Influences on Sediment Transportation and Deposition in a Lowland UK Heathland Catchment: Natural Flood and Sediment Management as Tools for Promoting Floodplain Deposition, Carbon Sequestration and Habitat Restoration.

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Abstract

A catchment in southern England, UK, included a substantial area of bare ground within the surrounding heathland and woodland. Runoff from this area has, in the past, contributed large volumes of sediment to a large lake; although this input is now significantly reduced as a result of previous and on-going management works that are reported on in this paper. Historic realignment and re-sectioning of the main watercourse, has also resulted in the overdeepening, vertical and lateral erosion of the stream channel resulting in downstream transport of sediment to the lake. In addition to sediment erosion, the associated limited connectivity with the floodplain and focus of sediment transport in the fluvial channel has been a key factor in the shallowing and deterioration in the condition of the lake. Over the last 15 years a wide range of investigative, monitoring and management work has been undertaken within the catchment by a partnership between UK Government organisations, a local authority and a charity, with continuous involment by the author throughout this period. This work has evaluated the causes and effects associated with this erosion and transportation, tested and defined viable practical solutions (the delivery of natural sediment and flood management solutions and habitat restoration) and delivered a series of sustainable management interventions to reduce erosion, promote sediment deposition and to reconnect the stage zero and larger fluvial pathways to the floodplain – supporting the restoration of the lake. These works have resulted in the reduction in erosion at source and increased deposition through the catchment system, ultimately contributing to the improvement in condition of the lake and associated wetland habitats. Works in the headwaters of the catchment focused on defining the existing distribution, status and significance of areas of sediment generation, transport and deposition to the stream and lake, facilitating sustainable sediment management within this area. Works in the lower reaches focused on slowing flow velocities and diverting higher velocity sediment rich flows into new channels to reconnect with the floodplain and promote deposition. Management measures included the use of small diversion channels through woodland with the creation of glades to increase understory recovery and sediment deposition; use of geotextile cells filled with sand, gravel or stone to increase the flow path, reduce velocity and promote out of channel flooding and deposition of sediment; use of scrub and woody material to form leaky dams and increase channel roughness promoting out of bank flooding and deposition; use of online ponds, backwaters and embayments; blanking off channels to promote overland flow through woodland to reduce flow depth and velocity and promote deposition; use of leaky dams to promote higher flows transporting sediment into new sinuous channels and allowing out of bank flooding to promote sediment deposition.

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INTRODUCTION

A sustainable approach to flood and sediment management is required to ensure long-term safeguarding against a range of negative impacts including damage to property and infrastructure, resources and ecosystems, the economic costs of recovery and loss of life (e.g. Scottish Environmental Protection Agency, 2015).

As a result of climate change, the frequency of high magnitude and duration rainfall events and associated flooding is increasing and is projected to continue to increase (Seneviratne et al. 2012). This, in combination with continued population growth and development in flood vulnerable locations is creating increasing pressure on conventional flood defence measures to maintain current levels of protection. In addition, there is also a likely related climate change increase in soil/sediment erosion and transportation during storm events, from hill slopes, fields and other locations resulting in the loss of highly valuable soil and downstream effects on receiving watercourses (e.g. Borrellie *et al* 2020).

Maintaining the status quo is not seen as sustainable, with significant associated economic, societal and ecological consequences. An integrated catchment-wide approach to land and water management is therefore urgently required, working with natural processes alongside other measures to achieve solutions.

A catchment-wide approach will utilise and promote natural features and processes to manage sources and pathways and covers a broad range of techniques. Multifunctional natural flood and sediment management solutions have the potential to deliver substantial wider benefits including to water quality, soil conservation, and biodiversity but also ecosystem services and carbon storage (alongside wider socio-economic benefits). These are of particular interest in the context of wetland and floodplain restoration strategies (e.g. Oana *et al* 2014).

There is a key requirement to demonstrate the efficacy of a range of natural flood and sediment management interventions that also support carbon storage and biodiversity recovery. This is difficult to achieve because experimental manipulation needs to be at the field-scale and must be monitored over a long/multi-year/decadal period. This achieves considerable additional value if the wider benefits can also be demonstrated, particularly if they contribute to real-world solutions to help adaptation to climate change and solutions to the biodiversity crisis.

CATCHMENT OVERVIEW

The study catchment is located in southern England, United Kingdom. This catchment provides an excellent opportunity for investigation – as there are possible analogies of this specific site with the general problems associated with flooding and sediment erosion, and use of natural management to both ameliorate this as well as seek to promote carbon management and ecosystem service recovery.

The catchment drains into a large, shallow freshwater lake that is a key component of a nationally important Site of Special Scientific Interest (SSSI) and Local Nature Reserve (LNR), which includes other habitats such as heathland and woodland etc. The lake forms a valuable historical, social, recreational and biodiversity resource for the community.

Over the years, the ecological and physical condition of the lake has deteriorated due to a number of reasons that include sediment deposition, reduction in water quality (in particular increased turbidity) and reduction in lake depth (from sediment deposition) which has resulted in the near complete absence of aquatic plants being present away from the lake margins.

A significant proportion of the fine sediments have been associated with upstream erosion and transportation of sand, silt and clay sized particles (along with soil organic matter) from an area of eroding land in the upper catchment. Runoff and sediment discharge into the lower part of the catchment and lake through a main stream channel that is typically overdeepened and disconnected with the floodplain (apart from very high magnitude and sustained rainfall events). Other sources of influence on the lake include urban runoff and occasional sewage overflows.

Over the last 15 years a wide range of investigative, monitoring and management work has been undertaken within the catchment, by a range of organisations and project partners comprising UK Government organisations, a local authority, and a charity. The author of this paper has played a key role in the investigative, management solution design, and the monitoring of these works throughout the last 15 years. The work has evaluated the causes and effects associated with this erosion and transportation, tested and defined viable practical solutions (the delivery of natural sediment and flood management solutions and habitat restoration) and delivered a series of sustainable management interventions to reduce erosion, promote sediment deposition and to reconnect the fluvial pathway to the floodplain – supporting the restoration of the lake SSSI and ongoing sustainable management of the upper catchment.

As such the catchment provides an ideal combination of source, pathway (sinks) and receptor relationships.

- A range of examples of sediment mobilisation by land-use from extreme to mild;
- Highly susceptible receptor – lake – within which a wide range of parameters may be impacted; providing multiple meaningful measurements of the performance of the management interventions;
- There are some features present that allow natural mechanisms of water and sediment attenuation;

But these features are also suitable for intervention and amendment.

In addition, because the (highly susceptible) receptor (lake) is a large body of freshwater in its ecosystem service value:

- it has made funds available for large-scale long-term interventions;
- and makes the project of specific regional importance.

This paper draws on the key findings of the combined works to date that have been documented by the author. It seeks to provide an overview of the works associated with upper catchmen, stream channel and lake confluence as examples of sediment and flood management interventions in this setting. It also highlights future research proposals that will investigate the effect of these works in more detail, partularly with respect to carbon flux and ecosystem service optimisation, and in guiding future management.

KEY CATCHMENT FEATURES

The topography of the catchment is generally flat in the north, rising from 23m (Above Ordnance Datum AoD) to more elevated land up to 190m AoD in the south. Land use within the catchment is dominated by deciduous and coniferous woodland, dense shrub heath, scrub orchard, suburban rural development and inland bare ground.

Many of these areas are an internationally important Special Protection Area and/or nationally important SSSI primarily for their heathland and standing water/wetland habitats as well as species of birds, invertebrates, reptiles and plants. The responsibility for managing and maintaining the quality of these important habitats falls to the land owners, which has promoted the implementation of the works described in this paper.

Inland bare ground is associated with an area of heathland in the upper part of the catchment. Although this bare ground represents only around 2% of the surface area, it has been a key source of sediment mobilisation and transport to the north to the lake, and forms a key focal point for this study.

Local geological deposits comprise Eocene sediments overlain by younger Quaternary deposits including Downwash Gravel (irregular patches of quartz and flint gravel, Barton Sands (fine-grained marine sands) and Bracklesham Beds (consisting of clays, glauconite sands and pebble beds). All of these deposits are likely sources of sediment carried by surface runoff. In particular, the Bracklesham Beds contain a very high level of montmorillonite, which is a very fine grained mineral that expands greatly in the presence of water, increasing its turbidity.

Soils are characterised by the Holiday Hill Association which are found on heathland and woodland on Tertiary sands, loams and clays in this part of southern England. This association is dominated by acid podzolic soils with slowly permeable substrates although some well drained soils and soils affected by groundwater are also present. These have permeable sand surfaces passing to fine loamy and slowly permeable clayey layers below.

Figure 1. Indicative soil profile

There are no permanently flowing watercourses directly associated with the part of the upper catchment containing the bare ground, although a combination of ephemeral channels, gullies, ditches and track ways drain this upper part of the catchment as the areas characterised by bare ground.

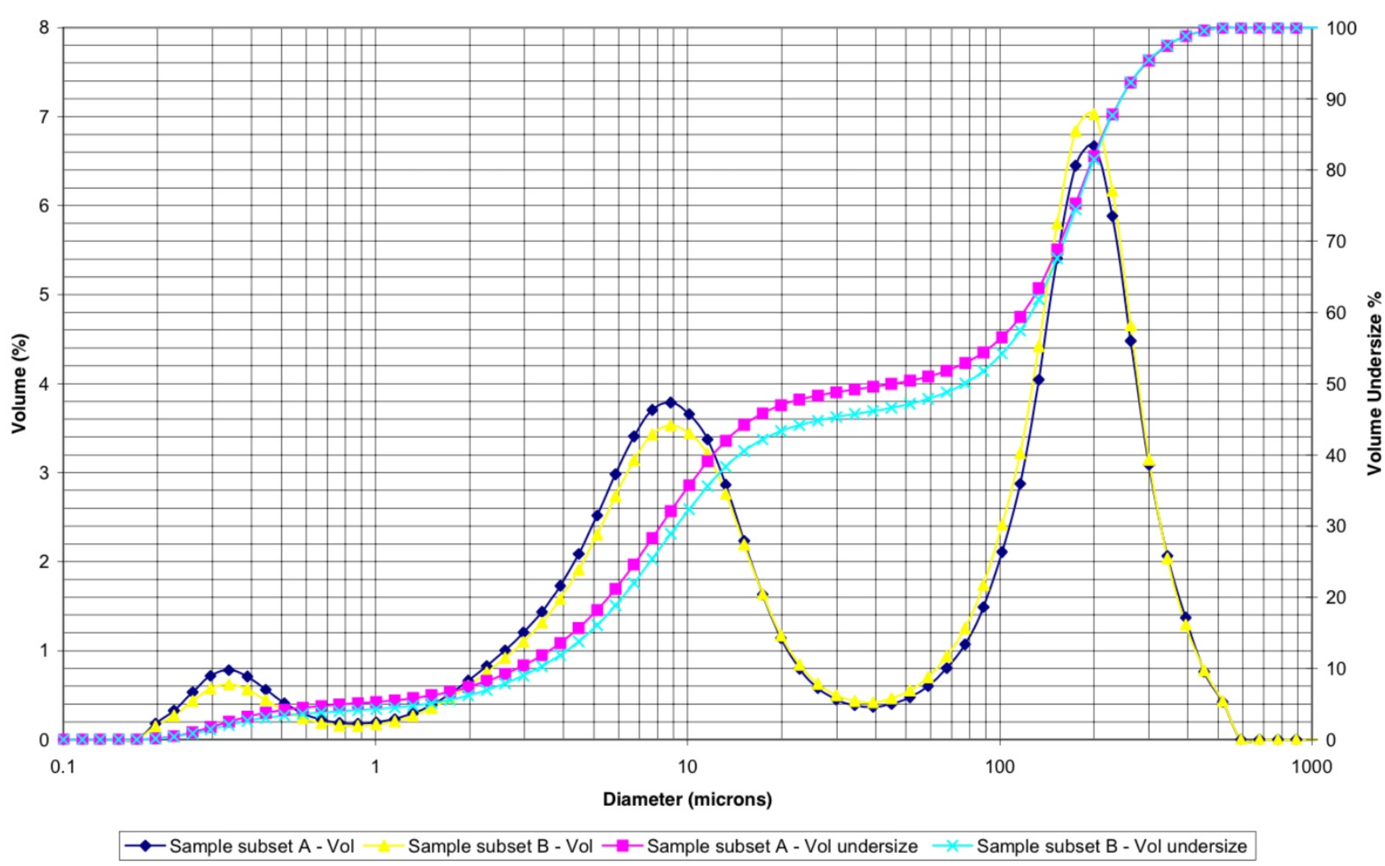
Despite the absence of permanent flowing water channels, after prolonged rainfall, once the soil becomes saturated and runoff occurs, flows concentrate into small channels that are typically associated with tracks. In addition, more natural channels have formed where flow has been sufficient to create such features. Man-made features including forestry drains are also present. These coalesce and discharge into the main catchment stream channel draining north to the lake.

Where drainage features coincide with clay exposures, high levels of sediment load and turbidity occur as can be seen in Figure 2.

Figure 2. Highly turbid and high concentrations of fine sediment where clay outcrops coincide.

Particle size analysis of samples taken from this area highlighted that surface runoff was dominated by three modal classes, clay particles (less than 4 microns), medium silt (dominant component between 1-10 microns) and fine sands (around 200 microns). This distribution can be seen in Figure 3.

Figure 3. Particle Size Distribution of the feature shown in Figure 2.



During high magnitude long duration rainfall events, notably in the winter months, the upper catchment can contribute a substantial component of the flows into the stream that drains north to the lake. Areas of runoff and sediment transport in the upper catchment are typically concentrated away from areas of permanent vegetation, draining to the north where they are directed into a settling pond before discharging into a single channel flowing towards the main stream and the lake.

There are a wide number of diffuse flow paths and generally, vegetation located adjacent to these areas helps to intercept rainfall and promotes evapotranspiration, improves soil drainage and percolation of water into the soil and increases surface roughness, slowing overland flow, trapping debris and encouraging sediment deposition and retention.

SEDIMENT SOURCES AND SINKS

SOURCES

The upstream catchment has a a substantial area of bare ground that exists within the surrounding heathland and woodland. Runoff from this area has, in the past, contributed large volumes of sediment to the lake; although this input is now significantly reduced as a result of previous and on-going management works that are reported on in this paper.

A range of examples of sediment mobilisation associated with land use activities, from mild to extreme are shown in the following photographs taken by the author.

Figure 4. Rainsplash and freeze-thaw

Figure 5. Bioturbation

Figure 6. Cattle poaching

Figure 7. Large volume releases of water from canal overflow

Figure 8. Gully formation and recreational activity

Figure 9. Tracks directing runoff caused by vehicles

Figure 10. Hydraulic action by vehicles within depressions and standing water

SINKS

Examples of features that allow natural mechanisms of attenuation are shown in in the following photographs taken by the author.

Figure 11. Sediment eroded and temporarily stored on tracks

Figure 12. Sediment temporarily stored in depressions and standing water

Figure 13. Sediment transported from water filled depressions and temporarily stored on adjacent land

Figure 14. Sediment temporarily stored within vegetation

Figure 15. Sediment stored and transported within stream channels

Figure 16. Sediment stored in channels behind defunct traps

Historic realignment and re-sectioning of the lower stream, has also resulted in the overdeepening, vertical and lateral erosion of the stream channel resulting in downstream transport of sediment to the lake.

In addition to sediment erosion, the associated limited connectivity with the floodplain and focus of sediment transport in the fluvial channel has been a key factor in the transportation sediment directly to the lake, once within the stream. This has resulted in the shallowing and deterioration in the condition of the lake SSSI.

Figure 17. Overdeepened stream channel and disconnection with flood plain

The lake is a highly vulnerable receptor and has acted as a key sink for sediment transported from upstream sources. It is regulated by a fixed crest weir with very little scope for further downstream sediment transport, other than colloidal fractions.

Figure 18. Sediment deposition at the confluence between the stream and the lake

MANAGEMENT MEASURES (INTERVENTIONS)

Sustainable management works in the headwaters of the catchment have focused on defining the existing distribution, status and significance of areas of sediment generation, transport and deposition to the stream and lake, which have facilitated stage zero water and sediment reconnections, slowing flow, promoting sediment management within this area. Works in the lower reaches associated with the stream and lake have focused on slowing flow velocities and diverting higher velocity sediment rich flows into new channels, scrapes and re-wetting marshland and woodland to reconnect with the floodplain and promote deposition.

Such low tech solutions are recognised as being valuable in the restoration of stage zero and wider river and floodplan rehabilitation (e.g. Wheaton *et al* [Eds.] 2019).

Specific management measures impemented included:

· the use of small diversion channels through woodland with the creation of glades to increase understory recovery and sediment deposition;

· use of geotextile cells filled with native sand, gravel or cobbles to increase the flow path, reduce velocity and promote out of channel flooding and deposition of sediment;

· use of scrub and woody material in small to medium channels to form leaky dams and increase channel roughness promoting out of bank flooding and deposition;

· use of online ponds, backwaters and embayments;

· blanking off channels to promote overland flow through woodland to reduce flow depth and velocity and promote deposition;

· use of leaky dams in fluvial channels to promote higher flows transporting sediment into new sinuous channels and allowing out of bank flooding to promote sediment deposition.

Examples of these measures, from the works that have been carried out, are illustrated below in the following photographs taken by the author.

The first set of examples relate to amendments to natural features.

Figure 19. Diversion bay

Figure 20. Felled trees to prevent use of gullies

Figure 21. Buried felled tree used to form flow deflector on wide track (flow diverts from left to right)

Figure 22. Cut vegetation placed in channels to promote deposition and runoff reconnection with adjacent land

Figure 23. Woodland management to thin trees, increase light levels, restore ground flora and use of cut material to act as leaky dams slowing diffuse flow and promoting deposition

The next set of examples relate to new features.

Figure 24. Use of cellular geotextiles and coarse sediment to trap fine sediment

Figure 25. Use of cellular geotextiles and coarse sediment to trap fine sediment

Figure 26. Stone filled gabion deflectors to promote deposition and divert flow paths

Figure 27. Creation of woodland glades to restore ground flora to increase surface roughness and deposition, in conjunction with stone filled gabion and geotextile traps

Figure 28. Creation of blank woodland channels to promote deposition

Figure 29. Diversion channels and embayments for sediment deposition

MONITORING

Monitoring methods have included the use of continuous flow measurements, electrical conductivity and turbidity monitoring, spot sampling of water temperature, dissolved oxygen electrical conductivity, pH turbidity and depth, suspended sediment analysis, use of erosion/deposition pins, repeat photographs, habitat surveys, and repeat walkover surveys carried out during different weather conditions.

Most of this monitoring was carried out immediately after the initial phase of restoration work was implemented and prior to 2010. Since this period, the focus has been on management of the features within the upper catchment and preventing the most clay rich areas from draining, and therefore contributing the greatest source of very fine particles, as well as implementing measures to divert potential sediment laden flows into new channels, features and rewetted heathland, woodland and marshland habitats.

OUTCOMES

These low tech works have resulted in the reintroduction of stage zero hydrological processes in a number of locations in the upper catchment and reconnection of certain features to the floodplain/surrounding land in the lower catchment. This has caused a reduction in erosion at source, including mobilisation and transport of fine sediment from very problematic source areas, and increased deposition through the out of channel / flow path areas. Initial measures have been successfully introduced in the lower stream to divert higher flows, transporting sediment into new woodland and marsh channels, with on-line features promoting fine sediment deposition and rewetting of woodland and marshland habitats.

This has, ultimately, contributed to the improvement in condition of the lake and associated wetland habitats as well as the heathland in the upper catchment, improving the conservation status and condition of the two SSSIs.

In general, the measures implemented in the upper catchment and the lower stream have been shown to be successful, slowing contributing runoff and channel flows, reducing erosion, promoting deposition of sediment out of channel (in a range of localised and more extensive situations), with re-vegetation in many circumstances aiding sediment stability and habitat restoration. There is clear deposition of sediment away from the lake SSSI, although the potential for further sediment mobilisation, transport and deposition away from the floodplain remains.

Examples of these improvements are shown in the following photographs taken by the author.

Figure 30. Disused tracks resulting in settlement and increased standing water transparency

Figure 31. Effective operation of new diversion channels and deposition bays

Figure 32. Fine sediment deposition away from the main stream and lake in the new diversion channels

Figure 33. Clear water conditions and aquatic vegetation growth in diversion channels and re-wetted areas

Figure 34. Discovery of aquatic macrophytes in the open water of the lake

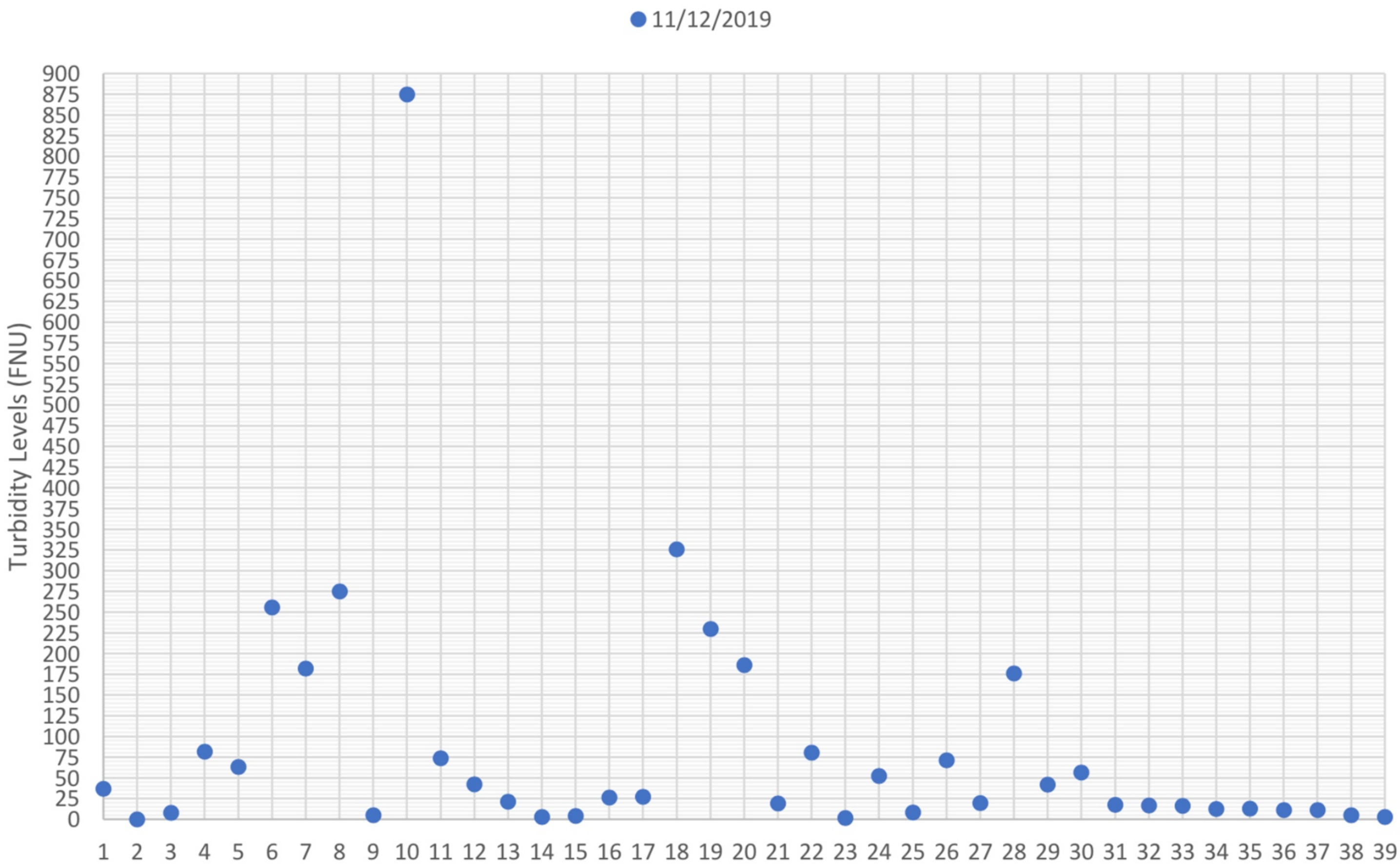
Figure 35. Restoration of improved water quality, transparency and habitats in the lake SSSI

An assessment of relative turbidity levels was carried out by the author in 2019 after a period of prolonged rainfall. This focused on the turbidity of water flowing through the upper catchment system, into the stream and in the lake .

More extensive monitoring is planned from 2021 as part of the PhD being undertaken by the author.

Turbidity levels in the upper catchment were seen to reduce downstream, with higher levels noted in locations draining from water filled depressions within tracks. The combined flow downstream of the lower settlement pond was very encouraging in terms of the low level of turbidity recorded leaving the upper catchment.

Figure 36. Upper catchment turbidity results in 2019



Water quality monitoring outputs using a multiparameter probe and meter can be seen in Figure 37.

Figure 37. Water quality results in the upper catchment in 2019

Turbidity in the lake is influenced by a wider range of factors including canal overflows, urban runoff, algae, resuspension from wind generated waved and disturbance from waterfowl. Turbidity levels in many locations in the lake were low in comparison to previously recorded levels and of particular interest was seeing these levels being lower than those recorded from the upper catchment. E.g the stream above the lake recorded less than 10 FNU, at the confluence with the lake this was 15 FNU, and within the lake ranged from 15 to 30 FNU. These can be compared to the turbidity of flow draining the upper catchment at 25 to less than 5 FNU.

Although a simple method of assessment, Secchi disc readings have been used to indicate water transparency in the lake. Those recorded in 2019 were far lower than most of the previous results and in all cases the bed of the lake could be seen. This was not the case prior to the commencement of the management and restoration works documented in this paper and is considered to be indicative of both a reduction in fine sediment input to the lake but also an improvement of in-lake water quality. These results can be seen in Figure 38.

Figure 38. Comparison of lake water depths and transparency

November 2011 Average Water Depth (cm)	November 2011 Average Secchi Depth (cm)	September 2014 Average Water Depth (cm)	September 2014 Average Secchi Depth (cm)	February 2015 Average Water Depth (cm)	February 2015 Average Secchi Depth (cm)	November 2019 Average Water Depth (cm)	November 2019 Average Secchi Depth (cm)
52.6	40.9	78.3	38.8	85.4	32.8	67.4	64.7



FUTURE RESEARCH

WWF-UK and RSPB (2020) clearly identify that '*With support for the right kind of activites, investment in nature could protect existing carbon stocks and enhance carbon removals, help address the biodiversity crisis, support climate chnage adaptation and deliver a range of other socio-economic benefits*'. It identifies that '*The role of nature is seen as critical in the delivery of the UK Nationally Determined Contribution (NDC) under the Paris Agreement. Activities to protect, restore, manage and create different priority habitats will store even more in vegetation and in the soil.*'

Alonso *et al* (2012) completed a review of carbon storage by habitat, looking at the evidence of the impacts of management decisions and condition of carbon stores and sources. Estimates of the carbon stock of heathlands indicate an average of 88 t C ha^{-1} in the soil (CS, 2007) and 2 t C ha^{-1} in the vegetation (Ostle *et al*, 2009) equating to 29.8 MT C in England (across 331 k ha) for this broad habitat type. The rate of carbon sequestration varies on the growth rate of the vegetation. The bare ground stage stage may be a net source of carbon, the building and mature stages ae net sinks and there is no significant sequestration in later stages. Alonso I (2012) considered that heathland restoration that relies on soil removal or disturbance will result in more carbon emissions that those associated vegetation chnages only, and that drainage of wet heaths result in the oxidation of the soil organic matter and releases CO2, mainly as dissolved organic carbon (Holden, 2009). This can therefore be compared to the restoration of heathland hydrology which would result in an increased carbon sequestation in both the vegetation (e.g. peat forming mosses) and in soils.

Further investigations within the heathland elements of this catchment are proposed through a PhD being undertaken by the author at the University of Manchester UK. The PhD seeks to confirm whether there are wider benefits from nature based solutions such as natural sediment and flood management methods within UK Mountain, Moorland and Heathland ecosystems, in particular the sequestering of carbon and the increase in ecosystem services through wetland habitat restoration, and how these can best be optimised. Two other UK locations associated with the Mountain and Moorland broad ecosystem types form part of the wider PhD research.

Mountain, Moorland and Heathland (MMH) is one of the eight broad ecosystem types associated with the UK. These ecosystem types are based on the broad habitats given in the UK National Ecosystem Assessment (UK NEA, 2011) and are used by the UK Office of National Statistics for natural capital accounting purposes in the development of ecosystem accounts (Office for National Statistics, 2017).

There are opportunities to introduce new Natural Flood Management and Natural Sediment Management features within the heathland ecosystem in the upper catchment and the lower stream closer to the lake.

This PhD will investigate the geochemical and geomicrobiological aspects of these features over a 6 year period. It is anticipated that these will involve the evaluation of the existing measures and processes that have been in place for up to 15 years, and the development and monitoring of a number of further measures based on natural flood and sediment management techniques to provide opportunities for detailed evaluation.

These works will investigate the sediment fluxes and the role of the management measures associated with the upper catchment, the stream and confluence with the lake, seeking to develop and assess:

· Models of the erosive fluxes (sediment movement) under key climate change scenarios – drying / higher rainfall intensity-duration

· Fractionation of soil – clastics, non-organic matter (NOM) and soil organic matter (SOM) when mobilised

· Gas fluxes from soils in relation to carbon

· Change in microbial soil conditions in relation to carbon

· Assessment of the natural flood and sediment management solutions – do they work both for clastics and NOM at the same time.

· Optimising the alignment of the management solutions towards meaningful wetland habitat restoration.

· What broader ecosystem services are created/restored, when natural flood and sediment management techniques are employed to promote wetland habitat restoration.

The PhD is supported and being facilitated by the Chartered Institution of Water and Environmental Management (CIWEM). CIWEM is the leading royal chartered professional body dedicated to sustainable management of the environment, globally. The support from CIWEM seeks to ensure the real world relevance and value of the PhD outcomes can be maximised to benefit environmental practitioners.

CIWEM Chartered Institution of Water and Environmental Management

It is anticipated that progress will be reported to the AGU in future publications.

DISCLOSURES

Clear and grateful acknoweldgements are given to the project partners for the opportunity to have been involved in this body of work for 15 years, as well as the support to conduct more detailed research through the PhD. These include the UK Ministry of Defence, Hart District Council, Environment Agency, Natural England and Fleet Pond Society.

AUTHOR INFORMATION

Matthew Johns is a first year part-time PhD research student in the Department of Earth and Environmental Sciences, University of Manchester. He has a BSc degree in Geology and Geology and MSc in Aquatic Resource Management. A Chartered Environmentalist, Matthew is also a Director and owner of Johns Associates Ltd, a UK-based multidisciplinary environmental consultancy. Matthew has over 25 years of experience working in this sector. He has considerable experience of a wide range of catchment based projects, including water and sediment management solutions, as well as habitat restoration.

ABSTRACT

A catchment in southern England, UK, included a substantial area of bare ground within the surrounding heathland and woodland. Runoff from this area has, in the past, contributed large volumes of sediment to a large lake; although this input is now significantly reduced as a result of previous and on-going management works that are reported on in this paper. Historic realignment and re-sectioning of the main watercourse, has also resulted in the overdeepening, vertical and lateral erosion of the stream channel resulting in downstream transport of sediment to the lake. In addition to sediment erosion, the associated limited connectivity with the floodplain and focus of sediment transport in the fluvial channel has been a key factor in the shallowing and deterioration in the condition of the lake.

Over the last 15 years a wide range of investigative, monitoring and management work has been undertaken within the catchment by a partnership between UK Government organisations, a local authority and a charity, with continuous involment by the author throughout this period. This work has evaluated the causes and effects associated with this erosion and transportation, tested and defined viable practical solutions (the delivery of natural sediment and flood management solutions and habitat restoration) and delivered a series of sustainable management interventions to reduce erosion, promote sediment deposition and to reconnect the stage zero and larger fluvial pathways to the floodplain – supporting the restoration of the lake.

These works have resulted in the reduction in erosion at source and increased deposition through the catchment system, ultimately contributing to the improvement in condition of the lake and associated wetland habitats.

Works in the headwaters of the catchment focused on defining the existing distribution, status and significance of areas of sediment generation, transport and deposition to the stream and lake, facilitating sustainable sediment management within this area. Works in the lower reaches focused on slowing flow velocities and diverting higher velocity sediment rich flows into new channels to reconnect with the floodplain and promote deposition.

Management measures included the use of small diversion channels through woodland with the creation of glades to increase understory recovery and sediment deposition; use of geotextile cells filled with sand, gravel or stone to increase the flow path, reduce velocity and promote out of channel flooding and deposition of sediment; use of scrub and woody material to form leaky dams and increase channel roughness promoting out of bank flooding and deposition; use of online ponds, backwaters and embayments; blanking off channels to promote overland flow through woodland to reduce flow depth and velocity and promote deposition; use of leaky dams to promote higher flows transporting sediment into new sinuous channels and allowing out of bank flooding to promote sediment deposition.

Monitoring methods included use of continuous flow, electrical conductivity and turbidity monitoring, spot sampling of water temperature, dissolved oxygen electrical conductivity, pH turbidity and depth, suspended sediment analysis, use of erosion/deposition pins, repeat photographs, habitat surveys, repeat walkover surveys during different weather conditions.

In general, the measures implemented have been shown to be successful, slowing contributing runoff and channel flows, reducing erosion, promoting deposition of sediment out of channel (in a range of localised and more extensive situations), with re-vegetation in many circumstances aiding sediment stability and habitat restoration. There is clear deposition of sediment away from the lake, although the potential for further sediment mobillisation, transport and deposition away from the floodplain remains.

Further investigations in this catchment are proposed as part of ongoing catchment management works led by the project partners and also a PhD being undertaken by the author at the University of Manchester UK. This PhD will investigate the geochemical and geomicrobiological aspects of these channel and floodplain management works over a 6 year period commencing in 2020. In particular, the PhD will seek to confirm whether there are wider benefits from natural sediment and flood management methods, in particular the sequestering of carbon from associated wetland habitat restoratio, and the increase in ecosystem services, and how these can best be optimised. It is anticipated that these will be reported on in future submissions to the AGU.

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