	50,025	66,335	21,817	21,817	21,817	21,817
Galenbindunuwewa	23,097	23,097	23,097	30,503	7,606	7,606	7,606	7,606
Ipalogama	96,114	96,114	96,114	118,686	20,150	20,150	20,150	20,150
Kekirawa	160,630	160,630	160,630	206,742	86,425	86,425	86,425	86,425
Maradankadawala	341,351	341,351	341,351	423,338	273,000	273,000	273,000	273,000
Madatugama	255,009	255,009	255,009	322,782	116,014	116,014	116,014	116,014
Mihintale	839	839	839	1,254	0	0	0	0
Shrawasthipura	162,474	162,474	162,474	216,407	31,487	31,487	31,487	31,487
Anuradhapura	12,627	12,627	12,627	16,760	6,713	6,713	6,713	6,713
Palugaswewa	399,714	399,714	399,714	465,819	246,264	246,264	246,264	246,264
Thirappane	629,629	629,629	629,629	835,730	472,092	472,092	472,092	472,092
Muriyakadawala	346,154	346,154	346,154	485,063	273,713	273,713	273,713	273,713
Kibissa	122,280	122,280	122,280	128,724	36,038	36,038	36,038	36,038
Total	2,923,983	2,923,983	2,923,983	3,684,488	1,892,784	1,892,784	1,892,784	1,892,784

Table A.3: Variation of Total Input and Total Uptake of Phosphorus (kg) in Each Year in Each ASC

ASC	Total P input (kg)				Total P Output (Plant Uptake) (kg)			
	2008	2009	2010	2011	2008	2009	2010	2011
Siwalakulama	79,099	79,099	79,099	118,254	126,819	126,819	126,819	126,819
Yakalla	12,110	12,110	12,110	18,572	9,472	9,472	9,472	9,472
Galenbindunuwewa	6,010	6,010	6,010	8,929	3,260	3,260	3,260	3,260
Ipalogama	20,115	20,115	20,115	29,349	12,404	12,404	12,404	12,404
Kekirawa	37,879	37,879	37,879	57,287	37,183	37,183	37,183	37,183
Maradankadawala	75,015	75,015	75,015	112,156	116,839	116,839	116,839	116,839
Madatugama	61,150	61,150	61,150	88,319	49,552	49,552	49,552	49,552
Mihintale	242	242	242	393	0	0	0	0
Shrawasthipura	42,663	42,663	42,663	65,104	13,438	13,438	13,438	13,438
Anuradhapura	1,719	1,719	1,719	3,129	3,498	3,498	3,498	3,498
Palugaswewa	56,315	56,315	56,315	84,219	130,187	130,187	130,187	130,187
Thirappane	116,874	116,874	116,874	202,774	216,837	216,837	216,837	216,837
Muriyakadawala	75,907	75,907	75,907	128,533	117,035	117,035	117,035	117,035
Kibissa	5,490	5,490	5,490	8,210	32,809	32,809	32,809	32,809
Total	590,586	590,586	590,586	925,228	869,332	869,332	869,332	869,332

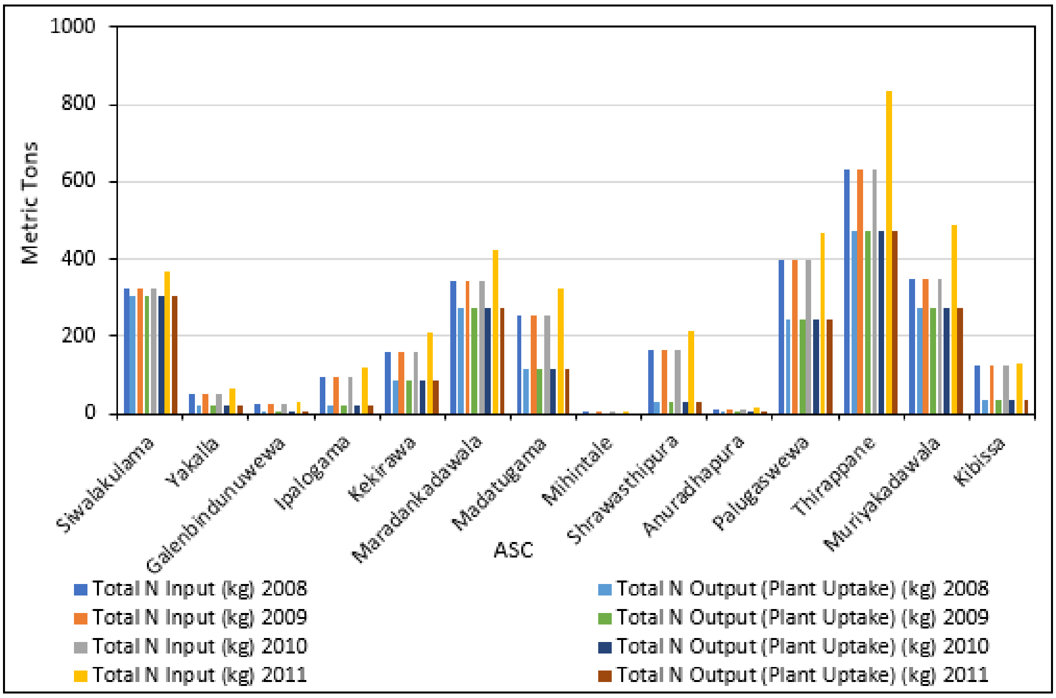


Figure A.45: Spatial Variation of Total N Input and Total N Output (original in colour)

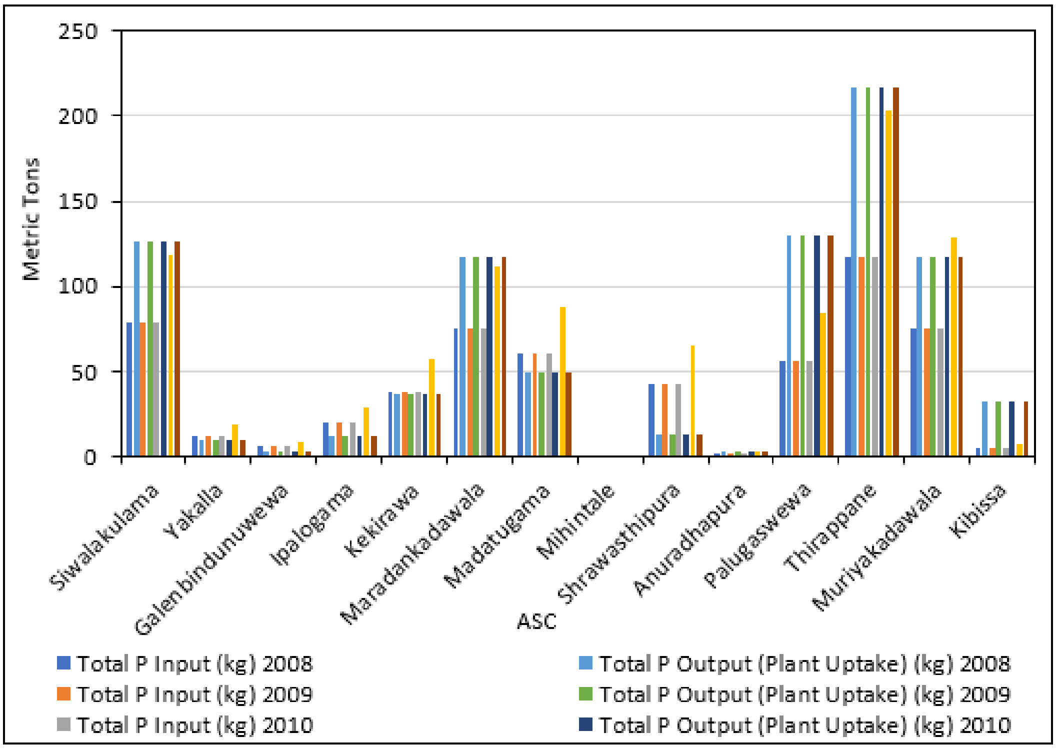


Figure A.46: Spatial Variation of Total P Input and Total P Output (original in colour)

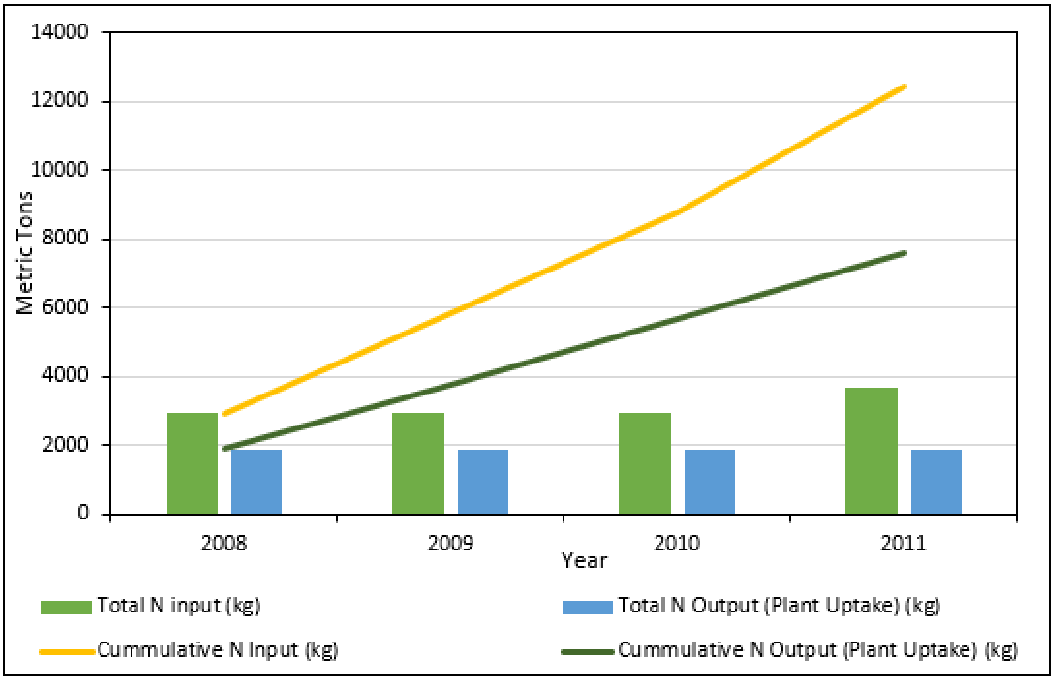


Figure A.47: Temporal Variation of Total N Input and Total N Output (original in colour)

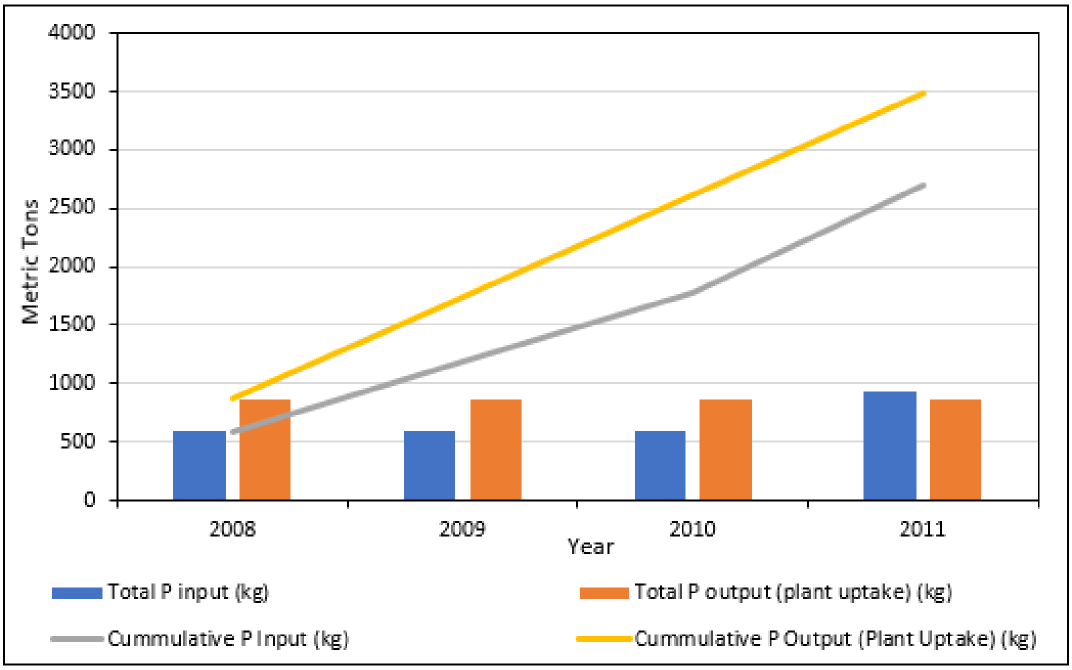


Figure A.48: Temporal Variation of Total P Input and Total P Output (original in colour)

APPENDIX B: ADDITIONAL RESULTS

B.1 WEP Model Results (for the Present Condition)

B.1.1 Temporal variation of results

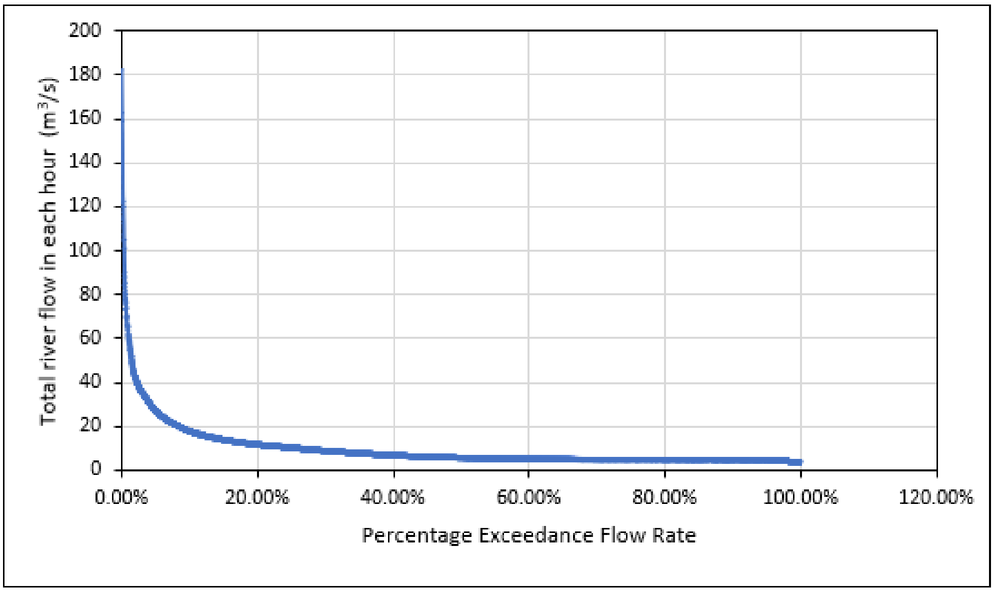


Figure B.1: Flow Duration Curve for WEP River Flow - Calibration Period

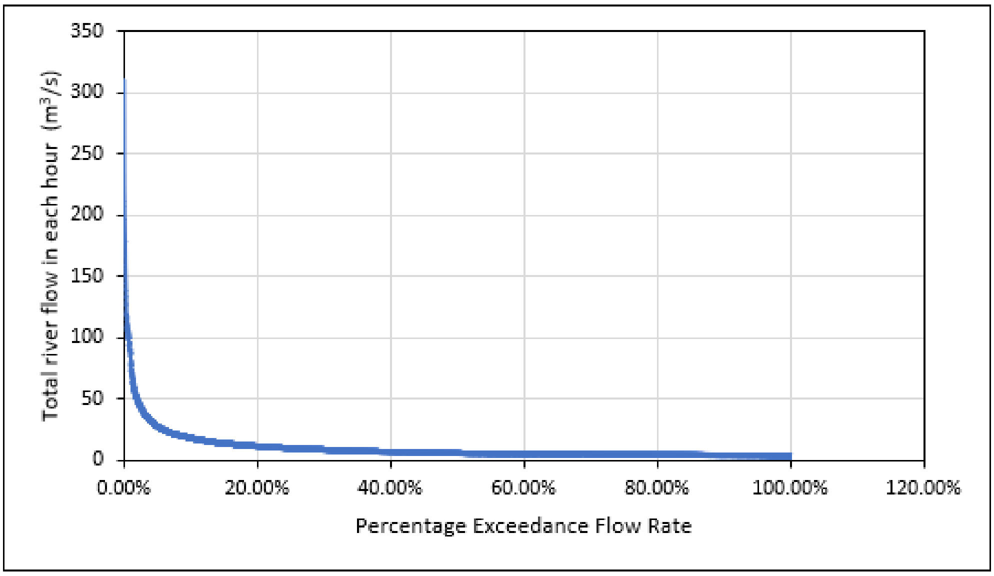


Figure B.2: Flow Duration Curve for WEP River Flow - Validation Period

B.1.1.1 Results of Nitrogen components

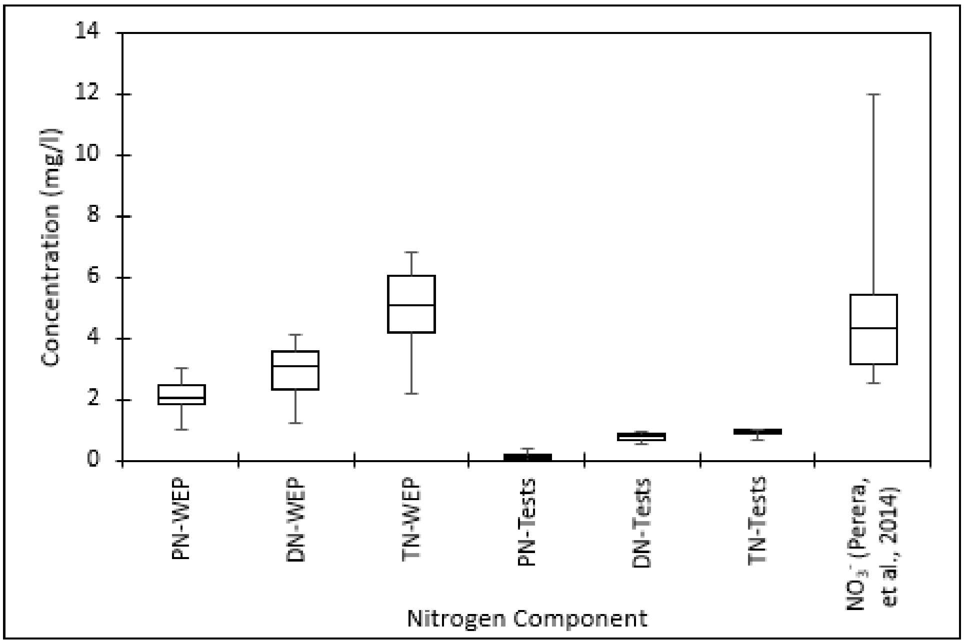


Figure B.3: Comparison of WEP Results, Test Results, and Published Results of Nitrogen Components - Calibration Period

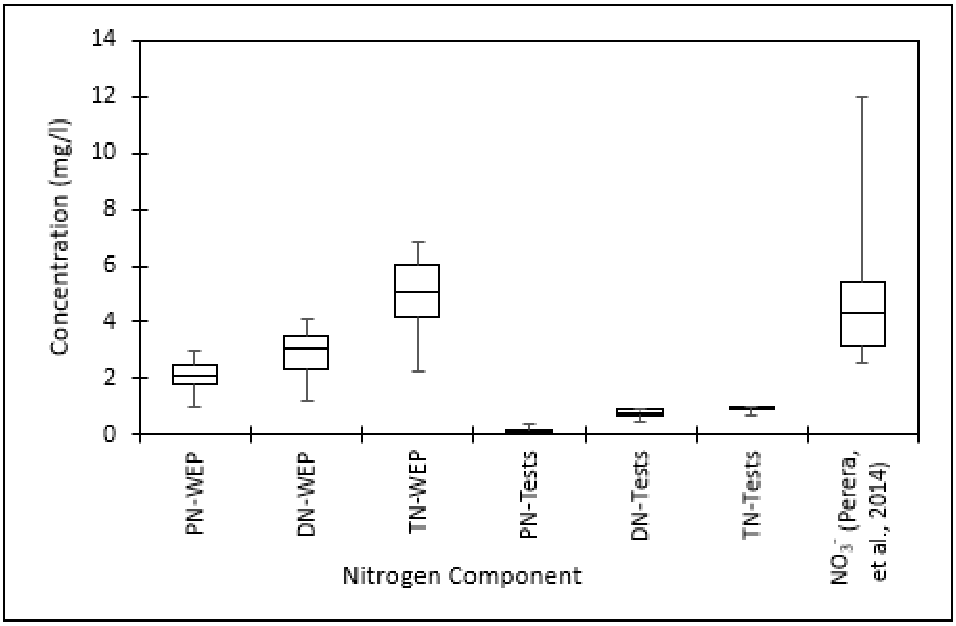


Figure B.4: Comparison of WEP Results, Test Results, and Published Results of Nitrogen Components - Validation Period

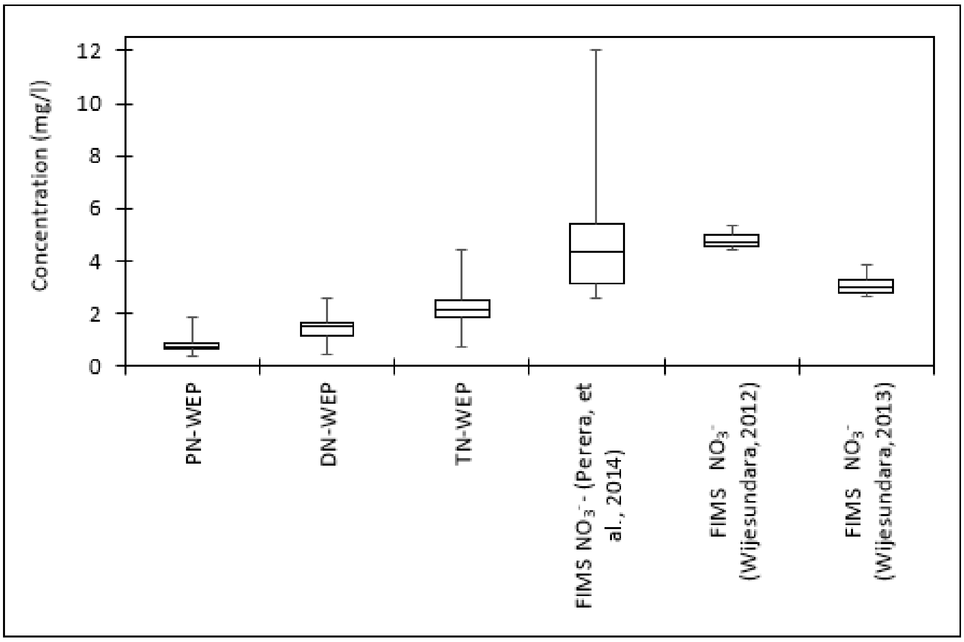


Figure B.5: Comparison of WEP Model Results of Nitrogen Components for FIMS (Calibration Period) with the FIMS Results of the Published Studies

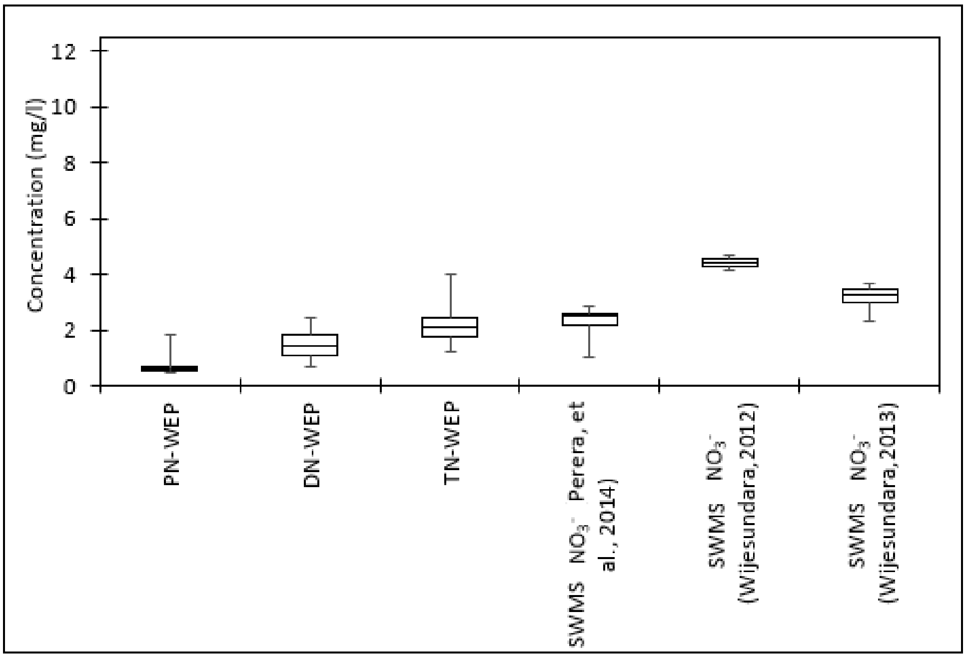


Figure B.6: Comparison of WEP Model Results of Nitrogen Components for SWMS (Calibration Period) with the SWMS Results of the Published Studies

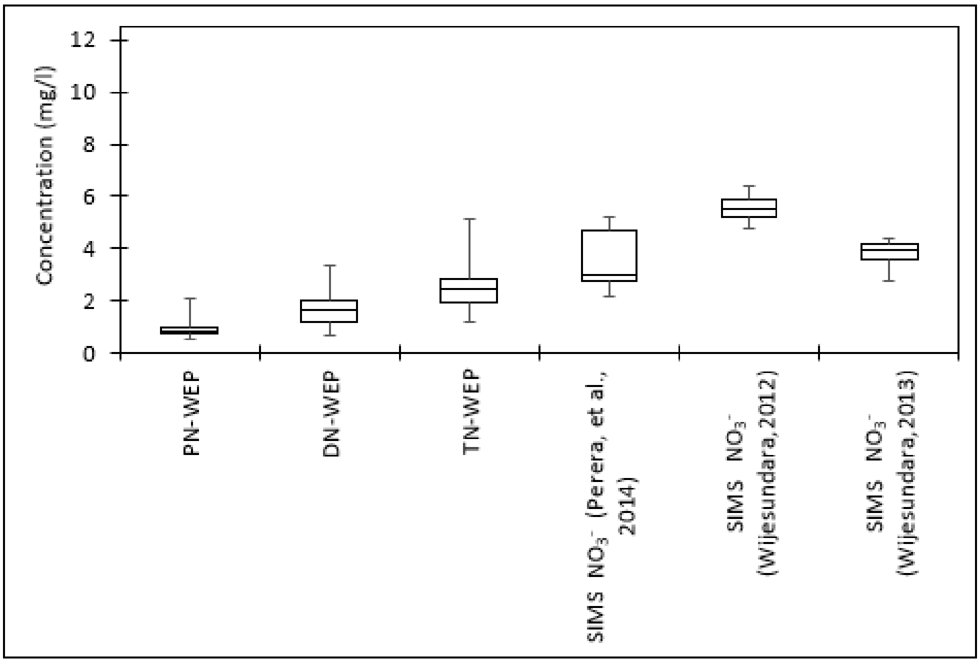


Figure B.7: Comparison of WEP Model Results of Nitrogen Components for SIMS (Calibration Period) with the SIMS Results of the Published Studies

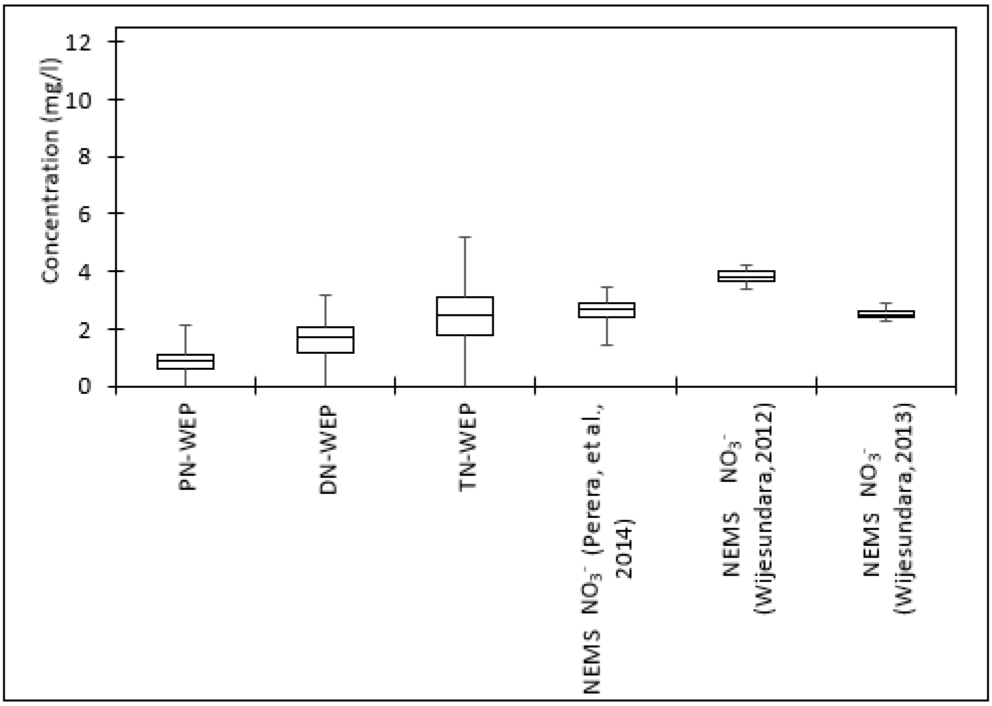


Figure B.8: Comparison of WEP Model Results of Nitrogen Components for NEMS (Calibration Period) with the NEMS Results of the Published Studies

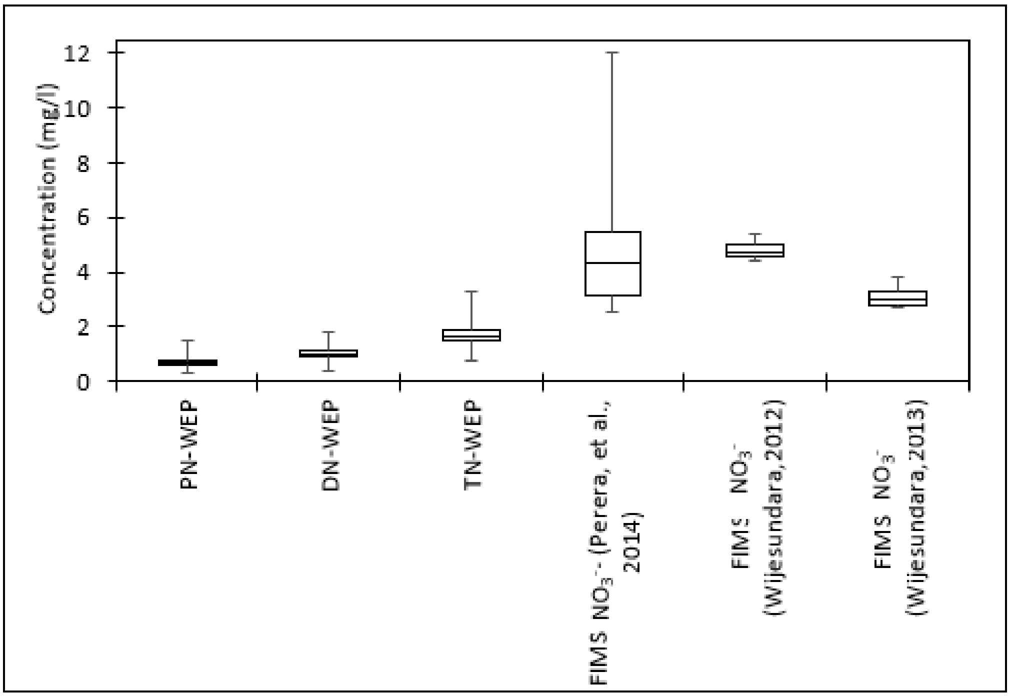


Figure B.9: Comparison of WEP Model Results of Nitrogen Components for FIMS (Validation Period) with the FIMS Results of the Published Studies

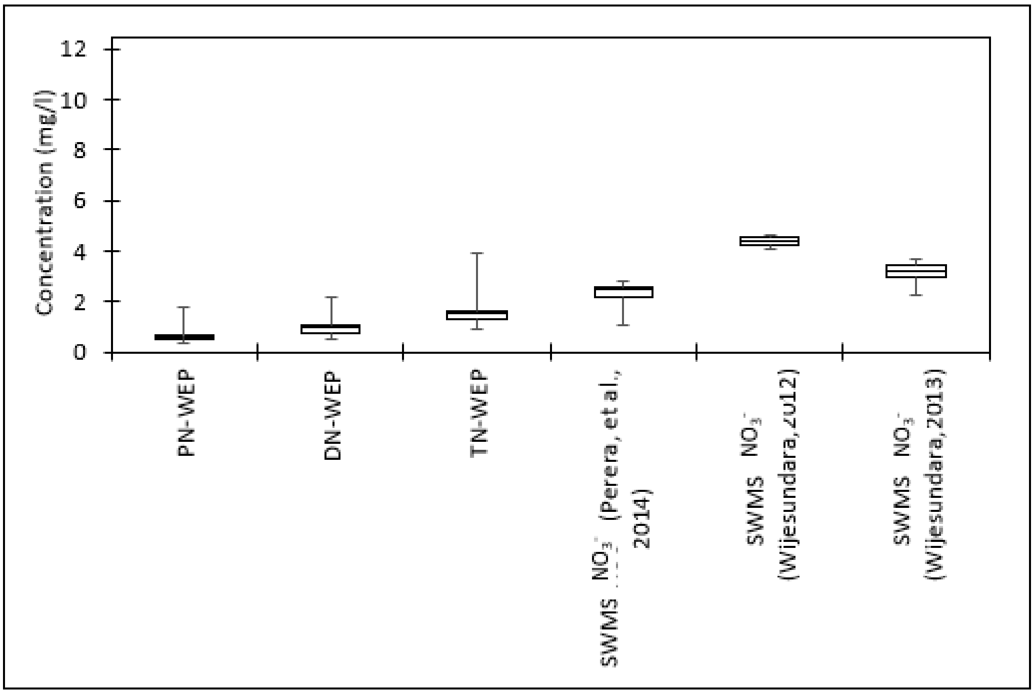


Figure B.10: Comparison of WEP Model Results of Nitrogen Components for SWMS (Validation Period) with the SWMS Results of the Published Studies

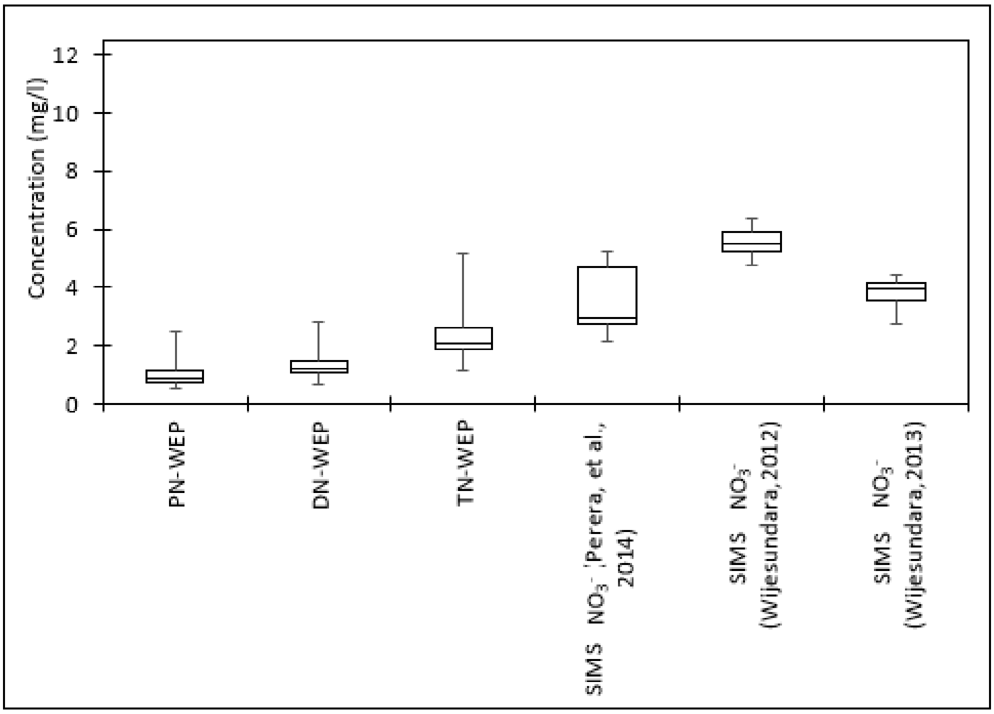


Figure B.11: Comparison of WEP Model Results of Nitrogen Components for SIMS (Validation Period) with the SIMS Results of the Published Studies

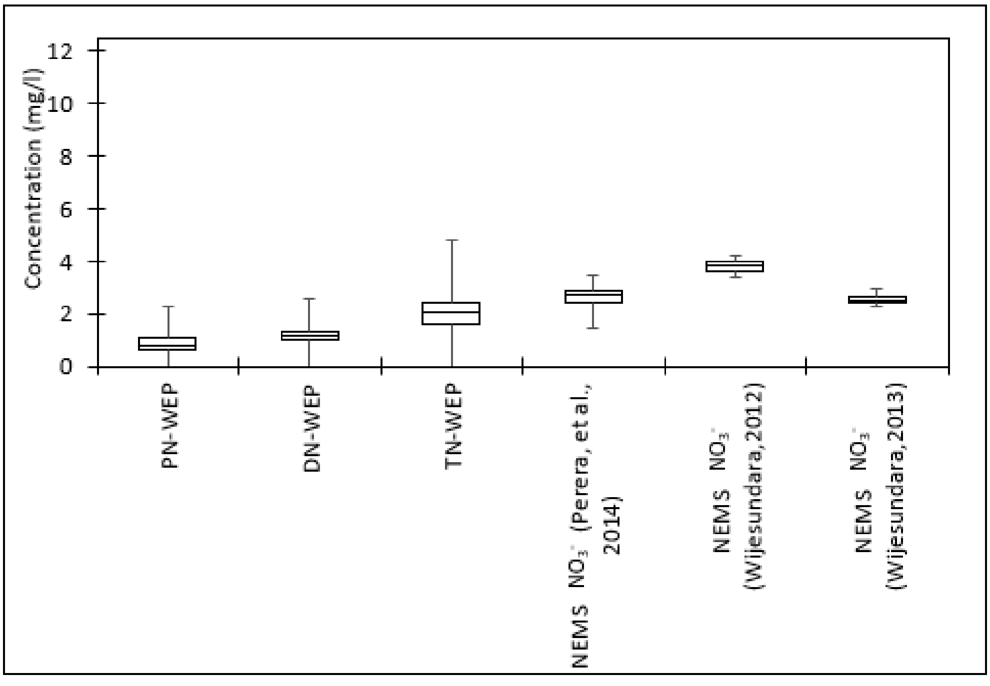


Figure B.12: Comparison of WEP Model Results of Nitrogen Components for NEMS (Validation Period) with the NEMS Results of the Published Studies

B.1.1.2 Results of Phosphorus components

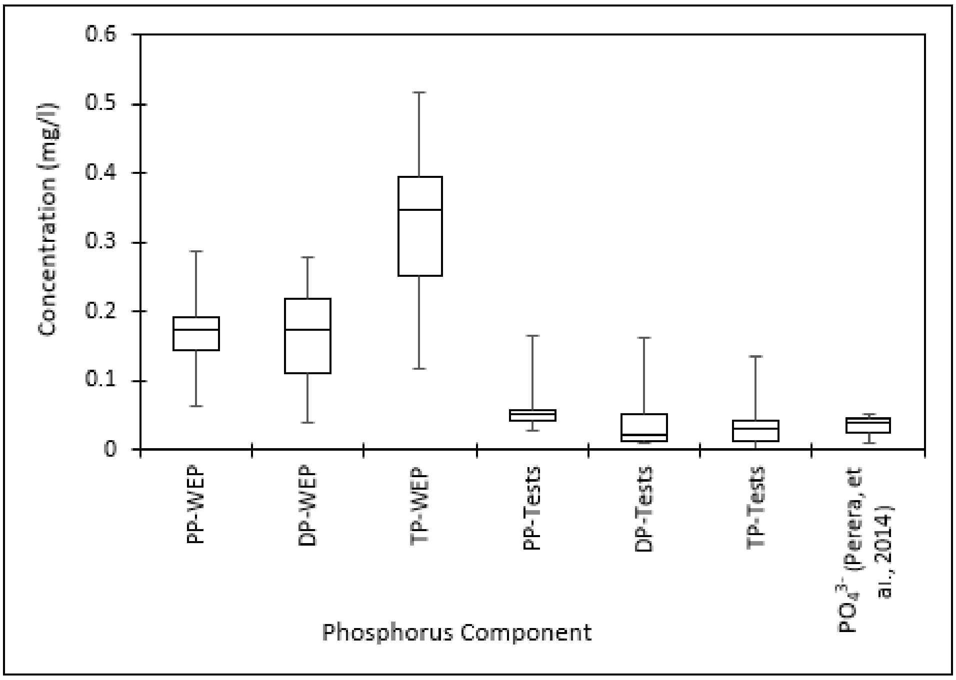


Figure B.13: Comparison of WEP Results, Test Results, and Published Results of Phosphorus Components - Calibration Period

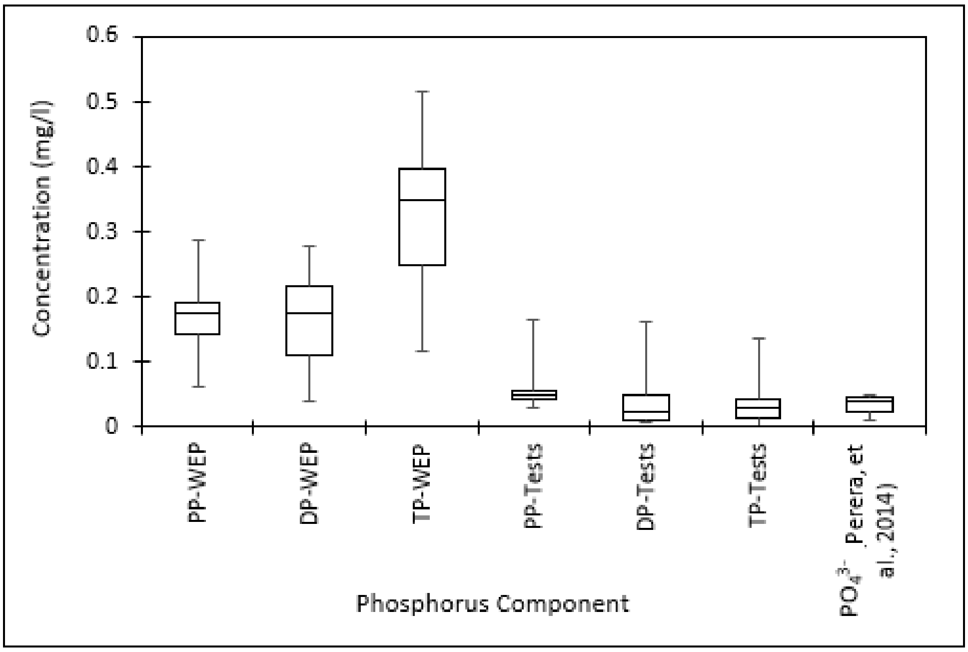


Figure B.14: Comparison of WEP Results, Test Results, and Published Results of Phosphorus Components - Validation Period

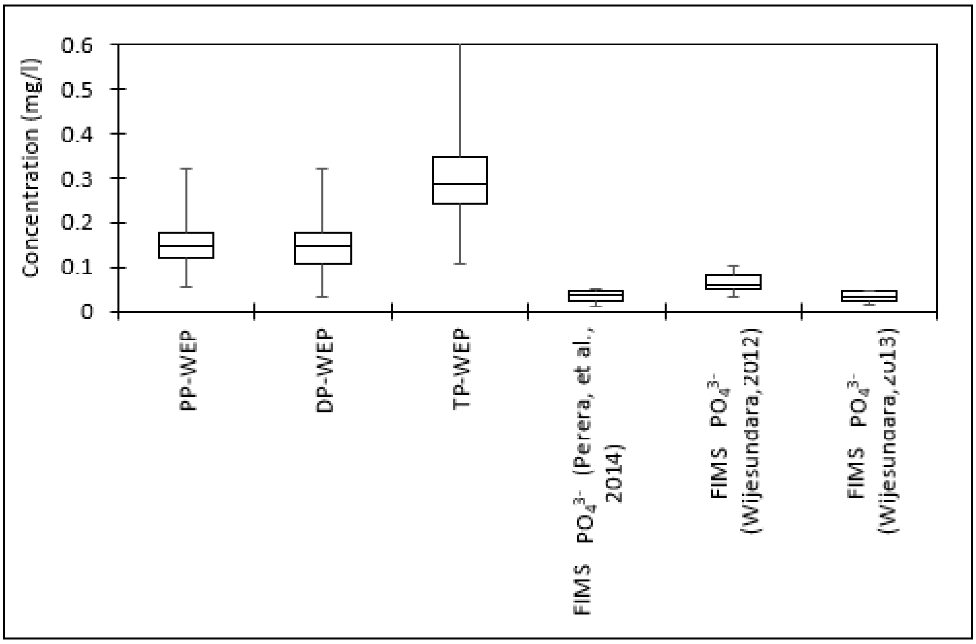


Figure B.15: Comparison of WEP Model Results of Phosphorus Components for FIMS (Calibration Period) with the FIMS Results of the Published Studies

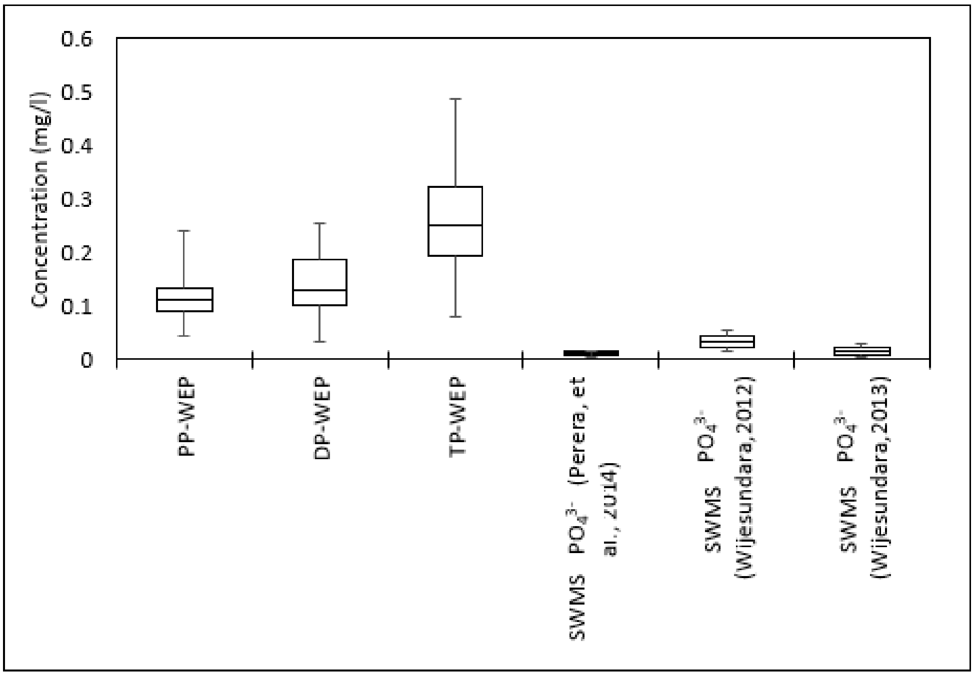


Figure B.16: Comparison of WEP Model Results of Phosphorus Components for SWMS (Calibration Period) with the SWMS Results of the Published Studies

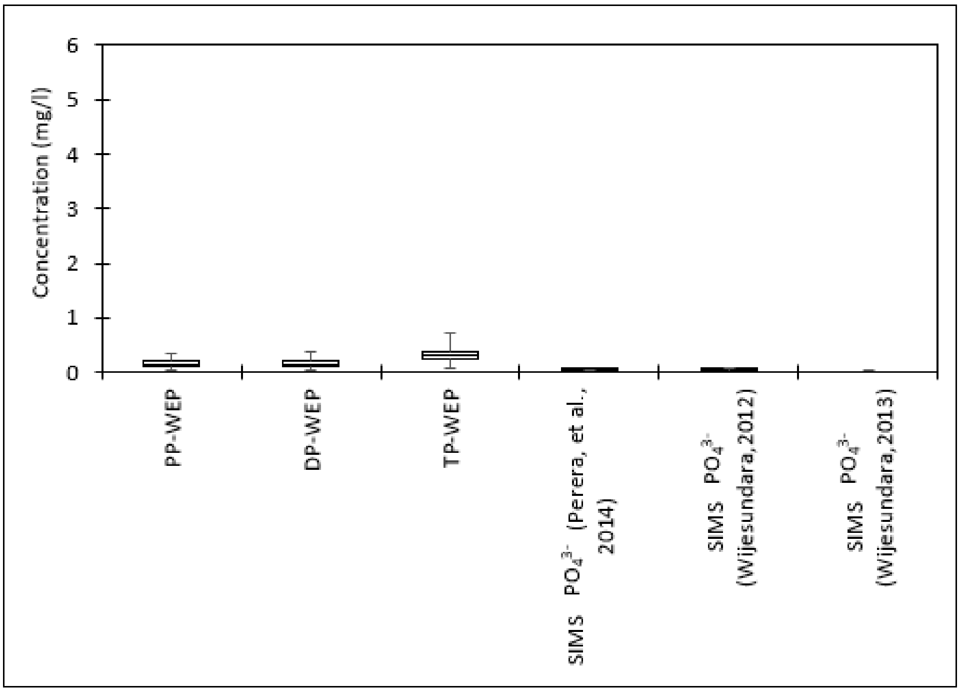


Figure B.17: Comparison of WEP Model Results of Phosphorus Components for SIMS (Calibration Period) with the SIMS Results of the Published Studies

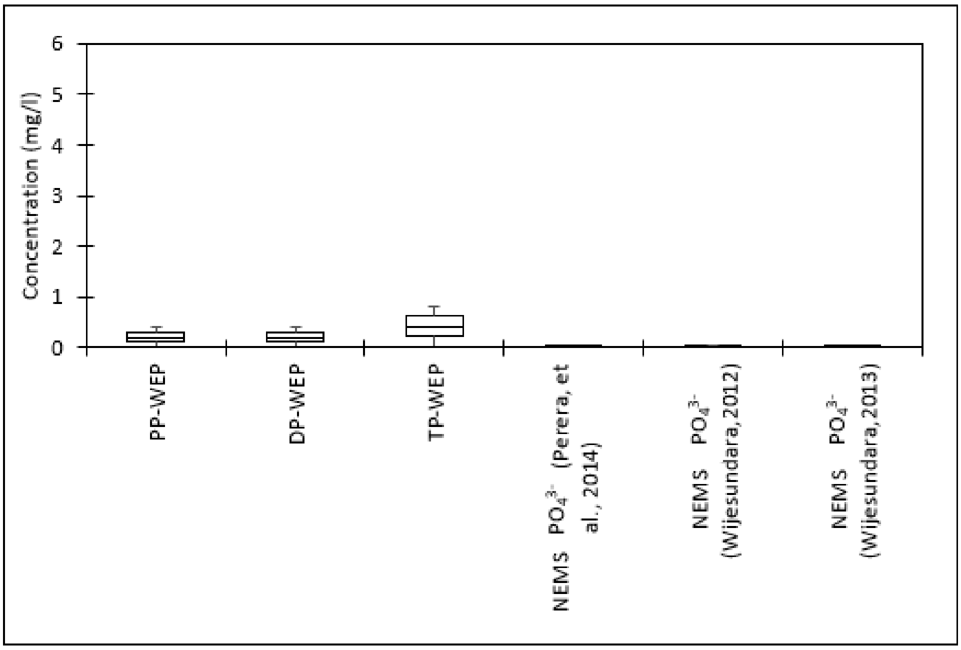


Figure B.18: Comparison of WEP Model Results of Phosphorus Components for NEMS (Calibration Period) with the NEMS Results of the Published Studies

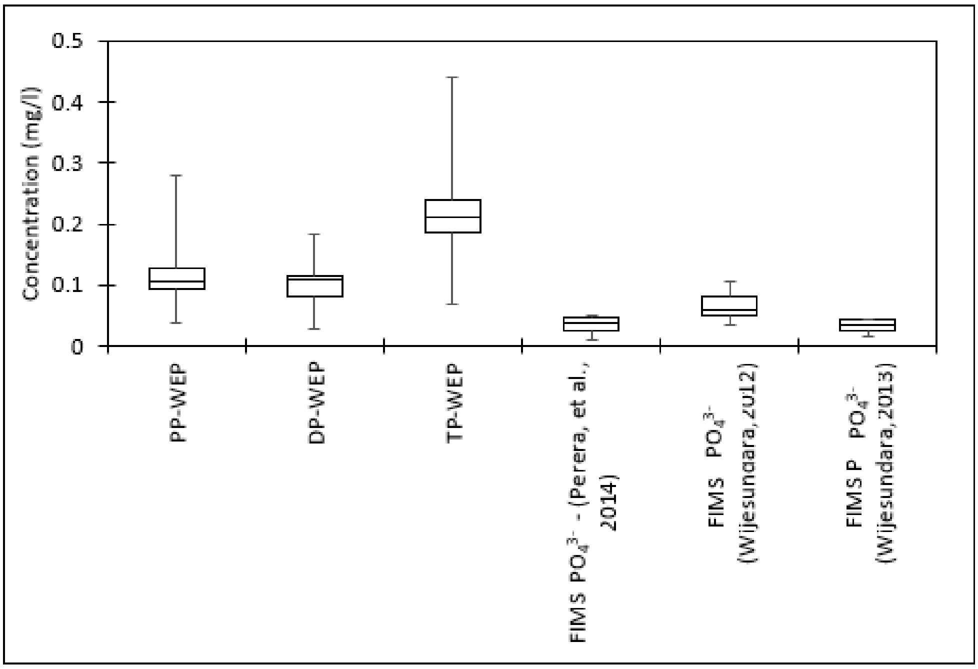


Figure B.19: Comparison of WEP Model Results of Phosphorus Components for FIMS (Validation Period) with the FIMS Results of the Published Studies

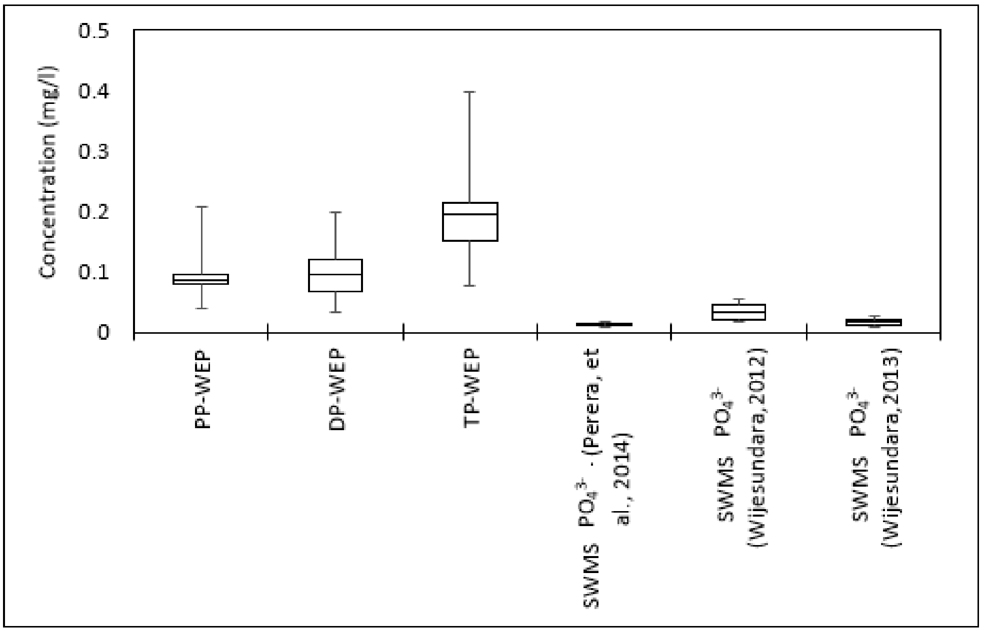


Figure B.20: Comparison of WEP Model Results of Phosphorus Components for SWMS (Validation Period) with the SWMS Results of the Published Studies

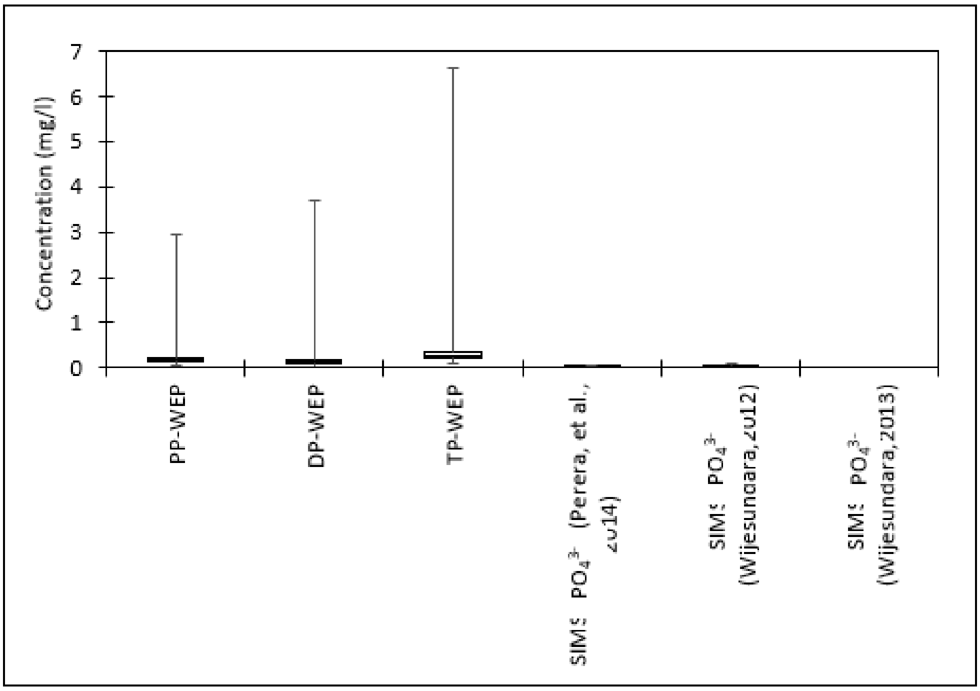


Figure B.21: Comparison of WEP Model Results of Phosphorus Components for SIMS (Validation Period) with the SIMS Results of the Published Studies

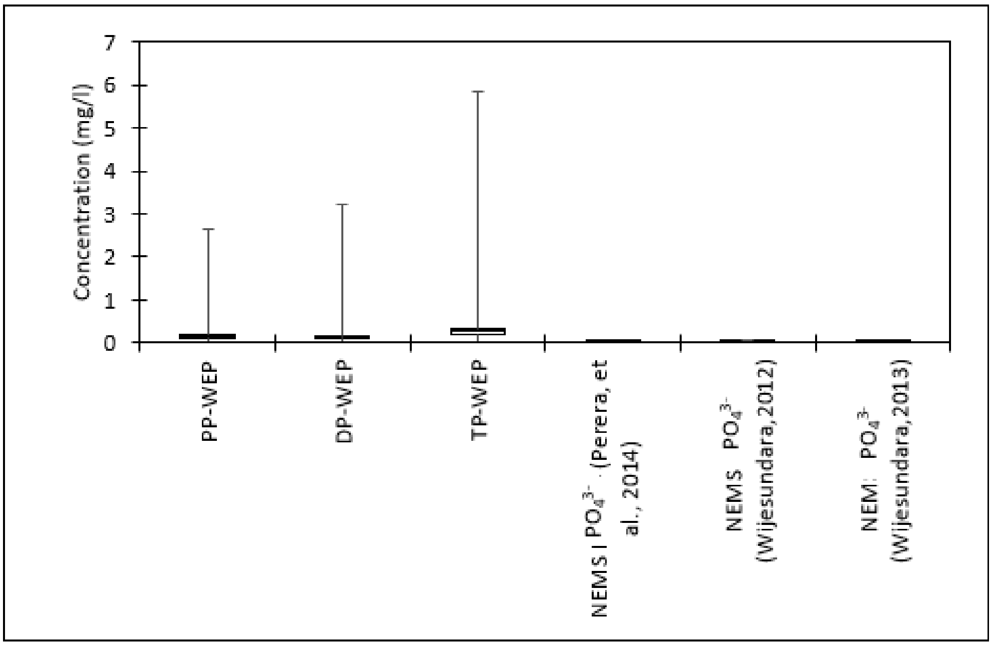


Figure B.22: Comparison of WEP Model Results of Phosphorus Components for NEMS (Validation Period) with the NEMS Results of the Published Studies

B.1.1.3 Results of other parameters

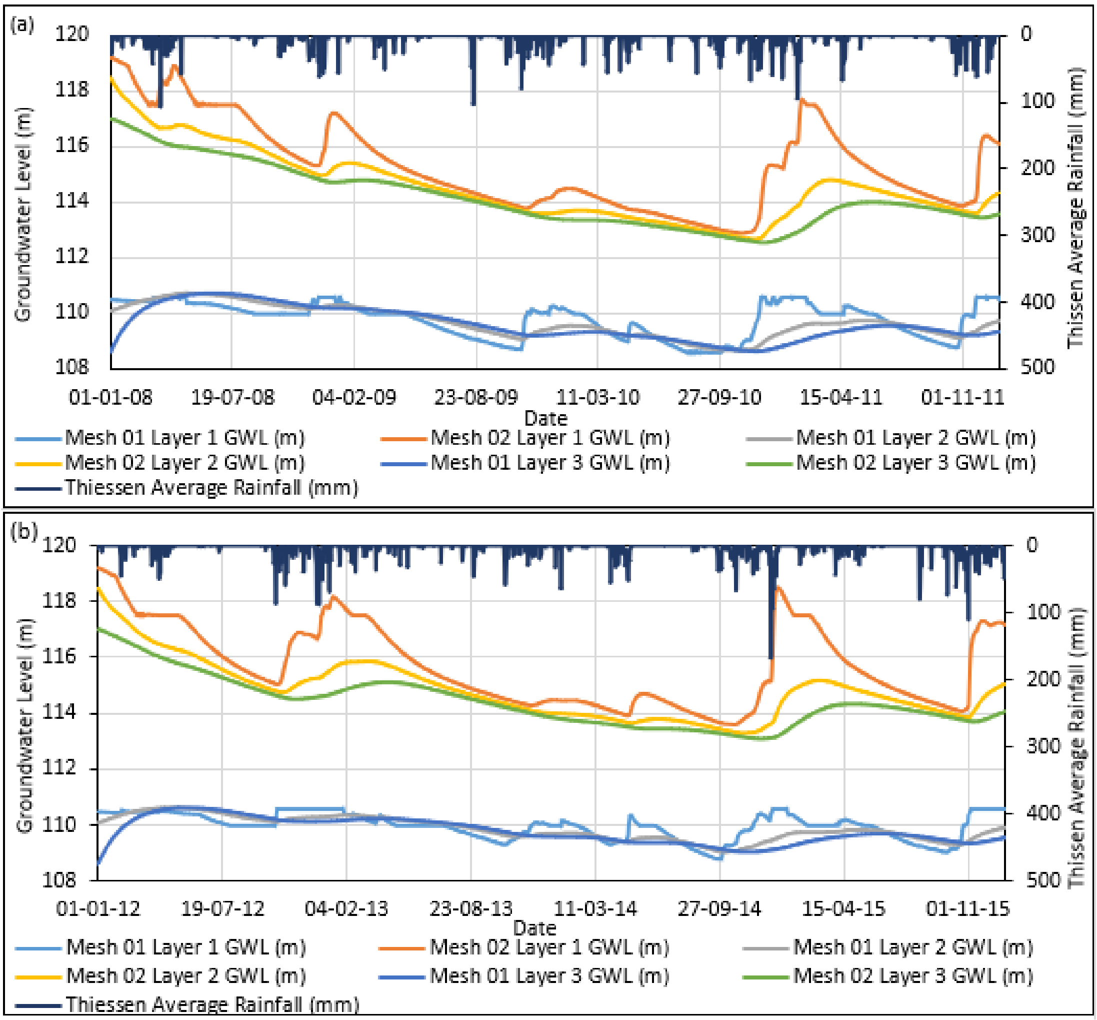


Figure B.23: Temporal Variation of Daily Groundwater Levels; (a) Calibration Period, (b) Validation Period (original in colour)

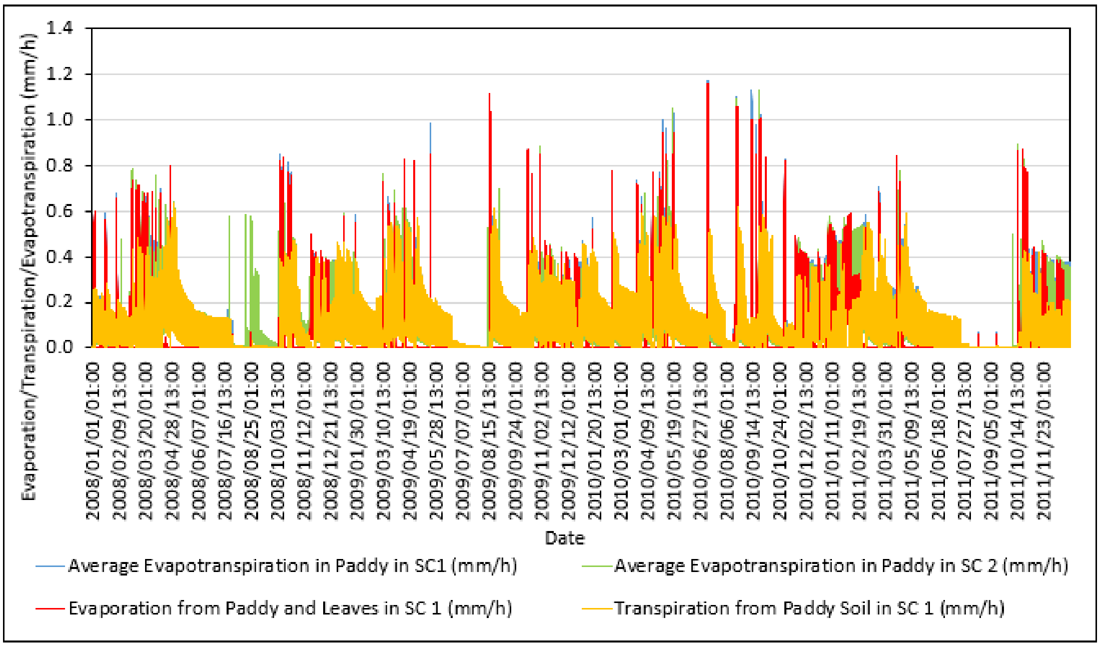


Figure B.24: Evaporation/Transpiration/Evapotranspiration - Calibration Period

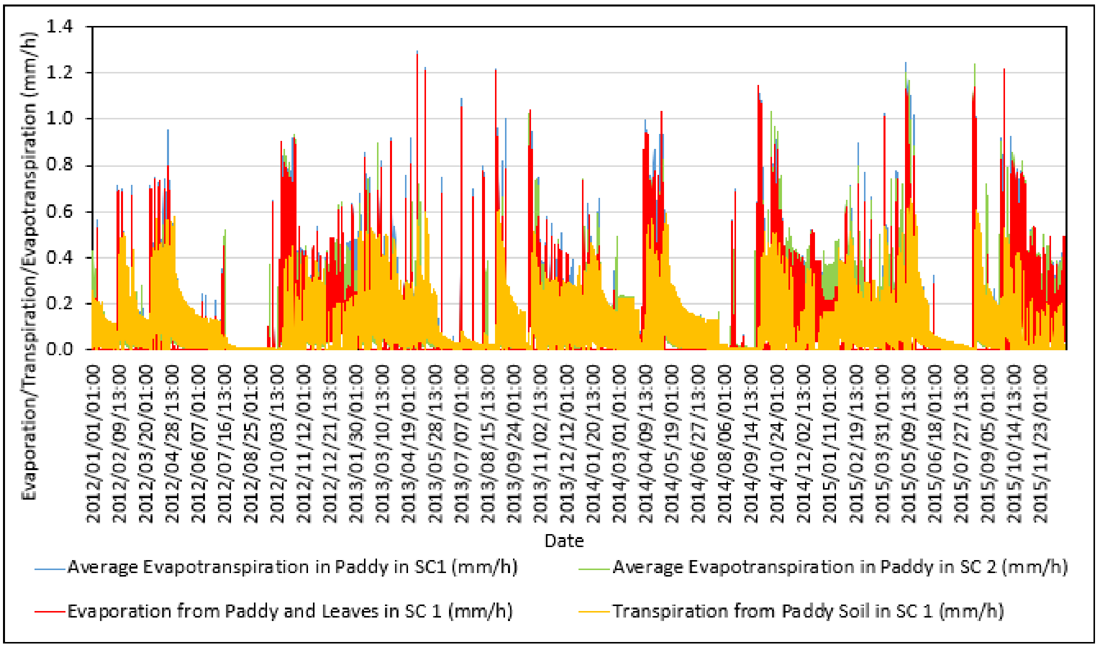


Figure B.25: Evaporation/Transpiration/Evapotranspiration - Validation Period

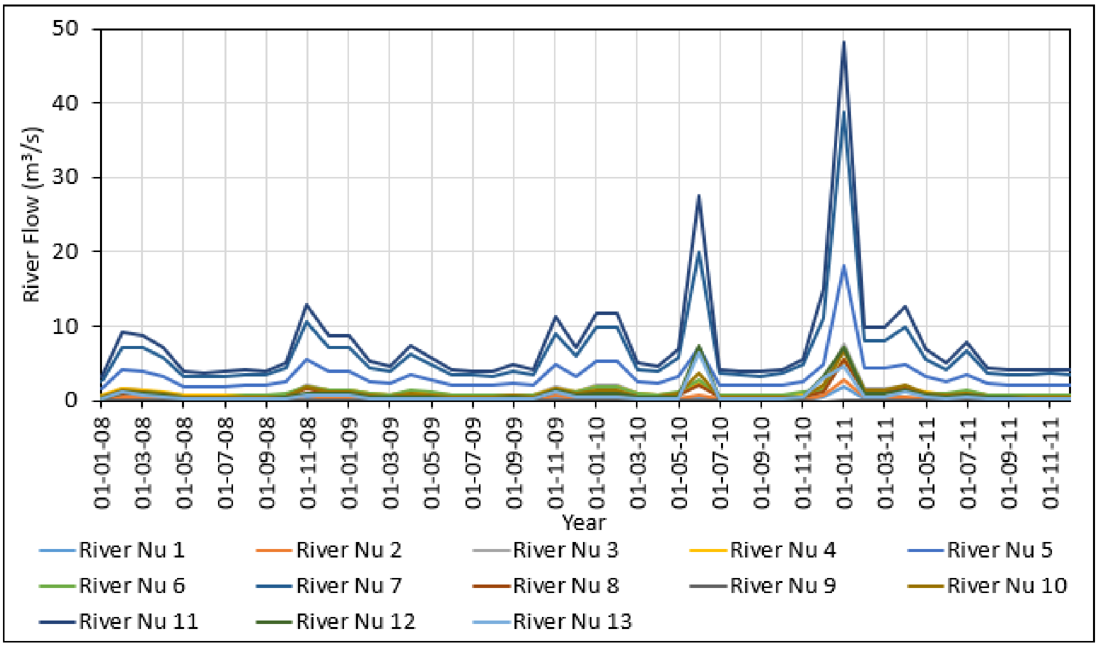


Figure B.26: River Flow at the Final Day of each Month for each River Segment - Calibration Period

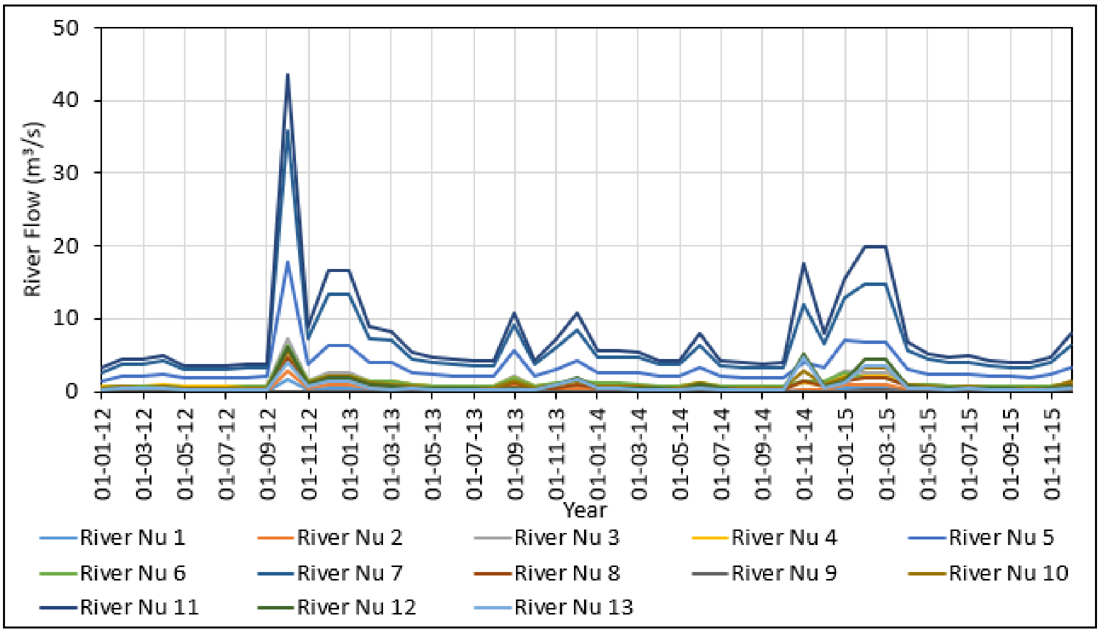


Figure B.27: River Flow at the Final Day of each Month for each River Segment - Validation Period

B.2 Scenario Analysis Results

B.2.1 Comparison of fertilizer related scenarios (Scenario 1, 2 and 3)

B.2.1.1 Comparison of cumulative loading

a) Results of Nitrogen components

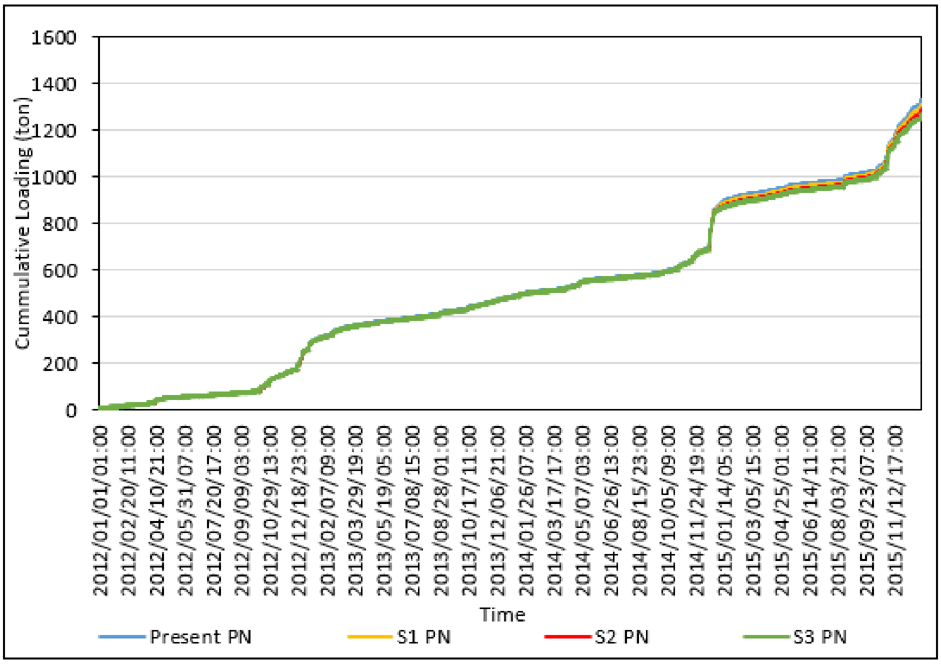


Figure B.28: Cumulative Loading Comparison of All Scenarios with the Present Condition - PN (original in colour)

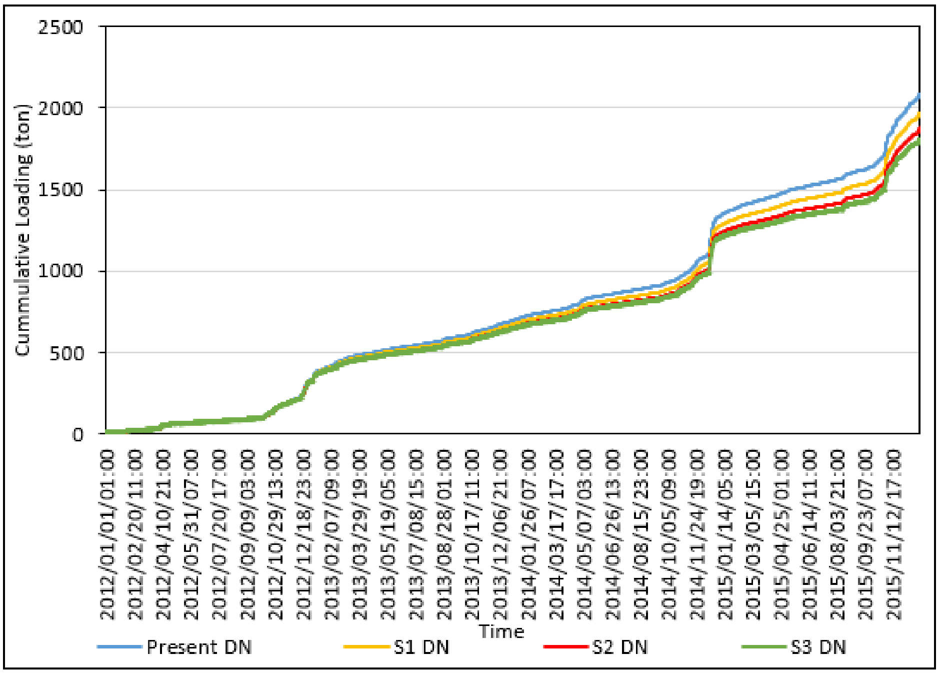


Figure B.29: Cumulative Loading Comparison of All Scenarios with the Present Condition - DN (original in colour)

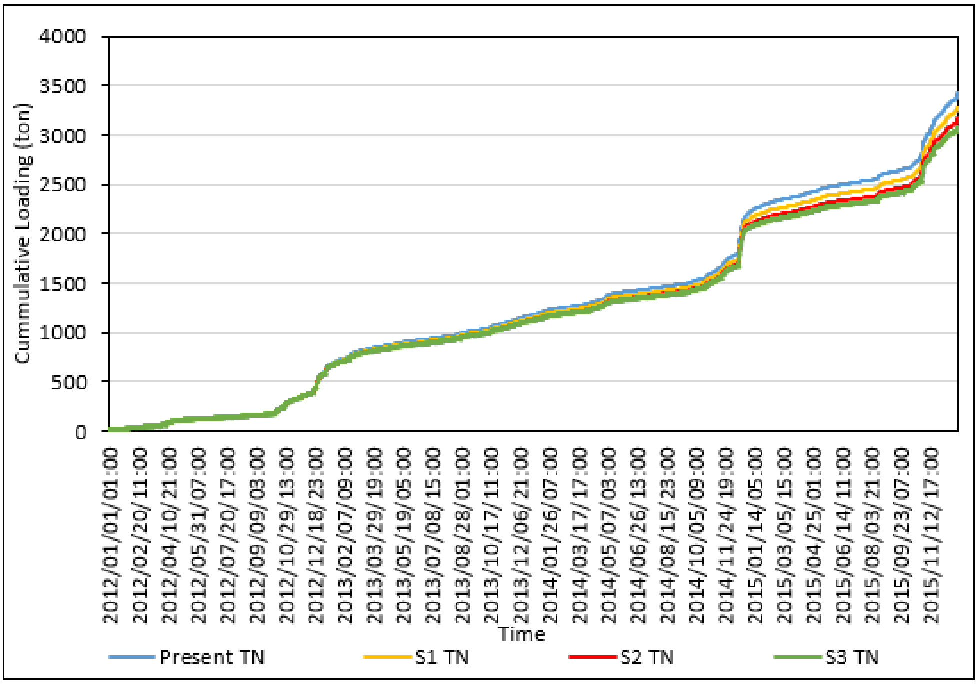


Figure B.30: Cumulative Loading Comparison of All Scenarios with the Present Condition - TN (original in colour)

b) Results of Phosphorus components

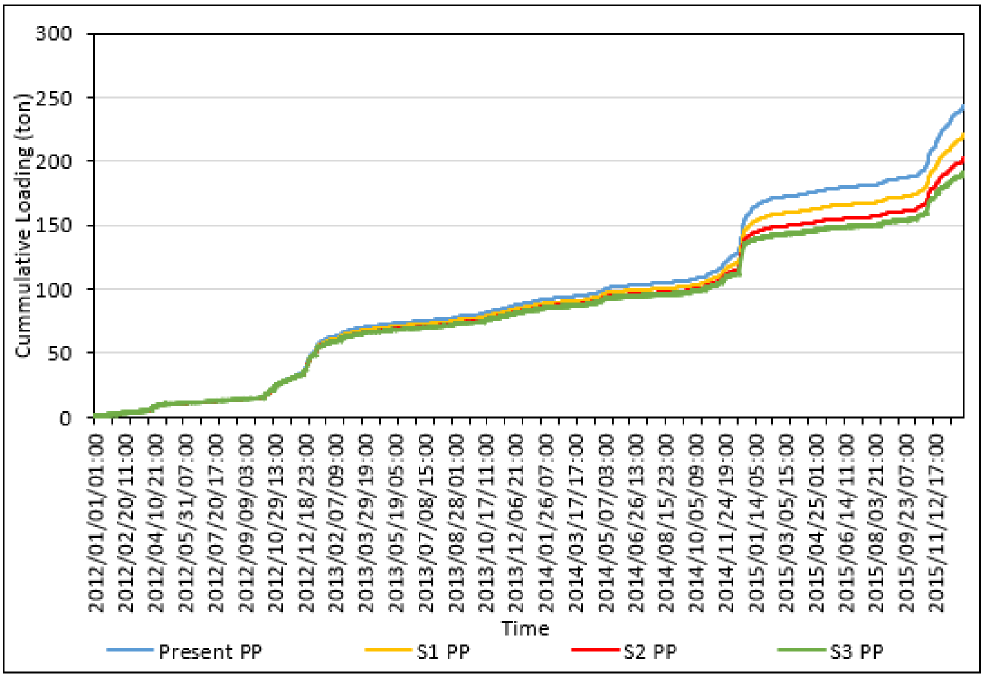


Figure B.31: Cumulative Loading Comparison of All Scenarios with the Present Condition - PP (original in colour)

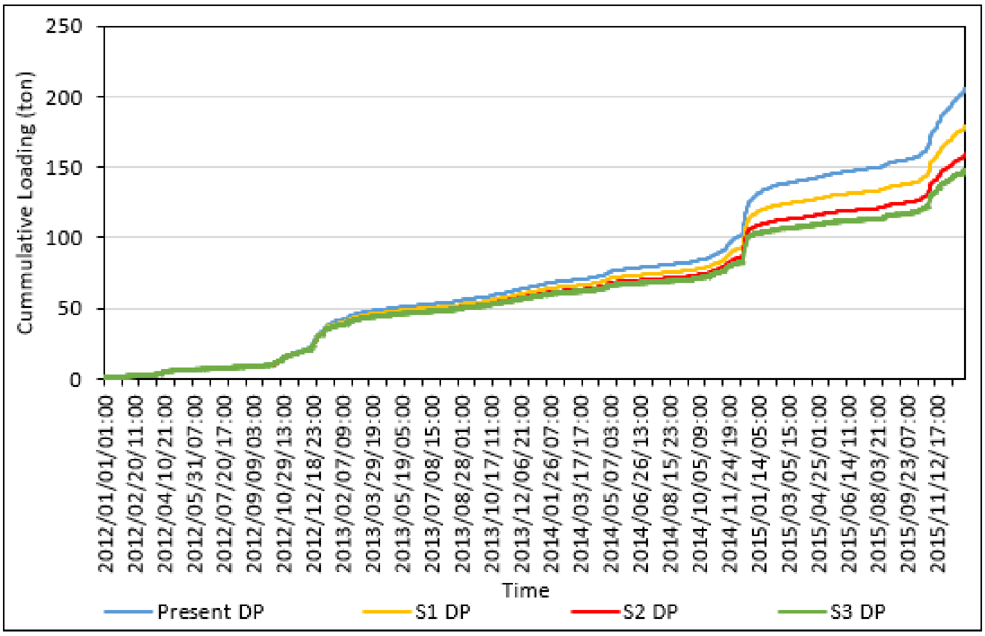


Figure B.32: Cumulative Loading Comparison of All Scenarios with the Present Condition - DP (original in colour)

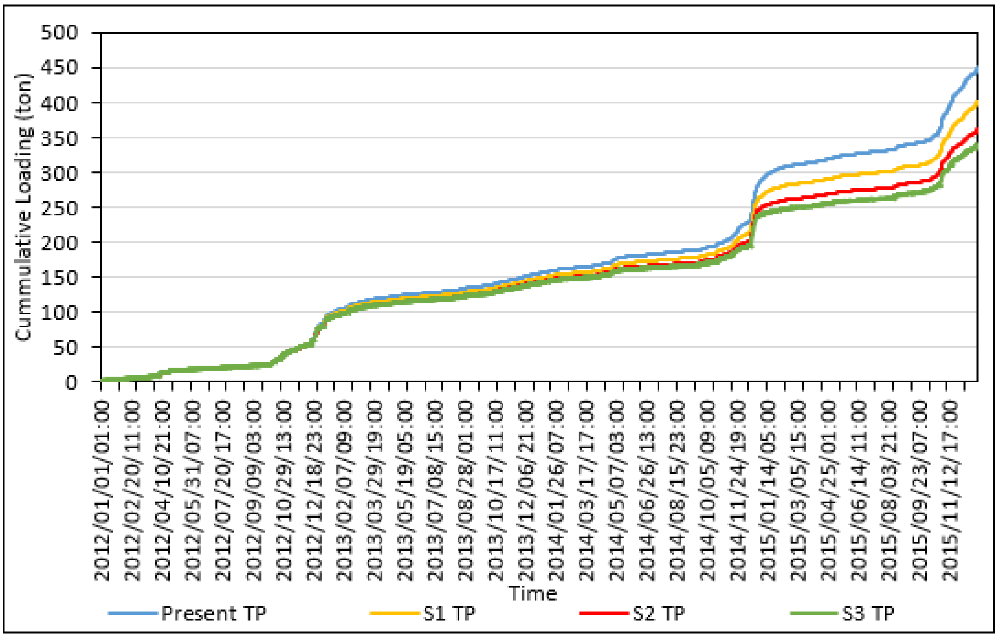


Figure B.33: Cumulative Loading Comparison of All Scenarios with the Present Condition - TP (original in colour)

c) *TSS variation*

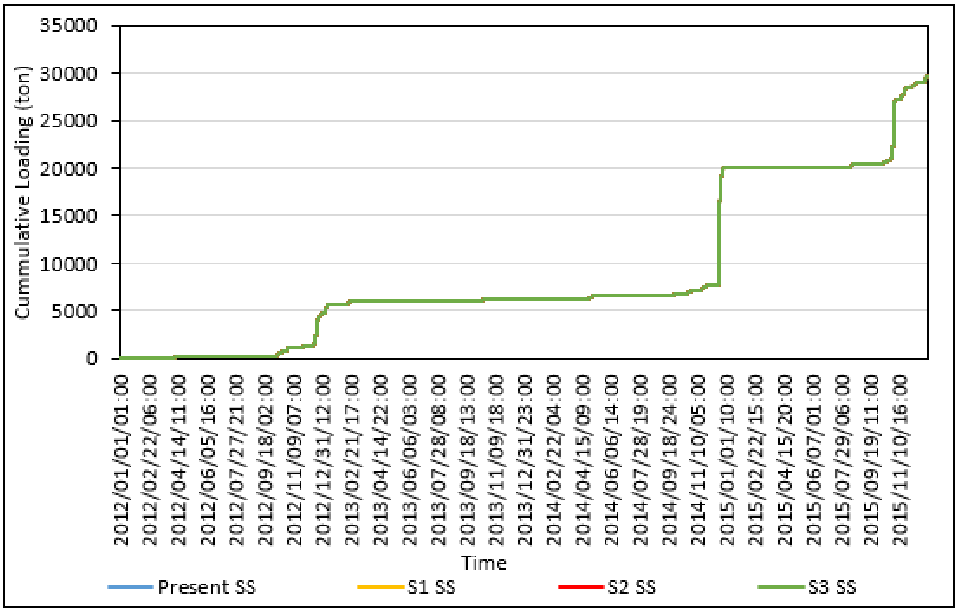


Figure B.34: Cumulative Loading Comparison of All Scenarios with the Present Condition - TSS (original in colour)