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Simulating discharge and contaminant loads from the Waipa Stream catchment under different irrigation scenarios using the SWAT model

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Cover photo:
Irrigated block**,** Puarenga catchment. Photo by Wang Me**.**

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Executive Summary

The water quality of Lake Rotorua has declined over several decades due to increasing inputs of nitrogen (N) and phosphorus (P). Prior to 1991, the Rotorua City wastewater treatment plant was a significant contributor to this decline through direct discharge of treated municipal wastewater to the lake. In 1991 the Rotorua Lakes Council (RLC) halted wastewater discharge to Lake Rotorua and commenced land disposal of treated wastewater by spay irrigation to 193 ha of the Whakarewarewa Forest. It was intended that plant uptake and microbial denitrification would reduce N levels, and P would be removed through absorption and retention to clay soil particles. The aim was to reduce wastewater nutrient loads to the point that wastewater runoff entering the Waipa Stream, and ultimately Lake Rotorua, would have a minimal impact on the trophic state of Lake Rotorua.

Resource consent conditions for wastewater disposal to the Whakarewarewa Forest restricted total nitrogen (TN) and total phosphorus (TP) wastewater losses to the Waipa Stream to 30 tonnes yr^{-1} and 3 tonnes yr^{-1}, respectively. Previous assessments of nutrient losses have indicated some non–compliance with the TN consent limit, there has also been an increase in TP loading to the Waipa Stream since 2002. These increases may be caused by a number of factors including the application rate of wastewater, increases in the nutrient load from non–irrigated areas within the catchment, forest operations not associated with wastewater irrigation and altered rainfall patterns. The Rotorua Lakes Council contracted the University of Waikato to provide an assessment of possible causes for the increased nutrient loading, and to investigate how varying the timing of wastewater irrigation regimes could affect nutrient loading to the Waipa Stream.

The Soil and Water Assessment Tool (SWAT) is a GIS based catchment model used to simulate water fluxes and contaminant transport. The model was parameterised using hydrological and water quality values from relevant literature, and values derived from model auto–calibration within fixed ranges using a Sequential Uncertainty Fitting (SUFI–2) procedure followed by manual adjustment. Model results showed a high correspondence ($r > 0.8$; $p < 0.001$) between measurements and simulations of discharge. However, the model underestimated several peaks of weekly mean TSS load during high rainfall events which were found to be related to harvesting of forest blocks. Underestimates of weekly mean TP peaks were also observed and appeared to be either a lagged response to high rainfall, high TP concentrations in the irrigated wastewater or harvesting of several forest blocks concurrently. Most peaks in hourly routing of NO_3–N and TN loads averaged to weekly time scale also corresponded to high rainfall as well as to high TN concentrations in the wastewater.

The effects of various wastewater irrigation scenarios on downstream water quality were also simulated using SWAT. Daily wastewater irrigation was the most effective scenario for reducing nutrient leaching and avoiding soil nutrient saturation when compared to weekly irrigation (i.e., identical total volume on a weekly basis). Cessation of irrigation on high rainfall days, with reassignment of the irrigation to the first subsequent low–rainfall day, produced unexpected small increases in annual TP (+5%) and TN loading (+2.5%). Simulations of increased area of irrigation or ceasing irrigation resulted in reductions of nutrient loads to the Waipa Stream.

These results indicate that harvesting of plantation forest blocks in the Waipa sub-catchment and wastewater irrigation during high rainfall were contributing to higher than estimated TSS and TP loading to the Waipa Stream. Modelling of variations in wastewater irrigation frequency showed that reductions in TP and TN loadings to the Waipa Stream could be achieved by switching to a programme of daily rather than weekly irrigation and avoidance of irrigation during or the day following heavy rainfall. These findings support the decision to switch irrigation frequency from weekly to daily and are likely to assist in reducing the impact of anthropogenic nutrient loading on Lake Rotorua.

Acknowledgments

We thank the following people and organisations for assistance with data collection: Andy Bruere from Bay of Plenty Regional Council (BoPRC), Alison Lowe from Rotorua Lakes Council (RLC), Penny MacCormick (BoPRC), Kim Lockie (RLC), and Cheryl Hindle from Timberlands Limited. Dr Kit Rutherford is thanked for providing detailed comments. The catchment modelling used SWAT2012 (rev629) developed by Dr Jeff Arnold (the United States Department of Agriculture, Agricultural Research Service) and available as open–source software (http://swat.tamu.edu/).

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Introduction

Across the world, inland cities have sought ways to treat their municipal wastewater effectively and avoid direct disposal of treated effluent into sensitive receiving waters (Raschid–Sally and Jayakody, 2008). An alternate approach to diversion of wastewater from sensitive ecosystems is to implement tertiary treatment to remove nutrients to levels whereby wastewater can still be discharged within the catchment of the affected water body without significantly impairing water quality. The use of forestry areas for wastewater irrigation has increasingly been adopted for this purpose (Kaur *et al.*, 2012). Despite the benefits associated with controlled wastewater irrigation, there are some disadvantages related to potential for soil waterlogging and enrichment, and ensuing nutrient leaching (Farahat and Linderholm, 2015). Forest harvesting can also aggravate erosion and nutrient losses from soils in irrigated areas (Carpenter *et al.*, 1998). For land–based treatment to be sustainable, it is necessary to balance the volume of wastewater applied with uptake rates from trees and losses from processes such as denitrification (Mussely and Goodwin, 2012), so that nutrient losses to runoff and leaching are minimised.

The evaluation of the long–term effectiveness of wastewater irrigation is also very important. Because field experiments are often not feasible, numerical-modelling is generally used to predict potential impacts from a range of irrigation management strategies (Behera and Panda, 2006). The Soil and Water Assessment Tool (SWAT) model was selected for this study due to its ability to simulate different catchment land management practices and to reproduce the temporal-spatial variability in catchment discharge and nutrient loading (Neitsch *et al.*, 2011). The SWAT model was developed through Agricultural Research Services of the United States Department of Agriculture (ARS USDA, Arnold *et al.*, 1998). It uses a GIS (Geographic Information System) platform and requires a digital elevation model (DEM), spatially–distributed land use and soil information, and meteorological data for simulations. SWAT delineates a study catchment and divides it into sub-catchments. The model then creates numerous Hydrologic Response Units (HRUs), each based on specific topographic conditions, land use types and soil properties. Model simulations are at the HRU level, with temporal and spatial variances then summarised for each sub-catchment. SWAT passes sub-catchment output to the relevant stream channel and calculates the in–stream discharge and nutrient transport to the catchment outlet. It requires both distributed and lumped parameters. Some can be derived from the existing data or knowledge gained in other studies. Others need to be assigned during a calibration process (Pechlivanidis *et al.*, 2011).

The study area for this research is one of the Lake Rotorua catchments (Bay of Plenty, North Island, New Zealand). As a nationally iconic water body, Lake Rotorua plays a significant role in recreation and tourism in New Zealand (Hamilton *et al.*, 2012). However, the water quality of Lake Rotorua has declined over several decades due to increasing inputs of N and P (Mueller *et al.*, 2015). Prior to 1991 municipal wastewater treated by the Rotorua Wastewater Treatment Plant was directly discharged to Lake Rotorua. Following concerns about nutrient loading and eutrophication of Lake Rotorua, in–lake wastewater disposal was halted and a programme of land disposal via irrigation of treated wastewater was initiated in 1991. The Rotorua land treatment system (RLTS) receives approximately 21,000 m^{-3} d^{-1} of wastewater (Lowe *et al.*, 2007) which is sprayed over 14 blocks (total area of 193 ha) of the Whakarewarewa plantation forest (Figure 1). Prior to 2002, the irrigation schedule of the RLTS entailed applying wastewater to two blocks per day so that each block was irrigated approximately weekly. Since 2002, 10 to 14 blocks have been irrigated simultaneously at daily frequency. Over recent years, mean nutrient concentrations in the irrigated water have gradually decreased as improvements have been made in the primary treatment of the wastewater (Lowe *et al*., 2007). The RLTS was designed to reduce N concentrations in irrigated wastewater using plant uptake of N or microbial denitrification, and for P to be retained in the soil by adsorption (Hu *et al*., 2007). Nutrients not removed from these processes are discharged from the catchment via the Waipa Stream, ultimately entering Lake Rotorua from the Puarenga Stream. The Waipa Stream catchment (area 16 km^2) is 4.5 km southeast of the Rotorua City and comprises 80% exotic pine forest (*Pinus radiata*). The soil of the catchment is mainly allophanic, sandy and well drained, with 85–95% P retention capacity (Beets *et al.*, 2013).

Resource consent conditions for wastewater disposal to the Whakarewarewa Forest restrict total nitrogen (TN) and total phosphorus (TP) losses to the Waipa Stream to 30 tonnes yr^{-1} and 3 tonnes yr^{-1}, respectively. Previous assessments of nutrient losses have indicated some non–compliance with the TN consent limit and there has been an increase in TP load in the Waipa Stream. These increases may be caused by a number of factors including the application rate of wastewater nutrients, changes in the nutrient load from the non–irrigated areas within the catchment, forest operations not associated with wastewater irrigation and altered rainfall patterns. The Rotorua Lakes Council contracted the University of Waikato to provide an assessment of possible causes for the increased nutrient loading, and to determine how varying the timing of wastewater irrigation regimes could affect nutrient loads in the Waipa Stream.

The SWAT2012 model (rev629) was used to simulate the effects of modifying the wastewater irrigation schedule on the water quality Waipa Stream catchment (Figure 1). Scenarios included increasing and decreasing the area of irrigation, avoiding irrigation on heavy rainfall days and, weekly versus daily irrigation. Modelling of these scenarios will assist with future strategies to mitigate P and N losses from the irrigated area by refining the area, timing and frequency of irrigation.

Methods

Sampling measurements

Monthly instantaneous discharge was measured at the Waipa D/S Hydrometric Station (Figure 1) at the catchment outlet. Weekly mean discharge (Q) and weekly flow–proportional concentrations of suspended sediment (SS), dissolved reactive phosphorus (DRP), total phosphorus (TP), nitrate–nitrogen (NO_3–N), ammonium–nitrogen (NH_4–N), total Kjeldahl nitrogen (TKN; NH_4–N + organic N), and total nitrogen (TN) were also measured by the Bay of Plenty Regional Council. A weekly flow–proportional sampling programme was carried out by the Rotorua Lakes Council using an automatic sampler to collect a single weekly composite sample which combined subsamples collected every 1800 m^3 of discharge. Thus each weekly sample was typically comprised of ~200 subsamples. Weekly contaminant loads were calculated based on weekly flow–proportional concentrations multiplied by weekly mean discharge, and the product was used for model evaluation purposes.

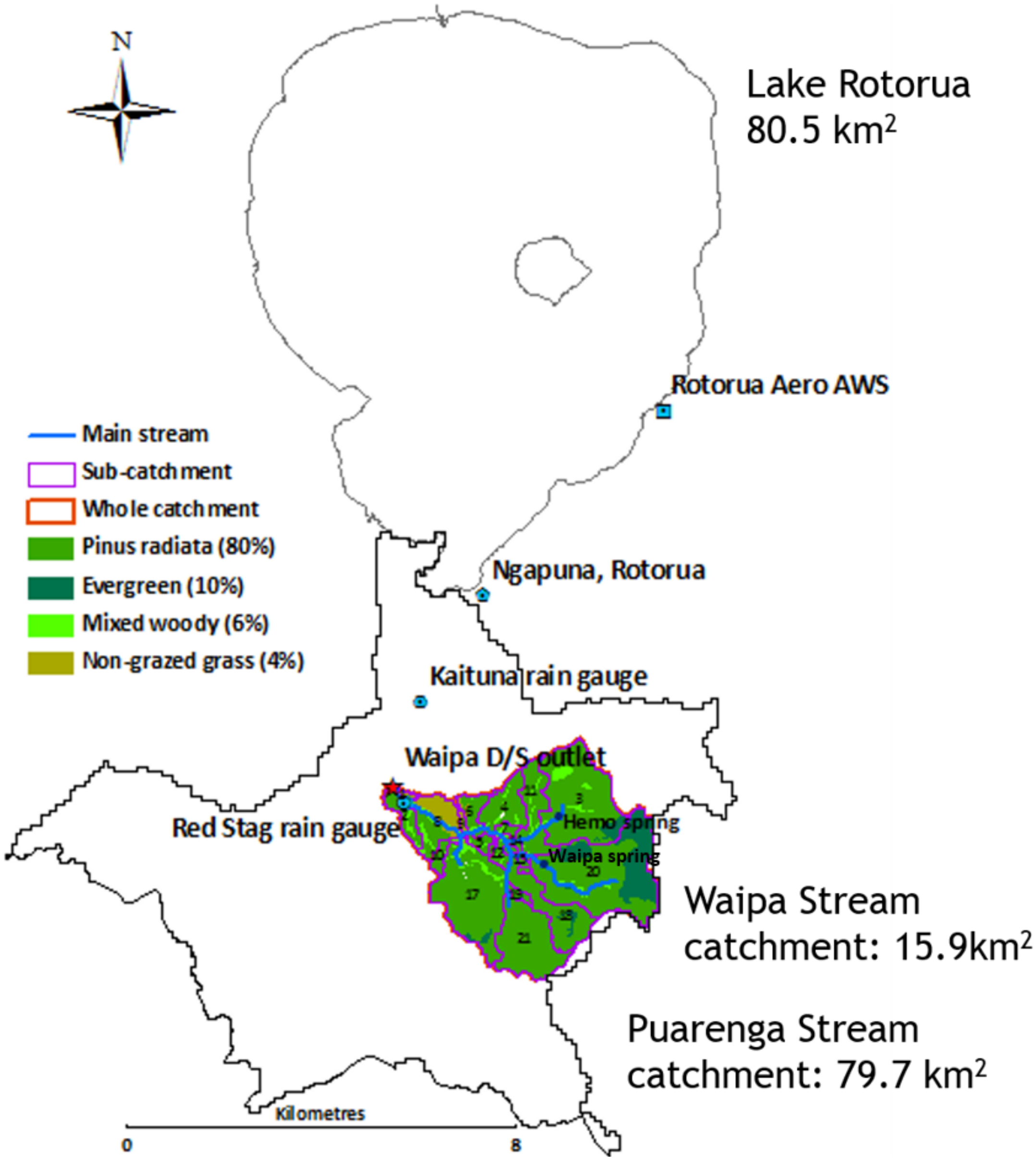

Figure 1: Boundary of Lake Rotorua, Puarenga Stream catchment, Waipa Stream catchment including delineation of 21 subcatchments, main streams and predominant land uses. Locations are shown for the climate station (Rotorua Aero AWS), Red Stag rain gauge, Waipa D/S monitoring station (represented by the red star), Hemo Spring, and Waipa Spring. Photos of some of the sites are shown in Appendix 1.

Model configuration

Catchment delineation

Briefly, key SWAT input data requirements included a digital elevation model (DEM) (25 m horizontal resolution) provided by Bay of Plenty Regional Council (BoPRC); meteorological records (obtained from National Climatic Data Centre); records of spring locations, discharge and water abstraction; a stream map (obtained from BoPRC); soil characteristics derived from S–map (developed by Landcare Research; see http://smap.landcareresearch.co.nz/home); land use classifications (obtained from New Zealand Land Cover Database Version 2, BoPRC), and management schedules for key land uses (i.e., wastewater irrigation and timber harvesting) which were obtained from BoPRC. The DEM was used to delineate boundaries for the whole catchment and individual subcatchments, with a stream map used to “burn–in” channel locations to create accurate flow routings. The Waipa D/S hydrometric station (Figure 1; downstream of the LTS, 537 m upstream of the confluence with the Puarenga Stream) was specified as the most downstream location in the model. Twenty–one subcatchments were represented in the Waipa Stream catchment, each comprising numerous hydrological response units (HRUs). Each HRU aggregates cells with the same combination of land cover, soil, and slope. A total of 441 HRUs was defined in the model. Runoff and nutrient transport were predicted separately by SWAT for each HRU, with predictions summed to obtain the total for each subcatchment. A detailed description of model configuration and parameterisation are given in Me *et al.* (2015).

Meteorological records

The Rotorua Aerodrome automatic weather station (Rotorua Aero AWS) is approximately 9.6 km northeast of Waipa D/S monitoring station (Figure 1). Meteorological data such as daily maximum and minimum temperature, daily mean relative humidity, daily global solar radiation, and daily 0900 h wind speed (10 m elevation) for Rotorua Aero AWS were obtained from the National Climate Database (http://cliflo.niwa.co.nz/) and were input into the SWAT2012 model.

Weekly total precipitation (hereafter "rainfall") data were obtained from the Red Stag rain gauge (Figure 1) located within the study catchment. These data were used together with hourly rainfall measured at the Kaituna rain gauge (Figure 1; ~2 km to the north of the Waipa Stream catchment) to derive hourly rainfall distribution for the Red Stag rain gauge. Hourly rainfall estimates were used as hydrologic forcing data and the hourly rainfall/infiltration (Green & Ampt)/hourly routing method (Arnold et al., 2013) was used to simulate upland and in–stream hydrological processes and nutrient transport.

Monthly mean N concentrations in rainfall (TN: 0.34 mg N L^{-1}) and rainfall recharge (TN: 1.15 mg N L^{-1}, NO_3–N: 0.6 mg N L^{-1}) were measured at Kaharoa (NZMG U15: 970 495; the northern side of Lake Rotorua) during the period of October 2006 to January 2008 (White *et al.*, 2008). Therefore, nitrogen concentration in rainfall required by the SWAT2012 model was assumed as 0.34 mg N L^{-1} for the Waipa Stream catchment. Fish (1976a) analysed mean concentrations of atmospheric deposition of NO_3–N, NH_4–N and DRP carried in sampled total rainfall of 341 mm (14 samples) between July 1972 and March 1974 at Ngapuna, which is approximately 4.5 km north of the Red Stag rain gauge (Figure 1). Fish (1976b) subsequently (April 1974 – April 1975) analysed the nutrients in dry fallout which occurred in the absence of rainfall, in 183 samples. He found no seasonal changes in both wet and dry atmospheric deposition. Parameter values for atmospheric deposition from the analysis by Fish (1976a, b) were used as input for the SWAT2012 model (see Table 1)

Table 1: Values and definitions of parameters for atmospheric deposition used in parameterising the SWAT2012 model, values are based on literature values by Fish (1976a, b).

Variable	Unit	Definition	Value
RCN_SUB	mg L^{-1}	Atmospheric wet deposition of nitrate–nitrogen	0.0215
RAMMO_SUB	mg L^{-1}	Atmospheric wet deposition of ammonium–nitrogen	0.0842
DRYDEP_NO3	kg ha^{-1} d^{-1}	Atmospheric dry deposition of nitrate–nitrogen	0.00024
DRYDEP_NH4	kg ha^{-1} d^{-1}	Atmospheric dry deposition of ammonium–nitrogen	0.00103

Springs and water abstraction

Two springs from pastoral–dominated subcatchments outside the RLTS drain into the Waipa Stream directly and were regarded as point source inputs for the Waipa Stream surface catchment for modelling purposes. Instantaneous flow rate and nutrient concentration at Hemo Spring D/S (Figure 1) and Waipa Spring D/S (Figure 1) were measured monthly by the Rotorua Lakes Council (RLC).

Discharge measurements at Hemo Spring averaged c. 0.159 m^3 s^{-1}. An apparent increase in discharge in recent years (Figure 2) may be related to increased sediment deposition in the bottom of the channel which has contributed to higher water levels, resulting in a change to the rating curve for the site and positive bias in discharge estimates (Alison Lowe, RLC, *pers. comm.*). The flow rate of Hemo Spring was deemed to be constant at 0.159 m^3 s^{-1} for model parameterisation.

Due to municipal water abstraction from Waipa Spring, measured discharge was highly variable (Alison Lowe, RLC, *pers. comm.*), ranging from 0.186 to 0.243 m^3 s^{-1} (Figure 2). Therefore, the mean of higher discharge values (0.22 m^3 s^{-1}) was deemed to be the discharge rate of Waipa Spring during the non–abstraction periods and abstracted monthly mean water volumes were subtracted from this estimated discharge rate during abstraction periods and input to the model.

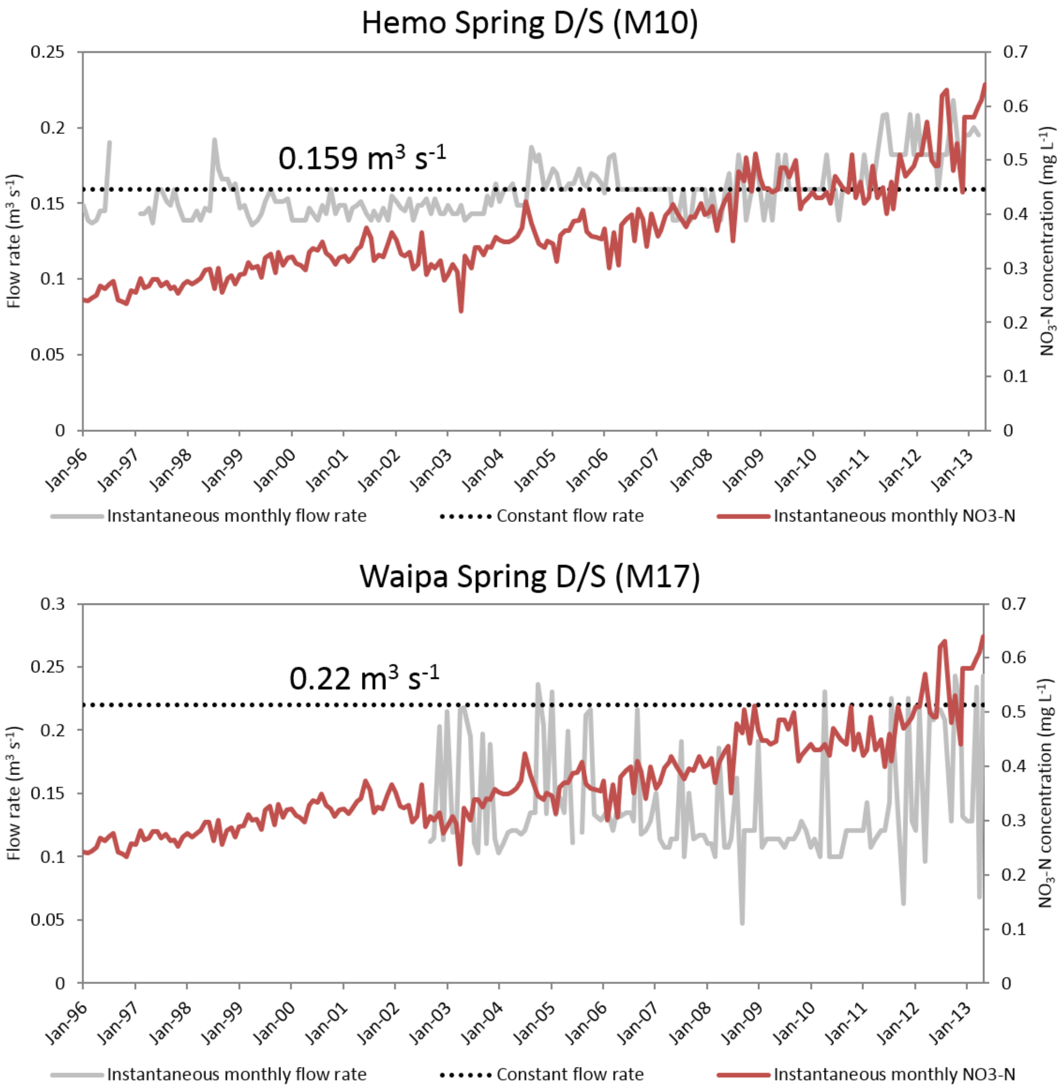

Figure 2: Monthly instantaneous flow rate and nitrate–nitrogen (NO_3–N) concentrations at Hemo Spring D/S and Waipa Spring D/S. Constant flow rates were assumed for the two springs (dashed lines).

Apart from NO_3–N, nutrient concentrations observed at Hemo and Waipa Springs were largely invariable and mean monthly concentrations for the period of 2003–2012 were used as inputs to the model (Table 2). Increases in NO_3–N concentrations over time were observed in both springs (Figure 2). These increases were likely due to infiltration from pastoral subcatchments outside of the spray–irrigated blocks (Alison Lowe, RLC, *pers. comm.*) and were input into the model (see Figure 2).

Table 2: Mean monthly nutrient concentrations (mg L^{-1}) for Hemo Spring and Waipa Springs for total suspended sediment (TSS), organic nitrogen (ORGN), ammonium–nitrogen (NH_4–N), organic phosphorus (ORGP), and dissolved phosphorus (DRP).

Spring	TSS (mg L^{-1})	ORGN (mg L^{-1})	NH_4–N (mg L^{-1})	ORGP (mg L^{-1})	DRP (mg L^{-1})
Hemo Spring	2.5	0.054	0.0034	0.001	0.056
Waipa Spring	2.5	0.042	0.0016	0.001	0.063

Land use classification

New Zealand Land Cover Database Version 2 (LCDB2) represents features of the land surface at 25 m resolution during 2001–02. LCDB2 was obtained from the BoPRC and was used to identify the land–cover categories for the Waipa Stream catchment. Four basic land–cover categories (Figure 1) were identified comprising approximately 80% exotic forest (*Pinus radiata*), 10% indigenous forest (evergreen), 6% mixed woody scrub, and 4% non–grazed grass (combined with a small proportion of urban area).

Some parameter values were estimated *a priori* for the dominant land use category (PINE: *Pinus radiata*) identified in this study (Table 3). The rest of the parameter values originated from the default values relating to plant growth in the SWAT2012 database.

Table 3: Pre–estimated parameter values for the dominant land use category identified in the Waipa Stream catchment. Values of other parameters were based on the default values in the SWAT2012 database

Land use type	Parameter	Definition	Value	Source
PINE (*Pinus radiata*)	HVSTI	Percentage of biomass harvested	0.75	Peter Beet, *pers. comm.*
	T_OPT (°C)	Optimal temperature for plant growth	19	Kirschbaum and Watt, 2011
	T_BASE (°C)	Minimum temperature for plant growth	6	Kirschbaum and Watt, 2011
	MAT_YRS	Number of years to reach full development	18	Alison Lowe, *pers. comm.*
	BMX_TREES (tonnes ha^{-1})	Maximum biomass carbon for a forest	400	Bi *et al*., 2010
	GSI ($m\ s^{-1}$)	Maximum stomatal conductance	0.00198	Whitehead *et al.*, 1994
	BLAI ($m^2\ m^{-2}$)	Maximum leaf area index	5.2	Watt *et al*., 2008
	BP3	Proportion of P in biomass carbon at maturity	0.000163	Hopmans and Elms, 2009
	BN3	Proportion of N in biomass carbon at maturity	0.00139	Hopmans and Elms, 2009

Management schedules

The 16 forested blocks where wastewater was spray–irrigated were manually digitised (Figure 3) based on maps provided by the LTS operators. Two blocks sit outside the Waipa Stream catchment delineated by SWAT and the remaining 14 blocks within the catchment were configured with management schedules in SWAT (Figure 3). Daily volume of treated municipal wastewater was recorded. Nutrients in the irrigated wastewater were represented in SWAT as fertiliser inputs, with a daily irrigated wastewater composition configured from monthly mean concentrations measured in 7–day composite samples.

Prior to 2002, one or two blocks were irrigated daily and the irrigation schedule rotated on a weekly cycle (i.e., two blocks were irrigated for one day, another two blocks were irrigated on the following day, etc.). Since 2002, 10–14 blocks have been irrigated on any given day. This meant that the total amount of irrigated wastewater was applied to a larger area, resulting in a lower areal application rate (Alison Lowe, RLC, *pers. comm.*). The fraction of surface runoff from the irrigated–wastewater draining from the sprayed block was estimated based on a digital filter method (Eckhardt filter) using the Hydrograph Analysis Tool (Lim *et al*., 2005). The remaining irrigated–wastewater was assumed to have infiltrated the soil.

Configuration of forest harvest operations was based on annual harvesting data provided by forestry managers. We assumed that *P. radiata* was well developed in the Waipa Stream catchment at the beginning of the simulation period. *Pinus radiata* trees are generally harvested at approximately 18 years of age and it takes one year for completion of harvesting operations (Alison Lowe, RLC, *pers. comm*.). Only one to three forested blocks were harvested at a time.

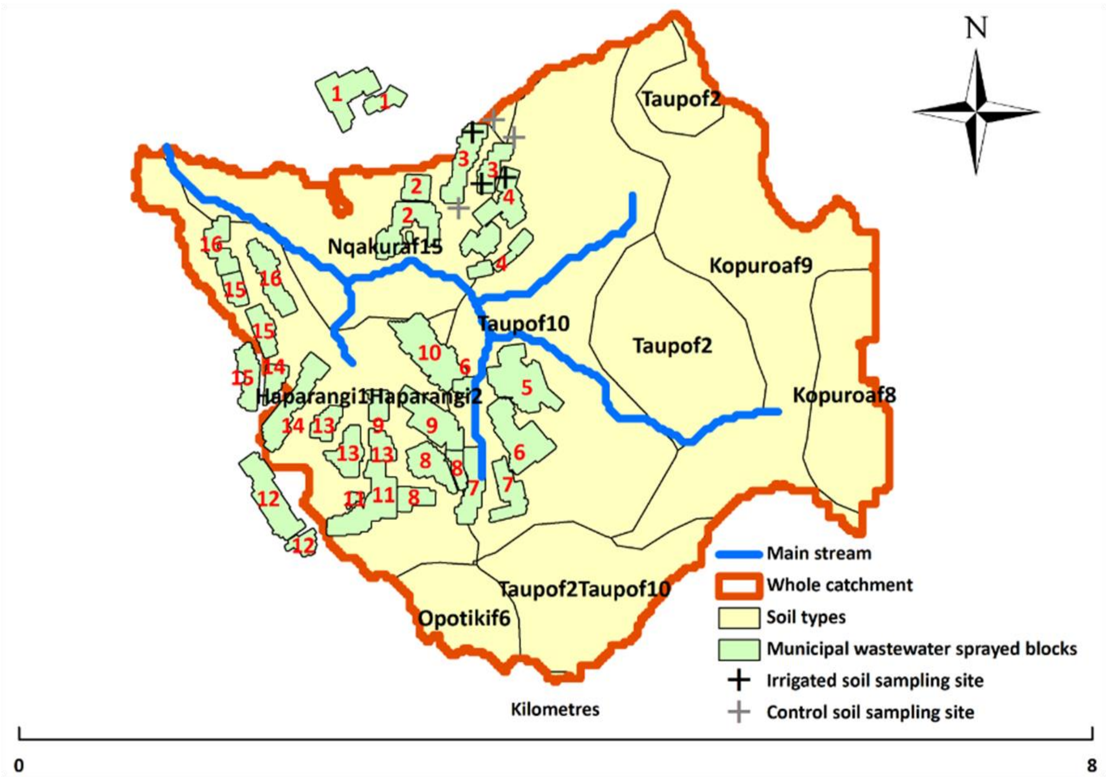

Figure 3: Locations of 16 treated municipal wastewater irrigated blocks. Two blocks sit outside the Waipa Stream catchment delineated by SWAT and the remaining 14 blocks that are within the catchment were configured in SWAT. Areal extents of eight soil types referred to online S–map. Soil samplings were taken at both controlled and irrigation sites.

Soil parameterization

Physical soil properties required to parameterise the SWAT2012 model (see Appendix 2) were obtained from the New Zealand Land Resource Inventory (NZLRI) and digital soil map (S–map) online tool (http://smap.landcareresearch.co.nz). Soil polygons from S–map were manually digitized for their areal extents and the resulting eight soil types were presented for the Waipa Stream catchment. Soil chemical properties were derived from Beets *et al*. (2013) who measured N and P at six permanent soil sampling sites in 2012 (Figure 3).

Parameter sensitivity and calibration

Values of SWAT2012 parameters were assigned based on (i) measured data (e.g., soil parameters), (ii) literature values from published studies of similar catchments, or (iii) auto–calibration followed by manual adjustment where parameters were not otherwise prescribed.

The SWAT2012 model was run from 2002 to 2012, i.e., for the period following a change from daily to weekly irrigation of each block. The first year (2002) was used for model 'warm–up'. The calibration period was from 2003 to 2010 and the validation period was from 2011 to 2012.

A one–at a–time (OAT) routine proposed by Morris (1991) was applied to examine parameter sensitivity for each simulated variable, i.e., Q, SS, ORGP, mineral P (MINP), ORGN, NH_4–N, and NO_3–N.

A Sequential Uncertainty Fitting (SUFI–2) procedure integrated with the SWAT Calibration and Uncertainty Program (SWAT–CUP) (Abbaspour *et al.*, 2004) was applied to auto–calibrate discharge by comparing monthly instantaneous discharge measurements made at the Waipa downstream monitoring station with simulated daily mean discharge for corresponding days. This program performs auto–calibration to minimize model error based on an objective function selected by the user. The version SWAT–CUP 5.1.6.2 was used in this study. The SWAT–CUP program, using the SWAT2012 outputs at daily, monthly, or yearly time steps, is not able to be used for weekly data comparisons. Therefore, hydrological parameters were calibrated manually based on the weekly mean measurements of discharge. Water quality parameters for simulations of SS, ORGP, MINP, ORGN, NH_4–N, and NO_3–N loads were also manually calibrated using weekly flow–proportional sampling loads.

Model evaluation

Model evaluation was based on the comparisons between weekly and monthly mean simulations and measurements for discharge and SS, TP, TN, NO_3–N loads. Model goodness–of–fit between simulated outputs and observations was initially assessed graphically and then quantified using two commonly–used model evaluation statistics (Moriasi *et al.*, 2007), Pearson product moment correlation coefficient (*r*) and percent bias (PBIAS). Values of *r* indicate the degree of linear relationship between simulated and measured data. Values of *r* were deemed statistically significant for values of $p < 0.05$ (Bewick *et al.*, 2003). PBIAS indicates the average tendency for model predictions to be larger or smaller than observations. Definitions and statistical inferences are shown in Table 4.

Table 4: Statistics used to evaluate model performance. Note: o_n is the n^{th} observed datum, s_n is the n^{th} simulated datum, $\bar{o}$ is the observed mean value, $\bar{s}$ is the simulated daily mean value, and N is the total number of observed data

Statistic	Definition	Features
Pearson product moment correlation coefficient	$r = \frac{\sum_{n=1}^{N}[(o_n - \bar{o})(s_n - \bar{s})]}{\sqrt{\sum_{n=1}^{N}(o_n - \bar{o})^2 \times \sum_{n=1}^{N}(s_n - \bar{s})^2}}$	Range from -1 to 1. The value of 0 indicates no linear relationship, while the value of 1 or -1 indicates a perfect positive or negative linear relationship between simulated and measured data.
Percent bias Statistic	$\text{PBIAS\%} = \frac{\sum_{n=1}^{N}(o_n - s_n)}{\sum_{n=1}^{N} o_n} \times 100\%$	A value of 0 indicates a perfect fit. Positive values indicate model underestimates and negative values indicate model overestimates.

Management scenarios

Five different treated municipal wastewater irrigation scenarios were simulated to evaluate impacts of (i) 10–14 forestry blocks irrigated daily (actual irrigation scenario), (ii) decreased irrigated area, (iii) irrigation on low rainfall days, (iv) weekly irrigation, and (v) no irrigation. Specifications for each of these scenarios are given in Table 5. The effects of different treated municipal wastewater irrigation scenarios on nutrient yields from the Waipa Stream catchment were analysed using the percentage change of a multi–year mean of annual nutrient loads aggregated from SWAT2012 daily outputs, compared with the simulations under the actual irrigation scenario.

Table 5: Descriptions of modelled wastewater irrigation scenarios using SWAT2012

Scenario	Purpose	Specification
(i) 10–14 blocks irrigated daily	Evaluate effects of the actual irrigation scenario	Wastewater applied to 10 blocks or 14 blocks on different soil types within the land treatment system for the period 2003–2012
(ii) Decreased irrigated area	Evaluate effects of decreasing the size of the irrigated area	Wastewater applied to either eight blocks (122 ha), four blocks (61 ha) or two blocks (26 ha) on the same soil type ('Haparangi 1 and 2') in 2003–2012
(iii) Irrigation on low rainfall days	Evaluate interactions between irrigation and rainfall	Irrigation during high rainfall days (≥ 20 mm d^{-1}) in 2003–2012 reassigned to the first subsequent low rainfall day (< 20 mm d^{-1}). For periods with multiple consecutive high rainfall days (maximum = 3 days), the combined total irrigation was reassigned from high rainfall days to the first subsequent low rainfall day
(iv) Weekly irrigation	Evaluate effect of reducing irrigation frequency	Weekly irrigation frequency for 2003–2012, i.e., total weekly wastewater was irrigated on the first day of a week and no irrigation was undertaken on the remaining days in that week
(v) No irrigation	Examine effect of no irrigation	No irrigation for the period 2003–2012

Results

Optimised parameters and model performance

The optimised values of the most sensitive parameters, based on (i) measured data (e.g., soil parameters), ii) fixed values from the literature of similar catchments, or iii) auto–calibration followed by manual adjustment, are shown in Appendix 3 for the following variables: Q, SS, ORGP, MINP, ORGN, NH_4–N, and NO_3–N. Parameter values were assigned for the whole catchment.

Simulations of discharge averaged to weekly time scale showed large fluctuations (Figure 4a) and provided strong correlations with weekly mean discharge measurements ($r > 0.8$, $p < 0.001$; Table 6). Weekly mean discharge peaks corresponding to high rainfall (weekly mean ≥ 20 mm d^{-1}) tended to be overestimated by the SWAT2012 model (see PBIAS in Table 6).

The SWAT2012 model underestimated several peaks of weekly mean TSS load during high rainfall events. The underestimates were found either during or after a large number of forestry blocks had been harvested (Figure 4b). However, the modelled simulations gave positive correlations with the measured weekly mean TSS load ($r > 0.4$, $p < 0.001$; Table 6).

Figure 4c shows that simulated TP load averaged to weekly time scale aligned well with the monitoring data prior to 2007, however the SWAT2012 model underestimated the weekly mean TP concentrations after 2007 (see PBIAS in Table 6). Underestimates of weekly mean TP peaks appeared to be either a lagged response to either high rainfall, high TP concentrations in wastewater or concurrent harvesting of several forestry blocks (Figure 4c).

Figure 5a–b indicates that most peaks in the simulations of NO_3–N and TN loads averaged to weekly time scale also corresponded to high rainfall as well as to high wastewater TN concentrations. Daily simulations of NO_3–N and TN loads averaged to weekly values were also strongly correlated ($r > 0.5$, $p < 0.001$; Table 6) with measurements.

Table 6: Statistical values of Pearson product moment correlation coefficient (*r*) and percent bias (PBIAS) used to indicate the SWAT model performance for daily simulations averaged to weekly time scale of discharge (Q), loads of total suspended sediment (TSS), total phosphorus (TP), nitrate–nitrogen (NO_3–N) and total nitrogen (TN). The significance of all correlation is $p < 0.001$

Simulation period	Statistics	Q	TSS	TP	NO_3–N	TN
Calibration (2003–2010)	*r*	0.81	0.43	0.45	0.57	0.73
	PBIAS%	-7.4	-17.9	22.5	11.3	12.4
Validation (2011–2012)	*r*	0.83	0.54	0.54	0.63	0.82
	PBIAS%	-5.2	-21.7	26.9	13.1	10.1

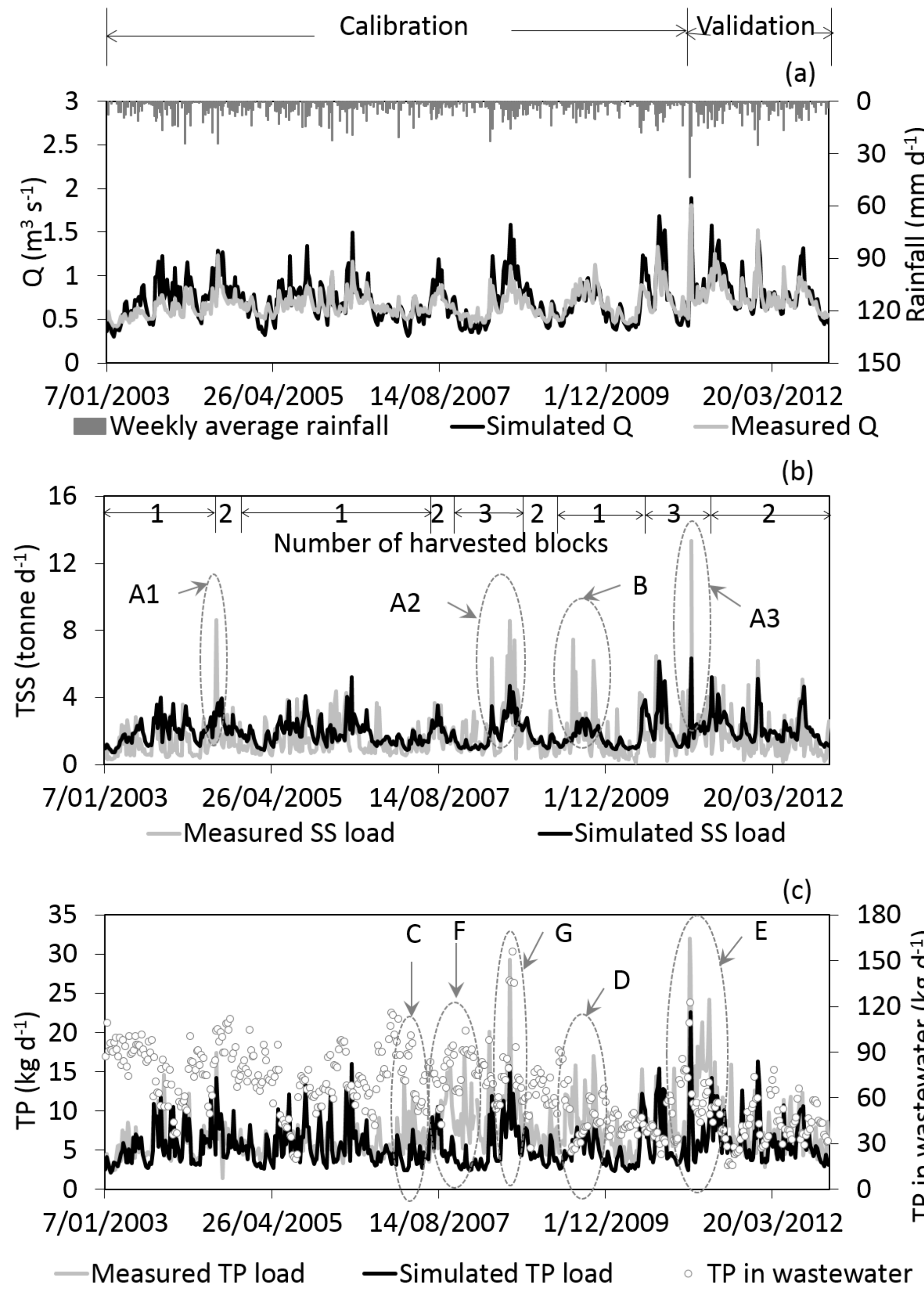

Figure 4: Comparison of weekly mean values derived from daily simulated with weekly mean measured (a) Q (discharge) and loads of (b) TSS (total suspended sediment), and (c) TP (total phosphorus) at Waipa D/S. The calibration period was from 2003 to 2010 and the validation period was from 2011 to 2012. The model underestimated TSS peaks when high rainfall occurred either during (A1–A3) or after (B) harvest of multiple blocks, as indicated by the number of harvested blocks in (b). Underestimates of TP peaks were related to a lagged response to high rainfall only (C), high rainfall following (D) or during (E) harvest of 2–3 blocks, only during harvest of more blocks without high rainfall (F), and high TP in wastewater during harvest of multiple blocks at once (G), as indicated by the number of harvested blocks in (c).

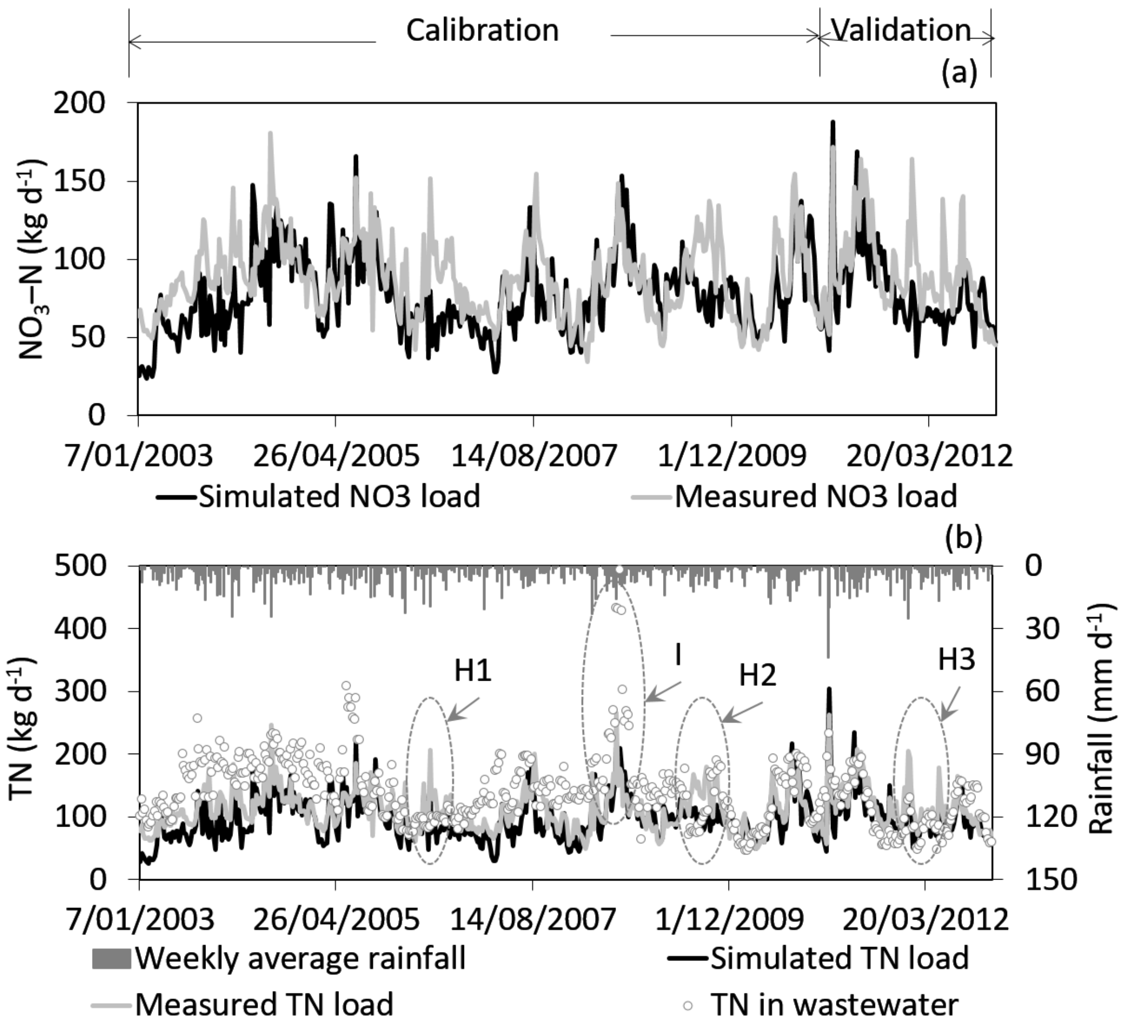

Figure 5: Comparison of weekly mean values derived from daily simulated with measured loads of (a) NO_3–N (nitrate–nitrogen) and (b) TN (total nitrogen) at Waipa D/S. The calibration period was from 2003 to 2010 and the validation period was from 2011 to 2012. Several underestimates of peaks in TN load were related to consecutive wet days (H1–H3) and high TN in wastewater (I).

Irrigation scenarios simulations

Irrigation scenarios are presented in Figure 6 as multi–year (2003–2012) means of annual nutrient loads aggregated from SWAT2012 daily outputs. Under the actual irrigation scenario (10–14 blocks irrigated daily), simulated multi–year mean TP load was 2 t yr^{-1} and TN load was 35.8 t yr^{-1} in the Waipa Stream. Compared with measured loading in the Waipa Stream, annual TP load was underestimated by 26% and annual TN load was underestimated by 12%.

The highest simulated nutrient loads occurred with decreasing the irrigated area from 10–14 blocks to two blocks (Figure 6). Compared with the simulations under the actual irrigation scenario, wastewater irrigation to only two blocks accounted for the largest increase in the annual nutrient load, i.e., annual TP load increased by 20% and annual TN load increased by 88%.

Simulations of annual mean nutrient loads under the scenario of irrigation reassigned from high rainfall days (≥ 20 mm d^{-1}) to low rainfall days (< 20 mm d^{-1}) showed a small unexpected increase compared with the actual irrigation scenario (Figure 6). For example, annual TP load increased by 5% and annual TN load increased by 2.5%.

Simulations of annual mean nutrient loads under the scenario of reducing irrigation frequency to weekly on 1 day each week, increased TN load by 2.5% from the simulations under the actual irrigation scenario, while almost no change was found in TP load (Figure 6).

Simulations of annual mean nutrient loads under the scenario of no irrigation gave a 66% decrease in TN load and 10% in TP load compared with the actual irrigation scenario (Figure 6). Figure 7 shows that it took ca. 9 months for NO_3–N load to decrease to within about 20% of its pre–irrigation values after irrigation ceased.

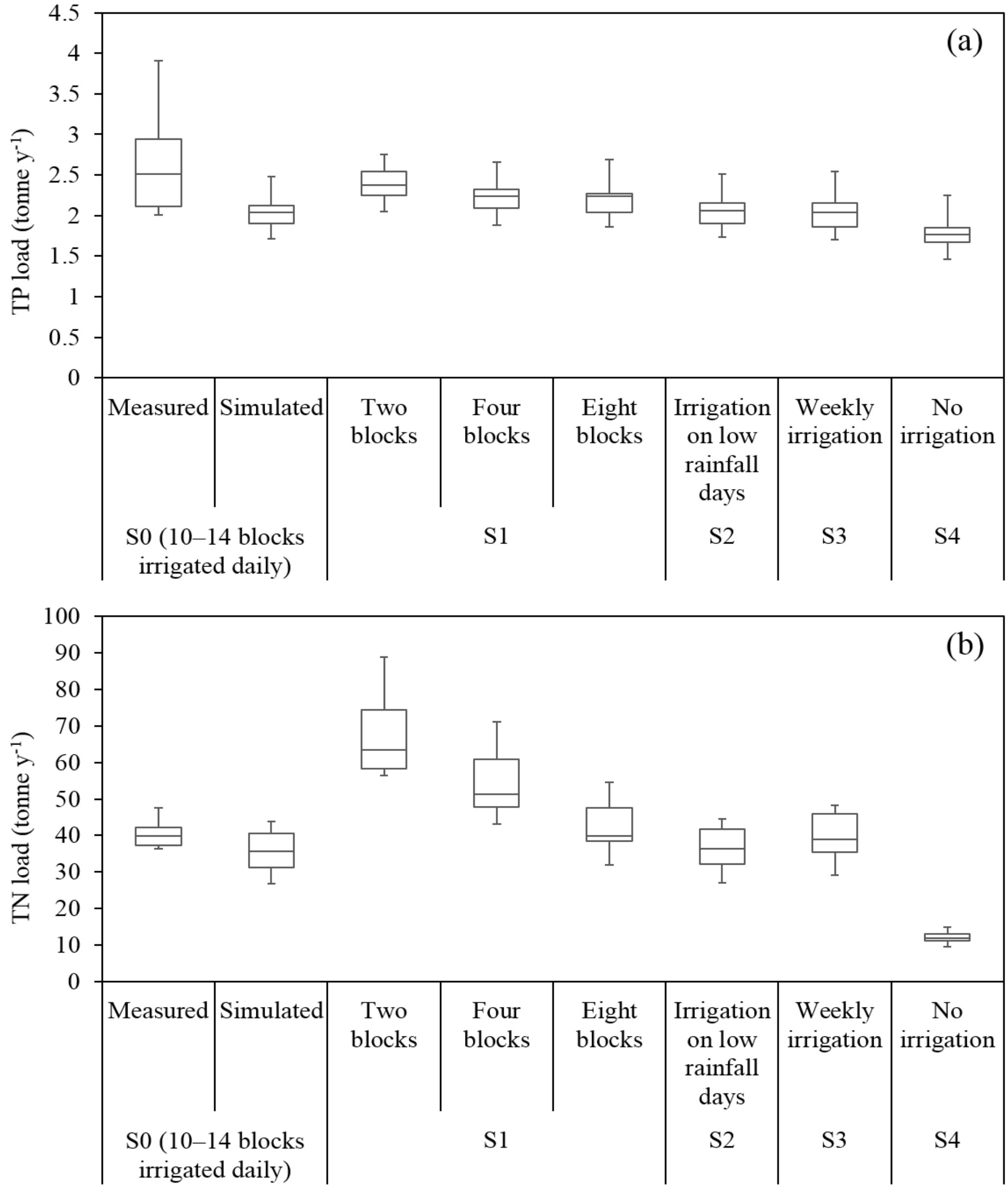

Figure 6: Multiyear (2003–2012) mean of total annual measured and simulated (a) total phosphorus (TP) and (b) total nitrogen (TN). S0 is 10–14 blocks irrigated daily, S1 is decreased irrigated area, S2 is reassigned irrigation from high rainfall (≥ 20 mm d^{-1}) days to low rainfall days, S3 is reduced irrigation frequency to one day per week and S4 is no irrigation. Boxes denote interquartile ranges (i.e., 25% and 75%); whiskers denote minimum and maximum values; horizontal lines denote median values.

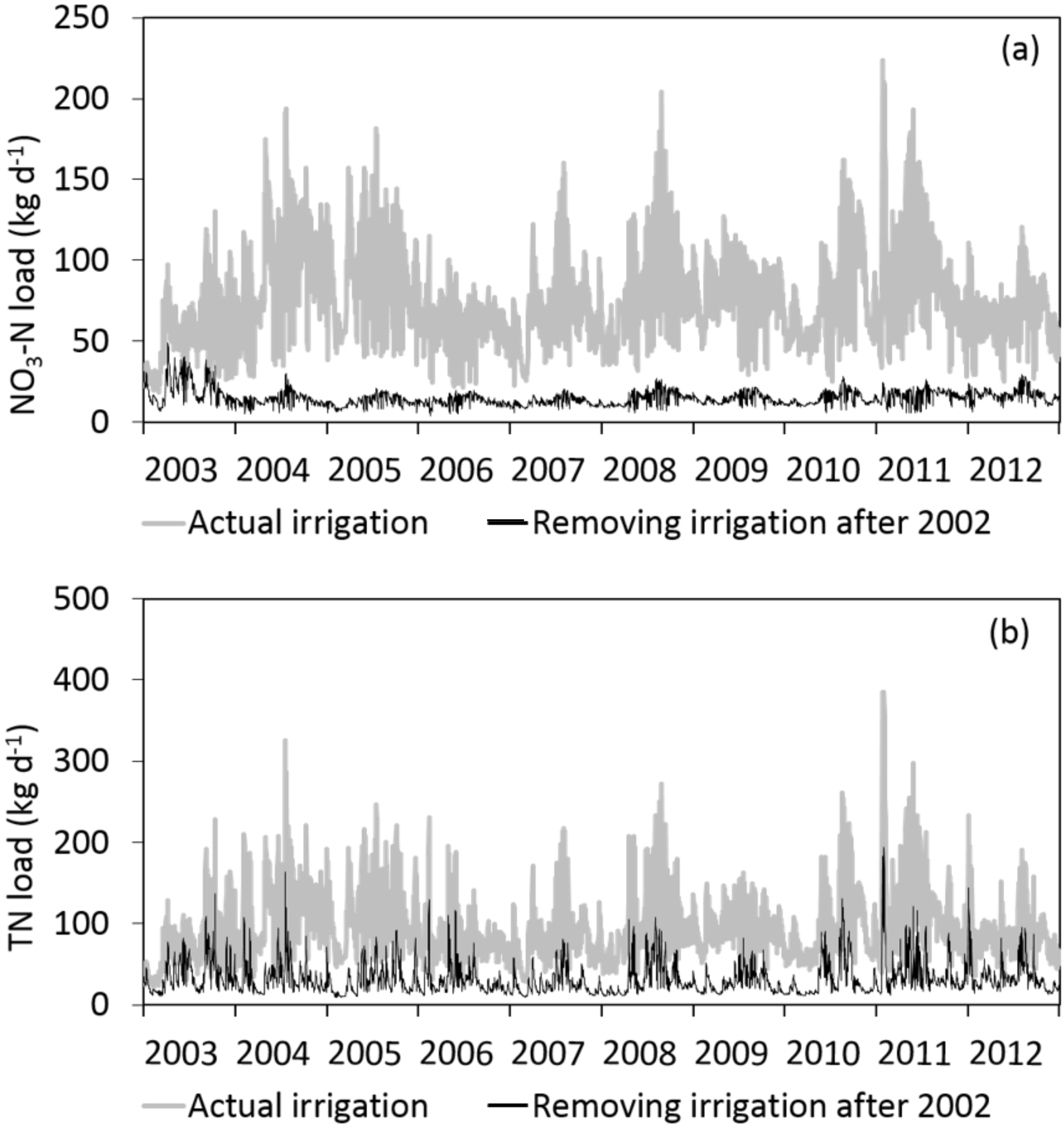

Figure 7: Daily mean load simulations of (a) nitrate–nitrogen (NO_3–N) and (b) total nitrogen (TN) under actual irrigation and no irrigation.

Discussion

The disposal of treated wastewater for forest irrigation has become commonplace around the world (Braatz and Kandiah, 1996), however, there are few evaluations of downstream environmental impacts of this practice (e.g., Pisinaras *et al.*, 2010; Aouissi *et al.*, 2014). Stream discharge and nutrient concentrations will be impacted by land disposal of wastewater which, in turn, will impact aquatic ecosystems downstream (Bouwman *et al.*, 2013). Therefore, determining the optimal strategies for wastewater irrigation that minimises nutrient runoff and is ecologically sustainable in the catchment and downstream systems is critical to supporting the disposal programme. The SWAT2012 model was used to model the Waipa Stream catchment in order to simulate a complex irrigation operation involving different spatial and temporal irrigation regimes. Simulated and measured weekly mean discharge, TSS, TP and TN loads were examined to evaluate impacts of alternative wastewater irrigation management regimes.

Impacts of management practices

In terms of model scenarios, the greatest increase in nutrient loads occurred with decreasing the irrigated area from 10–14 blocks to two blocks, yet maintaining the total irrigated volume unchanged. Irrigation applied on two upstream blocks accounted for an annual TP load increase of 20% and an annual TN load increase of 88%. Using the reverse scenario, increasing the area of wastewater irrigation (i.e., from two blocks to 14 blocks) could be expected to decrease nutrient loads by 20% for TP and 88% for TN reaching the Waipa Stream.

It is not unexpected that there was little change in P percolation and leaching into the stream with changing irrigation frequency from daily to weekly, as the soil P adsorption rate (P retention rate) value in SWAT2012 is not distributed through soil profiles (Arnold *et al.*, 2013). By contrast, the hydraulic conductivity mechanism of the SWAT2012 model varies through the soil profile, therefore P leaching can be expected to increase with weekly irrigation and saturation of surface soils, resulting in increases in stream TP loading. The results of reassigning irrigation during high rainfall days (maximum = three days) to the first subsequent low rainfall day produced effects similar to the scenario of low–frequency and/or high–rate wastewater application. Surface soil layers become saturated at higher application rates, leading to increased P percolation and leaching into the stream, producing a small (5%) increase in annual TP load.

Annual TN load increased considerably under weekly irrigation due to rapid leaching of NO_3–N through the soil profile. Compared with weekly irrigation, the current strategy of daily wastewater irrigation minimises N leaching and reduces saturation of the soil subsurface layer. Magesan *et al.* (1998) investigated nitrate leaching through volcanic and allophanic soil in the Waipa Stream catchment during 1992–1996, when irrigation frequency was weekly. They estimated about half of the NO_3–N load was leached and the rest was adsorbed by the allophanic soils which have a net positive charge. During the period of 2003–2012 when wastewater was irrigated daily on the forestry area, downstream measurements showed that ca. 30% of the wastewater N load from was lost to the stream. This is lower than the amount reported by Magesan *et al.* (1998) but comparable to SWAT2012 simulations (35% lost to the stream). The differences between in–stream nitrogen measurements undertaken during two irrigation regimes (weekly vs. daily) are consistent with modelling, showing decreased in–stream TN loads under daily irrigation. In stream TN load could also be decreased by increasing the irrigated area, thereby facilitating N losses to plant uptake and denitrification (Magesan *et al.,* 1998).

The Rotorua Lakes Council resource consent conditions restrict nutrient inputs into the Waipa Stream to 30 tonnes TN yr^{-1} and 3 tonnes TP yr^{-1} (Park and Holst, 2009). Removing irrigation completely was modelled in this study as the most effective approach to reducing nutrient loads. The Rotorua Lakes Council has committed to ceasing irrigation to the Whakarewarewa Forest by 2018, although there has been no decision on an alternate method of disposal of wastewater. Monitoring following irrigation removal can be expected to provide a robust test of model performance, particularly with respect to the duration over which NO_3–N concentrations can be expected to decrease in the Waipa Stream and to investigate deep groundwater legacy N contamination and persistence.

Evaluation of model performance

Higher standard deviations in the hourly routing model appear to be related to capturing the high variability of SS in small catchments that may tend to be "flashy" (Abell *et al.*, 2013).

However, the SWAT2012 model did not adequately capture the observed increases in stream TP loads during or following concurrent harvest of several forest blocks. This suggests that algorithms for overland erosion processes that mobilise P may need to be developed or refined for this purpose, i.e., in response to temporal and spatial variance in episodic events. The SWAT2012 model underestimated TP load in the stream after 2007, suggesting the algorithms did not perform well in representing processes associated with extended periods of wastewater irrigation, e.g., the build–up of P in the soil, the potential leaching of P into the groundwater system, and ultimately into the stream receiving waters (Beets *et al.*, 2013). In addition, the fixed parameter values utilized in the SWAT model appear to have been unable to adequately reproduce the expected high export of P from soils in response to shifting harvest areas and the soil legacy P built up from long–term wastewater application.

Simulated TN loads were found to be responsive to rainfall events and applied volume of wastewater. However, the SWAT2012 model only simulates shallow subsurface groundwater that ultimately contributes lateral flow to stream tributaries, it does not simulate deep groundwater. Therefore, how legacy N accumulated in deep groundwater from the prolonged (c. 5–year) wastewater irrigation needs to be considered in terms of its effects on N concentrations in the Waipa Stream. Improvements in groundwater processes in SWAT2012 (e.g., an embedded groundwater module MODFLOW) would likely capture the leaching process (Guzman *et al.*, 2015).

Conclusions

Alternative scenarios for managing and optimising the wastewater irrigation were modelled with respect to reducing nutrient losses to waterways from the irrigation area. Wastewater irrigation at daily frequency was the most effective way to reduce nutrient leaching and avoid soil saturation, compared with irrigation at weekly frequency (i.e., identical total volume on a weekly basis). The higher volume of each wastewater application for weekly irrigation increased nutrient percolation and leaching into the stream (see also Beets *et al.*, 2013). No irrigation on high rainfall days, with reassignment to the first subsequent low–rainfall day, also reduced nutrient losses from the irrigated area despite the increase in volume immediately following rainfall delay. Other cases of increasing the irrigated area or ceasing irrigation altogether produced the expected reduction in nutrient loads to the Waipa Stream which drains the irrigated area.

The increases in TP load observed during or following forest block harvesting were underestimated by the SWAT2012 model. Parameters relevant to soil enrichment by P determine the amount of both organic and mineral P which is attached to sediments that are eroded and enter the stream channel. This erosion will vary temporally and spatially, particularly in response to environmental drivers such as forest harvesting. The constant value of the soil erodibility factor used to simulate TSS losses through surface runoff may not be adequate in representing these complex harvesting operations. This suggests that algorithms for overland erosion processes that mobilise P may need to be developed or refined for this purpose, i.e., in response to temporal and spatial variance in episodic events. Under the present regime of daily irrigation of treated wastewater, soil sorption capacity and plant uptake rates of N may ultimately reach some quasi equilibrium, with minimal adsorption and high rates of N percolation to the groundwater. Therefore, an embedded groundwater module could be used to simulate the temporal dynamics of N leaching to groundwater and to give opportunities to explicitly account for the dynamics of the subsurface zone.

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Appendices

Appendix 1: Site photos

Appendix 1-1: Land surface sampling site (M5) at Waipa D/S monitoring station.

Appendix 1-2: Waipa Spring.

Appendix 1-3: Hemo Spring.

Appendix 1-4: Wetland between block 5 and 6 in the treated municipal wastewater irrigated area.

Appendix 2: Definition of soil parameters and source of parameter values specified in the soil database for each soil layer

Parameter	Definition	Source
SNAM	Soil name	S–map*
NLAYERS	Number of layers in the soil	S–map
HYDGRP	Soil hydrologic group (A, B, C, or D)	S–map
SOL_ZMX	Maximum rooting depth of the soil profile (mm)	S–map
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded	NZLRI**
SOL_CRK	Fraction of the maximum crack volume to the total soil volume	NZLRI
TEXTURE	Texture of the soil profile	S–map
SOL_Z	Depth from soil surface to bottom of layer (mm)	S–map
SOL_BD	Moist bulk density of the soil layer (mg m^{-3})	S–map
SOL_AWC	Available water capacity of the soil layer (mm H_2O mm^{-1} soil)	S–map
SOL_K	Saturated hydraulic conductivity of the soil layer (mm hr^{-1})	S–map
SOL_CBN	Organic carbon content of the soil layer (% soil weight)	NZLRI
CLAY	Clay content of the soil layer (% soil weight)	S–map
SILT	Silt content of the soil layer (% soil weight)	S–map
SAND	Sand content of the soil layer (% soil weight)	S–map
SOL_ALB	Moist soil albedo of the top soil layer	Cresswell et al., 1993
USLE_K	Soil erodibility factor of the top soil layer in the modified Universal Soil Loss Equation	Williams, 1995

*S–map: digital soil map online (smap.landcareresearch.co.nz)
**NZLRI: New Zealand Land Resource Inventory

Appendix 3: Optimised values and default ranges of sensitive parameters for discharge (Q), suspended sediment (SS), organic phosphorus (ORGP), mineral phosphorus (MINP), organic nitrogen (ORGN), ammonium–nitrogen (NH_4–N), and nitrate–nitrogen (NO_3–N) load simulations using SWAT2012 code. Parameters are unitless unless otherwise specified

Parameter	Optimum	Min	Max	Definition	Unit
				Q	
SLSOIL.hru	15	0	150	Slope length for lateral subsurface flow	m
CH_K2.rte	250	0	500	Effective hydraulic conductivity in the main channel alluvium	mm h^{-1}
CH_N2.rte	0.01	0	0.3	Manning's N value for the main channel	
HRU_SLP.hru	0.6	0	1	Average slope steepness	m m^{-1}
LAT_TTIME.hru	14	0	180	Lateral flow travel time	d
GWQMN.gw	400	0	5000	Threshold depth of water in the shallow aquifer required for return flow to occur	mm
RCHRG_DP.gw	0.65	0	1	Deep aquifer percolation fraction	
ALPHA_BF.gw	0.01	0	1	Base flow alpha factor	
				SS	
CH_COV1.rte	0.15	0	0.6	Channel erodibility factor	
CH_COV2.rte	0.15	0	1	Channel cover factor	
LAT_SED.hru	5	0	5000	Sediment concentration in lateral flow and groundwater flow	mg L^{-1}
PRF.bsn	2	0	2	Peak rate adjustment factor for sediment routing in the main channel	
SPCON.bsn	0.003	0.0001	0.01	Linear parameter for calculating the maximum amount of sediment that can be re–entrained during channel sediment routing	
SPEXP.bsn	2	1	2	Exponent for calculating sediment re–entrained in channel sediment routing	
OV_N.hru	20	0.01	30	Manning's N value for overland flow	
SLSUBBSN.hru	83	10	150	Average slope length	m

Parameter	Optimum	Min	Max	Definition	Unit
				ORGP	
LAT_ORGP.gw	10	0	200	Organic P in baseflow	mg P L^{-1}
BC4.swq	0.7	0.01	0.7	Rate constant for mineralisation of organic phosphorus to dissolved phosphorus in the reach at 20 °C	d^{-1}
RS4.swq	0.001	0.001	0.1	Organic phosphorus settling rate in the reach at 20 °C	d^{-1}
				MINP	
PSP.bsn	0.6	0.01	0.7	Phosphorus availability index	
PHOSKD.bsn	400	100	500	Phosphorus soil partitioning coefficient	m^3 t^{-1}
PPERCO.bsn	0.01	0.01	0.0175	Phosphorus percolation coefficient	m^3 t^{-1}
				ORGN & NH_4–N	
SURLAG.bsn	1	0.05	24	Surface runoff lag coefficient	
LAT_ORGN.gw	55	0	200	Organic nitrogen in the base flow	mg N L^{-1}
BC3.swq	0.4	0.2	0.4	Rate constant for hydrolysis of organic nitrogen to ammonium–nitrogen in the reach at 20 °C	d^{-1}
RS4.swq	0.001	0.001	0.1	Rate constant for organic nitrogen settling in the reach at 20 °C	d^{-1}
				NH_4–N	
BC1.swq	0.1	0.1	1	Rate constant for biological oxidation of ammonium–nitrogen to nitrite–nitrogen in the reach at 20 °C	d^{-1}
RS3.swq	10	0	50	Benthic (sediment) source rate for ammonium–nitrogen in the reach at 20 °C	mg m^{-2} d^{-1}
				NO_3–N	
CDN.bsn	0.01	0	3	Denitrification exponential rate coefficient	
CMN.bsn	0.001	0.001	0.003	Rate factor for humus mineralisation of active organic nitrogen	
NPERCO.bsn	0.001	0	1	Nitrogen percolation coefficient	
SDNCO.bsn	0.95	0	1	Denitrification threshold water content	
HLIFE_NGW.gw	500	0	5000	Half–life of nitrate in the shallow aquifer	d