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Optimizing land management strategies for maximum improvements in lake dissolved oxygen concentrations

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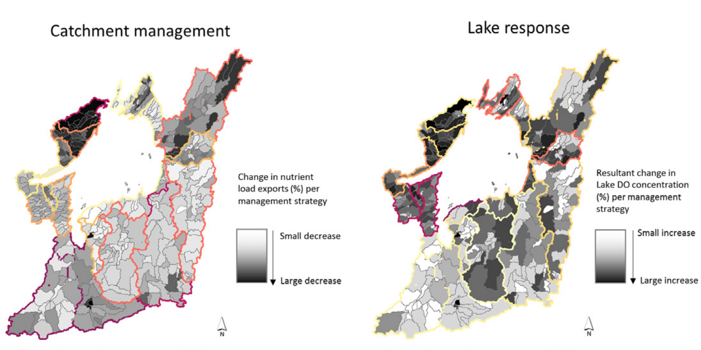
HIGHLIGHTS

- A model chain quantifies management strategy effects on lake dissolved oxygen (DO).
- Reductions in nutrients and flow exported to the lake significantly impacted lake DO.
- When multiple strategies were implemented, flow reductions warmed the hypolimnion.
- Negative impacts of lake warming overwhelmed positive effects of nutrient reductions.
- Optimum recovery rates may require consideration of interactions between strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Eutrophication and anoxia are unresolved issues in many large waterbodies. Globally, management success has been inconsistent, highlighting the need to identify approaches which reliably improve water quality. We used a process-based model chain to quantify effectiveness of terrestrial nutrient control measures on in-lake nitrogen, phosphorus, chlorophyll and dissolved oxygen (DO) concentrations in Lake Simcoe, Canada. Across a baseline period of 2010–2016 hydrochemical outputs from catchment models INCA-N and INCA-P were used to drive the lake model PROTECH, which simulated water quality in the three main basins of the lake. Five terrestrial nutrient control strategies were evaluated. Effectiveness differed between catchments, and water quality responses to nutrient load reductions varied between deep and shallow lake basins. Nutrient load reductions were a significant driver of increased DO concentrations, however strategies which reduced tributary inflow had a greater impact on lake restoration, associated with changes in water temperature and chemistry. Importantly, when multiple strategies were implemented simultaneously, resultant large flow reductions induced warming throughout the water column. Negative impacts of lake warming on DO overwhelmed the positive effects of nutrient reduction, and limited the effectiveness of lake restoration strategies. This study indicates that rates of lake recovery may be

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accelerated through a coordinated management approach, which considers strategy interactions, and the potential for temperature change-induced physical and biological feedbacks. Identified impacts of flow and temperature on rates of lake recovery have implications for management sustainability under a changing climate.

1. Introduction

Low dissolved oxygen (DO) concentrations in freshwaters are a global concern (MacLean et al., 1981; Evans et al., 1996; Nicholls, 1997), and have been linked with algal growth and decay due to excessive nutrient inputs (primarily nitrogen (N) and phosphorus (P)). Lack of oxygen can have negative effects on fish and other lake biota including reduced respiration rates, diminished reproductive activity, forced changes in habitat location, and ultimately reduced fish population sizes (e.g. Garside, 1959; Pollock et al., 2007). In the 1970s nutrient management plans were implemented across North America to reduce nutrient loads to surface waters. These had some initial success in reducing algal bloom frequencies (Smith et al., 2015) however over the past 10 years algal bloom issues have recurred, and DO concentration targets have not consistently been met. Examples include Chesapeake Bay (Reckhow et al., 2011), the Mississippi River (Dale et al., 2010), Lake Erie (Sharpley et al., 2012) and Lake Simcoe (Eimers et al., 2005).

While population growth and climate change have provided added challenges, intensive management has successfully reduced total phosphorus exports to large water bodies throughout North America. The reasons for the long term failure of these strategies to concurrently control eutrophication are a topic of active research (Young et al., 2011; Sharpley et al., 2013; Jarvie et al., 2017). It has been theorised that unintended consequences associated with some remediation approaches could contribute to eutrophication issues. For example efforts to reduce soil erosion and associated total P loads, have been associated with increased infiltration and changes in soil water residence times, which may increase the fraction of bioavailable P (Jarvie et al., 2017).

Despite the apparent insensitivity of algal blooms to total phosphorus (TP) reductions across North America, assessments of management strategy success continue to be based primarily on the extent of TP reduction (Hopkins and Webb, 1990; Baulch et al., 2013; Jin et al., 2013), rather than on actual responses of lake biogeochemistry and habitat availability. This missing link between land management and lake response is an important gap for researchers, land managers and the general public, who seek the ability to quantify direct effects of landuse actions on lake health.

This study assesses the effectiveness of nutrient management strategies in restoring DO within Lake Simcoe, which is one of the largest lakes in southern Ontario. As an important natural resource, Lake Simcoe is representative of many large water bodies in North America. It supplies drinking water to local municipalities (Palmer et al., 2011), and supports economically important cold-water recreational and commercial fisheries (LSEMS, 2008), both of which have been threatened by reduced water quality in the lake. Since the 1960's high nutrient inputs have been associated with low DO concentrations (MacLean et al., 1981; Evans et al., 1996; Nicholls, 1997), which have led to cold-water fish recruitment failure and necessitated annual stocking (Winter et al., 2007). Starting in the 1980s, a variety of management strategies have been implemented in the watershed to reduce external P loads. These interventions successfully reduced total P loads (Winter et al., 2011), and DO concentrations and natural fish recruitment rates within the lake are currently higher than in the 1980s and 1990s respectively (MOECC, 2016). However DO targets have not consistently been met (Eimers et al., 2005), and whitefish recruitment has recently declined. In addition, the lake is currently experiencing the effects of global change; similar to other large water bodies throughout Ontario (Assel et al., 2003) the duration of ice cover is getting shorter (Futter, 2003) and the duration of thermal stratification is increasing (Stainsby et al., 2011).

The combination of pressures within Lake Simcoe and its watershed have complicated the assessments of effectiveness of management strategies designed to reduce nutrient loadings and improve lake water quality. To date, most assessments of management success in large water bodies have relied on modelling, and focused upon strategy impacts on catchment nutrient exports (Baulch et al., 2013; Crossman et al., 2014). Rarely have in-lake responses to nutrient inputs been simulated (e.g. Gudimov et al., 2012; Crossman and Elliott, 2018), and in the few cases where lake responses were considered, specific land management simulations were not investigated. As a result, the effectiveness of individual management measures is not well understood.

This study is unique because unlike other model applications, (Rasmussen and Kalff, 1987; Snodgrass and Holubeshen, 1992; Nicholls, 1997; Nürnberg et al., 2013) individual responses to spatially explicit nutrient management strategies are established within different lake basins, enabling assessments of strategy effectiveness for specific areas of concern. In this study, a rainfall-runoff model is used to drive the hydrology of two integrated catchment models (INCA-P and INCA-N) which in turn are linked with a lake model (PROTECH), creating a holistic, process-based simulation of the entire Simcoe basin. The model chain offers a spatial (sub-catchment) and temporal (daily) resolution of nutrient and DO interactions not previously explored from source to impact, and more importantly the application of this model chain provides information on the potential effectiveness of individual management strategies based not just on their reduction of nutrient loads, but more directly on their ability to help maintain DO levels above critical ecological thresholds.

1.1. Aims and objectives

The overall project objective was to quantify the effectiveness of nutrient management strategies on lake DO levels. There were two specific aims to the program:

1) Simulate a series of nutrient management plans across all 20 major catchments of the Lake Simcoe watershed, based on existing strategies, and assess their effectiveness on lake recovery (DO concentration) at the catchment scale.
2) Quantify the unique contribution of each of the 424 sub-catchments to potential nutrient load reductions and assess management strategy effectiveness on lake recovery at the sub-catchment scale.

2. Methods

2.1. Site description

Lake Simcoe is a freshwater lake with a surface area of 722.5 km^2, comprised of a main basin (average depth 14 m), and two large bays, the shallower Cook's Bay to the south (maximum depth 15 m) and the deeper Kempenfelt Bay to the west (maximum depth 42 m) (Fig. 1). The watershed is 2899 km^2 (Winter et al., 2011) consisting of 20 tributary catchments, and is situated between Lake Ontario and Georgian Bay. Simcoe has a single outflow through the Atherly Narrows to Georgian Bay via the Trent Severn Waterway. Water quality and flow of most of the tributaries are monitored by either the Lake Simcoe

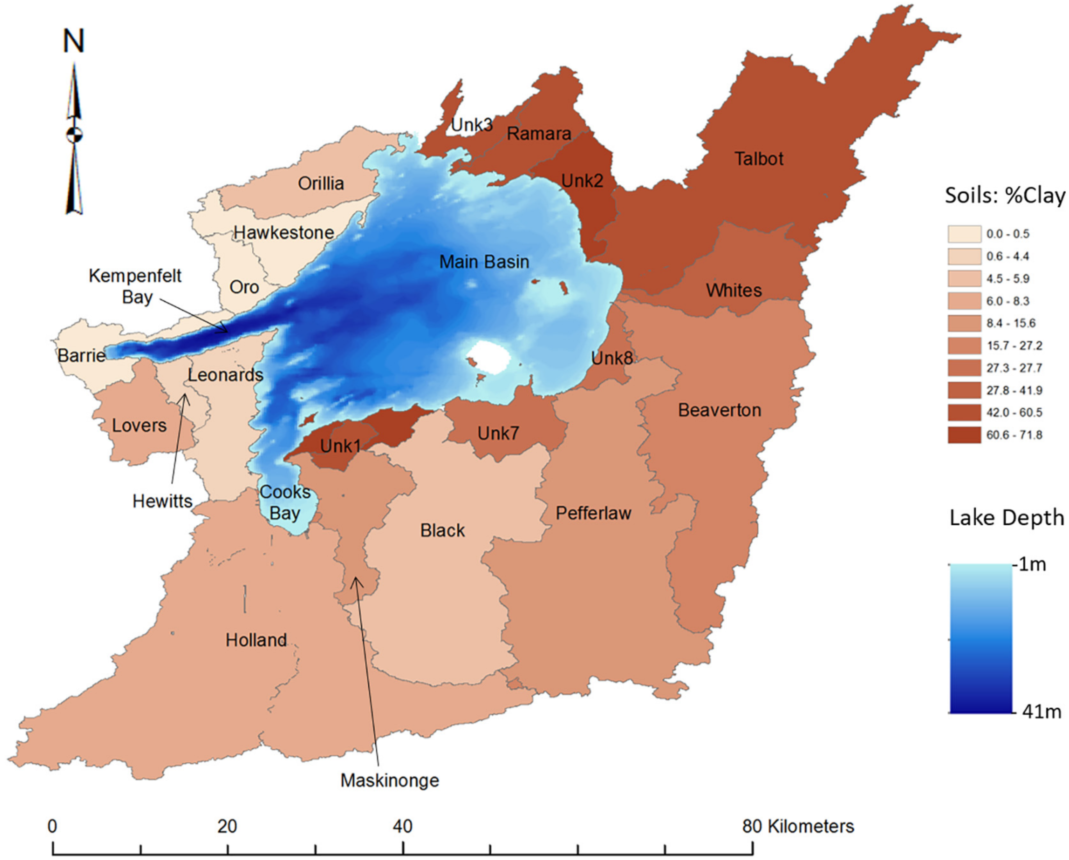

Fig. 1. Soils characteristics of the Simcoe watershed (derived from data available from Soil Landscapes of Canada Working Group, 2010 and Olding et al., 1956) and bathymetry of lake basins (derived from digitized bathymetric data provided by OMNR, which was originally interpreted from depth soundings taken by the Canadian Hydrographic Service (1957)).

Region Conservation Authority (LSRCA) or Environment Canada and Climate Change (ECCC).

Agriculture in the Simcoe watershed is a significant source of revenue for Ontario, annually contributing $500 million to provincial economies (LSEMS, 2008). With over 2000 individual farms, agriculture is the dominant land use in the watershed (Ecological Land Classification of Ontario data, Ontario Ministry of Natural Resources, 2007). The proportion of agricultural land cover is generally greatest in the south and east. There are several urban centres in the northern and western regions, which are associated with lower agricultural activities, including the rapidly growing cities of Barrie and Orillia. To the south lies the city of Bradford. Soil type varies from a very high clay content in the northeast (>71%) to <1% in the northwest (Fig. 1, Table 1).

There is little spatial variation in annual average air temperatures across the watershed (2010–2015) (Daymet daily surface weather data, Thornton et al., 2016) (Table 1), with greater variation in total

Table 1
Characteristics of Lake Simcoe watersheds used in calibration of INCA-PROTECH model.

Catchment	Area (km^2)	Landuse (%)				Soil type (% clay)	Precipitation 2010–2015 annual total (mm/year)	Temperature 2010–2015 annual average (°C)	Number of Cattle	Number of septic systems
		Agriculture	Urban	Forest	Wetland					
Unk3	51.88	59.7	8.9	13.1	18.3	56.1	818.7	6.96	136	1427
Ramara	56.20	42.2	4.4	16.9	36.5	60.5	871.0	6.63	307	633
Unk2	48.98	59.8	8.5	5.0	26.6	71.8	787.66	6.91	258	1139
Talbot	368.55	48.8	3.8	19.4	28.0	52.5	924.3	6.63	2206	18,803
Whites	87.93	65.8	1.7	11.2	21.3	41.9	899.4	6.80	602	4907
Beaver	328.5	65.1	5.2	10.5	19.3	27.2	756.2	7.22	2880	4724
Unk8	22.54	44.4	19.0	26.2	10.5	27.7	789.4	7.11	214	605
Pefferlaw	417.63	48.6	11.6	22.2	17.6	13.3	991.4	7.15	2116	14,973
Unk7	55.50	40.3	10.0	25.5	24.2	27.7	760.5	7.43	132	4050
Black	322.90	43.0	10.8	22.2	24.0	5.4	999.9	7.16	964	11,014
Unk1	39.84	34.0	19.3	28.8	17.8	55.9	933.5	7.40	39	1033
Maskinonge	79.34	66.0	16.1	10.8	7.1	15.6	1009.3	7.51	212	3735
Holland	616.98	50.8	21.3	16.9	11.1	8.3	827.2	7.18	3018	29,641
Leonards	85.34	44.2	22.7	21.4	11.7	4.4	638.6	7.18	247	6599
Hewits	19.09	51.3	27.8	15.6	5.3	3.7	727.1	7.15	64	1786
Lovers	59.4	39.1	29.8	17.2	13.9	7.9	1349.1	7.08	199	4733
Barrie	45.84	14.0	65.9	15.4	4.7	0	569.6	7.37	206	1531
Oro	30.67	48.6	8.6	30.4	12.3	0	1280.9	6.73	115	1828
Hawkestone	67.00	36.0	11.3	33.2	19.6	0.5	1007.5	6.51	249	3297
Orillia	75.96	39.2	19.1	31.5	10.2	5.9	730.2	6.31	282	2078

annual rainfall. In all catchments snowmelt is a key hydrochemical event, where spring flow maxim (March–May) decline to seasonal lows in late summer and early autumn (September–November) (Crossman et al., 2016). Periods of ice coverage range from 90 days in Kempenfelt Bay to 104 days in Cooks' Bay.

2.2. Model chain setup and calibration

The calibrated model setup presented by Crossman and Elliott (2018) was used to evaluate the effects of in-catchment nutrient management scenarios on lake DO concentrations. The daily time step model chain consisted of catchment models for nitrogen (INCA-N; Whitehead et al., 1998, Wade et al., 2002), phosphorus and sediments (INCA-P; Jackson-Blake et al., 2016), a riverine silica (SiO_2) model and a process-based lake model of nutrients, phytoplankton and DO dynamics (PROTECH; Elliott et al., 2010). The INCA and SiO_2 models were applied separately to 20 tributary catchments, comprised of 424 sub-catchments, so as to calculate daily fluxes of water, sediment and nutrients (nitrogen, phosphorus and silica) to the lake. These fluxes were used to force PROTECH applications for three basins of Lake Simcoe: Kempenfelt Bay, Cooks Bay and the main basin. Daily time series of temperature and precipitation were obtained from the Daymet gridded daily surface weather data portal (Thornton et al., 2016). The benefits of using gridded weather inputs for catchment-scale modelling have been demonstrated recently by Ledesma and Futter (2017). Further details of model setup are available in SI1.

2.2.1. INCA-N and INCA-P

Details of forcing data, model setup and calibration strategy are provided in Crossman and Elliott (2018). In each catchment, calibration periods were based on the maximum duration of available observed data, as this is considered the most effective way to enhance model predictive performance (Larssen et al., 2007). High frequency data collected using ISCO samplers between 2015 and 2016 were used to further refine calibrations in 9 of the 20 calibrated catchments. INCA requires daily time series of hydrologically effective rainfall (HER) and soil moisture deficit (SMD) data. These were generated for each of the 20 catchments using the rainfall-runoff model PERSIST (Futter et al., 2014). Catchment-specific point and diffuse nutrient sources included municipal sewage treatment works (STW), private sewage systems (septic systems), fertilizer applications, stormwater outflows, and atmospheric deposition. Land-cover specific rates of N and P application in fertilizer were estimated using a combination of local recommended application rates (OMAFRA, 2009), and crop growth statistics (Statistics Canada, 2011). For further details on N and P inputs, please see Crossman and Elliott (2018). Groundwater N and P concentrations were calibrated against Provincial Groundwater Monitoring Network (2012) data. Initial soil P concentrations were based on literature values (Fournier et al., 1994). Soil equilibrium coefficients were calculated using equilibrium phosphorus concentrations (EPCo) and Freundlich Isotherm values derived in the laboratory (Peltouvouri, 2006; Väänänen, 2008; Koski–Vähälä, 2001).

Earlier work has established that the legacy of past nutrient management can have a significant impact on nutrient load trends (Crossman et al., 2016). Thus, it was necessary during model calibration to include temporal changes in livestock access to watercourses, upgrades made to improperly functioning private sewage systems and operational effectiveness of urban stormwater ponds (Crossman et al., 2016; Crossman and Elliott, 2018).

2.2.2. PROTECH

The three PROTECH applications were forced by Daymet gridded temperature and precipitation data and instrumental wind speed, humidity and cloud cover data obtained from Environment Canada monitoring stations. Lake structural data including maximum depth, total water volume and surface area were derived from a digitized bathymetric map (OMNR, originally interpreted from depth soundings taken by the Canadian Hydrographic Service (1957)). Each model application was calibrated using data collected between 2010 and 2016 from Kempenfelt Bay (site K42), Cook's Bay (C9) and the main basin (E51). Calibration data included water temperature and concentrations of DO, N-NO_3, TP, SiO_2 and Chl-a. Lake phenological records (timing of ice-on and ice-off) were supplied by the Lake Ice Analysis Group (2012) based on Futter (2003); data gaps were infilled using data from local ice fishing forums. Rates of internal loading and zebra mussel effects are presented in S1.

2.2.3. Model performance evaluation

Model results were compared to monitoring data at multiple locations within the river, watershed and lake over the period 2010–2016 (for further details please see Crossman and Elliott, 2018 Section 2.2). Model skill was assessed using the coefficient of determination (R^2), normalized mean bias, and the difference between simulated and actual values expressed using root-mean-square-error (RMSE). The number of days during which DO concentrations fell below a minimum threshold (chosen as 7 mg/l and henceforth termed DO7) was also calculated. The 7 mg/l threshold is ecologically relevant as it has been identified as the level at which adverse impacts upon cold water fish are initially observed (Garside, 1959; EPA, 1986; Evans, 2006).

Typically DO concentrations are modelled or monitored at multiple depths, and then volume weighted over a region of interest. In DO studies of Lake Simcoe, regions of interest often incorporate the entire hypolimnion (18 m bottom zone) (e.g. Nicholls, 1997; Young et al., 2011). Reasons include that adult fish move to shallower regions of the hypolimnion in response to low DO concentrations (Kramer, 1987), therefore it is only necessary for the majority, but not all, of this zone to provide a suitable habitat (Evans, 2006). In this study however we assess the impacts of management strategies upon the nursery habitat of cold-water fish, where improvement of DO concentrations is especially important for survival of fish populations (Evans et al., 1991; Evans, 2006). Unlike adult fish, juveniles do not relocate from bottom zones in response to low DO concentrations, and have been observed to remain within suboptimal oxygen conditions on the lake floor in order to avoid predation (Davis et al., 1997). In this study therefore volume-weighted DO concentrations are taken over the bottom 5 m of the hypolimnion, which has been identified as the priority juvenile lake trout habitat during late summer (Evans et al., 1996).

2.3. Development and application of nutrient management scenarios

The consequences of five management scenarios were simulated using the model chain; three were based on existing LEAP policies, including upgrades of septic systems, restriction of livestock from watercourses, and retrofitting of urban ponds. "Retrofitting" refers to efforts to reduce nutrient outflow from the ponds, through installation of a range of engineered wetlands. Septic and livestock strategies were selected as they have been identified in previous work as having some of greatest impacts on nutrient exports (Crossman et al., 2016); and urban pond retrofitting was selected as its effectiveness had not previously been evaluated. In addition two policies (installation of urban parks and reduction in fertilizer applications to arable land) were examined which have not yet been fully implemented within the catchment. Details of calculations used to create these scenarios are provided in SI2.

Management strategies were initially run through 11 of the 20 catchments to which INCA-N and P had been applied. (This represents 322 of the 424 sub-catchments in the watershed). The selected catchments have a range of different soil types and contribute the highest P loads and some of the highest N-NO_3 loads entering the lake (Fig. 2). For each strategy (e.g. septic upgrades, livestock, retrofitting, urban parks and fertilizer reduction), two independent scenario runs were implemented within each INCA model. First the strategies were run across every sub-catchment within the selected catchments. Second, strategies

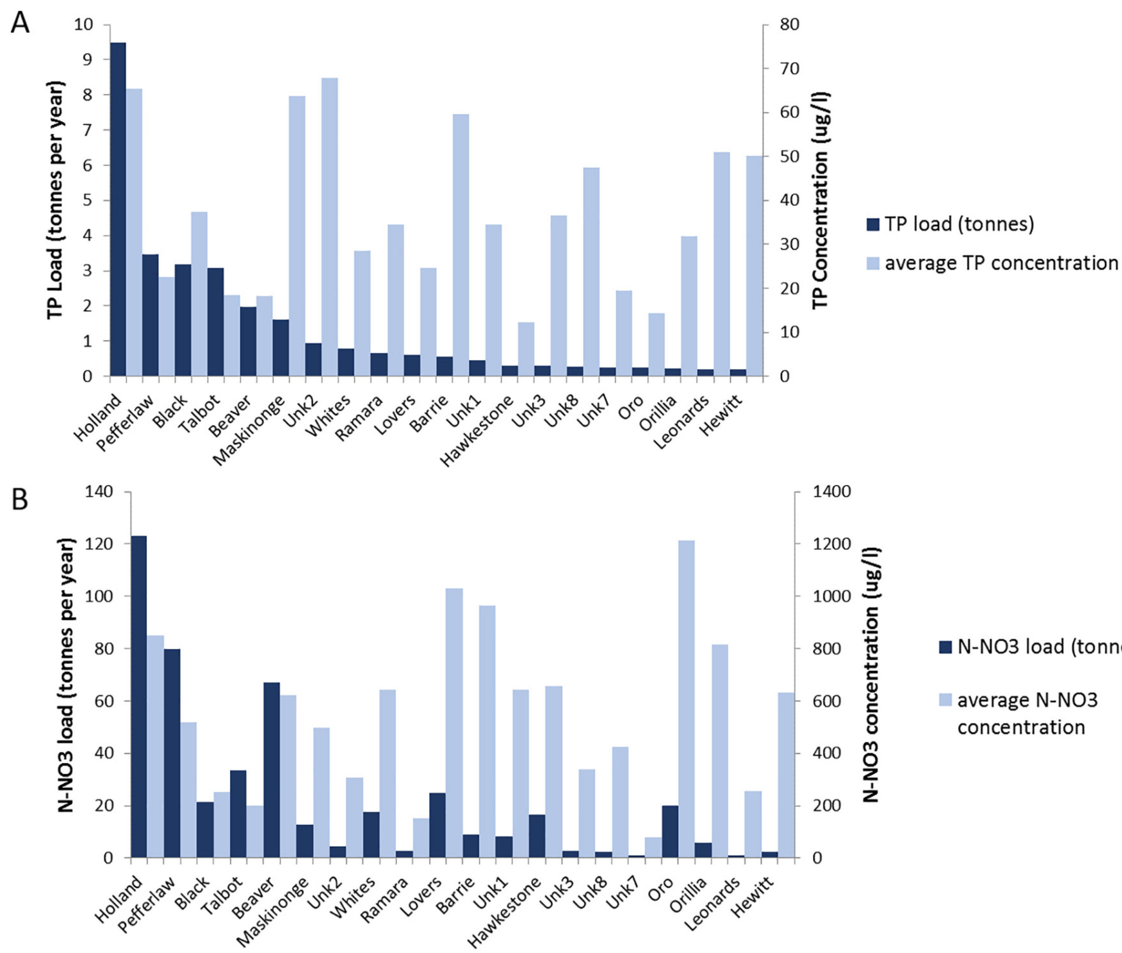

Fig. 2. Nutrient outputs to Lake Simcoe modelled by INCA rom all 20 catchments during the 2010–2016 baseline period.

were implemented in a subset of those sub-catchments; they were applied only in those areas located adjacent to the main channel. This method provided responses over a range of different land use and soil types, river network densities, and sub-catchment scales. Scenario results were extracted for the period 2010–2016, and compared to baseline runs of the same time frame.

The outputs from each INCA-N and INCA-P model were then individually run through the PROTECH model chain in turn, along with the baseline values from the unchanged remaining inflowing INCA models. This enabled lake basin responses to strategies carried out in each catchment to be assessed individually. Finally, scenario-adjusted values of all 11 INCA-N and P models were simultaneously run through the model chain, which allowed for an assessment of basin responses to multi-catchment applications of management scenarios, in the event that basin responses were non-linear.

2.4. Calculation of management effectiveness

2.4.1. Effectiveness of management strategies in reducing nutrient export

Management strategy effectiveness was assessed independently for nitrogen and phosphorus, both as a total measure of effectiveness across each catchment, and as isolated effectiveness measurements within areas proximal to the main channel. In order to achieve a management effectiveness score which was comparable between models (catchments), effectiveness was calculated as nutrient load reduction per management strategy, as a percentage of the total baseline nutrient load from all catchments. As management strategies are applied using different units (e.g. number of livestock, areas of vegetation planted), the number of management strategies were standardised into a "per unit effort" (e.g. Rao et al., 2009). Total areas of crops to which nutrient reductions were applied were divided by the average field size in the Simcoe watershed. The number of livestock restricted from watercourses was divided by the average number of cattle in a field, and the area of vegetation planted was divided by the size of urban parks. Upgrading of each septic system, and each urban pond was assessed as a single unit effort.

Management strategy effectiveness was also assessed as a combined measure of N and P, as nutrient reductions from management strategies are simultaneously experienced by the environment, and cannot realistically be considered in isolation (Heathwaite et al., 2000). This was calculated in an identical manner to that above, though here using the summed percentage reductions of both nutrients. A "total effectiveness score" was assessed for each model, which equalled the sum of effectiveness from each management strategy.

In order to assess the management effectiveness in all 424 subcatchments, a generalised linear model (GLM) with partial factorial analysis (IBM SPSS Statistics 24) was used. Here relationships between catchment characteristics and management strategy success in reducing nutrient loads were identified. A GLM was used because previous studies have indicated that the factors influencing management strategy success are catchment-specific (Crossman et al., 2016). In addition, unlike a standard linear model, GLMs can calculate interactive effects between predictor variables (e.g. stream density and soil type) upon the response variable (management strategy effectiveness), and can be applied to categorized independent variables (e.g. 'soil type'). The effectiveness results from the 11 models implemented (both from every sub-catchment, and from those located only adjacent to the main channel) were entered as dependent variables, with predictor variables consisting of catchment characteristics including land use, soil types, and river network densities.

The nutrient reduction potential (kg) for each sub-catchment was also calculated as

$$TNRP_{subcat} = SE\%_{subcat} \times BMP_{tot} \quad (1)$$

where $SE\%_{subcat}$ is the effectiveness at a sub-catchment scale, and BMP_{tot} is the total number of management units present in each sub-catchment.

2.4.2. Effectiveness of management strategies in improving lake health

To determine the direct effect of management strategies upon lake health, several calculations were performed. First, the relationship between lake responses (%) and changes in nutrient exports and flow (%) were established at a catchment scale through further GLMs. Lake responses from all scenarios implemented were entered as dependent variables, and lake basin area, depth, season, change in nutrient export and change in outflow were entered as predictor variables. Using the previously generated information on nutrient export reduction from all 20 catchments, these lake response relationships were used to calculate catchment impacts on lake health. For each of the catchments, lake responses per nutrient export reduction ($LakeR_{cat}$) were also calculated:

$$LakeR_{cat} = \frac{Lake_{\%change}}{NE_{\%}} \quad (2)$$

where $Lake_{\%change}$ is the change in variable of interest following implementation of a management scenario, and $NE_{\%}$ is the percentage change in nutrient exports from that catchment. The change in lake health specific to management strategies implemented in each of the 424 subcatchments ($LakeR_{Subcat}$) was then determine through the calculation:

$$LakeR_{subcat} = LakeR_{cat} \times NE\%_{subcat} \quad (3)$$

where NE%subcat is the percentage reduction in nutrient exports at the sub-catchment scale.

Finally, management strategy effectiveness, in terms of desired lake response ($SE\%_{lake}$) was calculated as:

$$SE\%_{lake} = LakeR_{subcat} \times SE\%_{subcat} \quad (4)$$

3. Results

3.1. Calibration and baseline dynamics

Full details of model calibration and performance are provided in Crossman and Elliott (2018). INCA performance statistics (R^2 and normalized mean bias) for TP and N-NO_3 concentrations were generally good at the catchment outflows with an average R^2 of 0.4 and 0.5 respectively, while average R^2 for flow was 0.8 (SI3). INCA calibrations captured the differences in nutrient concentrations between catchments with R^2 of 0.95 (TP) and 0.91 (N-NO_3). Nutrient loads were well characterized with R^2 generally above 0.65 across the catchments, and often above 0.7. The model fit was especially strong at simulating the conditions for the entire calibration period, with an R^2 of 0.95 and 0.91 (TP and N-NO_3 concentrations respectively), and 0.67 and 0.93 (TP and N-NO_3 loads respectively). The silica model simulated instream concentrations with an R^2 of 0.8 for all but one catchment. More details on model performance indicators are provided in SI3.

Between 2010 and 2016, the Holland and Pefferlaw rivers released the highest annual loads of both TP and N-NO_3 to the lake (Fig. 2). Of the ten catchments which exported the greatest TP loads over this time period, eight also released the greatest N-NO_3 loads. The catchments drained by these rivers have an average land use of 53% agriculture and 12% urbanization; with soils consisting of 24% clayey loam.

All three basins modelled by PROTECH reproduced observed behavior in measured euphotic zone temperatures and with 5 m bottom-zone DO concentrations ($R^2 > 0.8$), across a range of temporal scales (monthly, seasonal and annual) (Fig. 3, SI4). An exception was Cook's Bay where seasonal correspondence with DO concentrations were slightly lower, however the RMSE remained low (0.4 mg/l). Model performance for estimating nutrient concentrations was also high at the monthly and seasonal scale, with R^2 values up to 0.98 (N-NO_3) and 0.92 (SRP). Estimates of Chl-a showed good correspondence with measurements in all basins at the monthly scale with R^2 up to 0.53, and RMSE values of 0.3 μg/l. At the seasonal scale, R^2 remained high (up to 0.52) with the exception of the main basin (R^2 0.15), although the RMSE for this model was only 0.2 μg/l. The models were validated using daily data from April 20th to June 1st 2016, when high frequency monitoring of the lake basins was conducted. Temperatures and dissolved oxygen concentrations were simulated with an R^2 of >0.93 and >0.5 in all basins. Model performances of N-NO_3, SRP and Chl-a concentrations at the daily resolution were similar to those calculated at seasonal and monthly scales (Crossman and Elliott, 2018).

During the summer and autumn of the baseline period, Chl-a, TP and N-NO_3 concentrations simulated within Kempenfelt and Cook's Bay were similar (Fig. 4A), though marginally higher in the latter basin. Concentrations were much lower in the main basin, with an average of just 0.7 μg/l Chl-a compared to 1.4 μg/l in Cook's Bay. Water temperatures in the euphotic zone were similar in all basins, ranging from 14.9 °C in Kempenfelt Bay, to 18.7 °C in Cook's Bay. Average DO concentrations within the 5 m bottom zone were also similar between basins; varying between 8.7 mg/l in Kempenfelt Bay, and 9.3 mg/l in the main basin (Fig. 4B). Minimum DO concentrations and DO7 varied significantly between the shallower and deeper basins. In the main basin and Cook's Bay, DO7 ranged between 11.3 and 12.2 days per/year, but was much higher in Kempenfelt Bay at 32.7 days/year. Average stratification periods for the basins were simulated as 174 days (Cook's Bay), 191 days (main basin) and 194 days (Kempenfelt Bay). While the shallower basins were consistently the first to stratify, Kempenfelt Bay remained stratified longer into the autumn.

Monthly fluctuations in basin inflows during the baseline period were compared with observed changes in lake temperatures. Changes in flow were calculated as a percentage of total annual inflow to the lake:

$$\textit{Change in flow}\ (\%) = \frac{(\mathrm{M2b} - \mathrm{M1b})}{\mathrm{AF}}\ x\ 100 \quad (5)$$

where M2b is the total flow (m^3) to a basin during the month of interest; M1b is the total flow (m^3) to a basin in the preceding month; and AF is the total inflow (m^3) to the lake. Larger reductions in tributary inflows (>1% of the annual flow input to the lake) were associated with higher monitored lake water temperatures (Fig. 5). Both monitoring and modelling data demonstrated a significant negative linear correlation between water temperature and summer/autumn DO in the bottom zone of the shallower basins: Cook's Bay and the main basin ($p < 0.01$) (Fig. 6). In Kempenfelt Bay, however, a quadratic relationship was observed. Monitoring data in basin Kempenfelt Bay showed a significant negative association between bottom zone DO concentrations and Chl-a throughout the summer and autumn ($R^2 = 0.3$, $p < 0.01$). However, in the main basin and Cook's Bay there was a weak positive correlation between Chl-a and DO concentrations during periods of high algal growth ($R^2 = 0.3$ at the main basin, and 0.2 at Cooks Bay).

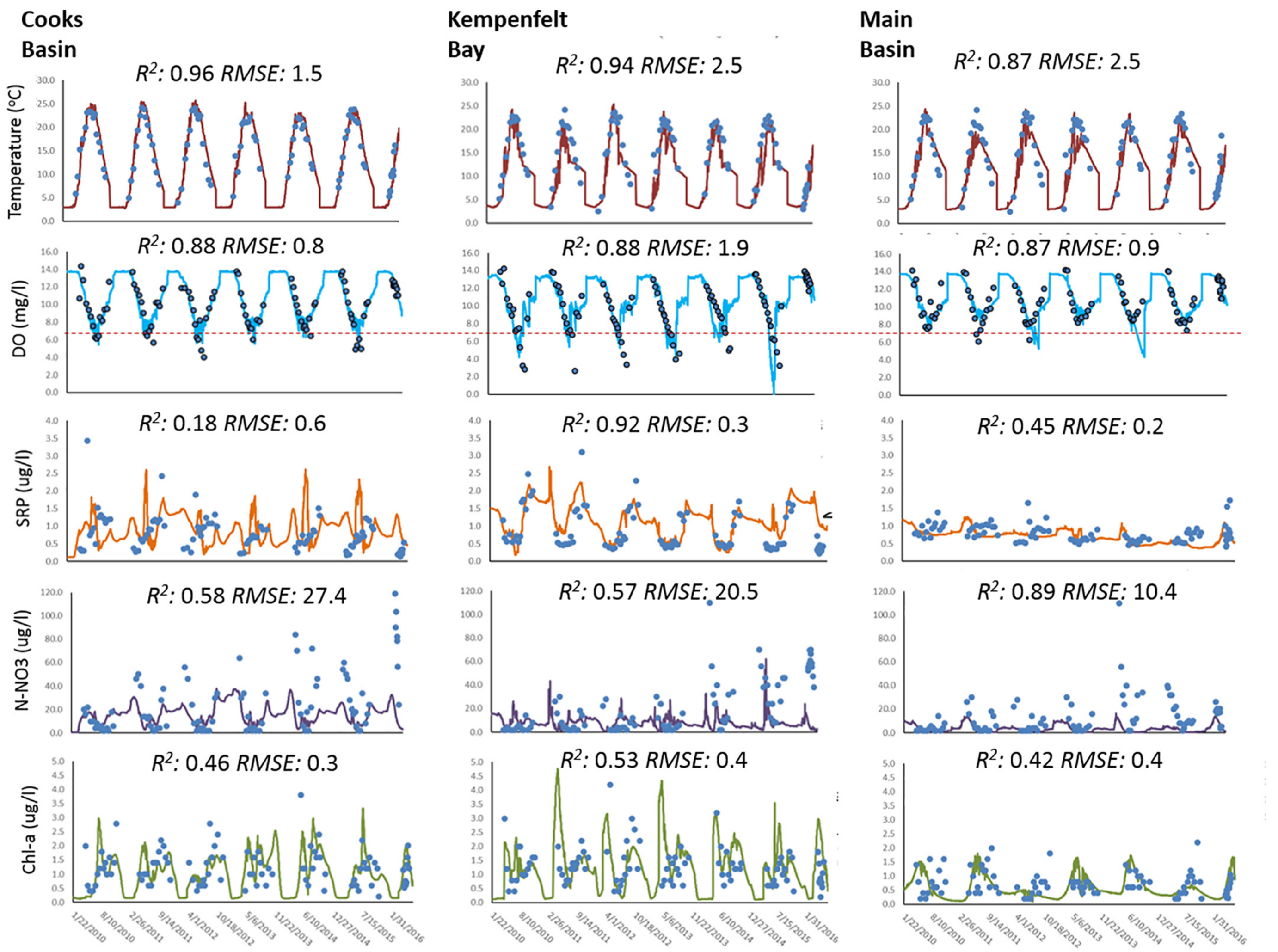

Fig. 3. Calibration of lake basins over 2010–2016 baseline period by lake model PROTECH at Cooks, Kempenfelt and Main basins. Solid lines represent model outputs, dots represent monitoring data. Red line across DO panel indicates 7 mg/l threshold. Statistics represent monthly calibration performance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Management scenarios

3.2.1. Effectiveness of nutrient export management

The implementation of simulated management strategies across the selected 11 catchments reduced total TP and $N\text{-}NO_3$ loads by 14.4 and 8.5% respectively (Table 2). This was achieved predominantly through reductions in river nutrient concentrations, but with a simultaneous small reduction in flow (0.2%). The highest reductions in nutrient loads were achieved in the Holland watershed (TP) and in the Pefferlaw ($N\text{-}NO_3$).

Different strategies achieved differing degrees of nutrient reductions within each catchment, although in the majority of areas, reductions in fertilizer applications to arable land achieved the greatest reductions in both $N\text{-}NO_3$ and TP loads (Fig. 7). In some more heavily urbanized catchments, a large proportion of nutrient load reductions were attributed to retrofitting of stormwater ponds (TP) and establishment of vegetated

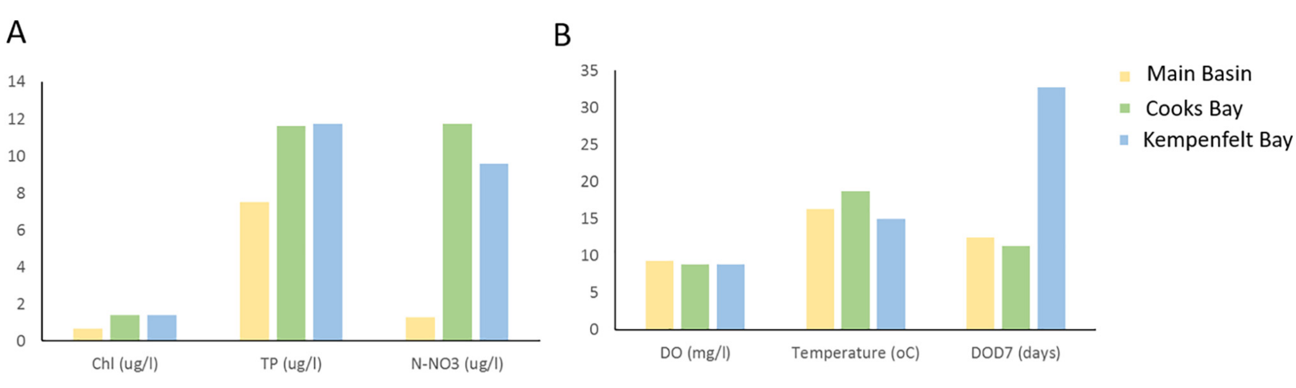

Fig. 4. Average surface water chemistry of lake basins during summertime of the baseline period; with the exception of DO which is modelled in the 5 m bottom zone.

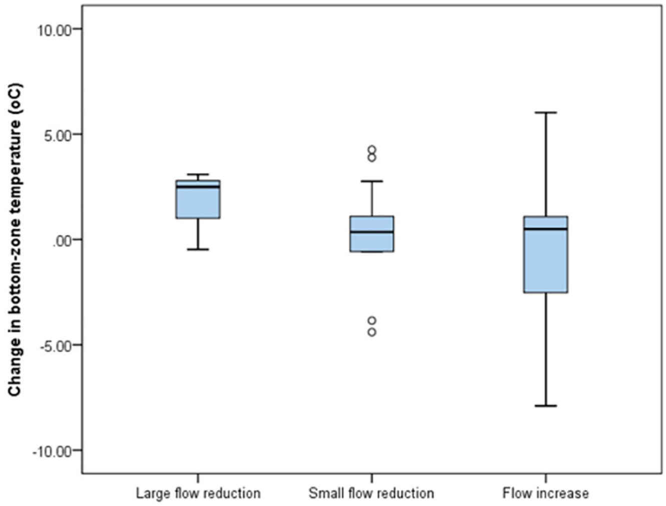

Fig. 5. Observed responses in lake bottom zone temperatures to reductions in tributary inflows (where 'large flow reduction' constitutes a monthly inflow reduction >1% of the annual flow input to the lake; and 'small flow reduction' in a reduction between 0 and 1%).

Table 2
Annual reductions of nutrient concentrations, loads and flow under all management strategies.

	TP (μg/l)	$N\text{-}NO_3$ (μg/l)	Flow (m^3/year)	TP load kg	$N\text{-}NO_3$ load kg
Whites	2.1	120.9	3742.4	58.1	3295.6
Pefferlaw	1.8	66.7	339,474.7	285.8	10,220.2
Holland	19.7	42.5	312,805.9	2786.4	6221.6
Talbot	1.1	34.6	135,335.6	182.9	5693.4
Ramara	0.8	2.5	1025.7	13.6	44.4
Maskinonge	6.5	62.6	29,431.94	164.2	1571.8
Black	0.7	39.1	232,109.9	70.4	3283.5
Beaver	0.9	13.2	27,917.49	91.3	1384.7
Lovers	10.2	218.2	55,905.7	242.7	5244.3
Unk2	3.0	3.7	1523.5	38.7	47.8
Barry	1.0	55.0	151,745.8	27.1	753.0
Total reduction across all 20 catchments	2.8	26.2	1,291,019	3961.0	37,760.2
Total catchment reduction over model period (%)	14.3	8.3	0.2	14.4	8.5

urban parks ($N\text{-}NO_3$). These load reductions largely reflect the total number of management options available in each catchment. For instance while the Holland demonstrated a high overall potential for reduction in $N\text{-}NO_3$ and P loads, the effectiveness of each individual strategy was low (SI5). In general pond retrofitting, fertilizer application reductions, and livestock restrictions were particularly effective methods of reducing nutrient loads, and removed respectively an average of 0.11%, 0.09%, and 0.07% of the catchment $N\text{-}NO_3$ and P load for every 10 measures implemented. Only the establishment of urban parks had a significant impact on flow, where planting of vegetation accounted for over 99% of total projected flow reductions.

3.2.1.1. Drivers of nutrient export effectiveness. Several factors influenced the effectiveness of strategies in reducing nutrient exports (SI5). Soil type, reflecting infiltration capacity, and river network density (or stream size/order) were important driving variables. Excluding livestock from water courses, crop fertilizer reduction and urban parks were all most effective in areas of clayey soils, whereas the effectiveness of septic (private sewage system) upgrades was highest in sandy regions. The density of river networks, or stream order (size) within the sub-catchments was also important, although the impact of this 'stream connectivity' varied depending on the dominant soil type. In areas of urban park and livestock exclusion, higher stream connectivity was associated with higher effectiveness in sandy soils, but reduced effectiveness where clayey soils dominated. Conversely in fertilizer reduction and septic upgrade strategies, higher connectivity was associated with greater effectiveness in clayey soils, and increased the effectiveness of pond retrofitting strategies across all soil types.

3.2.2. Impacts of catchment management on lake chemistry

In almost all catchments, management simulations achieved a reduction in annual average lake TP concentrations (scenario average of 9.3%) (Fig. 8A). Similarly, most scenarios led to a reduction in annual lake $N\text{-}NO_3$ concentrations with an average reduction across all basins

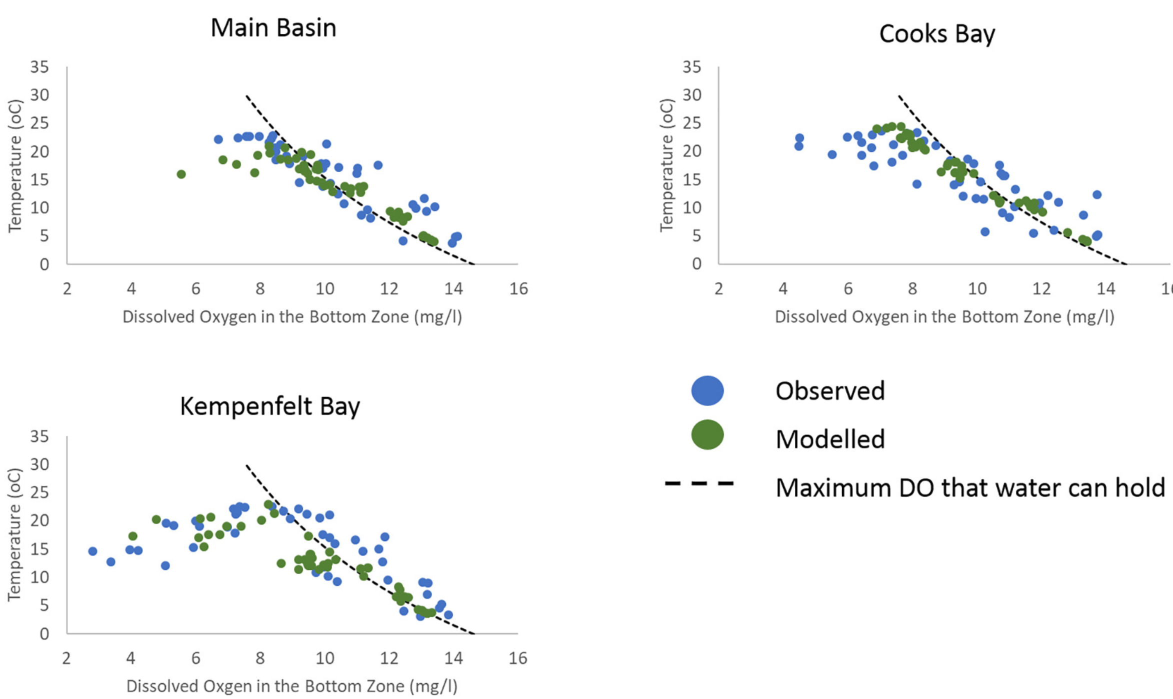

Fig. 6. Modelled and observed relationships between lake temperature and dissolved oxygen in the 5 m bottom zone (mg/l).

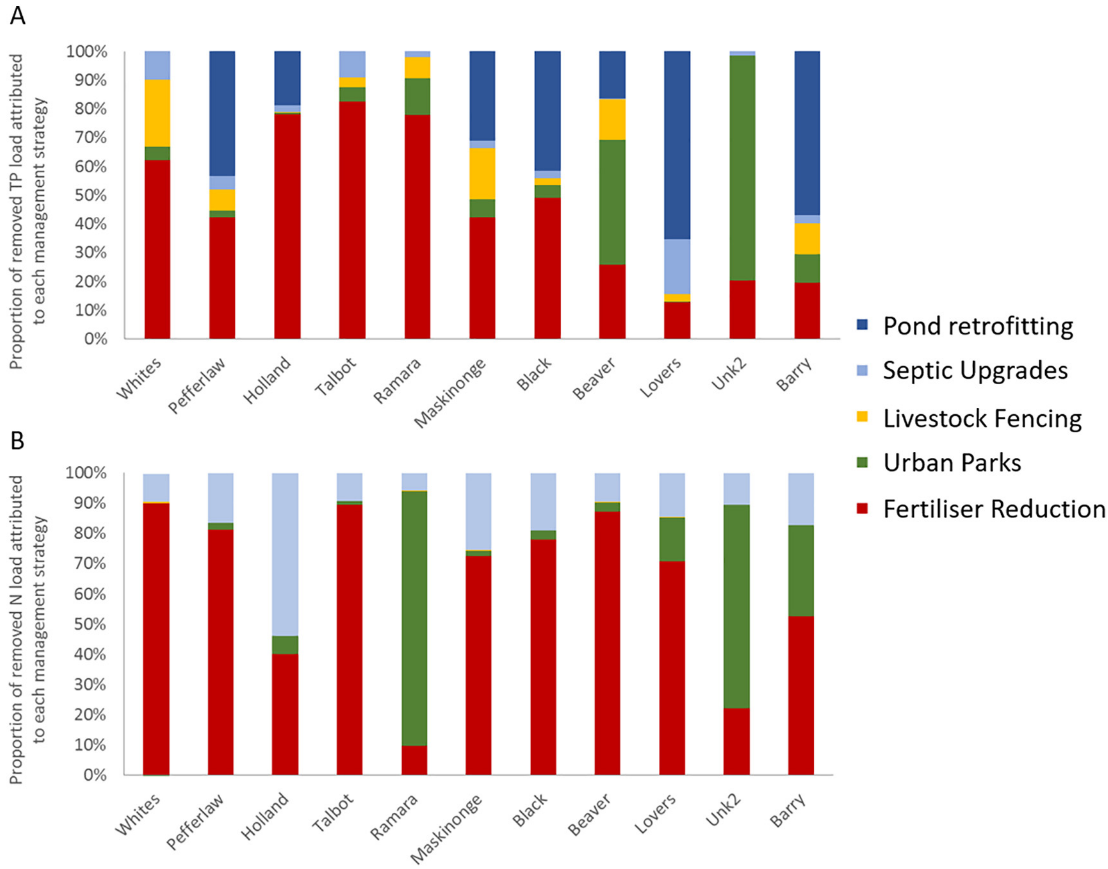

Fig. 7. Proportion of load reductions of a) TP and b) N-NO_3 attributable to each management strategy.

of 5.1%. Average annual Chl-a concentrations were however projected to increase under most scenarios, by up to 8.8%, although reductions of up to 58.2% were projected under scenarios which fed into Cook's Bay.

Despite projected increases in annual average Chl-a concentrations, there was an increase in the annual average DO concentration (scenario average of 2.1%), and a reduction in DO7 (scenario average of 19 days per year) (Fig. 8B) under all scenarios. In addition, a small reduction in annual average lake temperatures (scenario average of 0.02 °C) was demonstrated in most scenarios, with largest reductions typically occurring during June, July and August of up to 1.4 °C. Temperature increases were projected during winter months (SI6). A reduction in the length of the stratification period (specifically in an earlier turnover of the lake at the end of the summer) was also documented under all scenarios, along with a reduction in the thickness of the epilimnion during spring and summer, by an average of 0.24 m. Greatest changes in epilimnion thickness were generally projected in June with an average reduction of 1.5 m.

3.2.2.1. Drivers of lake chemistry responses. Catchment nutrient reduction strategies had differing degrees of effectiveness on improving lake water chemistry (Table 3). In general greater reductions in lake TP concentrations were achieved if the majority of percentage nutrient load reductions occurred in spring, as opposed to summer or autumn. Responses varied between basins where a 1% reduction in load achieved a much greater reduction in lake TP concentrations in Cook's Bay than in Kempenfelt Bay. While nutrient load reductions were significant drivers behind changes in lake Chl-a concentrations, each basin responded in a different manner. Basin specific 'impact thresholds' were identified which quantified the minimum reduction in nutrient inputs required before a reduction in Chl-a would be attained. In the main basin and Kempenfelt Bay, nutrient load reductions of 4.5% and 17.7% respectively would be required to attain reductions in Chl-a concentrations.

Lake temperature responses were primarily associated with changes in tributary inflows related to the management scenarios. Small reductions in flow were associated with cooler lake water temperatures, although larger flow reductions resulted in smaller temperature decreases. Reductions in nutrient loads were a significant driver behind changes in lake DO concentrations; specifically, greatest improvements in DO concentrations were projected when nutrient loads were reduced during autumn. Changes in tributary inflow however had the greatest impact both on DO and DO7. While flow reductions were generally associated with improved lake health (management scenarios resulted in an average annual DO increase of 2.1% and an average reduction in DO7 of 20 days), larger flow reductions limited the extent of DO increases. The impacts of flow reductions on lake temperature and average lake DO concentration were greatest in deeper basins.

3.2.3. Projected management effectiveness at the sub-catchment scale

Across Simcoe it was clear that some of the regions where the greatest nutrient load reductions could be achieved (total reduction potential, Fig. 9A) were located within sub-catchments of the Holland, Orillia, Pefferlaw and Talbot catchments. The regions where the greatest reductions in nutrient loads could be achieved for the lowest unit effort (greatest effectiveness) were more widespread throughout Simcoe, and included sub-catchments of the Talbot, Ramara, Oro, Orillia, Hawkstone catchments. Effectiveness of nutrient reduction strategies was low within the majority of sub-catchments of the Holland River catchment. Fertilizer reductions were generally the most effective strategies in each sub-catchment (Fig. 9B), with the exception of the heavily urbanized areas of Barrie and Holland, where pond upgrades were most effective.

All strategies implemented in catchments feeding into Cook's Bay, and notably the Holland sub-catchments, were particularly effective

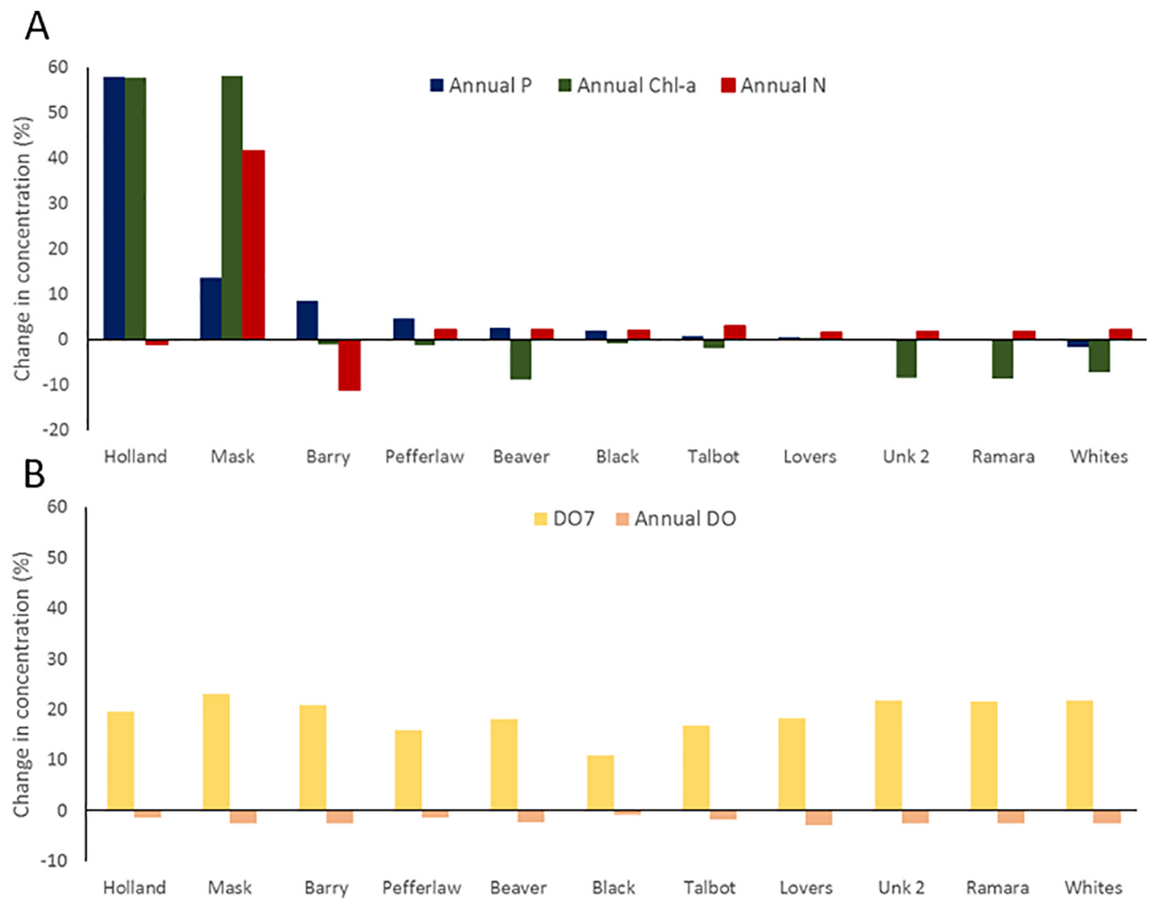

Fig. 8. Impact of management strategies on annual lake concentrations (% reduction) on a) TP, Chl-a, and N-NO_3, and b) DO and DO7.

both at reducing lake TP and lake Chl-a concentrations (Fig. 10A,B), In addition, some tributaries feeding the main basin where nutrient load reductions had been particularly effective did not stand out as being efficient in reducing lake TP concentrations (Hawkestone), or Chl-a (Orillia, Hawkstone and Talbot). Similarly nutrient load reductions in the Lovers and Barrie catchments (feeding into Kempenfelt Bay) were

Table 3
Generalised linear model performance of nutrient management impacts on lake chemistry.

GLM response variable	GLM predictor variable	Response per unit increase in predictor	% of data variance explained by GLM
Change in TP concentration	NL% reduction (C9)	4.45	97
	NL% reduction (E51)	0.84	
	NL% reduction (K42)	−0.08	
	Season (autumn)	−3.21	
	Season (spring)	5.89	
	Season (summer)	0.84	
	Season (winter)	3.14	
Change in Lake Chl-a concentration (%)	NL reduction (%)	0.25	99
	C9	56.07	
	E51	−5.62	
	K42	−0.51	
Change in lake temperature	Annual flow reduction (C9)	−9.6 (oC)	80
	Annual flow reduction (E51)	−15.6 (oc)	
	Annual flow reduction (K42)	−22.7 (oC)	
Change in lake Average DO concentration (%)	NL% Reduction (autumn)	−0.01	92
	NL% Reduction (spring)	0.06	
	NL% Reduction (summer)	0.001	
	NL% Reduction (winter)	0.81	
	Flow reduction (%)	31.10	
	C9	−3.21	
	E51	−2.50	
	K42	−3.15	
Change in Lake DO7 (days)	Flow reduction% (C9)	−27.2	70
	Flow reduction% (E51)	−203.8	
	Flow reduction% (K42)	−38.0	

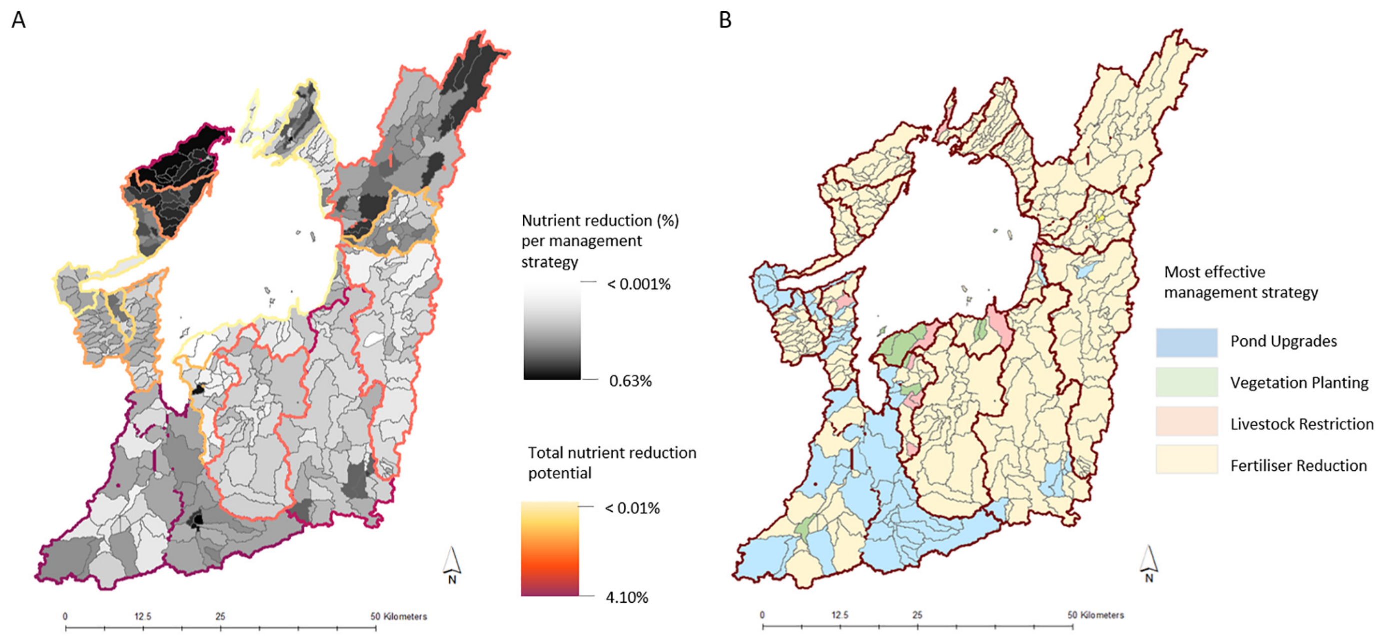

Fig. 9. Subcatchment-scale effectiveness of management strategies at reducing nutrient loads flowing into the lake a) of all management strategies b) indicating most effective management strategy type.

ineffective at reducing lake TP and Chl-a concentrations. Surprisingly, although the effectiveness of Chl-a reduction was relatively low in strategies implemented within sites feeding Kempenfelt Bay, some of the greatest effectiveness in improving DO and reducing DO7 was achieved in the Barrie, Lovers and Leonards catchments. (Fig. 11A, B). Similarly Orillia, Hawkestone, Oro and Talbot achieved high improvements in DO per management strategy implemented compared to the Holland and Maskinonge, despite the greater effectiveness of strategies in reducing lake TP and Chl-a at the latter two sites.

When all strategies in all catchments were implemented simultaneously the overall reductions in nutrient loads flowing into the lake was of course much higher (Table 4). However reductions in tributary inflows were also greater, and led to projected increases in lake temperatures. Under these combined strategies increases in DO concentrations were not as great as within individual scenarios, and reductions in DO concentrations were projected within some basins. The relationship between flow, nutrient loads and DO was examined within each basin to calculate the maximum flow reduction which each basin could facilitate (Table 5). In order to achieve the maximum increase in DO concentrations flow reduction should not exceed 0.1% for every 1% reduction in nutrient load.

4. Discussion

Anoxia has historically been assumed to be linked primarily to biological and chemical factors such as nutrient availability and algal

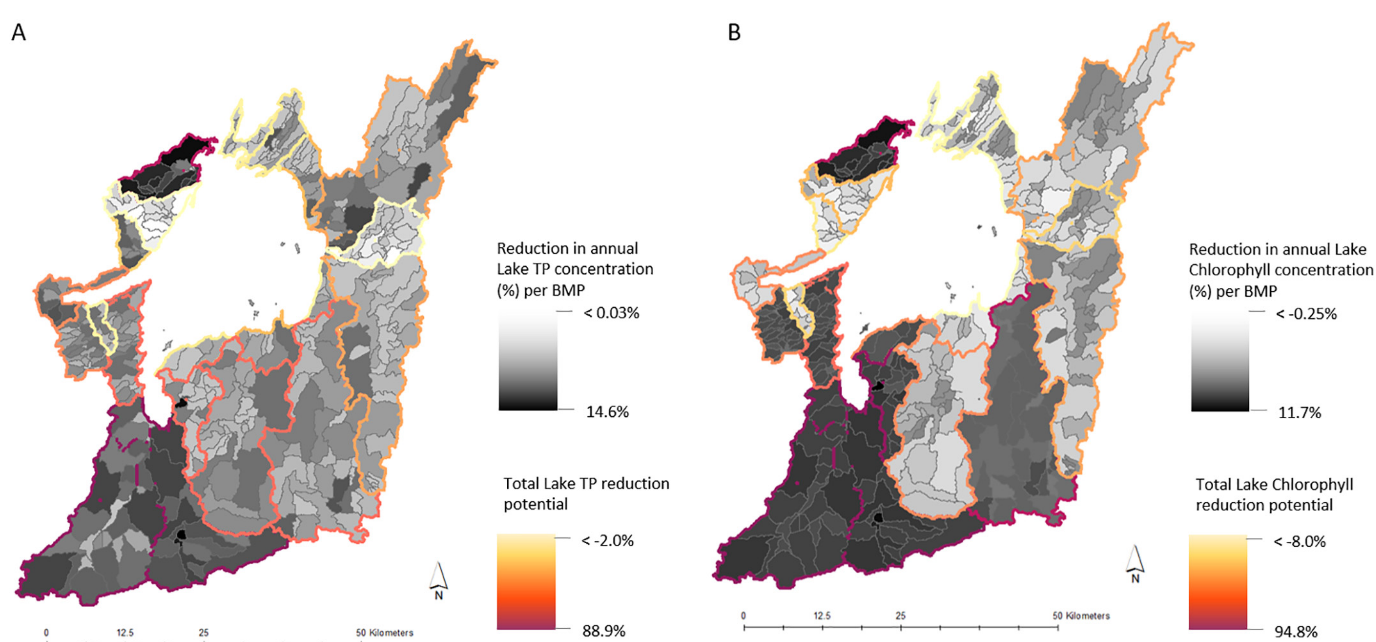

Fig. 10. Subcatchment-scale effectiveness of management strategies at reducing lake concentrations of a) TP and b) Chl-a. Results represent lake responses when catchments are managed in isolation (i.e. without simultaneous strategy implementation in all catchments).

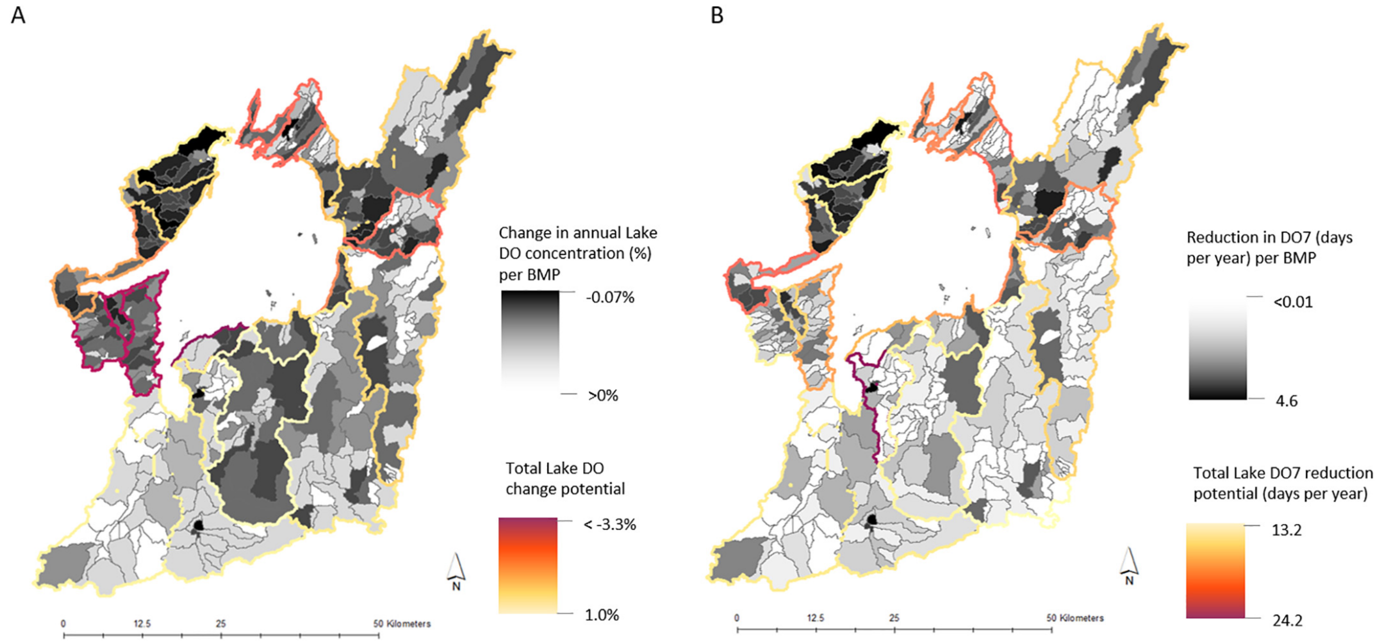

Fig. 11. Subcatchment-scale effectiveness of management strategies at reducing lake concentrations of a) DO and b) DO7. Results represent lake responses when catchments are managed in isolation (i.e. without simultaneous strategy implementation in all catchments).

decomposition (e.g. Sommer et al., 1986), however physical factors such as residence time, light and temperature are increasingly thought to play a significant role (Sommer et al., 2012; Bowes et al., 2016). The frequency and severity of eutrophic conditions within large water bodies has been projected to increase under a warming climate across North America and Europe (Whitehead et al., 2009), meaning resilient control measures must be adopted. However, the resilience of strategies cannot be assessed until the underlying relationships between land management and lake response are more fully understood. This study provides the first step in addressing this knowledge gap, by investigating the drivers of management effectiveness, where success is judged not solely on nutrient export reductions, but by attainment of lake biological and chemical targets.

4.1. Model baseline period

During the baseline period, reductions in river flows were associated with increases in lake temperatures. Strong negative correlations, both modelled and observed, identified between water temperatures and DO concentrations within the shallower basins during summer and autumn suggest that water temperature had a consistent influence on variability in DO concentrations during this period. The deeper Kempenfelt Bay experienced a higher number of DO7 events than other basins, and the quadratic relationship in this basin indicates that some of the lowest DO concentrations may be associated with additional factors. The observed association between lower bottom zone DO concentrations and euphotic zone Chl-a concentrations at this deeper more strongly stratified site indicates a rise in BOD may add to the DO depletion effect of the physical drivers, (as found by Blumberg and Toro, 1990). The impact of algal growth on DO varied between basins however; during periods of high algal growth in weakly stratified basins the weak positive correlation with DO combined with the lower number of DO7 events suggest that photosynthesis and re-aeration could limit the decline of DO concentrations caused by changing temperatures in shallower areas (Stefan et al., 1996).

4.2. Management impacts on nutrient exports

From the 11 catchments initially selected for scenario runs, the highest total potential reduction in nutrient loads was projected for the Holland and the lowest for the Ramara. Much of this is due to the difference in area, with a greater potential for implementing more management strategies in larger catchments. Similarly, the high reductions in nutrients achieved by fertilizer strategies at all sites is due in part to the wider scale application of this strategy, compared to plans such as livestock restriction which are limited to a few individual fields. The use of 'management effectiveness per unit effort' is an important tool for resource management (Rao et al., 2009) as it standardises this assessment by removing the issue of number and scale of measures implemented, and gives an indication as to how many strategies would be required to reach a particular target reduction in nutrient loads.

4.2.1. Effectiveness of nutrient load and flow reductions

Management effectiveness demonstrated that across Simcoe pond retrofitting, livestock restrictions and reduction of fertilizer applications to crops were all similarly effective strategies at reducing both $N\text{-}NO_3$ and TP loads, while upgrading of septic systems and development of urban green spaces (parks) were less effective. The ineffectiveness of private sewage (septic system) upgrades may be attributed to the study assumption that these systems were fully functional, whereas

Table 4
Lake basin responses to simultaneous management of all catchments.

Basin	INCA nutrient load change (%)	INCA flow change (%)	Lake temp change	Lake TP conc (%)	Lake Chl-a conc (%)	Days above mean chl (per year)	Annual average DO conc (%)	DOD7
Main	27.3	0.10	−1.0	24.0	3.1	63.9	0.7	−0.3
Kempenfelt	3.4	0.03	−0.1	5.6	−0.1	−1.2	−1.9	19.4
Cooks	20.3	0.07	−0.01	91.2	65.3	176.7	−2.7	20.2

Table 5
Summary of relationship between DO and flow within basins of Lake Simcoe.

	Ideal period of nutrient load (NL) reduction	Change in DO per % change in NL	Change in DO per % change in flow	Max advised flow reduction per 1% NL load decrease for design of management strategies
E51		−2.45	30.85	0.081
K42	Autumn	−3.14	31.45	0.101
C9		−3.23	30.99	0.105

previous studies have shown that targeting leaking tanks can be a more effective strategy (Crossman et al., 2016). The poor performance of vegetation planting schemes may be linked to the urban areas targeted, where runoff is directed through stormwater systems, reducing the impact that vegetation has on infiltration rates, nutrient uptake and soil erosion (Hogan and Walbridge, 2007).

The variance in effectiveness of strategies between different catchments highlights the location-specific suitability of some management approaches. This is a result of differences in soil types and landscape connectivity (stream order and river network density). In catchments dominated by clayey soils the main mechanism of nutrient transport is often overland flow (Kleinman et al., 2009; Crossman et al., 2014) which is amplified over longer runoff pathways, especially in urban settings where there is little opportunity for plant interception. Higher river densities reduce the length of flow pathways, thus reducing the overall nutrient delivery load (Simard et al., 2000). Strategies are most effective when implemented in areas where the targeted pathway carries the greatest proportion of a catchments' total nutrient load (Heathwaite et al., 2000), and thus for urban parks and livestock strategies, effectiveness was reduced in clayey soils where stream connectivity was higher. Conversely in sandy soils where infiltration rates are higher, longer pathways may result in higher proportions of nutrients being bound to soils (Heathwaite et al., 2000); and thus management effectiveness was greater where pathways are shortest (in areas with high stream densities).

The same was not true of all strategies however, for instance fertilizer reduction and septic upgrades were more effective under high stream densities in clayey soils. This may be associated with the more intensive agricultural settings in which they are applied. In areas with dense vegetation longer surface-runoff pathways do increase the opportunity for plant interception (e.g. through riparian zones; Weissteiner et al., 2013; Schoumans et al., 2013). Therefore where sites in clayey soils are located further from the main channel (or in areas of low stream densities), much of the runoff is intercepted. Conversely in sandy soils where throughflow is more dominant, longer flow pathways within fertilized soils of agricultural areas may increase contact time with near-surface soil water stores of P (Haygarth et al., 1998; Börling, 2003), thus increasing the potential impact of a management strategy. Finally, the dissociation of pond retrofitting from soil type is likely due to flow and nutrients passing over paved impermeable surfaces.

Flow reductions occurred through establishment of urban parks primarily as a result of simulated increased infiltration, plant uptake and subsequent evapotranspiration from the vegetative canopy (Armson et al., 2013). Flow reduction was greatest in catchments with larger urban areas and higher direct runoff (again associated with paved surfaces), as a larger proportion of total catchment flow was directed through the area set aside for park development.

4.3. Management impacts on lake chemistry

4.3.1. Changes in lake TP reductions

Management scenarios which resulted in reductions in nutrient input loads from catchment tributaries had a significant impact on lake TP concentrations. However as described by Sharpley et al. (2013), responses were complicated by factors such as basin water residence time, basin depth and climatic events. When river discharge is reduced so too is the flow rate through the lake, increasing lake residence time and facilitating higher proportional P inputs from internal loading (Jeppesen et al., 2015; Vincent, 2009; Rippey and Anderson, 1997). Within the lake, larger responses in lake TP concentrations to management scenarios were projected where strategies were focused during spring, when impacts of internal loading are lowest; and at Cook's Bay which has the weakest stratification (Young et al., 2010). Smaller lake TP responses were projected at Kempenfelt Bay, and might be associated with higher internal loading (LSRCA, 2005) which becomes more significant as inflow rates are reduced. Importantly where total catchment reductions in nutrient loads from inflowing tributaries were sufficient to effectively dilute lake concentrations (Cook's Bay and main basin), the effects of changes in residence time were counteracted and the greatest reductions in lake TP concentrations were achieved.

4.3.2. Changes in lake Chl-a reductions

Different thresholds of nutrient reductions required in each basin to achieve decreases in Chl-a are likely due in part to differences between basins in the lake TP response to load reductions (i.e. due to residence times and internal loading). Slight projected increases in Chl-a might also be attributed to changes in timing of nutrient inputs (e.g. increases in $N\text{-}NO_3$ expected in autumn, a peak time for algal growth). Only in Cook's Bay where lake nutrient reductions were particularly high were reductions in Chl-a expected. These thresholds might go some way to explaining the stability of Chl-a which has historically been observed in Lake Simcoe (Eimers et al., 2005).

4.3.3. Changes in lake DO

Despite the increases in Chl-a, all strategies achieved an increase in average DO concentrations and a reduction in DO7. Consistent with relationships established by Nicholls (1997) and Young et al. (2011) these increases in DO were directly associated with reductions in nutrient loads, however projected reductions in lake temperatures had a stronger impact, and were caused by changes in tributary inflows and associated changes in lake residence times. Lower flow rates and higher residence times can lead to a reduction in thickness of the epilimnion and a slight warming at the very surface of the lake (Rimmer et al., 2011), resulting in an increase in stability of the thermal profile (Straškraba and Hocking, 2002) which becomes more resistant to wind induced mixing. With more heat trapped at the surface, water throughout the water column becomes cooler (Vincent, 2009) leading to a reduction in average water temperature. Colder water has a higher DO saturation concentration causing the expected increase in DO within the bottom zone of the water column; a physical effect that would be much greater in more strongly stratified deeper basins, and which explains the greater impact of flow reductions on DO at Kempenfelt Bay. In addition, the proportion of heat derived from tributaries decreases with reduction in inflowing waters (Straškraba and Hocking, 2002); monitoring data of 2016 demonstrates that rivers were warmer than the lake euphotic zones by early summer, and small reductions in warm summer inflow may contribute to lake cooling.

The reduced turbulence and preferential warming at the lake surface could also be a contributing factor to the projected increase in Chl-a concentrations in the main basin and Kempenfelt Bay. Relationships established during the baseline would suggest that algal growth in the main basin could enhance DO content through re-aeration, and supports findings of other studies (e.g. Fang and Stefan, 2009). At Kempenfelt Bay, although algal growth was shown to limit DO concentrations during the baseline, the strong positive physical impact of small flow reductions exceeded the negative biological impact during the individually-run scenarios, facilitating improvements in lake DO concentrations.

Importantly however the study found that larger flow reductions could reduce the extent of water column temperature decreases, and limit improvements in DO concentrations. Several processes might explain this relationship, including increases in residence times resulting in extensive warming at the surface extending down into deeper layers. This would reduce the average reduction in temperatures and lead to lower increases in DO concentrations. Additionally, under greater residence times increases in the sediment oxygen demand may act to restrict bottom zone DO concentrations (Nakamura and Stefan, 1994). Simultaneous implementation of all strategies across the Simcoe watershed therefore impeded lake recovery in all basins, where the effectiveness of strategies in improving lake DO in one catchment was reduced through the implementation of management strategies in another, i.e. through excess flow reductions. The increases in water temperatures projected in association with these large flow reductions exceeded the impacts of nutrient reduction efforts and the positive biological feedbacks in the shallower basins (Cook's Bay and the main basin), and contributed to the negative biological impacts in the deeper basin (Kempenfelt Bay); and are consistent with relationships established in observed and monitored data during the baseline period. To optimise improvements in lake DO concentrations a ratio of changes in flow and nutrient loads needed to be maintained in each sub-catchment. In summary, the study calls for a basin-wide coordination of management plans.

4.4. Sub-catchment effectiveness and optimization of management strategies across Lake Simcoe

The high effectiveness of strategies at reducing nutrient load exports within sub-catchments of Orillia, Hawkestone and Talbot was predominantly attributable to fertilizer reduction strategies. As changes in nutrient loads were the dominant driver of lake TP concentrations, it was unsurprising that Orillia and Talbot catchments demonstrated similarly high effectiveness in reducing lake TP concentrations. Due to differing lake basin responses however some areas which were relatively ineffective in reducing nutrient loads were found to be efficient in reducing lake TP and Chl-a concentrations, notably sites within the Holland and Maskinonge, feeding into Cook's Bay. This is attributable to the lower internal load inputs and lower residence times within this basin (Nürnberg et al., 2013). The inefficiency of sites feeding Kempenfelt and the main basin at reducing Chl-a can be attributed to the established minimum reduction in nutrient loads required (17.7% and 4.5% respectively) to elicit a response in Chl-a, which were not exceeded by any of the scenarios.

In accordance with previous studies (Eimers et al., 2005) results indicated that Chl-a concentrations or phytoplankton biomass are only one of a multitude of parameters influencing variability in DO concentrations within Lake Simcoe. This accounts for the inconsistencies between the locations with greatest effectiveness in reducing Chl-a (catchments feeding Cook's Bay), and effectiveness of improving DO and DO7 (sub-catchments feeding basins Kempenfelt Bay and the main basin). The ineffectiveness of strategies in catchments feeding Cook's Bay in improving DO was largely attributable to larger flow reductions experienced in these areas; flow reductions projected for catchments flowing into basin Cook's Bay are 1.6 and 2.2 times greater than in Kempenfelt Bay and the main basin respectively.

4.5. Uncertainty

In this study assessments of model performance were made during key hydrochemical events (snowmelt periods) and at high spatial and temporal scales (Crossman and Elliott, 2018), using daily monitoring data, in order enhance characterisation of parameters, and minimise the possibility of uncertainties feeding forward.

4.5.1. Model chain structure

There were several benefits to coupling the INCA and PROTECH models, including their identical simulation timescale (daily), and PROTECH requiring hydrochemical inputs directly provided by INCA outputs. The spatial scales of the models are quite different, with INCA being semi-distributed, while PROTECH is more spatially restricted, although it simulates high resolution variations in vertical mixing (Elliott and Bell, 2011). This limitation was overcome by using three PROTECH models to simulate variance between lake basins. To restrict feed-forward errors, calibration points were selected at the basin mouths. While this may have resulted in the exclusion of some shoreline effects, e.g. higher phytoplankton biomass tends to be observed near the shoreline of Cooks bay, compared to the mouth (Eimers et al., 2005), efforts were made to include the overall impact of shoreline conditions, for example the total nutrient retention of each basin was calculated.

4.5.2. Use of generalised linear models

The use of GLMs was possible due to the wide range of land uses, soil types and stream densities across which the original model chain was applied. While this statistical approach is an additional source of uncertainty, the speed and efficiency of the GLM offers a significant benefit over repeated application of the time and resource intensive process-based model chain. Jeppesen et al. (2009) used a similar “lumped statistical” approach in analyzing TP losses across 80 Danish catchments, detailing that the approach was robust provided that the conditions under which it was applied did not deviate heavily from those under which it was developed. In this study the GLM performed well over the 11 watersheds across which it was constructed (with between 92% and 99% of basin responses being accounted for); and this combined with the similar nature of the remaining 9 basins (geology, range of nutrient inputs) justified its application across the watershed.

Despite the uncertainties associated with the study, the potential for adverse impacts of some of the management approaches outlined here (e.g. of inhibiting the rate of lake recovery), make it important to consider the precautionary principle (Walker et al., 2003a, 2003b) of accepting uncertainties in projections where potentially significant environmental impacts are concerned. Here a suitable precautionary approach could be to focus management efforts in the most effective areas highlighted in the study, while ensuring that total inflow is maintained far above the minimum threshold. This could help to provide a buffer against future potential climate-induced changes.

5. Conclusion

Eutrophication and low dissolved oxygen concentrations are issues facing Lake Simcoe and other large waterbodies across the world. Following a period of apparent success in improving lake water quality across North America, higher frequencies of algal blooms have recently recurred and DO concentration targets have not been consistently attained. It has been suggested (Jarvie et al., 2017) that management strategies applied to resolve these issues across many lakes in North America may in fact be contributing to the problem. The precise reasons why, and solutions for this have not yet been determined; this modelling study offers an insight into the complex interactions between land management and lake responses.

In general results support methods of targeting dominant nutrient transport pathways within individual sub-catchments as a mechanism of achieving maximum effectiveness of reductions in nutrient exports. Strategies simulated to establish urban parks had additional and unintended impacts on river discharge, where planting of vegetation altered infiltration rates and quantities of evapotranspiration. Sites which were most effective at reducing nutrient exports were not however necessarily those most effective at eliciting responses in lake chemistry. Particularly low effectiveness of strategies in reducing lake TP concentrations within Kempenfelt Bay were attributed to higher internal TP loading. Similarly each basin demonstrated a threshold of nutrient reductions which must be crossed before a significant drop in Chl-a was experienced. Changes in nutrient loads were a significant driver behind lake improvements in DO and DO7, however the small unintended reductions in tributary discharge did have a greater impact. It is important to note that the effect of flow on DO was an indirect result of its impact on lake temperature, through changes in basin water residence times, stratification periods and epilimnion depth. Positive biological feedbacks involving surface warming, increases in chlorophyll concentrations, and greater aeration may also have affected DO concentrations in shallower regions of the lake.

Importantly, negative impacts from larger reductions in flow exceeded any positive impacts of nutrient reductions, and led to increases in lake temperatures and sediment oxygen demand, and reductions in DO concentrations. This relationship between tributary flow and lake temperature was established in both modelled and monitoring data. A threshold analysis demonstrated that to achieve optimum improvements in lake DO concentrations it is important that strategies maintain a maximum ratio of 0.1% flow reduction for every 1% reduction in nutrient load. This is especially pertinent in Kempenfelt Bay where low DO levels are a current concern. This study therefore suggests that although lake improvements are achieved through exceeding minimum nutrient load reductions, optimum effectiveness could be reached through a coordinated management approach which considers the potential for both physical and biological feedbacks associated with changes in lake temperature.

Thresholds analysed in this study may alter under future climate change, and higher tributary inflows may be required to sustain current lake volumes, temperatures and DO concentrations. Further research is required to identify possible changes in sensitivity of biological and physical feedbacks, and ultimately to assess the likely resilience of current management approaches.

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Appendix A. Supplementary data

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