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A review of techniques for the monitoring of fine sediments: Discussion document to inform workshop

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1 Summary of findings

1) **The specific objectives of the fine sediment monitoring programme must be clearly defined**. This will determine which parameters should be monitored, where, at what frequency and for how long and so ensure that monitoring is fit for purpose.

2) The following **seven parameters can contribute to understanding fine sediment dynamics** and their effects on the FPM habitat:

- Stream water parameters: suspended sediment, flow, turbidity.
- Streambed parameters: sediment deposition rate, median grain size, redox potential and dissolved oxygen (DO) in free-flowing and pore water.

3) **Preliminary stream water surveys are required** at each site to determine whether single-point monitoring is representative of the within-reach spatial variability.

4) **Investigations at different scales are needed to describe different aspects of the sedimentary processes in a catchment:**

- Catchment-wide investigations - used to establish sediment sources, movements and dynamics.
- Reach scale assessments - used to provide information about local sedimentary conditions and offer the opportunity to use techniques that are not suitable for use amongst FPMs.
- Studies in freshwater pearl mussel beds - used to assess habitat condition.

5) **Relating dissolved oxygen (DO) and redox potential in the pore water to fine sediments needs further research**. This work should draw on evidence from other countries and for other species.

2 Background

Fine sediments (particles <2mm) in rivers and streams generally result from land management activities such as forestry, agriculture or development. Their ecological effects can be highly damaging (Owenes et al., 2005). In suspension, fine particles interfere with biological processes (e.g. reduced sunlight penetration impairs plant growth) and behaviours (e.g. restricting the ability to find prey). When deposited, fine sediments can smother the riverbed and restrict the infiltration of oxygen-rich free-flowing water. They also introduce organic matter and nutrients, which can increase biochemical oxygen demand (BOD) and promote eutrophication. Once present in a river system, fine sediments have the potential to cause a long-term cycle of environmental damage due to repeated mobilisation and resettlement.

Fine sediment is thought to be one of the principal pressures affecting the Freshwater pearl mussel (FPM) in Scotland - detrimental effects include prevention of feeding, damage to gills/ feeding structures, and degradation of inter-gravel habitat (CEN, 2016). However, as there is no agreed method for monitoring and regulating fine sediment in UK rivers, it is difficult to assess the extent of problems that may be affecting FPM sites and to target remedial measures effectively. Therefore, there is a desire to establish a monitoring programme in Scotland in order to better understand the effects of fine sediment on FPMs (alongside other water quality issues), targeted to those designated sites where populations are in unfavourable condition.

A workshop to be held at SNH, Battleby on 1 July 2016 will bring together experts in the field to inform the design of a fine sediment monitoring programme which will be tested at key FPM sites in Scotland. This review of fine sediment monitoring techniques was commissioned by SNH to form the basis of this workshop. Key questions addressed are:

a) Which parameters should be monitored to assess the levels and effects of fine sediments in watercourses supporting freshwater pearl mussels?
b) Which sampling techniques are suitable in Scotland?
c) What are the advantages and disadvantages of these techniques?

3 Methods

A literature review, complimented by discussions with workers in the field, was undertaken to establish the parameters and techniques that are relevant to monitoring fine sediments in the context of FPM catchments in Scotland. The different techniques were compared and assessed in the context of factors relating to FPMs e.g. habitat, tolerance limits, regulatory criteria and disturbance issues.

4 General points

Definitions of ‘fine sediment’ are inconsistent, making it difficult to compare data from different studies. The term may refer to:

- Suspended and/or streambed particles; this relates to the parameters being monitored (Edwards & Glysson, 1999; Gray & Landers, 2014).
- Suspended particles smaller than 2, 1, or 0.063 mm (e.g. Wood & Armitage, 1997; Owens et al., 2005; Kidner & Roesner, 2007); this relates to technique selection (e.g. Perks, 2014).
- Suspended particles larger than 0.45 - 2 μm; this relates to analytical cost and interpretations (e.g. APHA, 1999; Marquis, 2005; Grove et al., 2015; Sheriff et al., 2015).
- Different analytical and sampling techniques may produce different results and interpretations (APHA, 1999; Edwards & Glysson, 1999; Gray & Landers, 2014).

At least seven parameters are central to understanding the dynamics of fine sediments and their effects on the FPM habitat:

- Stream water parameters: suspended sediment, flow, turbidity.
- Streambed parameters: sediment deposition rate, median grain size, redox potential and dissolved oxygen (DO) in the pore water.

The advantages and disadvantages of the sampling techniques referring to each of these fine sediment parameters are presented in Tables 1A and 1B.

5 Parameters and techniques

Suspended sediments

1) Suspended sediment varies temporally and spatially:

- Particle size distribution and concentration vary with flow, between streams, and between verticals and points in the cross section of the channel (Edward & Glysson, 1999).
- Approximately 90% of the annual mass of sediment is

transported within approximately 10% of the time (during storm flows) (e.g. Walling and Webb, 1987). Therefore, sampling during high flow events is crucial to understanding suspended sediment dynamics.

2) Suspended sediment concentration is usually monitored using a combination of manual (e.g. spot sampling) and automated methods (Edwards & Glysson, 1999; Perks 2014). Manually collected data provide the benchmark for comparisons and corrections of data from automatic samples (USGS, 2011). Automated samples give the ability to measure episodic inputs (which are often missed by routine sampling programmes).

3) There are no guidelines as to the suspended sediment concentrations (SSC) required to maintain or restore biological integrity in a given environment but it is known that some aquatic organisms are sensitive to changes in the duration, frequency and timing of suspended sediment concentrations, collectively referred to as the "suspended sediment regime" (Grove et al., 2016).

4) Monthly sampling is sufficient to assess compliance with water quality guidelines (e.g. Grove et al., 2016). However, at sites where biological community composition and function have been impacted by high suspended sediment loads, a 24/7 sampling regime (one sample collected every 7 h, leading to 24 samples a week) is the optimum sampling strategy in terms of:

- Accuracy - mean concentrations calculated from this regime are, on average, within 2% of the mean concentrations calculated from 15-min frequency data.
- Practicality - samples can be collected by an automated sampler.
- Suitability to assess effect-response relationships (e.g. Jordan and Cassidy, 2011; Akoumianaki et al., 2016; Grove et al., 2016).

5) Key monitoring considerations for suspended sediments (Edwards & Glysson, 1999; Quinlan et al., 2015; Webb et al., 1997 Perks 2014; Gray & Landers (2014) include:

- Depth of sampling and point of sampling in the cross section.
- The need for paired measurements (same site/time) of suspended sediment and flow (particle size and concentrations vary with flow on a site-specific basis). This enables assessment of how SSC changes between and during runoff events.
- Concurrent continuous measurements of turbidity can be used to create a continuous SSC time-series.
- Frequency of sampling of suspended sediment/flow at regular intervals - hourly, daily, weekly or fortnightly sampling is preferable (as opposed to monthly) to ensure the entire range of sediment fluxes at a given site is captured.
- Sampling technique - some field sampling equipment may not be able to capture representatively all the range of suspended particle sizes at a given site.
- Laboratory technique. Two laboratory analytical methods are predominantly used to quantify concentrations of suspended sediments in surface waters: Suspended Sediment Concentration (SSC) and Total Suspended solids (TSS)[1]. For accuracy and comparability, suspended sediment should be measured as SSC, if this is not possible TSS needs to be inter-calibrated against SSC (Gray et al., 2000).

6) Suspended sediment data provide important information about the likely sediment sources and variations in fine sediment concentrations. However, measurements of suspended sediment alone cannot show whether/when fine sediments have caused dissolved oxygen declines in pore water (e.g. Quinlan et al., 2015).

Turbidity

7) Turbidity is an expression of cloudiness or 'murkiness' of water due to high suspended load and dissolved (smaller than 0.45μm in diameter) coloured material. It is the most common surrogate that is used for determining water clarity and calculating concentrations of suspended sediment (Gray & Landers, 2014).

8) Turbidity can be influenced by factors such as particle size and composition and the presence of dissolved humic or mineral substances (Marcquis, 2005; Gray & Landers, 2014).

9) Key monitoring considerations include (Marcquis, 2005; Gray & Landers, 2014):

- Site-specific calibration of the concentration of suspended sediment-turbidity relationship, because of the limited transferability of turbidity measurements to other sites.
- Flow-accounting calibration, because the suspended sediment-turbidity relationship depends on the variability in particle-size distribution of suspended sediment, which is flow-dependent.

Fine sediment deposition – siltation

10) Manual techniques involve collection of fine deposited material by agitating the riverbed and so induce sediment resuspension (Lambert and Walling, 1988; Collins and Walling, 2007; Quinn et al., 1997). The metric is g/m2. In general, these techniques are unsuitable for watercourses supporting FPMs due to (i) failure to provide a measurement of deposition rate in relation to stream water conditions (flow, suspended sediment) and (ii) the disturbance caused during handing of the equipment in-stream.

11) Automated techniques require the deployment of a sediment trap [2]. In gravel beds an infiltration basket is inserted in the streambed to collect settling particles over short periods to imitate the local conditions, flush with the streambed and filled and covered with a layer of coarse substrate material with same diameter as the streambed (e.g. Kozerski & Leuschen, 1999; 2000; Bond et al., 2002; Schindler-Widhaber et al., 2012; Mathers & Wood, 2016). The metric can be g/m2/day or mm/month. Sediment traps provide a reliable measurement of deposition rate and vertical exchange between stream water and streambed, and possibly of the colonisation potential of gravel beds.

12) A biomonitoring tool has been developed to assess sediment deposition: the Proportion of Sediment-sensitive Invertebrates (PSI) index is a sediment-sensitive macro-invertebrate metric which provides a proxy to describe the extent to which the surface of river beds are composed of, or covered by, fine sediments (Extence et al., 2011).This technique requires taxonomic data at a species level and quantitative data on sediment deposition, both of which are resource-intensive (Turley et al., 2014).

13) Key sampling considerations include (NEH, 2007; Hedrick et al., 2013):

- Patchiness, with fine sediment deposition being higher in pools rather than riffles within a stream-reach.

[1] SSC analysis refers to filtering the whole sample collected in the field whereas TSS analysis generally entails withdrawal of an aliquot of the original sample for subsequent analysis (Gray et al. 2002).

[2] The simplest sediment traps are box, pan, or tray type samplers, but more elaborate forms are also in use, such as suction traps; Whitlock-Vibert boxes (also used as fish-eggs incubators in gravel beds); and cylinders with perforated walls to account for horizontal movements of pore water and streambed organisms (Hedrick et al., 2013 and literature cited therein).

- Flow-dependence of siltation, which is usually elevated after events.

Streambed characterisation: grain size distribution

14) Characterising substrate grain size distribution is required to estimate median grain size, silt and clay percentage and indices (e.g. sorting coefficient), which can help in assessing changes in FPM habitat (Quinlan et al., 2015).

15) There are several techniques:

- Bulk sampling involves taking a sample of riverbed material using core, grabs or digging out larger areas defined by a quadrat. Bias in grain size distribution and fine fraction estimation can be caused by excluding larger particles, misleading assessments of mussel tolerances to fine sediment (Quinlan et al., 2015). Bulk sampling can destructive to FPM habitat and FPMs, especially at higher densities.
- Pebble counts (Hedrick et al., 2013) involve a structured grid of random sampling over a channel unit. The removal of clasts for measurement can be destabilising to mussel habitat.
- Visual assessment (e.g. percentage coverage according to the Wentworth scale) is non-destructive but does not characterise the deeper sediments occupied by juvenile FPMs.

16) The techniques can be combined to enable more accurate estimation of median grain size (Abtew and Powell, 2003).

17) The risk of disturbance limits potential sampling resolution in terms of both temporal frequency (e.g. monthly sampling is not recommended) and spatial resolution, e.g. every pool or riffle (Hedrick et al., 2013).

Pore water sampling: dissolved oxygen (DO)

18) Characterising DO in the pore water is key to understanding the factors influencing survival of juvenile FPMs (Quinlan et al., 2015). However, although the DO regime within gravel beds may be strongly influenced by the accumulation of fine sediment, DO studies of the pore water of gravel beds in Scotland indicated that interpretations or assumptions about fine sediment effects on the gravel habitat should be reassessed. Specifically, there are other factors affecting DO in pore water include surface water-groundwater exchange, thermal regime, and the consumption of oxygen by sediment and its associated organic matter (Sear et al., 2014).

- The role of flow and suspended sediment. During storm-flows the pore water environment is "re-set", as stream water ingresses into the sand/gravel streambed enriching it with oxygen and nutrients (Soulsby et al., 2009), but also, possibly, with fine sediments, which when deposited following storm flows infiltrate the gravel bed and clog intergravel space (Greig et al., 2007; Schindler-Wildhaber et al., 2014; Sear et al., 2014).
- The role of organic matter. A high organic matter content associated with the fine sediments infiltrating the streambed may lead to the formation of biofilms and, under elevated temperatures, increase oxygen demand due to microbial breakdown of the deposited organic material, thus reducing available DO in the pore water (Greig et al., 2007 and literature cited therein).
- The role of groundwater through stream water-groundwater exchange (Greig et al., 2007). Upwelling of oxygen-depleted groundwater has been found to lower DO in the pore water of gravel beds for periods that may be biologically too long (Soulsby et al., 2009; Sear et al., 2014). However, upwelling of oxygen-rich groundwater can counterbalance the effect of fine sediment accumulation on DO and packing of pool patches (Schindler-Wildhaber et al., 2014; Michel et al., 2014).
- Therefore, a crucial challenge is to collect pore water samples at temporal and spatial resolutions that capture the interplay between flow, fine sediments, organic matter and DO concentrations, as shown by studies in salmonid spawning grounds.

19) Dissolved oxygen in the pore water of FPM beds has been measured:

- Ex situ, by extracting a small sample of pore water for laboratory analyses (Budensiek et al., 1993).
- In-situ, using a hand-held optical sensor (e.g. Neil et al., 2014).
- In situ, using autonomous optode loggers (Quinlan et al., 2014). Continuous measurements are suitable when DO concentrations exhibit rapid fluctuations in relation to flow and upwelling groundwater and, thus, help assess the frequency of exposure to low DO.

20) Ex-situ and in situ, hand–held measurements of DO in the pore water are unsuitable for three main reasons (Quinlan et al., 2015): (i) failure to show the frequency/duration of low DO episodes experienced by FPMs (ii) risk from contamination by atmospheric oxygen (Murdoch and Azcue, 1995); and (iii) uncertainties in measuring vertical gradients.

21) Autonomous, in situ measurements with optode loggers in Scotland (Malcolm et al., 2006; 2009; Soulsby et al., 2009), England (Sear et al., 2014), and Germany (e.g. Riss et al., 2008; Schindler-Wildhaber et al., 2014) showed that in-situ continuous monitoring of DO in pore water can:

- Capture effectively the temporal variability and extremes in DO, particularly biologically important episodes of low DO; this can help identify frequency of exposure to low DO at a given site.
- Account for flow, groundwater and fine sediment effects on the variability of DO in the pore water.
- Collect reliable data throughout a six to twelve-month deployment without need for re-calibration (i.e. maintenance).
- Retrieve data at any time required.
- Cause minimum disturbance on the substrate.

22) Key monitoring considerations for continuous measurement of DO in the pore water include:

- Cost. For example, six optodes with associated cables and data logger cost approximately £25 000 (Quinlan et al., 2015). This may limit the spatial resolution of sampling.
- Long and labour-intensive calibration period before deployment. For example, Malcolm et al. (2006) reported a three-week period of calibration in the laboratory at a range of oxygen and temperature levels.
- Comparisons with data from ex-situ analyses at a given site. Oxygen extraction from pore water requires properly trained staff and fit-for-purpose equipment.

Pore water sampling: redox potential

23) Loss of redox potential between free flowing water and pore water has been shown to be significantly linked with FPM recruitment success (Geist and Auerswald, 2007; Gosselin et al, 2015). The technique has been used in the Germany (Geist), US, Ireland (work by Ian Kileen) and England (Gosselin et al, 2015) e.g. Irish FPM sites with juvenile recruitment were found to have no detectable differences between the redox potential (Eh) of the open water and the pore water at 5 or 10cm depth (North South Project 2, 2009).

24) Redox potential measures the rate of electron or oxygen transfer through reduction-oxidation (redox) chemical reactions going on side by side in water (Sigg, 2000). In the freshwater environment, redox is measured to track biogeochemical reactions and the presence of anoxic conditions (e.g. Christensen et al., 2001; Briggs et al., 2013; Heppell et al., 2014).

25) Redox potential is sensed by an inert platinum electrode (probe), upon which redox reactions take place, and read relative to a reference electrode. Redox measurements are often used in relation to other environmental parameters and often regarded more as a relative rather than an exact measurement (Søndergaard, 2010). Values indicate either an oxidising or reducing environment:

- Values above Eh[3] = 300 mV indicate predominance of oxygen and oxidised chemical species, e.g. iron(III); manganese(IV); and nitrates (Schlesinger, 1991).
- Values below Eh = 300 mV indicate a reducing environment, i.e. low, or lack of, oxygen, and predominance of reduced chemical species such as iron(II); manganese(II); ammonium; and low sulphate/high sulphide (Schlesinger, 1991).

26) Redox potential in the pore water of FPM beds has been measured in situ (hand-held). It is considered to be a proxy of the oxygenation of sediment compared to free flowing stream water (Geist and Auerswald, 2007; Irish EPA, 2012; Gosselin et al., 2015). Redox is suitable as a surrogate DO measurement when DO reduction in the pore water compared to free flowing stream water is linked to the deposition of fine sediment, a high content of organic matter and elevated temperatures, as in low-flows during summer months.

27) According to guidance by the Joint Nature Conservation Committee (JNCC, 2015) on FPM monitoring, redox surveys are a cost-effective way of: 1) Determining the reduction of available oxygen within the substrate compared with stream water as a result of fine sediment deposition and increased organic matter in the streambed. 2) Assessing anoxic conditions in the pore water environment during low flows in summer.

28) Key monitoring considerations (mainly related to accuracy of measurement) include:

- Correct location. It is essential to take measurements in apparently suitable FPM habitat. This requires a skilled FPM worker.
- Risk of misinterpretation. In the streambed environment, redox potential represents the intensity of biogeochemical reactions induced by burrowing fauna and microbial metabolism in relation to sediment organic matter content and temperature rather than oxygen concentrations (Christensen et al., 2000; Neil et al., 2014).
- Inconsistency. Although similar calibration procedures may be used, measurements may differ between different probes, perplexing comparisons (YIS-Technote, 2005).
- Need to maintain equipment. Regular maintenance is essential to ensure results are reliable and this may be the main factor in inconsistent results (I. Kileen, pers comm).
- Redox measurement can be very slow. Iron(II) and iron(II), which comprise the calibration solution, react within a few minutes with the redox (platinum) probe, but DO and other redox sensitive species in low concentrations react much more slowly (YIS-Technote, 2005).
- Temperatures during calibration and in the field should be comparable. Redox variation could be due to temperature changes compared to calibration rather than redox reactions; gross changes (>100 mV) are not due to the effect of temperature (YIS-Technote, 2005).
- Disturbance of redox conditions. Care must be taken not to introduce air or oxygenated water by inserting the redox probe carefully and taking readings quickly (Boyd, 2000).
- Difficulty in inserting the redox probe. Researchers from Scotland (author's experience) and Ireland (Neil et al., 2014) have reported difficulties, relating to insertion of the probe into coarse/gravel or compacted substrates.
- Redox potential data require careful interpretation e.g. redox potential measurements are unable to describe the oxygen requirements for juvenile FPMs (Quinlan et al., 2015).

Standards and criteria

29) In US/Canada, regulatory criteria have been developed for TSS/SSC, turbidity, median grain size, deposition rate and DO in pore water. See Table 2 and table of references.

30) European studies have proposed tolerance limits for TSS and median grain size. See Table 2 and references.

6 Recommendations

1) **Define the questions and objectives clearly and explicitly**. This will determine the spatial design, methods chosen and analytical techniques.

2) **Ensure that the monitoring programme will enable these objectives to be met**. Monitoring to understand the effects of fine sediment on FPM beds requires more parameters and comparisons, higher sampling frequency and finer spatial resolution (e.g. within-reach sampling sites) than monitoring to assess fine sediments as a water quality issue.

3) **Assess SEPA's suspended sediment data** (if available for the sites of interest). Key considerations include: frequency (e.g. is it weekly?); sampling sites (e.g. in relation to FPM sites and potential pressure on them?); flow gauging (e.g. are measurements for suspended sediment (or turbidity) concurrently (same site/time) taken with flow measurements?); parameter (e.g. is it SSC or TSS? Are turbidity measurements calibrated?)

4) **There are several considerations relating to automated suspended sediment monitoring**:

- Sampling should be based on a time-composite sampling method. This will enable the amount of sediment transported across the range of flows at a given site to be assessed cost-effectively; samples may be collected at 7-hourly intervals and composited, or not, upon retrieval on a weekly basis. Compositing is recommended on the grounds of practicality because it results in collecting 52 samples per year per site without missing any information.
- There are limitations due to the equipment being located at a single point in the catchment – complimentary data from a high resolution network of e.g. turbidity investigations may be necessary.
- Consider how (the large volumes of) date will be stored and analysed.

5) **Ensure that the needs for complementary samples have been considered and that these are taken at the same locations and times** e.g.; estimates of organic matter content of suspended sediment and in the streambed.

6) **Evaluate the transferability of the work on continuous measurement of DO in pore water** in salmonid spawning grounds in Scotland and FPM beds in England.

[3] Eh is the same as redox potential, the only difference being in the reference electrode (and thus the voltage offset) against which the potential of the platinum probe is reported. For example, redox readings calibrated with a pH $Ag/AgCl_2$ electrode and against a Zobell solution[3] can be converted to Eh values by simply adding 220 mV to redox (e.g. Geist and Auerswald, 2007)

7) **Evaluate the practicalities, evidence and limitations of the use of redox potential** to avoid misinterpretation of results and/or ensure reliable data collection.

- Redox potential as a parameter determining FPM recruitment success is not recommended at sites where: 1) DO concentrations fluctuate rapidly due to changes in stream water-groundwater exchange; 2) deposited fine sediments have low levels of organic matter and redox sensitive components.
- There are unknowns relating to its effectiveness as a proxy for the oxygen supply to juvenile FPMs should be evaluated against evidence about the causes and frequency of DO declines in the pore water and streambed organic matter content.
- A workshop held in Germany in May 2016 covered the monitoring of fine sediments for FPM conservation in detail (including use of the redox potential technique) and the information, knowledge and outputs from this workshop will be extremely beneficial in informing the design of the monitoring programme. A workshop to transfer the knowledge from this workshop to the Scottish context should be considered.

7 Tables

Table 1A: Summary of advantages and disadvantages of the techniques supporting the measurement of the parameters required for assessing fine sediments in streams with FPM beds: stream water parameters

Parameters	Sampling Technique	Operational principle	Advantages	Disadvantages
SSC/TSS	Manual – Ex situ	Spot sampling (single point /cross section	Measures suspended sediment concentration and particle size Accuracy Spatial representativeness (e.g. single point /vertical / cross section) Benchmark for data collected by autosampler/ measured in situ. Lower cost than automated sampling	Unsuitable for high frequency sampling Could be labour intensive at high spatial resolution. Unsuitable during high flows Requires concurrent measurement of flow (discharge)
SSC/TSS	Automated - Ex situ (autosampler)	Single-point pump sampling	Enables storm-flow sampling Suitable for high-frequency monitoring (e.g. hourly). Suitable for intensive stream water monitoring programmes Allows programming to fit needs (e.g. flow-proportional sampling, sampling at fixed intervals)	High resource needs: planning-maintenance /inter-calibration with manual methods/ cost Could be labour intensive when retrieval is required at a high frequency (e.g. weekly) Allows only single-point sampling at a site Bias risk for coarser sediment fractions Requires concurrent monitoring of flow (discharge)
Turbidity	In-situ (hand held or autonomous)	Probe measuring optical properties of a sample/stream water due to presence of sediment and coloured material	Easy, relatively low cost, use Autonomous data logging is suitable for long-term monitoring A network of sites can be covered for low cost	Measures stream water optical properties not suspended sediment concentrations Bias risk for certain particle sizes Requires inter-calibration with SSC/TSS, flow and temperature

SSC: Suspended sediment concentration; TSS: Total suspended solids. Source: Edwards & Glysson, 1999; Gray & Landers, 2014; Perks, 2014)

Table 1B: Summary of advantages and disadvantages of the techniques supporting the measurement of the parameters required for assessing fine sediments in streams with FPM beds: streambed parameters

Parameters	Sampling Technique	Operational principle	Advantages	Disadvantages
Median grain size	Manual – Ex situ	Grab (bulk) sampling and visual surveys	Enables understanding of FPM habitat	FPM habitat disturbance risk
Deposited fine sediment	Manual - Ex situ	Fine sediment resuspension (e.g. Quorer)	Enables assessments of fine sediment deposition Developed for gravels beds Widely used (e.g. UK) Low cost	FPM habitat disturbance risk Unsuitable to integrate sediment deposition during high flow and baseflow periods. Unsuitable for high flows/ high spatial resolution Suitable for fine sediment channel storage Unsuitable to assess MGS changes
Deposition rate	Automated - Ex situ	Sediment traps to sample sediment infiltrating streambed	Assesses siltation/colonisation Low cost Samples events/patches	Need to address site-specific conditions Risk of FPM habitat disturbance at a high spatial sampling resolution

Continuation of Table 1B

Parameters	Sampling Technique	Operational principle	Advantages	Disadvantages
DO pore water	Manual – Ex situ	Extraction of pore water for lab analysis	Benchmark for in situ DO measurements Low cost compared to in situ methods	Extraction increases risk of: -contamination by atmospheric oxygen. -errors in measuring vertical gradients Unsuitable to assess DO fluctuations
DO pore water	In situ hand-held	Luminescence and optical fibre technology (optodes): a fluorescent dye in the sensor is excited by light depending on DO concentrations	Measures DO reliably (e.g. no flow rate dependency/no consumption of DO in the process Lower cost than continuous data loggers Adaptable shapes and housings of sensor to facilitate insertion into hard substrates	Unsuitable to assess small scale DO temporal fluctuations/vertical gradients
DO pore water	In situ autonomous	Optodes for continuous data logging	Accuracy/reliability at sites with variable DO Low planning/maintenance/ data retrieval	High cost Long pre-installation calibration
Redox potential	In situ hand-held	Redox reactions taking place on platinum electrode	Measures intensity of redox reactions Proxy for DO at sites with high fine sediment/OM	Misinterpretation risk Inconsistency of readings Difficulty in inserting redox probe

MGS: Median grain size; DO: Dissolved oxygen; OM: organic matter. Source: Lambert & Walling, 1988; Quinn et al., 1997; Christensen et al., 2000; Hedrick et al., 2013; Neil et al., 2014Duerdoth et al., 2015; Quinlan et al., 2015.

Table 2: FPM tolerance levels to fine sediment parameters and regulatory targets/recommendations.

Fine sediment parameter	FPM tolerance limits	Regulatory targets/recommendations for fine sediments	
		EU Member States	Elsewhere[13]
(SSC/TSS)	Baseflow: TSS <10 mg/l [1, 2, 3, 4] Storm-flows: TSS<30 mg/l [1, 2, 3, 4]	Good status (WFD)[0] Favourable status (Habitats Directive)[10]	**US** – TSS: 30 - 158 mg/L monthly average **Canada** – SSC: no more than 25 mg/l from background levels
Turbidity	Turbidity<1-1.9 NTU [2, 4, 5]	No EU provisions in the context of freshwater organisms; but regulations for Bathing and Drinking waters exist. Sweden (guidelines): Turbidity<1FNU (spring flood)[11]	**US:** varies 2 -150 NTU **Canada:** no more than 8 NTU from background levels. **Australia**: 2-25 NTUs (upland rivers)
Deposition of fine sediment (siltation)	OM<0.5-1% [4], 6 BOD: <1.4 mg/l [4,7]	No EU provisions Ireland (recommendations): BOD<3 mg/l[12]	**US**: Rate<5mm per storm event in gravels % accumulation=< 5-30% increase form background. Riffle Stability Index < 70
MGS	Silt-clay <2% w/w [5,6] MGS>3-7 mm [4,8]	No EU provisions Sweden (guidelines): fine grain (<1mm) <25%[11]	**US**: Fines (<83μm) <10% w/w (gravel) **Canada:** Fines (<2 mm)< 10% (gravel)
DO in pore water		No EU provisions	**US:** DO>5 mg/l daily minimum or DO> 6.0 mg/L weekly average Canada: DO mg/l> 6 mg/l daily minimum or DO>8 (monthly average)
Redox potential	Loss between free flowing and pore water <20% (I.Kileen, pers comm; CEN standard 2016)	NO EU provisions Sweden (guidelines): Redox>300 mV[11]	

1. Valovirta, 1998; 2. Skinner et al., 2003; 3. Varandas et al.,2013; 4. Gosselin et al., 2014; 5. Österling et al., 2010; 6. Tarr, 2008; 7. Bauer, 1988; 8. Geist & Auerswald, 2007. 9. EU, 2000; 10. CEN Standard, 2016. 11. WWF Sweden – Restoration of Freshwater Pearl Mussel Streams 12. Irish EPA, 2012. 13. US EPA, 2015. MGS: Median grain size. OM: Organic matter.

Table 3: The main advantages and disadvantages of substrate characterisation techniques in the context of FPM beds

Methods	Description of method	Advantages	Disadvantages
All methods	Sampling must be spatially representative of the streambed patchiness[1]	Provide essential information about changes and controls on FPM habitat [1, 2, 3]	More time consuming and labour-intensive than measurements of suspended sediments[1, 2] Low sampling frequency (bi-annually to annually / not monthly) to avoid streambed disturbance[1, 2] Sampling unreliable in high flows[1, 2] Differences in reporting confound data comparisons, e.g. US EPA[7] refer to fine sediments in the sediment as particle smaller than 0.83 mm, whereas Tarr [8] uses the Wentworth scale classes.
Visual observations	Surface substrate type categorized by visual observation-based counts of cobble and gravel [1, 2]	Suitability for comparison of adult mussel densities between reaches or morphological units [1]	Pebble counts are unlikely to detect the differences in fines that are relevant to juvenile PM [1, 2]. Pebble counts are limited to particles > 8 mm [1;2]. Inaccurate measurement of fine particles in the field[1, 3]. Difficulty in sampling deep water [1].
Bulk sediment	Quantitative. Designed for patch (microhabitat) assessment and surface and sub-surface conditions. Collection of composite 1 -3 kg samples by hand, cylinders or syringe cores, each approximately >100 g [1, 4]	Suitable for grain size distribution, silt-clay % and indices (e.g. sorting coeffcient)[2, 3] and use in regulation[7] Representative of reach patchiness [2]	Bias in grain size distribution and fine fraction assessments can be caused by excluding larger particles, misleading assessments of mussel tolerances to fine sediment [3].

1. Hedrick et al. (2013); 2. Bunte and Abt (2001); 3. Quinlan et al. (2015a); 4. Geist & Auerswald (2007); 5. US EPA (2015); 6. Tarr (2008).

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