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THE IMPACTS OF NATURAL FLOOD MANAGEMENT APPROACHES ON IN-CHANNEL SEDIMENT QUALITY

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ABSTRACT

Natural Flood Management (NFM) techniques aim to reduce downstream flooding by storing and slowing the flow of stormwater to river channels. These techniques include a range of measures, including setback stormwater outfalls and the physical restoration of channels and floodplains, to improve the natural functioning of catchments. An additional benefit of NFM measures is the potential reduction in sediment and pollutant delivery to the channel. Urban development releases a variety of heavy metal and nutrient pollutants that enter rivers through stormwater outfalls with adverse effects on the aquatic ecosystem. In this study, the influence of channel modification and quality of the river habitat on the sediment quality surrounding stormwater outfalls was assessed. Sediment samples were taken at several outfalls within the Johnson Creek catchment, Oregon, USA, and analysed for a variety of urban pollutants. The level of river habitat quality and modification at each site were assessed using a semi-quantitative scoring methodology. Significant increases in pollutant levels were observed at outfalls, with a greater and more variable increase at direct compared to setback outfalls. Removal efficiency of certain pollutants was found to be significantly correlated to the level of habitat quality or modification (for Fe, Ba, Sn, Mg, P, K) indicating that more natural reaches had greater potential for pollutant removal. The findings highlight the multiple benefits associated with NFM and river restoration approaches in relation to sediment quality and pollutant content. © 2016 The Authors River Research and Applications Published by John Wiley & Sons, Ltd.

KEY WORDS: restoration; outfall; setback outfall; sediment; River Habitat Survey; pollutant; Natural Flood Management

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INTRODUCTION

Natural Flood Management (NFM) is becoming increasingly popular as a means of complementing existing traditional flood management schemes. NFM has the potential to reduce long-term costs in relation to river infrastructure and the adaptive capacity of NFM techniques to negate impacts of climate change. Governmental policies and guidelines, such as the EU Floods Directive (2007), the USA's Interagency Floodplain management review/Galloway Report (1994), and the UK Flood and Water Management Act (2010), recognize the linkages between catchment-scale land use and flood risk. These guidelines encourage restoration of natural hydrological and geomorphological processes and highlight the potential flood risk and water quality benefits of restored riparian areas and wetlands.

NFM aims to work with catchment-scale processes to delay and attenuate flood peaks by altering floodwater pathways through the catchment. This can be achieved in several ways including increasing storage within the catchment, increasing infiltration (and hence reduction of runoff), reducing runoff velocities, and disconnecting and lengthening flow pathways. It includes a broad collection of measures and activities that reduce flood risk (Parliamentary Offices, 2011; Thorne, 2014) from changes in land-use through to the construction of features that intercept and manage overland flow, for example wetlands and swales (Hey and Philippi, 1995; Stagge *et al.*, 2012; Acreman and Holden, 2013; Lucke *et al.*, 2014). Additionally, these natural approaches to flood risk management are believed to deliver further ecosystems services, for example provision of natural habitats (e.g. increased habitat heterogeneity through hydraulic diversity; Gilvear *et al.*, 2013), regulation of water quality (e.g. removal of sediment and pollutants from runoff by riparian zone vegetation; Lowrance *et al.*, 2002; Lee *et al.*, 2003; Yang *et al.*, 2015), support for biodiversity (e.g. vegetated riparian zones provide a range of habitats and promote biodiversity within the system; Naiman *et al.*, 1993; Rossi *et al.*, 2010), culture, recreation, and aesthetic value (e.g. reintroducing meandering in channelized reaches; Nakano and Nakamura, 2006; Lorenz *et al.*,

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2009). These claims of multiple benefits are commonly used to provide additional support to NFM schemes, but have not been as widely studied in the scientific literature as their impacts on the flood hydrograph.

Elevated levels of sediment, occurring through urbanization and the associated sediment laden stormwater runoff, impact several aspects of river quality including physical (e.g. increased flood risk and turbidity), ecological (e.g. changes to habitat structure and dynamics; Theurer, 1998; Soulsby *et al*., 2001; Owens and Batalla, 2005), and water chemistry (e.g. fine sediment acts as a transport vector for pollutants; Characklis and Wiesner, 1997). Heavy metal pollutants have been found to preferentially adsorb to sediment <250 μm, with a notable preferential adsorption to material approximately 63 μm (Hubbard, 2012; Selbig *et al*., 2013). A variety of sediment and associated pollutants are transported from urban areas in runoff events and reach rivers through stormwater outfalls. Heavy metals such as lead (Pb), manganese (Mn), nickel (Ni), copper (Cu), and zinc (Zn) commonly occur in urban runoff in urban areas because of their abundance in vehicle engines, tyres, oil, industrial land uses, etc. Several studies have highlighted elevated levels of sediment-associated contaminants such as chromium (Cr), Cu, Pb, Zn, and phosphorus (P) in urbanized catchments (Walker *et al*., 1999; Owens *et al*., 2001; Walling *et al*., 2003). Elevated levels of these pollutants can be toxic to aquatic organisms, and therefore discharges to rivers must be controlled. Whilst point sources of pollution can be managed by direct treatment of water (e.g. industrial treatment and septic systems), non-point (i.e. diffuse) sources are more complex to control. Catchment-based approaches to diffuse pollution control enable the consideration of numerous sources and transport pathways. When combined with mitigation measures such as Sustainable urban Drainage Systems (SuDS), catchment-based approaches provide a means of reducing both the magnitude of urban runoff and associated contaminant levels.

Setback outfalls and swales and wetlands are often used as part of SuDS and NFM restoration approaches. Unlike direct outfalls that discharge directly into the main channel, setback outfalls discharge into a wetland or swale prior to reaching the main channel (Figure 1). The increased resistance and hydraulic roughness in these features cause flow velocities to decrease, resulting in the deposition of sediment and associated pollutants (Hey and Philippi, 1995; Jordan *et al*., 2003; Acreman and Holden, 2013). This deposition in the setback outfall, swale, or filter strip is a form of water treatment, which reduces the delivery of pollutants to the channel. Sediment deposition accrues over time, and maintenance (sediment removal) may be necessary to prevent excessive localized contamination and material build-up (Woods Ballard *et al*., 2015). However, as an informal measure, setback outfalls are not generally managed or maintained while formal measures (such as swales) may be included in Local Authority maintenance schemes. The

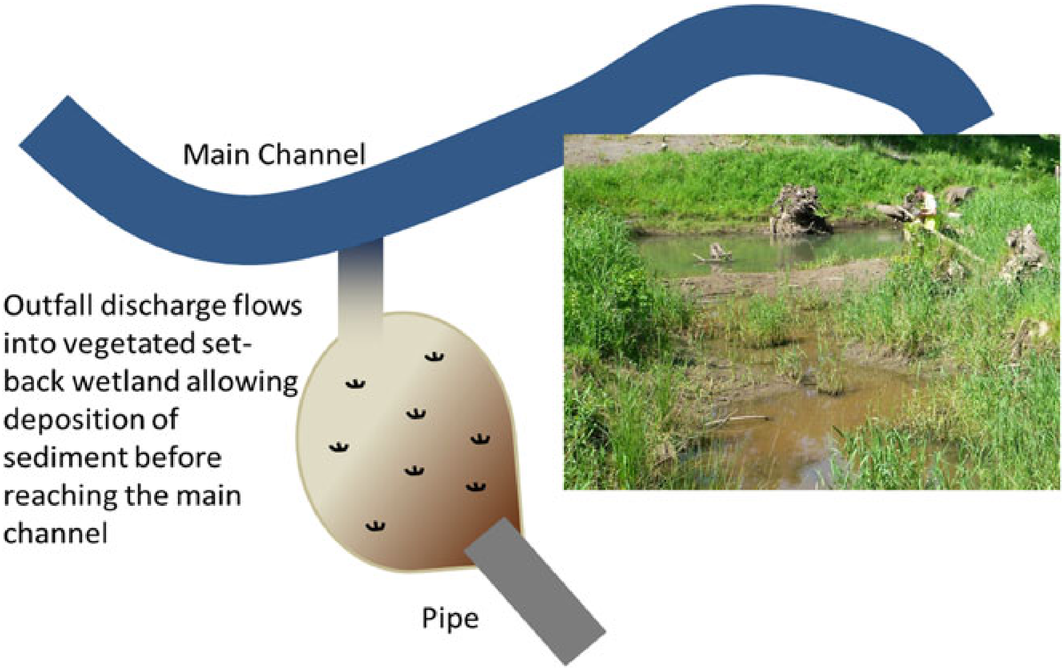

Figure 1. Setback outfall design. Photo insert shows an example of a setback outfall and associated wetland in Portland, Oregon, USA. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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potential for both formal and informal stormwater quality treatment and pollutant removal has been considered or quantified in few studies to date.

River restoration, when linked to floodplain restoration as part of NFM measures, has also been identified as a means of reducing pollutant levels within watercourses channels, in addition to other benefits such as habitat creation. Both in-stream and riparian features can serve to reduce the delivery of pollutants to the channel or induce deposition and storage of them once they are in the river system. For example, the restoration of riparian vegetation creates buffer strips that reduce runoff velocities and causes the deposition of sediment and associated pollutants prior to reaching the channel (Duchemin and Hogue, 2009; Rossi *et al*., 2010). Runoff attenuation features such as large woody debris and storage ponds to intercept flow, reducing peak discharges downstream (Nicholson *et al*., 2012) have been observed to reduce sediment and pollutant delivery in an agricultural setting (Fiener *et al*., 2005; Barber and Quinn, 2012). The presence/introduction of large woody debris within channels has been shown to promote sediment deposition and storage of a significant volume of sediment within channels (Andreoli *et al*., 2007) and provide a more stable channel profile (Faustini and Jones, 2003). River restoration measures that promote sediment deposition, particularly in area outside of the active channel (e.g. riparian or slack water areas), serve a similar function as setback outfalls, swales, and wetland, and therefore should also be removing sediment-bound pollutants from the water column.

This study aims to assess the impacts of setback outfalls and channel restoration approaches (especially related to re-meandering of channelized reaches, floodplain reconnection, addition of riparian vegetation, and in-channel large woody debris), as part of natural flood risk management, on the levels of sediment contamination at and downstream of stormwater outfalls. The level of modification from the river's natural state and the resulting influence on the sediment quality is quantified in an urbanized catchment that has been subject to extensive NFM and river restoration efforts using field surveys.

METHODS

Study area

Johnson Creek is a 40 km tributary of the Willamette River within Portland metropolitan area, Oregon, USA (Figure 2). The catchment is largely made up of silt loams, with low infiltration and rapid runoff. The catchment of the river (140 km^2) is largely urban, but contains significant agricultural land use in its headwaters, and includes the cities of Gresham, Milwaukie, and portions of Portland. The population of approximately 180 000 people (Johnson Creek Watershed Council, 2012) results in high anthropogenic pressures on the catchment and significant alteration of the catchment hydrology. Clement (1984) noted that the peak flow for a storm of given size in 1980 was 30% greater than in 1940 because of impervious surfaces within the catchment and changes to runoff. The area is prone to frequent flood events because of the large extent of impervious urban surfaces and strong seasonality in rainfall; 75% falls between November and March. High magnitude rainfall events during winter months may also be exacerbated by snowmelt. Additionally, low baseflow during late spring and early summer has been noted as an issue, with some tributaries drying up during summer months, posing a threat to fish and wildlife. As a result, since 2006 several NFM restoration strategies have been implemented along the course of the river by the Bureau of Environmental Services of the City of Portland, in

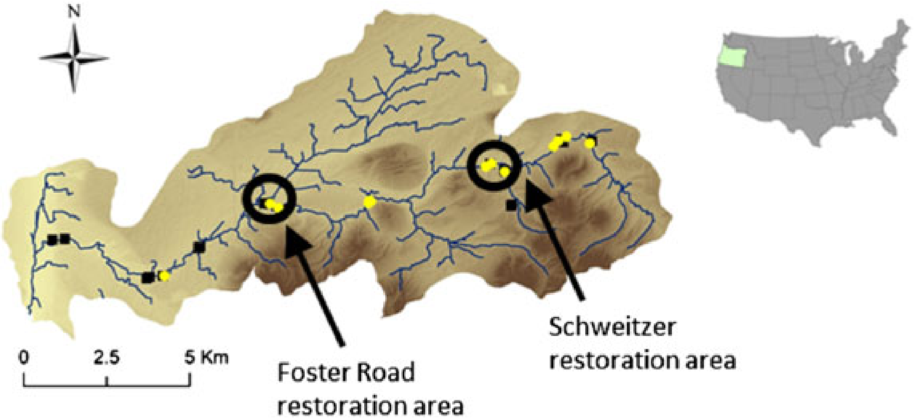

Figure 2. Johnson Creek, Portland, Oregon USA. Direct outfall sample points shown in back, and setback outfalls shown in yellow. Foster Road and Schweitzer restoration projects are located within highlighted areas. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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conjunction with the Johnson Creek Watershed Council. These include the implementation of bio-retention systems, drainage swales, improvement to the riparian corridor, wetland construction, and re-connection of the channel with its original floodplain. The primary objective of restoration measures is to increase flood storage and slow the flow of flood waters to attenuate flood peaks (partly by improved infiltration and enabling groundwater recharge); secondary objectives include improvement of the physical habitat, water quality and temperature, and biological communities.

Specific examples of restoration projects within Johnson Creek shown in Figure 2 include:

- Foster Road—Completed in 2012, a 0.25-km^2 site was restored involving reconnection of the channel to a 170 000 m^3 floodplain. Additional measures included stream bank restoration, storm water treatment (setback outfalls), addition of woody debris, re-vegetation, and removal of bridges and three roads. The primary aim was to reduce flooding on Foster Road, and additional benefits included habitat and biodiversity enhancement.
- Schweitzer project—Completed in 2009, a 0.14-km^2 site was restored. The modified rock-lined trapezoidal channel was removed, and new meandering channel was connected with a 91 000 m^3 floodplain. Additionally, the project included re-vegetation and addition of woody debris within the channel.

Field surveys

The River Habitat Survey is a standardized assessment method that records the physical structure and habitats of river reaches. The approach is used in the UK for river assessment and monitoring, where the results are summarized into two main indices: habitat quality assessment (HQA) and habitat modification score (HMS). HQA is a measure of the diversity and 'naturalness' of the physical habitat structure and is determined by the presence of habitat characteristics that are indicators at a site. The score incorporates physical attributes (bank material and structure, channel substrate, flow type), land use and vegetation structure on bank tops and surrounding the channel, and channel features (such as pools and riffles, channel bars waterfalls etc.). HMS indicates the level of artificial modification at a site, and scores are based on the relative impact of features indicative of human intervention at a site (Table I). Features included within the score include channel and bank reinforcement, embankments, and structures such as weirs, bridges, and dams. Details of how scores are calculated can be found in Raven *et al*. (1998). The point scoring system, whilst semi-qualitative, provides consistency for comparisons across reaches within similar river types, and is based on a consensus of informed professional judgment (Raven *et al*., 1998). Standard river habitat survey methods specify a reach length of 500 m with 10 spot checks equally spaced along the reach length, and one sweep up survey per reach.

Table I. Physical river channel classification based on habitat modification score

HMS score	Descriptive category of channel
0	Pristine
0–2	Semi-natural
3–8	Predominantly unmodified
9–20	Obviously modified
21–44	Significantly modified
45+	Severely modified

The RHS method was applied to 15 reaches in the Johnson Creek catchment. HMS, HQA, and a new 'un-natural' score were calculated from the RHS data for each reach. The un-natural score incorporates features from both the HQA and HMS scores and additional data on land use (not included within HQA). Higher scores indicate a high degree of modification within the reach, whereas low scores indicate unmodified reaches (scores can be negative). Further details on how scores are derived are provided in Appendix A. The basic RHS methodology was adapted to take account of the specific environmental conditions and to ensure that the data collected at the 'spot-checks' were directly linked to the data collected at the urban stormwater outfalls, and both up- and downstream of these outfalls. Because of the natural variation of reaches, not all assessments were carried out over the full 500 m. Furthermore, field assessment and scoring of the riparian areas were extended to include checks at 2 m and 10 m from bank top. This ensured that the link between the river and the immediate surrounding land used was adequately taken into account. This adapted approach allowed for a more detailed assessment of HQA and HMS scores which related directly to the sediment quality assessment. For reaches where the number of spot checks deviated from the standard 10, scores were divided by the number of spot checks taken and then multiplied by 10 to provide an internally comparable and consistent dataset.

Bed sediment samples were taken during May 2014 at 34 stormwater outfalls within Johnson Creek, 19 direct and 15 setback (Figure 2). Samples were taken upstream (U), at the junction of the outfall and the main channel (J), and downstream of the outfall (D). For setback outfalls, an additional sample was taken at the outfall pipe (S) (Figure 3). Sites and outfalls were selected with the aim of representing various local habitats, including both restored and un-restored areas. Single sediment core samples were taken from each sampling location, collected using a PVC disturbance collection mechanism to ensure that samples were not contaminated because of the sampling equipment. Samples were collected

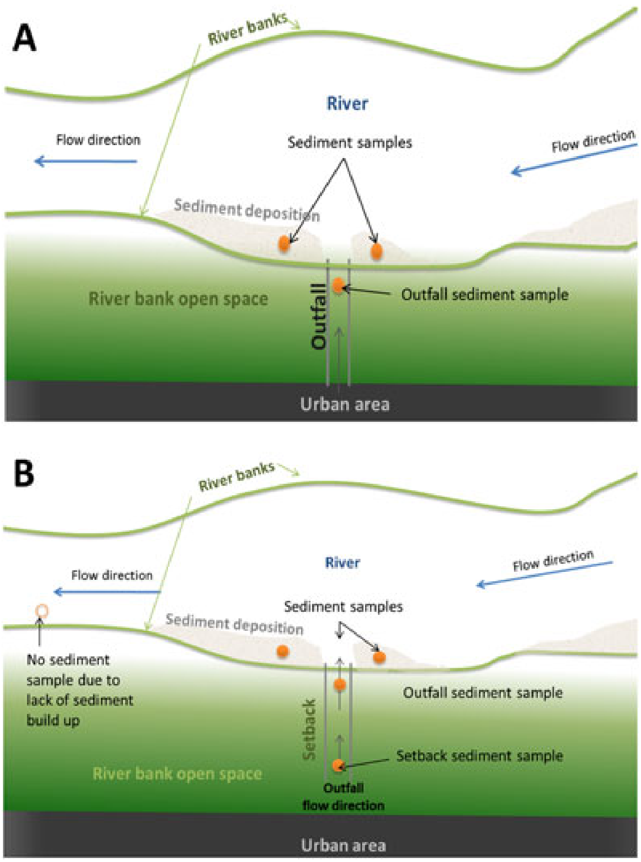

Figure 3. Schematic of sediment sampling strategy at outfalls. A – Direct outfalls, B – Setback outfalls. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

to the depth of deposited material or, where deposits were thick, to a maximum depth of 100-mm. Samples were then oven dried at 105 °C for 24 h and sieved to 2 mm, and analysed for 15 elements; Pb, Zn, Fe, Mn, Cu, Ni, Cr, Ca, Mg, Sn, Ba, Na, P, K, and Ca (Table II). Sample preparation for chemical analysis was undertaken by acid digestion and filtration following BS ISO 13547-2:2014 guidance and preparation methodology used by Hseu (2004). ICP OES calibration was undertaken using known prepared calibration fluids by the Scottish Universities Environment Research Centre (SUERC). Calibration was undertaken prior to all batch sampling (sampling was undertaken in a single batch). Uncertainty in laboratory analyses due to instrumentation error are approximately; Pb: 0.112 ppm, Zn: 0.881 ppm, Fe: 1.29 ppm, Mn: 0.345 ppm, Cu: 0.844 ppm, Ni: 0.84 ppm, Cr: 0.437 ppm, Ca: 7.69 ppm, Mg: 6.92 ppm, Sn: 0.916 ppm, Ba: 3.35 ppm, Na: 19.1 ppm, P: 0.495 ppm, K: 3.19 ppm, and Ca: 7.69 ppm. As several of these pollutants have both natural and anthropogenic sources, pollutants were grouped into three categories according to the likelihood of their origin being anthropogenic urban sources (Table II): common urban pollutants, urban pollutants, and T2 urban pollutants with natural sources.

Heavy metals adsorb preferentially to the fine-grained fraction of the sediment (<63 µm), and significant correlations (using non-parametric analysis) were observed between percentage of sediment <63 µm and pollutant content (for various pollutants). Therefore granulometric correction was performed by calculation of a dilution factor for each sample (similarly to Horowitz, 1991 and Gibbs *et al*., 2014):

$$\text{Dilution factor}: \; 100/(\text{Percentage of sediment} < 63\ \mu\text{m})$$

The pollutant content from the full sample is then multiplied by the dilution factor to provide a normalized estimate.

Table II. Sources of pollutants analysed

	Pollutant	Urban sources
Urban pollutants	Pb	Motor oil/grease, batteries, corrosion, landfill leaching, paint and pigments
	Zn	Fuel combustion, motor oil/grease, batteries, corrosion, antifreeze/de-icing, landfill leaching, paint and pigments
	Fe	Motor oil/grease, fuel combustion, antifreeze/de-icing
	Cu	Fuel combustion, corrosion, landfill leaching
	Cd	Fuel combustion, batteries, corrosion, landfill leaching, pigments
	Ni	Corrosion, motor oil/grease, batteries
	Mn	Vehicle wear, tyres, corrosion
	Ba	Tyres
	Sn	Paint and pigments, vehicle corrosion
	Cr	Fuel combustion, vehicle corrosion
	Mg	Vehicle corrosion
Urban pollutants with potentially significant natural sources	P	Failing septic systems, cleaning products, urban fertilizers
	K	Failing septic systems
	Na	De-icing
	Ca	De-icing

Sources: Gaillardet *et al*. (2005), Pitt *et al*. (2005), and Shaver *et al*. (2007).

The organic content of the sediment samples was analysed using a standard loss on ignition analysis. Similarly to the size fraction analysis, the influence of the organic content on pollutant content of samples was assessed using non-parametric correlation analysis. No significant correlation was observed indicating that correction of pollutant content based on organic content of the samples was not necessary.

The impacts of setback outfalls and river restoration on sediment contamination were tested separately. First, analysis was conducted on both raw and granulometrically corrected data to assess for statistically significant differences in pollutant content between sampling locations with respect to outfalls. As data were not normally distributed, non-parametric Kruskal–Wallis tests were used to highlight statistically significant differences between sample locations at direct and setback outfalls separately (i.e. three independent groups for direct outfalls, and four for setback outfalls). Mann–Whitney U tests then indicated which specific sample locations were statistically different. Pollutant content change relative to upstream conditions was compared within setbacks and at the junction with the main channel to assess the impact of setbacks. Second, the effect of river restoration on the removal of pollutants from the water column, that is deposition of sediment-bound contaminants and other processes, was assessed using non-parametric correlation analysis (Kendall's tau) with HQA, HMS, and un-natural scores providing three separate indicators of restoration/artificiality. Pollutant removal was represented as a removal efficiency (RE, mg kg^{-1} m^{-1}), calculated for each pollutant. The ability of the reach to remove pollutants was estimated at each outfall site for each pollutant. Removal efficiency (RE mg kg^{-1} m^{-1}) was determined as:

$$RE_i = \frac{C_{i\,J} - C_{i\,D}}{D},$$

where C_i is the content (mg kg^{-1} of sediment) of a given pollutant in the bed sediment at the junction (J) with or downstream (D) of the outfall and D_i is the distance between outfall and downstream samples (m) for each reach, i. Finally, removal efficiency of reaches was calculated according to the level of modification of the reach (HMS classes, Table I), and four example reaches which span the range of HMS observed in the area illustrate the findings.

RESULTS

Differences between sample locations

Results from the three-way Kruskal–Wallis indicate that at direct outfalls statistically significant differences in pollutant content between sampling locations were observed in the raw data for Zn, Cu, Ca, and Cd, and in granulometrically corrected data for Zn, Cu, and Cd. At setback outfalls, differences were observed in raw data for Cu, Ca, Mg, and K, and granulometrically corrected data for Ca.

Table III identifies the statistically significant differences in pollutant contents by sampling point for direct and indirect outfalls (Man Whitney U test). At direct outfalls, significant differences were observed in the raw data between upstream and junction samples ($U_D - J_D$) in elements Zn and Cu (99% level) and Ca and Cd (95% level). In the granulometrically corrected data, only cadmium showed a statistically significant difference (95% level). No significant differences were observed between upstream and downstream samples ($U_D - D_D$) in any of the elements analysed. Between

Table III. Mann–Whitney U significance values for differences between sampling points for direct and setback outfalls. Only elements that showed statistically significant differences in Kruskal–Wallis tests at either direct or setback outfalls are shown

		Raw data						Granulometrically corrected					
		U – J	U – S	U – D	S – J	S – D	J – D	U – J	U – S	U – D	S – J	S – D	J – D
Direct outfalls	Zn	0.001**		0.383			0.004**	0.016*		0.341			0.510
	Cu	0.009**		0.495			0.023*	0.033*		0.821			0.030*
	Ni	0.448		0.880			0.123	0.343		1.000			0.008**
	Ca	0.041*		0.880			0.017*	0.126		0.902			0.100
	Mg	0.667		0.910			0.563	0.287		1.000			0.049*
	Cd	0.011*		0.520			0.000**	0.027*		0.650			0.138
	K	0.135		0.170			0.425	0.209		0.363			0.001**
Setback outfalls	Zn	0.494	0.228	0.799	0.39	0.156	0.586	0.379	0.303	0.799	0.611	0.130	0.347
	Cu	0.361	0.041*	0.540	0.153	0.003**	0.08	0.649	0.072	0.540	0.243	0.007**	0.185
	Ni	0.531	0.063	0.838	0.113	0.058	0.467	0.608	0.119	0.838	0.347	0.041*	0.373
	Ca	0.424	0.006**	0.919	0.019*	0.001**	0.339	0.566	0.026*	0.919	0.180	0.005**	0.427
	Mg	0.491	0.013*	0.878	0.05	0.017*	0.316	0.786	0.082	0.878	0.470	0.019*	0.183
	Cd	0.424	0.030*	0.799	0.113	0.025*	0.717	0.449	0.030*	0.799	0.225	0.017*	0.548
	K	0.494	0.035*	0.357	0.169	0.011*	0.156	0.525	0.134	0.259	0.538	0.033*	0.103

**Statistically significant correlation—99% level. *Statistically significant correlation—95% level.

junction and downstream samples ($J_D - D_D$), significant differences were observed in the raw data between Zn and Cd (99% level) Cu and Ca (95% level). In the granulometrically corrected data, significant differences were observed between Zn, Cu, and Ca (95% level) and Cd (99% level). These results indicate that across the whole reach there is no significant change in pollutant content; however, at direct outfalls the content of these elements within sediment is significantly different compared to upstream and downstream conditions. Average pollutant content for Zn, Cu, Ca, and Cd (for both raw and granulometrically corrected data) peaks at J_D, which is expected because of the proximity of the sampling point to discharge from outfalls (Figure 4A).

Within setback samples, no statistically significant differences were observed in either raw or granulometrically corrected data between upstream and junction ($U_S - J_S$), junction and downstream ($J_S - D_S$), or upstream and downstream samples ($U_S - D_S$). Samples within setbacks (S_S) showed statistically significant differences with all other sample locations in both raw and granulometrically corrected data. Significant differences were observed in elements Cu, Ca, and Mg (at 95 and 99% levels). Figure 4-B indicates a peak in content of these pollutants at samples within the setbacks.

Impact of setbacks

All sediment samples showed, on average, an increase in pollutant contamination at outfalls (J) relative to upstream locations (U), ranging from 5 to 183% (Figure 5). Higher average increases and greater variability in pollutant content were observed at direct rather than setback outfalls. As the dataset includes a greater number of direct than setback outfalls, a sub-set of the data using paired setback and direct outfalls was analysed. Pairs were defined as the nearest direct outfall to each setback outfall (either upstream or downstream of the setback outfall). This dataset, which attempts to control for some of the variability caused by spatially dissimilar sampling points in the original dataset, also indicated increased variability at direct outfalls for all pollutants except cadmium. Kruskal–Wallis analysis was then conducted on the paired outfall data sub-set, similarly to the previous section. No significant differences were observed between sampling sites at direct outfalls (in either raw or granulometrically corrected data). At setback outfalls significant differences were observed in pollutant content Ca and Mg in granulometrically corrected data.

As this comparison between direct and setback outfalls does not account for variability of outfall catchment characteristics, such as catchment size, outfall discharge, land-use, and population, any observed differences between setback and direct outfalls cannot be attributed solely to the influence of setbacks. However, the relative change in pollutant content from upstream to the junction of setback outfalls with the main channel ($U_S - J_S$), and also within setbacks ($U_S - S_S$) should relate to the effect of the setbacks (Figure 5). Moreover, for all pollutants analysed, there is a general trend of greater percentage change and increased variability within the setback compared with the junction

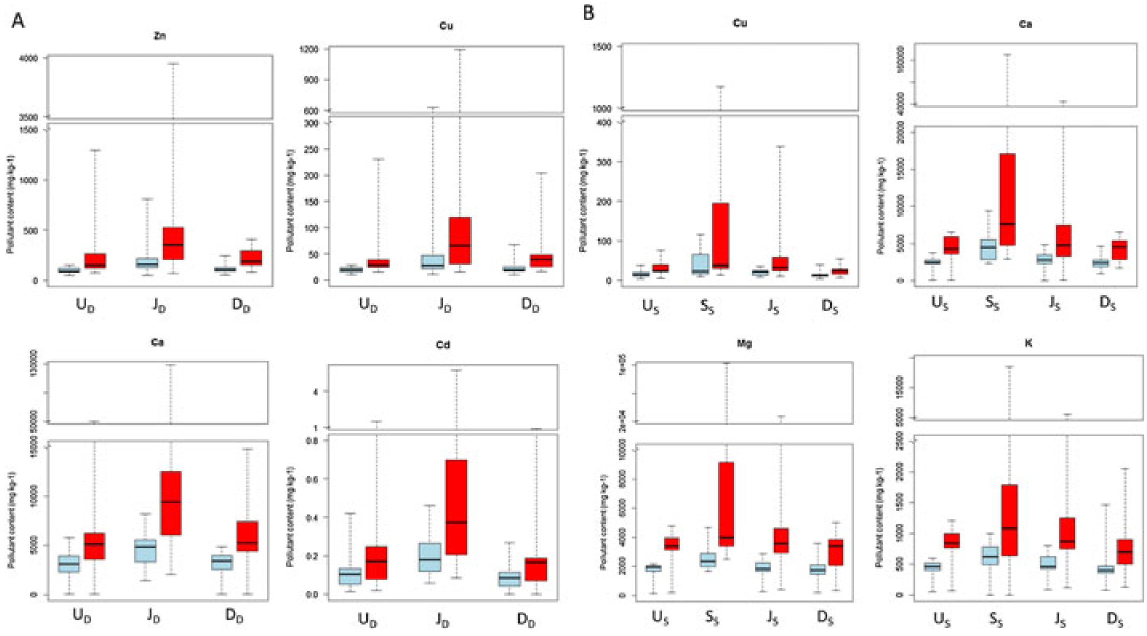

Figure 4. A - Pollutant content at direct outfalls (U_D, J_D, D_D samples) and B - Pollutant content at setback outfalls (U_S, S_S, J_S, D_S samples). Blue plots indicate raw data at these locations, and red are granulometrically corrected data. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

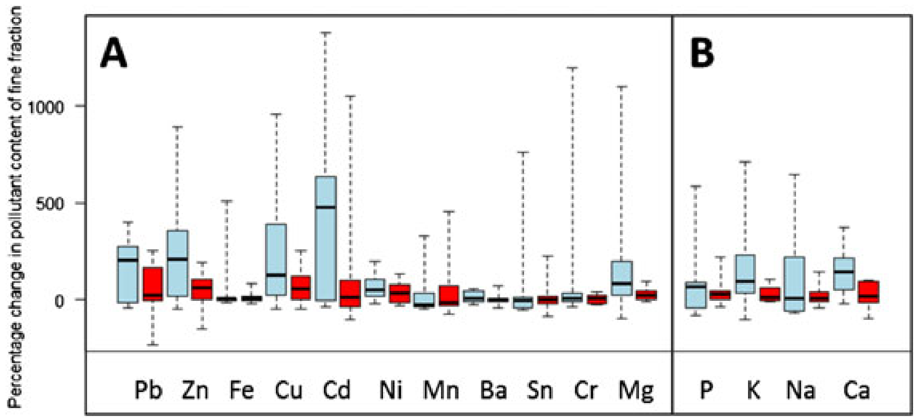

Figure 5. Percentage pollutant content change between upstream and junction of setback with main channel (Us - Js; red), and to setback outfall pipe (Us - Ss; blue). Pollutants are grouped into 2 categories; A — Urban pollutants, B— Urban pollutants with potentially significant natural sources. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

with the channel (Figure 5). Mn is the only exception, showing a lower average percent change within the setback (S_S) compared to at the junction of the setback with the main channel (J_S), and only Mn and Ba show reduced variability at S_S. The range of average increase within the setback was 16–439%, compared to 0–143% at the junction of the setback with the main channel.

Downstream change and habitat scoring

The removal efficiency of reaches of differing habitat quality/modification indices varies by pollutant (Table IV). One pollutant, Mg, showed a significant positive correlation with HQA (95% level), whilst four pollutants (Fe, Ba, Sn, P, and K) showed a significant negative correlation with the new un-naturalness score ($P < 0.05$). No significant correlations were identified with the RHS's standard modification score (HMS). In other words, the rate of pollutant removal from the water column for these six pollutants (i.e. the rate of sediment content decrease per m river length) was statistically greater in reaches that had higher levels of habitat diversity (HQA) or lower levers of artificiality (i.e. un-naturalness).

As expected, HQA scores are negatively correlated with modification and un-natural scores ($P < 0.01$), and modification scores and un-natural scores are positively correlated ($P < 0.01$). When the correlation analyses were re-run with normalized (granulometrically corrected) data, no statistically significant correlations were found between pollutant content and HQA, and modification or un-natural scores, and therefore these results are not included within Table IV.

Analysis by modification score classification

The HMS showed no significant correlations with removal efficiency (Table IV). The lack of correlation suggests that there is limited linkage between river sediment quality change (treatment) and river restoration or riparian habitat provision. However, the HMS is the only method that currently has a classification based on the scoring system (see Table I). It is therefore useful to explore how removal efficiency varies for different reach classifications, and thus selected case studies for each HMS classification are presented here. Within the study reaches, HMS ranged from 3 to 46; therefore, no reaches in this dataset were classified as pristine or semi-natural. Figure 6 illustrates an example of each of the HMS reach classes. Reach A is heavily modified, contains three direct outfalls, and flows through a

Table IV. Kendall's tau correlation coefficients between removal efficiency of pollutants within sediment samples (raw data), and habitat quality assessment, modification, and un-natural scores

		Pollutant	HQA	HMS	Un-natural
Raw data	Common urban pollutants	Pb	−0.066	0.100	−0.086
		Zn	−0.079	0.128	0.024
		Fe	0.176	−0.087	−0.281*
		Cu	0.062	0.004	−0.017
		Cd	−0.077	0.145	0.138
	Urban pollutants	Ni	0.087	0.070	−0.049
		Mn	0.028	0.154	−0.135
		Ba	0.158	−0.071	−0.255*
		Sn	0.207	−0.130	−0.277*
		Cr	−0.004	0.113	−0.129
		Mg	0.259*	−0.162	−0.229
	Urban pollutants with additional natural sources	P	0.195	−0.130	−0.281*
		K	0.132	−0.010	−0.265*
		Na	0.083	−0.023	−0.028
		Ca	0.116	−0.011	−0.028
		HQA		−0.618**	−0.311**
		Modification			0.422**
		% <63 m	0.040	−0.023	0.081

**Statistically significant correlation—99% level.
*Statistically significant correlation—95% level.

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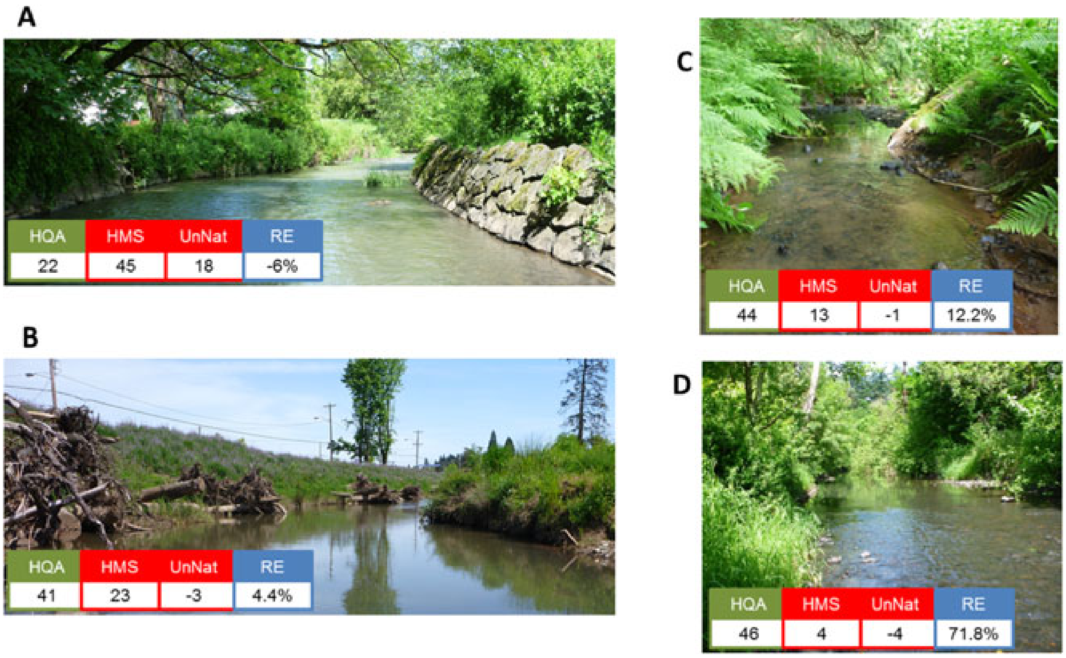

Figure 6. Example reaches of each classification group; A—Severely modified reach; B—Significantly modified (restored reach, Foster road project); C—Obviously modified (restored reach Schweitzer project); D—Predominantly un-modified reach. HQA—Habitat Quality Assessment, HMS—Habitat Modification Score, UnNat—Un-natural score, RE—average removal efficiency for all pollutants. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

predominately urban/suburban area. Reaches B and C include the Foster Road and Schweitzer restoration projects (detailed in the previous section) and contained two direct and one setback outfall, and two setback outfalls, respectively. Reach D is a natural and un-restored reach; both banks are heavily vegetated and un-modified, and surrounding land-use is predominately mixed woodland and contained two direct and one setback outfalls. Similarly to the average efficiencies for each classification, average removal efficiency is greatest for the most natural reach (D) and decreases as the level of modification increases (i.e. modification and un-natural scores increase).

DISCUSSION

This study investigated the impact that NFM measures, in particular setback outfalls and physical channel restoration, have on pollutant removal, an oft-cited additional benefit of these schemes. Pollutant removal was assessed as the relative decrease in contamination of the bed sediment adjacent to setbacks and with distance downstream of an outfall within the channel. First, the study found that setbacks have the potential to reduce the sediment pollutant concentration from outfalls. Second, the removal of certain pollutants was positively correlated with habitat quality/naturalness scores.

Impact of setback outfalls on sediment quality

Urban pollutants are delivered to watercourses either bound to sediment and organic matter or dissolved within the water column. The impact of setback outfalls and river restoration on these pollutants are twofold: (i) the increased deposition of sediment-bound contaminants; and (ii) the increased uptake of dissolved (or readily available bound) contaminants by aquatic organisms (e.g. nutrient uptake by plants). Both of these mechanisms are likely operating in setback outfalls and within the channel, but, because of the difficulty in monitoring sediment and contaminant flux in stormwater systems, the effectiveness of pollutant removal overall by the schemes is inferred from changes in sediment contamination in this study.

The relative change of pollutant contents observed at setback outfalls (U_S-J_S) was lower than at direct outfalls (U_D-J_D). This is likely because of deposition of sediment between the setback outfall pipe and the main channel. The differences observed between sample locations indicate deposition within setbacks; significant differences were observed in the content of certain pollutants (in both raw and granulometrically corrected data sets) between samples taken upstream and adjacent to direct outfalls ($U_D - J_D$), and no corresponding difference was observed at setback outfalls ($U_S - J_S$). Comparison of the granulometrically corrected data illustrates that setbacks have a higher pollutant content than background levels (upstream), indicating that they are functioning to remove pollutants.

As pollutants preferentially bind to the finer fraction of sediment (<63 mm), granulometric correction removes the effect of sediment size distribution within the data. Pollutant contents were observed to peak within the setbacks (Figure 4-B) but decrease to values similar to upstream levels prior to reaching the main channel. As corresponding peaks were observed in both raw and granulometrically corrected data the observed reduction in pollutant content is not solely because of deposition of fine sediment within setbacks. As shown in Figure 1, setback outfalls discharge into a vegetated wetland or swale, prior to reaching the main channel. The presence of vegetation increases flow resistance, which decreases flow velocities and the transport capacity of the flow. As a result, sediments are deposited and trapped by the vegetation within the wetland. Previous studies have noted the impact of swales on total suspended solids and total phosphorus removal from runoff (Deletic and Fletcher, 2006; Lucke *et al*., 2014). Concentrations of pollutants in the flow are then significantly reduced when reaching the main channel. Whilst storage of contaminated sediments within setbacks may be detrimental to the local environment, previous studies have indicated the potential for phytoremediation within swales (Fritioff and Greger, 2003; Leroy *et al*., 2016), and as such the long-term consequences of storage are likely to be ameliorated by the vegetative remediation processes within the setback. Stagge *et al*. (2012) noted that swales were effective for heavy metal removal from water samples: in decreasing order, zinc (18–93%) > copper (42–81%) > lead (27–75%) > cadmium (41–72%). As shown in Figure 5, the present study also observed a reduction in both the average and maximum percentage change compared to upstream for these pollutants.

Pollutant concentrations in outfall discharges vary because of differences in runoff volume and characteristics of land area the outfall drains (such as size and land use). Setback outfalls attenuate runoff and hence outfall discharge prior to reaching the main channel, as observed by Bäckström *et al*. (2006) and Lucke *et al*. (2014). Therefore the magnitude of the outfall impact, including pollutant content, on the main channel is reduced. This influence explains the reduced variability of pollutant increase at setback compared to direct outfalls. Temporal variation in outfall discharge characteristics would also be expected but has not been analysed within this study. For example, considerable variation (ranging from a reduction of 40% to an increase of 35% Zn from road runoff) between storm events has been noted in previous studies (Bäckström *et al*., 2006).

Impact of river restoration on sediment quality

Results indicate that reaches with higher HQA scores (more natural and less modified) have a greater ability to return to the background conditions observed upstream of outfalls. Correlations shown in Table IV show that removal efficiency for pollutants Fe, Mg, Sn, Ba, P, and K is greater for natural/un-modified reaches, with high HQA scores, and lower modification and un-natural scores. This is likely because of the increased density of vegetation, and increased geomorphic diversity associated with higher HQA and lower un-natural and modification scores. These characteristics provide more areas for deposition of fine sediment within the channel. Similarly to setback outfalls, vegetation reduces flow velocities and increases trapping and deposition of sediment and associated pollutants from outfalls. The storage of contaminants could pose a risk locally to vulnerable organisms. However the downstream impact of deposition (as calculated here through removal efficiency of pollutants) indicates a beneficial impact at the reach scale. In addition, some pollutants will be adsorbed by vegetation; P and K are nutrients required by plants and will be preferentially taken up, which may explain the statistically significant relationship between these variables. Observed phytoaccumulation rates of heavy metals from previous studies indicate greater removal efficiency of Fe compared to other urban pollutants; Kamal *et al*. (2004) noted removal efficiencies Fe 76.7%, Cu 41.62%, and Zn 33.9%; Irshard *et al*. (2015) ranked phytoaccumulation rates as follows Fe > Zn > Cr > Pb > Ni > Cd. Of these elements only Fe showed a statistically significant negative relationship with un-natural score which may be a result of preferential adsorption of this metal by vegetation (assuming a decrease in vegetation density, and hence phytoaccumulation of Fe as un-natural score increases). However, it is noted that phytoaccumulation is a very slow process, and this effect is likely to be less significant than pollutant deposition.

No significant relationships were observed between HQA, HMS, or un-natural score and removal efficiency of pollutants after granulometric normalization. Whilst it was thought this could be because of deposition of fine sediment, no correlations were observed between HQA, HMS, or un-natural scores and the percentage of sediment sample below < 63 μm. Organic matter has been found to show an affinity to pollutants; however, in this study, no significant correlation was found between organic matter and pollutant content within the samples. This could be because of the presence of organic content in coarser size fractions as observed by Schorer (1997). Therefore the lack of correlation between habitat scoring and removal efficiency of pollutants in granulometrically corrected data is likely because of other factors such as water pH, Fe, and Mn oxides and clay minerals all shown to control chemical adsorption of pollutants (Horowitz, 1991).

Significant scatter is observed within these correlations, and is expected, given the numerous additional factors influencing this relationship that have been considered in this analysis. For example, the ability of the scoring system to indicate the variety of vegetation types and density of vegetation is limited; spot checks indicate the presence of vegetation, and a broad classification type, and reach scores provide an indication of the density and variety across the reach. The roughness coefficient and level of hydraulic resistance vary with vegetation type (Kirkby *et al*., 2005), and hence trapping capacity of vegetation will vary also. The lack of statistically significant relationships for some pollutants is partly because of the wide variety habitat quality within the dataset. Similarly, Gibbs *et al*. (2014) observed no significant difference in Cr, Cu, Ni, Pb, or Zn concentration between restored and un-restored reaches because of the variety of restoration approaches used.

This study indicates the ability of restoration measures to reduce pollutant content within the main channel by trapping and deposition of sediment and associated pollutants. Single sediment samples at each location were analysed within this study, and temporal variation of pollutant contents was not available or analysed. It is important to note that the setback outfalls sampled have undergone no maintenance and that all setbacks, other than those within the Foster Road restoration area, are over 5 years old. However, seasonal variation of removal efficiency would be expected. It is possible that the decrease in leaf area in winter will reduce flow resistance and hence sediment trapping efficiency; evapotranspiration will also decrease, resulting in a decrease in adsorption rates. Additionally the influence of flood event frequency and magnitude on the effectiveness of both setbacks and restoration approaches has not been investigated here. Allen *et al*. (2015) found that sediment moves through swales during subsequent runoff events by resuspension, conveyance, and re-deposition. This has implications for longer-term efficiency of these measures.

CONCLUSIONS

This study found that setback outfalls and river restoration measures, introduced as part of catchment-based NFM, facilitate the deposition and storage of sediment and sediment-bound pollutants, and thus their removal from the water column. Pollutant levels were greater and more variable at direct outfalls as compared to setback outfalls, and the removal efficiency of certain pollutants was positively correlated to indicators of habitat quality or modification.

Furthermore, the study presents a novel use of a river habitat scoring methodology to assess the benefits of channel restoration to water quality at stormwater outfalls. The scoring system provides a semi-quantitative assessment of the level of modification that is then used to compare the ability of the reach to reduce pollutant concentrations around stormwater outfalls. Results indicate channel reaches with less modification, or that have undergone restoration measures such as the Foster Road and the Schweitzer projects, show a greater ability to reduce pollutant contents with distance downstream than unrestored and highly modified reaches. In restored reaches, the increased coverage and density of riparian vegetation enable deposition and storage of pollutants.

This research highlights the multiple benefits associated with NFM and channel restoration approaches. Improvements to water quality associated with the measures presented here assist in evaluation of the cost-effectiveness of such methods, particularly when considering an ecosystems services approach. However, a key consideration when implementing flood management measures is the capacity to cope with climate change, and projected changes in both flood magnitude and frequency. Therefore, further research is needed to investigate the behaviour of these systems over time, and particularly during flood events, and to evaluate the suitability of NFM to mitigate the effects of environmental change.

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APPENDIX A

UN-NATURAL ASSESSMENT SCORING SYSTEM

SPOT-CHECK SCORES

The score for a spot-check is the total of all component scores in categories listed below.

Bank

Each bank is scored separately.

Each un-natural spot-check material (Concrete, Sheet piling, Wood piling, Gabion, Brick/laid stone, Rip-rap, Builders' waste) scores 1.

Modification per spot-check:

- Reinforcement to banks 1
- Reinforcement to bed 2
- Resections bank or bed 1
- Two-stage bank modification 0.5
- Embankment 0.5
- Culvert 4
- Dam, weir, ford 2
- Bank poached by livestock 0 (<3 spot-checks), 1 (3–5 spot-checks), 2 (>6 spot-checks)

Channel

Artificial predominant substrate at a spot-check scores 1.

Channel modifications at spot-checks see above.

Land-use

Each bank is scored separately. Each distance grouping (i.e. within 2 m, 5 m, 10 m) is scored separately.

Each un-natural land-use at spot checks scores the following:

1 Coniferous/plantation, orchard, rough pasture, and improved grass
2 Tilled land, suburban/urban, rock, and scree

Scores for site as whole

The total un-natural score for a site is the total of all component score in the categories listed below, in addition to average of spot-check scores within that site (as above).

Modification

- Footbridge 0
- Roadbridge 1 (2 when more than one present)
- Enhancements, for example groynes 1 (2 when more than one present)
- Site partly affected by flow control 1
- Site extensively affected by flow control 2
- Partly realigned channel 5
- Extensively or wholly realigned channel 10

Bank vegetation structure

Each bank is scored separately.

Bankface—If simple or complex is recorded at one spot-check it scores −1; if simple and/or complex are recorded at two to three spot-checks, score −2; if simple and/or complex occurs at four or more spot-checks, the score will be −3.

Banktop—If simple or complex is recorded at one spot-check it score −1; if simple and/or complex recorded at two to three spot-checks, score −2; if simple and/or complex occurs at four or more spot-checks score will be −3.

Land use

Fifty meters from banktop (within sweep-up). Each is scored separately with the following with score ×1 if present, and score ×2 if extensive:

1 Coniferous/plantation, orchard, rough pasture, and improved grass
2 Tilled land, suburban/urban, rock, and scree

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The impacts of natural flood management approaches on in-channel sediment quality

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