A preliminary assessment of the potential for augmentation of the inflows of Lake Hayes with Arrow River irrigation water to speed the recovery of the lake

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Background

Lake Hayes usually undergoes thermal stratification in from September to May or June. During this period, the warmer surface water is separated from the denser, colder water at the bottom of the lake. Due to the breakdown of algal material which settles to the bottom, the oxygen content of the bottom water declines during the stratified period, with the lake bed beginning to become anoxic in in December to January (Fig. 1).

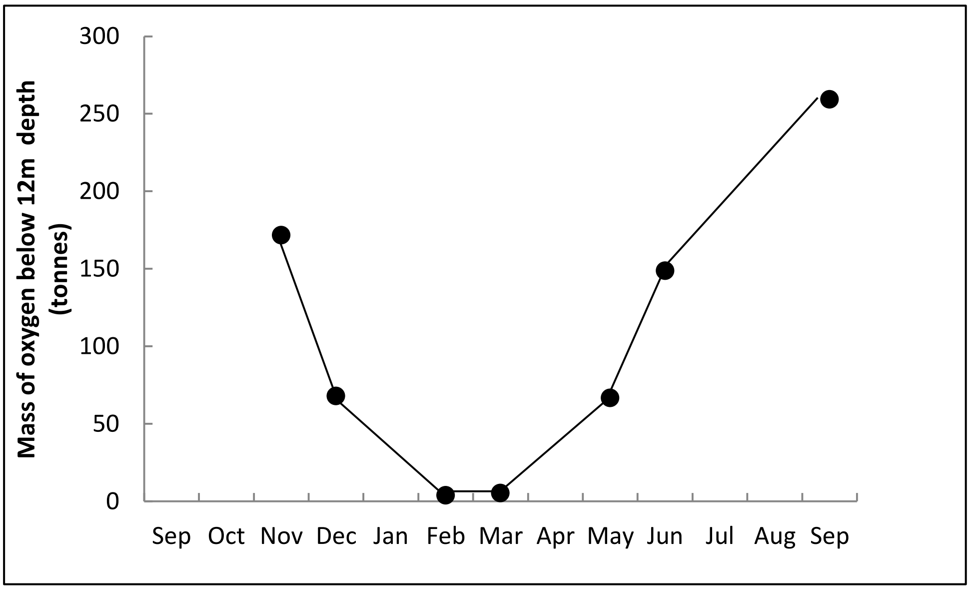

Figure 1. Mass of oxygen in the bottom waters (below 12m) of Lake Hayes, summer 2012/13.

As this occurs, phosphorus, which is bound to the sediments when oxygen is present, become liberated from the sediment and diffuses into the bottom waters, reaching very high levels by the end of the stratified period (Fig. 2).

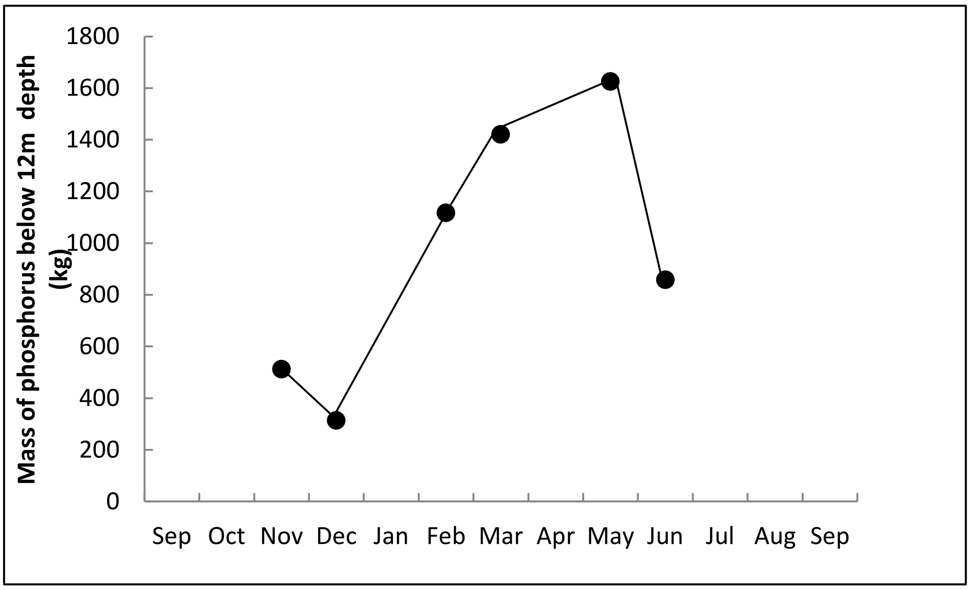

Figure 2. Mass of phosphorus in the bottom waters (below 12m) of Lake Hayes, summer 2012/13.

As stratification breaks down and the lake again mixes from top to bottom in June, this dissolved phosphorus becomes available to algae, fuelling the algal blooms that plague Lake Hayes during spring, summer and autumn.

The Friends of Lake Hayes have been examining potential methods for reducing the internal recycling of phosphorus in the lake, which, if successful, would likely lead to an improvement in water quality and clarity in the lake. A proposal has been put forward to help speed the recovery of Lake Hayes by augmenting the inflow to the lake at Mill Creek with water from the Arrow River Irrigation Scheme, sourced from the Arrow River near Macetown (Fig. 3).

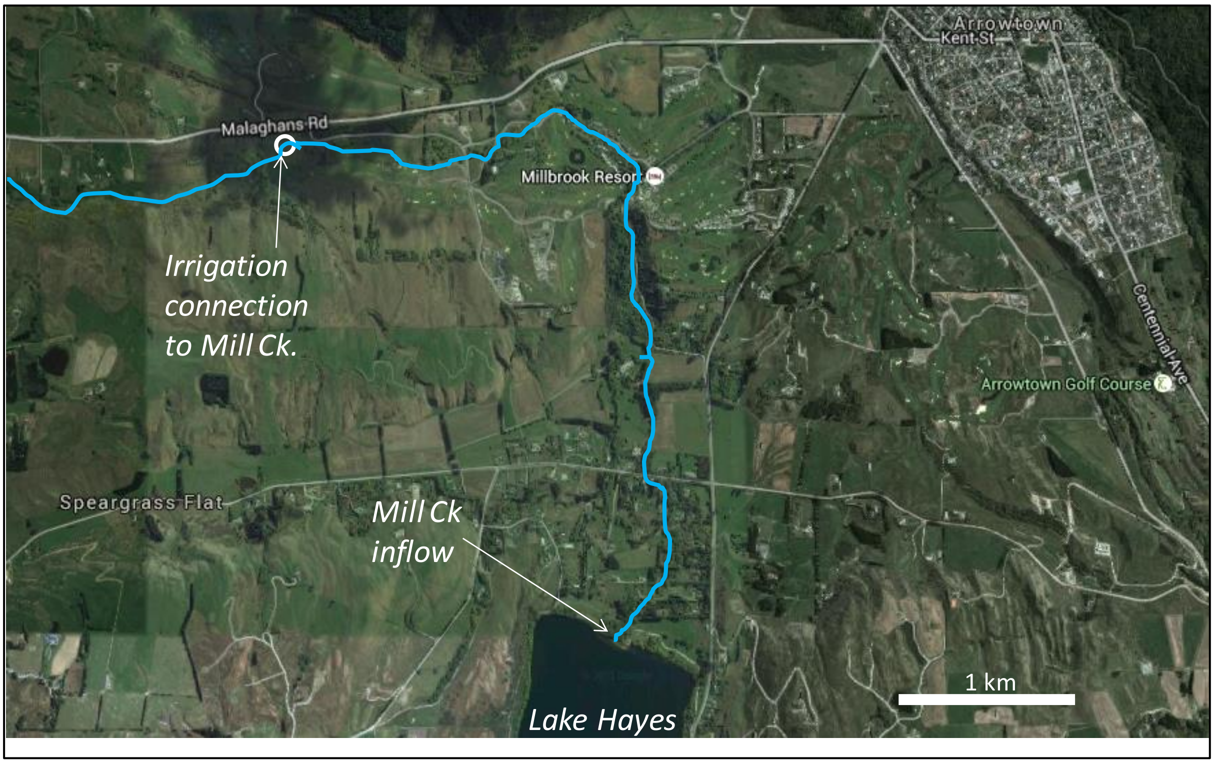

Figure 3. Map of the Lake Hayes area, showing Mill Creek and the potential connection point of the Arrow River Irrigation Scheme.

In this preliminary report, I use available data to try to answer four key questions regarding this potential restoration idea: 1. Could the augmented inflow flush substantial amounts of phosphorus (P) from the lake? 2. Would the inflow water dilute and displace the P-rich bottom water? 3. Could the augmented inflow supply enough dissolved oxygen to the bottom water to prevent its deoxygenation and, thereby, prevent P release? and, 4. assuming that the augmented flow doesn't displace the bottom water (but displaces surface water), what percentages of the lake surface water, the surface water total phosphorus and the surface water chlorophyll *a* would be removed per year by the augmented flow?

1. Could the augmented inflow flush substantial amounts of phosphorus from the lake?

This proposal would increase the flushing of the lake, which currently replaces its water roughly every 18 months. If the Arrow River water is more dilute that the lake water (with respect to phosphorus), then the flushing effect could remove some of the recycled phosphorus from the lake by displacement. The magnitude of the enhanced flushing effect would be proportional to: 1. the difference in nutrient concentrations between the Arrow River and the lake water that it displaces and 2. the amount of water available for flushing.

To maximise the flushing effect, it would be desirable for the Arrow River water to displace the colder bottom water of the lake during summer and autumn, when the phosphorus level in the bottom water is high (when bottom water phosphorus concentrations can be over 100 times greater than the surface waters). For this to occur, the augmented Mill Creek inflow would have to be substantially colder/denser than the surface water of the lake, forcing the inflow water to plunge to the bottom of the lake rather than flow into the surface water, where the concentration of available P is generally much lower in summer and autumn.

Below, I have examine how beneficial the augmented flow could be for flushing phosphorus from the lake.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Arrow river phosphorus concentrations (Otago Regional Council data; Table 2)

3. Lake temperature profiles (University of Otago; Fig. 4)

4. Lake phosphorus concentration profiles (University of Otago; Fig. 5)

Table 1: Available water from the Arrow River Irrigation Scheme (info provided by Rob Hay).

Month	Cubic m per day	Cubic m per month	Cumulative irrigation inflow
Sept	18000	540000	540000
Oct	18000	540000	1080000
Nov	9000	270000	1620000
Dec	9000	270000	1890000
Jan	9000	270000	2160000
Feb	9000	270000	2430000
March	9000	270000	2700000
Apr	18000	540000	2970000
May	18000	540000	3510000
June	18000	540000	4050000

Table 2. Typical phosphorus concentrations of the waters of Lake Hayes (University of Otago) and the Arrow River (Otago Regional Council data from site at Morven Ferry Rd.).

Month	Lake Hayes surface water TP (µg/L)	Lake Hayes bottom water TP (µg/L)	Arrow R. TP (µg/L; ORC data*)
Nov	27	69	14
Dec	52	50	9
Feb	47	113	7
March	116	164	8
May	43	205	9
June	69	97	5

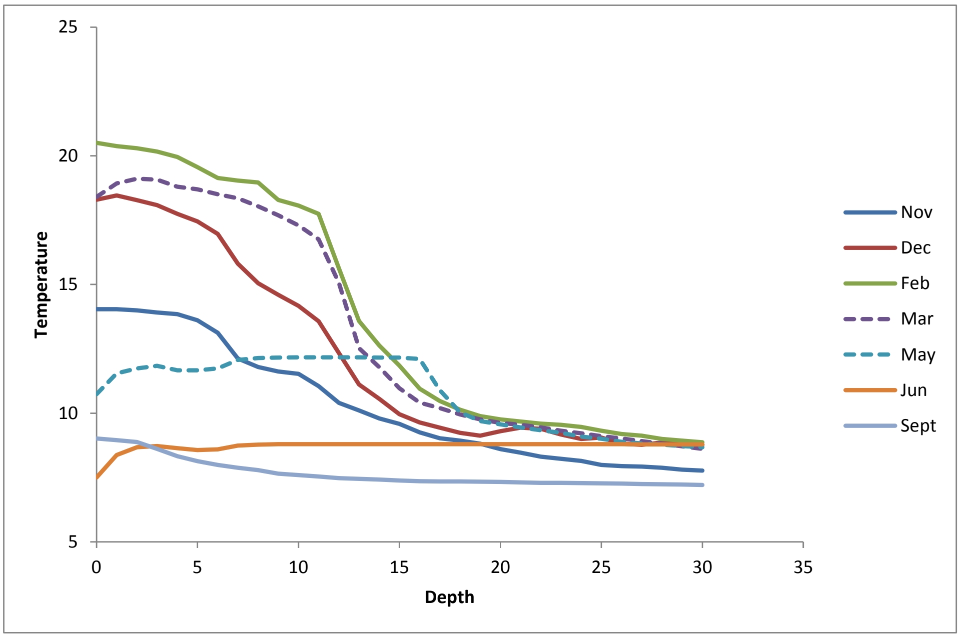

Figure 4. Lake temperature profiles from the summer of 2012/13.

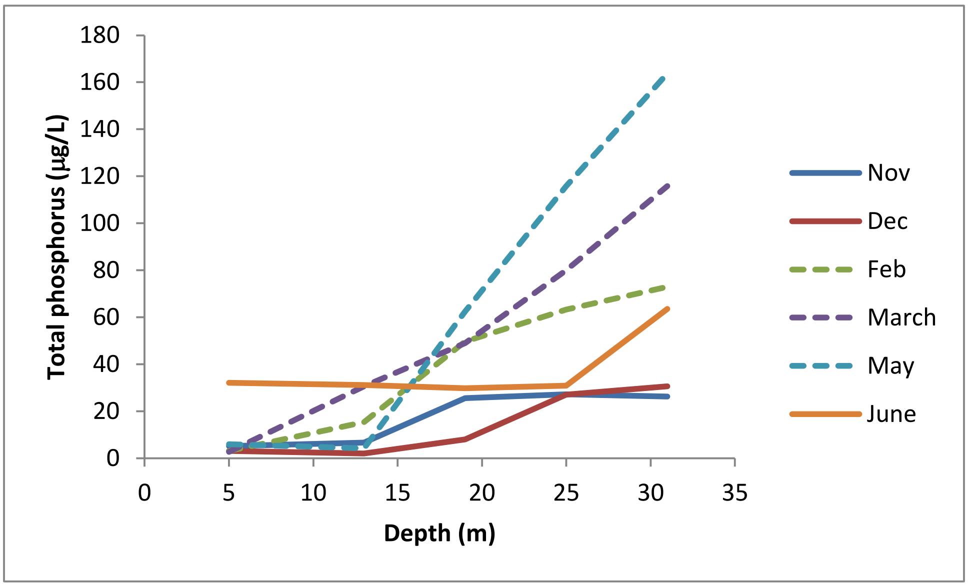

Figure 5. Lake phosphorus profiles from the summer of 2012/13.

Table 3 shows that the P concentration in the Arrow River is much lower than the lake P concentration of the lake, indicating that the Arrow River water would be suitable for the dilution and displacement of P-rich lake water.

Using the above information, I calculated the cumulative input of Arrow River water from September to June and compared that with the lake volume. I calculated this cumulative flushing volume as a percent of the whole lake volume and also as a percent of the volume of the bottom water layer (the layer that accumulates phosphorus in summer and autumn). This second calculation would be relevant if the Mill Creek/Arrow River were to discharge into the phosphorus-rich bottom layer of the lake and if the lake bottom water were directly displace by siphoning it to the lake's outflow.

The calculations show that the flushing effect of the Arrow River augmented inflow would displace a small percentage of the lake volume – only approximately 7% of the whole lake volume by the end of the stratified period (Fig. 6). If the inflow could be managed so that it displaced phosphorus rich bottom water, then the Arrow River could displace approximately 14% of the bottom water volume by the end of the stratified period.

While these flushing effects are not substantial, they are not insignificant either, especially if the combined Mill Creek/Arrow River discharge were cold/dense enough to be able to displace phosphorus-rich bottom waters. Displacing phosphorus-poor surface water during the summer would not provide nearly as substantial a benefit towards lake recovery. So the flushing benefit would be minimal unless bottom waters could be displaced.

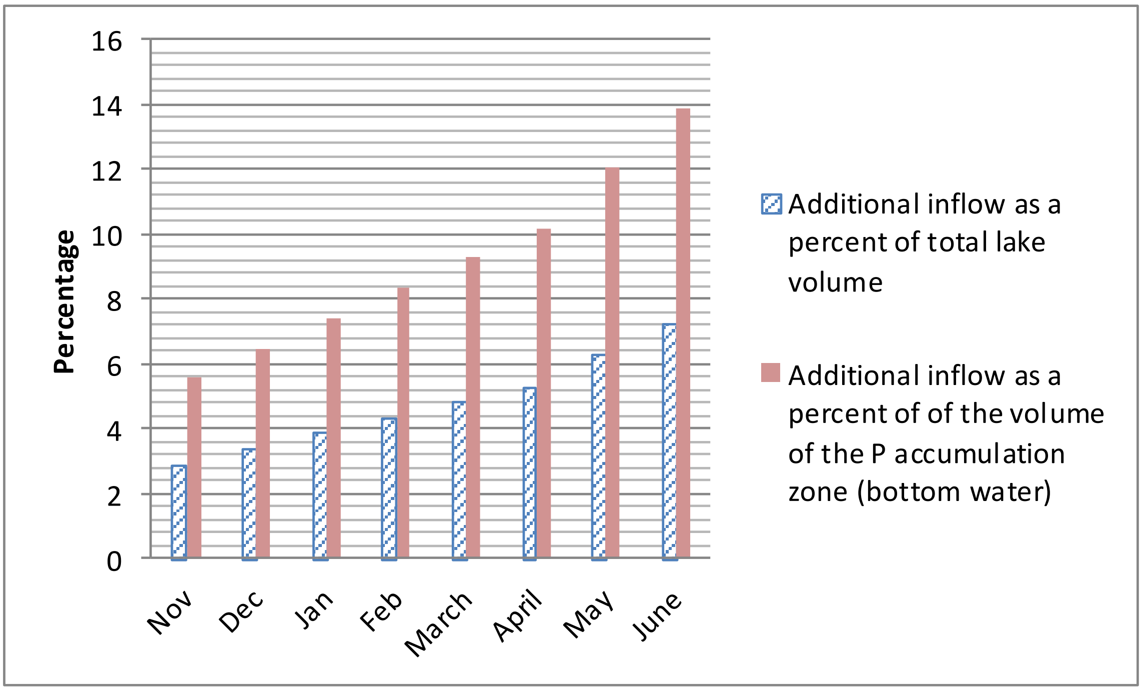

Figure 6. Proportion of total lake and of the bottom water that could be flushed by Arrow River water, using the maximum amount of augmentation water available (200 L/s in shoulder seasons and 100 L/s in summer).

2. Would the augmentation water dilute and displace the P-rich bottom water?

The colder the water, the denser it is (this is true down to 4°C). So to displace the colder bottom water of Lake Hayes, the combined Mill Creek/Arrow River inflow would have to be colder than the surface layer of the lake and, ideally, it should be as cold/dense as the bottom water of the lake. If this could be achieved and if the lake's displaced water could be siphoned out of the lake, then the flushing could remove around 14% of the recycled phosphorus from of the lake per year. However this depends on the augmented inflow flowing down to the bottom of the lake before mixing with the lake water.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Lake temperature profiles (University of Otago; Fig. 4)

3. Mill Creek temperatures (Otago Regional Council data; Fig. 7).

I have assumed the following for these calculations:

1. The combined Mill Creek/Arrow River inflow would be the same temperature as the current Mill Creek inflow.

To test whether the inflow would be likely to plunge to the bottom layer of Lake Hayes, I compared the temperatures of Mill Creek with the temperatures of the lake, over the stratified period (Fig. 7). The data show that only toward the very end of the stratified period (in May), does the temperature of Mill Creek. approach that of the bottom water of the lake. Prior to that time, the inflow would either flow into the warm surface water or would flow between the layers (but not enter the bottom water layer). This indicates that without some kind of cooling or direct physical injection of the inflow into the bottom water during summer, the augmented inflow water would not dilute or displace the phosphorus-rich bottom waters of the lake.

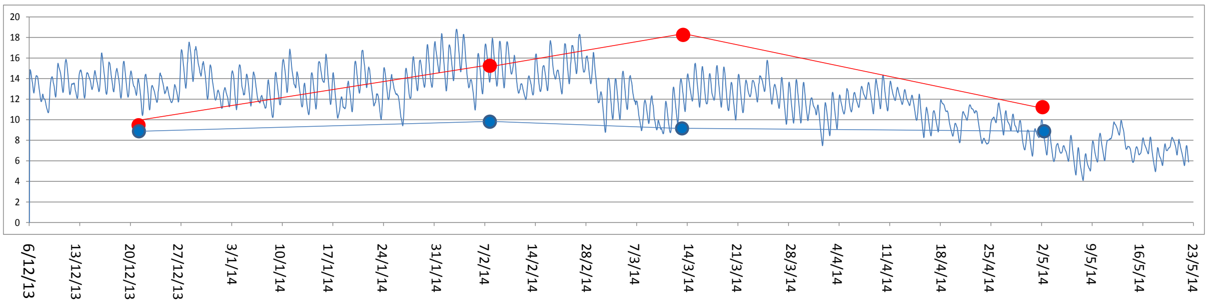

Figure 7. Temperature data for Mill Creek (blue line; 2013/14) and Lake Hayes (blue and red dotted line; 2012/13). The blue dots show the lake bottom water temperatures and the red dots show the lake surface water temperatures. Mill Creek data were supplied by the Otago Regional Council.

Addressing the above assumption, is it possible that the temperature of the Arrow River augmented flow might lower the temperature of Mill Creek enough to allow both volumes of water to plunge into the bottom of Lake Hayes? Unfortunately, we don't have temperature data for the Arrow River at the offtake site or at the site where the irrigation water would connect to Mill Creek. This connection site is 4km upstream from where Mill Creek enters Lake Hayes (Fig. 3), so even if the Arrow River water were substantially colder than Mill Creek, by the time it was transported from near Macetown to the Mill Ck connection site, diluted by Mill Ck and then transported 4km downstream, any temperature benefit from the Arrow River is likely to have been lost. However, I have not been able to confirm this with data or modelling.

3. Could the augmented inflow supply enough dissolved oxygen to the bottom water of Lake Hayes to prevent its deoxygenation?

Another potential benefit of the injection of Arrow River water into the bottom waters of Lake Hayes is that the addition of oxygenated Arrow River water to the bottom waters of the lake might prevent deoxygenation of the bottom waters, maintaining P binding in the sediment of the lake.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Lake temperature profiles (University of Otago; Fig. 4)

3. Estimates of the volume of 1 m-thick slices of Lake Hayes (calculated from the NZ Oceanographic Institute bathymetric chart)

I have assumed the following for these calculations:

1. The combined Mill Creek/Arrow River inflow would discharge into the bottom waters of Lake Hayes
2. That the combined Mill Creek/Arrow River inflow would have an oxygen content approximating 100% air saturation (i.e., equilibration with the atmosphere).

For these calculations, I cumulatively added the mass of oxygen that would exist in the Arrow River augmented flow over the period for which water would be available. This mass of oxygen was then compared to the mass of oxygen in the bottom waters of Lake Hayes during the same period (the stratified period). Figure 8 shows that the cumulative input of oxygen is only relatively minor compared to the oxygen holding capacity of the bottom waters of Lake Hayes (indicated by the September value, when the bottom waters were mostly oxygenated). The rate of oxygen supply to the bottom waters (the slope of the line = 0.0888 tonnes of oxygen supplied per day) is also small compared with the rate of oxygen loss from the bottom waters in spring and summer (from November-February; 1.93 tonnes of oxygen consumed per day). Thus, the rate of oxygen consumption in the bottom water is 22 times greater than the rate of oxygen supply which could be contributed to the Arrow River augmentation, if it were injected directly into the bottom waters. This indicates that injecting the Arrow River augmentation flow directly into the bottom waters would not overcome deoxygenation in this lake.

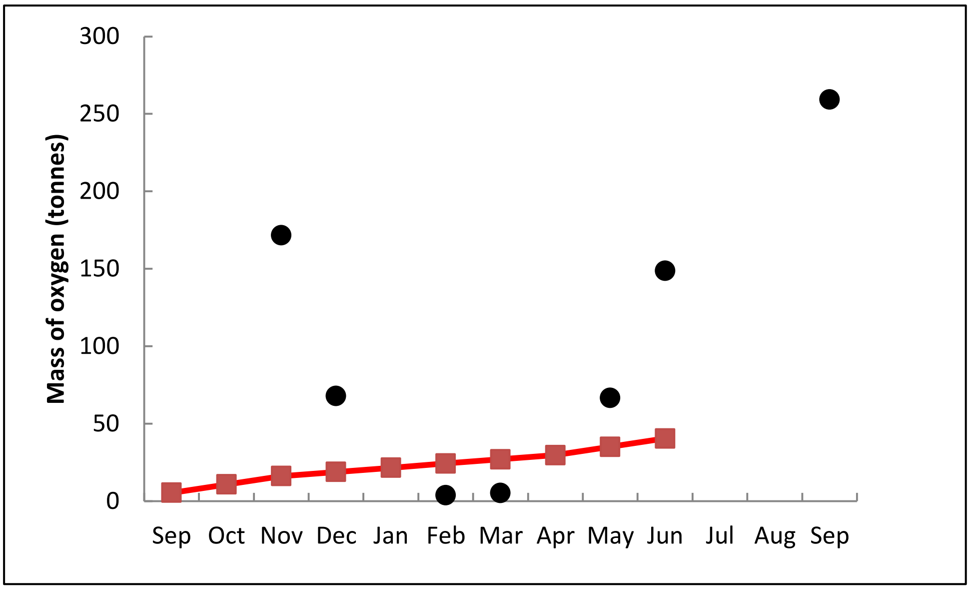

Figure 8. The mass of oxygen in the bottom water of Lake Hayes (2012/13; black dots) and the mass of oxygen estimated to be in the proposed augmented Arrow River inflow (red squares).

4. How much of the lake's surface water, its TP and chlorophyll *a* would the augmented flow displace?

Displacement of surface water:

It appears from the above analysis in Section 3 that the augmented flow from the Arrow River would largely flow into the upper surface water layer of Lake Hayes. I calculated the amount of lake surface water that would be displaced by the cumulative input of Arrow River water from September to June. The volume of the surface water layer (to 12 m depth) is 31.03 million cubic metres, and the cumulative inflow from the Arrow River is 4.05 million cubic metres by the end of June. Thus, the Arrow River would displace around 13% of the lake's surface water over the stratified period.

Displacement of total phosphorus:

The average total phosphorus concentration in the surface water of Lake Hayes from September to June is 59 mg/m^3, while that in the Arrow River (at Morven Ferry) is 9 mg/m^3 (Table 2). The difference in concentration is 50 mg/m^3. When multiplied by the volume of the lake's surface layer and by the cumulative inflow from the Arrow River, respectively, the phosphorus in the lake displaced by the augmented flow would equal approximately 11% of the phosphorus content of the surface layer of the lake. This would bring the average phosphorus concentration in the surface water down from 59 mg/m^3 to around 52.5 mg/m^3, by the end of the augmentation period in June. The lake's trophic state would remain high as the boundary between mesotrophic (moderately productive) and eutrophic (productive) is 20 mg P/m^3. By these estimates of the average augmented lake phosphorus concentration, the lake would remain in the supertrophic category (48 – 96 mg P/m^3) (see Appendix 1). However, persistent flushing of this sort over a number of years could contribute to an improvement of the lake's trophic state.

Displacement of chlorophyll *a* (algal biomass):

The average chlorophyll *a* content of the surface water of Lake Hayes from September to June is estimated to be around 30 mg/m^3 (Bayer & Schallenberg 2009). We have no chlorophyll *a* data for the Arrow River, but this is expected to be quite low during moderate to low flow periods (probably not more than 2 mg/m^3 of chlorophyll *a* during the augmentation period). Again, multiplying by the volume of the lake's surface layer and by the cumulative inflow from the Arrow River, respectively, the chlorophyll *a* in the lake displaced by the augmented flow would equal approximately 12% of the chlorophyll *a* content of the surface layer of the lake. This would bring the average chlorophyll *a* concentration in the surface water down from 30 mg/m^3 to around 26.7 mg/m^3, by the end of the augmentation period in June. The lake's trophic state would remain high as the boundary between mesotrophic (moderately productive) and eutrophic (productive) is 5 mg Chla/m^3. By these estimates of the average augmented lake chlorophyll *a* concentration, the lake would remain in the supertrophic category (12 – 31 mg Chla/m^3) (see Appendix 1). However, persistent flushing of this sort over a number of years could contribute to an improvement of the lake's trophic state.

Summary

In Table 3, I summarise the information presented in this report and I show some issues to consider regarding the findings of the report.

Table 3. Summary of findings of the assessment of the potential of Arrow River augmentation to speed the recovery of Lake Hayes.

Augmentation questions	Answer	Things to consider
1. Would it flush a substantial amount of phosphorus from the lake?	• Only if the augmentation flow would enter and displace the bottom layer of water during the summer stratified period • If the bottom water could be displaced in this fashion (which would require siphoning of bottom water out of the lake), then around 14% of the internal P load could be flushed annually.	• Will the inflow naturally plunge into the bottom waters? • If not, how could it be injected into the bottom waters? • Could a siphon be constructed to help displace high P bottom waters? • Where could this deoxygenated water (containing high levels of P and toxic hydrogen sulphide) be disposed of?
2. Would it naturally plunge into the bottom waters or would it flow into the surface waters of the lake?	• Naturally, the inflow is likely to be less dense than the cold bottom water, meaning it will flow over top of the bottom water, displacing and flushing surface water only.	• This conclusion assumes that the combined Mill Creek/Arrow River inflow would not be colder/denser than the current Mill Creek inflow. Temperature data are lacking to test this assumption.
3. If it were injected into the bottom waters, could it supply enough oxygen	• No, the oxygen augmentation effect is small compared to the oxygen demand of the bottom waters of the lake.	• In the calculations, I didn't include the oxygen that could also be supplied by the Mill Creek inflow. • Assuming that the Mill Creek discharge is around the same as the Arrow River

to prevent the bottom water from losing all of its oxygen during the stratified period?		augmented flow, and assuming that Mill Creek flows could also be harnessed and injected into the bottom waters of the lake, then the oxygen supply rate that I calculated would be doubled. • Injecting both these inflows into the bottom waters would still be insufficient to prevent deoxygenation of the bottom waters because the oxygen demand is around 10 times greater than the combined supply rate would be.
4. If the augmented flow were to displaced the lake's surface water, could it substantially reduce the phosphorus and chlorophyll *a* content of the surface water?	• The augmented flow would reduce the average surface water phosphorus concentration in the period from September to June by 11% and the chlorophyll *a* concentration by 12%. Neither of these reductions would reduce the trophic status of the lake from its current supertrophic condition.	• The best use of the irrigation flow would be direct injection to the bottom waters, where it would have a greater effect by oxygenating the bottom water and by displacing more phosphorus. Displacement of surface water would have a smaller effect in speeding the recovery of the lake. • However, persistent flushing of around 11% of the phosphorus from the lake per year could contribute to a speeding of the lake's recovery if maintained for 5 to 10 years.

Acknowledgements

I thank Rob Hay (Friends of Lake Hayes) for providing information on the available flows from the Arrow River irrigation scheme and for other background information about the proposed augmented inflow. I thank Dean Olsen from the Otago Regional Council for providing data on Mill Creek and Arrow River temperatures and water quality. The New Zealand Ministry of Business, Innovation and Employment have funded this work via a subcontract with NIWA.

Reference

Bayer T., Schallenberg M. (2009). Lake Hayes: Trends in water quality and potential restoration options. Report prepared for the Otago Regional Council. 39 p. (Limnology Report No. 14).

Note: This report is considered preliminary as it has not been peer-reviewed.

Appendix 1

Attribute ranges for different lake trophic levels. From Burns, N, Bryers, G, & Bowman, E (2000). <u>Protocols for monitoring trophic levels of New Zealand lakes and reservoirs</u>. Available from www.mfe.govt.nz.

Lake type	Trophic level	Chla (mg m^{-3})	Secchi depth (m)	TP (mg m^{-3})	TN (mg m^{-3})
Ultra–microtrophic	0.0–1.0	0.13–0.33	31-23.5	0.84–1.8	16–34
Microtrophic	1.0–2.0	0.33–0.82	23.5-14.8	1.8–4.1	34–73
Oligotrophic	2.0–3.0	0.82–2.0	14.8-7.8	4.1–9.0	73–157
Mesotrophic	3.0–4.0	2.0–5.0	7.8-3.6	9.0–20	157–337
Eutrophic	4.0–5.0	5.0–12	3.6-0.7	20–43	337–725
Supertrophic	5.0–6.0	12–31	0.7-0.3	43–96	725–1558
Hypertrophic	6.0–7.0	>31	<0.3	>96	>1558