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## **Supplementary Information Files for 'The influence of climate change on the restoration trajectory of a nutrient-rich deep lake'**

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**Supplementary information for Radbourne and others: ‘The influence of climate change on the restoration trajectory of a nutrient-rich deep lake’.**

*WRT<sub>m</sub> calculation*

The WRT estimated in this study (0.82 years) suggests Rostherne Mere flushes quicker than was previously thought (estimated as 1.6 - 2.4 years; Harrison and Rogers, 1977, Moss and others, 2005). The discrepancy in residence time to previously published estimates is thought likely due to the availability of increased flow data frequency undertaken in this study (with stage height intervals measured every 5 minutes) compared to that of previous studies (~2 week intervals with correlation to daily precipitation). Comparison of the precipitation values for the two study periods show the 2016 precipitation was ~10% higher than 1990-92 (1990-92 = 630 mm yr<sup>-1</sup>, 2016 = 693 mm yr<sup>-1</sup>), which may result in a slightly faster flushing rate for 2016 but does not explain the difference present here.

Furthermore, due to the annually strong thermal stratification at Rostherne Mere the available lake volume for outflow is reduced greatly, this impacting the nutrients available in the epilimnion for algal uptake. Therefore, the stratified lake WRT method (WRT<sub>m</sub>) takes into account this strong stratification for 8.5 months (mid-March to end-November), limiting the available lake volume for outflow export, resulting in a reduced summer water residence time that would suggest the entire epilimnion would completely flush during stratification and would create an annual water retention time estimate of 0.57 years.

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**Supplementary Table 1.** 2016 monthly and annual water retention time using revised method ( $WRT_m$ ) of available lake volume over outflow rate.

Month	Revised WRT method		Monthly WRT (yr)
	Available volume (L x10 <sup>9</sup> )	Outflow rate (L per month x10 <sup>8</sup> )	
January	6.85	7.45	0.92
February	6.85	6.96	0.98
March	4.69	3.43	1.37
April	2.67	3.66	0.73
May	2.82	6.18	0.46
June	2.97	6.20	0.48
July	3.12	6.68	0.47
August	3.27	6.84	0.48
September	3.41	6.37	0.54
October	3.71	6.35	0.58
November	4.31	7.07	0.61
December	6.85	8.24	0.83
<i>Annual totals</i>	4.29	75.4	
<b>WRT<sub>m</sub> (yr)</b>	<b>0.57</b>		

### *Updated Rostherne Mere phosphorus budget*

The P budget for Rostherne Mere calculated by Carvalho and others (1995), likely underestimated the inflow and outflow of nutrient loads. High-resolution 5-minute stage height data collected during 2016 indicates the main inflow and outflow of the lake to have a high flow range. Therefore, previous water budget calculations without this high-resolution data have likely missed the variable flow at the lake, and have underestimated the nutrient load, by about 75%. Without correction of the previous nutrient flow values, the nutrient budget suggests the inflowing P load would have increased between 1992 and 2016 (see Supplementary Table 2), which is unlikely given the history of continued action in the catchment to reduce agricultural nutrient inputs. However, the corrected nutrient loads show an identical inflow load as that estimated in 1992 (2.4 kg day<sup>-1</sup>; Supplementary Table 2). Although the correction factor is an estimate based on single year's WRT with a ~10% higher total annual

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precipitation, and without considering the influence of catchment saturation and run off rates (Moore, 2007, Marchi and others, 2010), it results in a similar estimation of catchment P loading following STW diversion, suggesting it is plausible.

Following management intervention in 1991 a dynamic response is seen in the Rostherne Mere TP budget, with a large mass balance change between pre-STW diversion and immediately post-STW diversion. External TP load following STW diversion responded quickly (3999 kg pre-STW diversion to 958 kg post-STW diversion; Supplementary Table 2), being sustained to present day with continued catchment management (959 kg; Supplementary Table 2). However, following STW diversion, the outflow load did not decrease in the same way as the inflow load, remaining at a similar value to the pre-STW diversion loads (3166 kg export pre-STW diversion, 3443 kg export post-STW diversion; Supplementary Table 2). This is a relic of the high lake nutrient load already *in situ*, leading to a higher net export of TP from the lake as seen in the change in lake storage (-345 kg; Supplementary Table 2).

A key change in Rostherne Mere's P budget following STW diversion was the reduction of total inputs, yet maintaining a stable outflow load (Supplementary Table 2). Pre-STW diversion, Rostherne's TP balance suggests a large net burial of TP (-933 kg in 1990-91; Supplementary Table 2), yet following the reduction of inflow load post-STW diversion, the budget suggests a net loss from the system, initially very high (outflow load +2140 kg in 1991-92; Supplementary Table 2) but falling to a smaller, yet still substantial, net loss in more recent years (+635 kg in 2016; Supplementary Table 2). The consistent export of P from Rostherne Mere since STW diversion is a result of the internal sediment P release that has replenished the lake P values annually at stratification overturn.

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In their study reviewing the initial 11 years following STW diversion at Rostherne Mere, Moss and others (2005) showed after an initial 2-year increase in maximum P values, likely due to the impact of catchment disturbance from the STW diversion (i.e. engineering groundworks in the catchment), a rapid decline in in-lake P values followed, with the rate slowing towards the end of the study in 2002. This study suggests the slowdown in recovery witnessed previously was the start of a stabilisation of in-lake P concentrations, with annual P replenishment sustained by the internal sediment legacy P. The stabilisation of in-lake P concentrations shortly after the diversion of the major point source nutrient load is a concern for management practitioners. While the recovery from extremely high P concentrations pre-STW has been successful, with a reduction in total external inputs from 3999 kg in 1990 to 959 kg in 2016 (Supplementary Table 2), further reductions in nutrient concentrations have not happened, leaving Rostherne Mere still classified as highly eutrophic and far outside management targets.

### *Phosphorus sample analysis: Use of interpolation and sample freezing*

The ~3 weekly monitoring sample collections will unavoidably smooth the short-term variation in nutrient delivery to the lake, potentially being seen as quite a coarse assessment. However, due to limitations of time and finance for site visits the monitoring frequency was set in the best possible way for this study. Daily interpolation has been used in the study to estimate the daily loads of nutrients. To support the use of daily interpolation, another algorithm was assessed using the previous measured value as the representative value for the following time period until the next measurement (i.e. concentration remains the same over the three weekly interval from a measurement). These two methods produce similar results (1416 kg outflow export via daily interpolation, 1421 kg outflow export via set

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measurement, 0.4% difference between methods). The use of daily interpolation follows the same methods used previously at Rostherne Mere, creating comparable data sets. There was no significant relationship between TP concentration and discharge (another potential method if relationship significant), therefore this method could not be used to calculate TP load.

In this study the samples were frozen the same day as collection and shipped frozen to the external laboratory service for analysis, as recommended for shipment by the service. However, it has been suggested freezing samples before analysis, especially those with low values, can potentially alter P concentrations. Here, we do not find any cause for concern with the freezing of samples prior to analysis.

Previously samples have been collected at Rostherne Mere (a section of this data is presented in Fig. 6) and analysed for SRP with and without freezing prior to analysis. Within this data set there was no discrepancies between the two samples processes, suggesting no alteration occurred following freezing. Comparison of the 2016 data to these past collections (frozen and un-frozen) show good agreement, being in a similar range. A small number of samples at lower SRP concentrations are within a 15% range of both methods, with only one sample outside the combined error range. Furthermore, we did not notice any precipitate in the samples on freezing or thawing of the samples, suggesting the sample storage has not been an issue. Taking the 15% maximum range for low value samples, a +15% error correction could be applied to samples where  $\text{SRP} < 35 \mu\text{g L}^{-1}$  (mostly affecting the inflow samples). This correction would increase inflow load by only 6.9%, or  $59.6\text{kg yr}^{-1}$ .

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**Supplementary Table 2.** Total phosphorus budget for Rostherne Mere. Values in kg, except loads in kg day<sup>-1</sup>. 1990 to 1992 data taken from Carvalho and others (1995). A correction of inflow\*1.73 based on comparison of water budgets from this study and Carvalho (1993). 2016 direct rainfall, catchment north drainage and catchment north groundwater all calculated as Carvalho and others (1995), with bird roost estimate using the same value as 1992. Percentage of external input contribution in parenthesis. For Balance, + values are net losses from lake system, - are net gains. Shading indicates pre-STW diversion.

Period	Days	Inflow	Inflow load	Catchment North drainage	Catchment north groundwater	Direct rainfall	Bird roost	Total inputs	Δ P lake	Out flow	Outflow load	Balance
5/2/90 - 14/5/91	377	2250 (96)	6.0	55 (2)	7 (0)	21 (1)	23 (1)	2356	-100	1830	4.8	-626
23/7/91 - 21/7/92	365	504 (85)	1.4	42 (7)	5 (1)	19 (3)	20 (3)	590	-345	1990	5.5	+1055
5/2/90 - 14/5/91 (WRT corrected)	377	3893 (97)	10.4	55 (1)	7 (0)	21 (1)	23 (1)	3999	-100	3166	8.3	-933
23/7/91 - 21/7/92 (WRT corrected)	365	872 (91)	2.4	42 (4)	5 (1)	19 (2)	20 (2)	958	-345	3443	9.5	+2140
14/1/16 - 4/1/17	356	864 (88)	2.4	49 (5)	5 (1)	21 (2)	20 (2)	959	+178	1416	3.9	+635

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