memo

Environmental Research Institute, University of Waikato

To: Greater Wellington Regional Council

From: Mathew Allan

CC: Natasha Tomic and John Bright

Date: 02/11/2017

Re: Lakes Wairarapa and Onoke scenarios in comparison to baseline

Purpose

To deliver a succinct memo regarding lake water quality changes in relation to baseline scenarios.

Scenario Inputs that can influence changes

Catchment related scenarios are discussed in memos from other modelers and won't be covered in great detail here. BAU, SILVER and GOLD scenarios were all ran using time periods is 2025, 2040 and 2080. The scenarios apply various mitigation options including retirement of land, pole planting, land treatment of wastewater, minimum flow rules, and on-farm mitigations.

Lake specific modelling scenarios were run in addition to catchment scenarios (Table 1, Appendix). The Lake Wairarapa specific scenarios included: **Modelling shorthand naming conventions**	**Description**
ALL_RUA_SILVER2080 ALL_RUA GOLD2080	All flows of the Ruamāhanga River entering Lake Wairarapa. No flow by-passing via the diversion.
MEDIAN_RUA_SILVER2025/2040/2080	Flows below median flow go into Lake Wairarapa, and flows above median flow are by-passed
Outlet_Close_SILVER2025/2040/2080, Outlet_Close_Rua_All_SILVER2025/2040/2080	Lake Onoke outlet closed January to March every year. Lake Onoke outlet closed Jan to Mar, all Ruamahanga flows diverted into Lake Wairarrapa before entering Onoke
1m_Inc_SILVER2025/2040/2080	Deepening both lakes by 1m

Significant assumptions

Within lakes nutrient loading comes from external loads (catchment surface and groundwater flows) and internal loads (derived from diffusion and resuspension from nutrients stored in lake bed sediments). These nutrients derived from the lake sediments can comprise a significant proportion of the total load to the lake and therefore any modelling of lake ecology must consider these. Therefore any changes to nutrient concentrations derived from catchment modelling or from changes in flow regimes (Ruamāhanga division into Lake Wairarapa) were applied to sediment nutrient release rates based on a percentage reduction or increase of sediment nutrient release rates in relation to baseline conditions. This was in order to simulate how different catchment loads influence the release rates within the sediment. In reality, there is a lag time for sediments to reach equilibrium, usually between 10 and 15 years (Jeppesen et al 2005), but sometimes persisting for more than 20 years for internal loading of phosphorus (Søndergaard, Jensen & Jeppesen 2003).

DYRESM CAEDYM 1-D modelling is a simplification of reality whereby we assume the lake is fully mixed across the lake's surface, and only simulate variation over lake depth. This means we have multiple cells from the lake surface to the lake bottom. This allows models to run fast, and therefore run over long time periods, and be easily calibrated.

AED CAEDYM 3-D modelling is a close representation of reality where we can simulate and look at the lake from any prospective. This method divides the lake into cells across the lake surface and from the lake surface to the lake bottom. 3-D models require much more processing power, a much more difficult to calibrate, and take much longer to run. Therefore these models will run over short time periods of three months in the summer of 2012 from January to the end of March.

For BAU, GOLD and SILVER lake water levels were based on historical measurements.

For modelling of *E.coli*, the following assumptions were used:

- Bacteria are present in the water column and do not accumulate in the sediment;
- Bacteria do not grow in the lake;
- Bacteria have a constant settling rate and mortality rate.

Result outputs for discussion

Reporting locations for 1-D

For 1-D modelling there are only two reporting points. The ideal Lake Wairarapa monitoring location for comparison to 1-D models is Lake Wairarapa Middle Site, due to its central location at the deepest point (2.6 m) within the lake (Fig 1). However monitoring data for this site is only available from January 2014. Therefore, for 1-D model calibration and validation data from Wairarapa Site 2 was adopted, as data was available from February 1994. This is also the second deepest monitoring site (2.2 m). While the model was calibrated for Site 2, our opinion is that model output data is valid for a reporting point at Lake Wairarapa Middle Site. Within Lake Onoke, data from the only monitoring point within the lake (Site 1, 1.4 m depth) was used for calibration and validation, therefore model output could be used as a reporting point for Site 1 (Fig 2).

Reporting locations for 3-D

For three-dimensional lake modelling the reporting points included Lake Wairarapa Site 2, Middle, Alsops and Outlet (labelled DS barrage gates)(Fig. 1). For Lake Onoke sites included Site 1, Middle and Deepest, with the middle and deepest point sites being additional to those requested by GWRC. The deepest point site is located to the south east of Lake Onoke at C. 6.8 m depth (Fig. 2).

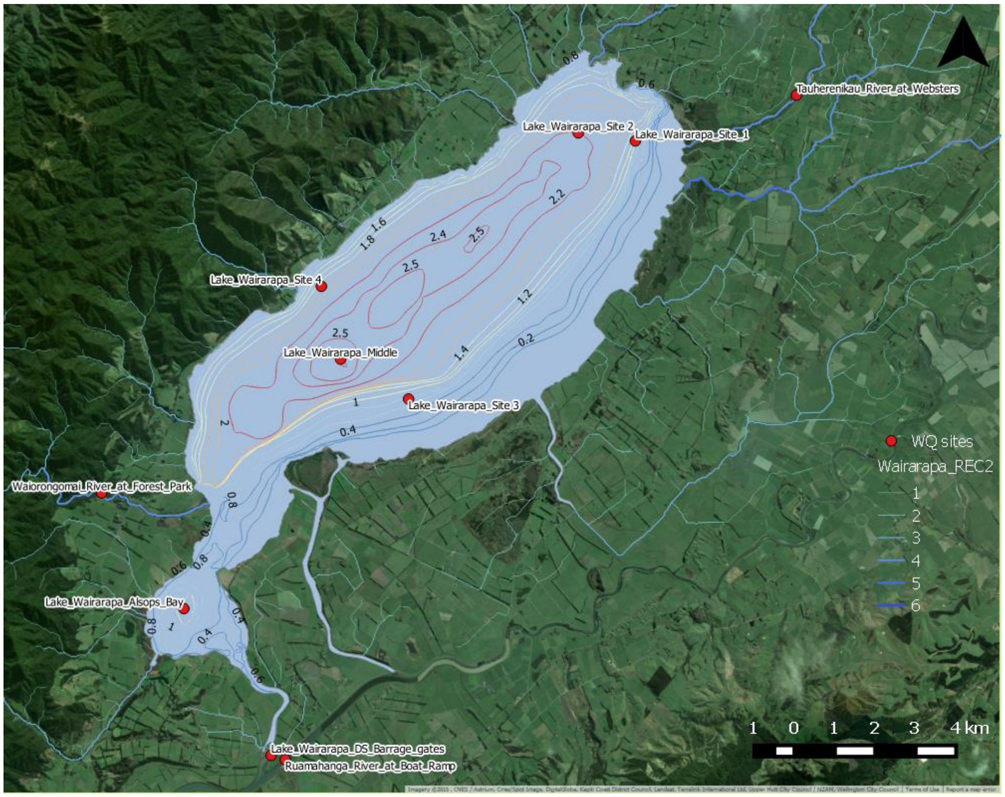

Figure 1. Lake Wairarapa study site with water quality (WQ) monitoring locations, River Environment Classification stream order (shades of blue), and bathymetric isobaths labelled by depth (m).

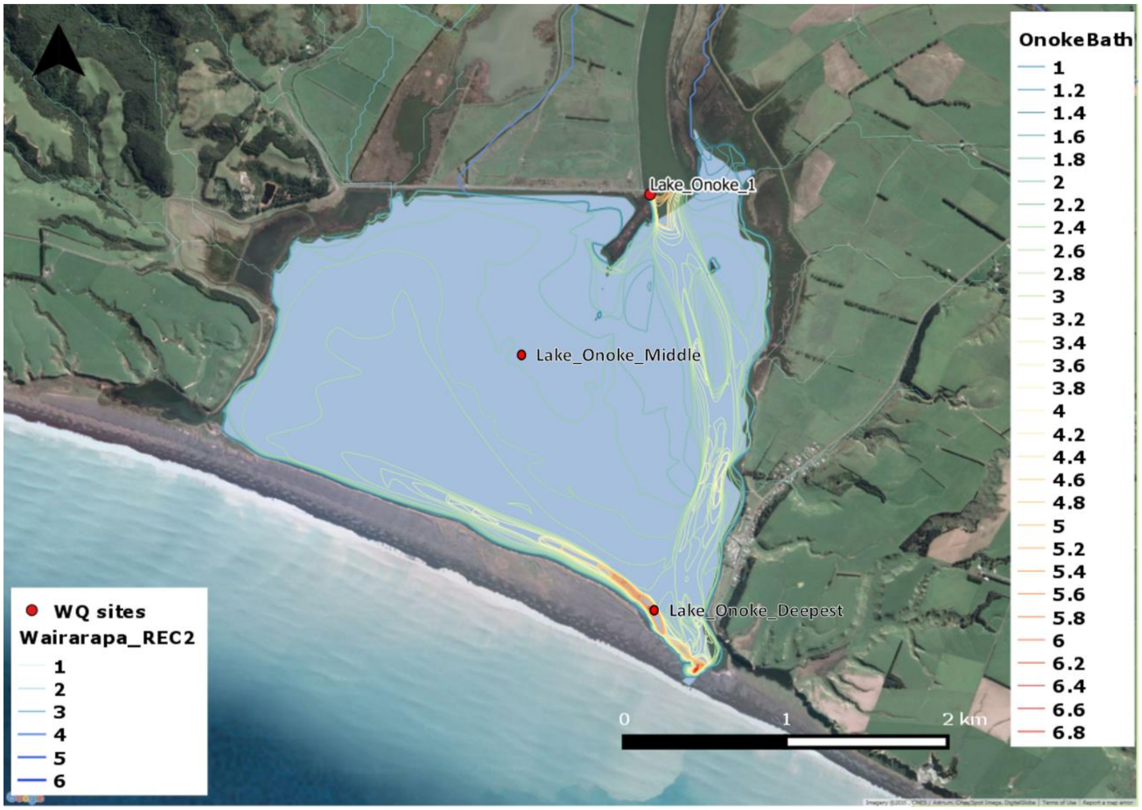

Figure 2. Lake Onoke study site with water quality (WQ) monitoring location shown (Lake_Onoke_1) with bathymetric isobaths (m) displayed in the legend.

1-D Scenario results

Within Lake Wairarapa, 23 different scenarios were run (Appendix table 1) resulting in water quality variable changes from baseline between 92.6% reduction (cyanobacteria under the ALL_RUA_GOLD2080 scenario) and 345.7% increase (*E. coli* under the ALL_RUA_SILVER2025 scenario).

The lakes catchment scenarios GOLD and SILVER resulted in improved water quality, however for SILVER and GOLD scenarios increases in nitrate concentrations ranged from 0.6% (SILVER2025) to 17.2% (SILVER2080), primarily driven by lower phytoplankton uptake associated with greater phosphorous limitation.

1-D Catchment scenario lakes results

The BAU scenarios only marginally improved water quality, for example BAU2080 resulted in a 1.5% reduction in total phosphorus concentrations and a 2.7 % reduction in TN concentrations (Fig. 3). However, the SILVER and GOLD scenarios both had a significant influence on water quality, and as expected the largest improvement in water quality occurred on the 2080 scenarios. The GOLD2080 and SILVER2080 scenarios simulated very similar reductions in nutrient concentrations in both Onoke and Wairarapa, and increases in water clarity (Fig 3 and 4). For example in Wairarapa, SILVER2080 simulated a 10.32 % reduction in total phosphorus whereas as GOLD2080 simulated a 10.34% reduction. Generally, the largest changes in water quality parameters were seen in chlorophyll *a* and cyanobacteria concentrations. For example GOLD2080 saw a 44.1% reduction in chlorophyll *a* concentrations.

1-D Lake Scenario results water quality

The diversion of the Ruamāhanga River into Lake Wairarapa, combined with changes in catchment scenarios discussed above, brought about the greatest changes in water quality, both positive and negative. While the scenario generally improved water quality in Lake Wairarapa, scenarios where the entire flow was diverted increased *E. coli* concentrations by 342 %, due to high concentrations in the Ruamāhanga River. In addition, residence time reduced to 9.1 days compared to 38.1 days under baseline.

The diversion of Ruamāhanga River flows below median (SILVER2080 flows) saw the greatest improvement in water quality of all scenarios, due to increased flushing, lower inflow nutrient and total suspended solid concentrations (even though total loads increased), leading to shorter residence times (23.5 days compared to 38.1 days under baseline), reducing the impact of high internal loading and sediment resuspension.

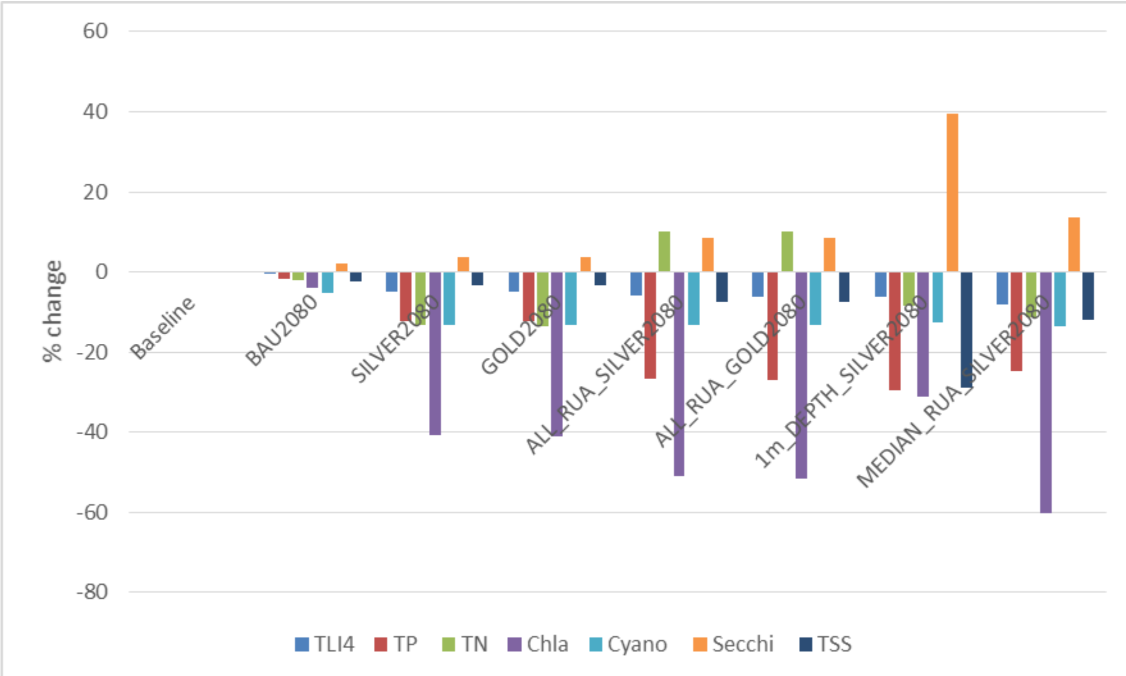

Figure 3. Lake Wairarapa 1-D simulation summary percentage change for 2080 (positive is increase, negative is decrease).

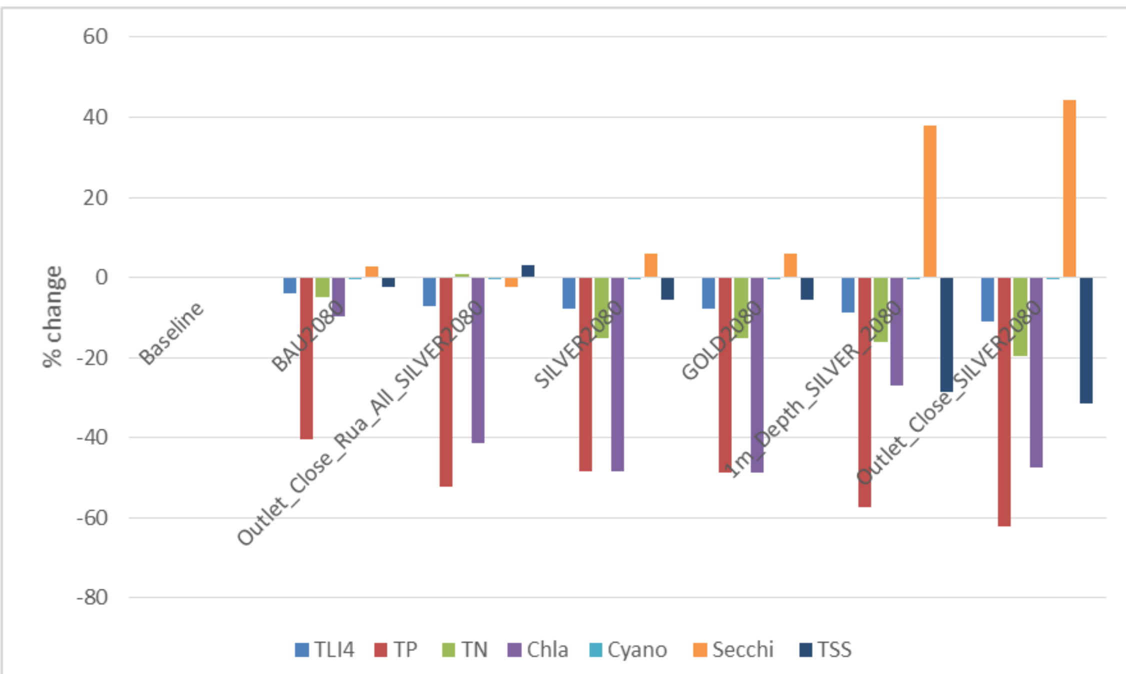

Figure 4. Lake Onoke 1-D simulation summary percentage change (positive is increase, negative is decrease) for 2080.

1-D and 3-D lake scenario results water E.coli

Three-dimensional (3-D) ecologically coupled hydrodynamic models were applied for the scenarios using only 2080 inflows. For lake specific scenarios including diversions, flow manipulations and lake level changes, 3-D models used SILVER2080 inflows (see appendix table 1).

Relatively small reductions in the external loading (from inflow) of *E.coli* were amplified within Lakes Wairarapa (Fig 5, Table 1). The *E.coli* concentrations in the major Lake Wairarapa inflow (Tauherenikau) are generally low, and flows are of Excellent NPS swimmability. Catchment mitigation scenarios resulted in comparatively small reductions in *E.coli* inflow loads (e.g. 0.8% for GOLD2080). This was reflected in simulated within lake concentrations and Excellent NOF swimmability for Lake Wairarapa scenarios (Fig 5). Note that while there were large simulated percentage reductions in *E.coli* in Lake Wairarapa under SILVER and GOLD (e.g. -40% under GOLD2080), the actual simulated median concentrations within the lake were very low with median concentrations being less than 1 CFU for all simulations including Ruamāhanga diversion scenarios. Therefore the reductions under catchment management scenarios are negligible in terms of changes in swimmability for Lake Wairarapa.

The Ruamāhanga River was simulated as having Good NPS swimmability (Rua at US Lake Wai Outlet). However there were some very high concentration flow events over the period (e.g. max *E.coli* concentration of 9060 CFU). This resulted that diversion scenarios of all Ruamāhanga water into Lake Wairarapa meant large percentage increases in within lake concentration (321 % increase). However, due to the rapid dilution and decay of *E.coli* this did not change the Excellent swimmability at any monitored site in both the 1-D and 3-D simulations. However, there may be localized areas within lakes with a lower swimmability (e.g. Figure 7), as is the case for simulated swimmabilty from 3-D simulations in Lake Onoke (Table 1). For example within the vicinity of the historical Ruamāhanga inflow location, Ruamāhanga diversion scenarios increased concentrations, especially “downstream” in the prevailing flow path to the south (Fig. 7).

One dimensional simulations of *E.coli* in Lake Onoke all determined Excellent swimmability, but this is not the case for site specific swimmability simulated with 3-D models. Lower swimmability category was evident in 3-D simulations of *E.coli* (Table 1). Under baseline and SILVER2080 scenarios, swimmability was simulated as Good at Onoke Site 1 and Middle, in contrast to that simulated Excellent under all 1-D simulations, while at the deep site swimmabilty was Fair.

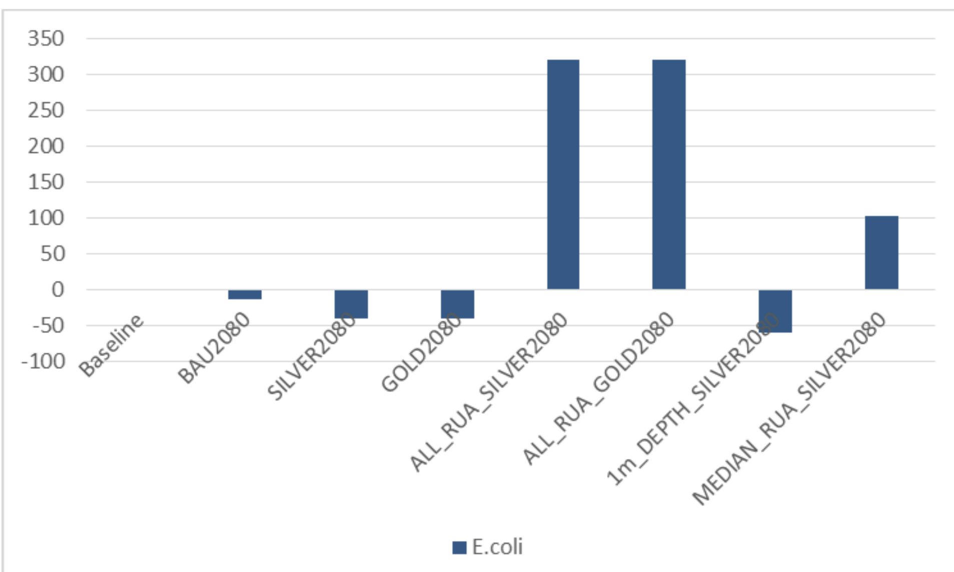

Figure 5. The 1-D simulated percentage change in *E.coli* concentrations in Lake Wairarapa comparing Baseline to 2080 scenarios.

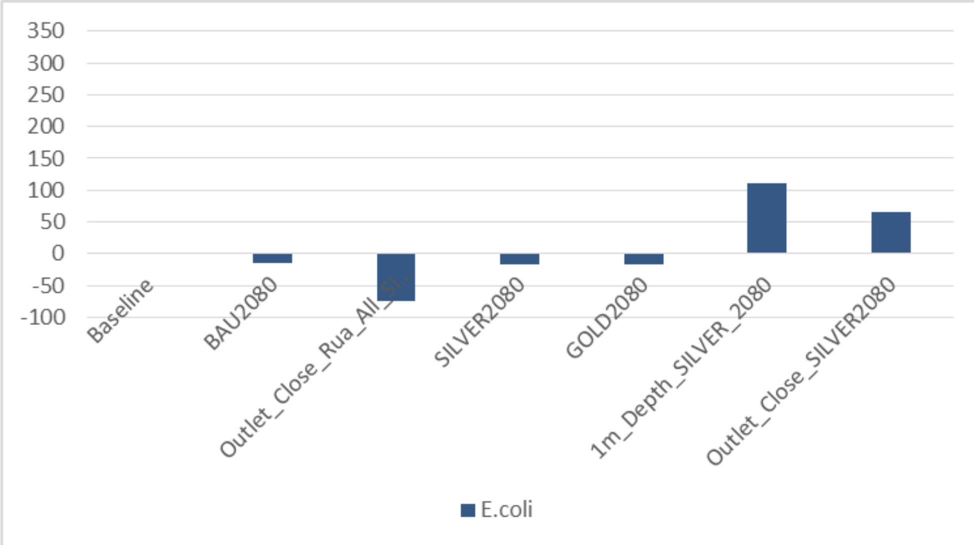

Figure 6. The 1-D simulated percentage change in *E.coli* concentrations in Lake Onoke comparing Baseline to 2080 scenarios.

Reductions in the external loading (from inflow) of *E.coli* in Onoke (19 % reduction for Silver and GOLD 2080) did not change swimmability in 1-D or 3-D scenarios. It is important to note that while lake level and flow manipulation scenarios in Lake Onoke sometimes increased *E.coli* concentrations in both 1-D and 3-D, changes in median lake averaged concentration (represented by 1-D simulations) were small and less than 1 CFU. These changes result primarily from changes in hydrodynamics and residence times and less flushing under the outlet closed scenario and the 1m increase scenario. Under 3-D simulations these changes resulted in changes to swimmability criteria (Table 1). For example under the SILVER2080 1m depth increase scenario swimmmability changed from good to intermittent for Onoke Middle and from Fair to Good for Site 1. This is driven by changes in hydrodynamics, and the resulting dispersion/flush rate of *E.coli*. This effects the residence time and settling rate.

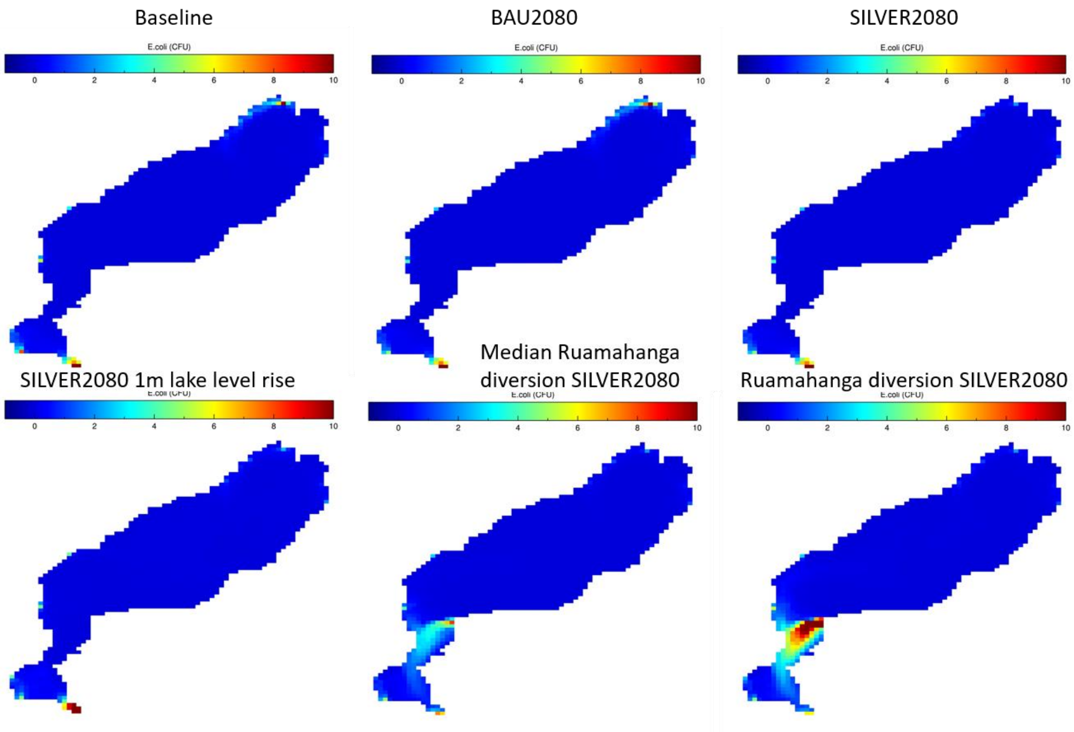

Figure 7. Median 3-D simulated *E.coli* concentration in Lake Wairarapa over a 91 day period beginning 1 Jan 2012 at 12pm. Note this is not calculated via. Hazen methods, however all other NOF NPS related stats use Hazen. The scale runs from 0 to 10 CFU. Illustrative ONLY.

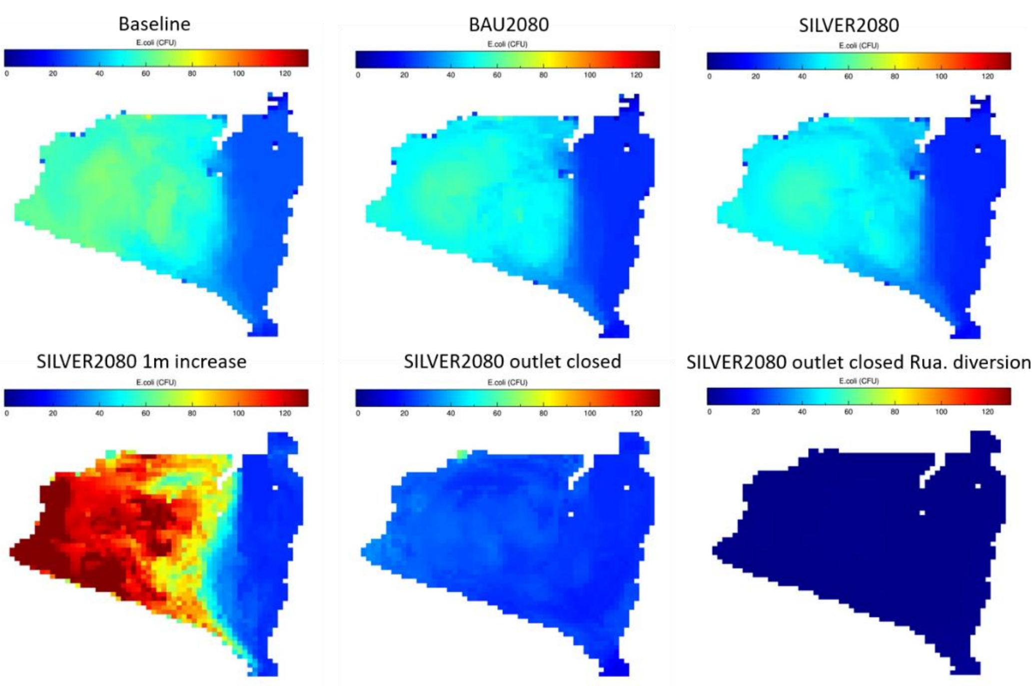

Figure 8. Median 3-D simulated *E.coli* concentration in Lake Onoke over a 91 day period beginning 1 Jan 2012 at 12pm. The scale runs from 0 to 130 CFU, with median 130 CFU being the swimmability boundary between excellent and intermittent. Note this is not

calculated via. Hazen methods, however all other NOF NPS related stats use Hazen. Illustrative ONLY.

Table 1. Site specific results of 3-D ecologically coupled hydrodynamic modelling of E.coli swimmability (NPS)

Site	Baseline	BAU2080	SILVER2080	GOLD2080	1m depth increase_SILVER2080	Outlet_close_SILVER2080	Outlet_close_RUA_SILVER2080	ALL_RUA_SILVER2080	MEDIAN_RUA_SILVER2080
Onoke S1	B	B	B	B	B	B	A		
Onoke Middle	B	B	B	B	D	B	A		
Onoke Deep	C	C	C	C	B	B	A		
Wai S2	A	A	A	A	A			A	A
Wai Middle	A	A	A	A	A			A	A
Wai Alsops	A	A	A	A	A			A	A
Wai Outlet	A	A	A	A	A			A	A

Summary

- High internal loading of Phosphorous from sediments in Lake Wairarapa results in reduction of effectiveness of mitigations compared to Lake Onoke.

- High sediment resuspension from the bottom sediments in Lake Wairarapa results in continued low clarity under all scenarios, with best water clarity achieved in the 1 m depth increase scenario (0.2 m Secchi, compared to 0.15 m under Baseline). Secchi depth is a measurement of water clarity whereby a black-and-white disk is lowered down from the lake surface until it disappears from view from the observer. The depth with the disc disappears from view is termed the Secchi depth. For significant macrophyte re-establishment Secchi depth would need to reach 0.5 m (Jeppesen et al 2005). The 3-D modelling showed potential for this to be achieved with lake level manipulation.

- Within Lake Wairarapa, a 1 m increase in lake depth combined with SILVER2080 catchment scenario increased **mean** chlorophyll *a* concentrations when compared to the SILVER2080 scenario. This was caused by less light limitation due to less sediment resuspension from the lake bottom. However, the net effect would increase water clarity and the potential for macrophyte re-establishment. These conclusions also apply for the 1 m increase scenario in Lake Onoke.

- SILVER2080 and GOLD2080 catchment scenarios were not significantly different in lakes Wairarapa and Onoke, especially when compared to catchment and lake model uncertainty.

- While 'the summer outlet closed scenario' generally brought about the greatest improvement in water quality in Onoke, there was increased risk of Cyanobacterial blooms. However, as long as the residence time remains under 20 days this risk would be very low. Under this scenario, when Ruamāhanga waters were diverted through Lake Wairarapa, there was a 63.2% reduction in *E.coli* within Onoke, owing to higher mortality and settling within Lake Wairarapa, related to the longer residence time involved in taking the Lake Wairarapa flow path.

- Catchment scenarios had a greater influence on Lake Onoke trophic status when compared to Wairarapa, due to the shorter residence time and lower internal load relative to external load (from the sediments) in Onoke.

- Water quality in Lake Onoke is susceptible to changes in water quality in Lake Wairarapa, particularly in relation to chlorophyll *a* and total suspended solids. High lakebed sediment resuspension events in Lake Wairarapa are transported to Lake Onoke. Modelling shows most chlorophyll *a* in Onoke is derived from Lake Wairarapa. The very low residence time in Onoke (0.5 days) does not allow for significant phytoplankton growth. However, 3-D simulations show longer residence times in the western lake.

- The greater reduction in total phosphorus then total nitrogen throughout the scenarios has resulted in more in Nitrogen limitation relative to Phosphorous limitation. This would further reduce the likelihood of cyanobacterial blooms.

- For the restoration of Lake Wairarapa, control of internal load of Phosphorous and suspended sediments is the key. The diversion of below median flows in combination with SILVER2080 flows brought about the greatest improvement in water quality, due to increased flushing, lower inflow concentrations (even though total load was increased).

- From a management perspective, the Ruamāhanga division scenarios present another management option. When wind speeds are high in Lake Wairarapa, high sediment resuspension occurs. Under these conditions, the lake could be flushed with Ruamāhanga flows, thereby exporting suspended sediment, and any bound Phosphorous and suspended organic matter. This would be an effective strategy to potentially reduce

internal nutrient and sediment loading from the lake bed, and mitigate the very high sedimentation rate. However, under this scenario there would be high total suspended solids transport into Lake Onoke. Provided the mouth is open much of this flow would be exported to the ocean. However, the effects on local seabed benthic communities may need to be considered.

References

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Jeppesen E, Søndergaard M, Søndergaard M, Christoffersen K (1997) The structuring role of submerged macrophytes in lakes.

Søndergaard, M., Jeppesen, E. & Jensen, J.P. (2003) Internal phosphorus loading and the resilience of Danish lakes. Lakeline, 23, 17–20.

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Appendix

Table 2. Scenarios and assumptions.

Management option	Modelling inputs	Notes	Shorthand associated naming conventions
BASELINE	**Calibrated catchment model**	**All flows and concentrations based off a 22 year flow simulation from 1/7/1992 to 30/6/2014 (applies to all scenarios)**	**BASELINE**
BAU	Steep slope retirement/planting, stock exclusion from waterways, wastewater discharging partially to land, Minimum flows and allocation amounts based on limits set in Proposed Natural Resources Plan (PNRP), Tier 1 immediately.		**BAU2025/2040/2080**
SILVER	Steep slope retirement/planting, stock exclusion from waterways, riparian planting, wastewater discharging only to land, Minimum flows and allocation amounts based on limits set in Proposed Natural Resources Plan (PNRP), Tier 1 immediately Tier 2 mitigations by 2040 Tier 3 mitigations by 2080		**SILVER2025/2040/2080**

GOLD	Steep slope retirement/planting, stock exclusion from waterways, riparian planting, wastewater discharging only to land, Minimum flows and allocation amounts based on limits set in Proposed Natural Resources Plan (PNRP), Tier 1 mitigations immediately (as BAU), Tier 2 mitigations by 2025, Tier 3 mitigations by 2040		**GOLD2025/2040/2080**
All flows of the Ruamahanga River entering Lake Wairarapa. No flow by-passing via the diversion.	Gold scenario inflows (river flows and concentrations)	DYCD 057 Replaced with 200. GOLD2080 Flows, ELCD 057 Replaced with 200. GOLD2080 Flows	**ALL_RUA_GOLD2025/2040/2080**
As above.	Silver scenario inflows (river flows and concentrations)		**ALL_RUA_SILVER2025/2040/2080**
Flows below median flow go into Lake Wairarapa, and flows above median flow are by-passed.	Silver scenario contaminant concentrations inflows	DYCD 057 Replaced with 200. Silver2080 Flows. Flows below median of 78.10 m3 s-1	**MEDIAN_RUA_SILVER2025/2040/2080**
Lake Onoke outlet closed January to March every year.	Silver scenario contaminant concentrations inflows.	This includes a separate sub-scenario with the Ruamāhanga River diverted back into Lake Wairarapa	**Outlet_Close_SILVER2025/2040/2080** **Outlet_Close_Rua_All_SILVER2025/2040/2080**

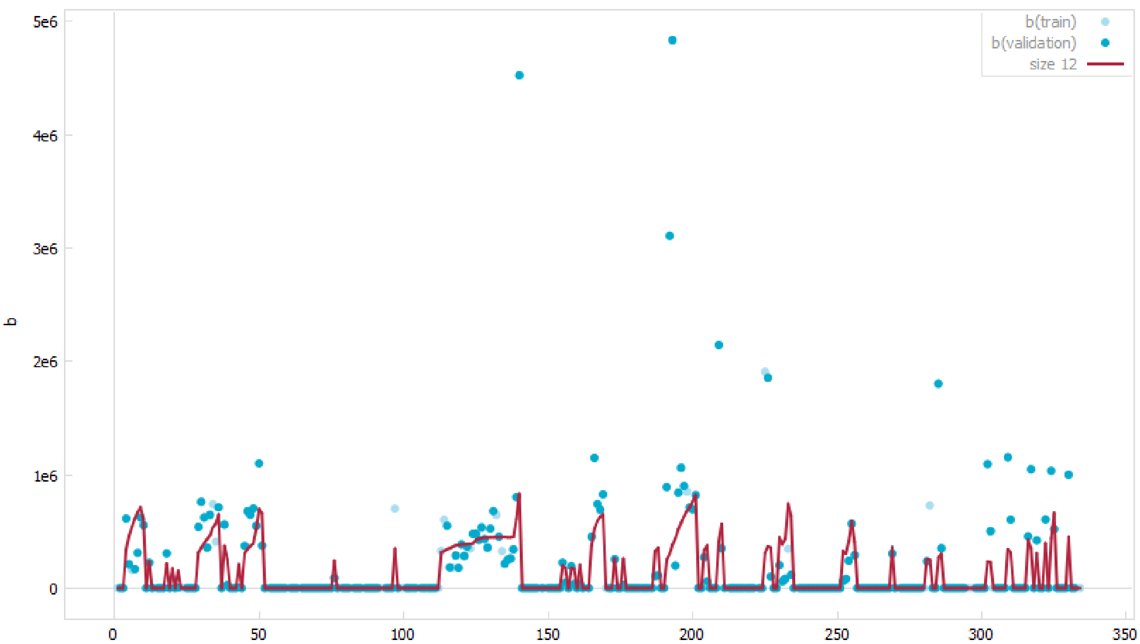
		(used onoke_all_zero_200 folder), New water balance with no ocean inflow Jan-March and high water level (95 percentile).	
Deepening both lakes by 1m.	Extra depth created by operating at a higher level. Silver scenario inputs	Operate at 1m higher level	**1m_Inc_SILVER2025/2040/2080**

Barrage inflow

There is uncertainty in deriving barrage inflow into Lake Wairarapa. The flow at the barrage gates has been monitored since August 2012, using a side-looking Acoustic Doppler Current Profiler (ADCP) (Thompson & Mzila, 2015), however estimations for backflow into Lake Wairarapa were needed for the entire simulation period. A statistical model was using a symbolic regression model trained over the monitored barrage flow period. This model used Onoke water levels and Lake Wairarapa outflow as inputs:

Barrage inflow = (324.89*Onoke water level - 3018618.30)/exp(*barrage outflow*)

for simulations *barrage outflow* was determined using a water balance. Correlation Coefficient = 0.58, mean absolute error=122125.75 m3/day. Note that this method underestimated large barrage inflows (Appendix Fig. 1).



Appendix Figure 1. Barrett inflow estimations (redline) compared to in situ measurements (blue dots).