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Short Communication

Developing an improved biomonitoring tool for fine sediment: Combining expert knowledge and empirical data

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A B S T R A C T

The Proportion of Sediment-sensitive Invertebrates (PSI) index is a biomonitoring tool that is designed to identify the degree of sedimentation in rivers and streams. Despite having a sound biological basis, the tool has been shown to have only a moderate correlation with fine sediment, which although comparable to other pressure specific indices, limits confidence in its application. The aim of this study was to investigate if the performance of the PSI index could be enhanced through the use of empirical data to supplement the expert knowledge and literature which were used to determine the original four fine sediment sensitivity ratings. The empirical data used, comprised observations of invertebrate abundance and percentage fine sediment, collected across a wide range of reference condition temperate stream and river ecosystems (model training dataset $n = 2252$). Species were assigned sensitivity weights within a range based on their previously determined sensitivity rating. Using a range of weights acknowledges the breadth of ecological niches that invertebrates occupy and also their differing potential as indicators. The optimum species-specific sensitivity weights were identified using non-linear optimisation, as those that resulted in the highest Spearman's rank correlation coefficient between the Empirically-weighted PSI (E-PSI) scores and deposited fine sediment in the model training dataset. The correlation between percentage fine sediment and E-PSI scores in the test dataset ($n = 252$) was eight percentage points higher than the correlation between percentage fine sediment and the original PSI scores (E-PSI $r_s = -0.74$, $p < 0.01$ compared to PSI $r_s = -0.66$, $p < 0.01$). This study demonstrates the value of combining a sound biological basis with evidence from large empirical datasets, to test and enhance the performance of biomonitoring tools to increase confidence in their application.

1. Introduction

Fine sediment (<2 mm) is an essential component of freshwater ecosystems, critical for habitat heterogeneity and ecosystem functioning (Owens et al., 2005). However, when levels deviate from natural conditions, ecological degradation can occur (reviewed in Bilotta and Brazier, 2008). The PSI index is a pressure-specific biomonitoring tool, designed to identify the impacts of deposited fine sediment, using standardised kick-samples of the benthic invertebrate community (Extence et al., 2011). The tool was developed using previous literature and expert knowledge of invertebrate morphological/physiological traits that are associated with either a sensitivity or tolerance to fine sediment, in order to select and assign species to one of four Fine Sediment Sensitivity Ratings (FSSRs).[1] The tool thus has a sound biological basis and is linked to ecological niche theory (Hirzel and Le Lay, 2008). The sensitivity ratings are used to assign abundance-weighted scores, which are then used to calculate (Eq. (1)) PSI scores ranging from 0 (heavily sedimented) to 100 (unsedimented). Given that rivers vary in their natural sediment conditions/dynamics (Bilotta et al., 2012; Grove et al., 2015), the index is designed to be used alongside a reference-based model (e.g. River Invertebrate Classification Tool), where observed PSI scores

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[1] Fine Sediment Sensitivity Ratings (FSSRs): Group A (highly sensitive) and Group D (highly insensitive) – Log abundance scores: 1–9 individuals present = 2; 10–99 = 3; 100–999 = 4; 1000+ = 5; Group B (moderately sensitive) and Group C (moderately insensitive) – Log abundance scores: 1–9 individuals present = 1; 10–99 = 2; 100–999 = 3; 1000+ = 4.

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Table 1
Characteristics of the River InVertebrate Prediction And Classification System sites.

Site characteristics	
Mean annual precipitation (between 1961 and 1990)	430 mm–2930 mm
Mean annual temperature (between 1961 and 1990)	7.93–11.45 °C
Geology	Various – from hard igneous rock to soft sedimentary rock
Altitude at river source	5–1216 m
Average river width	0.4–117 m
Average river depth	0.02–3.00 m
Mean annual discharge	<0.31 $m^3 s^{-1}$ to >80.00 $m^3 s^{-1}$
Slope	0–150 m km^{-1}
Substratum percentage cover of fine sediment (<2 mm)	0–100%
Substratum percentage cover of gravels and pebbles	0–98%
Substratum percentage cover of cobbles and boulders	0–100%

can be compared to the expected reference-condition PSI scores to determine whether the site is impacted by fine sediment:

$$\mathrm{PSI}(\Psi) = \frac{\sum \text{Scores for Sediment Sensitivity Groups A and B}}{\sum \text{Scores for all Sediment Sensitivity Groups A–D}} \cdot 100 \quad (1)$$

Eq. (1): Formula used to calculate PSI scores using abundance weighted scores.

A recent evaluation of the performance of the index has shown it to have a moderate correlation ($r_s = -0.64$, $p < 0.01$) with fine sediment (Turley et al., 2014). Based on an analysis of 297 biomonitoring tools used throughout Europe (Birk et al., 2012), which found the median correlation coefficient of invertebrate-based indices to be 0.64 in relation to their respective pressure, the correlation between PSI score and percentage cover of fine sediment is comparable to other indices used in the implementation of the EU Water Framework Directive. However, given the implications of incorrect assignment of ecological status of streams for both water and land managers (from unjustified burdens being placed on the users of water resources, to environmental damage going undetected), greater effort is needed to improve the performance of the PSI index and other similar indices. The aim of this study was to investigate if the performance of the PSI index could be enhanced through weighting individual species in each of the FSSRs of the PSI index, based on empirical observations of invertebrate abundance and percentage cover of fine sediment, collected across a wide range of reference condition temperate stream and river ecosystems.

2. Methods

2.1. Data

The main data set used in this study was the RIVPACS IV (May 2011 version) data set (River Invertebrate Prediction and Classification System – NERC [CEH] 2006. Database rights NERC [CEH] 2006 all rights reserved). For a detailed description of the RIVPACS IV data set, see Wright et al. (2000) and Clarke et al. (2003). In summary, the database contains invertebrate, water quality and catchment characteristics data, recorded at each site over at least one year, between 1978 and 2004. The 835 sites, on temperate streams and rivers, were considered to be in reference condition with no, or only very minor anthropogenic disturbances and supporting biota usually associated with such undisturbed or minimally disturbed conditions. The sites comprise a wide range of environments (Table 1), varying in their (i) climate, (ii) catchment geology, (iii) topography and (vi) morphometry.

The invertebrate data within the RIVPACS IV data set were collected from the 835 sites, using a standardised 3 min active kick sample technique with a 900 μm mesh pond net, where all instream habitats within the site were sampled in proportion to their occurrence (Environment Agency, 2009). Invertebrate abundance was recorded to species level or to the lowest possible taxonomic unit (Wright et al., 2000). Each site has a season-specific record of community composition[2]: spring (March–May), summer (June–August) and autumn (September–November).

Fine sediment data were available for all 835 sites within the RIVPACS IV database, including the percentage of the substratum consisting of (i) silt and clay (<0.06 mm), and (ii) sand (≥0.06 and <2.00 mm). The visual assessment method, described in the River Habitat Survey Field Survey Guidance Manual (Environment Agency, 2003) was used to collect these data. This method involves the operator, estimating the substratum composition over a given reach, based on a visual inspection. The values used represent a mean of three seasonal measurements[2]. Whilst this technique does not quantify the volume of deposited fine sediment, which PSI is designed to relate to, it does provide a measure of the percentage cover, which theoretically should be related to the PSI index (Glendell et al., 2013).

2.2. Statistical analyses

2.2.1. Developing the E-PSI index

The relevant data were extracted from the RIVPACS IV database and compiled in Microsoft Excel. Prior to analysis the substratum data <2 mm (sand, silt and clay) were combined and are referred to as percentage fine sediment. The reasons for this were that a recent evaluation of the PSI index found this metric to be the most related to PSI scores (Turley et al., 2014) and further, to acknowledge the difficulties in differentiating between the various fractions using the visual assessment method. Using SPSS statistical software (IBM SPSS Statistics 20), the data were found to be non-normally distributed and show heteroscedasticity and could not be successfully transformed. Therefore, the nonparametric Spearman's rank correlation was used to analyse the relationships. The 835 sites were split using random allocation, to create a training dataset (751 sites, $n = 2252$) and an independent test dataset (84 sites, $n = 252$). This 90:10 split (similar to Kelly et al., 2012) of the dataset was chosen in order to maximise the number of sites used to develop the species weightings, whilst leaving a sufficient amount of data to test these weightings. The PSI formula (Eq. (1)) was re-cast as follows:

$$\text{E-PSI} = \frac{\sum_{j=1}^{M} w_j \cdot \log A_j}{\sum_{i=1}^{N} w_i \cdot \log A_i} \cdot 100 \quad (2)$$

Eq. (2): Formula used to calculate E-PSI scores using empirically-derived species sensitivity weights and simplified abundance weighted scores. *Note*: Log abundance categories ($\log A$) in E-PSI were simplified to: 1–9 individuals present = 1; 10–99 = 2; 100–999 = 3; 1000+ = 4.

In this equation, $\log A_i$ and w_i are the log-abundance categories and corresponding sensitivity weights for all N species, while $\log A_j$ and w_j are the log-abundance categories and sensitivity weights for M sensitive species. Eq. (2) is more flexible than Eq. (1) in varying the sensitivity weightings on a species by species level. In the original PSI index, all species within the same FSSR receive the same log-abundance weights, which were developed through an extensive literature review (Extence et al., 2011) and expert judgements, and were based on invertebrate traits such as physiological and/or morphological adaptations that are associated with either a

[2] 834 sites have three seasons of data, one site has only two seasons of data.

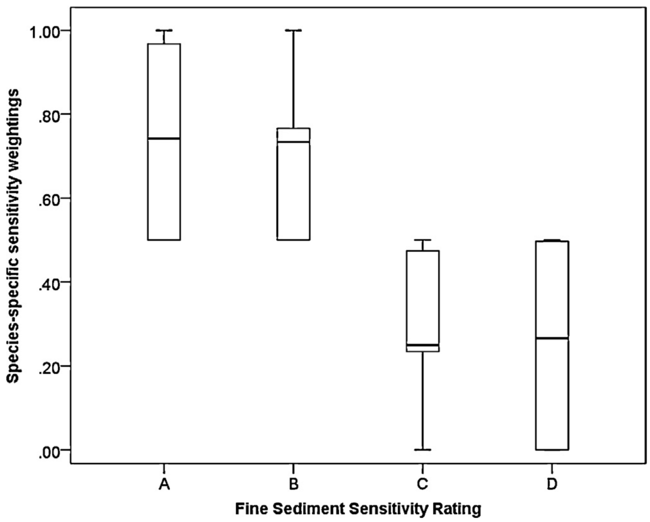

Fig. 1. Distribution of the optimum empirically derived species-specific sensitivity weights selected for the E-PSI index, within each of the original four Fine Sediment Sensitivity Ratings of the PSI index. Minimum, maximum (shown in the lower and upper whiskers respectively), median (-), interquartile range (boxes).

sensitivity or tolerance to fine sediment. In this study, species weightings were constrained within a range around their original estimates of sensitivity (FSSRs) so as to deviate only slightly, from the expert judgements (Fig. 1) and biological basis. Those species originally identified (FSSRs) as moderately to highly sensitive to fine sediment were assigned a range between 0.5 and 1.0, whilst species identified as moderately to highly insensitive were weighted between 0.0 and <0.5. Sensitive species were assigned this larger weighting as they were deemed to be the most significant species in terms of identifying sediment pressures, whereas those species identified as insensitive, are tolerant of fine sediment but not necessarily directly reliant on it. Using a range of weights acknowledges the breadth of ecological niches that invertebrates occupy and also their differing potential as indicators. The optimum species sensitivity weights were identified using the *fmincon* function (active-set algorithm) of MATLAB (Mathworks, version R2014a). The fmincon function is a constrained nonlinear optimisation method (see Mathworks, 2014), which in this study was used to test 100,000 iterations of species sensitivity weightings (within the constraints mentioned above) to find the set of weightings that produced the highest Spearman's rank correlation coefficient between PSI and fine sediment. The set of sensitivity weights that yielded the maximum correlation were used as the Empirically-weighted PSI (E-PSI) for further analysis.

2.2.2. Testing the E-PSI index

In order to evaluate the E-PSI index, the correlation between E-PSI scores and percentage fine sediment was calculated using the test dataset. This correlation was then compared to the benchmark; the correlation between PSI and percentage fine sediment in the same test dataset. In addition, the correlation was compared with those correlations between percentage fine sediment and other non-sediment-specific indices; Average Score Per Taxon (ASPT) (Murray-Bligh, 1999), Lotic-invertebrate Index for Flow Evaluation (LIFE) (Extence et al., 1999), Ephemeroptera, Plecoptera and Trichoptera (EPT) percentage abundance, and EPT percentage richness.

Kruskal–Wallis tests were carried out on both PSI and E-PSI, by grouping the scores into independent groups (0–10, 11–20, 21–30, 31–40, 41–50, 51–60, 61–70, 71–80, 81–90 and 91–100). The Kruskal–Wallis test returns a p-value which is used to determine whether any of the groups are significantly different. Groups of this size were selected due to the importance of discriminating between different levels of sedimentation, but also to account for the uncertainties in both the sediment and invertebrate data (smaller groups would need to be based on highly accurate and precise data). Pairwise comparisons were then performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons, to determine which groups were significantly different.

Table 2
Spearman's rank correlation coefficients for PSI, E-PSI, LIFE, EPT% abundance, EPT% richness, ASPT, versus percentage fine sediment (<2 mm) for the model training dataset (n = 2252) and the model test dataset (n = 252).

Index[a]	Training dataset correlation[b]	Test dataset correlation[b]
E-PSI	−0.76	−0.74
PSI	−0.63	−0.66
LIFE	−0.59	−0.57
EPT% abundance	−0.59	−0.56
EPT% richness	−0.55	−0.52
ASPT	−0.50	−0.43

[a] Proportion of Sediment-sensitive Invertebrates (PSI), Empirically-weighted PSI (E-PSI), Average Score Per Taxon (ASPT), Lotic-invertebrate Index for Flow Evaluation (LIFE), Ephemeroptera, Plecoptera and Trichoptera (EPT) percentage abundance, and EPT percentage richness.
[b] All correlations are significant at the 0.01 level (2-tailed).

3. Results

Fig. 1 shows the distribution of the optimum species sensitivity weightings which were used to calculate E-PSI scores. The set of weights that comprise the E-PSI index are available in the online supplementary information.

The Spearman's rank correlation coefficients for E-PSI scores versus percentage fine sediment for the model training dataset and the model test dataset are displayed in Table 2. The Spearman's rank correlation for E-PSI versus percentage fine sediment for the model test dataset ($r_s = -0.74$ $p < 0.01$) was eight percentage points higher than the correlation between percentage fine sediment and the original PSI index for the model test dataset ($r_s = -0.66$ $p < 0.01$) and was also stronger than for the other indices tested. Additionally, the correlations between the indices were analysed (Table 3) with all (except ASPT versus E-PSI) showing strong correlations with each other. The E-PSI had a weaker correlation with LIFE, compared to PSI with LIFE ($r_s = 0.77$, $p < 0.01$ and $r_s = 0.91$, $p < 0.01$, respectively).

Fig. 2 illustrates the relationship between grouped E-PSI and PSI scores and percentage fine sediment across the test dataset. Kruskal–Wallis tests showed that percentage fine sediment values were statistically significantly different between the different groups of both E-PSI and PSI scores (χ^2 (9) = 138.44, $p < 0.01$ and χ^2 (9) = 112.80, $p < 0.01$, respectively). Post hoc analysis (pairwise comparisons) identified the groups whose distributions were statistically significantly different from one another. In total, 21

Table 3
Spearman's rank correlation coefficients for relationships between biological indices for the model test dataset (n = 252).

Index[a]	E-PSI[b]	PSI[b]
PSI	0.86	1.00
LIFE	0.77	0.91
EPT% abundance	0.73	0.76
EPT% richness	0.68	0.73
ASPT	0.58	0.69

[a] Proportion of Sediment-sensitive Invertebrates (PSI), Empirically-weighted PSI (E-PSI), Average Score Per Taxon (ASPT), Lotic-invertebrate Index for Flow Evaluation (LIFE), Ephemeroptera, Plecoptera and Trichoptera (EPT) % abundance, and EPT % richness.
[b] All correlations are significant at the 0.01 level (2-tailed).

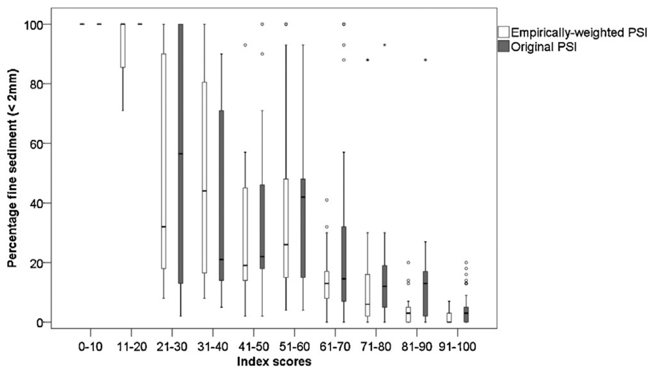

Fig. 2. Boxplot showing the relationship between percentage fine sediment (based on visual assessment) and grouped E-PSI and PSI scores for the test dataset. Note: Minimum, Maximum (shown in the lower and upper whiskers respectively), Median (-), interquartile range (boxes). SPSS identifies potential outliers as >1.5 times (◯) or >3 times (*) the interquartile range above the 75th percentile.

significant differences were shown between grouped E-PSI scores, compared to 13 significant differences for grouped PSI scores. These extra group differences were largely between groups with low E-PSI and high E-PSI scores.

4. Discussion

The results of this study show that modelling using an extensive empirical sediment-invertebrate dataset in order to find optimum species-specific sensitivity weightings, has increased the sediment specificity of the E-PSI index in comparison to the PSI index (relationship with percentage fine sediment in test dataset: $r_s = -0.74$ $p < 0.01$, compared to $r_s = -0.66$ $p < 0.01$). By constraining these sensitivity weightings around the original FSSRs, the sound biological basis and mechanistic linkage within the original PSI index has been retained. An increased specificity is also shown by the results of the Kruskal–Wallis test which demonstrated an increase in the number of significant differences between fine sediment values in grouped E-PSI scores, compared to grouped PSI scores.

The E-PSI index has a strong correlation with fine sediment, which is higher than the median correlation coefficient (0.64) of invertebrate-based indices (in relation to their respective pressures) that have been reviewed in Europe (Birk et al., 2012). The correlation between percentage fine sediment and E-PSI scores in the test dataset is also stronger than for the other indices tested. Although those indices are not sediment-specific, EPT indices in particular, are often used to identify sediment pressures, and have been shown to respond to fine sediment to varying degrees (Larsen et al., 2009; Wagenhoff et al., 2012; Zweig and Rabeni, 2001). The LIFE index has been shown to be moderately correlated with fine sediment and highly correlated with PSI (Glendell et al., 2013; Turley et al., 2014) which is likely to be due to the relationship between flow regime and fine sediment dynamics (Matthaei et al., 2010). The Spearman's rank correlation between E-PSI and LIFE is weaker than for PSI and LIFE in the test dataset. Although both are still strongly correlated ($r_s = 0.77$, $p < 0.01$ and $r_s = 0.91$, $p < 0.01$, respectively), this reduced correlation between E-PSI and LIFE may indicate a greater independence of E-PSI from LIFE in comparison to the original index.

Whilst there are limitations to opportunistic data analysis (Vaughan and Ormerod, 2010), it is shown to be useful in the present study to improve the specificity of the PSI index over a wide range of reference condition temperate river and stream ecosystems. The E-PSI index appears more able to identify deposited fine sediment conditions, but as previously discussed, sediment is a natural component of rivers and streams and therefore, any interpretation of E-PSI scores in terms of impact, should consider observed versus expected scores taken from a reference-based model. Given the uncertainties associated with methods of measuring deposited fine sediment, including the visual assessment method utilised here, any further improvements to the E-PSI index are likely to necessitate higher quality (more accurate and precise) sediment data, which also incorporates the sediment dynamics preceding the invertebrate sampling.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2015.02.011.

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