AN ENVIRONMENTAL STUDY OF THE NANT-Y-FENDROD STREAM IN SOUTH WALES

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ABSTRACT
The Nant-y-Fendrod stream in South Wales fails to meet the water quality standards set out by the European Union Water Framework Directive (2000/60/EC). The Directive requires that all waterbodies in the United Kingdom reach "Good" Status by 2027. The consequences of failing to meet this standard would be a failure to protect our most vital natural resource and a risk of infraction proceedings being taken against UK Government. The water quality of the Fendrod stream is affected by many sources of pollution, most notably ecotoxic heavy metals, arising from an industrial legacy of metal smelting. This study examines the environmental factors affecting the physical, chemical and biological state of the Fendrod stream and whether it would be possible to remediate it in order to achieve "Good" Status. This research will facilitate an informed assessment of any options for remediation, including potential for phytoremediation using water hyacinth (*Eichhornia crassipes*). A multi-disciplinary approach has been employed, using state of the art water quality sampling, biological sampling, hydrometric surveying and laboratory analytical techniques such as Inductively Coupled Plasma – Mass Spectrometry. Diffuse Gradient in Thin Films and Acoustic Doppler Current Profiling for water quantity and quality measurement have also been applied. Our initial findings show that zinc and cadmium are consistently elevated in excess of environmental quality standards. Further studies are in progress including phytoremediation trials, of which initial results obtained are encouraging. Study outcomes will assist UK Government reporting to the European Union in relation to status, any suggested remediation options, and whether these options may be feasible. This work will inform further research and/or modelling which may be required to implement findings and can possibly be repeated or transferred to other failing water bodies within Europe and possibly beyond within the wider scientific community.
Keywords: Nant-y-Fendrod, water quality, water framework directive, heavy metals, aquatic pollution, good ecological status, biotic ligand model, sustainable management, phytoremediation, diffuse gradient in thin films, Eichhornia crassipes.

1 INTRODUCTION

Research is being conducted upon the Fendrod Stream, or Nant-y-Fendrod, to give it its local name in the Welsh language, that is a tributary of the River Tawe, which in turn drains the Lower Swansea Valley into the Bristol Channel at Swansea Bay in South Wales (see Fig. 1). The water body is situated approximately 5km north east of Swansea City Centre and flows over land that has a variety of both current and historical uses including industrial, agricultural, retail, domestic and recreational use. The stream is 4.2 km in length and has a catchment area of 20 km^2. The stream has been heavily modified for the purposes of flood protection and urbanisation. Swansea Bay is a popular tourist destination due to its expansive sandy beaches, Blue Flag Marina and is known as Wales' Waterfront city.

The Fendrod enters the River Tawe on the eastern bank within Swansea, about 4.5 km from the coast. The two main tributaries, the Nant Bran and the Nant-y-Ffin have contrasting hydro-morphology, with the Fendrod itself rising within the flood plain of the River Tawe at an altitude of only 30 m, whereas the Nant Bran emerges northeast of Birchgrove at around 220 m.

WIT Transactions on Ecology and The Environment, Vol 216, © 2017 WIT Press
www.witpress.com, ISSN 1746-448X (on-line)
doi:10.2495/WS170131

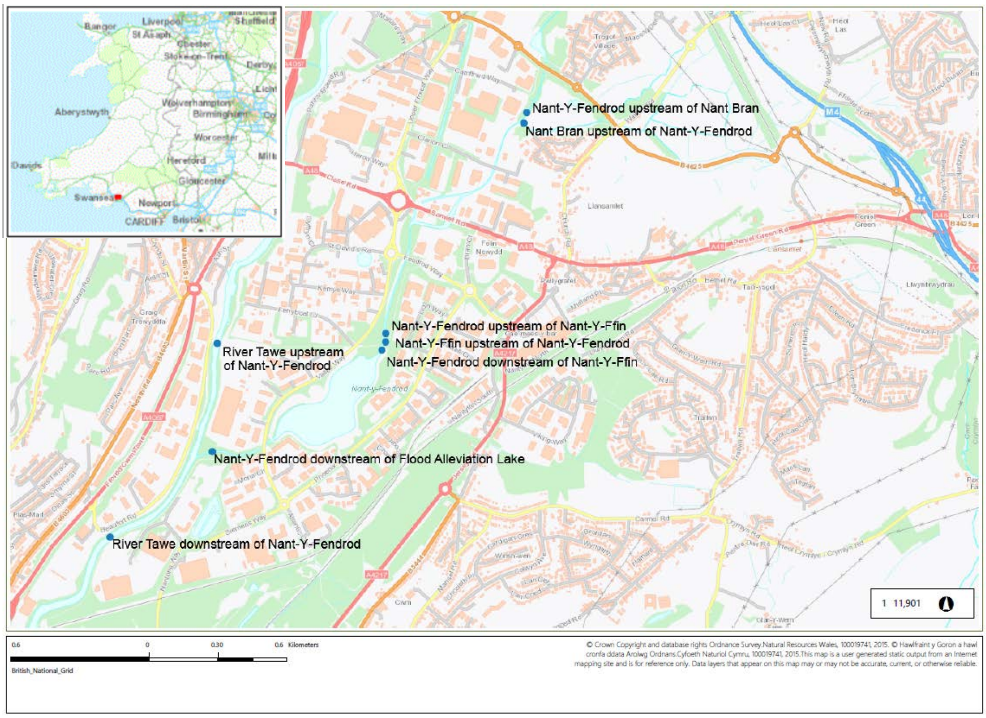


Figure 1: Location map of study area and sample points.

The Fendrod differs markedly in character from the majority of rivers in South Wales due to its low gradient as it flows over the valley floor. It is relatively deep, slow-flowing with a bed consisting mainly of fine gravel, sand, silt and detritus. Its physical character is also affected by the construction of two on-line lakes and various flood defence structures. The area is reputed to be the birth place of the Industrial Revolution and was a focal point of global copper production during the 19th and 20th Centuries [1].

1.1 Industrial impact

The Lower Swansea Valley and Fendrod stream is unique in a global context, given its geographical setting and previous dereliction arising from anthropogenic activity. An estimated 7 million tonnes of copper and zinc smelting waste was abandoned on the valley floor [2]. As land became full of waste, factory owners would acquire more land to dispose of their waste [3]. Lavender [2] explained that some of the older smelting techniques were so inefficient that it would be profitable to re-smelt some of the waste arising from the tips. He also stated that ‘nowhere in Britain, was the problem of dereliction more acute. Over two hundred years of metal smelting activities created a thriving industrial community out of a small village due to a suitable location and a local abundance of coal’. Waste tips led to decimation of vegetation and habitats that this supported. Swansea is also one of the wettest cities in the United Kingdom, so high levels of precipitation would transport toxic leachates into the soils and watercourses.

In 1961 the Lower Swansea Valley Project was commissioned, which ran for four years [4]. Physical studies of the geology, hydrology and biology were conducted, alongside investigation of techniques for re-vegetation. A significant output of the project was the suggestion of culverting the Fendrod for flood protection and redevelopment. However, this was perhaps misguided as culverting of watercourses is no longer condoned within the UK due to exacerbation of flooding. Furthermore, only small sections of the Fendrod were culverted, leaving the remainder of the watercourse in open connectivity with contaminated land. Although this remediation work was conducted, residual contamination remains, which is affecting water quality in the vicinity.

1.2 Water Framework Directive

The standard of 'Good Ecological Status' is one of environmental quality imposed by Directive 2000/60/EC [5]. 'Good Ecological Status' indicates that a water body is generally sustainable and supports healthy plants and wildlife. If a water body fails to reach 'good' status for any of the described tests, then reasons for failure must be investigated and wherever possible, plans should be developed to improve it. Failure to meet the standards imposed by the Water Framework Directive (WFD) may result in UK Government being faced with infraction proceedings by European Parliament, which carries significant financial penalties.

The classification is based upon the physical, chemical and biological status of a waterbody. If one element fails, then that is the overall classification status of that waterbody. Under the WFD, the Fendrod is classified as a Heavily Modified Water Body (HMWB) and multiple parameters for failure are evident, namely fish, macrophytes, phytobenthos, macroinvertebrates, dissolved oxygen, zinc, manganese and cadmium (priority metals due to their ecotoxicity).

The present research examines the environmental factors affecting the physical, chemical and biological water quality of the Fendrod. The aim of the research is to develop an evidence base for a series of recommendations and options for further research, remediation, mitigation and improvements, required in order to achieve 'Good Ecological Status' or 'Good Ecological Potential'. The study also explores the phytoremediation potential of *Eichhornia crassipes* (water hyacinth) for removal of metals from the Nant-y-Fendrod stream. This has not been previously explored for water bodies in the United Kingdom, although it has been shown to be effective in the removal of metals from water [6]

2 MATERIALS AND METHODS

The study area and associated sample sites are illustrated in Fig. 1. Fortnightly water quality samples were obtained from eight sites over a twelve-month period. Measurements have been obtained for multiple parameters that include metal concentrations (both total and dissolved), temperature, pH, biological oxygen demand (BOD), suspended solids, hardness, conductivity and dissolved organic carbon (DOC).

2.1 Sampling for heavy metals

It is preferable to obtain water quality samples directly (without the use of a secondary vessel) in order to minimise the risk of any contamination. However, due to physical restrictions and safety reasons, namely undercut riverbanks and bridges, the use of indirect sampling was employed using a food grade stainless steel bulk container attached to a rope and hand reel. Metal samples were obtained by first taking a bulk sample. Nalgene metals bottles and caps were first rinsed before the bottles were filled. Total metal samples were filled from the bulk sample first, so that suspended solids within the water had not had a chance to settle. Before filtering of the dissolved metals samples, the bulk sample was left for a short period to allow solids to settle.

During the twelve-month water quality sampling period, a total of 696 samples were obtained along with 1160 in-field measurements. Water samples for dissolved metal analysis were filtered in-field by using disposable single-use encapsulated filters. Single use disposable sterile syringes were used to draw off sample to then fill a 125 ml Nalgene bottle via an encapsulated filter. Both the syringes and filters were rinsed prior to obtaining the sample, by passing 10 ml of sample through the filter and syringe. Rinsing filtrate was then safely discarded prior to filling the bottles for analysis. The data has been analysed utilising the UK Technical Advisory Group (UKTAG) River and Lake Assessment Method for Specific Pollutants (Metals) Metal Bioavailability Assessment Tool (M-BAT) [7].

2.2 In-field measurements

Field observations were made concurrent with water sampling. Visual, olfactory and meteorological observations were recorded at each sample site. Water temperature, pH, dissolved oxygen, conductivity and salinity were recorded using a YSI pro hand-held multi-parameter meter that was correctly calibrated prior to each sample run.

2.3 Macroinvertebrate sampling

Macro-invertebrate sampling has been conducted in order to assess the biological health of the stream. This involved a three-minute kick sampling technique using a standard FBA-pattern long handled pond net that has a lower straight edge of 20–25 cm and straight, vertical sides of 19–22 cm and is 50 cm deep. This type of net is less easily blocked due to its greater mesh surface. The pond net was used in varying ways to accommodate the nature of the sampling area. The use of a stopwatch ensured that precisely three minutes was spent actively sampling at each site.

In a riverbed comprising mainly of gravel or cobbles, the samples were collected by disturbing the substratum with one foot and holding the net close in the plume of disturbed sediment to catch the animals that were dislodged. Whilst sampling in clay or soft sediment on the riverbed, care was taken to avoid the net from quickly becoming blocked. Blockages were minimised by skimming the bottom edge of the net gently through the top few centimetres of the substratum in order to agitate it. To obtain the sample, the open net was then passed through the clouded water column immediately above the riverbed. Samples were placed in a cool box at 1–3°C for transportation to the laboratory. Samples were then sorted into various taxa in the laboratory.

2.4 Laboratory analysis

The laboratory analysis of samples collected was conducted at Natural Resources Wales' UKAS accredited laboratory, in accordance with the relevant British Standards and Standing Committee of Analysts Blue Book of methods for the examination of Waters and Associated materials [8]. Upon receipt, the samples were fixed using nitric acid to preserve the dissolved metal concentration. The primary technique used for metals analysis was Inductively Coupled Plasma – Mass Spectrometry (ICP-MS), along with Gas Chromatography Mass Spectrometry (GCMS) and Liquid Chromatography Mass Spectrometry (LCMS).

2.5 Hydrometric data

Hydrometric stage (m) data was collected via a continuously recording pressure transducer located within a stilling pipe and linked to telemetry. Flow data (cumecs) was obtained via monthly spot flow gauging conducted using a Sontek M9 gaugeboard, which uses Acoustic Doppler Current Profiling technology to measure flow across the channel width.

2.6 Phytoremediation using *Eichhornia crassipes*

A pilot study was conducted in the use of water hyacinth for removing metals from contaminated river water taken from the Fendrod. Pairs of adult water hyacinth plants were placed into five sterile 10 litre plastic food grade containers holding different solutions. The plants utilised were mid-way through an annual growth cycle. This was duplicated so that two tests were run concurrently and repeated on three separate occasions over seven hours on three separate days during the summer of 2016. The third run was also sampled after 24 hours, five days, seven days, 14 days and then 21 days giving a total of 290 observations.

Each container held a different solution. Firstly, a synthetic zinc solution prepared in the laboratory from zinc acetate and deionised water, at a concentration of 4000 μg/L. This was equal to the highest recorded concentration in river water prior to the pilot study. Secondly, a synthetic zinc solution made up to 600 μg/L. This was equal to the average concentration recorded. Thirdly, a river sample taken from the Fendrod upstream of the confluence with the River Tawe, which represented the average concentration of zinc contamination observed within the watercourse. Then a river sample taken from the Fendrod immediately downstream of the Nant-y-Ffin, which represented the maximum concentration of zinc contamination observed. Finally, a control sample of mains supply drinking water.

The starting concentrations of each sample were recorded prior to plant introduction, along with measurements of temperature, pH, dissolved oxygen, conductivity and salinity. Plants were weighed, measured, photographed and tagged and then two plants selected at random were placed in each container. Each container was then sampled hourly for seven hours both total and dissolved metals samples were obtained via filtered and unfiltered samples.

3 RESULTS AND DISCUSSION

Presented below are the findings of our study thus far.

3.1 Heavy metals

Table 1 shows maximum, minimum and mean concentrations for zinc, cadmium and manganese in micrograms per litre at each of the eight sample sites under investigation. All three metals are observed in excess of the existing UK Environmental Quality Standards (EQS) over the 12-month sampling period from 09/04/2015 to 06/05/2017.

M-BAT data outputs exhibit exceedances of the Site Specific $EQS_{bioavailable}$, or Predicted no effect dissolved concentration ($PNEC_{dissolved}$). These are summarised in Table 2. There is currently no M-BAT tool in existence for cadmium, though based upon the current UK Maximum Allowable Concentration EQS of 0.9 (MAC-EQS) (μg/L). Of the samples obtained in this study, the Fendrod fails to meet the latter standard at the two worst affected sites in 100%, downstream of the Nant-y-Ffin and 93.1% downstream of the flood alleviation lake. Typical concentrations range from 1.87 µg/L to 14.9 µg/L. Fig. 2 illustrates the observed relationship between recorded daily mean hydrometric stage (m) vs sampled zinc concentrations at the worst polluted site.

Table 1: Maximum, minimum and mean metal concentrations from the eight sample sites.

Site name	**Max/Min/ Mean**	**Zinc (µg/L)**	**Cadmium (µg/L)**	**Manganese (µg/L)**
Nant-y-Fendrod d/s of flood alleviation lake	Maximum	2400	4.28	563
	Minimum	150	0.19	142
	Mean	***870.14**	**1.25**	**314.57**
Nant-y-Fendrod u/s of Nant-y-Ffin	Maximum	4320	12.9	9.5
	Minimum	183	0.19	2.42
	Mean	**2039.28**	**1.25**	5.67
Nant-y-Ffin u/s of Nant-y-Fendrod	Maximum	2600	17.9	21.8
	Minimum	150	0.44	2.18
	Mean	**870.14**	**5.2**	5.84
Nant-y-Fendrod d/s of Nant-y-Ffin	Maximum	4320	14.4	9.87
	Minimum	327	1.43	3.13
	Mean	**2399.41**	**7.65**	6.23
River Tawe d/s of Nant-y-Fendrod	Maximum	1080	9.18	6.04
	Minimum	11.9	0.111	1.02
	Mean	**78.34**	**0.93**	1.87
River Tawe u/s of Nant-y-Fendrod	Maximum	45.3	0.14	2.82
	Minimum	5.29	0.11	1.07
	Mean	11.23	0.12	1.66
Nant Bran u/s of Nant-y-Fendrod	Maximum	27.4	6.41	5.65
	Minimum	6.54	16.1	9.22
	Mean	15.4	0.1	1.1
Nant-y-Fendrod u/s of Nant Bran	Maximum	29.2	6.68	10.7
	Minimum	5.46	0.12	1.05
	Mean	13.99	0.82	4.03

*Figures in bold are in excess of the relevant Environmental Quality Standard.

Table 2: Showing M-BAT exceedances for zinc, copper, manganese and nickel at different sites.

Number of Metal-Bioavailability Assessment Tool (M-BAT) exceedances (out of 29)				
Site Name	**Copper**	**Zinc**	**Manganese**	**Nickel**
Nant-y-Fendrod d/s of Flood Alleviation Scheme	1	29	6	2
Nant-y-Fendrod u/s of Nant-y-Ffin	1	29	4	0
Nant-y-Fffin u/s of Nant-y-Fendrod	5	29	0	2
Nant-y-Fendrod d/s of Nant-y-Ffin	1	29	2	0
River Tawe d/s of Nant-y-Fendrod	0	22	0	21
River Tawe u/s of Nant-y-Fendrod	0	5	0	22
Nant Bran u/s of Nant-y-Fendrod	1	8	0	0
Nant-y-Fendrod u/s of Nant Bran	0	5	1	0

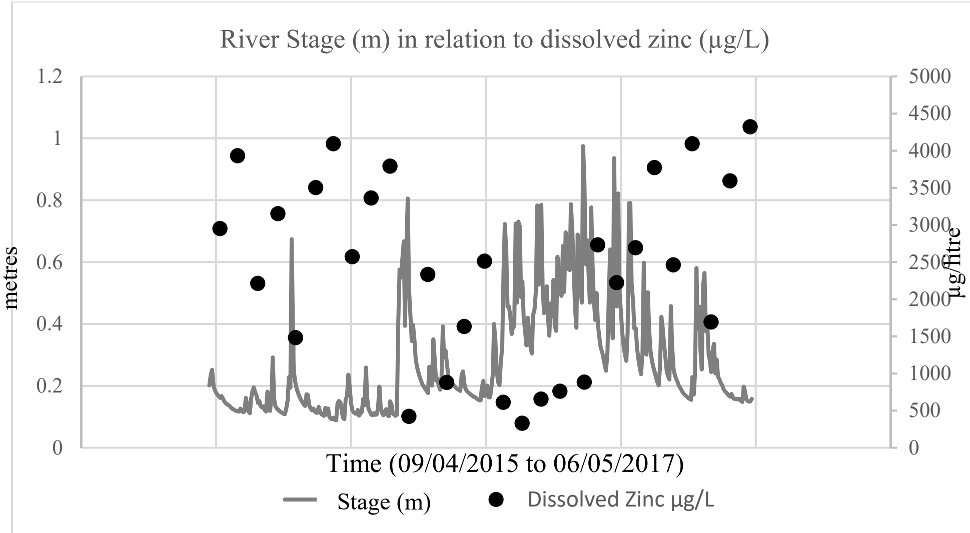


Figure 2: Relationship between river level (distance in metres) vs zinc concentration (in micrograms per litre).

Massie and Vivian [9] first noted metal contamination in the River Tawe arising from waters draining the contaminated land of the Lower Swansea Valley. According to Bird [10] the River Tawe is one of the worst polluted in Wales with regard to trace metals. As illustrated by the above tables and figures, heavy metals have been observed to be in excess of the currently imposed Environmental Quality standards. Aside from background concentrations arising from the local geology and industrial discharges, the Fendrod is a primary source of excessive concentrations. This is evidenced by the upstream and downstream samples collected as part of this investigation and is illustrated in Tables 1 and 2. The nickel failure evident in the Tawe is likely to be from two upstream nickel refineries, as the levels in the Fendrod do not appear to be persistently elevated.

3.2 M-BAT tool assessment

The M-BAT tool [7] provides a mechanism for assessing the bioavailable concentration of toxic metals present in relation to the background water quality for a specific water body. The tool takes into account the formation of metal complexes based on water chemistry and competitive binding at the gill of biota. Parameters entered into the model were Dissolved Organic Carbon, pH and Calcium (to determine hardness), and then the dissolved concentrations for each of the metals under investigation.

Table 1 demonstrates the occurrence of mean concentrations of zinc, cadmium and manganese in excess of the relevant Water Framework Directive standards. The M-BAT tool has not been developed for cadmium, though for copper, zinc, manganese and nickel, Table 2 shows the number of times that the levels present are in excess of the appropriate background level for the Fendrod, taking into account the Biotic Ligand Model as explained in Di Torro et al. [11].

Investigations by Bird [10] suggest that cadmium, zinc and manganese contamination is clearly linked with river flow, antecedent meteorological conditions and pH. Thornton et al. [12] and Bird [10] have used flow data from the main river Tawe, which hydrologically is completely different to the flows in the Fendrod itself. This study has collected flow and level data from the Fendrod and Fig. 2 illustrates the relationship between concentrations and measured river level within the Fendrod. With higher river levels, the concentrations present are lower due to dilution, then the opposite is true in lower flows, with much higher metal concentrations evident.

3.3 Macroinvertebrate studies

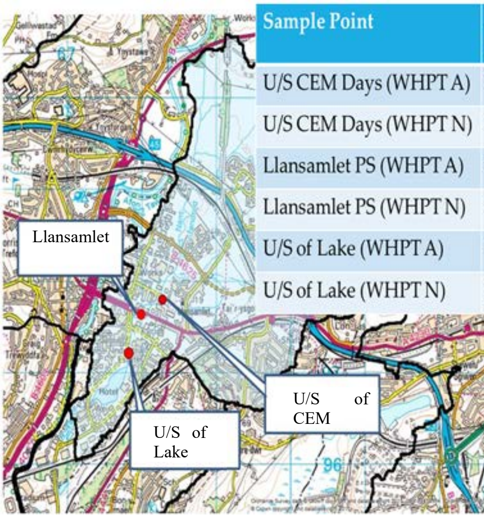
Fig. 3 shows the biological status of the Fendrod in relation to macroinvertebrates surveyed by the regulating authorities between 1993 and 2013. The results have been calculated in accordance with the Whalley, Hawkes, Paisley and Trigg (WHPT) River Invertebrate Classification Tool (RICT) [13]. The RICT provides an overall Environmental Quality Ratio (EQR) for a waterbody. The tool comprises two metrics, the first being the average score per Taxon (WHPT A). The second metric utilises the number of taxa contributing to the assessment (WHPT N).

The tool utilises predictive variables that include both variant and invariant data. Variant data parameters are alkalinity, mean river width, mean river depth, percentage bed cover of boulders/cobbles, percentage bed cover of pebbles/gravel, percentage bed cover of sand and percentage cover of silt/clay. Invariant data parameters are National Grid Reference (location coordinates), degree of slope, river discharge category, distance from the source of the river and river altitude.

The WHPT RICT classification of the Fendrod is currently moderate overall, which in accordance with the WFD is derived from the lowest class present within a waterbody. However, this research has highlighted that the tool used may not be wholly appropriate for use in this case, as the waterbody has been heavily modified, i.e. straightened and culverted within artificial channels, so results must be treated with caution. Regulatory sample point selection does not currently take into account the worst affected reaches that are evidenced by the water quality data. This is being addressed via further monitoring as part of this research.

3.4 Phytoremediation trial using *Eichhornia crassipes*

Work by Rezania et al. [14], Parma and Sing [15] and Buta et al. [16] amongst others, has reported the potential of water hyacinth in the removal of pollutants from an aqueous solution. Das et al. [17] have investigated the physiological response of water hyacinth to cadmium and its phytoremediation potential whilst Gupta and Balomajumder [18] have reported its use in chromium removal. Singh et al. [19] have utilised a rotary drum composter to remove Zn, Cu, Mn, Fe, Ni, Pb, Cd and Cr. Al-Rmalli et al. [6] have demonstrated the potential of using dry water hyacinth biomass for removal of arsenic from water. The current study tested the efficiency of living water hyacinth plant for removal of zinc from actual Fendrod water in the UK climate, with the very encouraging results ranging from 20 to 33% removal after just seven hours within river samples and almost 100% removal after 21 days. These results are illustrated in Table 3.



Sample Point	Average Environmental Quality Ratio (EQR)	Water Framework Directive (WFD) Status
U/S CEM Days (WHPT A)	0.883	Good
U/S CEM Days (WHPT N)	1.006	High
Llansamlet PS (WHPT A)	0.899	Good
Llansamlet PS (WHPT N)	0.716	Good
U/S of Lake (WHPT A)	0.785	Moderate
U/S of Lake (WHPT N)	0.650	Moderate

Biological classification derived from kick sampling of macroinvertebrates. Current overall classification is “Moderate” according to the WATER FRAMEWORK DIRECTIVE UK Technical Advice Group’s River Assessment Method for Benthic Invertebrate fauna, “Invertebrates (General Degradation): Whalley, Hawkes, Paisley and Trigg (WHPT) metric in River Invertebrate Classification Tool (RICT)” (2009)

Figure 3: Biology average environmental quality ratios for macroinvertebrates.

The data in Table 3 shows the percentage of zinc removal from each of the samples under observation. Percentages are shown for both total and dissolved zinc removal for observations conducted on three separate occasions. The first two sets of results, on the 16th and 23rd of August, show removal after seven hours of plant exposure to samples. The third set of results from the 24th of August to the 13th of September show the amount of removal after a period of 21 days. The Nant-y-Fendrod downstream of the Flood Alleviation Scheme was chosen as a site that represents average concentrations of zinc within the watercourse as a whole, whilst the Nant-y-Fendrod downstream of the Nant-y-Ffin is representative of the maximum concentrations observed during water quality sampling. Two synthetic solutions were made up using de-ionised water and zinc acetate to approximate the two in-river concentrations. The synthetic samples were used to measure zinc uptake in the absence of competition with other nutrients that are present in river water.

The differences in zinc uptake appear to be influenced by many factors including temperature, amount of UV radiation, initial concentration, and competition with other nutrients. The percentage zinc removal is comparable in both the river samples and the synthetic solutions. However, zinc removal appears to be less effective in the samples containing the highest concentrations i.e. synthetic zinc solution A and Nant-y-Fendrod downstream of the Nant-y-Ffin, possibly due to its initial toxicity to the plants.

During the third trial, which was extended to 21 days, the percentage of zinc removal within the samples with average concentrations is almost 99% (for Nant-y-Fendrod downstream of Flood Alleviation Scheme and synthetic solution B). Even in the samples containing the highest concentration of zinc (synthetic solution A and Nant-y-Fendrod downstream of Nant-y-Ffin), the percentage removal is up to 68.47% and 86.68% respectively. The phytoremediation study has also shown the plants to be effective in removing other metals such as cadmium, nickel, manganese, copper and lead (data not shown). To the best of our knowledge, this is the first study to use living water hyacinth plant

Table 3: Percentage removal rates of zinc from water using *Eichhornia crassipes.*

Percentage zinc removal using *Eichhornia crassipes*						
Site name	**16/08/2016**		**23/08/2016**		**24/08/2016 to 13/09/16**	
	T	**D**	**T**	**D**	**T**	**D**
Nant-y-Fendrod d/s of Flood Alleviation Scheme	29.68	29.01	33.20	24.28	99.00	98.62
Duplicate of Nant-y-Fendrod d/s of Flood Alleviation Scheme	21.42	20.55	34.92	27.08	95.10	98.72
Nant-y-Fendrod d/s of Nant-y-Ffin	10.23	15.84	17.27	6.16	81.31	84.46
Duplicate Nant-y-Fendrod d/s of Nant-y-Ffin	9.61	16.65	18.22	12.46	84.88	86.68
Synthetic zinc Solution A (4070 µg/L)	34.21	34.88	27.83	37.26	64.66	68.47
Duplicate Synthetic zinc Solution A	9.09	32.12	38.35	27.40	65.14	66.40
Synthetic zinc Solution B (596 µg/L)	58.54	58.15	54.21	53.98	91.22	93.05
Duplicate Synthetic zinc Solution B	56.61	57.88	50.84	62.16	95.40	96.20
Control sample (drinking water)	0	0	0	0	0	0
Duplicate of Control (drinking water)	0	0	0	0	3.94	≈100

Legend: T = Total metal, D = Dissolved metal.
16/08/2016 (7 hours exposure); 23/08/2016 (7 hours exposure); 24/08/2016 to 13/09/2016 (21 days continuous exposure).

for phytoremediation of UK river water. The fact that water hyacinth is regarded as a weed in many parts of the world due to its prolific growth rates and is reported to have sufficient calorific value to be used as a biofuel, this presents a potentially sustainable remediation method for dealing with water pollution and will be investigated further.

4 CONCLUSION

Given the industrial legacy of the investigation area, it is not surprising that some metal concentrations are contributing to failure of the standards imposed by the WFD. Levels of contamination remain high more than 50 years after attempts were made to remediate the problem. Clearly, further work needs to be done to secure the sustainable management of this environmental problem, as natural attenuation could take millennia. Further statistical analysis will be conducted to assess the significance of the various spatial, temporal and seasonal distributions that exist between the many variables within this dynamic system. The findings of the water hyacinth trial are encouraging as a potential remediation option. An in-river phytoremediation and larger scale bankside trial have also been conducted. The findings of the further analysis and trials will be reported in subsequent research papers and may eventually provide a solution to this particular environmental problem.

ACKNOWLEDGEMENTS

The authors would like to thank Natural Resources Wales for their continuing support in this work, particularly the analytical staff at their National Laboratory Service. The authors would also like to thank De Montfort University for supporting the research.

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