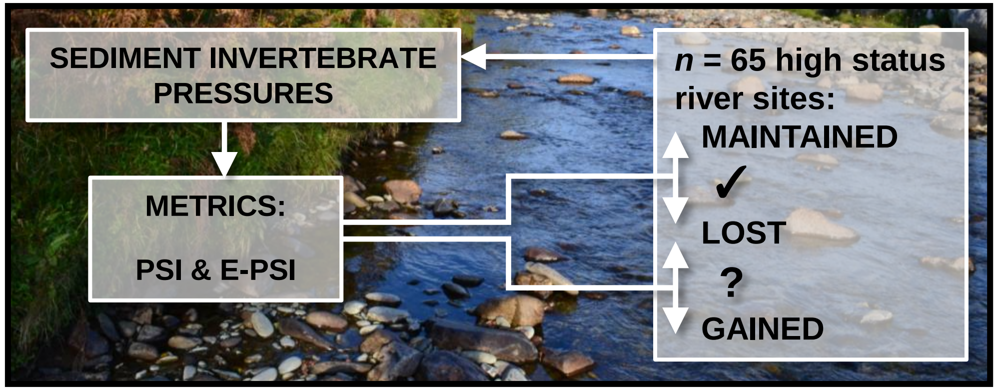
*Graphical Abstract



*Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Highlights

- The number of important high status (HS) water-bodies in Ireland has declined
- River macro-invertebrate sediment metrics and physical variables were assessed
- Macro-invertebrate sediment metrics differ at sites that Lost and Maintained HS
- Caveat - no difference between Lost HS sites and those improving/varying (Gained)
- No difference between status categories for any of the physical sediment variables

Title: Assessing the impact of fine sediment on high status river sites

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Abstract

The European Union (EU) Water Framework Directive (WFD) designates as “high status” rivers, lakes, transitional and coastal waters that are close to natural status and relatively un-impacted by anthropogenic activities. These high status water-bodies (HSWs) are sensitive areas that require special attention. Ireland had a globally important distribution of HSWs (10.5 % of rivers and 16.2 % of lakes classified as high ecological status in Europe occurred in Ireland), but there have been declines of almost 50 % between 1987-2018, with excessive sediment implicated as a pressure. In this study, an extensive assessment of macro-invertebrate sediment metrics were used to assess sediment as a pressure in sixty-five high or formerly high status river sites in Ireland that were determined to have either: “Lost” their high status (e.g. gone from high to good, moderate, poor or bad; 20 sites); consistently “Maintained” high status (24 sites); or “Gained” in status (e.g. from good to high; 21 sites). Macro-invertebrate taxa occurring in the sixty-five sites were pre-dominantly sediment sensitive taxa. However, for two specific sediment metrics, the Proportion of Sediment-sensitive Index (PSI) and the Empirically-weighted PSI (E-PSI), significant differences were observed between sites that Lost status and those that Maintained status, implying that at some sites, sediment is impacting on macro-invertebrates. However, no significant difference between Lost and Gained sites was observed, leaving an important caveat. While weak to moderate relationships were observed between the macro-invertebrate sediment metrics and the physical sediment variables, no difference between status categories for any of the physical sediment variables was observed. Further research priorities should consider the sampling resolution of these physical variables (e.g. patch vs reach scale), the properties of sediment (e.g. chemical composition) in addition to concentration, the potential interaction of multiple-stressors, and the life cycle characteristics of invertebrate taxa.

Keywords: High status water-bodies; sediment; water quality; Proportion of Sediment-sensitive Index (PSI); Water Framework Directive.

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1. Introduction

Degradation of freshwaters resulting from excess inputs of sediment is a global concern (Richter et al., 1997; Malmqvist and Rundle, 2002; Dudgeon et al., 2006; Heino et al., 2020), with studies from New Zealand (Townsend et al., 2008; Ramezani et al., 2016), the United States (Rabení et al., 2005), United Kingdom (Extence et al., 2017), Canada (Benoy et al., 2012), Ireland (Conroy et al., 2016a) and Spain (Buendia et al., 2013) highlighting its impacts on aquatic biota. In the US for example, excessive sediment occurs in 15 % of river and stream length (USEPA, 2016). While some sediment outside of the influence of human activity does occur, for example, naturally occurring soil erosion of stream-banks, and plays an important role in freshwater systems (Buendia et al., 2013; Turley et al., 2014), this is greatly exacerbated by anthropogenic actives (Waters, 1995; Richter et al., 1997). Additionally, in many parts of the world (e.g. Meade and Moody, 2010; Dang et al., 2010; Yang et al., 2014), dams and weirs, which interrupt and limit the natural movement of sediment, and in doing so have their own structural and ecological impacts such as river bed erosion (Habersack et al., 2013; Hauer et al., 2018), may result in abnormal sediment pulses during, for example, cleaning/flushing operations and extreme events (Habersack et al., 2016; Grimardias et al., 2017; Palinkas et al., 2019; Lepage et al., 2020).

While dam constructions may restrict and alter the movement of sediment, land use practices, particularly those associated with agriculture, are a major contributor of excessive sediment input to surface waters (Collins and Anthony, 2008; Benoy et al., 2012; dos Reis Oliveira et al., 2018). Thompson et al. (2014) suggests that for two Irish catchments, anthropogenic and agricultural activities were a key factor in the mobilisation of sediments that resulted in suspended sediment levels in excess of 25 mg l^{-1}. The main agriculture sources of sediment relate to, for example, soil erosion resulting from intensively managed land, especially in relation to arable cultivation practices, and grazing of riparian areas by livestock (Waters, 1995; Benoy et al., 2012). Conroy et al. (2016b) and O'Sullivan et al. (2019) additionally highlight the potential for cattle accessing water-bodies as a sediment source through disturbance. While measures such as contour ploughing and fencing-off waterways should limit these pressures, sediment still remains a major ecological concern (Matthaei et al., 2006; Sutherland et al., 2010; 2012; Bilotta et al., 2012; Glendell et al., 2014; Ramezani et al., 2014). Forestry operations, especially in relation to logging roads constructed close to streams, along with other practices such as mining, bare, un-vegetated land, and urbanisation through land development, are also major sediment sources (Waters, 1995;; Collins and Anthony, 2008; Al-Chokhachy et al., 2016).

Fine sediment may have detrimental consequences for the ecological communities present in a water body, impacting on primary producers, invertebrates and fish (Wood and Armitage, 1997; Collins et al., 2011; Jones et al., 2012). Piggott et al. (2012) for example, found sediment to be the most prevalent stressor to aquatic invertebrates, in a comparison with nutrient enrichment and increased temperatures. In an experiment manipulating the addition and removal of sediment to two farmland streams, Ramezani et al. (2014) found both invertebrates and fish responded negatively to the addition of sediment and positively to its removal (but see also Hauer et al., 2018; and Kondolf, 1997; for the implications of reduced sediment movement caused by dams, e.g. river bed scouring and loss of fish spawning habitats).

Within a fluvial system sediment occurs as either suspended sediment in the water column or as deposited sediment that covers the benthic surface, although given the nature of movement within a water column, there is some degree of transfer between both types (Benoy et al., 2012). The primary impact of fine or suspended sediment on macrophytes and algae occurs through light impedance in the water column, which may alter the ability for periphyton and submerged and/or emergent plants to carry out photosynthesis (Bilotta and Brazier, 2008). For invertebrates, impacts occur either directly through: abrasions, clogging up of respiration mechanisms, smothering/burial, and clogging up niches in the river-bed, or indirectly through the alteration of macrophyte and algal communities (Wood and Armitage, 1997; Jones et al., 2012; Extence et al., 2013). Similarly, for salmonid fish, key impacts include abrasions and blocking of gill mechanisms, along with the smothering of respiring eggs/larvae (Bilotta and Brazier, 2008). The impacts of sediment are related to the particle size, which in turn determines whether the sediment is suspended in the water or deposited in the substrate (Waters, 1995; Wood and Armitage, 1997; Sutherland et al., 2012). To this end, many studies that assess sediment pressures tend to focus on particle sizes of either less than 0.6 mm (Glendell et al., 2014) or less than 2 mm (Zweig and Rabeni, 2001; Von Bertrab et al., 2013), as particle sizes below 2 mm are considered most harmful to aquatic biota (Waters, 1995; Ramezani et al., 2014). The amount of sediment entering a water body (Suttle et al., 2004), and the duration of sediment exposure (pulses) (Shaw and Richardson, 2001) are also important considerations (see also Lepage et al., 2020; and Grimardias et al., 2017). Along with the afore-mentioned factors, Bilotta and Brazier (2008) additionally highlight how the effect on aquatic biota may vary depending on the chemical composition of suspended sediment, and its potential to alter the chemical composition of receiving waters (e.g. pH, salinity, nutrient concentrations).

As well as direct pressures, sediment may interact with "multiple stressors" (Matthaei et al., 2010; Piggott et al., 2012; Lange et al., 2014a). Turley et al. (2016) provides a summary of confounding pressures associated with fine sediment and their impact on invertebrates that includes flow, nutrients, pesticides, metals and pathogens. A reduced flow from, for example, increased water abstraction, may increase the amount of sediment in, and temperature of, a stream, as well as altering dissolved oxygen (DO), pH and nutrient levels (Dewson et al., 2007). Suspended sediment may also be increased by high flows, as Beckmann et al. (2005) reports that current velocity in the tributary mouths of the River Rhine, decreases by 40-50% during high flow, which potentially increases the levels of fine sediment in the water column.

High status water-bodies (HSWs) are rivers, lakes, transitional and coastal waters, that are defined under the European Union Water Framework Directive (OJEC, 2000) as being close to reference conditions, based on a limited/minimal influence from anthropogenic activities (WG 2.3, 2003; Mayes and Codling, 2009). Relative to other EU countries, Ireland had a high number of HSWs (e.g. 10.5 % rivers and 16.2 % of lakes classified as high ecological status in the EU after the first reporting of River Basin Management Plans occurred in Ireland - data extracted from the Europe (WISE) - WFD database - EEA, 2020) and so may be considered globally important (Ní Chatháin et al., 2012). However, the percentage of sites at high status in Ireland has declined by almost 50% between 1987-2018 (EPA, 2012; 2016; 2020; White et al., 2014), with Ireland now accounting for 2 % and 7.4 % of the EU's rivers and lakes classified at high ecological status, respectively (EEA, 2020). Along with nutrient enrichment, flow modifications and pesticide/herbicide usage, these deteriorations have potentially been attributed to increasing levels of sediment (Ní Chatháin et al., 2012; White et al., 2014). For example, increased fine sediment is cited as a key factor associated with declines in the Freshwater Pearl Mussel (*Margaritifera margaritifera*) (Leitner et al., 2015; Gumpinger et al., 2015), a species very often associated with HSWs. It is this relationship between HSW deteriorations and increasing fine sediment levels that was investigated in this study.

Invertebrates have routinely been used for assessing water quality degradation because of, for example, 1) the relative ease of sampling, 2) a sensitivity to various pollution stressors and habitat modifications especially in relation to streamflow and siltation, 3) a variation in the tolerance/sensitivity levels of taxa, which allows for a scoring system, such as the Biological Monitoring Working Party (BMWP) (Hawkes, 1998), to be utilised, and 4) dichotomous keys are available for most groups (Hellawell, 1986; Rosenberg and Resh, 1993; Zalack et al., 2010). Additionally, they represent a middle trophic ground, between primary producers (algae) and top end predators (fish) (Relyea et al., 2011), and their use is a key requirement of the WFD (OJEC, 2000). In line with this, recent efforts for assessing the impacts of sediment have focused on the use of invertebrates. For example, Relyea et al. (2011) developed, using historic datasets, the Fine Sediment Biotic Index (FSBI) to assess the impact of fine sediment (<2 mm) on North-western United States streams. In the UK metrics have been developed using a literature review (Extence et al., 2013), empirical evidence (Murphy et al., 2015) or a combination of both Turley et al. (2015).

With this background, and with regard to the deterioration of HSWs in Ireland, the aim of this study was to examine fine sediment as a pressure on high status river biology. The objectives were therefore to: 1) use invertebrates and sediment specific indices as developed by Extence et al. (2013), Murphy et al. (2015) and Turley et al. (2015; 2016), to assess the impact of fine sediment on river biology; and 2) assess the relationship between physical sediment variables and the change in status of HSW rivers. These objectives were tested under the null-hypothesis that there was no relationship between pressures from sediment and declines in HSW rivers.

2. Materials and Methods

2.1. Site selection

In Ireland, the Q-value scoring system is used by the Irish Environmental Protection Agency (EPA) to assign ecological status to river sites. This system, which is primarily based on the relative proportions of macro-invertebrates occurring at a river site, assigns a WFD status of High to Q-value scores of Q4-5 and Q5, Good to Q4 scores, Moderate to Q3-4 scores, Poor to Q3 and Q2-3 scores, and Bad to Q2, Q1-2 and Q1 scores (EPA, 2013). From a data-set of 167 river sites in the west of Ireland that were initially coded for slope and hardness based on the RIVtypes classification (Kelly-Quinn et.al., 2005) and that were all previously classified as being of high ecological status during the 2007 - 2009 and/or 2010 - 2012 monitoring periods by the EPA, an initial sixty river sites were selected. These sixty sites were randomly selected based on the RIVtypes classification, but represented in equal proportion (and following the example of Roberts et al. (2016)), river sites that had either: Lost their high status (e.g. gone from high to good, moderate, poor or bad); consistently Maintained high status; or had Gained in status (e.g. from good to high). A further five sites that were at the more pristine end of the high status category (EPA Q5 sites) were added to the Maintained status category, resulting in sixty-five sites. Given the potential for the EPA status classification to change up to and during the sampling conducted in this study, a final status was assigned to the sixty-five sites based on the most up-to-date data at the time of the sampling period of this study (2016-2017). These data were obtained online from the EPA's ecological quality (Q-value) reports (http://epa.ie/QValue/webusers/). This resulted in the selection/classification of 20 Lost sites, 24 Maintained sites and 21 Gained sites. Poor sampling conditions excluded three sites from each of the Summer 2016 and Summer 2017 sampling programmes.

2.2. Sampling and sediment metrics

Macro-invertebrates were collected on four sampling occasions from the sixty-five river sites using a three-minute kick-sample, followed by a one-minute stone searching, as described by methods in BS-ISO (2012) and Environment Agency (2012). The macro-invertebrate samples were preserved in 75 % alcohol on the day of collection. The sample dates were in April/May (Spring) and August (Summer) in 2016 and 2017. Macro-invertebrates were identified to the lowest practical taxonomic level using an Olympus (SZX16) stereo microscope and relevant dichotomous keys (a list of keys is provided in Supplementary Material Appendix B). This was generally to species or genus level, with the exception of Oligochaetes (Order) and Dipterans (Family or Tribe). Following identification, sediment specific biotic metrics were applied.

[Insert Figure 1]

The Proportion of Sediment-sensitive Index (PSI) as described by Extence et al. (2013) assesses the impact of fine sediment deposition on lotic ecosystems using a macro-invertebrate scoring system. It was developed by carrying out an extensive literature review, as well as assessing the physical and physiological characteristics of invertebrate taxa, relative to sediments (Extence et al., 2013). Invertebrate taxa (either to species or family level) are assigned to groups A, B, C and D depending on their sensitivity to sediment levels, with these groups representing: highly sensitive, moderately sensitive, moderately insensitive and highly insensitive, respectively. The PSI score also takes account of abundances and is calculated as:

$$PSI(\Psi) = \frac{\sum Scores\ for\ Sediment\ Sensitivity\ Groups\ A\&B}{\sum Scores\ for\ Sediment\ Sensitivity\ Groups\ A,B,C\ \&\ D} \times 100 \quad \text{[Eq. 1]}$$

where taxa are assigned to a group determined from a list of taxa in the Appendix of Extence et al. (2013), and scores are generated based on a combination of the taxa's assigned group and abundance category at which it occurs (i.e. Table 4.1 from Extence et al. (2013)). Extence et al. (2013) also provides a table for interpreting the generated PSI scores (Supplementary Material Table C1).

Additionally, the Combined Fine Sediment Index (CoFSI) which was developed by Murphy et al. (2015), with the aid of empirical evidence and multivariate ordination techniques, was employed to assess the impacts of sediment on invertebrates. The CoFSI index assigns an organic Fine Sediment Index (oFSI) score out of ten and a Total Fine Sediment Index (ToFSI) score out of ten to a list of one hundred and five taxa, with a score of zero being sediment tolerant and ten being sediment sensitive. The oFSI and ToFSI scores are then combined to give a total CoFSI score using:

$$CoFSIsp = 0.349\ (oFSIsp) + 0.569\ (ToFSIsp) \qquad \text{[Eq. 2]}$$

The higher the CoFSI score the greater the sensitivity to sediment of the invertebrate community.

A third metric for assessing sediment, the Empirically-weighted PSI (E-PSI) as developed by Turley et al. (2016) was also employed in this study. The E-PSI metric combines elements of the PSI metric with optimal weightings extracted from an empirically generated training dataset (see Turley et al., 2016, for weighting scores). Invertebrates are classified as either sensitive or insensitive to sedimentation, and within these categories empirically derived weightings are applied. The metric is calculated as:

$$E - PSI = \frac{\sum(logAsens \times W)}{\sum(logAll \times W)} \times 100$$ [Eq. 3]

where the sum of the log of the abundance of sensitive taxa ($logA_{sens}$) multiplied by its associated weighting, is divided by the sum of the log of the abundance of all the taxa (sensitive and insensitive combined) ($logA_{all}$) multiplied by the associated weighting. The result is then multiplied by 100 to give the E-PSI score. For this metric, the log abundance categories were generated as: 1-9 individuals = 1; 10-99 = 2, 100-999 = 3 and 999+ = 4 (Turley et al., 2016). In this study mixed taxon/species level E-PSI scores were generated. Again, higher E-PSI scores are associated with reduced sediment pressures.

Using the R software programme (R Core Team, 2018), Wilcoxon-Mann-Whitney tests, were used to test for differences between the PSI scores of different status categories, e.g. Lost against Maintained, within each sample period. Wilcoxon-Mann-Whitney tests were used as the data were not normally distributed and were un-transformable, and the datasets were independent of each other. Wilcoxon-Mann-Whitney tests were also used to test for direction of differences between categories (i.e. greater or less than). Wilcox Signed Rank tests were used to test for differences in PSI scores between seasons and also between years, as datasets in this case were paired. This was also repeated within each status category, and again the direction of change was analysed. Some caution is required with the interpretation of these results as both the classification of status categories, and the generation of for example, PSI scores, employ invertebrates, and so are not therefore, fully independent of each other. However, while the generation of status categories through the EPA Q-value system is more aimed at assessing general/organic pollution patterns, the generation of, for example, PSI, CoFSI and E-PSI scores are specifically related to the sensitivity of invertebrate taxa to sediment pressures.

2.3. Physical assessment of fine sediment

To assess fine sediment (<2 mm) pressures at the sixty-five river sites, five sediment assessment methods (two re-suspendable sediment and three deposited methods) were carried out. The primary re-suspendable sediment analysis method employed was the "Quorer" method, adapted from methods described by Quinn et al. (1997), Collins and Walling (2007), Clapcott et al. (2011), Glendell et al. (2014), Lange et al. (2014a; 2014b) and Duerdoth et al. (2015). In this method, a metal bin of diameter 40 cm and height 60 cm was pushed into the river-bed sediment to a depth of ca. 2-5 cm, forming a seal with the river-bed substrate. Using a metre rule, the height of water within the bin was measured three times and the average height recorded. The water and upper 5 cm of the substrate within the bin was then disturbed with a metal rod for approximately 60 seconds. A 500 ml sample bottle was then immediately submerged into the bin/water to take a representative aliquot of the mobilised sediment. This process was repeated three times across the width of each river. Following collection and return to the laboratory, the 500 ml samples were stored in a fridge until analysis, at which time they were returned to room temperature. The vacuum filtration method, using 0.45 μm Whatmann glass-fibre filters, was used to determine the sediment concentration Cs(t) (g L^{-1}) within the 500 ml sample bottles. Following this, the amount of fine sediment per unit surface area $B_r(t)$ (g m^{-2}) was determined, as described by Collins and Walling (2007), using the equation:

$$B_r(t) = \frac{C_s(t)W_v(t)}{A} \qquad \text{[Eq. 4]}$$

Where $W_v(t)$ (L) is the volume of water within the sampling bottle (500 ml) and A is the surface area ($2\pi rh+2\pi r^2$) of the sampling bin whose height h (m) is equivalent to the depth of water within the bin, and r is the bin radius.

A second re-suspendable sediment method "Tile", as described by Clapcott et al. (2011), involved disturbing the river bed substrate upstream of a white tile (15 cm x 15 cm) placed on the substratum, and assigning a score of one to five based on the visibility and duration of the resulting plume. A score of one was associated with no plume and a still visible white tile, while a score of five was given if the white tile completely disappeared under the resulting plume. In comparison to the Quorer method, the white tile provides a rapid qualitative assessment of the "total suspendable solids" present on the river substratum.

Details of three methods that were used to assess "deposited sediment", including two visual assessment methods, "% Fine" and "Scope", and an assessment of sediment depth, "Depth", are presented in Supplementary Material (Appendix C). Wilcoxon-Mann-Whitney tests, were used to test for differences between the sediment variables of different status categories, e.g. Lost against Maintained, within each sample period. Wilcox Signed Rank tests (paired datasets) were used to test for differences in sediment variables between seasons and also between years.

2.4. Spearman Rank correlations.

Non-parametric Spearman Rank correlation tests were conducted between each of the biological metrics and each of the sediment variables for each sampling period using SPSS version 23 (IBM, 2015) as the datasets were non-normally distributed and un-transformable.

3. Results

3.1. PSI, CoFSI and E-PSI Scores

The average PSI scores for each status category for each sample period, and the average number of scoring taxa for each status category are presented in Table 1 (see also Supplementary Material Appendix D for full list of PSI, CoFSI and E-PSI scores, and for details of the invertebrate communities present). Across all sampling periods, the majority of sites were either minimally sedimented/unsedimented (i.e. PSI scores between 81-100) or slightly sedimented (PSI scores 61-80) (Table 2). Only one site (34C100300 – Lost status) had a PSI score that classified it as sedimented, although this site fluctuated between slightly sedimented and moderately sedimented by Summer 2017. Between Spring and Summer for both years, the number of sites that were minimally sedimented/unsedimented decreased, while in contrast, the number of slightly sedimented sites increased (Table 2).

Analysis of PSI scores found a significant difference between Maintained and Lost sites in Spring 2016, Summer 2016, Spring 2017 and Summer 2017, with p values of 0.014, 0.017, 0.043 and 0.016, respectively. For all significant differences Maintained sites had significantly greater PSI scores than Lost sites. Across all sampling periods, no significant difference in PSI scores was found between Lost and Gained sites, and Maintained and Gained sites. Analysis over the two years of sampling found no difference between PSI scores from Spring 2016 and Spring 2017, or between Summer 2016 and Summer 2017. Seasonal analysis found a significant difference between Spring 2016 and Summer 2016 ($p = 0.014$) and between Spring 2017 and Summer 2017 ($p < 0.01$), with Spring scores being greater than Summer scores for both years ($p < 0.01$). Within the Maintained category there were no significant differences between Maintained PSI scores in Spring 2016 and Spring 2017, and Summer 2016 and Summer 2017, but there were seasonal differences between Spring 2016 and Summer 2016 ($p = 0.045$), and

Spring 2017 against Summer 2017 ($p = 0.013$). Spring scores were greater than Summer scores in 2016 ($p = 0.022$) and 2017 ($p < 0.01$). Within the Lost and Gained categories only seasonal differences were found: between Spring and Summer 2017 ($p = 0.026$ - Lost); and Spring and Summer 2016 ($p = 0.05$ - Gained). Spring scores were greater than Summer scores on each occasion.

[Insert Table 1]

[Insert Table 2]

For the variable CoFSI, statistical differences were only found in Spring 2016, between Lost and Maintained ($p = 0.041$) and Lost and Gained ($p = 0.048$), with Lost being lower on both occasions, ($p = 0.02$ and $p = 0.024$, respectively). Significant yearly differences in CoFSI scores between Spring 2016 and Spring 2017, and between Summer 2016 and Summer 2017 were found, both at $p < 0.01$. Seasonal differences, between Spring 2016 and Summer 2016, and between Spring 2017 and Summer 2017, were also found, with both again at $p < 0.01$.

Within the Gained and Maintained status categories, there were significant differences between CoFSI values found in: Spring 2016 and Spring 2017 (Gained - $p = 0.038$; Maintained - $p = 0.029$); Spring 2016 and Summer 2016 (both $p < 0.01$); and Spring 2017 and Summer 2017 (both $p < 0.01$). Within the Lost status category, there was a significant difference only between CoFSI values found in Spring 2017 and those found in Summer 2017 ($p < 0.01$).

All sample sites, with the exception of site 34C100300 (Lost) in Spring 2016 (which had an E-PSI score of 55.08), had an E-PSI score greater than 70. E-PSI statistical differences were only found between Lost and Maintained, with these differences occurring in Spring 2016 ($p = 0.021$), Summer 2016 ($p = 0.034$), Spring 2017 ($p < 0.01$) and Summer 2017 ($p = 0.016$). On each occasion Maintained scores were greater than Lost scores. No yearly differences in E-PSI scores were found, although seasonal differences, between Spring 2016 and Summer 2016 ($p = 0.031$), and between Spring 2017 and Summer 2017 ($p < 0.01$), were found, with Spring scores being greater than Summer scores on each occasion. Within the Gained status category, no differences between years or between seasons were found. Within the Lost and Maintained status categories, there were significant differences between E-PSI values found in Spring 2017 and Summer 2017 (both $p < 0.01$); while Spring 2017 and Summer 2017 had a p-value of 0.054 in the Maintained category; and Spring 2016 and Spring 2017 had a p-value of 0.082 in the Lost category.

3.2. Physical sediment properties

The average Scope, Depth, Tile, % Fine and Quorer scores are presented in Tables 3 and 4, with a full list of scores for the sixty-five sample sites presented in Supplementary Material Appendix D, Tables D4 and D5. The highest % Fine score occurred in Summer 2017 at site 32O040250 (64 %), with the highest Quorer score (6.3 g m^{-2}) occurring in Summer 2016 at site 34Y020275. The highest Scope score occurred at site 26I030300 in Spring 2016 and the highest Depth score (14.67 cm) occurred at site 34Y020275 in Spring 2016. For all the physical sediment variables, for each sampling period, the only significant difference between any of the status categories, was in Summer 2017 for the Quorer between Gained and Lost, with a p value of 0.03. Significant differences (yearly) for Depth and Tile scores recorded in Spring 2016 and those recorded in Spring 2017 were found, both at $p < 0.01$, while Scope ($p = 0.011$) and Quorer ($p = 0.013$) scores recorded in Summer 2016 were significantly different from those recorded in Summer 2017.

[Insert Table 3]

[Insert Table 4]

3.3. Spearman Rank correlations between physical and biological variables

In general, each of the physical sediment variables across all seasons displayed significant moderate to strong relationships with each of the other physical sediment variables (Tables 5 and 6). The strongest relationships were observed between Quorer and Tile (excluding Summer 2017), and between Scope and % Fine. The weakest relationship occurred in Spring 2016 between Depth and Quorer. Of the biological variables, E-PSI and PSI had the strongest significant relationships with the physical sediment variables. Negative weak to moderate relationships between these variables and the physical variables were observed, with stronger relationships tending to occur in the Summer sampling periods. The strongest relationship occurring in Spring 2016 was between E-PSI and % Fine; in Summer 2016 was between E-PSI and Scope; in Spring 2017 was between PSI and Quorer; and in Summer 2017 was between PSI and Tile. Strong/very strong relationships were observed between the E-PSI and PSI variables. With the exception of Depth in Summer 2016, no significant relationship between CoFSI and any of the physical sediment variables was observed, nor between CoFSI and PSI or E-PSI. A comparison of each sediment variable across each season is presented in Supplementary Material Table D6.

[Insert Table 5]

[Insert Table 6]

4. Discussion

The general trend across all sample sites and seasons was for invertebrate taxa that are either highly sensitive or moderately sensitive to sediment to dominate in terms of taxa present and abundances. This was reflected in the PSI scores which, with the exception of four sites across all sampling periods, were all above the slightly sedimented base score of sixty-one. Similarly, E-PSI scores, which were predominantly above 70 %, indicated a dominance of sediment sensitive taxa. However, significant PSI and E-PSI score differences were found between sites classified as Lost and Maintained for all sampling periods, with Maintained sites scoring higher than Lost sites, indicating that invertebrate communities in Maintained sites were more sediment sensitive. Additionally, Lost sites had a greater number and proportion of sites classified as slightly sedimented, in comparison to Maintained and Gained. While the significant differences between Lost and Maintained for PSI and E-PSI scores implies that deterioration in status is associated with sediment, the lack of any significant difference in PSI and E-PSI scores between Lost and Gained highlights an important caveat. However, this caveat may be associated with the fluctuating nature of Gained sites and their potential to drop in and out of high status over several sampling periods, in comparison to the consistently high status of Maintained sites.

Although only recently introduced, several studies have utilised PSI scores for assessing sediment pressures (Poole et al., 2013; Glendell et al., 2014; Conroy et al., 2016a; Bradley et al., 2017; Extence et al., 2017). Extence et al. (2017) for example, found using a national data set, a significantly strong ($r^2 = 0.597$) relationship between PSI scores and a channel substrate index (CSI) designed to assess levels of fine sediment. Glendell et al. (2014) similarly, found a significant relationship between PSI and percent fine bed sediment cover, although no relationship between PSI and three other sediment assessment variables (two suspended sediment – including a Quorer method; and % exceedance method) was observed. Conroy et al. (2016a) and Turley et al. (2014) both found PSI to correlate with sediment cover, although Conroy et al. (2016a) found a stronger relationship with sediment cover for percent EPT (Ephemeroptera, Plecoptera and Trichoptera).

Here, the Spearman Rank analysis found both PSI and E-PSI were more associated with the physical sediment variables than CoFSI, although only negative weak to moderate relationships were observed. Glendell et al. (2014) suggests the lack of a relationship between PSI and the suspended sediment variables in their study may have been related to the sample resolution, with suspended sediment being measured at the patch scale, while invertebrate monitoring for the PSI was conducted at the reach level. While similar sampling practices (i.e. patch for suspended sediment and reach scale for invertebrates) were conducted in this study, with the exception of PSI in Spring 2016 and Summer 2017, a moderate relationship was observed between PSI, E-PSI and suspended sediment (Quorer).

In contrast to the PSI and E-PSI scores, CoFSI only found a significant difference between Lost and Maintained sites in one sampling period (Spring 2016). Other studies found a strong negative correlation between CoFSI and fine sediment levels, and strong positive correlations between CoFSI and PSI and E-PSI (Murphy et al., 2015; Turley et al., 2016). Here, however, Spearman Rank correlations found no relationship between CoFSI scores and (with the exception of Depth in Summer 2016) any of the physical sediment analysis methods, in strong contrast to the PSI and E-PSI metrics. This perhaps suggests that the CoFSI metric may need to be re-appraised prior to application at minimally impacted Irish sites. CoFSI, for example, was calibrated using empirical data from stream sites located in England and Wales (Murphy et al., 2015), as opposed to the PSI index which was primarily developed based on literature and expert knowledge, and the E-PSI index which is a combination of the PSI and optimal weightings extracted from an empirically generated training dataset (Turley et al., 2016).

Despite the observed relationships between PSI, E-PSI and the sediment variables, with the exception of Gained against Lost for the Quorer method in Summer 2016 and Summer 2017, no difference between the three status categories was observed for any of the five physical sediment analysis methods. Contrary to the PSI and E-PSI scores, the lack of a significant difference between Lost and Maintained, and Lost and Gained, for the physical sediment variables implies sediment is not a significant factor associated with the deterioration of the HSWs, at least with the methods employed here. This contradiction is difficult to explain. While sampling resolution reasons may hold true for the two re-suspension techniques (Quorer and Tile), the visual assessment method is more of a reach scale assessment. Several studies have demonstrated the benefits of visual assessment methods for assessing sediment (Zweig and Rabeni, 2001; Sutherland et al., 2012; Conroy et al., 2016c). While visual assessments may be somewhat subjective in nature and potentially susceptible to operator bias (but see Conroy et al., 2016c), this may be limited when, as in this study, all assessments are carried out by a single operator (Zweig and Rabeni, 2001).

One possible explanation may be related to the nature and properties of sediment that were not examined in this study. These properties include the chemical/nutrient composition of the sediment and its potential to alter the chemical composition of receiving waters, and the possible presence of further contaminants (e.g. pesticides) on the sediment solids (e.g. Bilotta and Brazier, 2008; dos Reis Oliveira et al., 2018; Wolf et al., 2020). The potential for differences between status categories based on these sediment characteristics requires further investigation, especially as the five physical sediment assessment methods used in this study were only focused on sediment concentrations. These properties may also be a factor related to the weak relationship observed between the PSI and E-PSI, and the physical sediment variables. Additionally, Conroy et al. (2016a) in a mesocosm study, found PSI scores at very high sediment loadings, to be far in excess of that expected, and questioned the suitability of the PSI metric to accurately assess sediment pressures. Furthermore, Buendia et al. (2013) found *Baetis* to be sediment tolerant, which differs from the sensitive classification within the PSI metric (Extence et al., 2013), although other studies have reported declines in the abundance of *Baetis rhodani* in response to increased levels of sediment (Larsen et al., 2011). Resilience of taxa, conferred from for example, less specialised feeding habits and high fecundity rates, may potentially lead to misleading conclusions with biotic metrics (Buendia et al., 2013), such as with the PSI and E-PSI metrics.

Low to moderate increases in silt may impact invertebrate communities (Larsen et al., 2011), with this potentially having a disproportionally large impact on HSWs, in comparison to the same silt increase in already degraded water-bodies (White et al., 2014). Furthermore, there is a risk in assuming that biological communities from different rivers and streams share a uniform response to the same pressure, especially given the potential interaction of multiple stressors, and the possibility of certain taxa developing a resilience to specific stressors (Turley et al., 2016). The interaction of stressors may be antagonistic - whereby two or more stressors are acting on the same species therefore their net effect is less than, for example, the same stressors acting individually on different species; or synergistic – where a species is only impacted by a combination of stressors; additive – where different stressors act on different taxa; or reversal – where one stressor reverses the impact of another stressor (Jackson et al., 2016), although see also Gieswein et al. (2017). Disentangling specific stressors, and the impact individual parameters have on benthic organisms is therefore difficult (Rempel et al., 2000; Marzin et al., 2012). Matthaei et al. (2010), in an experiment to assess the multiple stressor effects of sediment, water abstraction and nutrient enrichment, found the interaction between reduced flow and sediment addition to have the most impact on biological parameters. This interaction between multiple stressors, such as sediment, streamflow and general/organic pollution, at HSW sites in particular, should be urgently examined further.

Seasonal differences for PSI and E-PSI were found in this study, with Spring scores being greater than Summer scores. This contrasts with Glendell et al. (2014), who did not find any seasonal differences between PSI scores, although a difference between years was observed, while Poole et al. (2013) found PSI scores were higher in Autumn in comparison to Spring scores. The decreasing PSI (and E-PSI) Summer scores in this study were primarily driven by a reduction in sensitive taxa (Groups A and B – see Supplementary Material Figures D.1 and D.2), with Table 2 also conveying shifts from minimally sedimented/unsedimented to slightly sedimented during this period. This may partially be explained by life cycle strategies, with for example, the Group A taxa *Rhithrogena* sp., which are univoltine and over-winter as larvae before emerging as adults in the Summer months (Elliott and Humpesch, 2012), occurring in high numbers during Spring samples in this study, but with seldom occurrence in Summer samples. Similarly, *Isoperla grammatica*, which were again prominent in Spring samples but relatively absent in Summer, emerge as adults during Summer months in Ireland, although nymphs may occur for two Summers and the overwintering prior to emergence (Feeley et al., 2016). However, this requires further investigation to fully appreciate the observed seasonal differences.

Seasonal differences for three and four of the physical sediment variables were also observed in 2016 and 2017, respectively. With the exception of Tile, Spring sediment levels were greater than Summer levels. Sherriff et al. (2018) highlights some evidence of seasonal increases in sediment, which were attributed in part to extreme rainfall events (but see Thompson et al., 2014). Seasonal variation in sediment is important, especially in relation to life cycle stages of aquatic biota. For example, excessive suspended sediment during redd construction and egg incubation periods for spawning salmon, is likely to be more detrimental, than for the same increase in sediment occurring during winter (Bilotta and Brazier, 2008). The lower biotic metric scores in Summer along with the lower Summer sediment levels, again adds weight to the influence of life cycle strategies as the reason for seasonal discrepancies in biotic metric scores observed in this study, although this again may be associated with the unexplored properties of the sediment. Finally, the results of this study may serve as a baseline with which to compare future sediment/invertebrate analysis especially in relation to HSWs in Ireland. The extensive survey and assessment approach may also serve as a foundation for HSW surveillance elsewhere.

5. Conclusions

This study found that, although HSWs are pre-dominantly made up of taxa which are sensitive to sediment, for two sediment specific metrics, the PSI and E-PSI, significant differences were observed between sites that Lost status and those that Maintained status, implying that sediment is impacting on macro-invertebrates at some sites. The lack of any significant difference between Lost and Gained sites, however, leaves an important caveat. With the exception of one sampling period, no relationship was observed for a third metric the CoFSI, which may need to be re-assessed for use in Irish HSWs. Contrastingly, although weak to moderate relationships were observed between PSI, E-PSI and the physical sediment variables, no difference between status categories for any of the physical sediment variables was observed, although this may be related to the sampling resolution and/or the nature and properties of the sediment itself. The potential interaction of multiple stressors, such as sediment, streamflow and general/organic pollution, may additionally explain some discrepancies, and this is something that should be urgently examined further. Finally, although seasonal differences were observed in this study, a likely explanation for this is the life cycle characteristics, specifically adult emergent times, of certain taxa, and this should also be prioritised for further investigation.

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Table 1. The average PSI, E-PSI and CoFSI scores for each status category (Gained, Lost and Maintained) for Spring and Summer 2016, and for Spring and Summer 2017, with standard deviation in parenthesis.

	Spring 2016			Summer 2016		
	PSI	**CoFSI**	**E-PSI**	**PSI**	**CoFSI**	**E-PSI**
All	81.62 (9.4)	126.27 (22.5)	94.56 (7.0)	80.47 (7.5)	111.05 (23.0)	93.88 (5.7)
Gained	82.79 (4.9)	131.75 (21.5)	95.52 (3.7)	80.44 (5.6)	113.42 (25.9)	93.88 (4.0)
Lost	77.05 (12.3)	115.52 (23.6)	91.42 (10.3)	77.82 (6.6)	105.84 (24.5)	92.2 (6.4)
Maintained	84.37 (8.3)	130.2 (19.2)	96.34 (4.7)	82.57 (8.8)	112.96 (17.8)	95.18 (6.0)

	Spring 2017			Summer 2017		
	PSI	**CoFSI**	**E-PSI**	**PSI**	**CoFSI**	**E-PSI**
All	83.12 (6.3)	137.87 (27.1)	95.8 (3.9)	79.39 (8.6)	101.61 (24.4)	93.06 (6.1)
Gained	82.48 (5.8)	143.72 (22.3)	95.42 (3.8)	80.03 (7.1)	104.68 (29.9)	93.58 (5.4)
Lost	81.3 (7.0)	125.99 (34.1)	94.54 (4.1)	75.57 (9.9)	101 (21.9)	90.53 (6.9)
Maintained	85.19 (5.6)	142.66 (20.6)	97.19 (3.4)	82.27 (7.1)	99.37 (20.5)	94.9 (5.1)

Table 2. Number of sites with PSI scores as per Extence et al. (2013) of: 81-100 - Minimally sedimented/unsedimented; 61-80 - Slightly sedimented; 41-60 - Moderately sedimented; 21-40 - Sedimented; and 0-20 - Heavily sedimented; for each status category (Gained, Lost and Maintained) for Spring and Summer 2016, and for Spring and Summer 2017.

Interpretation of PSI scores	**Spring 2016**				**Summer 2016**			
PSI River bed condition	**Gained**	**Lost**	**Maint.**	**Total**	**Gained**	**Lost**	**Maint.**	**Total**
81–100 Min. sedim./unsedim.	16	10	19	45	11	6	16	33
61–80 Slightly sedimented	5	9	4	18	10	12	6	28
41–60 Moderately sedimented			1	1			1	1
21–40 Sedimented		1		1				
0–20 Heavily sedimented								

Interpretation of PSI scores	**Spring 2017**				**Summer 2017**			
PSI River bed condition	**Gained**	**Lost**	**Maint.**	**Total**	**Gained**	**Lost**	**Maint.**	**Total**
81–100 Min. sedim./unsedim.	16	12	18	46	8	6	15	29
61–80 Slightly sedimented	5	8	6	19	12	13	7	32
41–60 Moderately sedimented						1		1
21–40 Sedimented								
0–20 Heavily sedimented								

Table 3. The average Scope (%), Depth (cm) and Tile (score between 1-5) scores for the sixty-five sample sites during Spring 2016, Summer 2016, Spring 2017 and Summer 2017, with standard deviations in parenthesis.

	Scope (%)				**Depth (cm)**				**Tile (score bet. 1-5)**			
	Spring 2016	**Summer 2016**	**Spring 2017**	**Summer 2017**	**Spring 2016**	**Summer 2016**	**Spring 2017**	**Summer 2017**	**Spring 2016**	**Summer 2016**	**Spring 2017**	**Summer 2017**
All	15.2 (15.8)	14 (18.5)	14 (18.6)	8.5 (14.6)	1.6 (2.4)	0.6 (1.1)	0.8 (1.8)	0.5 (2)	2.6 (1)	3 (1.1)	3 (1)	3 (1)
Gained	15.5 (17.5)	12.4 (19.4)	16.1 (23.3)	7.6 (13.5)	2.3 (3.3)	0.9 (1.5)	1 (2.8)	1 (3.1)	2.8 (1.1)	3.1 (1.1)	3.2 (1)	3.4 (1.1)
Lost	15.7 (15.5)	12.1 (20.7)	12.9 (11.9)	8.8 (18.4)	1 (1.9)	0.4 (1.1)	1 (1)	0.4 (1.2)	2.5 (1.1)	3.1 (0.9)	2.8 (1.1)	3 (0.9)
Maintained	14.5 (11.4)	17 (15.1)	13 (17)	9.1 (12)	1.4 (1.3)	0.6 (1)	0.4 (0.5)	0.4 (1)	2.5 (0.8)	2.9 (1.1)	3 (0.9)	2.6 (0.6)

Table 4. The average % Fine (%) and Quorer (g m^{-2}) scores for the sixty-five sample sites during Spring 2016, Summer 2016, Spring 2017 and Summer 2017, with standard deviations in parenthesis.

	% Fine				Quorer (g m^{-2})			
	Spring 2016	**Summer 2016**	**Spring 2017**	**Summer 2017**	**Spring 2016**	**Summer 2016**	**Spring 2017**	**Summer 2017**
All	11.3 (12.6)	10.4 (12)	11.9 (13.6)	9.9 (13.5)	0.6 (1.1)	0.3 (0.4)	0.5 (0.5)	0.2 (0.2)
Gained	10.5 (14.5)	8 (9)	12.6 (17.7)	10.8 (16.6)	0.9 (1.3)	0.3 (0.3)	0.6 (0.6)	0.2 (0.1)
Lost	12.7 (13.2)	11.4 (15.4)	10.5 (8.1)	11.4 (14.8)	0.5 (1.1)	0.4 (0.6)	0.4 (0.4)	0.2 (0.1)
Maintained	10.6 (7.1)	11.8 (10.8)	12.5 (13.2)	7.5 (6.3)	0.5 (0.2)	0.4 (0.3)	0.4 (0.2)	0.2 (0.3)

Table 5. Spearman Rank correlations between each physical sediment variable (Scope, Depth, Tile, % Fine and Quorer) and biological indices (PSI, CoFSI and E-PSI) for Spring 2016 and Summer 2016.

Spring 2016	Scope	Depth	Tile	% Fine	Quorer	PSI	CoFSI	E-PSI
Scope	1	0.582**	0.539**	0.755**	0.434**	-0.347**	-0.007	-0.554**
Depth	0.582**	1	0.462**	0.486**	0.388**	-0.342*	0.053	-0.455**
Tile	0.539**	0.462**	1	0.530**	0.734**	-0.293*	0.008	-0.494**
% Fine	0.755**	0.486**	0.530**	1	0.451**	-0.437**	-0.133	-0.595**
Quorer	0.434**	0.388**	0.734**	0.451**	1	-0.211	-0.051	-0.381**
PSI	-0.347**	-0.342*	-0.293*	-0.437**	-0.211	1	0.160	0.806**
CoFSI	-0.007	0.053	0.008	-0.133	-0.051	0.160	1	0.047
E-PSI	-0.554**	-0.455**	-0.494**	-0.595**	-0.381**	0.806**	0.047	1

Summer 2016	Scope	Depth	Tile	% Fine	Quorer	PSI	CoFSI	E-PSI
Scope	1	0.508**	0.562**	0.689**	0.531**	-0.588**	-0.109	-0.618**
Depth	0.508**	1	0.605**	0.532**	0.608**	-0.348**	-0.317*	-0.400**
Tile	0.562**	0.605**	1	0.405**	0.763**	-0.571**	0.070	-0.520**
% Fine	0.689**	0.532**	0.405**	1	0.337**	-0.2254	-0.155	-0.271*
Quorer	0.531**	0.608**	0.763**	0.337**	1	-0.472**	0.114	-0.532**
PSI	-0.588**	-0.348**	-0.571**	-0.225	-0.472**	1	-0.063	0.868**
CoFSI	-0.109	-0.317*	0.070	-0.155	0.114	-0.063	1	-0.176
E-PSI	-0.618**	-0.400**	-0.520**	-0.271*	-0.532**	0.868**	-0.176	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 6. Spearman Rank correlations between each physical sediment variable (Scope, Depth, Tile, % Fine and Quorer) and biological indices (PSI, CoFSI and E-PSI) for Spring 2017 and Summer 2017.

Spring 2017	Scope	Depth	Tile	% Fine	Quorer	PSI	CoFSI	E-PSI
Scope	1	0.610**	0.560**	0.665**	0.489**	-0.249*	-0.106	-0.352**
Depth	0.610**	1	0.466**	0.519**	0.519**	-0.241	-0.207	-0.373**
Tile	0.560**	0.466**	1	0.545**	0.693**	-0.272*	-0.108	-0.358**
% Fine	0.665**	0.519**	0.545**	1	0.469**	-0.240	-0.180	-0.383**
Quorer	0.489**	0.519**	0.693**	0.469**	1	-0.426**	-0.198	-0.406**
PSI	-0.249*	-0.241	-0.272*	-0.240	-0.426**	1	0.086	0.824**
CoFSI	-0.106	-0.207	-0.108	-0.180	-0.198	0.086	1	-0.020
E-PSI	-0.352**	-0.373**	-0.358**	-0.383**	-0.406**	0.824**	-0.020	1

Summer 2017	Scope	Depth	Tile	% Fine	Quorer	PSI	CoFSI	E-PSI
Scope	1	0.638**	0.763**	0.805**	0.611**	-0.496**	-0.026	-0.490**
Depth	0.638**	1	0.586**	0.630**	0.472**	-0.411**	0.090	-0.421**
Tile	0.763**	0.586**	1	0.613**	0.589**	-0.557**	0.007	-0.528**
% Fine	0.805**	0.630**	0.613**	1	0.475**	-0.508**	-0.092	-0.530**
Quorer	0.611**	0.472**	0.589**	0.475**	1	-0.351**	0.132	-0.443**
PSI	-0.496**	-0.411**	-0.557**	-0.508**	-0.351**	1	-0.090	0.837**
CoFSI	-0.026	0.090	0.007	-0.092	0.132	-0.090	1	-0.200
E-PSI	-0.490**	-0.421**	-0.528**	-0.530**	-0.443**	0.837**	-0.200	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

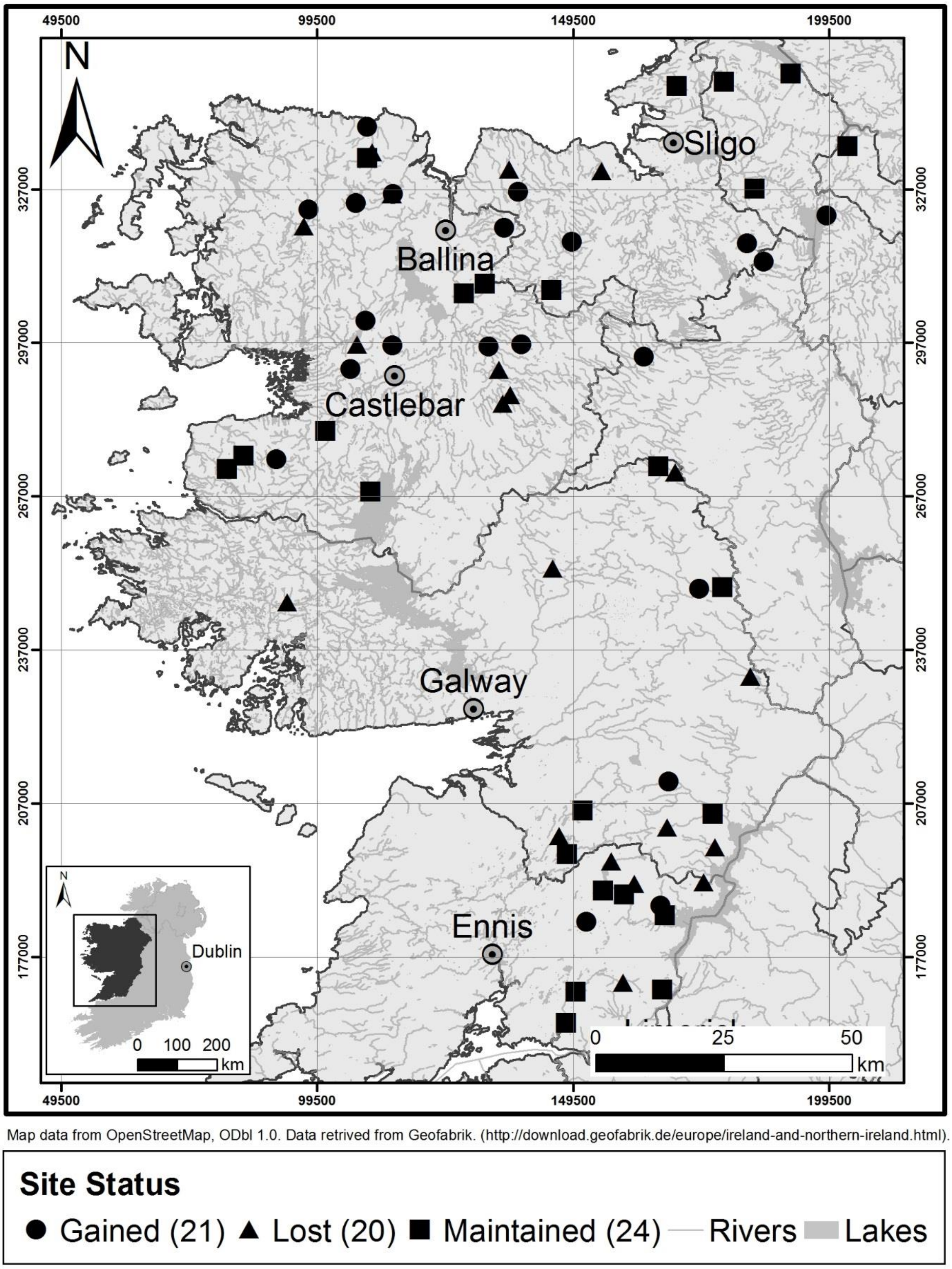

Figure 1. Location of the sixty-five sampling sites in the west of Ireland that are categorised as having either: Lost their high status (e.g. gone from high to good, moderate, poor or bad); consistently Maintained high status; or Gained in status (e.g. from good to high).

CRediT author statement

Gabriel Gaffney: Conceptualization, Methodology, Data curation, Investigation, Analysis and interpretation of data, Writing original draft manuscript, Editing and draft reviews

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: