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Water and Nutrient Budgeting of Rostherne Mere, Cheshire, UK

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This paper presents a simple model of the Rostherne Mere water catchment. The model allows calculation of water and elemental budgets on meteorological data using regressions derived from a monitoring data set. Estimates of yearly inputs and outputs of Ca, Mg, K and N suggest that the lake is currently acting as a sink for these elements. Comparison with earlier estimates shows an increase in N loading. High inputs of particulate P appear to be balanced by outputs of inorganic P, suggesting that the two may be coupled by certain physical and biogeochemical processes within the lake ecosystem, including adsorption to/desorption from particles, coprecipitation with various chemical compounds, uptake and excretion by biota, mineralisation and release from sediments.

Introduction

Rostherne Mere (Fig. 1) is one of the well-studied British freshwater lakes (see *e.g.* Stephen 1997; Krivtsov *et al.* 1998, 2001d, and references therein). Good knowledge of the lake's morphometry (Woof and Wall 1984), the long term monitoring record of its water chemistry (*e.g.* Tatersall and Coward 1914; Gorham 1957; Grimshaw and Hudson 1970; NWWA 1983; Tipping 1984; Clay 1992; Carvalho 1993; Krivtsov 1995; Stephen 1997; Krivtsov *et al.* 1999a,e; Krivtsov 2000) and planktonic community (*e.g.* Pearsall 1923; Griffiths 1925; Lind 1944; David 1963; Belhcher and Storey 1968; Reynolds and Rogers 1976; Reynolds 1978; Reynolds

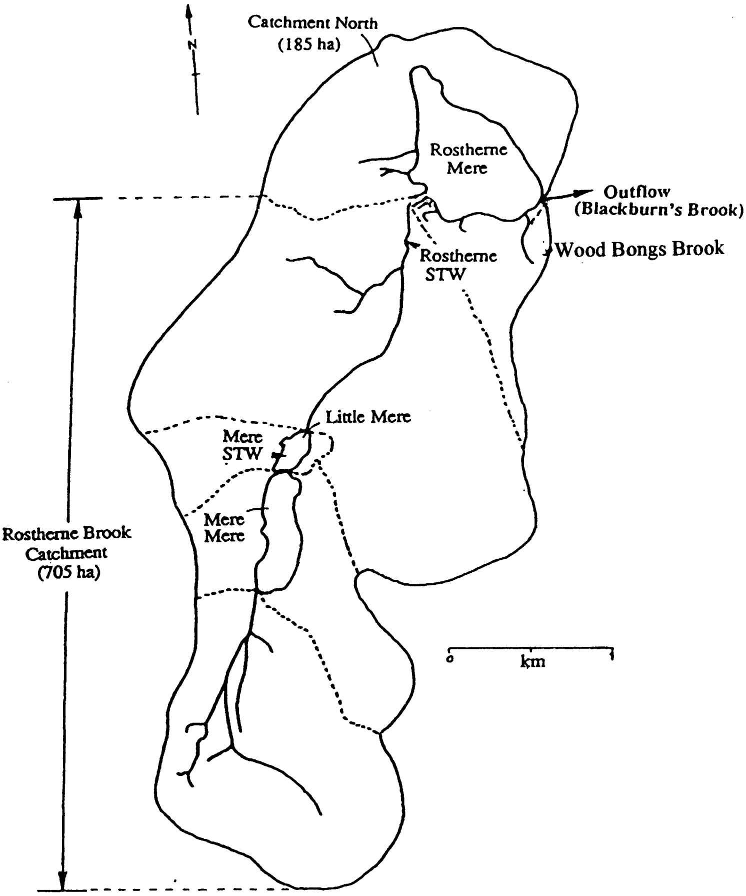

Fig. 1. Schematic representation of the Rostherne Mere water catchment (adopted from Carvalho 1993). Note that the position of the Wood Bongs Brook inflow point is indicated by a dashed line approximately, as it was found to follow different courses on different sampling occasions.

and Bellinger 1992; Sigee and Holland 1997; Sigee *et al.* 1998, 1999a-b; Krivtsov *et al.* 1999c,f, 2000b, 2001c, 2002), and availability of a specially designed simulation mathematical model (Krivtsov *et al.* 1998) make the mere a suitable subject for analysis of complex interactions among various ecosystem components (*e.g.* Krivtsov *et al.* 1999b,d, 2000d, 2001a). These analyses are important not only for the management of Rostherne Mere itself, but may have profound implications for other temperate lakes in general (Krivtsov *et al.* 2000a,c).

An understanding of the overall water and nutrient budget is important in considering the functioning of an aquatic ecosystem, including an assessment of its history, current status, and long-term future dynamics (Schindler 1987). Gross estimation of water and elemental budgets may be obtained by simple averaging of monitoring data. However, calculation of budgets may be considerably facilitated by specially designed site-specific computer models. This may be especially useful for ungauged catchments, where continuos measurements are not available. Furthermore, even simple mathematical models allow testing various "what if" scenarios, thus facilitating prediction of the future and interpretation of the past dynamics observed (*e.g.* Krivtsov *et al.* 2001a, 2000a,d). Combination of monitoring studies with simulation modelling is particularly useful in this respect, since the comparison of simulations with real observations provides an objective criterion for our understanding of the ecosystem studied (*e.g.* Krivtsov *et al.* 1998, 1999b). A number of previous studies have considered various aspects of the Rostherne Mere nutrient budgeting (including Rogers 1975; Walker 1987; Adams 1987; Brinkhurst and Walsh 1967; Moriera 1996). Recent studies carried out at Liverpool University have addressed the problem in comprehensive integrative detail (Carvalho 1993; Carvalho *et al.* 1995). However, mathematical modelling of the lake's water catchment has been lacking, and the hydrological balance was estimated on the basis of discrete flow measurements. The objectives of this paper are to:

1) present the theoretical grounds for the calculation of a nutrient/water budget for Rostherne Mere;
2) compile a model of the lake's water catchment;
3) use the model for computation of water and elemental budgets from meteorological data and monitoring results;
4) evaluate the calculated budget in relation to previous work and the long-term ecosystem dynamics.

Materials, Methods and Model Development

Site Description

Rostherne Mere (20 m asl, see ordnance survey map sheet SJ 78 SW) is situated in the withinity of Manchester airport. The lake occupies a deep hollow (max depth 31 m, mean depth 13.6 m), overlying a practically impermable layer of drift. Nutrient enrichment of the lake has been increased by runoff from the surrounding farmland (Nelms 1984) and, between 1935 and 1991, by sewage discharge. The following sources were identified as the most important water inputs for Rostherne Mere (Carvalho 1993): direct precipitation on the lake surface, runoff and groundwater drainage from catchment North, and integrated inflow from the Rostherne Brook catchment (see Fig. 1 for subdivisions of the water catchment). The output of water from the lake combines losses via outflow (*i.e.* Blackburn Brook), evaporation from the lake surface, and groundwater seepage.

Water Inflow

Assuming there are no supplies from outside the Rostherne watershed, the relative contribution of the above mentioned sources will depend upon the relative size of their catchment areas. Thus, not surprisingly, Rostherne Brook, whose catchment area constitutes 75% of the total watershed, was previously shown to be the main input of water to Rostherne Mere (Rogers 1975; Carvalho 1993).

The flow of Rostherne Brook consists of two components: the outflow of the upstream lakes (*i.e.* Mere Mere / Little Mere system), and surface runoff and groundwater drainage from the part of the catchment below Little Mere. The first component (*i.e.* outflow from Little Mere) is buffered by the upstream lakes (*i.e.* Mere Mere and Little Mere) and could be expected to have only limited short term variation, solely depending on the total amount of water accumulated in the upstream lakes. The second component (*i.e.* the contribution of the lower part of the catchment), should, however, strongly depend upon the precipitation pattern. Depending on conditions of soil, vegetation, *etc*., peak discharge of water contributed by this component in a catchment similar to Rostherne's would be expected in a matter of hours after rainfall (see *e.g.* Kirpich 1940). Hence the flow rate of Rostherne Brook measured at any one time may not reflect the mean water flow even for the same day. Thus for a reasonable estimation of the mean water flow, measurements should be taken at least a few times a day, especially when there are rainfall events. As this would result in substantial additional costs and technical complications, detailed flow measurements for the Rostherne Mere inflow have not yet been performed. Previous calculations of the inputs via Rostherne Brook were based solely on discrete measurements of the water flow (*e.g.* Adams 1987; Walker 1987; Carvalho 1993), which had the limitations already described (see also Leonard *et al.* 1979). At the time that was the most practicable solution. Recently, however, the UK Meteorological Office made a comprehensive meteorological dataset available on the internet, including daily temperature, vapour pressure and precipitation data from the Ringway station at Manchester Airport, situated approximately 4 miles away from Rostherne Mere (Carvalho 1993). From these data it is possible to calculate daily evaporation and runoff components.

Water Outflow

For practical reasons Rostherne Mere monitoring programmes have traditionally sampled the outflow of the lake (*i.e.* Blackburn Brook) at a bridge situated almost 0.5 km below the actual outflow point. This sampling point offers easy access and the possibility of measuring a laminar flow straightened by the bridge. This sampling point, however, is inevitably influenced by the contribution of the groundwater drainage and surface runoff from the area situated along the water course between the lake and the bridge. There are a couple of ditches joining Blackburn Brook from the south between the lake and the bridge, and one of those ditches appears to contain a major tributary, collecting inputs from a relatively large area outside the Rostherne Mere catchment. Furthermore, it is possible that the Brook in the Wood Bongs currently draining into the lake's reed beds near the outlet (dashed line in Fig. 1), may, during high lake levels, contribute to the outflow directly. Hence, the monitoring data of the Blackburn Brook should be treated with caution. Following the calculation of inputs and evaporation, an alternative independent estimate of water losses from the lake could be made using data on changes in lake water level.

Field Data

For calculations of elemental budgets we used the data available from the long-term monitoring programme conducted at the site, within which regular (up to 4 times a month) samples are taken from the streams and up to 4 points at the lake. Methods of sampling, physical and chemical analysis were standard, and are variously described in Krivtsov (1995), Sigee and Holland (1997), Krivtsov *et al.* (1998, 1999a,b, 2000b, 2001a), Sigee *et al.* (1998), Krivtsov (2000).

Estimation of Evaporation, Evapotranspiration and Surface Runoff

Estimation of Evaporation from the Open Surface

Evaporation from a lake surface was estimated from the following measured and calculated values: mean daily temperatures, wind speed, vapour pressure, potential and recorded sunshine hours. The following calculations were performed using Visual Basic (VB) and Microsoft Excel.

Daily average temperatures were calculated as the mean of minimal and maximal day and night temperatures. Then the estimated temperature values were used for calculation of the saturated vapour pressure. For this purpose a polynomial approximation of the relationship found in Shaw (1983) was used (Fig. 2). Likewise, the estimated temperature values were also used for calculation of the Delta/Gamma correction (for details see Shaw 1983) using a quadratic approximation of a table function found in the same source (Fig. 3)

1) Wind speed at 10m height was converted to the wind speed at 2m height and expressed in miles per day.
2) Table relationship (Shaw 1983) between solar radiation (*Ra*) and Julian Day was approximated as a periodic function (Fig. 4). This approximation was subsequently used for calculation of daily values of *Ra*.
3) Outgoing radiation (*Ro*) was calculated from the value of the Stefan-Boltsman constant, vapour pressure, and estimated temperature data in accordance with Shaw (1983, 1994).
4) Maximum daily sunshine hours were calculated as described in Walsby *et al.* (1997) using the geographical co-ordinates of Rostherne Mere.

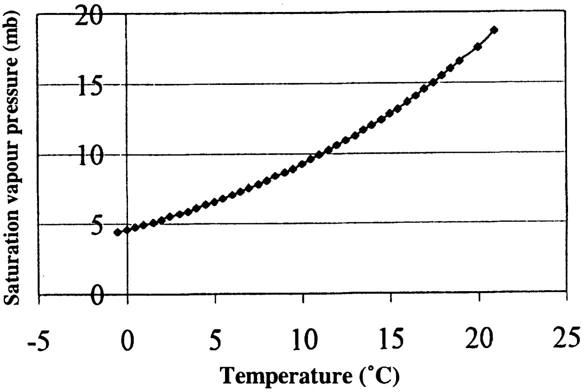

Fig. 2. Approximation of a table relationship (points based on data from Shaw 1983) between air temperature (*Ta*) and saturated vapour pressure (SatVapour) by a third order polynomial function (represented by a line):
SatVapour ≡ 342.3986372 + 0.000364522 Ta – 0.014730673 Ta^2 + 0.0000373553 Ta^3.

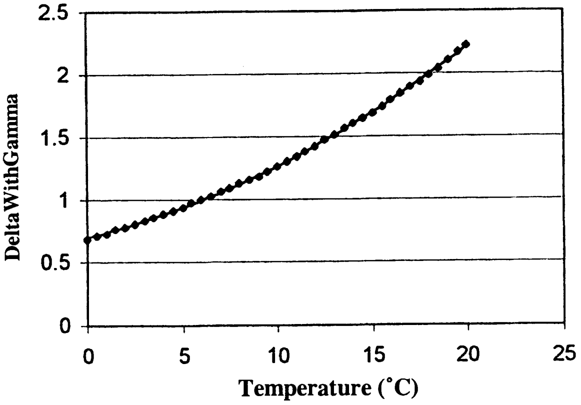

Fig. 3. Approximation of a table relationship (points, see Shaw 1983) between air temperature (*T*) and a Weighting Factor Δ/γ (DeltaWithGama) by a second order polynomial function (represented by a line):
DeltaWithGama = 0.696 + 0.0381Ta + 0.0019 Ta^2.

5) Available heat (H) was estimated from the data on recorded sunshine hours and estimates of *Ra*, *Ro* and maximum possible sunshine.
6) Evaporation rate based on the aerodynamic equation (*Ea*) was calculated from data on wind speed and difference in actual and saturated vapour pressure.

Daily values of evaporation from the open water surface (*Eo*) were subsequently calculated as described by Shaw (1983) from the estimates of *H*, *Ea* and the Δ/γ correction (Shaw 1983, 1994). Evaporation was assumed to attain only positive values, and condensation events were neglected for the purpose of this study.

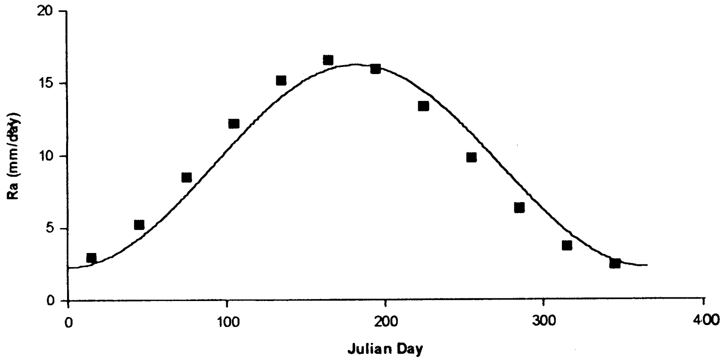

Fig. 4. Approximation of a table relationship (points, see Shaw 1983) between a typical value of solar radiation (*Ra*, expressed in mm/day of equivalent evaporation *sensu* Shaw 1983) and a Julian day (JulDay) by a harmonic function (represented by a line): $Ra = 2.15 + 14.3 / 2\ (1 + (\mathrm{Sin}((2\ (\mathrm{JulDay} - 11.9860182942465) / 365 - 0.5)\ 3.14)))$

Estimation of Evapotranspiration from Terrestrial Catchment

To estimate potential evaporation (*PE*) the previously obtained values of *Eo* were corrected by a month-dependent coefficient (Penman 1950).

Calculation of evapotranspiration was based on the concept of soil moisture deficit (*SMD*). The latter was assumed to increase if the daily precipitation was less than the estimated *PE*, and decrease (down to the minimal possible value of 0) otherwise. Actual evapotranspiration was calculated using so-called root constant functions (Figs. 5-6), derived from the table relationships normally used for such estimations (Shaw 1983). For practical reasons catchments of Rostherne's kind may be assumed to consist of 30% woodland, 50% grassland and 20% of riparian areas, permanently saturated with water (Shaw 1994). The exact account of all the differences within the catchment would have to include fast changing information on crop types, irrigation patterns, *etc.*, and would complicate the task dramatically. Thus, although it is realised that in reality the representation of the catchment is somewhat different (see *e.g.* Adams 1987), it was decided to use the average figures recommended by Shaw (1994) for the sake of simplicity.

Estimation of Surface Runoff

The total amount of water available for the surface and subsurface runoff (hereafter 'Effective Runoff') was estimated as the difference between the recorded precipitation, and estimated evapotranspiration and changes in *SMD*. If the sum of estimated evapotranspiration and *SMD* exceeded the recorded precipitation, the Effective Runoff was assumed to be non-existent. For the sake of simplicity, small scale differences in pedology and geomorphology were neglected and each subcatchment compartment was regarded as homogenous (see below).

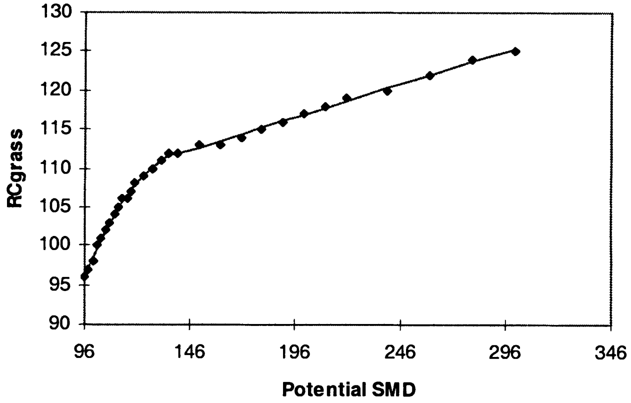

Fig. 6. Approximation of a table relationship (points, see Shaw 1983) for derivation of the actual soil moisture deficit (RCwood) of the woodland from the potential one (PotSMD), by a following piecewise function (represented by a line):

If PotSMD <= 200 Then RCwood = PotSMD Else

If PotSMD > 200 and PotSMD < 266 Then RCwood = 3.117xPotSMD – 0.0056 ×PotSMD^2 – 193.58 Else

If PotSMD >= 266 and PotSMD <= 400 Then RCwood = 218.059 + 0.0794×PotSMD Else

If PotSMD > 400 Then RCwood = 250

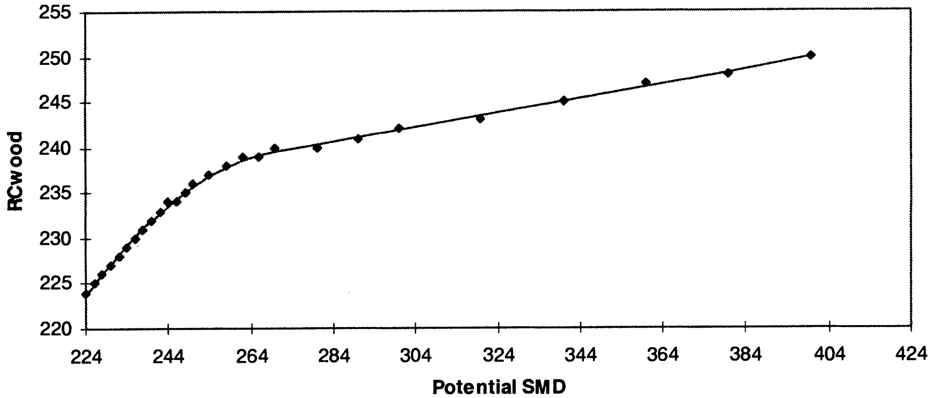

Fig. 5. Approximation of a table relationship (points, see Shaw 1983) for derivation of the actual soil moisture deficit (RCgrass) of the grassland from the potential one (PotSMD), by a following piecewise function (represented by a line):

If PotSMD <= 75 Then RCgrass = PotSMD Else

If PotSMD <= 140 and PotSMD > 75 Then RCgrass = 1.9233xPotSMD – 0.0066× PotSMD^2 – 27.906 Else

If PotSMD > 140 and PotSMD <= 300 Then RCgrass = 99.956 + 0.0847× PotSMD Else

If PotSMD > 300 Then RCgrass = 125.4

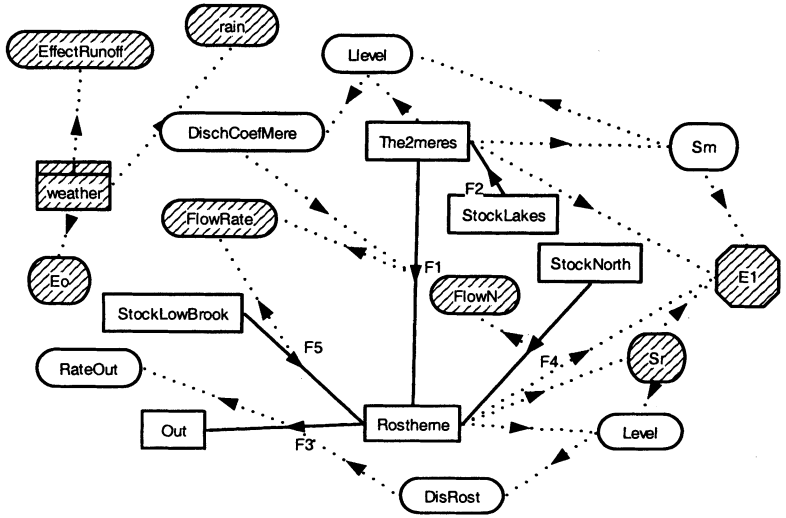

Fig. 7. Basic Summary Diagram of the Water Catchment Model. Shaded compartments are global (*i.e.* accessible from any place within the model structure)

Description of a Water Catchment Model

The present study involves calculation of the water balance, by means of a simple water catchment model from data collected at the Ringway Meteorological Station and arbitrarily treated monitoring data of the present research.

The model diagram is shown in Fig. 7. A lookup table 'Weather' contains daily data on Rainfall, *Eo* and Effective Runoff, imported from an Excel file (see above). These input data are used for calculating values of inputs and outputs for the following important compartments:

1) **The2meres** compartment represents a combined system of the upstream lakes, *i.e.* Little Mere and Mere Mere.
2) Compartment **Rostherne** represents Rostherne Mere itself.
3) **StockLakes** represents a transient compartment for accumulation of the Effective Runoff over the catchment area of **The2meres.**
4) **StockLowBrook** represents a transient compartment for accumulation of the Effective Runoff over the catchment area of Rostherne brook, situated below **The2meres.**
5) **StockNorth** represents a transient compartment for accumulation of the Effective Runoff over the Catchment North area of Rostherne Mere.
6) **Out** is a hypothetical compartment accumulating water lost from Rostherne Mere via outflow from the beginning of the run

To ensure that certain numerical techniques would not result in absurd negative values, all the compartments were assigned relevant thresholds below which outflow ceases. The meaning and accumulative dynamics of the last compartment are simple and self-explanatory. The rest of the compartments could be subdivided into 2 different groups, *i.e.* those representing lakes, and those representing catchment subdivisions.

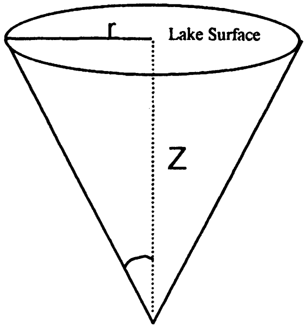

Fig. 8. Approximation of the basin morphometry as an inverted cone.

Lake Compartments

Both **Rostherne** and **The2meres** are assumed to have a 3D shape of an inverted cone (Fig. 8). For Rostherne Mere initial maximum depth (*Zo*) of such an approximated cone can be calculated from the parameter values of the lake's volume (V, 6.6 E+6 m^3) and surface area (S, 4.87E+05 m^2), as 3V/S. Since the lake's surface is approximated as a circle, its effective radius (*r*) can be calculated as $(S/3.14)^{0.5}$. From the estimated values of *r* (393.82 m) and *Zo* (40.66 m) it is now possible to determine the tangent of the half-crossection angle α at the bottom of the cone: TanAlfaRost=*r*/*Zo*= 9.69. The latter is subsequently used for calculation of current values of lake area (*Sr*)

$$Sr = 3\,\mathtt{Rostherne}/(\mathtt{Rostherne}\;3/(3.14\,\mathtt{TanAlfaRost}^2))^{1/3}$$

Actual values of the lake surface area (*Sr*) and volume (Rostherne) can now be used for calculation of the actual depth of the approximated cone. The latter could be transformed to the reading of a water level by applying a subtracting correction (Gauge Correction), calculated to give an initial water level value for 1996 of approximately 75 cm (available from Stephen 1997).

It should be noted that both Little Mere and Mere Mere are combined in a single compartment (*i.e.* The2Meres). Considering that the lakes are only separated by a weir, such an assumption represents a convenient and reasonable compromise, allowing fairly easy calculation of their overall budget.

The above described representation of lakes as inverted cones implies incorporation of a surface area buffering mechanism common in natural lakes. When the volume of a lake is increased, the area increases as well, resulting in the increase of evaporation losses. In contrast, if the volume of a lake is decreased, its area shrinks, leading to the decrease in the water loss via evaporation. Thus the area buffering mechanism always works against the deviation from a long-term equilibrium.

At each time step a lake compartment receives inputs from the relevant subcatchments (represented by flows) and direct rainfall (modelled via an Independent Event E1). In addition to that Rostherne receives a flow from The2meres. Losses are represented by the direct evaporation from the lake surface and an outflow to the downstream compartment. Outflows are modelled on the assumption that discharge ceases below a certain threshold lake level, and is maximum if the lake level exceeds the maximum assigned value. In between, the discharge fraction is proportional to the lake level. Such representation of a discharge fraction implies another buffering mechanism, always working against the deviation from a long-term average water level.

Subcatchment Compartments

All the subcatchments are modelled as linear reservoirs (Dawdy and O'Donnell 1965). During each time step they receive some non-negative amount of precipitation, calculated by multiplication of catchment areas and Effective Runoff, and lose a part of their content preset by the discharge coefficient (StockDecrease). Subcatchment compartments do not distinguish the water available for the surface and sub-surface runoff. For calculation of a hydrological balance such an assumption does not matter, since all the runoff is accounted for. It may, however, affect subsequent calculations of an elemental balance. However, Cheshire meres were thought to be sealed on the bottom by a practically impermeable clay and silt layer (Reynolds 1979). Deep groundwater inputs, therefore, should be negligible and can be discounted. Thus the current integrating representation of shallower groundwater inputs together with surface runoff from subcatchment compartments at present provides a satisfactory estimate.

Results and Discussion

Model Calibration

Calibration of the model was performed in two steps. First the coefficient of maximum discharge from the upstream lakes (DischMaxMere) was optimised to give a base flow in accordance with lower measurement values of the Rostherne Brook flow rate. Then StockDecrease and the maximum coefficient of discharge from Rostherne Mere were optimised using data on the Rostherne water level. Both optimisations were performed using the Marquardt algorithm by an automatic optimisation procedure of Model Maker.

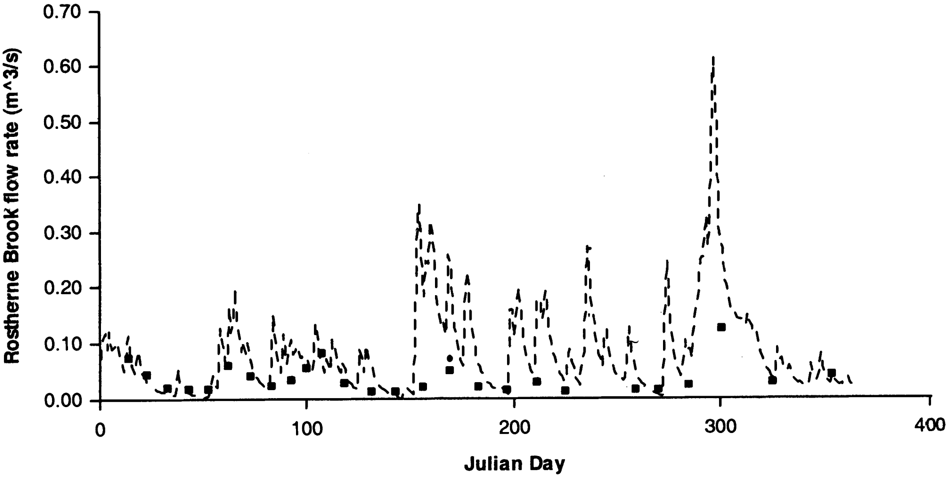

Fig. 9. Example of fit between model simulation (line) of the Rostherne Brook flow rate in 1998 and observations (points).

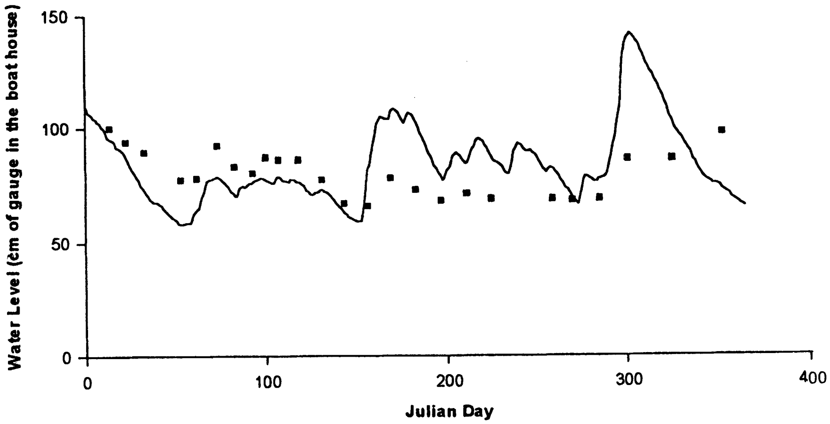

Fig. 10. Example of fit between model simulation (line) of the Rostherne Mere water levels in 1998 and observations (points), as measured at the gauge in the boat house.

Hydrological Budget

After calibration the model was used for quantifying the hydrological balance. Examples of the resulting fit between the measured data and model simulations of the Rostherne Brook flow rate and the Rostherne Mere water level are shown in Figs. 9 and 10 respectively. Discrepancies between simulations and observations result both from a number of assumptions and approximations (*e.g.* cone approximation of the 3D structure, approximation of table equations used for evaporation calculations, approximation of root constant functions, *etc.*), uncertainty of some measurement and parameter values, and a simplified representation of the catchment hydrology. It is evident, however, that the model correctly reproduced the pattern of the inflow hydrological dynamics (Fig. 9), and the range of changes in the lake level (Fig. 10). Thus, despite the obvious deficiencies, the model presented here represents the best currently available tool for calculating the Rostherne Mere water budget. As was shown, the hydrological system studied responds fast to changes in precipitation. This creates difficulties for accurate calibration. Future research should, therefore, concentrate on the improvement of parameter estimates. It is suggested to implement gauging stations at the major inflows to the meres, and to provide continuous monitoring of the water levels. This, however, would only be possible if additional funding became available.

Calculation of Elemental Budgets

Daily budgets of chemical elements were calculated by the Water Catchment Model using data on lake water chemical concentrations and relationships between temperature, flow rate, and inflow chemical concentrations. These were derived from the monitoring data of Rostherne Brook (both above Mere Mere and Rostherne Mere)

Table 1a – Summary of the Rostherne Inflow Monitoring. Regular (1-4 times per month) samples were taken in 1996 and 1998.

	N	Unit	Minimum	Maximum	Mean	Std. Error
Ca	53	ppm	24.71	112.30	76.34	2.62
CHL	49	ppb	0.54	62.82	20.00	1.85
CONDIN	46	μS	350.00	640.00	537.17	10.40
CONDOUT	46	μS	320.00	590.00	432.07	7.91
DOC	26	ppm	4.10	29.35	9.65	0.99
FLOW	50	m^3/s	0.01	0.26	0.05	0.01
K	52	ppm	1.96	13.27	5.22	0.35
Mg	52	ppm	3.81	18.77	12.94	0.41
Na	27	ppm	8.90	31.17	19.77	0.86
NH_4	51	ppm N	0.00	0.85	0.14	0.02
NO_3	53	ppm N	1.75	11.04	3.56	0.27
O_2	44	ppm	5.20	19.00	10.52	0.43
ORGN	51	ppm N	0.15	5.83	1.13	0.12
ORGP	33	ppm P	0.00	0.41	0.05	0.02
pH	45	units	5.20	8.30	7.36	0.08
PN	36	ppm N	0.00	3.07	0.52	0.11
PO_4	52	ppm P	0.00	0.37	0.05	0.01
PP	41	ppm P	0.08	3.50	0.35	0.09
S	27	ppm	7.36	36.17	24.61	1.26
Si	52	ppm	1.17	5.18	2.97	0.12
SSORG	40	ppm	0.00	1.77	0.05	0.04
T	46	degrees C	4.80	16.00	10.65	0.42
TSS	47	g/l	0.00	1.78	0.07	0.04

Table 1b – Summary of the Mere Mere Inflow Monitoring. Regular (1-2 times per month) samples were taken in 1998.

	N	Unit	Minimum	Maximum	Mean	Std Error
Ca	23	ppm	26.17	76.88	53.10	2.58
CHL	22	ppb	0.96	32.49	5.75	1.52
CONDIN	21	μS	195.00	605.00	416.90	19.91
CONDOUT	21	μS	165.00	500.00	347.38	17.22
DOC	21	ppm	8.00	34.98	19.69	1.46
FLOW	22	m^3/s	0.00	0.03	0.01	0.00
K	23	ppm	4.39	12.70	7.01	0.42
Mg	23	ppm	4.74	14.32	9.74	0.56
Na	22	ppm	13.38	40.10	22.84	1.58
NH_4	23	ppm N	0.01	0.46	0.15	0.02
NO_3	23	ppm N	1.03	8.63	3.78	0.40
O_2	21	ppm	5.70	19.00	9.13	0.64
ORGN	19	ppm	0.54	2.14	1.26	0.11
ORGP	8	ppm	0.00	0.26	0.07	0.03
PH	20	units	6.44	7.55	7.04	0.06
PN	18	ppm	0.09	0.69	0.21	0.04
PO_4	23	ppm P	0.02	0.25	0.10	0.01
PP	17	ppm	0.04	0.50	0.17	0.03
S	22	ppm	12.96	33.69	22.04	1.36
SI	23	ppm	2.18	5.22	3.49	0.17
SSORG	22	ppm	0.00	0.02	0.00	0.00
T	21	degrees C	3.80	15.70	10.05	0.76
TSS	22	g/l	0.00	0.04	0.01	0.00

summarised in Table 1. If the calculated value of an estimated variable fell outside the recorded interval, it was assigned the closest recorded extreme limit for this variable. Regressions for chemical concentrations of Catchment North were derived from the monitoring data of Rostherne Brook above its inflow to Mere Mere, on the assumption that these two parts of the catchment (*i.e.* Catchment North and Rostherne Brook catchment above Mere Mere) have a broadly similar land use (Carvalho 1993). In some cases derivation of relationships was based on a combined data set, incorporating, apart from the author's own data, those from Stephen (1997). For some chemicals no significant relationship was found either with temperature and flow rate, or with other measured macroelements. In such cases either linear interpolation of observed values, or mean values for the studied period were used. Inputs with the rainfall falling directly on the lake surface were neglected for all the chemicals, apart from orthophosphate P and nitrate N. For the former, a value of 0.06 ppm, reported by Williams (1976) for Rothamsted, was used, while for the latter a value of 0.05 ppm, reported for dissolved inorganic nitrogen (DIN) levels in the precipitation at Lake district (Sutcliffe *et al.* 1982) was applied.

Table 2 – Elemental Budgets for the study periods (g).

Year 98	Si	K	Ca	Mg	PO4	OrgP	PP	NOx	NH_4	OrgN	PN
In	7.68E+06	2.20E+07	2.19E+08	2.92E+07	2.78E+05	1.43E+05	1.62E+06	1.81E+07	4.70E+05	4.78E+06	2.03E+06
out	4.22E+06	1.99E+07	2.06E+08	4.31E+07	7.91E+05	2.11E+05	2.24E+05	4.13E+06	1.98E+05	3.31E+06	1.13E+06
Net	3.46E+06	2.07E+06	1.29E+07	-1.39E+07	-5.13E+05	-6.88E+04	1.39E+06	1.39E+07	2.72E+05	1.47E+06	8.99E+05

Year 96	Si	K	Ca	Mg	PO4	OrgP	PP	NOx	NH_4	OrgN	PN
In	6.26E+06	1.75E+07	1.79E+08	2.37E+07	1.12E+05	1.76E+05	5.14E+05	1.46E+07	3.89E+05	3.85E+06	1.29E+06
out	1.29E+06	1.27E+07	1.42E+08	2.18E+07	5.22E+05	1.83E+05	1.11E+05	1.93E+06	3.25E+05	3.38E+06	9.78E+05
Net	4.97E+06	4.80E+06	3.70E+07	1.91E+06	-4.10E+05	-6.94E+03	4.03E+05	1.26E+07	6.34E+04	4.70E+05	3.09E+05

Tables 2-4 – Inputs and outputs of chemicals for Rostherne Mere.

Values for orthophosphates (PO4), total dissolved P (TDP), organic P (orgP), particulate P (PP) and total P (TP) are given in terms of P.

Values for nitrates/nitrites (NOx), ammonia (NH_4), organic N (orgN), particulate N (PN) and total N (TN) are given in terms of N.

Elemental Balance

For both years the lake appeared to have acted as a sink for most of the chemicals studied (Table 2), *i.e.* lake overall input considerably exceeded the output. This was especially clearly shown in cases of N, Ca and K. A negative balance was calculated only for Mg in 1998 and dissolved P species in both years. It should be noted that calculations of Ca, Mg and K budgets were based solely on the analysis of their dissolved fractions. It is reasonable to expect, however, that considerable amounts of these elements are transported into the lake in the particulate form as well. Thus a considerable amount of chemicals contributes each year to the build up of bottom sediments.

Dissolved P

The net output of dissolved P could have resulted from the internal sediment release (see also Vogt 1987; Carvalho 1993; Krivtsov 2000, Krivtsov *et al.* 2001b) and was slightly larger in 1998 than in 1996 (5.82E+05 g compared with 4.17E+05 g). Expressed per unit of lake area, P release amounted to the internal yearly loading of approximately 1.2 and 0.9 g/m^2 for 1998 and 1996 respectively (Table 3). A major part of these changes was associated with orthophosphate P (88 and 98% in 1998 and 1996 respectively).

Average estimates of the internal P release obtained in laboratory experiments

Table 3a – N & P changes in 1998 (g).

	Absolute	Per m^2
ChangePO4	-513269	-1.05
ChangeOrgP	-68803	-0.14
ChangePP	1391295	2.86
Change TDP	-582072	-1.20
% PO4/TDP	88.18	
ChangeTP	809223	1.66
ChangeNOx	13924950	28.59
ChangeNH$_4$	271630	0.56
ChangeOrgN	1468560	3.02
ChangePN	898830	1.85
TNchange	16563970	34.01
%Nox/TN	84.07	
%NOx/TDN	88.89	
Input ratios:		
TDN/TDP	55	
DIN/PO4	67	
TN/TP	12	

Table 3b N & P changes in 1996 (g)

	Absolute	Per m^2
ChangePO4	-410339	-0.84
ChangeOrgP	-6939	-0.01
ChangePP	403316	0.83
Change TDP	-417278	-0.86
% PO4/TDP	98.34	
ChangeTP	-13962	-0.03
ChangeNOx	12630050	25.93
ChangeNH$_4$	63354	0.13
ChangeOrgN	470060	0.97
ChangePN	308714	0.63
TNchange	13472178	27.66
%NOx/TN	94	
%NOx/TDN	96	
Input ratios:		
TDN/TDP	65	
DIN/PO4	134	
TN/TP	25	

with Rostherne Mere sediments range from 9 (Krivtsov 2000, Krivtsov *et al.* 2001b) to 15 (Vogt 1987) mg/m^2/d. Assuming a 150-day stratification period, these figures will correspond to a total release of approximately 1350 – 2250 mg/m^2. It should be noted, however, that the latter estimate is applicable only for the deepest part of the lake. Sediments of shallower areas are situated within the mixed zone, and could be expected to have a much smaller P release. If the cut-off depth for sediment P release was assumed to be 10 m (*i.e.* the commonly observed depth of the epilimnion), then the deeper part of the lake would amount for approximately 57% of the lake area (calculated using an inverted cone approximation). Assuming a negligible release from the shallower sediments, the estimates of P release made using experimental data extrapolated for the whole lake will give a range of approximately 0.8 – 1.3 g P/m^2. The latter is highly in line with the internal load estimated using the catchment model.

Particulate P

It is worth pointing out that although the lake appears to have acted as a net source for dissolved P species, for particulate P the balance was positive. Net inputs of particulate P were estimated as 1391 and 403 kg P in 1998 and 1996 respectively. Reflecting high particulate P inputs, the balance of total P in 1998 was positive, and only slightly negative in 1996. In 1998 the estimated net input of PP was more than twice as high as the estimated net output of total dissolved phosphorus (TDP), while in 1996 the former was only marginally smaller than the latter. 1998 received more precipitation than 1996, and differences in the estimated PP inputs may, therefore, have reflected differences in rainfall.

It is normally assumed that up to 80% of the particulate load could be sedimented near the inflow point, *i.e.* essentially before entering biogeochemical cycles within a lake ecosystem (Andersen 1997; see also Edmondson and Lehman 1981; Prairie 1988). In Rostherne, however, a depth gradient at the Rostherne Brook inflow point is very steep. It is therefore likely that, depending upon particle size distribution, weather conditions, degree of stratification, *etc.*, a substantial part of the particulate load may be carried to the deeper areas, consequently providing materials for the delayed internal P release. However, it is also possible that the recorded phenomenon was due to particular environmental conditions of the research period.

At present there is not enough information to assess the fate of the particulate load within the lake. A broad correspondence of the net TDP outputs with net PP input is, however, alerting. If all the P species are considered simultaneously, the overall estimated net balance would be positive for 1998 (1.7 g/m^2) and negative for 1996 (-0.03 g/m^2). Thus, providing that particulate P load replenishes the source of the gradual internal release, it is possible that the lake has approached an equilibrium point, where the surplus of particulate inputs are compensated by outputs of dissolved P, with a gradual summer sediment release coupling the two. Both physical and biogeochemical processes may be important for the noted change in P specia-

Table 4 - Long term input changes for DIN and TP (kg)
Values for 1990/91 and 1991/92 are taken from Carvalho(1993) and Carvalho *et al.* (1995). Total rainfall (mm) was calculated from data of UK Meteorological Office

Year	1990/91	1991/92	1996	1998
Net TP	628	-1059	-14.0	809.2
inputs TP	2280	590	802.5	2035.9
NetTN			13472.2	16564.0
InputsTN			20089.1	25330.2
Net DIN			12693.4	12693.4
Inputs DIN	12307	7486	14949.0	18524.0
Total Rain	711.5	671.3	676.8	924.9

tion within the lake ecosystem, including adsorption to/desorption from particles, coprecipitation with various chemical compounds, uptake and excretion by biota, mineralisation and release from sediments (Krivtsov 2000).

Comparison with Previous Work

Table 4 shows estimates of N and P budgets for the study periods, together with two 12-month estimates made by Carvalho (1993) before and after sewage diversion. It is worth pointing out that Carvalho's estimation of water budget was based on averaging out fortnightly measurements. As was shown above, the average value obtained in such a way may not necessarily reflect a true mean value. Inspection of Fig. 9 and theoretical considerations suggest that for such a small catchment as that of Rostherne Brook, large flow peaks are rapidly retreating, and could therefore be easily missed out. It is therefore possible that water (and, subsequently, nutrient inputs) in the calculations of Carvalho (1993) could have been underestimated. It should be noted, however, that groundwater inputs from Catchment North in the above mentioned study were effectively double counted (firstly as equal to the dry base flow of Rostherne Brook, and secondly as a part of rainfall corrected for evapotranspiration). Thus a likely underestimation of the Rostherne Brook inputs might have been partly cancelled out by overestimation of the inputs from Catchment North. In view of the fact that the same methodology was applied for the whole period of the study, the conclusions of Carvalho (1993) are still likely to be valid. However, given the potential errors in the estimates (acknowledged by Carvalho himself), all consequent considerations (*e.g.* Carvalho *et al.* 1995; Moss *et al.* 1997), although still likely to hold true, should be treated with caution.

It appears, that despite the dramatic reduction in the dissolved P loads (Carvalho 1993), P inputs to the lake are still high, owing primarily to PP in the runoff.

Whether these inputs provide a source for a subsequent internal dissolved P release, preventing a change in the lake's trophic status, should be clarified by further research. It should be also noted, that the present application of the Catchment model assumed PP concentration in the integrated Catchment North input as 0.17 ppm (*i.e.* mean value for inflow Mere in 1998). For PP concentrations in Rostherne Brook, a linear interpolation of the collected data was used. Clearly, both assumptions may appear rather a gross representation of reality. It is possible, for instance, that a considerable part of the PP load from the Catchment North runoff gets trapped by the fringe of reed swamp surrounding the lake. Thus the calculated PP loads are likely to be overestimated and should be treated with caution.

Nitrogen Budget

Nitrogen inputs greatly exceeded outputs for both years, and were even larger than estimated inputs prior to the sewage diversion (Carvalho 1993). This may have reflected differences in the precipitation pattern, progressive accumulation of N in the catchment (possibly beyond the threshold level) due to atmospheric deposition, and changes in the land use and rates of fertiliser application, but might have also partly arisen from differences in the approaches used and uncertainties related to the calculations. Nitrogen to Phosphorus ratio calculated for different chemical forms ranged from 25 to 134 in 1996, and from 12 to 55 in 1998. Hence the ratio invariably exceeded the Redfield ratio of 7.2 (by weight) optimal for a biological growth.

Conclusions

The Rostherne Catchment model presented in this paper allows calculation of water and elemental budgets from meteorological data and a standard monitoring dataset. A number of assumptions incorporated in the model may result in considerable uncertainty for the calculated figures. However, estimates of the internal P load calculated using the model, are in good agreement with the estimates obtained by different methods. Hence, the Catchment Model can now be used in further studies of the mere. Its combination with the well-established lake ecosystem model "Rostherne" (Krivtsov *et al.* 1998, 1999b, 2000a,c,d, 2001a) may be particularly useful for prediction of the future and interpretation of the past dynamics observed.

Comparison with earlier estimates showed an increase in N loading. This could be related to changes in the land use and fertiliser application, progressive accumulation of N in the catchment owing to atmospheric deposition, and/or differences in the precipitation pattern.

Estimates of yearly inputs and outputs of N, Ca, Mg and K suggest that the lake is currently acting as a sink for these elements. Among the elements studied, only the dissolved P balance appears to be convincingly negative, owing to the high release from bottom sediments. It appears to be compensated by particulate P inputs, but the matter requires further clarification. A number of processes may prove important in coupling particulate P inputs with inorganic P outputs, including adsorption to/desorption from particles, excretion by biota, mineralisation and release from sediments.

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