Providing Ecological Solutions

Semerwater SSSI

Literature Review and Action Plan 2022



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Declaration of Compliance

This report has been undertaken in accordance with British Standard 42020:2013 “Biodiversity: Code of practice for planning and development” (BSI 2013), the CIEEM’s Code of Professional Conduct (CIEEM 2019) and Guidelines for Ecological Report Writing (CIEEM 2017).

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CONTENTS

Executive Summary 4
1. Introduction 5
1.1. Terms of reference 5
2. Literature Review 5
2.1. Semerwater and the Raydale catchment 5
2.2. Pressures facing Semerwater 8
2.2.1. Sediment 8
2.2.2. Phosphorus 9
2.2.3. Nitrogen 9
2.3. Pathways of pollution within the Raydale catchment 10
2.4. Zones of impact within Semerwater lake 14
2.5. Existing initiatives within the Raydale catchment 17
2.6. Management options and constraints for shallow lakes 19
2.7. Knowledge gaps and data deficiencies 21
3. Action Plan 21
3.1. Prioritisation of management actions and recovery timeline and options 21
3.1.1. Short to medium term (1 – 5 years) 22
3.2. Pathways to improving the condition of Semerwater SSSI (c. 5 – 30 years) 24
3.3. Cost:benefit exercise 27
4. Conclusion 29
5. References 30

Figures

Figure 1: Bathymetric map of Semerwater showing water depths (m), adapted from Barlow (1998). ... 7

Figure 2: Bathymetric map of Semerwater showing water depths (m), adapted from Chiverrell *et al.* (2008). ... 7

Figure 3: Total phosphorus as P for Semerwater from Environment Agency online dataset, spanning 2012-2022 (sampling point ID NE-40000443, SD 92181 87473). Moving average applied for interpretation of seasonal periodicity, with average of dataset (red dash) and TP limit for 'deeper' mesotrophic lakes (CSM, 2015: green dot dash) included. Source data https://environment.data.gov.uk/water-quality/view/sampling-point/NE-40000443?all=true 11

Figure 4: Total nitrogen as N for Semerwater from Environment Agency online dataset, spanning 2012-2022 (sampling point ID NE-40000443, SD 92181 87473). Moving average applied for interpretation of seasonal periodicity, with average of dataset (red dash) and TN limit for very shallow mesotrophic lakes (CSM, 2015: green dot dash) included. Source data https://environment.data.gov.uk/water-quality/view/sampling-point/NE-40000443?all=true 12

Figure 5: Maps of a) sediment risk areas mapped through YDNPA (2022) data, with additional SCIMAP derived smoothed sediment risk areas (SCIMAP, 2007) and b) phosphorus risk areas mapped through YDNPA (2022) data, with corresponding P risk categories mapped from Tejero (2015). ... 13

Figure 6: Summary of indicative legacy of the retention and recycling of phosphorus (P) stores in watersheds and waterbodies. The resulting chronic release of "legacy P" from lake and soil cycling can impact water quality over years to decades (Adapted from Jarvie *et al*., 2013, with data provided by Sharpley *et al*., 2013). ... 14

Figure 7: Map of Yorkshire Peat Partnership work, to include upstream of Semerwater (arrow) in the upper Raydale catchment (YPP, 2021). ... 16

Figure 8: Evidence of high nutrient loading and dense algal mats forming in the River Bain outflow during summer 2021 (photo credit, Environment Agency). ... 16

Figure 9: Contemporary coverage (2020) of a) land use and b) agri-environmental schemes for the Raydale catchment (CSS data RPA, 2021; Landsat 10m resolution, Morton *et al.* 2021). ... 18

Figure 10: Indictive flow diagram of the interlinkages of restoration objectives and entry points for different techniques (adapted from Phillips *et al*., 2015). ... 20

Figure 11: Proposed timeline for management actions within the Raydale catchment to improve the condition of Semerwater SSSI. ... 26

Tables

Table 1: Land use change in the Raydale catchment from 1994 – 2020. Data sources are - [1] Barlow 1998, [2] Morton *et al.* 2014, and [3] Morton *et al.* 2021. ... 6

Table 2: Macrophyte community composition within Semerwater lake, noting characteristic flora for mesotrophic (bold) and hard water (underlined) lakes (data sources [1] Bennion *et al*., 1997 and [2] ENSIS CSM surveys 2005-2016). ... 15

Table 3: Cost:benefit of existing and proposed management strategies within the Raydale catchment with the aim of improving the condition of Semerwater lake in the short and/or medium-long term. ... 27

EXECUTIVE SUMMARY

Semerwater SSSI and the Raydale catchment are significant features within the ecological, cultural and economic landscape of Wensleydale. The condition of Semerwater has deteriorated over the previous 50+ years, and there is renewed interest and political pressure to restore the lake to a more sustainable, resilient and healthy state. Through the review of information on Semerwater lake and the Raydale catchment, an assessment of the status of Semerwater is provided with consideration of direction of biological and chemical factors and the ambition to improve the condition of Semerwater to at least Recovering WFD/SSSI condition. Nitrogen does not appear to be a significant pressure within Semerwater, and concentrations have remained consistent within Semerwater over the previous decade. Macrophytes remain present within Semerwater, but have declined in both species diversity and abundance. Native white-clawed crayfish also are persisting in lotic components of the catchment, and at a low population level within Semerwater. Efforts to restore natural functioning to the upland peats and reduce both point source and diffuse pollution from agriculture have been undertaken within the catchment, although the available evidence suggests these have not yet delivered recovery within Semerwater. Biological and chemical data indicate that internal conditions have not responded to these interventions over the previous 10-20 years, and may be driven by internal nutrient loadings.

Actions to ultimately improve the condition of Semerwater should focus around understanding the source and volumes of P and sediment entering the lake from the Raydale catchment, but are currently impaired by a lack of modern accurate data. Further, the process by which current and future actions are recorded and collated does not support cohesive efficient working, and hinder the evidence-based decision making which is key to successful management. This should be addressed through a centralised repository for works on Semerwater, as a necessary means for tracking what is being done, identifying evidence gaps and reducing duplication of effort. Recommendations contained within this report outline the benefits of addressing these issues and provide a pathway through which to define and initiate bespoke recovery targets for Semerwater via appropriate means and timescales, likely beyond the previously considered 2030 objective. To achieve realistic recovery targets requires cooperation and coordination of all catchment partners including landowners, and as such maintaining established relationships and involving stakeholders throughout this process is vital. The defining and uptake of a collaborative vision for Semerwater and the Raydale catchment may further strengthen these relationships and provide additional clarity and direction to future management actions.

Short term (ca. 1 – 5 years) management options

- nutrient budget to understand input volume, source location, residence time within and release from Semerwater;
- sediment budget to understand input volume, source location, residence time within and release from Semerwater;
- macrofossil study of Semerwater sediments to define realistic and appropriate recovery targets;
- creation of a central repository for recording work done within the catchment and Semerwater Steering Group for an efficient, collaborative approach;
- establishment of a collaborative, ambitious, evidence-based vision for Semerwater;

Additional management options that will further support improvement of Semerwater are:

- updated high resolution bathymetric survey of the lake;
- fish population assessment of the community in Semerwater, to produce an estimate of planktivorous fish biomass;
- continued macrophyte surveys to evidence status and direction of Semerwater condition.

1. INTRODUCTION

1.1. TERMS OF REFERENCE

PBA Applied Ecology Ltd. was commissioned by the Yorkshire Dales National Park Authority (YDNPA) to produce a literature review and action plan for Semerwater SSSI. Semerwater is nationally recognised for its ecological, agricultural and cultural significance, but also for anthropogenic pressures that are impacting the condition of the lake. A review of the available literature, including grey literature sources, and subsequent action plan based on findings of this review is required. The overarching target for Semerwater is currently 'Good Ecological Status' by 2030 as defined by the Water Framework Directive. The challenges, potential approaches and achievability of this target are considered within this document.

2. LITERATURE REVIEW

A review of the scientific literature was conducted using the databases Web of Science and Google Scholar. Search terms included 'Semerwater' and 'Semer water', to capture any relevant published literature using the most common variations. Gibbons (1990) was considered relevant, but a copy could not be sourced despite personal enquiries to and cooperation from the host institution. Additionally, grey literature including postgraduate theses, commercial datasets and reports, and previously commissioned surveys were consulted as part of this exercise. To be in scope, these documents were required to contain any quantitative or supporting information relevant to the condition of Semerwater. This information primarily comprises data on the water quality, sediment transfer and associated processes, hydrological regime, and biological communities within Semerwater. The broader catchment of Raydale is outside the scope of this systematic review process, however the upper catchment and tributaries in particular have relevance to the condition of Semerwater, and as such these information sources are included where appropriate.

2.1. SEMERWATER AND THE RAYDALE CATCHMENT

Semerwater (SD 91954 87223) is the second largest natural lake in the Yorkshire Dales, with the largest being Malham Tarn SAC. Semerwater lies within the Raydale catchment of Wensleydale which spans some 4,361 hectares. Crooks Beck is the primary inflow of Semerwater, formed through the confluence of the three main tributaries of Bardale/Marsett Beck, Raydale Beck and Cragdale Water which flow from their sources in the upper catchment in the southwest through localised agricultural land. An additional smaller inflow, Little Ings Sike, enters Semerwater on the eastern shore, as well as several gills on the western and eastern shores. The River Bain is the outflow of Semerwater, which runs for approximately 3.8 km where it meets the main River Ure (SD 93544 90777). The water is calcareous as a result of the limestone geology of the catchment, being alkaline (mean pH 8.01; EA, 2022) with high levels of alkalinity (mean 82 mg/L $CaCO_3$) peaking in the summer months (range 33-130 mg/L $CaCO_3$). Semerwater is the remains of a glacial lake that formed at the end of the last ice age when glacial material blocked the outflow. Historically, the lake level was lowered in 1937 by 55 cm (SSSI citation, 2016) and the old shoreline is still visible, with areas of the western shore now dominated by fen vegetation. The Semerwater SSSI encompasses the lake as well as areas of neutral grassland, fen, upland mixed ash and yew woodland. First notified in 1975 and revised in 1984 the SSSI covers an area of 101.4 hectares. It contains 17 units of which in the last condition assessment 20% were in Favourable condition, 48% in Unfavourable – recovering condition and the remaining 32% Unfavourable – no change or Unfavourable – declining (2008 to 2016).

Land use in the catchment has been relatively consistent over the last three decades (Table 1). Limited urbanisation is present in the Semerwater catchment, with land cover currently (and historically) dominated by upland rough grazing on acid grassland (32%) and heather moorland (including drained bog; 29%), to more intensive dairy and livestock farming (Table 1). Soils comprise largely of peats of varying depths with thick peat confined to the moorland plateau, fine loamy soils to the eastern slopes

of the watershed, fine loamy soils over clay along the western slopes of the watershed and fine loamy soils with peat along the lower southern slopes and in the flat dale bottom (SSP, 2009). All have a tendency to be seasonally waterlogged. Hamlets and farms in the catchment appear to be under private septic tanks treatment plants or individual systems. Lower Raydale that surrounds Semerwater itself is mainly managed as semi-intensive grassland with some small areas of plantation and native woodland. Grasslands and meadows are cut for silage and haylage. Land management across the whole Raydale catchment is a focus for regulatory bodies and government. The catchment is viewed as a high Countryside Stewardship Water Priority Area (RPA, 2021), a high Phosphate Issues Priority Area, a high Surface Water Nitrate Issues Priority Area, and a high Sediment Issues Priority Area. In addition, some areas of the catchment are classified as high priority flood Risk Management Priorities Area. Consistent with this 84% of the catchment is under agri-environmental schemes with a range of activities including tree planting, riparian and field margins, nutrient management plans. The whole catchment falls under a Higher Level Stewardship Target Area (NE, 2018), although currently less than half of the land under agri-environmental schemes in holdings that fall at least in part within the catchment are in higher level stewardship. A Catchment Sensitive Farming Priority Area covered the catchment for the period 2011 – 2015. Catchment sensitive farming advice measures were provided to 22 large land holding farmers within the catchment from 2011. These measures covered farm infrastructure, livestock management, fertiliser management, manure management and soil management. There is evidence to suggest only nine of these land holders have actioned any of these recommendations to this stage, although the status, timeframe and auditing process of these actions remains unclear (YDNPA, 2022).

Table 1: Land use change in the Raydale catchment from 1994 – 2020. Data sources are - [1] Barlow 1998, [2] Morton *et al.* 2014, and [3] Morton *et al.* 2021.

Broad Land Use [1]	1994 [1] (%)	Land Cover [2]	2007 [2] (Hectares)	2007 [2] (%)	2020 [3] (Hectares)	2020 [3] (%)
Woodland	4.7	Deciduous woodland	71.37	1.51	24.63	0.52
		Coniferous woodland	173.56	3.68	199.92	4.24
Grassland for Grazing/ Hay	25.6	Arable	7.63	0.16	0.01	<0.01
		Improved grassland	748.00	15.85	358.66	7.60
		Calcareous grassland	0.00	0.00	1195.18	25.33
Rough Grazing	69.7	Rough grassland	293.56	6.22	NA	NA
		Acid grassland	1431.75	30.33	1521.85	32.25
		Heather	263.94	5.59	0.18	<0.01
		Heather grassland	1094.25	23.18	205.23	4.35
		Bog	434.31	9.20	1152.31	24.42
		Montane habitats	152.69	3.24	NA	NA
		Inland rock	1.38	0.03	6.40	0.14
		Freshwater	29.00	0.61	29.63	0.63
		Urban	0.00	0.00	1.17	0.02
		Suburban	18.6875	0.40	23.52	0.50

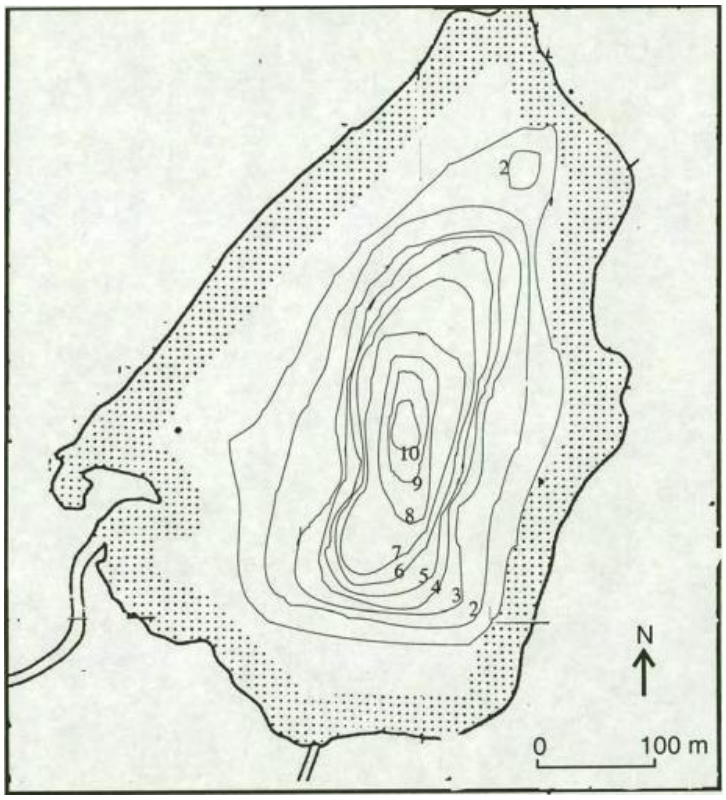


Figure 1: Bathymetric map of Semerwater showing water depths (m), adapted from Barlow (1998).

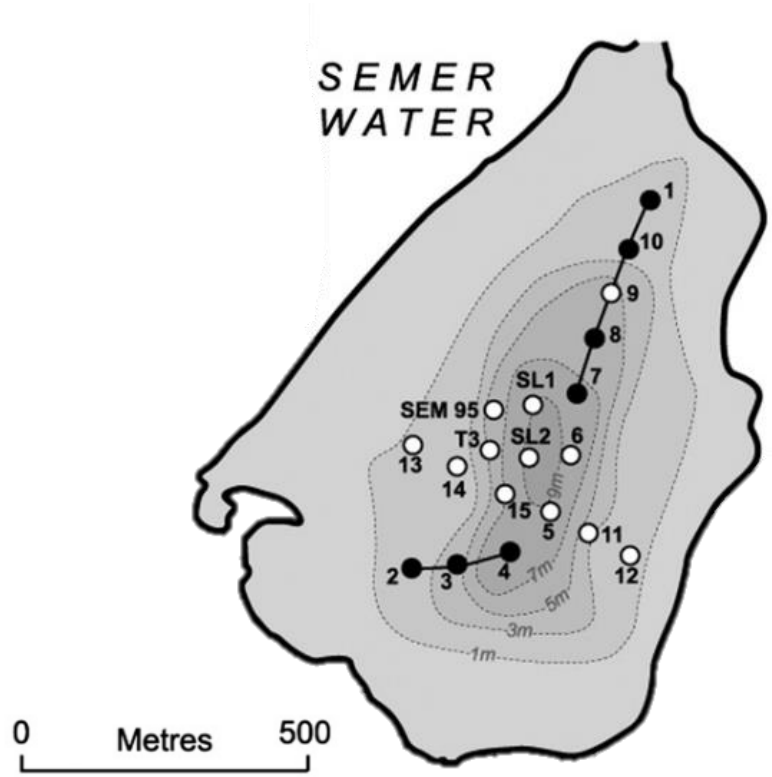


Figure 2: Bathymetric map of Semerwater showing water depths (m), adapted from Chiverrell *et al.* (2008).

2.2. PRESSURES FACING SEMERWATER

Semerwater has a catchment-to-lake ratio of 150.4:1 (CEH, 2022), being very high for an upland waterbody, and as such is vulnerable to chemical and physical disruption from catchment level processes. Pulley & Collins (2021) characterised the Raydale catchment land use between 2018-2020 as Hillslope topsoils (59%), Valley bottom farmland (18%), Blanket peat (18%), and Woodland (5%), and noted its steep gradient (mean 9.27º). The broader Raydale catchment was assessed as Moderate condition throughout Cycle 1 and 2 of the Water Framework Directive (WFD), with the exception of Poor condition in 2014. The broader Raydale catchment condition assessments are, however, based primarily off limited and dated data, with 9 of the 10 sampling locations assessments comprised of single items or fewer in Cycle 2 (2015-2021), and phosphate data only being provided for the Bain at Bainbridge monitoring point (Site ID 49100024). The current WFD status of Semerwater is Moderate for 2019, which has remained so since the first Cycle 1 (2009-2015) annual assessment. Of particular note, total phosphorus has been classified as Poor for Semerwater in all assessed years, asides from three annual assessments (Moderate in 2012-2013 and in 2015). The Reasons for Not Achieving Good (RNAG) condition provided within these assessments are stated as diffuse source pollution from nutrient, moorland, livestock and soil mismanagement, and point source pollution from private sewage treatment processes. Semerwater was assessed as being naturally mesotrophic in the 2011 CSM assessment, which concluded the lake was in Unfavourable condition due to the impoverished macrophyte and excessive P loading (CSM, 2011). Natural England are currently undertaking a review of the SSSI condition based on 2013 and 2016 data, which shows no improvement in biological or chemical status (Ben Goldsmith, pers. comms.).

2.2.1. *SEDIMENT*

Erosion and deposition are natural fluvial processes that transport sediments within aquatic systems. The volume and source of these sediments largely dictates the effect on the recipient systems, with natural amounts of material transportation important for driving channel form and function. However, anthropogenic increases or alterations to sediment transport can negatively impact waterbodies, particularly in low energy systems such as lakes where sediment turnover is reduced. Sediment inputs can negatively impact lakes through incremental reductions to water depth, decreasing the thermal and chemical buffering capacity of lakes. Excessive sediment influx can also increase turbidity within the water column, reducing light availability for macrophyte growth. These surface sediments can become more readily resuspended as lakes become shallower and stabilising beds of macrophytes become scarcer, creating a negative feedback loop by which the impacts of sedimentation exacerbate themselves.

Semerwater is reported as a very shallow lake (mean depth <3 m, CSM, 2015), being generally no deeper than 2 m for the majority of the lake, asides from a deep glacial hole of 10-12 m in the centre of the lake (Figure 1 & Figure 2). Summer mean depths can be as low as 0.3 m in marginal areas of the lake (SSSI citation, 2016), remaining shallow (≤0.9 m) up to 50 m out from the shoreline. However, Semerwater is contrastingly considered as a 'deeper' mesotrophic lake under the Centre for Ecology and Hydrology's Lakes Portal with a mean depth of 3.5 m (Hughes *et* al., 2004). This has relevance to chemical targets (discussed further below, 2.2.2). In Semerwater, excess recruitment and deposition of sediments has been identified as one of the key drivers of declining condition. Primary sources of these materials include erosion of the peat in the upper catchment, mobilisation of bed and bank materials in the high gradient inflow gully's, and runoff from agricultural activities throughout the catchment.

Data on the source and volume of sediments being recruited into Semerwater however are scarce, being primarily observational data. However, Bennion *et al.* (2008), following sampling and analysis of the sediments via piston coring, estimated annual deposition rates of 0.15 cm, with annual catchment erosion rates of 92.9 kg/ha and annual sediment inputs into the lake of 405 m^3. A second study by Chiverell *et al*. (2008) reached a broad consensus with these values, reporting estimated annual deposition rates of 0.2 cm, with annual catchment erosion rates of 123.9 kg/ha and annual sediment

inputs into the lake of 540 m^3. However, additional cores from this study analysed using an alternative approach extended this rate to almost 1.0 cm of deposition per year. This broad range is supported through earlier analyses detailed in Barlow (1998) who suggest average sediment accumulation rates of 0.37-0.90 cm per year since the 1950s (^{210}Pb and ^{137}Cs dated Mackereth lake cores), with a mean influx into the lake of 0.62cm per year. Barlow also noted the depth and high deposition rates found within the valley bottom upstream of Semerwater lake itself, stating accumulation at rates of 0.23 cm per year over the preceding ca. 4500 years, 10-20 times greater than many British sites. Taken together, all previous sedimentation rate works conclude that a 2-3 times increase in accumulation rates has occurred since the 1950s within Semerwater lake. However, the uncertainties surrounding uneven accumulations and resuspension reduce the strength of these inferences.

2.2.2. *PHOSPHORUS*

Eutrophication, being human driven increases in P and N, is a prevalent pressure in UK waters, with 73% of lakes in the UK failing for P loading against WFD standards in 2019 (EA, 2019) and historic evidence of eutrophication in upwards of 80% of lentic SSSI's (Carvalho & Moss, 1995). Due to the closer ratio of the lakebed area and the volume of the lake, shallow lakes are disproportionally affected by eutrophication as compared to deep lakes. Nutrient rich surface sediments can act as large repositories for P and N, which become available through resuspension via wave and wind action, and fluxes at the sediment-water interface. Phosphorus is often the limiting nutrient in the growth of aquatic photosynthetic organisms such as phytoplankton and macrophytes. When organisms such as phytoplankton are released from being P limited problematic algal blooms can occur, producing toxic and unsightly films on the water, and reducing light penetration driving a shift from clear water macrophyte dominated systems into turbid water eutrophic phytoplankton dominated systems which can induce anoxia.

Semerwater is considered as a mesotrophic lake, but also has chemical characteristics consistent with a hard water lake and could therefore be considered against both sets of CSM targets, whilst not fitting fully within either. If classified as a 'very shallow' lake, maximum mean annual TP targets are set at 20 μg/L for mesotrophic lakes, with 15 μg/L set for either hard waters or both lake types if 'deeper' (mean depth > 3 m). Semerwater has consistently been in excess of the less stringent mesotrophic target, with the only long-term data set (EA, 2012-2022) reporting mean concentrations of 41 μg/L throughout the monitoring period at the north-eastern shore monitoring point, with a range of 19.4 – 117.0 μg/L (Figure 3). Reaney *et al.* 2013 provided additional P data for the major tributaries of Semerwater, reporting monthly values covering a period of January 1996 to December 2002 sourced from EA monitoring. Considering the major inflow tributaries from west to east, Marsett Beck had a mean TP concentration of 29 μg/L (n = 67), with a maximum recorded peak of 124 μg/L. Raydale Beck had a mean TP concentration of 28 μg/L (n = 65), with a maximum recorded peak of 155 μg/L. Cragdale Water had a mean TP concentration of 40 μg/L (n = 70), with a maximum recorded peak of 203 μg/L. The final notable inflow, being Little Ings Sike located on the north-eastern shore, had the highest mean TP concentration of the inflows being 48 μg/L (n = 71), with a corresponding maximum recorded peak of 206 μg/L. Reaney *et al.* also report P data for the River Bain outflow, with a mean TP concentration of 35 μg/L (n = 69), and a maximum recorded peak of 220 μg/L from the 1996-2002 reporting period. These data for the period 1996-2002, before Cycle 1 and 2 of the WFD (2009-2021), are broadly consistent with the most recent data for Semerwater lake itself. The TP values are elevated around 30-50 μg/L and consistently in excess of the target 15 μg/L threshold indicating a chronic pressure. Of note, periodic large spikes in P loading are also highlighted indicating that specific occurrences within the catchment are generating these.

2.2.3. *NITROGEN*

Nitrogen levels within the lake are recorded as consistently below the CSM (2015) target (annual mean TN concentration of ≤1.5 mg/L) and an agreed site-specific target of 1.3 mg/L, having been recorded in excess of this on only four occasions (Figure 4). Nitrogen is not often considered a primary cause of

deteriorating condition in lakes, as P is much more commonly the limiting factor. Total nitrogen (TN) to total phosphorus (TP) ratios range from in the region of 100:1 for highly inorganic substrates such as unfertilised field runoff through to <3:1 in eutrophic sediments, septic tank effluence and sewage (Downing & McCauley, 1992). The TN:TP ratio of Semerwater, using the EA dataset, has a reported mean of 23.2 TN:TP (range 9.5-42 TN:TP), consistent with exports from agricultural watersheds with the lowest TN:TP ratio consistent with seepage from cattle manure.

2.3. PATHWAYS OF POLLUTION WITHIN THE RAYDALE CATCHMENT

Phosphorus and sediment modelling within the Raydale catchment through data provided by YDNPA (2022) has enabled rapid visual assessment of key sources and locations of pollution into Semerwater (Figure 5), derived from historic (2000s) EA data. This is further supported by a catchment specific SCIMAP analyses. SCIMAP applies a risk mapping framework to identify where in the landscape diffuse pollution in the form of sediment is most readily originating. The method uses a relative measure of risk to identify sources and connectivity of these sources to watercourses resulting in a channel associated risk. In the method a DEM, land cover data and precipitation data are used to derive an accumulated risk layer for the watercourses within a given catchment. This was applied in the Raydale catchment identifying a number of inflows and tributaries as high risk of sediment transport and acting as sources of pollution via fine sediment. Principally these are found along the north-western slope and south-eastern slope of the catchment flowing into the lowland valley area upstream of Semerwater and directly into the lake (Figure 5). Of note is the lack of congruence between the two sediment projections for the valley draining north-western slopes. In addition, the north-western slope tributaries of Bardale Beck represent high risk sources of diffuse sediment pollution. Finally, the mid-section of Cragdale Water carries a high accumulated risk of acting as a source of sediment pollution from the upper and middle catchment.

Further, recent analyses by Tejero (2015) modelled areas of high risk for the transport of P laden soils within the Raydale catchment. This analysis focussed on runoff potential, modelled during two discrete risk periods (April-October and November-March) and included factors such as rainfall, slope, P loading of soils and land management. To ground truth these high-risk runoff areas within the Raydale catchment which were primarily located in the valley bottom, Tejero tested soil samples, reporting that all samples contained moderate to high P loadings (ca. 25-45 mg kg^{-1}; Figure 5). Tejero also noted slurry storage limitations within several of the studied farms, and direct recruitment of highly P loaded faeces from runoff over areas of hardstanding, stating financial restrictions prevented reduction in these pollution pathways. Peat erosion in the upper Raydale catchment has also been recognised, bringing sediment and more modest nutrient loadings into Semerwater (Figure 5). Grips were historically created to drain these upland areas, and initiatives such as the Yorkshire Peat Project have undertaken survey and initial restoration work within Raydale to reinstate natural hydrological regimes and reduce erosion (Figure 7; YPP, 2021).

Sediment source fingerprinting analyses were undertaken in the Raydale catchment in 2018-2020, aimed at determining the likely sources of sediments accruing within Semerwater (Pulley & Collins, 2021). Sediment samples were collected from all likely sediment sources in the catchment and used to identify source and comparative volumes of sediment collected from strategically placed sediment traps using modelling and analyses through SIFT (SedIment Fingerprinting Tool v1.2.3). Sources of sediments within Raydale were reported as being approximately equally apportioned between the Hillslope topsoils (59% coverage), Valley bottom farmland (18% coverage) and from Landslips and subsurface inputs. Low inputs were reported for both Blanket peat and Woodland sources, with disproportionally high sediment inputs reported from the Valley bottom despite it only covering 18% of the catchment (Pulley & Collins, 2021). In addition to these existing channel bed deposits and landslips that were recognised in these analyses, sewage treatment (including private installations) was recognised as potential sources of inputs into the catchment but assigning values to these was regarded as difficult.

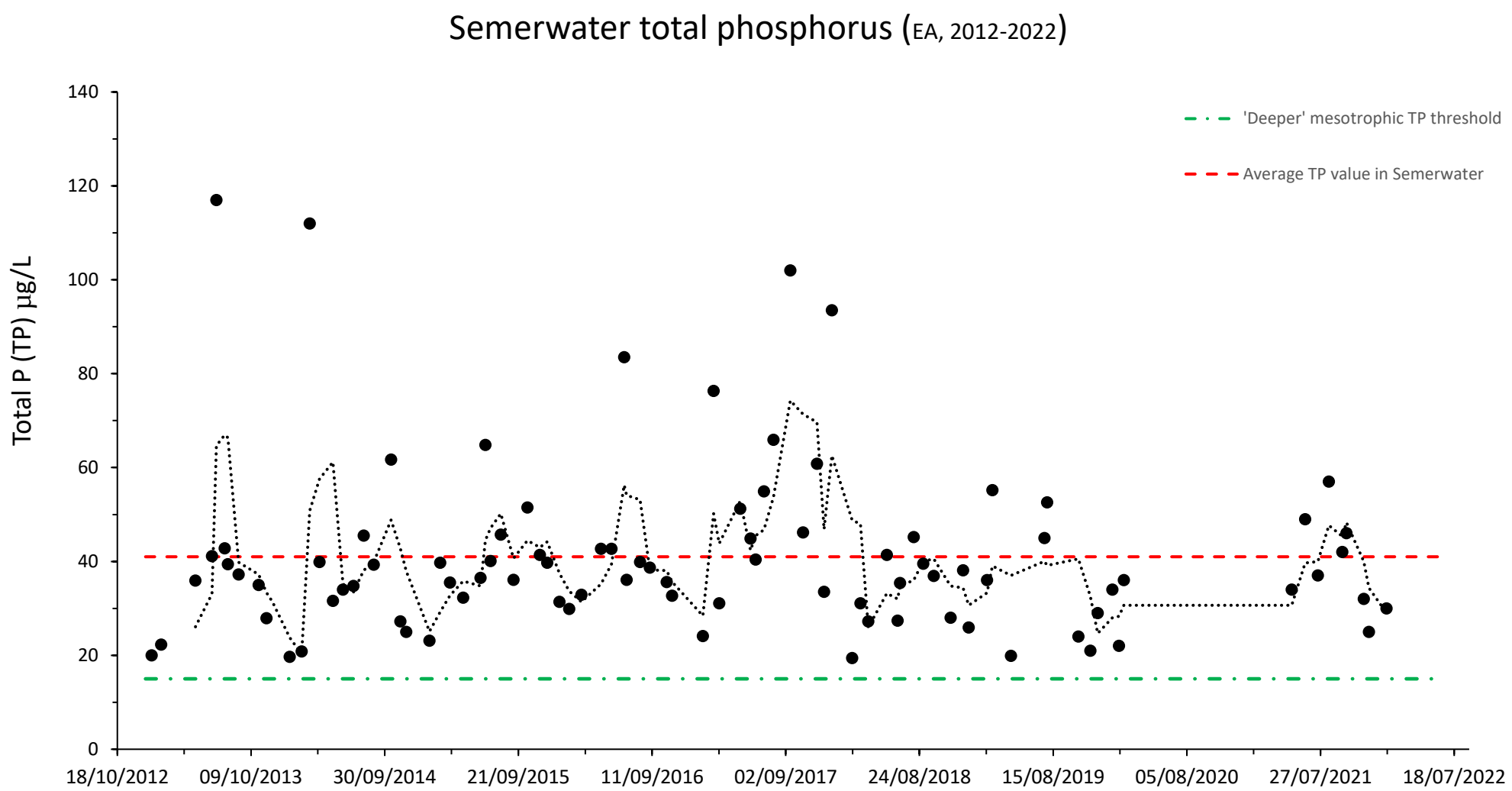


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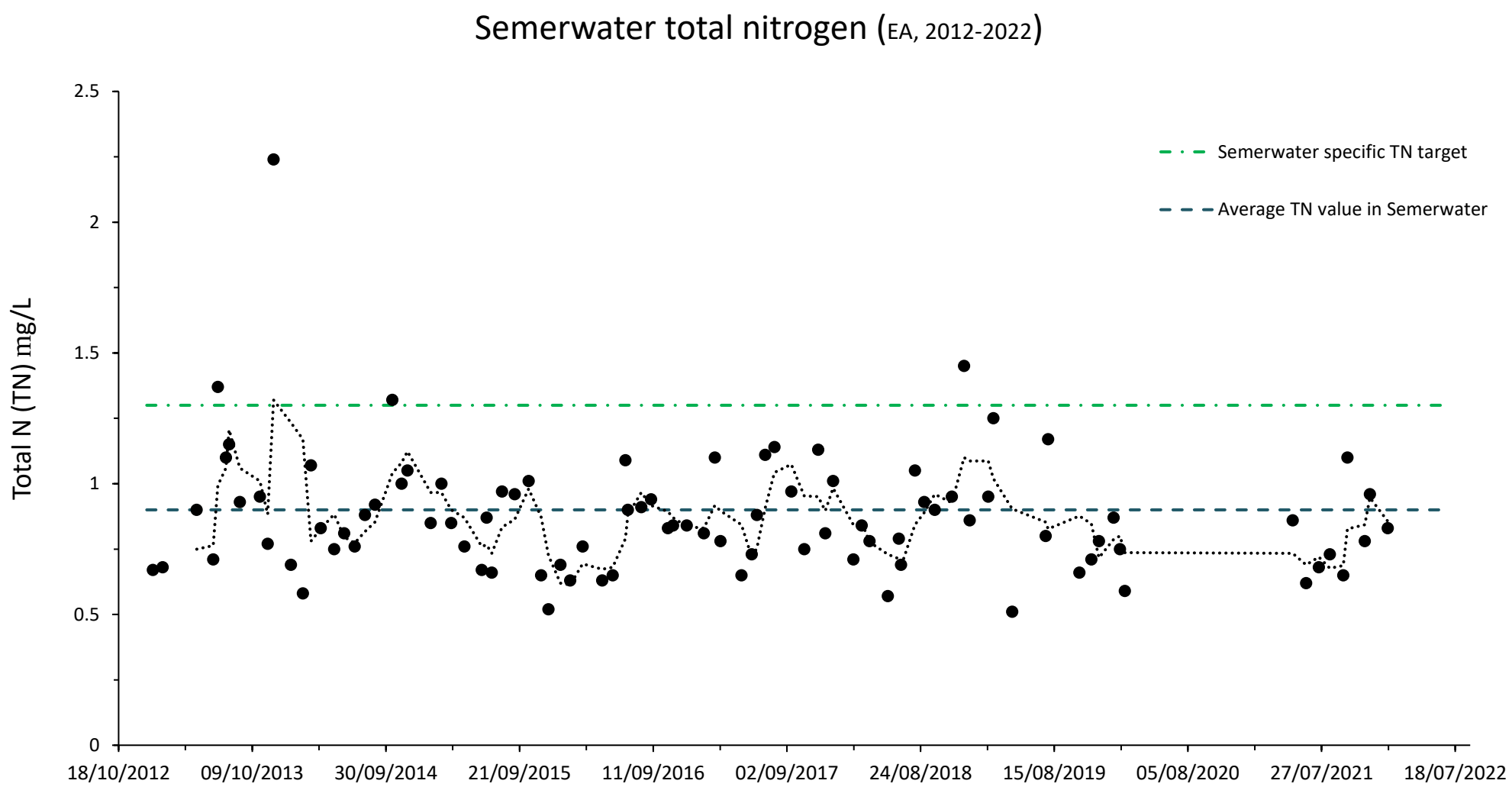


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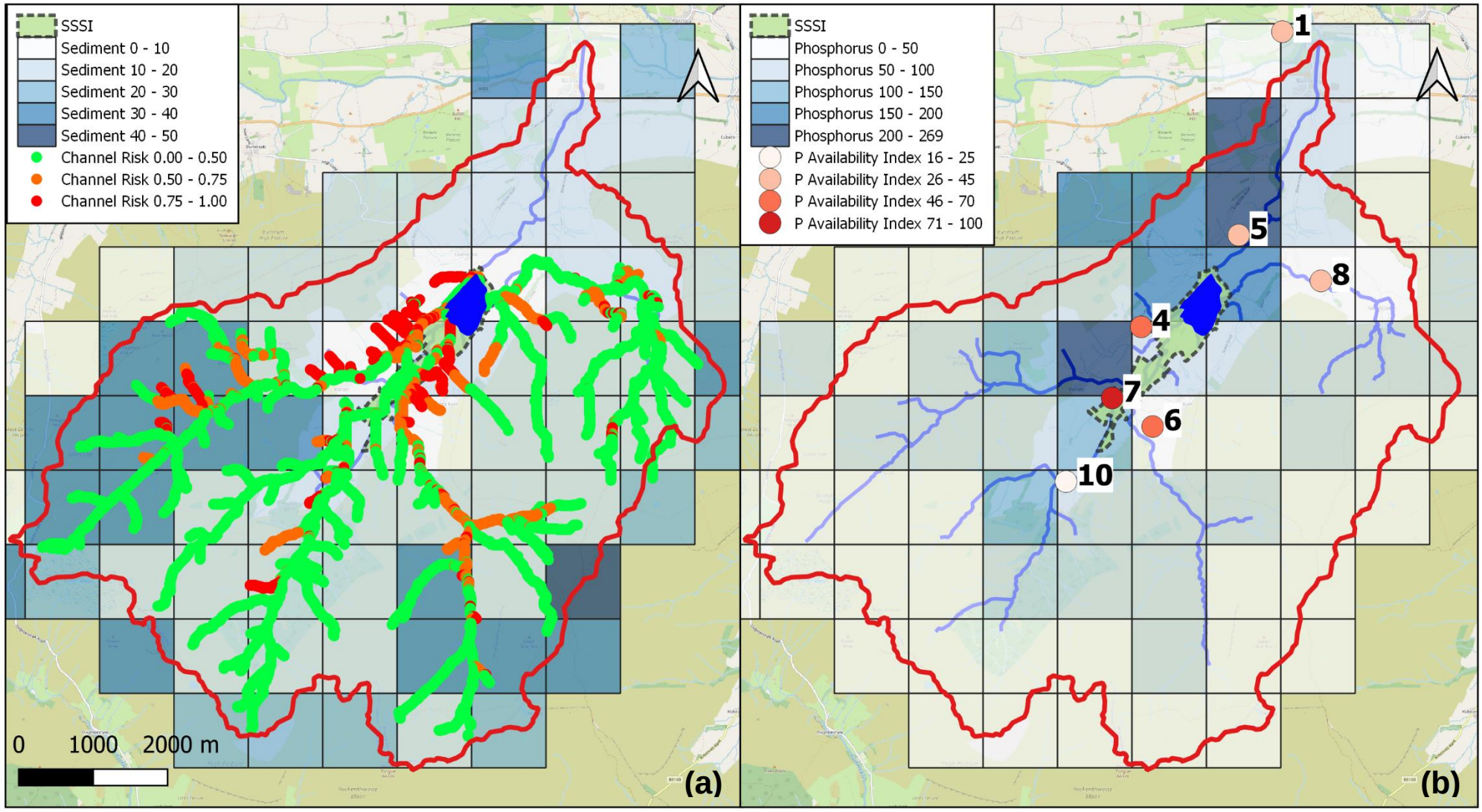


Figure 5: Maps of a) sediment risk areas mapped through YDNPA (2022) data, with additional SCIMAP derived smoothed sediment risk areas (SCIMAP, 2007) and b) phosphorus risk areas mapped through YDNPA (2022) data, with corresponding P risk categories mapped from Tejero (2015).

2.4. ZONES OF IMPACT WITHIN SEMERWATER LAKE

Estimates place the retention of P applied to agricultural land at around 70-80%, shared in part between soils, groundwater and lake sediments (Jarvie *et al*., 2013). The chronic release of this stored P can impact water quality both within waterbodies and their downstream system for decades after external P reductions are implemented (Figure 6). Surface sediments within Semerwater itself are likely to be highly enriched with P, and provide a large, readily mobilised source of P during physical disturbances such as wind and floods, and more passively through flux at the sediment:water interface (May *et al.*, 2020). This impact upon water clarity is twofold, in that enriched surface sediments remove the P limitation of phytoplankton promoting growth and reducing light penetration, and the physical volume of sediment being recruited into the waterbody results in bioturbation levels that prevent macrophyte establishment even when chemical conditions are improved enough to permit growth.

Macrophyte species community composition and coverage within the lake has been periodically assessed in line with CSM guidance. Due to the uncertainty of lake type, the macrophyte community has been assessed against both mesotrophic and hard waters types (ENSIS, 2016), and is in an Unfavourable condition. General trends from this data for Semerwater indicate declines in all surveyed species (ENSIS, 2016; Table 2), reporting failing numbers (2 of ≥8 required) and distributions (≤3% of ≥60% samples required) of mesotrophic characteristic species (Table 2) and an absence of the hard water *Chara* spp. characteristic species since 1995 (Bennion *et al*., 1997; Pentecost, 2009). To satisfy Favourable status, both mesotrophic and hard water lakes would be expected to support aquatic vegetation at depths of ≥2.5 m. Despite Semerwater lakes shallow bathymetry (mean depth c. 2 m) survey work reports maximum recorded depths supporting colonisation of macrophytes (Z_v) of only 0.8 m, substantially below CSM targets for mesotrophic (Z_v ≥3.5 m) and hard waters (Z_v ≥5 m). This is further complicated by the brown water conditions which also limit light. The extent to which the brown water is natural or exacerbated by peat erosion in the upper catchment is unclear.

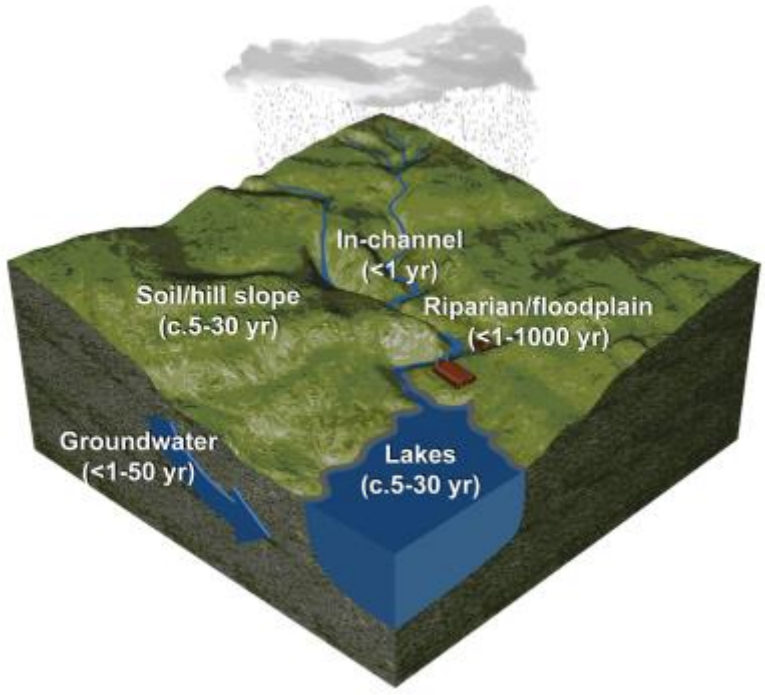


Figure 6: Summary of indicative legacy of the retention and recycling of phosphorus (P) stores in watersheds and waterbodies. The resulting chronic release of "legacy P" from lake and soil cycling can impact water quality over years to decades (Adapted from Jarvie *et al*., 2013, with data provided by Sharpley *et al*., 2013).

Table 2: Macrophyte community composition within Semerwater lake, noting characteristic flora for mesotrophic (bold) and hard water (underlined) lakes (data sources [1] Bennion *et al*., 1997 and [2] ENSIS CSM surveys 2005-2016).

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

White-clawed crayfish *Austropotamobius pallipes* are listed under Annex II and V of the EC Habitats Directive (1992) and Schedule 5 of the Wildlife and Countryside Act (as amended 1981), with the north of England holding several high-density metapopulations for the species within the River Eden SAC, the River Kent SAC and the River Ure systems. The population of white-clawed crayfish found within the River Ure and surrounding waterbodies, including Semerwater, are of national importance. However, crayfish plague *Aphanomyces astaci* was confirmed as present upstream of Aysgarth Falls in the main River Ure during summer 2020 (PBA, 2020). The upstream spread of this epizootic is of major concern, both for the future of white-clawed crayfish within the Ure system, but also the biosecurity risk it poses to nearby catchments as a source of plague spores. This assigns a high strategic importance to the metapopulation contained within Semerwater and its tributaries, as sections of bedrock steps in the River Bain may prevent the upstream spread of plague and thus Semerwater could possibly sustain white-clawed crayfish beyond the current epizootic. However, white-clawed crayfish require high water quality including ample dissolved oxygen and low siltation pressures (Haddaway *et al*., 2015), and as such the impact of the sedimentation pressures identified within Semerwater may be impacting the condition of this metapopulation.

The summation of these compound stressors also contributes to high levels of nutrients and sediment within the River Bain, the outflow of lake Semerwater. Algal matts have been reported forming in summer, during periods of warmer lower flows and peak nutrient delivery (Figure 8). Connectivity of Semerwater to the River Ure through the River Bain is important (although see above), and sections of highly eutrophic waters reduce this connectivity, fragmenting habitats and isolating species, as well as likely contributing to localised mortality.

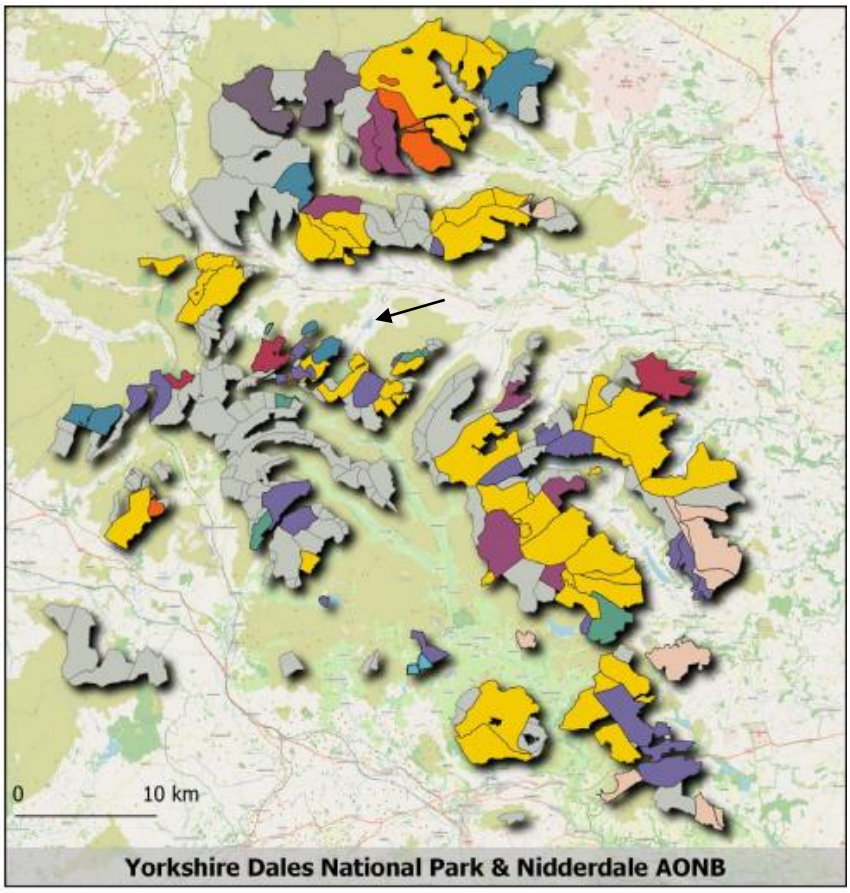


Figure 7: Map of Yorkshire Peat Partnership work, to include upstream of Semerwater (arrow) in the upper Raydale catchment (YPP, 2021).



Figure 8: Evidence of high nutrient loading and dense algal mats forming in the River Bain outflow during summer 2021 (photo credit, Environment Agency).

2.5. EXISTING INITIATIVES WITHIN THE RAYDALE CATCHMENT

In England and Wales, concerns regarding non-compliance with WFD targets owing to diffuse water pollution from agriculture (DWPA) resulted in the Catchment Sensitive Farming (CSF) initiative. Since inception in 2009, CSF initiatives have been ongoing through a collaborative approach between the Yorkshire Dales National Parks Authority (YDNPA), Natural England (NE) and the Yorkshire Dales Rivers Trust (YDRT). A primary target of this scheme was to reduce the risk of diffuse water pollution from agriculture. Additionally, almost 90% of the actively farmed land within Raydale is under Environmental Stewardship Scheme (ESS) agreements (Figure 9). The advice for likely sources of pollutants and management opportunities within the Raydale catchment provided by the Catchment Sensitive Farming Officers (CSFOs) has been generally well targeted (Pulley & Collins, 2021), with sediment sources corresponding well to CSFOs perceived sources and therefore current CSF actions. The only noted deviance from this is the attention attributed by CSFOs to Woodland as a priority source of sediments into Semerwater, which is not in agreement with modelled erosion risks (Pulley & Collins, 2021).

Further work was delivered through the Semerwater and Upper Lune Catchment Partnership (SULCP), summarised in a final report from 2015. The SULCP, through a range of farm visits, one-to-one engagement, training and demonstration events delivered targeted advice to farmers on the management of manure, soil and fertilisers, and nutrients, securing the award of over £600,000 of Capital Grant Scheme (CGS) funding to make improvements to tackle DWPA (2012-2015). These include roofing of muck middens and livestock yards, renewals of infrastructure such as concrete yards, and watercourse fencing.

Programmes such as the Raydale Project (2009) sought to determine and plan for future risk, focussing on catchment level response to climate change. Run by the Yorkshire Dales Rivers Trust (YDRT), and focussed on stakeholder engagement, nutrient management plans and manure management plans were developed and implemented (DWP, 2014). Additionally, ca. 1 km of riparian fencing was installed, with tree planting and wet woodland establishment undertaken where appropriate.

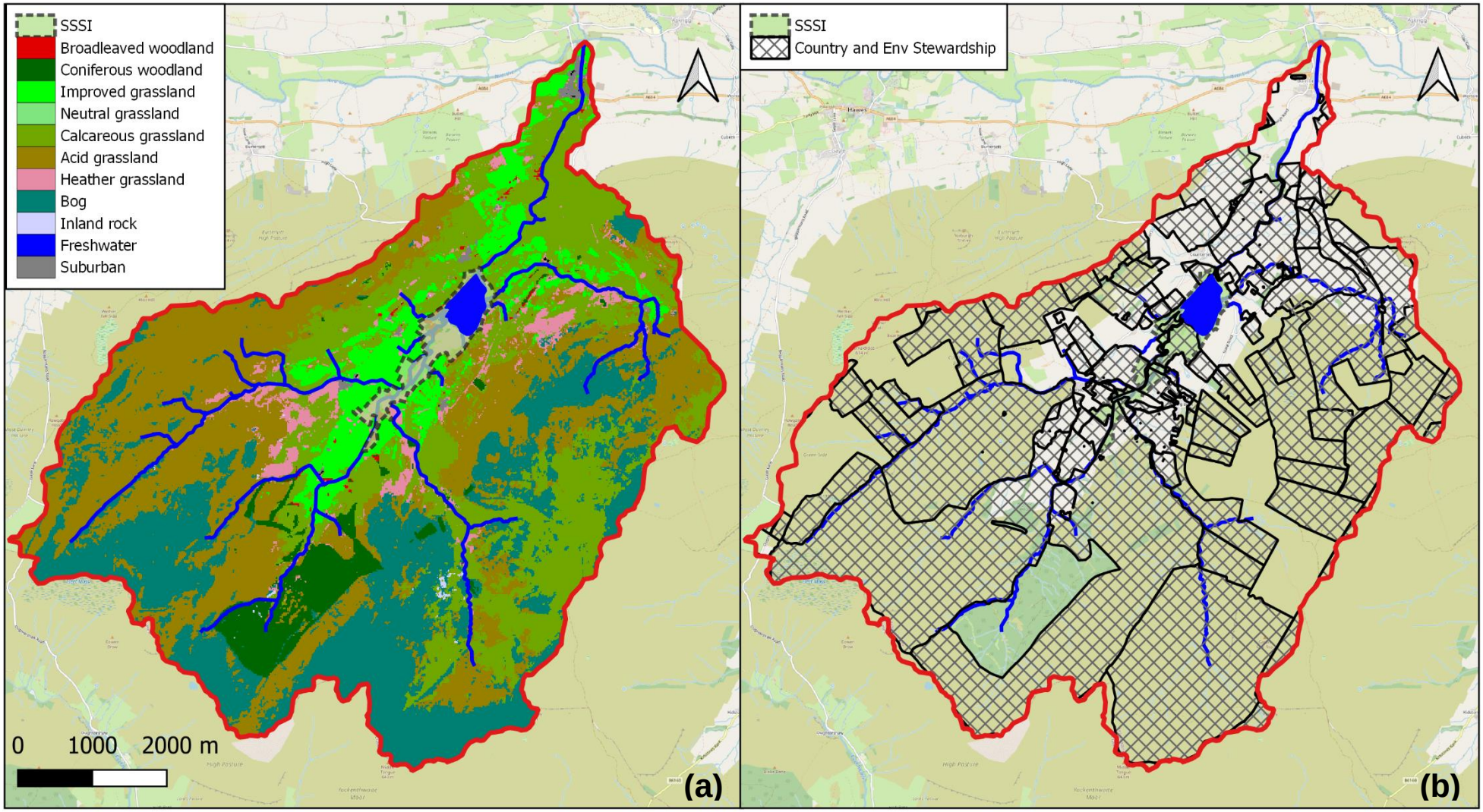


Figure 9: Contemporary coverage (2020) of a) land use and b) agri-environmental schemes for the Raydale catchment (CSS data RPA, 2021; Landsat 10m resolution, Morton *et al.* 2021).

2.6. MANAGEMENT OPTIONS AND CONSTRAINTS FOR SHALLOW LAKES

Management options for addressing eutrophication of shallow lakes are well considered in Abell *et al*. (2020), with the Section 4 (Lake Restoration) of Søndergaard's thesis (2007) further reviewing restoration approaches for analogous Danish shallow lakes with respect to sediment and nutrient pressures. These fall broadly under four distinct categories, being 1) control and reduction of external inputs, 2) reductions in internal loadings, 3) biomanipulation and 4) hydrological manipulation (Figure 10; Abell *et al*., 2020). As the delivery mechanism for nutrients into a recipient waterbody is often closely linked to sedimentation regimes at a catchment level, approaches under categories 1 and 2 often also prove effective for managing excess sediment recruitment.

Following analyses of 32 European shallow lakes which received external nutrient reduction management, Jeppesen *et al.* (2005) noted declines in the annual mean TP in 86% of studied lakes (5-35 years, mean 16 years), with declines typically occurring in shallow lakes 10-15 years after; this biogeochemical lag is common following targeted management of external nutrient loadings due to residual internal loadings. The preparation of a lake nutrient budget is an important management step for assessing controls on external nutrient loads in shallow lakes. Many control techniques available for lake management are specific to pathways and types of impact, and as such knowledge of the source, timing or seasonality, and mechanisms of nutrient losses is critical. Extending these models out to the broader catchment can support estimations of time needed to achieve restoration targets, through quantification of inputs and outputs to the system. Diffuse and point source control of nutrient sources to reduce the overall external loading is ultimately a fundamental requirement, as this management targets the root cause of the eutrophication, and not achieving this is often a primary cause of failed lake restoration (Abell *et al*., 2020). However, the costs associated with the required changes, such as land-use alterations or improved wastewater treatment, can be prohibitive. Achieving the required improvements to external load reductions through 'best management practices' (BMPs) alone is considered infeasible (Osgood, 2007), who reported reductions in P load of >80/% can be required to restore eutrophic lakes, of which only ca. 50% reductions are achievable through BMPs and typically <25% reductions in external P loads are realised. This can be further complicated by biogeochemical lags driven by erosion of highly P enriched soils within the catchment delaying lake recovery, which are particularly prevalent in high-intensity agricultural catchments (Carpenter, 2005). Time scales for recovery towards baseline conditions have been estimated at 15 – 31 years depending on the extent of external nutrient reductions (McCrackin *et al*., 2017), with the authors noting the slowest recovery rates in agricultural catchments.

Reductions in internal nutrient loads can be approached through both physical and chemical means. Dredging is undertaken to remove nutrient rich surface sediments in shallow lakes, which has the secondary benefit of increasing the depth of the recipient waterbody. However, this practice is highly damaging to benthic fauna and flora, and the required equipment and disposing of the dredgeate can be expensive. Capping is also used to treat nutrient-rich surface sediments, which passively covers benthic substrates with inert materials to reduce flux at the sediment-water interface. This practice however also impacts benthic fauna and flora, poses biosecurity risks when importing materials, and may have implications for the visual amenity of sites. Chemical removal of internal nutrient loadings is commonly undertaken through adsorption of P, often coupled with flocculants to reduce organic materials in the water column. The response within waterbodies can be rapid and the practice is well-established and cost-effective, however the effectiveness of the treatment can be impaired in very shallow lakes due to how readily sediments are resuspended. Best practice in lake management stresses the need to address external problems, particularly nutrients, before resorting to major within-lake restoration measure such as sediment removal (Mainstone *et al.*, 2016). Current evidence points to the need to address external nutrient inputs as the major threat to ecological function.

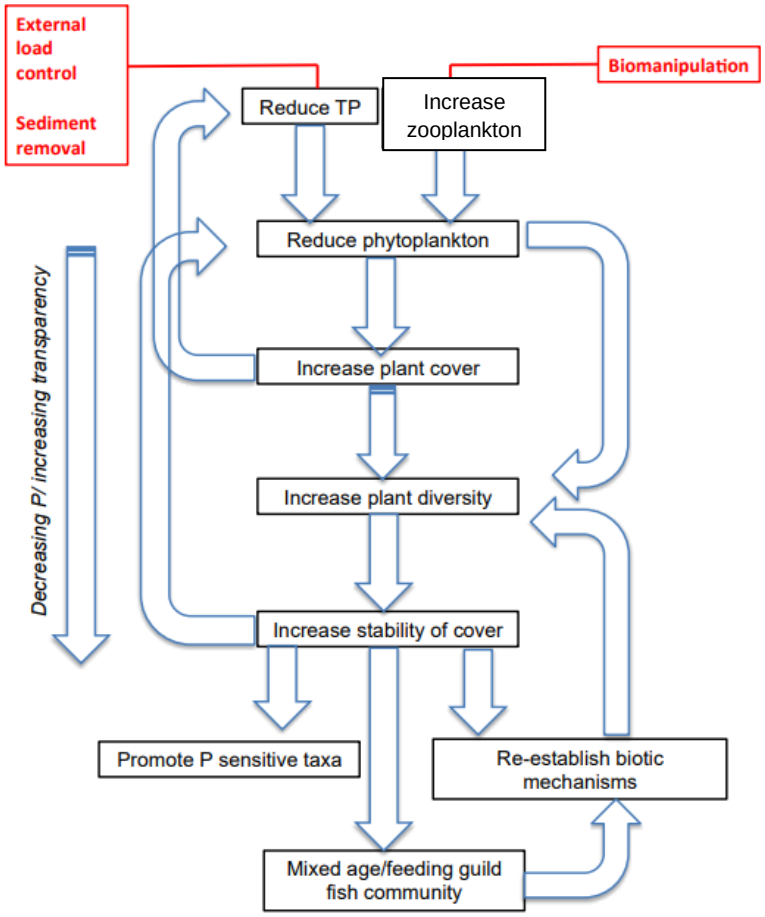


Figure 10: Indictive flow diagram of the interlinkages of restoration objectives and entry points for different techniques (adapted from Phillips *et al*., 2015).

Biomanipulation has been undertaken in many shallow lakes, generally aimed at either zooplanktivorous or benthivorous fishes. Targeting zooplanktivores such as rudd *Scardinius erythrophthalmus* and roach *Rutilus rutilus* is often achieved through physical removal (e.g. via seine netting) and through stocking of predatory fishes such as pike *Esox lucius.* Zooplankton are then trophically released from predation pressure, in turn reducing the phytoplankton biomass on which they predate. Benthivorous fishes such as common carp *Cyprinus carpio* and bream *Abramis brama* create bioturbation through their benthic feeding habits. Bream, roach and pike are currently recorded as present within Semerwater. Removal of these fishes does however require frequent intervention to maintain low biomasses, and the results of both 'top-down' control and 'bottom-up' control through fish removals have been inconsistent in reducing nutrient loadings and delivering sustained improvements (Søndergaard, 2007).

A management option for lakes that have undergone significant alterations within their recent history is to reverse these changes, enabling the waterbody to return to a more natural hydrological state. The lowering of Semerwater in 1937 through the removal of glacial till within the outflow is likely to have accelerated the declining ecological status of the lake. Reinstatement of these materials would lead to a rise in the water level of Semerwater, and the resulting outcomes of this may help to slow or potentially reverse the decline in ecological status. Material could be reinstated over a long period (10+ years), perhaps in the form of a 'leaky boulder' addition to the outflow, with concurrent hydrological and ecological monitoring. This would require specialist hydrological modelling to determine feasibility, likely outcomes and potential benefits such as flood attenuation, which is outside the scope of the current report.

2.7. KNOWLEDGE GAPS AND DATA DEFICIENCIES

Modern surveys of Semerwater and its catchment would enable management efforts to be more accurately and meaningfully interpreted. However, very few such studies and reports exist, often being conducted in isolation of each other. Contemporary data on the bathymetry of Semerwater, the ecological communities present in the lake including fishes, and the status of the main tributaries is lacking. Further, macrofossil studies including plant remains and Cladocera within Semerwater are scarce, despite providing key information on past conditions and therefore targets for the lake.

More broadly, there has been repeated recognition of the value that would be provided through both nutrient budgets and sediment budgets of the Raydale catchment (Bennion *et al*., 1997; CSM, 2011; Reaney *et al.*, 2013; DWP, 2014). These analyses would help to understand the input volume and source locations of sediments and nutrients recruited within the Raydale catchment, and the residence time and distribution of sediments and nutrients within Semerwater and into the River Bain. In the absence of this data, management interventions risk being ineffectual through targeting areas or sources that have low overall impacts, and cost:benefit analyses that are undertaken without this data will contain large uncertainties.

Whilst a number of management actions have been undertaken within Raydale, no cohesive approach to recording these land-based initiatives and schemes, including their actions and outputs, exists. In the absence of this repository, coordination of efforts becomes difficult and risks inefficiencies due to for example repetition of effort. Further, recording and evidencing tangible progress is also made difficult without comprehensive records that provide continuity in the longer term between projects. Furthermore, whilst the above (Section 2.5) shows a concerted effort to identify and address perceived pressures on Semerwater, the available water quality data (2012-2022) indicate no change in the nutrient loadings of the lake itself throughout this time period. In the absence of centralised records of advice uptake, baseline outputs and reductions of targeted pollutants (e.g., agricultural runoff), it would appear that the P loading in the lake is operating independently of these actions, suggesting a biogeochemical lag and that nutrient cycling is internally driven. However, this has yet to be confirmed; representing a major limitation of the current data.

Semerwater is atypical and does not conform well to WFD or CSM lake types and ecological targets. To this end, the collection of additional data on the current and historic biology and chemistry will help to define site-specific targets and set realistic restoration targets against which the site condition can be ben assessed.

3. ACTION PLAN

3.1. PRIORITISATION OF MANAGEMENT ACTIONS AND RECOVERY TIMELINE AND OPTIONS

The timescale for the recovery period of lakes is primarily driven by a range of key pressures and lake-specific factors, including lake depth, history of pollution, retention time of pollutants, and volume and nature of P in the sediments (May *et al*., 2020). For lakes, the process of restoration can take longer to achieve than the period of disturbance and degradation that caused it (May *et al*., 2020), with targets aiming to expedite recovery at short time scales often considered unrealistic. For example, surveys of macrophyte community composition and distribution, often considered an effective tool of tracking this recovery, have provided evidence of biogeochemical lags of 20-30 years in studied lake systems (May *et al*., 2020) even following external P reductions of 95% (Sand-Jensen *et al*., 2008).

As noted by Reaney *et al.* (2013), the baseline evidence over the now past four decades points to a consistent set of pressures acting on Semerwater within the Raydale catchment, being phosphorus and sediment. Modelling of catchment scale processes including erosion risks and land-use, coupled with limited but robust empirical evidence of strong and sustained reductions in key indicator species such as aquatic macrophytes and excessive TP within Semerwater lake and surrounding soils, support the condition assessment of Semerwater as Unfavourable - No change. The WFD requires GES by 2030

adding further complexity through delivery schedule requirements imposed by these legislative drivers, and as a SSSI Semerwater is required to be in at least a Recovering condition if not Favourable. The Raydale catchment is large in comparison to Semerwater, and has agriculture intrinsically bound to its human history and land-use practices. The limited empirical evidence available against which to assess the status and direction of Semerwater suggest that efforts so far to reduce external loadings have yet to demonstrate an improvement in the chemical (Figure 3 & Figure 4) or biological (Table 2) condition of Semerwater lake. This is not to reduce the importance of these efforts, as some historic data suggest that TP concentrations in Semerwater have been as high as 125 µg/L in 1990 (mean TP 80 µg/L; Gibbons, 1990 in Bennion *et al*., 1997), and so management to date may well have delivered substantial improvements on these historical concentrations; however, they remain more than target concentrations. Solutions are therefore sought that facilitate the retention of well managed agriculture, whilst allowing Semerwater SSSI to recover its biogeochemical condition.

Ultimately, it is a fundamental requirement to reduce the combined external diffuse and point source nutrient and sediment loadings to below that which is released from the lake to address the root causes of degradation and deliver sustainable improvements (Abell *et al*., 2020). The rate and likelihood of recovery could be meaningfully enhanced through targeted interventions to internal loadings of nutrients and sediments once excess external recruitment is addressed and if periodic flushing of the lake from the large watershed fails to deliver satisfactory progress. It is, however, the opinion of the authors that Semerwater cannot reach Good Ecological Status by 2030, and that well considered management over appropriate timescales offers the greatest opportunity for recovery. Actions that are recommended for Semerwater in the short-medium term can be grouped into three broad categories, comprising 1) targeted surveys and analyses to provide novel data identified by knowledge gaps, 2) continuation or revisiting of monitoring and survey work, and 3) consolidation of existing management activities (Figure 11).

If these actions are undertaken, then meaningful secondary management can be actioned that is evidence driven. Secondary management actions over the medium-longer term would detail 1) targeted management of the identified primary external sources of sediment from the Raydale catchment into Semerwater, 2) targeted management of the identified primary external sources of P from the Raydale catchment into Semerwater, 3) actions to address internal P and sediment loading within Semerwater lake, where appropriate.

3.1.1. *SHORT TO MEDIUM TERM (1 – 5 YEARS)*

Novel information for management

To focus resources and increase likelihood and timeframe of success, a detailed nutrient budget should be undertaken for Semerwater and the wider Raydale catchment. This should aim to identify the input volumes and source locations of primarily P from the watershed into Semerwater, and further modern detail on the work of Tejero (2015). In addition, the temporary fate of nutrients within the lake would be useful to determine in terms of comparative concentrations of substrates and the water column, and quantifying residence times of P would inform likely timescales for effectiveness of secondary management interventions (Zhang *et al*., 2020). A particular focus of this catchment scale nutrient assessment should be a full audit of domestic sewage treatment within Raydale, ideally ground-truthed with site visits of previously known, aging and previously unrecorded facilities. The authors are aware of 5 consented discharges able to influence conditions within Semerwater (Appendix 1), with a number of additional septic tanks located within the Raydale catchment serving residents (Wilson, 1995). Under modelled external P export for Raydale (Wilson, 1995) the Crooks Beck inflow concentration was 42-141 µg/L TP and the Semerwater lake itself was 28-77 µg/L TP (under low and high export scenarios, respectively). Agricultural sources accounted for >80-90% of this, being split between organic (20-21%) and inorganic fertilisers (64-71%). Wilson recommended a lessening of agricultural intensity and nutrient inputs, with a 20% reduction in both stocking density and inorganic fertiliser application, alongside establishment of 20 m riparian buffer zones would reduce Crooks Beck and Semerwater to within

mesotrophic target levels. These figures are however now outdated, with both intensity of stocking and fertiliser application likely to have changed as well as the relative contributions of nutrients made by the different pollutant sources into Semerwater.

Likewise, undertaking sediment fingerprinting of Semerwater and the Raydale catchment, to apportion sediment sources into the lake forming a sediment budget, would directly inform secondary management and make best use of resources. Installation of sediment traps to capture sediment rain within the primary inflows (Crooks Beck and 3 smaller upstream tributaries, and Little Ings Sike) as well as within Semerwater may also provide estimates of accretion rates within the lake. Further, determining the current contributions of peat will aid understanding of 'natural' turbidity conditions within Semerwater, which may be elevated compared to other mesotrophic lakes due to colouration from peat within the upper Raydale catchment. This in practice can range from the relatively low resource intense approach of monthly water sampling coupled with flow estimates from each sub-catchment, to loggers and instruments being installed that monitor flow and auto-capture water samples. The coverage and therefore quality of the data scales with the costs, however the focus of this work remains identifying the main sources of P and sediments, and thus target areas for reductions.

To further clarify restoration targets and associated management, paleo studies of plant macrofossils including seeds and other remains and Cladocera sub-fossils should be undertaken. The analyses of these cores would inform what Semerwater likely looked like in terms of chemical, biological and ecological condition prior to enrichment, and would therefore offer bespoke restoration targets for Semerwater given its unique nature of natural upland peat and limestone inputs within the Yorkshire Dales.

Updated surveys and monitoring

Sedimentation leading to the increasingly shallow, enriched condition of Semerwater is noted as a major pressure on the system. However, the most contemporary and detailed bathymetry data (Figure 1 & Figure 2) available from the literature are of low resolution, due to not being purposefully undertaken as bathymetric surveys. Additionally, there are contrasting opinions within the more established literature and contemporary assessments as to whether Semerwater is indeed 'Very shallow' as defined by CSM or is in fact 'Moderately Deep' (being either side of the mean 3 m depth threshold); this is of particular importance as it dictates appropriate nutrient thresholds for Semerwater. Reported deposition rates into Semerwater are varied (0.2 - 1 cm per year) and it is unclear whether deposition is occurring evenly or is concentrated in certain areas, although large volumes of sediments appear visually to have been deposited where Crooks Beck joins Semerwater. Accurate and detailed bathymetric surveys should therefore be conducted, to provide a modern baseline from which to inform the current assessment of condition and gauge future progress.

It is clear that Semerwater fully fits into neither a mesotrophic waterbody or a hard water lake, having elements of both. As such, target driven management, such as GES for WFD, risks pursuing unrealistic or inappropriate conservation objectives, actions and timelines in order to attain these targets. Through the undertaking of macrofossil work, a greater understanding of past conditions could be gained which would inform more achievable and representative restoration targets.

The CSM macrophyte surveys comprise one of the strongest empirical biological datasets for Semerwater. The biological response to both internal and external pressures within Semerwater has been documented through these reliable macrophyte community records dating back to 1995, with corresponding sustained declines evidencing a lack of improvement in the condition of Semerwater. This periodic CSM compliant macrophyte surveying should be continued, to provide information on distribution and status of the macrophyte community in Semerwater, and therefore any likely direction in biological response to restoration efforts.

Whilst direct biomanipulation of resident fish populations at this stage would yield highly uncertain results, a detailed understanding of the fish community within Semerwater would be a suitable and valuable first step. Determining species compositions, as well as estimates of biomass, would inform whether removal of either zooplanktivorous or benthivorous species would result in benefits to water quality within Semerwater. These can be achieved through physical survey means such as seine and fyke netting, as well as sonar, with appropriate fish welfare and biosecurity considerations in place.

Given the ongoing epizootic of crayfish plague in the upper River Ure, likely the largest in Europe at the time of this report, Semerwater and its tributaries are of high strategic interest for the persistence of white-clawed crayfish in this system. Population assessments of white-clawed crayfish in the lake and tributaries should be conducted, using a highly precautionary biosecure method and schedule of works. Introduction of crayfish plague or signal crayfish, both considered as invasive species of international concern, would further reduce the condition of Semerwater in the short term against GES criteria, as well as potentially permanently through secondary impacts such as burrowing. A review of biosecurity procedures for Semerwater should be conducted, in the context of linkages with the broader River Ure catchment and anthropogenic activities such as water sports and angling, to identify and where practicable eliminate biosecurity risks. Specific attention should be assigned to invasive non-native species (INNS) that may further degrade and exacerbate the stresses on the lake, such as Himalayan balsam *Impatiens glandulifera* which would increase erosion risks and New Zealand pygmyweed *Crassula helmsii* which can dominate stillwaters, drastically reducing macrophyte biodiversity and dissolved oxygen concentrations. It is possible that citizen science has a role to play in the collection of high frequency low resolution data relevant to the condition of the lake such as INNS distribution. There exists a respectful balance of agriculture and regulators working there in partnership, and any citizen science schemes will have to be carefully considered so as not to pressurise this. Further, due to the current biosecurity risks within the catchment, primarily the crayfish plague epizootic, it is recommended that citizen science is not utilised in the aquatic environment for Semerwater.

Coordination and recording of management activities

This document provides a foundation for the third set of short-medium term recommended actions. However, there exists both past work that is only partially captured here due to the absence of a centralised recording system, and likely future actions whose scope and outputs may also fail to be adequately captured if not addressed. Documents collected for this review fell into several broad areas, including 1) empirical datasets from survey and monitoring works (both internally and externally derived), 2) published literature relating to Semerwater and its catchment, 3) interviews, meeting summaries and other engagement activities with farmers and other local stakeholders 4) grey literature focussed on reporting actions and outcomes of management activities within the catchment (e.g. nutrient management plans for specific holdings) and 5) grey literature focussed on larger scale or longer term summaries and reviews of progress. These broad categories could well serve as a primary structure for a coordinated repository documents relating to Semerwater within Raydale. Contributors to this repository should include all relevant stakeholders, namely YDNPA, EA and NE, local trusts such as YDRT and Yorkshire Wildlife Trust, and any CSFOs and similar roles not captured through the previous organisations. Further, a strategic action group should be considered, such as a Semerwater Steering Group (SSG), formed of key high level stakeholders who could meet periodically to provide oversight and collaborative direction to management efforts.

3.2. Pathways to improving the condition of Semerwater SSSI (ca. 5 – 30 years)

Providing the nutrient and sediment budgets for Semerwater and Raydale can be actioned within 2022/23, the findings of these can be used to inform the next stages of management. Confirmation of the source, comparative volumes of the sediments and likely associated P loads entering Semerwater allow for efficient, targeted management. The next stages following on from this process would also need to fully involve local sources of P and sediments, such as those identified from farms and forestry. Without stakeholder buy-in and compliance, substantial and sustained reductions in pollutants into

Semerwater will not occur. This may include not only reductions in inputs or stocking densities, but simply alterations to timing or locations of activities. This is a challenge facing practitioners and stakeholders alike within Raydale, and one that will require continuation of the already well established and developed working relationships between organisations such as YDNPA and users of the Raydale catchment.

Given the likelihood that internally derived P loads are contributing to the enriched condition of Semerwater (inferred from periodicity and trajectory of P monitoring data within Semerwater - Figure 3; Phillips *et al*., 2015), physical or chemical management of the sediments may be appropriate. However, the Raydale catchment is very large in comparison to the surface area and volume of Semerwater, and as such it could be expected that there is a fast rate of water turnover from periodic flushing of Semerwater lake, with a reported mean hydraulic residence time of 15.8 days (Wilson, 1995). If the identified external nutrient and sediment inputs could be controlled to a sufficient extent, these natural processes could enable Semerwater to become a net source and relinquish both P and sediments, rather than a sink. This approach would however depend on both sufficient reductions in external loading, and also stakeholder and legislative acceptance of the likely longer recovery timeframe for improvement to internal conditions due to biogeochemical lag and potential hysteresis within the system.

Finally, to further consolidate the required collaboration between the partners operating within the Raydale catchment, it is suggested that a ‘vision’ for Semerwater is formed between these stakeholders, that sets evidence-based targets for the recovery of Semerwater within its current and historical context. This is a brief descriptive overview of what Semerwater should look like in favourable condition and what is required to bring this about. It brings together the evidence, best practice, policy and partnerships that are required to achieve the conservation goals at the site into a single, integrated statement. This could set objectives surrounding the specific nature of Semerwater, such as to restore the near-natural functioning of the upland peatlands, and would enable definition of targets that are not aimed at broader potentially inappropriate categorisations of Semerwater. Schemes and legislation such as Farming in Protected Landscapes (FiPL) and the Farming Rules for Water (2018) could provide guidance and potential funding sources for the realisation of some of these objectives.

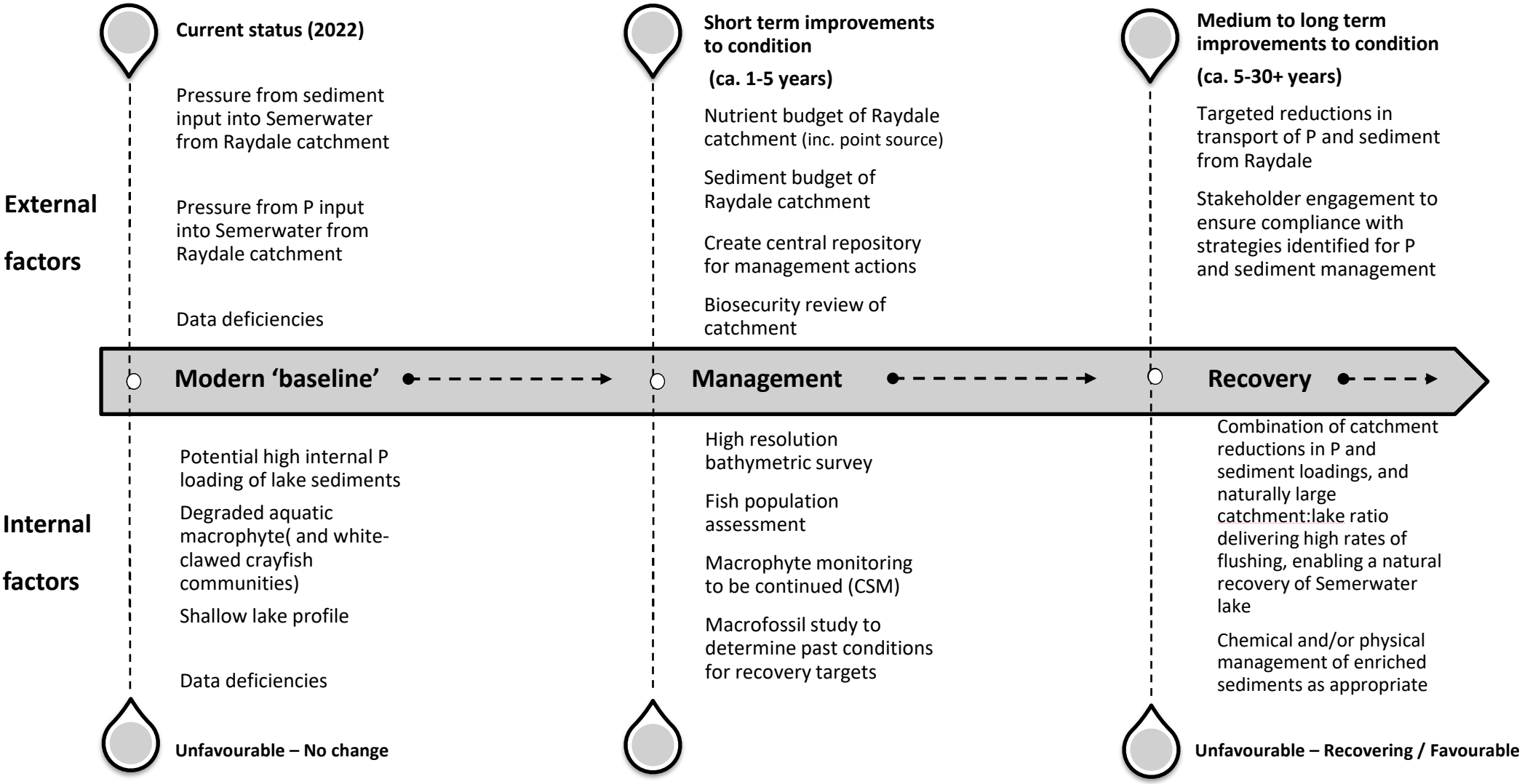


Figure 11: Proposed timeline for management actions within the Raydale catchment to improve the condition of Semerwater SSSI.

3.3. COST:BENEFIT EXERCISE

Analysis of the comparative cost:benefit of recommended actions is a useful tool through which managers can prioritise actions that deliver the greatest benefit using finite resources. Where current data either do not support the scale of works required (i.e. the cost) or the potential gains from an intervention (i.e. the benefit) the process is impaired and the outcomes of such analyses become limited. Consequently, contemporary catchment-scale information on sediment and nutrient loadings are considered essential pre-requisites for cost:benefit analyses, such as by Spears et al. (2018) in their review of phosphorous control for English lakes which included four-year restoration programmes in Hatchmere and Mere.

A high-level cost:benefit analysis for the recommended actions at Semerwater is provided below, within the limitations of the current data summarised in this report. Additionally, current management actions including restoration of the upland peat, CSF grant-funded improvements to agriculture within Raydale, and engagement with stakeholders and subsequent changes in agricultural practice are assessed where possible. These actions are considered with respect to improving the condition of Semerwater lake either in the short or medium-long term, defined through the most robust empirical chemical (EA water quality) and biological (CSM macrophytes) datasets available at the time of this report. The annual costs are considered through broad (estimated) categorisations of low (L), medium (M) and high (H) costs, representing £1-10,000, £>10,000-50,000, and £>50,000 respectively. Estimated benefits are similarly categorised, with additional detail provided as comments where evidenced. Where the data do not currently support an assessment of either the estimated cost or benefit, this is indicated (?), and result in no overall priority rank being assigned. Ranking is calculated through multiplying cost (Low scoring 3 points, High scoring 1) by benefit (Low scoring 1 point, High scoring 3) to achieve an overall priority rank (1-3 Low, 4-6 Medium, >6 High), with scores assigned through expert judgement and using published sources where appropriate.

A clear result from the cost:benefit matrix applied in Table 3 is that a number of the current management activities require the application of a nutrient and sediment budget to gauge their efficacy. These budgets, along with the establishment of a collaborative vision for Semerwater that fully engages stakeholders, are the likely to be the most impactful management that can be undertaken in the short term for achieving the ultimate ambition of improving condition within Semerwater lake. Secondary survey and monitoring work provides important, low-cost empirical support of these actions, along with maintaining strong working relationships with catchment partners. Capturing the process and outcomes of these actions within a centralised, well-maintained repository is considered highly beneficial.

Table 3: Cost:benefit of existing and proposed management strategies within the Raydale catchment with the aim of improving the condition of Semerwater lake in the short and/or medium-long term.

Action	Recipient	Timescale	Annual Cost	Benefit	Supporting evidence	Overall priority rank
Peat gripping/blocking upper catchment	Upper Raydale catchment	Ongoing	M	?	Sediment and nutrient loadings in Semerwater not reduced (2012-2022).	?
CSF led agricultural improvements	Land-users across Raydale catchment	Ongoing	H	?	Sediment and nutrient loadings in Semerwater not reduced (2012-2022).	?
Engagement with land-users to encourage	Land-users across Raydale catchment	Ongoing	M	?	Sediment and nutrient loadings in Semerwater not	?

best practice (e.g. timings)					reduced (2012-2022).	
Commission of review of current information and resources on Semerwater	Semerwater lake & Raydale catchment	Ongoing	L	M	Data gap identification and vision plan for lakes initiated recovery (e.g. Llangorse, Hatchmere).	M
Centralised repository for data and reports and SSG	Semerwater lake & Raydale catchment	Short term (ca.1-5 years)	L	M - H	Identifies evidence gaps and reduces duplication of effort, high level strategy	M - H
Biosecurity catchment review	Semerwater lake & Raydale catchment	Short term (ca.1-5 years)	L	M	Epizootic identified in Ure catchment. No biosecurity review for Ure catchment to date.	M
Continuation of CSM aquatic macrophyte surveys	Semerwater lake	Short term (ca.1-5 years)	L	M	Longest standing biological dataset from which to gauge improvement.	M
Macrofossil work	Semerwater lake	Short term (ca.1-5 years)	L	H	Set realistic recovery targets.	H
Bathymetric survey	Semerwater lake	Short term (ca.1-5 years)	L	M		M
Fish community assessments	Semerwater lake	Short term (ca.1-5 years)	L	L	Determine likelihood of impact of future fish removals.	L
Nutrient budget	Semerwater lake & Raydale catchment	Short term (ca.1-5 years)	M	H	Essential to determine efficacy of current and future management.	M - H
Sediment budget	Semerwater lake & Raydale catchment	Short term (ca.1-5 years)	M	H		M - H
Establishment of Semerwater 'vision'	Semerwater lake & Raydale catchment	Short term (ca.1-5 years)	L	M - H	Data gap identification and vision plan for lakes initiated recovery (e.g. Llangorse, Hatchmere).	M - H

Chemical treatment of enriched surface sediments e.g. Phoslock	Semerwater lake	Mid-long term (ca. 5-30+ years)	M - H	M – H	Effective in other enriched waterbodies (e.g. Hatchmere; Spears *et al.*, 2018). Ineffective if catchment sources not controlled.	L - M

4. CONCLUSION

Semerwater SSSI and the Raydale catchment are significant features within the ecological, cultural and economic landscape of Wensleydale. The condition of Semerwater has deteriorated over the previous 50+ years, and there is renewed interest and political pressure to restore the lake to a more sustainable, resilient and healthy state. Through the review of information on Semerwater lake and the Raydale catchment, an assessment of the status of Semerwater is provided with consideration of direction of biological and chemical factors and the ambition to improve the condition of Semerwater to at least Recovering.

Nitrogen does not appear to be a significant pressure within Semerwater, and concentrations have remained consistent within Semerwater over the previous decade. Macrophytes remain present within Semerwater, but have declined in both species diversity and abundance. Native white-clawed crayfish also are persisting in lotic components of the catchment, and at a low population level within Semerwater. Efforts to restore natural functioning to the upland peats and reduce both point source and diffuse pollution from agriculture have been undertaken within the catchment, although the evidence these have not yet delivered recovery within Semerwater. Biological and chemical data indicate that internal conditions have not responded to these interventions over the previous 10-20 years, and may be driven by internal nutrient loadings.

Actions to ultimately improve the condition of Semerwater should focus around understanding the source and volumes of P and sediment entering the lake from the Raydale catchment, but are currently impaired by a lack of modern accurate data. Further, the process by which current and future actions are recorded and collated does not support cohesive efficient working, and hinder the evidence-based decision making which is key to successful management. This should be addressed through a centralised repository for works on Semerwater and establishment of the SSG, as a necessary means for tracking what is being done, identifying evidence gaps and reducing duplication of effort. Recommendations contained within this report outline the benefits of addressing these issues and provide a pathway through which to define and initiate bespoke recovery targets for Semerwater via appropriate means and timescales, likely beyond the previously considered 2030 objective. To achieve realistic recovery targets requires cooperation and coordination of all catchment partners including landowners, and as such maintaining established relationships and involving stakeholders throughout this process is vital. The defining and uptake of a collaborative vision for Semerwater and the Raydale catchment may further strengthen these relationships and provide additional clarity and direction to future management actions.

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Appendix 1. Known consented discharges within Raydale, denoting the 5 discharges (labelled) capable of influencing Semerwater (source: YDNPA, 2022).

