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Semer Water hydrology, phosphorus budget, and aquatic macrophytes: environmental condition and nutrient sources

Report to Yorkshire Dales National Park Authority

Madeleine Moyle, John Boyle, Ben Goldsmith & Paul Bradley

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1 Executive summary

- The macrophyte survey revealed aquatic plants are limited to depths of less than 85 cm, and often much less, with many areas of the lake having no aquatic vegetation. Of the typical species that we expect to find in this type of lake, only one mesotrophic species and one hard water species were recorded in 2024. *Potamogeton alpinus* was not found in 2024 and the loss of *Nuphar lutea* since 2016 is of concern.
- The sediment record analysis revealed that the current phosphorus load at Semer Water is slightly below its peak around the beginning of the 21st century.
- The sediment record analysis combined with analysis of the Environment Agency published total phosphorus concentrations permitted estimation of the total phosphorus input load, equalling approximately 2550 kg/yr.
- Analysis of indicative catchment loads shows at the most significant phosphorus source is degraded blanket peat, with lesser amounts derived from cattle and sheep.
- To help further inform lake rehabilitation, we recommend that:
    - Stream flows from Semer Water should be gauged to improve accuracy of the total budget and to track the impact of restoration measures.
    - The water quality sampling point at Semer Water be moved from its current location to the outflow stream to avoid edge effects.
    - One or more of the streams draining the blanket peat should be regularly monitored for stream flow and total phosphorus concentration.
    - Options for continued improvement in animal waste management should be explored, but keeping clearly in minds that peatland restoration is the key to reducing external loads of P to Semer Water.
    - Subfossil analysis of sediment cores should be undertaken to determine historic composition of the aquatic flora in order to set better targets for assessment and restoration.

2 Introduction

As a part of the YDNPA Semer Water Restoration Project, this report describes research conducted in 2024 by Dr John Boyle, Dr Madeleine Moyle (both University of Liverpool), and Dr Ben Goldsmith (Goldsmith Ecology) into the water quality, aquatic macrophytes, hydrology and nutrient loads of Semer Water and its catchment. It builds on catchment surveys (PBA Ecology), fish surveys (PBA Ecology) and a bathymetric (Atlantic Geomatics, PBA Ecology), and together aims at informing a restoration strategy for Semer Water.

The specific aims of this part of the research are:

- To establish the state of the aquatic macrophyte assemblage as a sensitive indicator of lake condition.
- To determine the hydrological balance of the lake based on a combination of field observations and comparison with neighbouring gauged rivers.
- To determine a long-term phosphorus mass balance for the lake and its catchment, evaluating specific nutrient sources.

This information is combined to consider restoration options for the lake.

To achieve these aims we:

- Undertook an aquatic macrophyte survey of Semer Water.
- Gauged and sampled a number of upland tributaries.
- Analysed the record of a pre-existing sediment core (SEM3, 2018), determining an age depth model, and determining from it the sediment phosphorus burial history of Semer Water.
- Undertook analysis of historic total phosphorus concentrations measured and reported by the Environment Agency.
- Undertook a GIS analysis of topographic and land cover maps to determine indicative nutrient loads from elements of the landscape, using an export coefficient modelling approach.
- Developed a whole system phosphorus budget, and critical evaluation of specific nutrient sources.

3 Current condition of Semer Water

Long term monitoring is needed to examine changes in lake water quality at a site. Lake water annual average nutrient concentrations can be evaluated against long term trends and freshwater nutrient standards and targets to establish any improvement or decline in nutrient status.

3.1 Site overview and water quality targets

This section summarises the existing available data for Semer Water, including water quality targets. For the management of freshwater lakes, two schemes are used to determine water quality standards and targets for lake water TP concentration. These are the Water Framework Directive (WFD) and the Common Standard Monitoring Guidance for Freshwater Lakes (CSM). Water quality targets for TP can be calculated on a site specific or type specific basis. Both approaches use lake physical and chemical properties to determine the target value(s). Note that small differences are seen between data sources for parameters such as lake and catchment areas, arising from uncertainty in edge or divide estimations. The differences are small enough to have no substantial impact on interpretations.

Table 1 summarises site data for Semer Water from the EA catchment data explorer and the UK Lakes Portal.

Table 1: Summary data from EA Catchment Data Explorer (https://environment.data.gov.uk/catchment-planning) and the UK Lakes Portal (https://eip.ceh.ac.uk/apps/lakes/).

Parameter	Units	Value
Grid reference	BNG	SD9192587158
Lake area	km^2	0.286
Catchment area	km^2	42.98
Altitude	m asl	246
Mean depth	m	3.5
Mean alkalinity	uEq/L	1469

Table 2 summarises the Water Framework Directive (WFD) lake typologies for Semer Water.

Table 2: Summary of the WFD lake typologies. Data from UK Lakes Portal (https://eip.ceh.ac.uk/apps/lakes/).

Typology	Classification
Elevation type	Mid elevation
Size type	Small
Depth type	Shallow
Geology type	Marl lake
Humic type	Humic

Under the WFD geology type, Semer Water is categorised as a Marl lake. Under the CSM habitat feature type, Semer Water is classified as Hard Water with a depth category of Deeper (mean depth > 3m). The WFD and CSM type specific standards and targets for Semer Water based on these typologies are shown in Table 3.

Table 3: Type specific WFD targets for total phosphorus for lakes classified as Marl; Shallow and the type specific CSM target for lakes classified as Hard Water; Deeper. Note WFD uses the geometric mean whereas CSM uses the arithmetic mean.

Target	Mean annual TP (µg/L)
WFD High	9
WFD Good	20
WFD Moderate	40
WFD Poor	80
CSM	10

3.2 Methods

3.2.1 Water quality

Conducted by the EA between 2010 and 2024 at sampling point SEMER WATER (ID: NE-40000443) on the northeast shore (SD9218087475). The monitoring data can be accessed via the EA water quality data archive (https://environment.data.gov.uk/water-quality/view/landing).

3.2.2 Aquatic plants

The full description of the survey methods used to collect the aquatic plant data are detailed in the Joint Nature Conservation Committee publication for the Common Standard Methods (CSM) guidance for standing waters (JNCC 2015). The CSM assessment is presented in full in Goldsmith 2025 - Semer Water - SSSI Condition Assessment 2024.

In brief, the aquatic plant survey consists of four components: a strandline survey of species uprooted and washed to the shore; a survey of the emergent and marginal species at the shore edge and in shallow water; a wader survey of the shallow littoral zone to approximately 1.0 m depth; and a boat survey encompassing species in open water and extending to the depth of maximum macrophyte colonisation. The four survey components are each undertaken at four discrete 100 m lengths of shoreline (a "section") which are considered representative of the lake and gives good geographical coverage.

At lakes such as Semer Water, which have previously been surveyed, these sections are repeated in order to maximise comparability between surveys. The locations of all survey sections and boat transects were recorded using a Global Positioning System (GPS), backed up with digital photographs where necessary.

Where possible, surveying was performed using a bathyscope, but a double-headed rake was used in deeper water, where material needed to be collected for identification, or where poor water clarity restricted visibility.

3.3 Results and discussion

3.3.1 Water quality

The water quality at Semer Water has been monitored by the EA between 2010 and 2024 at sampling point *SEMER WATER* (ID: NE-40000443) on the northeast shore (SD9218087475). The monitoring data can be accessed via the EA water quality data archive (https://environment.data.gov.uk/water-quality/view/landing). Figure 1 shows the TP concentration record taken at approximately monthly intervals.

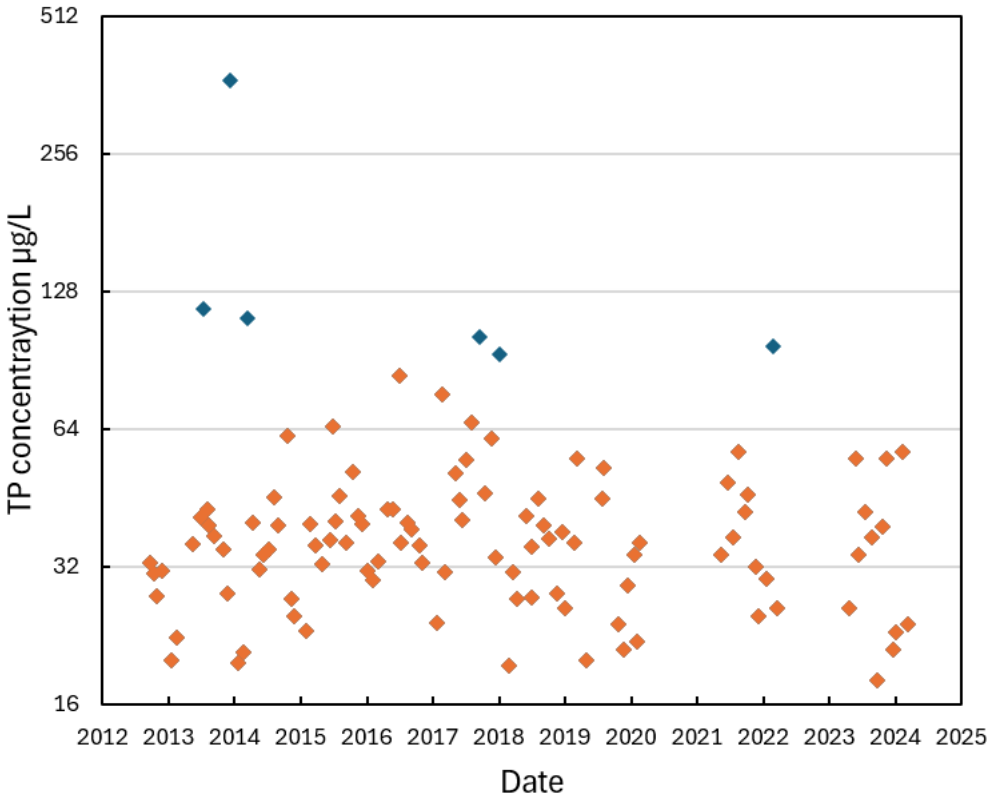


Figure 1: Environment Agency monitored TP concentrations for Semer Water. These are lake edge samples taken at sampling point SEMER WATER (SD9218087475). Values in blue are assumed to have been impacted by decaying algae at the lake edge, and to not represent the open water lake conditions. They have been excluded from the calculated mean concentration.

3.3.2 Macrophyte survey

Semer Water is classified as CSM Type: "H3130 Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea",* and WFD Type: "Marl / Shallow (under review)". It is these targets against which the conservation status is assessed.

In actuality, the classification of Semer Water as a mesotrophic, deep lake is contrary to the measured alkalinity which is above that expected for this lake type, yet neither does it have very high alkalinity, nor carbonate deposition, that one would expect to see for the marl typology. Furthermore, the humic inputs from the peat in the upper catchment colour the water brown and therefore limit light penetration, and plant growth, in deeper water.

In 2024, only seven species of aquatic plant were recorded growing in the lake and of these, many have seen a decline (Table 4). Normally we expect to species growing to 2.5 m or greater in mesotrophic or high alkalinity lakes, but at Semer Water we find no plant growing at more than 85 cm depth.

Table 4: Aquatic macrophyte data from CSM surveys of Semer Water 2005, 2010, 2013, 2016 & 2024. NB the 1995 survey was conducted using different methods.

Submerged and floating vegetation	**DAFOR**	**% Frequency**				
	1995	**2005 (n = 54)**	**2010 (n = 58)**	**2013 (n = 120)**	**2016 (n = 125)**	**2024 (n = 125)**
Callitriche hamulata			22	1	1	1
Callitriche sp.	R	20	7			1
Chara sp. (globularis)	**O**					**3**
Eleocharis acicularis	O	46	24	11	3	12
Elodea canadensis	R	2		1		
Elodea nuttallii			2			
Fontinalis antipyretica	F		5	1	1	
Limosella aquatica		7	3	1	1	3
***Nitella flexilis* agg.**		**2**			**2**	**1**
Nuphar lutea	R	37	29	13	13	
Potamogeton alpinus			**+**		**1**	
Potamogeton berchtoldii		2		1		
Potamogeton crispus		+		1		
Potamogeton pectinatus	F	6		1		1
Zannichellia palustris		7				
Species richness	**7**	**10**	**8**	**9**	**7**	**7**

The aquatic plant assemblage is neither typical of mesotrophic or hard water lakes. Of the seven aquatic species recorded in 2024, *Nitella flexilis* agg. was the only characteristic mesotrophic species and this only occurring in a single location (SD9205686890). *Potamogeton alpinus* was recorded at a single location in 2016 (SD9164387145) and washed up in the strandline in 2010. An extensive search was made for this species in 2024, but to no avail.

Chara globularis was recorded from only three locations near the SE shore and only as single plants, not as the extensive beds considered as typical for hard water lakes.

Previously the most recent record for *Chara* was from a 1995 survey (Bennion et al.1997) when it was recorded as “occasional”.

Nuphar lutea has been present within the site since at least 1995 and in 2016 formed an extensive bed throughout sector 2 around the southeast shore, growing to a depth of 80 cm (survey section 2 - SD9205686890). In July 2024, this bed was completely absent, and the species not seen within the site (although still present in the River Bain, downstream of the lake). The reason for its is unclear. *Nuphar lutea* is a perennial species, growing from large tuberous roots and is normally very resilient where established. Its loss from the site is a serious concern.

Eleocharis acicularis is relatively common around the shoreline, but recorded only rarely growing at 25 cm and deeper and thus the overall frequency score is low. Similarly, *Limosella aquatica* was abundant on the exposed mud around the southwestern shore and inflow stream (Crooks Beck), but recorded only rarely at 25 cm. Water levels were slightly higher during the 2005 and 2010 surveys, resulting in more *E. acicularis* and *L aquatica* being recorded in shallow water, the actual population size of these species is therefore unlikely to have changed significantly at the site over the past two decades.

Callitriche brutia var. *hamulata* was recorded only once growing in the water, but present around the shoreline where it was relatively common in very shallow water (<25 cm) or just above the waterline on wet mud and sand.

On a positive note, Semer Water supports a good population of Mudwort *Limosella aquatica* in the shallow drawdown zone around the west side of the inflow. This is an uncommon species in the UK, and declining due to habitat loss. The population here appears stable and is therefore significant.

Despite large areas of Semer Water being less than 2.5 m in depth, the majority has no plants present. Nuphar lutea formed the only extensive area of plant cover within the water, but this has been lost since 2016.

The marginal and transitional habitats are good in places. The western shore supports areas of willow and mixed sedge fen, with emergent beds of *Carex rostrata, Equisetum fluviatile, Schoenoplectus lacustris* and *Phragmites australis*.

The area around the Crooks Beck inflow at the south end has an extensive area of exposed deposits of sand and mud on which Limosella aquatica and Eleocharis acicularis are common. The wetlands behind this and around the inflow include a number of pools, which connect to the lake at high water levels, but are left isolated during the lower summer levels. While not extensively surveyed in 2024, it is significant to note that Starworts *Callitriche* spp. were present as was Small pondweed *Potamogeton berchtoldii*, in addition to other species recorded in the lake.

The east shoreline is predominantly cobbles and pebbles backed by pasture and has very little by way of wetland plants and is extensively grazed by geese, and in some areas livestock too.

It should be noted that Semer Water has relatively high humic content, derived from areas of peat in the upper catchment, and a mean annual water Colour measured at 57 Hazen units (light brown). The brown water limits light penetration which will have bearing on the maximum depth of plant colonisation at the site. The current limit of plant growth was measured at 85 cm in 2024, which is well below expectation for a site of this type. Secchi depths taken during the past three CSM surveys ranged between 54 – 80 cm, with turbidity as well as the brown colour noted for causing the low values. Furthermore, many of the hard substrates and submerged plants were noted as having a layer of fine sediment covering them, which will further impede plant growth within the site.

3.4 Key takeaways

Aquatic plants are limited to depths of less than 85 cm, and often much less, with many areas of the lake having no aquatic vegetation. Of the typical species that we expect to find in this type of lake, only one mesotrophic species was recorded in 2024 (*Nitella flexilis* agg.) and one hard water species (*Chara globularis*). *Potamogeton alpinus*, was not found in 2024.

The loss of Yellow waterlilies (*Nuphar lutea*) since 2016 is of concern. The reason for the loss is unclear and we should collect further evidence with respect to the timing and rate of loss. *Nuphar lutea* can regenerate from the seedbank, but this is less likely where water quality, and particularly clarity, is poor (high turbidity and colour).

Total phosphorus concentrations in the lake have exceeded the expected targets for shallow mesotrophic and hardwater lakes for many years. Gibbons (1990) reported a mean TP of 80 μgl^{-1} in 1990 and Bennion et al (1997) report Environment Agency data from 1995 – 1996 with a mean value 30 μgl^{-1}.

Work on apportioning the sources of P from within the catchment is ongoing and a well-informed nutrient budget should help identify and mitigate external P sources at the site. Additionally, high levels of historic P are likely to result in high internal P loadings within the lake sediments and thus recovery should be expected to take many years (decades), even after external sources are reduced.

The lake is utilised for leisure activities including angling, kayaking and swimming, placing it at increased risk from the introduction of INNS and ‘crayfish plague’. The use of the lake for waterskiing has a notable impact on shore erosion, particularly around the west side, and is likely to contribute to increased sediment resuspension and turbidity.

Semer Water fails to meet its primary conservation objectives with respect to water quality and aquatic plants. In part, this may be a result of the site typology being poorly

defined, and therefore the conservation expectation being set too high. A better understanding of the lake and wider catchment will help to redefine these objectives and set more realistic targets. We cannot ignore however, that the biology of the lake has declined over the past few decades and efforts should therefore continue to identify the major sources of nutrients, sediments and disturbance at a catchment-wide scale in order to mitigate the impacts and improve the site into the future.

4 Hydrology

Knowledge of local hydrology, the flow of water through the landscape, is essential for understanding nutrient pollution of lakes. Combined with nutrient concentration measurements, flow data is used to calculate nutrient loadings, enabling catchment nutrient budgets to be established. Without an understanding of loadings, the sources of nutrient pollution in the catchment cannot be robustly interrogated. Water flow data is the element crucially lacking from previous studies of Semer Water, limiting the value of the TP data gathered. Our analysis thus unlocks the full potential of more than a decade of measured TP concentrations.

Here, we describe and explain the measurements and secondary data we have used to quantify water flows through the Semer Water catchment.

4.1 Methods & data sources

4.1.1 Regional depth equivalent discharge estimation

The Semer Water catchment has no automatic river flow gauging. Consequently, we have looked to nearby gauging stations to determine depth equivalent discharges for the region as our closest estimate to the flows through Semer Water. Depth equivalent discharge, where flows are normalised to land area, is a way of expressing water flows through a landscape that is scale independent and transportable. For example, consider a stream with a 20 km^2 catchment area that discharged 1 m^3/s on average. Converting the flow to m^3/yr (by multiplying by seconds in a year), and dividing by the catchment area (in m^2), would give a value in units of m/yr ($m^3/m^2/yr$, simplified). In this example the depth equivalent discharge would be 1.58 m/yr, a value that can then be applied to nearby systems without measured data.

For this report we have found values for depth equivalent discharge for gauged rivers in the vicinity of Semer Water at five different locations. These are shown in Figure 2. These gauging stations can be used to reliably predict the total water budget for Semer Water in the absence of sufficient flow gauging at the site. The flow data for each of these stations is taken from the National River Flow Archive (NRFA), a resource provided by the Centre for Ecology and Hydrology (https://nrfa.ceh.ac.uk/). The last 50 years of flow data over the period 1972 to 2022 were used to produce a mean annual depth equivalent discharge for the region. This was then combined with the catchment area for Semer Water to estimate the annual discharge from the lake.

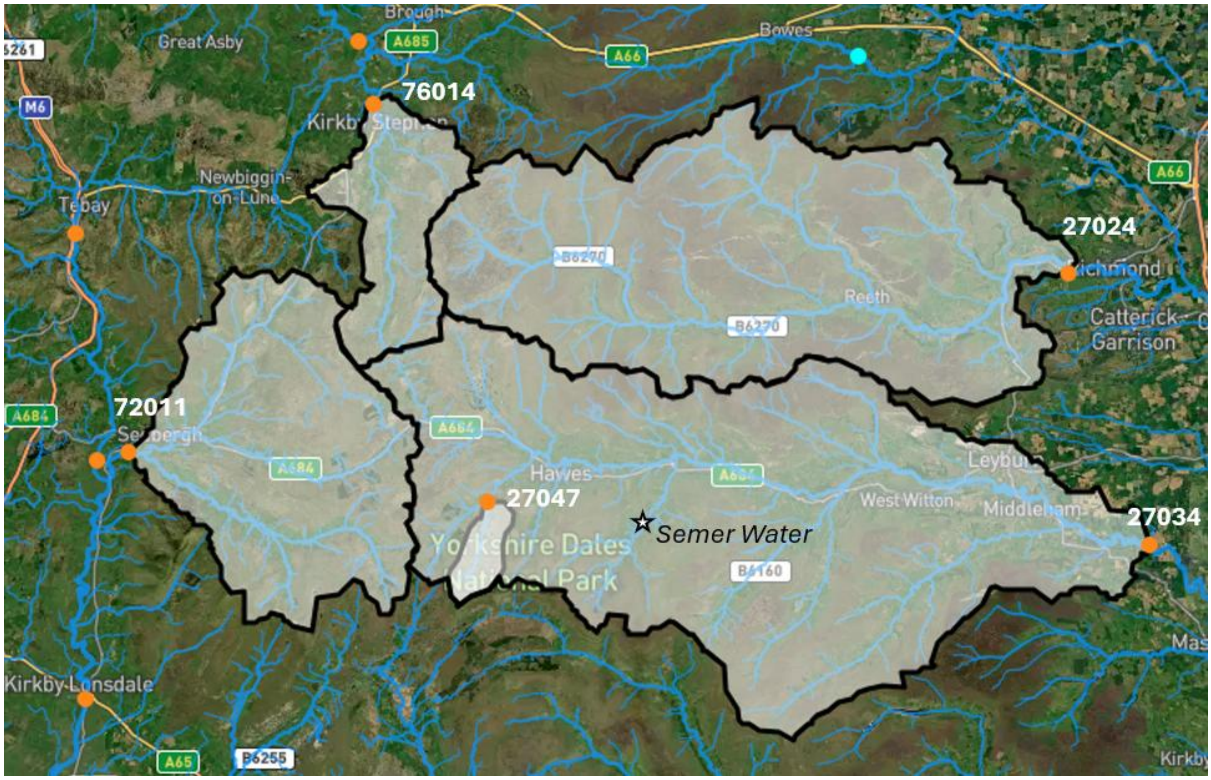


Figure 2: Map of NRFA gauging stations in the vicinity of Semer Water (orange dots). The stations used in this project are 72011 - Rawthey at Brigflatts; 27047 - Snaizeholme Beck at Low Houses; 27024 - Swale at Richmond; 27034 - Ure at Kilgram Bridge; and 76014 - Eden at Kirkby Stephen. The star marks the location of Semer Water.

4.1.2 Spot flow gauging

Two different gauging methods have been used to generate flow measurements for Semer Water.

PBA Ecology used the area-velocity method. The measured channel cross-sectional areas (m^2) is multiplied by the measured flow velocities (m/s) to yield the flow rate (m^3/s).

University of Liverpool used salt gulp dilution gauging. A small known quantity of table salt (NaCl) is added to the stream water at an upstream point that is 10 stream widths above a measurement point, this distance allowing sufficient mixing. At the measurement point, a logging TDS (Total Dissolved Solids) meter (Hanna HI 98197) that is calibrated for salt is used to record the salt concentration every 5 seconds until the pulse (or, gulp) of salt-enriched water has flowed past. Using the excess salt concentration (measured value minus background salt), the area under the gulp curve (mg x seconds/m^3) is calculated. The flow rate, in m^3/s, is then given by salt dose mass (mg) divided by the area under the curve.

4.2 Results and discussion

4.2.1 Regional depth equivalent discharge

The flow data from the five NRFA gauging stations near Semer Water (Figure 2) is shown in Table 5. These stations give a mean depth equivalent discharge of 1.28 m/yr. Given this value and a total catchment area of 42.6 km^2, the long-term mean water discharge from Semer Water is inferred to be 1.73 m^3/s.

Table 5: Details of the NRFA gauging stations in the vicinity of Semer Water and associated discharge data. From this information the long-term mean water discharge can be calculated

NRFA Station code and name	Area km^2	Mean flow m^3/s	Depth equivalent discharge m/yr
72011 - Rawthey at Brigflatts	200	9.75	1.54
27047 - Snaizeholme Beck at Low Houses	10.2	0.56	1.74
27024 - Swale at Richmond	381	10.44	0.87
27034 - Ure at Kilgram Bridge	510.2	16.53	1.02
76014 - Eden at Kirkby Stephen	69.4	2.70	1.23
Mean			1.28

4.2.2 Spot flow measurements

The NRFA sites provide the long-term perspective of flows within the region of Semer Water. This can be compared with the spot measurements taken at the outflow to Semer Water (Table 6).

Table 6: Comparison of spot measured outflow discharges from Semer Water with predicted long-term mean discharge based on nearby gauged rivers.

Date/period	m^3/s	Source
27/2/24	1.27	PBA
26/3/24	1.50	PBA
26/6/24	0.21	PBA
9/7/24	0.31	UoL
30/7/24	0.53	PBA
Measured mean	0.76	
Long-term NRFA	1.74	

The measured outflow discharges from Semer Water (Table 6) are all lower than the mean long-term value inferred from NRFA gauging data from nearby rivers, with a mean spot value of less than half the long-term estimate. This is consistent with the flashy hydrological regime expected at Semer Water. The nearest gauged river, Snaizeholme Beck (NRFA data), has a baseflow index of just 0.18, showing minimal groundwater storage which promotes a rapid response to rain events. In such catchments a high proportion of the total water export takes place during a few exceptionally wet days. A consequence of this is that measured nutrient input loadings based on a small number

of spot samplings will also likely underestimate the mean nutrient loading value for the catchment.

4.3 Key Takeaways

- Semer Water does not have a gauging station and therefore there are insufficient outflow discharge measurements for calculating robust values for nutrient loading.
- Nearby gauged rivers provide a sound basis for inferring the long-term mean water through flow for Semer Water. These data form the basis for determining nutrient budgets and water residence time.
- The estimated mean outflow rate will be close to the true outflow rate, but we cannot know how close, or whether we are likely underestimating or overestimating the true value. The small set of measured outflow rates is too small to provide a meaningful test. If more accuracy is considered desirable, then installation of an automatic gauging station on the outflow channel would be necessary.

5 Sediment record

In the absence of long-term monitoring, the application of analytical techniques to lake sediment records offers an approach for reconstructing changes in lake nutrient status, and therefore catchment P supply, over time. This palaeolimnological approach works on the basis that the sequential accumulation of particles (sedimentation by settling) on the bed of a lake leads to a build-up of a sediment layer that can be many metres in thickness. These particles can be generated within the lake (dead algae and other aquatic plant and animal fragments) or in washed from the catchment (eroded soil, terrestrial plant fragments, pollen, etc.) and represent the concurrent state of the lake and its surrounding landscape. As these particles build up, they reflect changes in the lake and environment over time. By sampling the sediment sequence, determining the age of the different layers, and "reading" the information stored in the particles, we can reconstruct how the lake and its catchment has changed through time.

Applying this approach to Semer Water will enable us to answer the following questions:

1. What is the current phosphorus (P) burial rate in the sediment? This is an important part of the total P budget, and without it we cannot know the current lake condition.
2. Has the rate of P supply changed through time?

5.1 Methods

5.1.1 Sediment sampling

The sediment record (SEM3) was collected in September 2018 by Prof. Richard Chiverrell, Prof. David Sear and Mrs Jen Bradley from the western edge of the deep central part of the lake (54°16'47.45"N, 2° 7'30.51"W) at a water depth of 8.2 m (Figure 3). Two different coring methods were used. The uppermost sediment was collected using an 80 mm diameter gravity corer (Boyle 1995) to capture the sediment-water interface. The deeper sediment was collected at the same location using a 75 mm × 1.5 m capacity hand-percussive Russian corer deployed from an anchored floating platform.

The 20.5 cm length gravity core was sliced in the field into 0.25 cm intervals. The Russian core collected 2.9 m of sediment in 2 overlapping drives. These were sliced into 1 cm intervals. All core samples were stored in the dark at 4 °C in sealed polythene bags prior to freeze drying, to prevent biological degradation of the material.

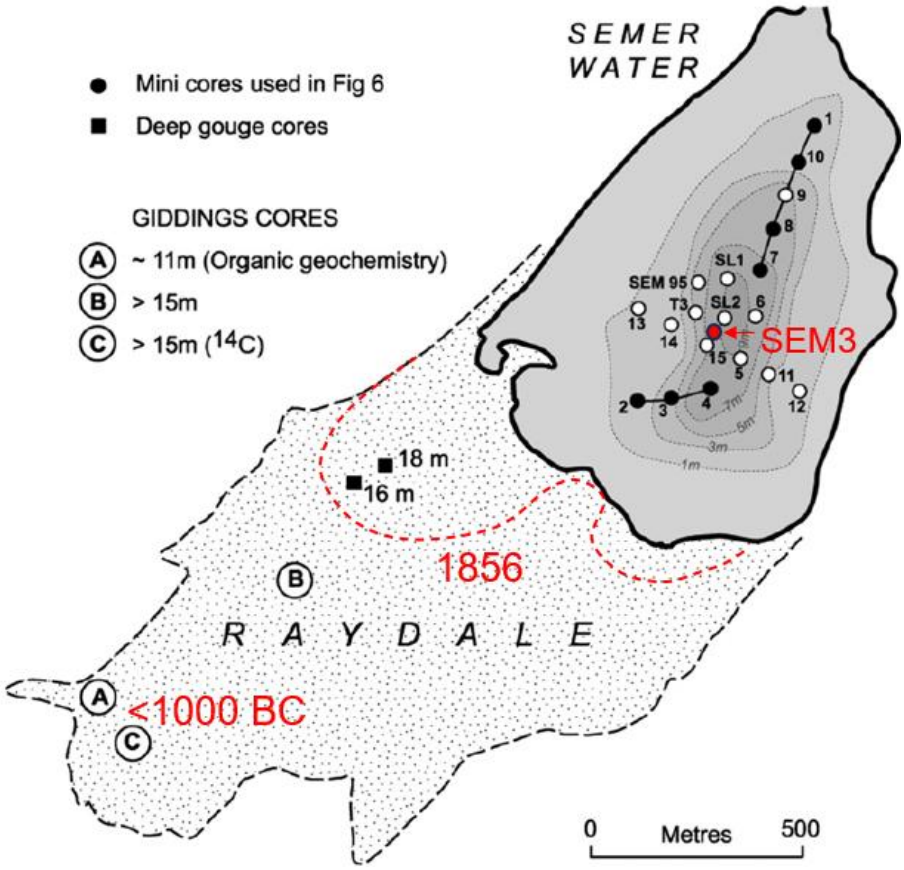


Figure 3: The location of core SEM3 in relation to previous cores taken at Semer Water. The base map is copied from Chiverrell et al. (2008). The 1856 lake boundary is redrawn from the Ordnance Survey 1:2500 County Series map of that year.

5.1.2 Element concentrations by XRF

Sediment element concentrations were measured on loose sediment powder using a Spectro XEPOS Energy Dispersive X-Ray Fluorescence (XRF) Analyser. We used factory set calibrations initially, and ran certified reference materials as unknowns to verify the calibration. Where element concentrations measured for the reference material differed from the certified values, secondary calibration was used. Figure 4 shows the calibration test for phosphorus.

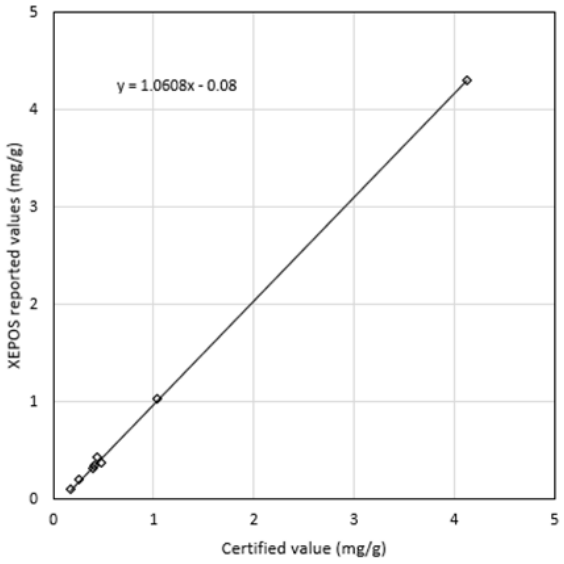


Figure 4 Calibration test for phosphorus using 8 certified reference materials.

5.1.3 Sediment dry density measurement

Sediment dry density values are required to calculate sediment mass accumulation rates. A GEOTEK/Olympus DELTA scanning μXRF was used to collect X-ray spectra from wet sediment material, and the backscatter signal was processed in EXCEL to calculate the dry density using the method of Boyle et al. (2015b).

5.1.4 ^{137}Cs, Pb pollution, and age-depth modelling

The activity of ^{137}Cs was measured on selected sediment samples by Stephen Chappell (Radiation Laboratory, Central Teaching Hub, University of Liverpool), using a Broad Energy Ge Detector (BEGe5030). The ^{137}Cs profile (Figure 5) shows clear activity maxima that we attribute to the peaks in atmospheric testing of thermonuclear bombs in 1963 and the nuclear accident at Chernobyl in 1987.

Additional age information is provided by the Pb concentration record (Figure 6), which shows a strong peak at depth of 219 cm. Substantial early atmospheric Pb pollution is expected in this area due to intensive 19th century mining and smelting in the region. However, we cannot know the exact age of its maximum value. Records of the closest mines (Aithwaite End and Askrigg Moor, Wensleydale) appear incomplete, so we have used the date of maximum Pb ore production (1857) for the whole of Yorkshire (Burt et al., 1982) to give an age estimate for the Pb peak. This is a plausible date but we cannot rule out dates of up to two decades later. We use the value to generate an age-depth model but advise dates much earlier than 1950 should be treated with caution, as robust but imprecise.

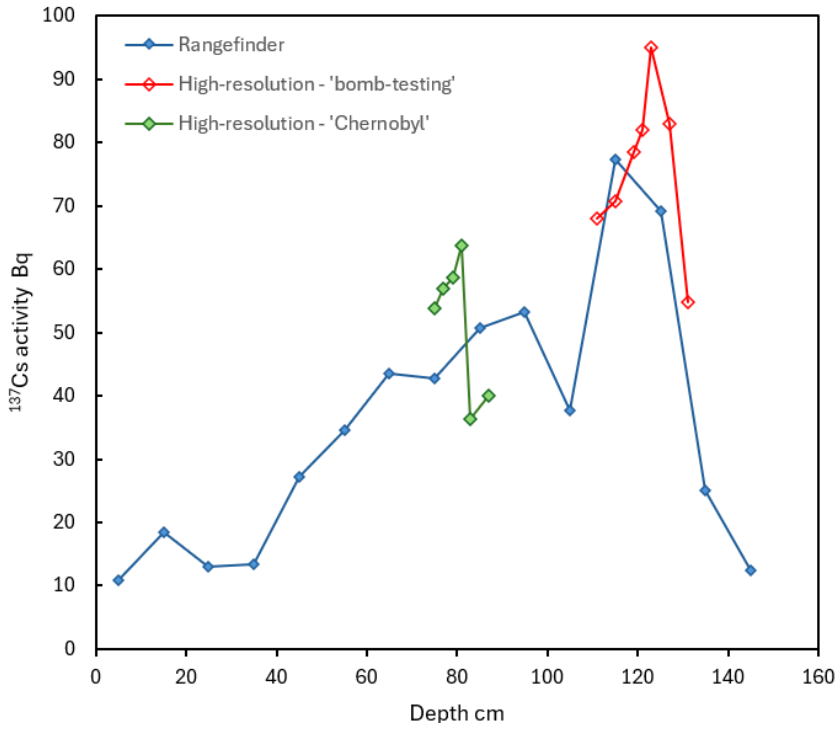


Figure 5: ^{137}Cs activity profile in SEM3. The Ranger finder measurements are low resolution and low count times (low precision). The high-resolution measurements are long count times to target the two ^{137}Cs event peaks.

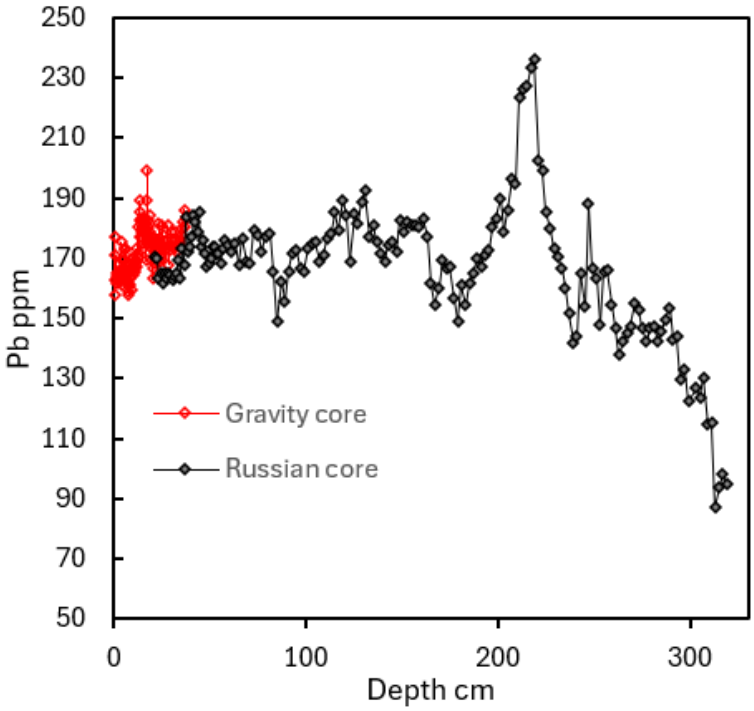


Figure 6 Sediment Pb concentration measured by XRF

The ages from the ^{137}Cs and Pb profiles and the coring date (September 2018) have been used to generate the age depth model shown in Figure 7.

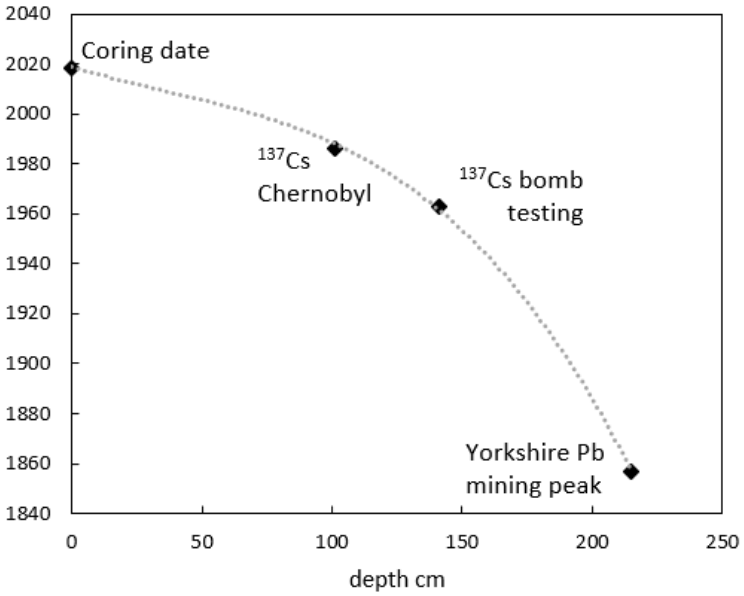


Figure 7 Age - depth model for SEM3

The age-depth model is most accurate for ages after about 1950. We calculate ages as far back as 1857 but caution that these are speculative.

Sediment accumulation rates are highly sensitive to age-model curvature. Given the uncertainty in the 19th century date, we have used only the sampling date and two ^{137}Cs dates to determine sediment accumulation rates. We fitted an inverse polynomial regression, the first derivative of which gives the accumulation rate (cm/yr) from the age model. The rate ranges from 1.2 cm/yr in 1963 to 3.9 cm/yr in 2018.

5.1.5 Mass balance modelling of phosphorus

Our approach to calculating P budgets is based on the recognition that lake nutrient dynamics cannot be understood without measuring nutrient fluxes. Measured concentrations of TP are an essential component of this, but unless water flows are also measured the concentration data cannot be used to determine state of the system. Likewise, sediment concentration data for P must be measured, but sediment burial rates must also be measured to generate P flux data if the system is to be quantified.

The key nutrient fluxes in a lake system can be grouped into the input fluxes to the lake via the inflows and the output fluxes from the lake via outflow and via burial in the sediment. Expressing these as loads (fluxes per unit area of lake), allows a steady state mass balance to be calculated, as illustrated in Figure 8. This permits both critical evaluation of how comprehensively the system is understood, and estimation of the future trajectory of change.

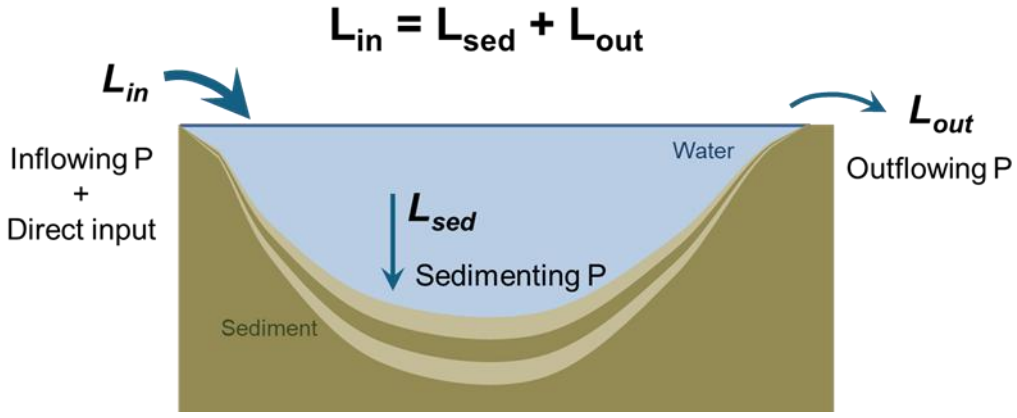


Figure 8 A lake mass balance. A simple lake mass balance recognises that the input loading (Lin) must equal the outflow loading (L_{out}) plus the sediment burial loading (L_{sed}). Evaluation of this balance provides a critical test of our understanding of the nutrient budget (Moyle and Boyle, 2021).

The steps needed to go from sediment measurements to the loadings described in Figure 8 are given in detail by Moyle and Boyle (2021) and are briefly outlined here. We also describe the approach for converting the sediment P concentration record to a record of historic lake water TP concentrations to which measured lake water concentrations can be compared.

Calculating mass accumulation rate: The sediment mass accumulation rate is calculated from the sedimentation rate (cm/yr) and to the dry density (g/cm^3), and expressed as g/m^2/yr. The sedimentation rate method is described above (See section 5.1.4).

Calculating sediment core P burial rate: Multiplying the mass accumulation rate by the phosphorus concentration (mg/g) gives the sediment apparent P burial rate for the SEM3 core in mg/m^2/yr.

Upscaling to lake-wide mean P burial rate: To convert this core burial rate to an estimate of the lake wide P burial rate we need to correct for sediment focusing. Sediment focusing is the result of a combination of process is that cause higher sedimentation rates in the deep central sediments of a lake. The focusing factor (FF) is a measure of the magnitude of this effect. If FF = 2, then the P burial rate of a core is 2 times higher than the average lake wide P burial rate. Moyle and Boyle (2021) recommend an approach based on a lake sedimentation model Håkanson (2003), but owing to the unusual bathymetry of Semer Water, which is largely shallow but has a deep central hole, this method cannot be applied. Instead, we take advantage of the mud limit concept of Rowan et al. (1992), which shows that sufficient water depth is required for fine sediment accumulate in wind exposed lakes. We suppose on this basis that only sediment deeper than a threshold value is accumulating. We base our threshold value on the analysis of Chiverrell et al. (2008) showing that the shallowest partially coherent ^{210}Pb record was at

5 m water depth. The 5 m depth contour has an area that is 1/7 of the total lake size. From this we take FF to be equal to 7.

Calculating P retention coefficient: Moyle and Boyle (2021) and Moyle et al. (2021) develop and explain the role of the P retention coefficient (R_P) in lake modelling, offering a sediment perspective that repurposes modelling approaches developed in the 1970s. The coefficient, R_P, is simply the proportion of supplied P that is transferred to the sediment rather than exported via the lake outflow. Its magnitude is closely related to the water load (q_s), the amount of water flowing though the lake annually, normalised to the lake area. There are several ways to calculate R_P, reviewed by Moyle and Boyle (2021). Here, we use the expression:

$$R_P = \frac{v}{v + q_s}$$

Where v is the effective sediment settling velocity (m/yr). In lakes with high sediment accumulation rates, v is high. We take it to be 50 m/yr for Semer Water. Mean q_s for Semer Water is given the expression:

$$q_s(m/yr) = discharge\left(\frac{m}{yr}\right) \times \frac{catchment\ area\ (km2)}{lake\ area\ (km2)} = 1.28 \times \frac{4.98}{0.29} = 190$$

With q_s at 190 and v at 50, R_P = 0.21 (Dimensionless).

Calculating sediment inferred lake water TP (SI-TP): Moyle et al. (2021) demonstrates using the mass balance model described above that past lake water TP can be calculated from a sediment record of past P burial loading, L_{sed}. To distinguish this parameter from direct water measurement, the sediment inferred TP is termed SI-TP. It is found using the equation:

$$SI - TP = \frac{L_{sed}}{R_P \times q_s}(1 - R_P)$$

Tested at a number of sites where monitored TP data and sediment records are both available (Moyle and Boyle, 2021; Moyle et al. 2021), SI-TP is found to be an accurate measure of the long-term mean TP concentration. Owing to smoothing processes in both the lake and the sediment, the temporal resolution cannot be below 1 year, and typically would be longer (1 to 10 years). SI-TP therefore provides a long-term perspective, the mean value about which short term fluctuations occur.

5.2 Results and discussion

5.2.1 Record of landscape change at Semer Water

Much information can be obtained from dated lake sediment elemental concentration records, a review of which can be found in Boyle (2001). Here we have chosen three elements that reveal aspects of the lake and landscape history. Figure 9 shows these element profiles against age indicating substantial change over the last 170 years.

Zirconium (Zr) is an element associated with the silt-sized mineral zircon and is a good indicator of mineral soil erosion. Figure 9 shows a rising trend from the base of the record until ~1920 suggesting increasing soil erosion rates through the late 19th century. This is followed by relatively constant rates indicative through the latter part of the 20th century and falling rates after about 1990 with the lowest Zr concentrations seen at the top of the core.

Bromine (Br) is a halide, ultimately derived from the sea via wind-blown sea salt, but very efficient trapped by soil organic matter. Peat accumulations, of the type abundant on the higher ground surrounding Semer Water, are generally highly enriched in Br compared with organic matter from lake plants. Consequently, the concentration of Br in lake sediments is an excellent indicator of peat erosion. Figure 9 shows a fall in Br concentration through the early part of the record to a minimum at around 1920. Following this, Br concentrations increase indicating peat erosion in the catchment. A period of higher concentrations from about 1940 is broken by a minimum in the 1980. This is followed by a sharp rise in Br concentration at ~1990, indicating rapid peat erosion, with increasing concentrations towards the top of the record showing the erosion has continued to the present day.

Figure 9 shows P concentration climbing steadily from a minimum at approximately 1900, with step-wise increases in the 1960s and sharp increase in the late 1980s. This points to increasing P loads from the catchment through the 20th century. The increase in P loading coincides with a reduction in soil erosion and an increase in peat erosion indicated by the Zr and Br records. Since around 1990 P concentrations have stabilised and then fallen towards the present day, suggesting a possible decline in catchment P supply in the last 10-15 years.

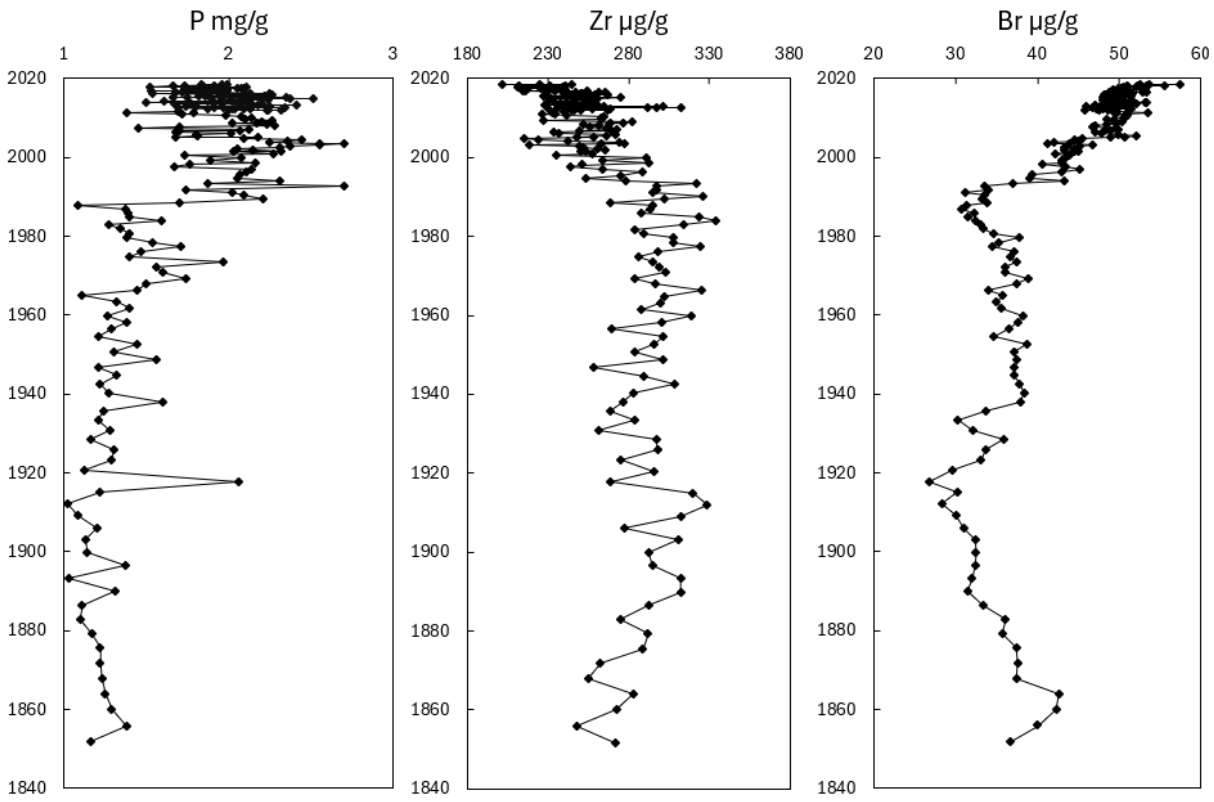


Figure 9 Concentration-age profiles at Semer Water for three selected elements

5.2.2 Sediment inferred catchment phosphorus load

Figure 10 A shows our calculated an estimate of the lake wide P burial rate and Figure 10 B shows the sediment inferred lake water total phosphorus concentration (SI-TP). Given the limitation of the age model used here, the shorter term variations in both records, such as apparent peaks at 1990 and 2005, should be treated with great caution because they may simply be methodological artefacts. We therefore focus on the longer trends visible in the records. The P burial rate and SI-TP records both show a strong temporal pattern, comprising a mid 20th century rise, a broad maximum between ~1980 and ~2010, and a subsequent decline towards the present day. This pattern indicates a growing catchment P load followed by a period of stabilisation and eventual partial recovery.

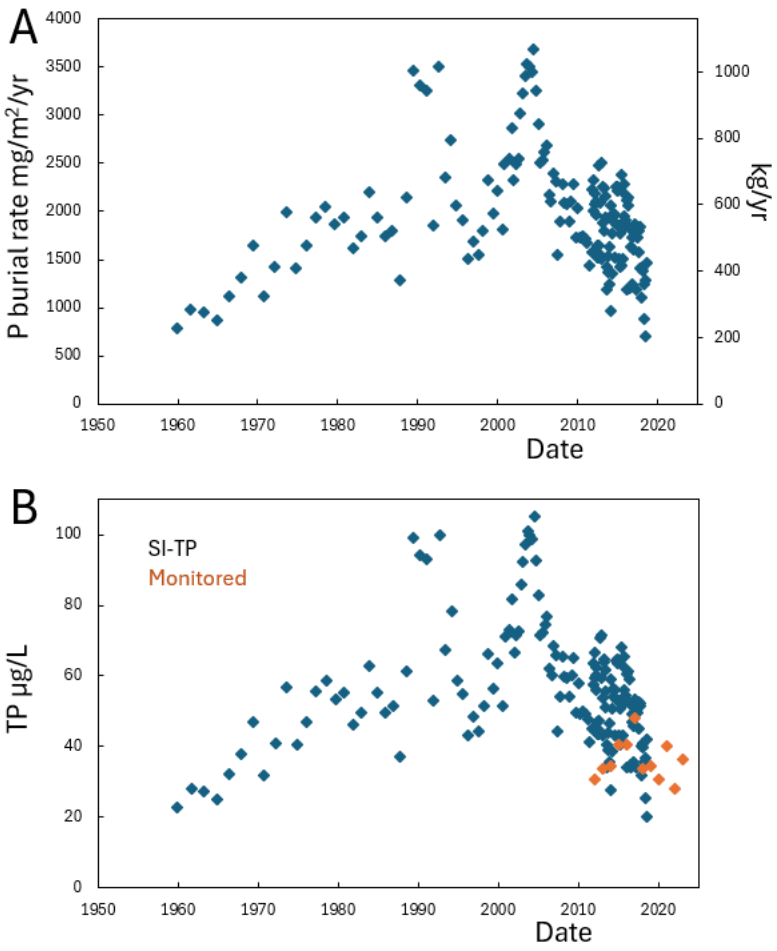


Figure 10 A: The lake P burial rate (L_{sed}) shown in both mg/m²/yr and kg/yr. B: The sediment inferred lake water total phosphorus concentration (SI-TP) (blue) compared with Environment Agency monitored values, recalculated as mean annual values (orange).

5.3 Key takeaways

- Variation in the concentrations of Zr and Br tell us about mineral soil erosion and peat erosion respectively. The overall story is for: gently rising mineral soil erosion, but falling peat erosion, through the second half of the 19th century; broad stability through the mid 20th century; and falling mineral soil erosion with increasing peat erosion since ~1990.
- The landscape P supply has not been constant at Semer Water. Rather, it rose through the second half of the 20th century, stabilised around the turn of the century, and has fallen slightly since the early 2000s.
- The lake sediment record evidences these trends, but cannot inform us of the sources of the P.

6 Output P loads and mass balance inferred budget

A part of the P budget has been addressed in the previous section – the sediment P burial load. Here we address the P outflow load, and briefly discuss what is tells us about P input loads.

6.1 Methods

Provided TP concentration is not correlated with outflow rate, the mean outflow load can be calculated by multiplying the mean lake total P (TP) concentration by the mean rate of flow in the outflowing water.

6.2 Results and discussion

6.2.1 Output loadings

Sediment burial: Using the data shown in Figure 10, the lake-wide sediment P burial loading has been calculated for the period for 2012 to 2024 (to correspond with the dates of Environment Agency monitored TP concentrations, Figure 1). This amounts to 493 kg/yr. Based on a single core, it is not possible to estimate an uncertainty for this value. Though the survey of Moyle and Boyle (2021) gives confidence to this approach, this cannot be quantified in individual cases.

Outflow: The mean concentration of all EA monitored TP values for Semer Water is 43.5 µg/L. If the 6 extreme values are removed, assuming them to be unrepresentative of the open lake water, then the mean falls to 37.3 µg/L with a standard error of 1.2 µg/L.

Given a mean outflow water loading of 190 m/yr (section 5.1.5), and a lake area of 0.29 km^2, the outflow annual load is 2053 kg/yr.

Total output loading: Summing these numbers, we estimate the total annual output of P from Semer Water to be 2547 kg/yr. We cannot give a full critical evaluation of the uncertainty on these estimates. The following points can however be made:

- The estimate for outflow loading, 2053 kg/yr, is the number with greatest certainty. There is ample data for TP concentration, but our estimated mean water export is uncertain. The standard error for the river flow estimates of depth equivalent discharge is13% of the mean. At face value, this might indicate upper and lower estimates of 558 and 430 kg/yr. However, we are not in a position to judge whether the stations selected are appropriate so this estimate of uncertainty is itself uncertain.
- The ratio of our estimates, burial/ (burial plus outflow), 0.19 is a direct measure of the retention coefficient, R_P. This value is very close to our estimate (0.21) based on independent information, giving confidence to our estimate for the sediment burial loading.

- Despite the uncertainties, our estimate of the combined output loading can be regarded as robust, and forms a reliable basis for estimating the total lake system P budget.

6.2.2 Inflow loading estimates

Because the output loadings are well measured, we also have an accurate figure for the total input loading as this must equal the sum of L_{out} and L_{sed} (see Figure 8).

$L_{in} = L_{out} + L_{sed}$ = 493 + 2053 = 2547 kg/yr

Direct measurement of inflow loadings is always more difficult and more uncertain than estimation of the sediment burial loading and outflow loading (Moyle and Boyle, 2021). This is particularly the case for Semer Water as the flashy nature the inflow streams makes measurement of mean inflow stream loads highly problematic. We return to this question when we evaluate the indicative estimates of catchment P sources (Section 7).

6.3 Key takeaways

- The calculated total annual output loading of P from Semer Water is well quantified, it has a value of 2547 kg/yr

7 Indicative catchment nutrient sources

This section applies the export coefficient method to estimate diffuse catchment loads. As it is based on generalised coefficients rather than specific measurements, the values represent expectation rather than fact. The term indicative is applied to acknowledge this. It should be pointed out, however, that the approach is widely used and trusted, and in practise there are no alternative approaches.

7.1 Methods

7.1.1 Catchment delineation

The catchment to Semer Water, and to sub-catchments corresponding to sampling locations, have been quantified in QGIS Desktop 3.36.3 by visual identification of catchment divides based on the assumption that flow is always perpendicular to contours (Figure 11).

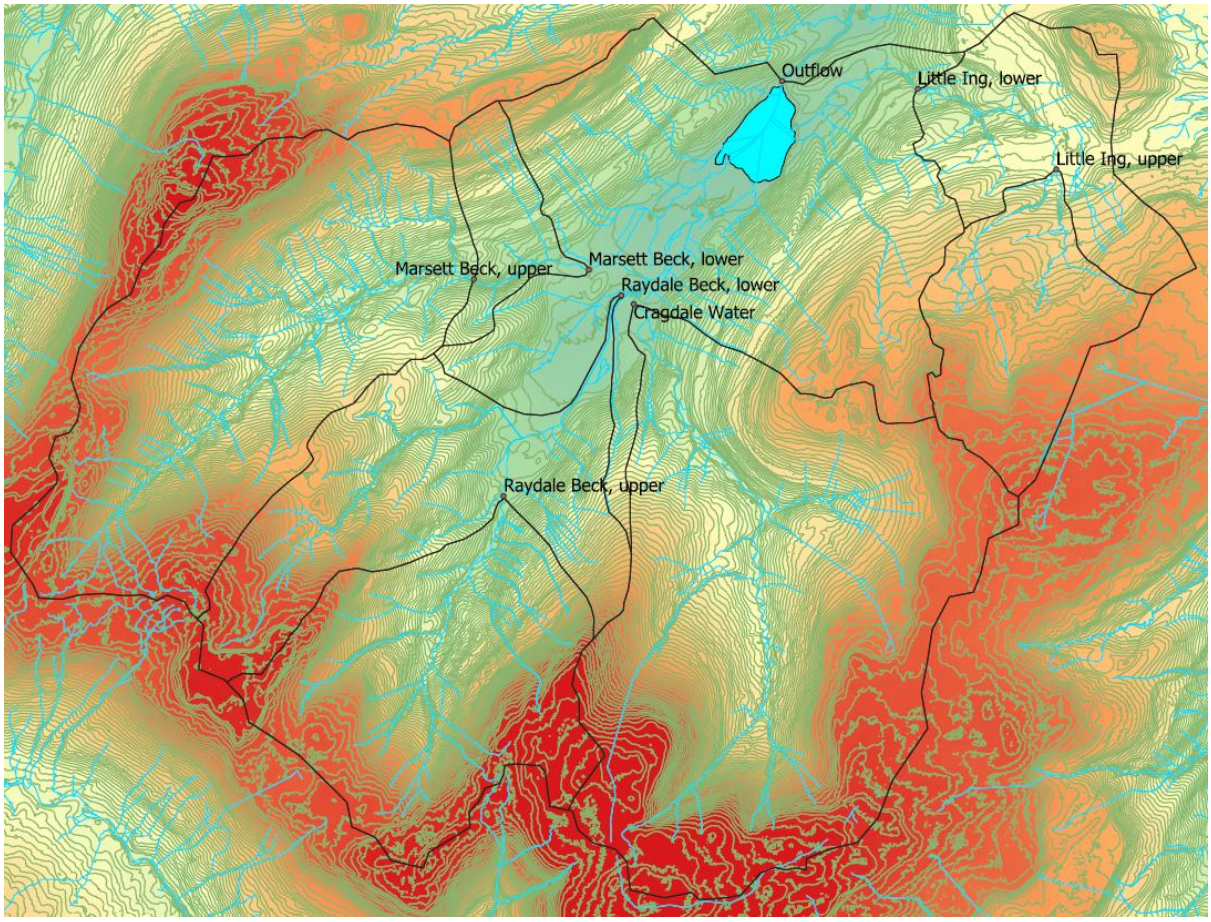


Figure 11 Map of the Semer Water catchment and sub catchments. Elevation (colour and contours) is based on Lidar Composite Digital Terrain Model England 1m resolution [TIFF geospatial data], Scale 1:500, downloaded from EDINA LIDAR Digimap Service. Channels are based on Ordnance Survey MasterMap Water Network [GML3 geospatial data], Scale 1:2500 data.

Catchment areas were measured using QGIS vector analysis.

7.1.2 Land cover analysis and land cover change

Landcover is based on the Land Cover map of Great Britain (2021) [TIFF geospatial data], Scale 1:250000 (10 m resolution raster map). This classifies land cover using remote sensing. We have applied our catchment boundaries to this, determining the percentage contribution of each land cover category to each catchment (Figure 12).

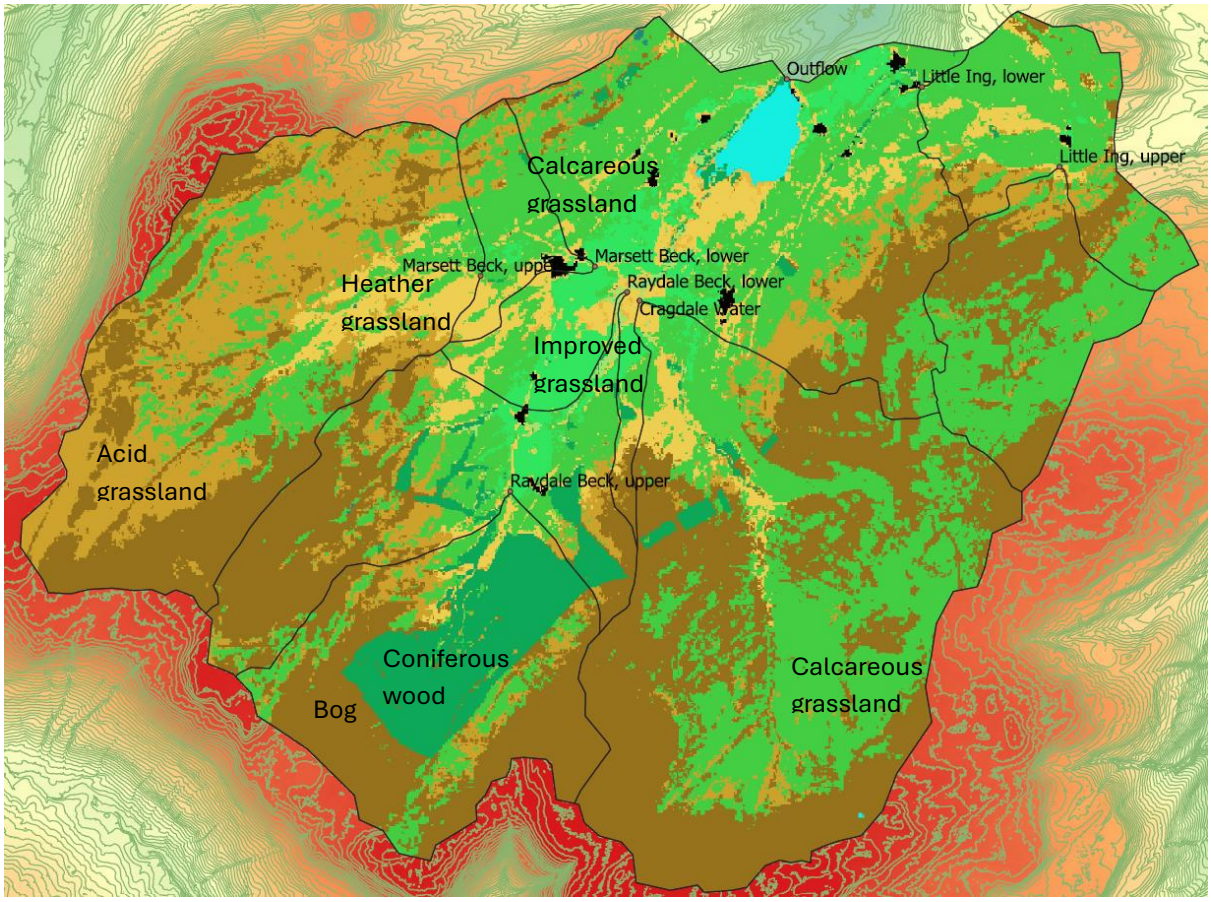


Figure 12 Distribution of landcover types based on LCM2021 10 m raster data.

This remote sensed land cover is an approximation that will not fully represent the reality on the ground. For the category Bog, the area is substantially greater than indicted by the drift geology category Peat (not shown). However, it is this measure of bog that is used in UK Lakes portal (Lake information database maintained by the Centre for Ecology and Hydrology, https://uklakes.ceh.ac.uk/) estimates of land cover, so use of the LCM data assures comparability with other lakes.

7.1.3 Export coefficients

The export coefficient approach to predicting the diffuse export of nutrients from the landscape is clearly explained by Johnes (1995). The basic concept is that for each type of land cover there will be a typical nutrient yield, or emission per unit area, the value of which can be established by measuring a number of examples. Once sufficient examples are measured for a specific category, such as improved grassland, then the typical value is referred to as an export coefficient, expressed with areal yield units such as mg P/m^2/yr.

To apply this method, it is simply necessary to multiply the area represented by the category by its export coefficient. For example, a 100,000 m^2 area of improved grass with an export coefficient of 47 $mg/m^2/yr$, is predicted to yield a P quantity of 4.7 kg/yr.

Table 7 Export coefficients used in this study

Land cover	EC values $mg/m^2/yr$
Deciduous	**27.5**
Coniferous	**19.5**
Improved grass	**47**
Calcareous grass	**11.5**
Acid grass	**11.5**
Heather	**11.5**
Heather grassland	**11.5**
Bog	**54**
Urban	**138**
Suburban	**138**

Here we use mean coefficients derived mainly from the PLUS model (Table 7, Donnelly et al., 2020), choosing values for medium slopes for bog and improved grass, and steep slopes for the other land cover categories. For one category, bog, we have generated a revised value, very much higher, based on data in Figure 13.

Figure 13 shows that upland lakes with a high proportion of bog have P yields far higher than predicted by the PLUS export coefficient, and with values that correlate with peat percent cover. The simple linear regression projects to 54 $mg/m^2/yr$ P yield, while PLUS gives a value of 4 $mg/m^2/yr$. We believe that the low value quoted by PLUS arise from lack of suitable data, being based only on intact bogs. More recent studies, particularly those based in Finland, have also examined disturbed bogs. Bhattacharjee et al. (2021), working on Finnish peats, quotes mean export coefficients based on a number of studies that find 5 $mg/m^2/yr$ for intact peat but 100-170 $mg/m^2/yr$ for peat that has been ditched to improve drainage. Closer to home, based on the soluble reactive phosphorus (SRP) measurements of Howson et al. (2021), who studied two bogs in Scotland, we found the intact raised bogs to export 7 $mg/m^2/yr$, while afforested raised bog exported 119 $mg/m^2/yr$. Restored bogs exported 14-95 $mg/m^2/yr$ depending on time since restoration. Data for the blanket bog shows 6 $mg/m^2/yr$ for intact and 37 $mg/m^2/yr$ for afforested (5-54 $mg/m^2/yr$ for restored sites).

These examples serve to show that disturbed bogs can yield amounts of P fully consistent with, or even greater than, our inferred bog export coefficient.

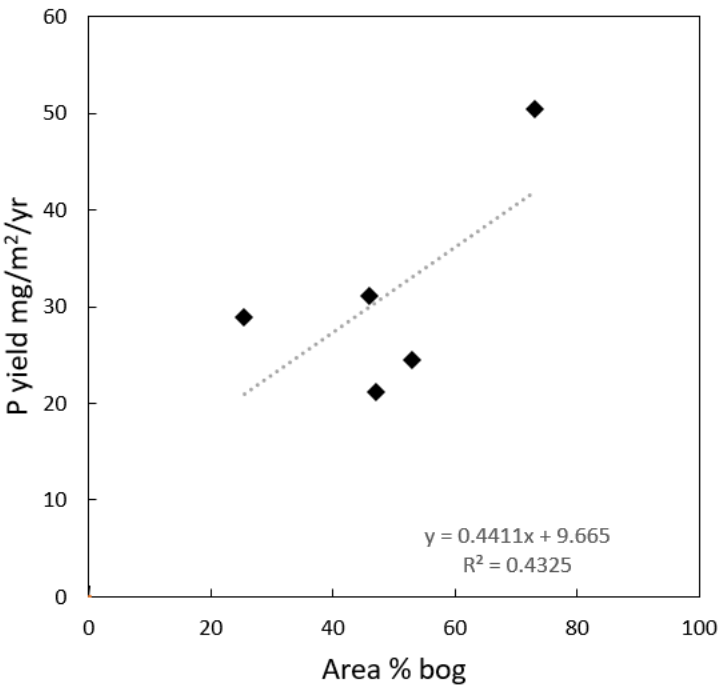


Figure 13 Export coefficient estimated for UK Lakes Portal sites where catchments are dominated by bog and montane landcover. These sites are: Grassholme Reservoir, Selset Reservoir, Waskerley Reservoir, Cow Green Reservoir, Burnhope Reservoir, and Balderhead Reservoir.

7.1.4 Direct contributions

Birds: Bird count observations are reported and reviewed by Court (2025). P export loadings have been calculated from the observations using the method of Manny et al. (1994).

Bird count data give monthly total counts since late 2023 (427 Canada and greylag geese in 2024), but this value postdates the EA lake water quality data (which ends in 2021), and the sediment record of P burial (which represents up to September 2018). Earlier data for 2021-22, and annually before 2012, give only maximum counts. These data are sufficient to show large increases since 2012, but leave the value for the period 2012-2018 without reliable data. We have followed the suggestion of Paul Bradley (PBA-Ecology) of using a figure of 400 head. This is likely an overestimate but serves to place a cap on the total wildfowl contribution.

Livestock: No quantitative data exist on livestock numbers. For cattle we assume 200 dairy cattle and 100 beef based on an approximation offered by Jane Le Cocq, Farm Conservation Adviser with Yorkshire Dales National Park Authority. For sheep we have assumed that the minimum stocking density is as specified by the UK Government scheme "UPL2: Low livestock grazing on moorland" (https://www.gov.uk/find-funding-for-land-or-farms/upl2-low-livestock-grazing-on-moorland). With Medium sheep stocked at 0.1 Grazing Livestock Units (GLU) per hectare, this amounts to 0.8 head per

hectare (80 head/km^2). Our assumed maximum stocking density is based on a National Farmers Union article on the Sustainable Farming Incentive (SFI) scheme (The SFI and grazed livestock – what you need to know, https://www.nfuonline.com/updates-and-information/sfi-and-grazed-livestock/), which state that sheep stocking densities in moorland range up to 0.16 GLU (or 160 head/km^2). Given 23.8 km^2 of calcareous grassland, acid grassland, and heather grassland, this gives a total sheep count ranging 1906-3811.

We use the per head P export coefficients for sheep taken from Johnes (1996), 0.045 kg/head/yr for sheep. For cattle we assume 14 kg P/head/yr total emission and 10% export (Boyle et al., 2015a), giving an export coefficient of 1.4 kg P/head/yr.

People: There is no full census of residents or visitors to the Semer Water catchments. An email exchange with the YDNPA suggested that a figure of 100 would be realistic for testing the direct human P load contribution. Naden et al. (2016) report that annual per capita P emission prior to treatment (for example, septic tanks) is 0.524 kg P/yr. Retention of P by septic tanks is estimated to be between 6% and 25% (May and Woods, 2015). Taking the mean of these (15.5%) we assume an export coefficient of 0.443 kg P/person/yr.

Atmospheric deposition: A review of P atmospheric deposition studies (Tipping et al., 2014) found a mean of 27 mg/m^2/yr. We apply this to the lake surface area to estimate the total atmospheric P load.

Sediment P release: Often referred to as lake internal loading, P in the sediment of the lake bed can dissolve and be released to the overlying lake water. Modelling approaches are illustrated by (Boyle et al., 2023) but are not yet available for general application. We are also developing a simpler empirical method, together with the Canadian lake internal loading expert Gertrud Nürnberg, in a paper to be published later this year, which shows that the external load of ten year ago is a good predicter of the current internal P loading, with 50% of this being released. Our sediment record for the 2002-2011 (a decade prior to the EA monitoring data) gives a mean P burial loading of 692 kg/yr. From this we infer that the internal loading in 2021 was 346 kg/yr.

7.2 Results and discussion

Diffuse landscape P sources

To estimate P exports from Semer Water sub-catchments, their areas have been calculated by QGIS (Table 8).

Table 8 Catchment areas

Catchment	area km^2
Semer Water, total	42.63
Cragdale Water	10.61

Little Ing, lower	2.44
Little Ing, upper	2.55
Marsett Beck, lower	1.00
Marsett Beck, upper	8.06
Raydale Beck, lower	4.32
Raydale Beck, upper	4.95
Semer Water, proximal	8.67

QGIS analysis of the land cover data quantifies the area of each landcover category in each of the Semer Water sub catchments (Table 9). Overall, the dominant categories in LCM2021 are bog and calcareous grassland. Multiplying these values by the export coefficients in Table 7, adjusting units appropriately, give the indicative P export for each category in kg/yr (Table 10). Considering only the whole catchment value, the indicated total is 1190 kg/yr, of which bog accounts for 773 kg, equal to 65% of the diffuse load.

Table 9 Area (km^2) of each land cover category in each of the Semer Water sub-catchments

	Whole	Cragdale	L LittleIng	U LittleIng	L Marsett	U Marsett	L Raydale	U Raydale	L Semer
Deciduous	0.20	0.01	0.00	0.00	0.00	0.00	0.06	0.00	0.12
Coniferous	2.21	0.13	0.00	0.00	0.01	0.00	0.36	1.55	0.15
Improved grass	1.63	0.05	0.02	0.00	0.05	0.00	0.26	0.00	1.24
Calcareous grass	14.82	4.11	1.62	1.32	0.58	1.49	1.09	0.66	3.94
Acid grass	6.00	0.36	0.25	0.15	0.12	3.53	0.58	0.39	0.63
Heather	0.13	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.10
Heather grassland	2.86	0.38	0.26	0.01	0.19	0.59	0.22	0.11	1.10
Bog	14.31	5.56	0.27	1.06	0.03	2.44	1.72	2.23	0.97
Inland rock	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Freshwater	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
Urban	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Suburban	0.12	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.08
Sum	42.63	10.61	2.44	2.55	1.00	8.06	4.32	4.95	8.67

Table 10 Indicative P export (kg P/yr) for each of the land covers in each of the Semer Water sub-catchments

	Whole	Cragdale	L LittleIng	U LittleIng	L Marsett	U Marsett	L Raydale	U Raydale	L Semer
Deciduous	5.4	0.2	0.0	0.0	0.1	0.1	1.7	0.0	3.3
Coniferous	43.0	2.5	0.1	0.0	0.2	0.0	7.0	30.3	2.9
Improved grass	76.5	2.4	0.9	0.0	2.4	0.1	12.2	0.0	58.3
Calcareous grass	170.4	47.3	18.6	15.2	6.6	17.1	12.5	7.6	45.3
Acid grass	69.0	4.1	2.9	1.7	1.3	40.6	6.6	4.5	7.2
Heather	1.5	0.1	0.0	0.0	0.0	0.1	0.1	0.1	1.1
Heather grassl.	32.9	4.4	3.0	0.1	2.2	6.8	2.6	1.2	12.7
Bog	772.9	300.0	14.8	57.5	1.9	131.8	92.9	120.4	52.3
Inland rock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Freshwater	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Urban	1.5	0.0	0.1	0.0	0.0	0.0	0.4	0.0	1.1
Suburban	16.9	0.0	0.9	0.0	3.2	0.0	1.9	0.0	10.9

Total	1190.1	361.1	41.4	74.6	17.9	196.6	138.0	164.1	195.2

7.2.1 Direct contributions

Combining the export coefficients and animal count data and presented in Section 7.1.4, we get the indicative total export rates shown in Table 11.

Table 11 Indicative load calculations for direct contributions

	EC kg/head/yr	EC mg/m^2/yr	Head/Area N/km^2	Load kg/yr
Geese	0.179		400	72
Cattle (EC 0.42 - 1.4)	0.91		300	273
Sheep (Count 1906-3811)	0.045		2859	129
People	0.443		100	44
Atmospheric deposition		27	0.29	8
Sediment P release #				346
Total load				872

7.2.2 Comparison with whole lake budget

Adding the total indicative P loads from Table 10 (1190 kg/yr) and Table 11 (872 kg/yr) yields a total value of 2062 kg/yr. This value, while lower than the lake budget inferred value (Section 6.2.2) of 2547 kg/yr is in fact remarkably close given that these are fully independent measures of the load.

In principle, we could apply a third independent method – to measure the inflow stream loads. However, this would require a great many more measured values, and is in reality, impractical. It would require both continuous gauging of water flows (Practicable but very expensive), and frequent flow-weighted automatic sampling of stream water. This is where samples are taken at a frequency based on the amount of water flowing through the channel. This would take few samples when the flow is low, but many sample of the important high flows. This, too, would be expense. However, a bigger problem is that on flashy rivers it is difficult to build an autosampler that would survive exceptional high flow events.

The importance of quantifying output loads cannot be overstated. In general, the outflow load is the component of the P budget that can be most accurately quantified, with the sediment P burial load a close second. The sum of these, therefore, provides an accurate and precise measure of the total input P load. This information does not necessarily help with identifying where the P has come from, but knowing this precise value is critical part of evaluating probable P sources.

7.2.3 Assessment of P sources and mitigation opportunities

Comparison of the P loads shown in Table 10 and Table 11reveals that diffuse landscape sources dominate, with bog contributing a total of 773 kg/yr, amounting to 65% of the

diffuse load and 37% of the total indicative load. Based on the information discussed in (Section 7.1.3) we can expect that the natural P load from bog would have been approximately 1/10th of this. This clearly offers a mitigation opportunity, and we must suppose that given sufficient time a restored bog might achieve this end. It must be noted, however, that the time frame of recovery is unknown. And it is important to remember that, in the case of forested bogs, Howson et al. (2021) found little evidence that partial bog restoration reduced their export loads, at least in the short run.

The next largest indicative P source is livestock, with cattle and sheep together inferred to supply 402 kg/yr, amounting to 19% of the total indicative load. Clearly, this offers mitigation potential. However, we gathered no data on management practises and thus have no reason to suppose the changed management would substantially reduce this load. We must also stress that our estimate of the livestock load is not based on reliable stocking numbers.

The impact of people and of wild fowl on the total supply of P is also based on incomplete information. However, our analysis is sufficient to show that these are not substantial contributors to the total.

We also show that internal sediment P loading to the lake is also substantial, being little smaller than the total inferred livestock loading. This is a robust estimate of this contributor, and is of sufficient reliability for the purposes of the budget analysis. It must be pointed out that this is essentially a natural component of the system, and there is no way of reducing it.

7.3 Key takeaways

Individual sources, particularly livestock and bog, plus dismissing bird and people

- Using export coefficient modelling we have calculated the indicative P load to Semer Water, finding a total (2062 kg/yr) that is acceptably similar to the more reliable budget calculation for the total input (2547 kg/yr). This agreement does not assure the reliability of any specific P input source, but serves to show our approach yields sensible numbers.
- We show that export coefficients for bog estimated from Environment Agency data at other upland peat catchments in England, and compatible with values reported from Finland, are sufficiently high that degraded blanket bogs are the single largest source of P to the system.
- Livestock is the next largest contributor after bog.
- People and wild fowl are only a minor contributor of P at this site.

8 Recommendations

We recommend:

- Establishing a flow gauging station on the River Bain close to the outflow from Semer Water. This, combined with TP monitoring data from the lake will permit full quantification of the changing lake P budget.
- Moving the water quality monitoring point to the outflow. This will eliminate edge effects, where drifted algal blooms cause local anomalous concentrations.
- Establishing a monitoring programme for water quality and discharge rates on one or more inflow streams draining the southern blanket peats, to track the impact of peat restoration on P export loads.
- Exploring options for continued improvement in animal waste management, but keeping clearly in minds that peatland restoration is the key to reducing external loads of P to Semer Water.
- Undertake subfossil analysis of sediment cores to determine historic composition of the aquatic flora in order to set better targets for assessment and restoration.

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