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Clear as mud: A meta-analysis on the effects of sedimentation on freshwater fish and the effectiveness of sediment-control measures

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ABSTRACT

Increase in fine sediments in freshwater resulting from anthropogenic development is a potential stressor for fish and thus may cause population declines. Though a large body of literature exists on the topic, there have been few attempts to synthesize this information in a quantitative manner. Through meta-analysis we investigated the effects of sediment in lotic environments on resident ichthyofauna using ecologically-relevant endpoints for tolerant (e.g., northern pike *Esox lucius*) and intolerant (e.g., brook trout *Salvelinus fontinalis*) species. Further, the efficiency of sediment-control devices was explored to inform mitigation measures. An increase in suspended and deposited sediments was demonstrated to have a negative effect on all parameters and tolerances tested (feeding behavior [feeding rate, reaction distance to food item]; spawning success [survival of fry to eyed stage, fry emergence]; species richness; $P < 0.001$) except fish abundance ($P = 0.058$). Heterogeneity between studies was a factor in all analyses. Although there were insufficient studies to conduct meta-analysis on sediment-control devices, weighted percent efficiency estimates revealed that properly installed sediment-control fences tended to have a higher percent efficiency (73–80%) than sediment traps and basins (40–52%). These results highlight the negative impact that increases in suspended and deposited sediments can have on resident fishes from the individual to the population, and the need for more transparent and thorough statistical reporting. The analysis also identifies a clear need for rigorous experimental studies contrasting different sediment-control devices and strategies given that little such work has been published. That alone is remarkable given that sediment-control devices are often a requirement of regulators for riparian development activities, yet the evidence to support the effectiveness of the primary mitigative strategies is weak.

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Contents

1. Introduction

Freshwater ecosystems are among the most threatened environments in the world (Richter et al., 1997; Malmqvist and Rundle, 2002). Though all freshwaters are facing a barrage of threats, fluvial systems are particularly vulnerable (reviewed in Dudgeon et al., 2006) in part due to increased erosion in the form of sedimentation,[1] a process that is recognized as a primary form of aquatic habitat degradation and anticipated to increase alongside increased precipitation resultant from global climate change (Easterling et al., 2000). In general, many human land-use activities contribute to sedimentation by altering natural rates of sediment flux and organic matter inputs to freshwater systems (Waters, 1995). Anthropogenic disturbances such as agriculture, logging, mining, and urbanization, can negatively affect rivers and streams, in part by increasing sedimentation and ultimately altering biodiversity and ecological processes (Hornung and Reynolds, 1995). Human development and other activities tend to promote high rates of soil erosion as riparian vegetation is removed and bank soil is exposed (Patten et al., 2001). As surface water moves from catchments to watercourses, it transports eroded materials into waterways, where they become either suspended or deposited sediment (Hornung and Reynolds, 1995). Water with increased suspended sediments and altered substrates may be suitable for only a limited aquatic fauna (Swanson et al., 1988). As healthy freshwater ecosystems are responsible for many ecosystem services including water purification, decomposition, and nutrient cycling (Holmlund and Hammer, 1999), research on sediment effects and control measures is important to inform management objectives focused on maintaining overall freshwater ecosystem health.

Fine sediment loading can impact lotic ecosystems in the form of either suspended and/or deposited materials. Fine sediments suspended in the water column alter water quality and impede light penetration while decreasing pH at the substrate–water interface (Lemly, 1982). This results in potential decreases in photosynthetic activity (Marzolf and Arruda, 1980; McCubbin et al., 1990) and primary production (Murphy et al., 1981). In respect to freshwater fish, direct exposure to high levels of suspended fine sediment has been demonstrated to have a negative impact. For example,

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[1] For consistency, sedimentation in this article includes increases in suspended sediment, siltation and turbidity.

increased turbidity may decrease the foraging efficiency by obscuring prey items for visual predators (Utne-Palm, 2002), while direct contact with suspended particles may impede oxygen exchange by abrasive interactions with the mucus coating of the gills (Redding et al., 1987). Fine sediment deposition occurs as suspended particles settle out of the water column, coming into contact with aquatic vegetation, substrate and resident organisms. This sedimentation process increases substrate embeddedness, and has been implicated in the alteration of plant (Lewis, 1973; Moss, 1977) and invertebrate (Lemly, 1982; McCabe and O'Brien, 1983; Kirk, 1991) communities. Decreased water flow through benthic substrate caused by deposited fine sediment has been attributed to poor embryo survival of substrate spawning species fish species (Chapman, 1988; Greig et al., 2005) and subsequent habitat homogenization and decreases in biodiversity, may lead to the extirpation of sediment sensitive species from impacted areas (Swanson et al., 1988; McCubbin et al., 1990; Sutherland et al., 2002).

The effects of fine sediments on fish movement, feeding, reproduction, and assemblage structure are well-documented by numerous empirical studies on a variety of fishes. Although several syntheses have been compiled (Lloyd, 1987; Ryan, 1991; Kerr, 1995; Waters, 1995; Henley et al., 2000; Kemp et al., 2011), those reviews are qualitative. Efforts to conduct quantitative reviews have been extensive and focused on modeling fish responses (Newcombe and Jensen, 1996; Newcombe, 2003) or on a single group of fishes, most notably salmonids (Lloyd, 1987; Jensen et al., 2009). As a result there is currently a knowledge gap in our overall understanding regarding the relationship between increased sedimentation and effects on various lotic species.

Due to concerns regarding the effects of sedimentation, various techniques are used globally to reduce the introduction of point-source suspended sediments to lakes, rivers, and streams. Techniques include filtering systems such as sediment-control fences and compost filter socks, and settling apparatus such as basins (Kerr, 1995; Faucette et al., 2008). Filter mechanisms use geotextiles to filter suspended sediments from the water column as water slowly passes through the material, whereas basins act as impoundment structures that capture runoff, allowing suspended sediments to settle out of the water prior to its discharge (Fennessey and Jarrett, 1994). Both require slow-moving or stagnant waters to allow for natural deposition of fine sediments (Verstraeten and Poesen, 2000). Sediment-control fence geotextiles are designed to sieve suspended particulate and are positioned in key locations to prevent the dispersion of suspended sediments into a body of water. Fences of this nature are the most frequently used sediment-control method because they are relatively inexpensive, easy to install, durable, and can be used on a variety of topographies compared to other techniques (Robichaud et al., 2001). Each method ranges in efficiency for sediment removal depending on the specific characteristics of the application scenario (Ontario Ministry of Transportation and Communications, 1981; Dendy and Cooper, 1984) by including factors such as mean flow velocity, installation design, the length-to-width ratio, and sediment particle size (American Society of Civil Engineers, 1973; Fennessey and Jarrett, 1994; McCaleb and McLaughlin, 2008). In addition, sediment-control fences are not always properly installed, allowing sediments to undermine or disperse around the barrier (Robichaud et al., 2001).

In spite of intensive research efforts, a general consensus regarding the overall effects of sedimentation on fishes and the effectiveness of sediment controls has not been reached (Newcombe and MacDonald, 1991; Barrett et al., 1998; Robichaud et al., 2001), contributing to discrepancies in preventative and mitigative practices among jurisdictions (Cook et al., 2009). Meta-analyses are becoming more common in natural sciences to effectively synthesize data and assimilate independent studies in an effort to strengthen knowledge of broad-scale trends and address key issues in conservation and management practices (Pullin and Stewart, 2006; Stewart, 2010). Rigorous systematic reviews that evaluate credible evidence have been identified as a crucial step towards the sustainable management of aquatic ecosystems (Stewart, 2010; Lapointe et al., in press). Combining and analyzing results from a variety of studies, conducted both in the field and laboratory, may increase understanding on the effects of sedimentation on fishes, and whether or not commonly used sediment-control devices are effective under normal conditions. Through meta-analysis, this paper aims to determine whether sedimentation influences fish feeding and embryo survival as well as fish assemblages (abundance and species richness). In addition, we examine the evidence regarding the efficiency of sediment-control devices with a focus on filter (sediment-control fences, compost filter socks) and basin (modified and unmodified) mitigation tools. The results of this paper will provide a starting point for the development of similar analyses geared towards developing evidence-based management and policy making (Sutherland et al., 2004) related to fine sediment impacts and control efforts in freshwaters.

2. Materials and methods

2.1. *Data collection*

References were obtained through ISI Web of Science and Google Scholar, guided by a annotated bibliography (Kerr, 1995), which lists key citations for the impact of sedimentation on spawning beds, fish growth, feeding, movement, mortality, and fish assemblages. This review further lists publications on the efficiency of silt fences and sediment traps in removing suspended sediments. A general keyword search was conducted using the word "fish" in combination with sedimentation descriptors "sediment*", "silt*", "turbid*", and "suspended solid*"alongside keywords for each research question. Because different phases of sedimentation impact fish differently, studies related to embryo development and hatch success focus on deposited sediment, feeding behavior on suspended sediment (namely turbidity), and fish assemblage on both suspended and deposited sediments. Field studies occurring in lotic habitats and laboratory testing of freshwater species were retained. We chose to exclude lentic habitats from field studies on fish health metrics and community composition for comparative purposes. For the effect of deposited sediments on embryo survival we defined fine sediments as particles smaller than 4 mm in diameter (Greig et al., 2005; Yamada and Nakamura, 2009). Below the salient aspects of data extraction for the different analyses are presented.

2.1.1. *The effect of deposited fine sediment on embryo development and survival*

The key term "spawn*" was used to search for papers related to embryo development and survival. Through the method stated above, a total of 212 papers was found. Of these, only 29 were included in the analysis; the remaining studies were excluded because (i) the study did not focus on the relationship between survival to eyed stage or survival to fry emergence for % fines less than or equal to 4 mm (e.g., sediment presented by weight, permeability, geometric particle size) (156), (ii) the type of analysis did not permit the necessary data extraction (e.g., no effect size reported and authors did not respond to inquiries) (14), (iii) the article was a review (10), (iv) inability to access the article (out of print gray literature not available through interlibrary loans) (2), or (v) the study had a lentic focus (1).

2.1.2. *The effect of suspended sediment on feeding behavior*

The keywords "feeding*" and "consumption*" were used to describe fish feeding behavior. It became evident that two types of suspended sediment effects were present within the literature: changes in feeding rate and reaction distance. As such, "rate" and "reaction distance" were added to the keyword searches. Both the citation search of the 36 relevant references found in Kerr (1995) and a keyword search yielded a total of 71 articles. Papers were excluded from analysis because (i) the type of analysis did not permit the necessary data extraction (e.g., no effect size reported and authors did not respond to inquiries, multivariate interactions with turbidity not considered independent of light) (24), (ii) the study did not focus on the relationship between turbidity and feeding rate or reaction distance (e.g., prey size selection in relation to turbidity levels) (19), (iii) the study involved marine species (5), or (iv) the article was a review (3).

2.1.3. *The effect of sedimentation on fish assemblage*

The terms "abundance", "diversity", "species richness", and "composition" were applied to the search for articles related to fish assemblage. A total of 142 papers was found from a citation search using 20 relevant references in Kerr (1995) and a general keyword search. Many of these were eliminated because the studies (i) did not provide data on fish or sedimentation (55), (ii) the type of analysis did not permit the necessary data extraction (e.g., no effect size and authors did not respond to inquiries, indirect association with sedimentation) (45), (iii) the study was not in a lotic system (17), (iv) the analysis was not done at the community level (i.e., only one or a subset of species was included) (10), and finally (v) the sample size of systems compared was insufficient ($N \leq 3$) (3).

2.1.4. *Sediment-control fence efficiency*

To find papers measuring the efficiency of sediment-control fences, "fence", "barrier", and "efficien*" were used as search terms. Two types of sediment filter were present within the literature: the sediment-control fence and the compost sock. As such, a new search with "compost sock" was conducted, yielding a total of 39 papers. Of these, eight were included in the analysis. The remaining studies were excluded because the studies (i) did not focus on efficiency of the silt fence (8), (ii) tested only the materials or material applications (19) (iii) had no quantitative data (3), or (iv) were marine focused (1).

2.1.5. *Sediment trap efficiency*

The terms "basin", "wet pond", "removal", "retention" and "efficiency" were applied to the search for articles related to sediment trap efficiency. The search terms "construction" and "storm water drain" were added to refine our search, yielding a total of 153 papers. Of these, 15 were included in the analysis. The remaining studies were excluded because (i) they addressed transportation of constituents associated with sediments (e.g., heavy metals, nutrients) (42); (ii) the study was not in a lotic environment (38); (iv) the study was not on a single wet retention basin (e.g., constructed wetlands, bioretention, dry ponds, in-stream ponds, or a system of ponds) (23), (v) the type of analysis did not permit the necessary data extraction (e.g., samples were not taken from the inlet and outlet, the sample size could not be obtained, the mean concentration events were not calculated) (18), or (vi) the article was a review of best management practices (17).

2.2. *Data extraction*

Turbidity and total suspended sediments were accepted as independent variables representing sedimentation as they are strongly positively correlated (Richardson and Jowett, 2002). The following data were extracted from each study: 1) author and year of publication; 2) model species; 3) species tolerance to sedimentation; 4) sample size; 5) location of study; 6) type of statistical analysis used; and; 7) effect size and direction. All life stages were included in order to investigate overall effect of sedimentation as well as ensure adequate sample size for analysis. In cases where the authors did not explicitly state the tolerance to sedimentation, the tolerance of fish species was determined through reference materials (e.g., Scott and Crossman, 1973; Holm et al., 2009). For species where reliable tolerance was not available, congeners were used (e.g., Masu salmon *Oncorhynchus masou*). Grey literature was included in analyses when deemed to be from a reputable source (e.g., government documents, industry reports), however these articles often did not contain the specific statistics required for data extraction. In all cases where necessary data were missing, corresponding authors were contacted. Most authors reported multiple results from the same study, for example different effect sizes for different species feeding rates from the same article (e.g., Rowe et al., 2003). We recognize that multiple effect sizes could cause issues with non-independence (Gates, 2002); however, in cases where multiple effects were extracted from a single study, each effect size represented tests associated with either different species or different characteristics of the predictor, such as size of sediment particles. Sensitivity analyses were used in order to explore potential non-independence of data (Gates, 2002). The conclusions of the meta-analyses did not change and for this reason we considered each effect size to be independent. We had initially intended to examine the effects of sedimentation on a variety of other endpoints including fish growth, predator avoidance, mortality, assemblage composition, and assemblage diversity. However, too few studies with appropriate tests reported were found to enable meta-analyses of these endpoints.

2.3. *Data analysis*

2.3.1. *Effect of sedimentation on fish*

All *r* coefficients were transformed to Fisher's *z* coefficients to ensure normality and homogeneity of variances (Cooper et al., 2009; Viechtbauer, 2010). Correlation coefficients were obtained from the studies directly when the *r* coefficient was provided, converted from an R^2, *F* or *t*-value to *r* coefficients, or calculated from available data when an effect size was not provided. A random-effect model was used with correlation coefficients to represent effect size, given that the current study aimed to estimate the true overall effect of fine sediment levels on several fish parameters (Hunter et al., 1982; Field, 2001; Viechtbauer, 2010). There were no observable trends when the extracted data were grouped at different levels (e.g., location, latitude, longitude); therefore no moderators were added to the models. Different meta-analyses were conducted for tolerant (e.g., northern pike *Esox lucius*) and intolerant species (e.g., brook trout *Salvelinus fontinalis*).

To assess potential publication bias, funnel plots for each analysis were generated using the calculated effect size from each included test plotted against the sample size from that test. Graphs deviating from the pyramidal shape suggest publication bias, most often in the positive direction, implying that significant results are more often published (Rosenthal, 1979). In a meta-analysis, homogeneity refers to the degree of similarity in the results of the individual studies included in the analysis (Walker, 2008). A test of homogeneity therefore determines whether the average effect size is representative of all of the effect sizes in the meta-analysis. To assess this we used the Cochran Q test, I^2, and τ^2 statistical tests were examined in R. Cochran's Q statistic informs about the presence or absence of heterogeneity, the I^2 index quantifies the degree of heterogeneity in a meta-analysis, and τ^2 estimates the amount of heterogeneity which results from between-study variance. All statistical analyses were performed in R 2.15.2 (R development core team, Vienna, Austria) using the 'meta package' (Schwarzer, 2010) and *P*-values <0.05 were considered as significant.

2.3.2. *Sediment-control measures*

To quantify sediment-control device (sediment-control fences, compost filter socks, and modified and unmodified basins) efficiency, a weighted percent efficiency was calculated. Too few studies contained sufficient statistical analysis or information to enable proper meta-analysis. For the purposes of this study, silt fences were defined as a temporary sediment-control device constructed from geotextiles placed in sheets installed perpendicular to the ground, generally on a slope or bank of a watercourse. Fences varied in height and material of construction, but the general form remained consistent to the typical fence style. Studies for silt fences were separated into laboratory and field studies to determine potential for decreased efficiency in real-life applications. Compost filter socks were any geotextile-based tube filled with either vegetative or non-vegetative materials placed directly on the ground perpendicular to the flow of water. Standard basins were categorized into standard wet retention basins and basins with modifications. A standard basin was defined as a wet retention pond/basin having either vertical or sloped walls or berms with any means of water inflow and outflow, including pipes, weird, wash stones, orifices and in some cases, emergency spillways. Modifications included in this study were baffles, skimmers or chemical treatments designed to improve the sediment trapping efficiency. Where more elaborate and unique modifications were tested studies were excluded from analysis, as they were deemed inappropriate for comparison (e.g., Winston et al., 2013).

3. Results

3.1. *Overall publication bias and heterogeneity*

Heterogeneity and publication bias were assessed for all meta-analyses (Fig. 1; Table 2). Heterogeneity was very high for fry emergence and embryo survival to eyed stage ($Q = 393.14$ and $Q = 312.06$) and feeding rate of tolerant and intolerant species ($Q = 619.97$; $Q = 759.00$) as well as fish reaction distance ($Q = 89.22$ respectively) data, and relatively high in the abundance ($Q = 31.12$) and species richness ($Q = 24.43$) data (Table 2). Further quantification of heterogeneity indicated that the variability in the effect sizes of abundance ($I^2 = 64.6\%$) and species richness ($I^2 = 55\%$) data was a result of both sampling error and true heterogeneity. True heterogeneity due to between-study variance was a factor for the remaining data categories.

A large number of articles was obtained that did not report either the effect size or direction of the relationship when results were non-significant; consequently, the majority of data points included report significant relationships. In instances where authors were unable to supply the appropriate data, studies were excluded from the analysis, creating a bias towards significant effects. Non-uniform statistical reporting also contributed to a bias towards significant findings in this study. The combination of biased reporting and heterogeneity may explain the lack of pyramidal shape associated with the funnel plots for each analysis (Fig. 1).

3.2. *The effect of deposited fine sediments on developing embryos*

Effect sizes from a total of 102 individual tests were obtained from 26 studies. Of these, 47 effect sizes were derived from studies of fry emergence in deposited fine sediment and 44 from studies assessing survival of embryos to the eyed stage.

Fry emergence and the survival of eggs to eyed stage of intolerant fish species were negatively associated with deposited sediment ($P < 0.0001$; Table 1). The effect of sedimentation on tolerant fish species was not analyzed due to an insufficient sample size ($N = 1$). All but one study (i.e., robust redhorse *Moxostoma robustus*; Jennings et al., 2010) included in the analysis examined the effects of sediments on salmonids (e.g., brook trout *S. fontinalis*, rainbow trout *Oncorhynchus*

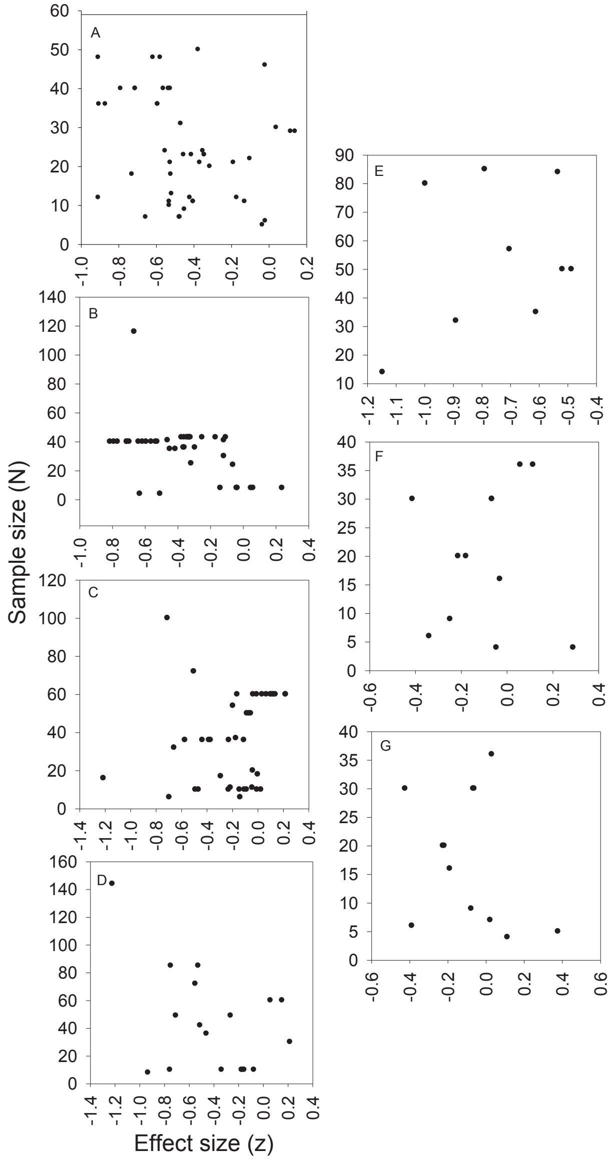

Fig. 1 – Funnel plots of effect sizes ($\dot{z}$) and sample sizes (N) for each extracted effect size used in meta-analyses for embryo development: (A) fry emergence and (B) survival to eyed stage, (ii) feeding behavior, (C) feeding rate (suspended sediment tolerant), (D) feeding rate (suspended sediment intolerant), and (E) reaction distance; (F) abundance, and (G) species richness meta-analyses.

Table 1 – Results from each random-effects meta-analysis model indicating the number of extracted effect sizes used in each meta-analysis (*k*) and overall effect size ($\dot{z}$). Fish species tolerance to sedimentation is classified as tolerant (T), moderately intolerant (MI) or intolerant (I).

Meta-analysis	Tolerance	Effect size ($\dot{z}$)	*k*	95% CI	P-value
a. Embryo Development					
Fry Emergence	MI/I	−0.7824	47	[−0.8419; −0.7041]	<0.0001*
Eyed Stage	MI	−0.7535	44	[−0.8136; −0.6776]	<0.0001*
b. Feeding Behavior					
Feeding Rate	MT/T	−0.400	41	[−0.5644; −0.2052]	0.0001*
	MI/I	−0.7241	18	[−0.8902; −0.3882]	0.0004*
Reaction Distance	T/MI/I	−0.9333	9	[−0.9638; −0.8787]	<0.0001*
c. Abundance		−0.2426	12	[−0.4645, 0.0079]	0.0575
d. Species Richness		−0.3034	12	[−0.5062; −0.0687]	0.012*

*Significant at $P < 0.05$.

mykiss, chinook salmon *Oncorhynchus tshawytscha*), which are classified as intolerant to sedimentation.

3.3. *The effect of suspended sediment on feeding behavior*

Effect sizes from a total of 68 individual tests were obtained from 18 studies. Of these, 41 were derived from studies of feeding rates in moderately tolerant or tolerant fish species, and 18 from studies of feeding rates in moderately intolerant and intolerant fish species. Fish reaction distance to prey items was assessed using effect sizes from nine studies, with tolerant and intolerant species combined due to insufficient sample size to conduct separate analyses.

Feeding rates in both tolerant ($P = 0.0004$) and intolerant fish species ($P < 0.0001$; Table 1) were negatively associated with suspended sediments. Similarly, the reaction distance of intolerant and tolerant fish species to prey items ($P < 0.0001$; Table 1) were negatively associated with suspended sediments.

3.4. *The effect of sedimentation on fish abundance and species richness*

Effect sizes from a total of 24 individual tests were obtained from 11 studies. We found no significant association between suspended sediments and fish abundance ($P = 0.058$) and a slight negative association between suspended sediments and fish species richness ($P = 0.012$; Table 1).

3.5. *The effectiveness of sediment-control measures*

Sediment fences were found to have the highest efficiency for removing suspended sediments (lab: 80.2% and field: 72.6%), followed by compost filter socks (56.9%) (Table 3). Standard basins with no modifications were the least effective at removing suspended sediment (40.8%), with basic modifications (baffles, skimmers or chemical treatments) increasing efficiency by 11%.

4. Discussion

This first meta-analysis on the effects of sedimentation on a variety of biological endpoints for lotic fishes supports the

Table 2 – Variability within and between studies for each random-effects meta-analysis. Cochran's Q statistic indicates the presence or absence of heterogeneity, I^2 index quantifies the degree of heterogeneity, and τ^2 estimates the amount of heterogeneity that results from between-study variance. Fish species tolerance to sedimentation is classified as either tolerant (T), moderately intolerant (MI) or intolerant (I).

Meta-analysis	Tolerance	τ^2	H	I^2 (%)	Q	P-value
a. Spawning beds						
Fry Emergence	MI/I	0.3085	2.92	88.3	393.14	<0.0001*
Eyed Stage	MI	0.2191	2.69	86.2	312.06	<0.0001*
b. Feeding						
Feeding Rate	T	0.4351	3.94	93.5	619.97	<0.0001*
	MI/I	1.1350	6.68	97.8	759	<0.0001*
Reaction Distance	T/MI/I	0.2041	3.34	91	89.22	<0.0001*
c. Abundance		0.1119	1.68	64.6	31.12	0.0011*
d. Species Richness		0.0873	1.49	55	24.43	0.011*

*Significant at $P < 0.05$.

general consensus that sediment in both suspended and deposited forms has negative consequences on fish feeding behavior and embryo development and survival, while fish abundance was not found to be significantly associated with sedimentation. Surprisingly, though negative effects of increased sedimentation and resultant turbidity on fish populations are widely reported, changes in abundance and species richness were comparatively under-represented in the literature, and we were not able find strong effects of sedimentation on these endpoints. The lack of homogeneity between studies is important to note and suggests that collaboration and consistent and standardized methodology are important aspects of study design if results are to be compared across multiple studies.

The deviation from pyramidal shapes found in funnel plots constructed for this analysis suggests that the true effect size may be masked by true heterogeneity and publication bias (Egger et al., 1997) (Fig. 1). Deviation suggests either lack of publication of non-significant results, heterogeneity introduced through variations in study methodology, or a combination of both factors. This highlights both the need for increased publication of non-significant results within the literature to facilitate comprehensive meta-analyses as well as the importance of consistent, collaborative methodology to address over-arching effects such as these.

Heterogeneity was statistically significant in all cases but for fish abundance and fish richness, causing interpretation of results to be made with a certain amount of caution. It appears to be strongest in the case of the feeding rate meta-analysis ($Q = 619.97$; $P < 0.0001$* and $Q = 759$; $P < 0.0001$* respectively) as a high percentage of the variation across studies is due to heterogeneity rather than chance ($I^2 = 93.5\%$ and 97.8%) respectively. In the case of feeding rate, the overall negative results could be due to studies with extremely high sample sizes (e.g., Reid et al., 1999, $N = 190$; Zamor and Grossman, 2007, $N = 80$ and 85) that report suspended sediment to have a negative effect on feeding rate. These high sample sizes could potentially bias the pooled effect size, obscuring the true effect size.

Table 3 – Weighted % efficiency for sediment-control fences, compost filter socks and basin and trap sediment-control measures in laboratory and field settings.

Study type	Weighted % efficiency	N
Laboratory		
Sediment-control fence	80.22	27
Compost filter socks	56.94	10
Field		
Sediment-control fence	72.58	8
Standard basin/trap	40.83	27
Basin/trap with modification	52.04	19

4.1. *The effect of deposited fine sediment on developing embryos*

Effects of deposited fine sediment on fish eggs are extremely complex, but can be generalized as a result of the following: the filling of interstitial spaces between pieces of substrate preventing intergranular water flow, and/or by directly smothering developing embryos (Greig et al., 2007). Under ideal conditions, spawning substrate provides a stable environment with adequate water flow to maintaining oxygen levels and metabolite removal (Lapointe et al., 2004; Greig et al., 2005) and temperatures (Baxter and McPhail, 1999). On coarse substrates the introduction of fine sediments, particularly those less than 2 mm in diameter and with a high silt to sand ratios, has been demonstrated to decrease intragravel flow velocity, blocking passage of oxygenated water to incubating eggs (Chapman, 1988; Greig et al., 2005). Decreased interstitial flow may further impact embryo development and survival by preventing the expulsion of metabolic wastes through the chorion of the developing egg (Burkhalter and Kaya, 1975; Bennett et al., 2003). This can lead to delays in embryo development and early emergence (MacCrimmon and Gots, 1986), and decreased size of emergent fry (Chapman, 1988). The smothering of embryos both decreases oxygen and metabolite permeability while physically preventing fry emergence, allowing only larger fry to move through the deposited layer (Koski, 1966; Beschta and Jackson, 1979; Fudge et al., 2008). However the susceptibility of embryos to these factors appears to be species dependent, with some species more tolerant than others; chinook salmon embryos and alevins tolerate higher amounts of fine sediments compared to kokanee, cutthroat *Oncorhynchus clarkii*, and rainbow trout *O. mykiss* (Chapman, 1988), chum *Oncorhynchus keta* and coho salmon *Oncorhynchus kisutch* (Hall, 1986).

Nearly all studies suitable for meta-analysis examined the effects of deposited fine sediment on salmonid embryos. The great economic and societal importance of salmonids and their well-documented global decline (Kareiva et al., 2000; Friedland et al., 2009) combined with the acknowledgment of increased sedimentation in lotic systems (Kemp et al., 2011) has elicited a strong research focus on this family in regards to the relationship between sedimentation and recruitment. As a result this analysis did not include species that spawn in locations other than coarse substrate, as they are under-represented in the literature and those that were present were not testing comparable independent variables.

4.2. *The effect of suspended sediment on feeding behavior*

The negative effect of increased sedimentation on fish feeding rate varied between turbidity-tolerant and intolerant species, with tolerant species demonstrating a moderately negative effect compared to a strong negative effect for intolerant species (Table 1). Studies included a large range of fish species including tolerant warm water species from both North America and Europe (e.g., Rowe and Dean, 1998; Ljunggren and Sandström, 2007; Shoup and Wahl, 2009), sensitive cyprinid species (e.g., Horppila et al., 2004; Zamor and Grossman, 2007) and juvenile salmonids (e.g., Gregory and Northcote, 1993; Sweka and Hartman, 2001). All studies indicated a decrease in feeding rate at the highest tested turbidity levels. However it is worth noting that tolerant species were able to maintain feeding rates in higher turbidity levels compared to intolerant species (e.g., Ljunggren and Sandström, 2007), suggesting that important adaptive strategies to turbidity include sensory physiology and foraging behavior.

The effect of increased suspended sediments on feeding behavior may be influenced by the stage of development. As an example, several studies demonstrated certain species of fish larvae feed optimally at slightly increased turbidity, resulting in a parabolic relationship between feeding rate and increasing turbidity (Gregory and Northcote, 1993; Miner and Stein, 1993; Utne-Palm, 2004). Species such as chinook salmon are adapted to the range of turbidity found naturally throughout natal systems; however, when turbidity exceeds adaptive levels, feeding rate declines dramatically. Adult salmonids, for example, are primarily visual predators (Ali, 1959; Flamarique and Hawryshyn, 1996) for which the reduction in prey contrast when light is limited by turbidity may decrease their ability to forage effectively (De Robertis et al., 2003). As life stage was not included as a parameter in this study in order to maintain adequate sample size, the effect of increased turbidity may be over-generalized for applications to all life stages.

The largest negative effect size in this study was found for the reaction distance of fish to prey items (Table 1). With only one study reporting results for tolerant species (largemouth bass *Micropterus salmoides*; Crowl, 1989), all tolerance levels were combined, and increasing turbidity was correlated with decreasing reaction distance for all species tested. High concentrations of suspended sediments increase scattered light, decreasing contrast and thus the ability of fish to distinguish between the background and prey. However, Miner and Stein (1993) found a strong interaction between light and turbidity where prey consumption by bluegill (*Lepomis macrochirus*) increased in turbid waters with high light (>450 lx) conditions compared to low light, believed to be due to an increase in the prey-background contrast caused by turbid waters. Although this analysis focused on turbidity as an independent factor, turbidity has been demonstrated to interact with other physical characteristics of the water column, as well as the characteristics of prey items (Utne-Palm, 2002). The presented feeding behavior meta-analyses contain exclusively effect sizes related to feeding rate and reaction distance of fish to homogenous prey species in constant lux, and thus does not account for the synergistic relationships between increased sedimentation and light conditions, prey contrast, and potential for alternative prey species that occur in situ that have the potential to mitigate the effect of increased suspended sediments. In addition, while these results support the understanding that many fishes rely on visual recognition to initially respond to potential food items, it should be noted that species with adaptations to feed in low visual environments (e.g., barbels) were not well represented in the literature.

The range in turbidity levels tested differed among feeding studies, particularly in maximum intensity (e.g., 0–4000 NTU; Bonner and Wilde, 2002 versus 0–43 NTU; Sweka and Hartman, 2001); however, all studies reported negative trends, albeit not always significant, at the highest tested NTU. The maximum NTU tested did not appear to depend on the tolerance of species tested, with some intolerant species tested at relatively high NTU (e.g., 810 NTU; Gregory and Northcote, 1993) and tolerant species tested at comparatively low NTU (e.g., 25 NTU; Ljunggren and Sandström, 2007), though the aim of most studies was to detect a biologically significant threshold for model species. As such, it may be helpful to assess the effect of increased turbidity on additional common fish species within the laboratory to understand the reactions of fishes to typical, standardized increases in turbidity from anthropogenic activity such as mining or forestry. As more studies are conducted, it would be beneficial to assess the effect of specific turbidity levels across a variety of species. These results could further be incorporated into monitoring protocols as part of evidence-based management practices.

4.3. *The effect of sedimentation on fish abundance and species richness*

While there was a significant effect of sediments on species richness, there was no significant effect of suspended sediment on fish abundance. The included studies were conducted in areas that were disturbed by a variety of anthropogenic activities resulting in a marked increase in sedimentation (e.g., deforestation and mining, Brown et al., 1998; intense agriculture, Stephens et al., 2008; urbanization; Roy et al., 2005). Indeed, because of the multiple stressors acting on most natural aquatic ecosystems, it may be difficult to isolate the effect of sedimentation on fish assemblages through observational studies. Increases in sedimentation caused by human development that surpass natural fluxes in the sediment cycle can cause prolonged and potentially irreversible damage to streams (Brown et al., 1998). There is an increasing body of evidence that land perturbation corresponds with an increase in turbidity within drainage basins (Newcombe and MacDonald, 1991; Waters, 1995; Sutherland et al., 2002), in turn contributing to fish species homogenization through the extirpation of intolerant species and by facilitating the dominance of tolerant species (Walters et al., 2003).

Our results highlight the need for more quantitative studies on the effect of suspended and deposited fine sediments on fish assemblage composition, ideally using empirical experimental approaches. Assemblage composition can be a more valuable indicator of ecosystem health (Karr, 1981). Species that are able to establish healthy populations in highly degraded areas, such as percids and centrarchids, accounted for the majority of biomass in systems with high suspended-solid concentrations, replacing sensitive species (Walters et al., 2003; Roy et al., 2005). The replacement of species sensitive to suspended by species with higher tolerances (Rahel, 2010) could be masking the effects of increased sedimentation on fish assemblages. Abundance and fish species richness may not undergo significant changes of tolerant or invasive species in response to increased sedimentation (Robertson et al., 2006). As a result, studies that monitor changes in species identity could serve as a better measurement of fish assemblage response to sedimentation.

4.4. *The effectiveness of sediment-control measures*

All tests that were included in our study were done on sediment-control devices that were properly installed to test maximal efficiency, though in practice several factors influence the efficiency of sediment-control fences including suspended-solids characteristics, hydraulic and filtration characteristics of the fabric, and the maintenance of the system (Barrett et al., 1998). In addition, poor installation and/or poor maintenance of the barrier can also reduce the effectiveness by allowing water to pass over, under, and beside the barrier (Zech et al., 2008). It is not uncommon to see fences that have been compromised by either breaches or poor installation and maintenance. Few studies examined the efficiency of sediment-control fences in the field, and for those that did conclusive results were often not obtained. Studies that did not properly calculate the change in sediment concentration attributable to the sediment-control device were excluded from analyses (e.g., Barrett et al., 1998).

Contrary to Waters (1995), our results suggest that sediment-control fences are more effective than both sediment basins and compost filter socks. The studies reviewed here were conducted on a range of basin sizes, from small impoundments or excavations to large excavated basins. Smaller systems are intended for short-term use and require no maintenance (Tryon et al., 1976; Harwood, 1979; Bucek, 1981), whereas larger basins are intended for long periods (i.e., years to decades) and may require dredging in situations where long-term filling is not desired (Waters, 1995). Many variables influence the effectiveness of these control measures: retention time, surface area, storage depth, pond geometry, basin effective length-to-width ratio, water temperature, mean seasonal winds, and particle size (Fennessey and Jarrett, 1994; Waters, 1995). Further modifications can be added to the basin to increase efficiency, including but not limited to inlets, baffles, filters, and perforated risers. Basins have the potential to be very effective, but require large investments in planning and execution to be maximally efficient (Fennessey and Jarrett, 1994). A wide variety of additional sediment-control measures is used in concert with basin-style sediment-control devices that have not been quantitatively tested, and there was insufficient replication of studies to compare the effectiveness of the alternative measures that were reviewed in this study.

Few peer-reviewed experimental studies of sediment-control devices were available, limiting the quality of data available for meta-analysis. Sediment-control measures are routinely required by regulatory agencies on the premise that they are effective at controlling sediment loading in lotic systems. As revealed here, there is immense variation in effectiveness among sediment-control measures, and in how they are applied. Given that this meta-analysis revealed negative consequences of sediment on lotic fish, there is a dire need for additional, rigorous studies of the relative effectiveness of various sediment-control measures.

4.5. *Implications for research and management*

There have been numerous reviews focused on the effects of sedimentation on freshwater communities to inform management practices (Lloyd, 1987; Kerr, 1995; Waters, 1995; Greig et al., 2005; Robertson et al., 2006). Kemp et al. (2011) identified the need to increase quantitative understanding of the complex relationships between aquatic ecosystem health and changes in fine sediment. This manuscript has amassed and analyzed existing data on freshwater ichthyofauna to help accomplish this goal. To apply meta-analyses to ecological systems, there are a number of assumptions (most notably homogeneity between studies) that must be made; however, we believe that this study accurately demonstrates the broad negative influence that increases in fine sediments can have on a variety of fish species. In cases where results from meta-analyses are intended to guide management decisions, heterogeneity should be heavily scrutinized and when possible avoided to ensure accurate interpretation of results. Nonetheless, there is a need for additional studies on a broader diversity of fish species, including those beyond north temperate regions. Relatively few of the data used in these meta-analyses were derived from work outside of north temperate regions, with a strong bias towards North America and Europe. There is also benefit in studies that include both field and laboratory components and adopt a controlled experimental approach. Such studies should involve levels of sedimentation that emulate a range of natural and anthropogenic inputs.

Both the publication and reporting biases (i.e., failure to publish non-significant findings) encountered throughout the literature search highlight the need for more thorough reporting of both significant and non-significant findings. The use of meta-analyses has been identified as an important tool for guiding scientific management practices, however if non-significant findings remain unpublished, this could bias understanding of a given research question. It is conceivable that we have over-estimated the effects of sedimentation on fish, although we also posit that in general most studies testing whether sedimentation has negative consequences on fish suffer from problems with experimental design (e.g., lack of appropriate replicates, focus on short-term responses). Understanding the role of exposure duration is particularly important to inform environmental policy (e.g., Bilotta et al., 2012). Only recently have studies that consider duration of fine sediment inputs and elevation emerged (e.g., Bilotta et al., 2010; Thompson et al., 2014). The history, both in terms of short-term and evolutionary (i.e., potential for local adaptation) time should be considered when interpreting results and ideally would be incorporated into quantitative analyses. An important omission from this study was our inability to identify specific thresholds upon which sediment should be of concern to managers. Indeed, it is difficult to enact rigorous environmental policy without knowledge of thresholds (Bilotta et al., 2012). To do so quantitatively, especially given the diversity of fishes, would require a much larger dataset than we were able to amass here. Nonetheless, such a meta-analytical approach to identification of specific thresholds (beyond the "effect" versus "no effect" approach used here) is sorely needed and may be possible in the future as more empirical studies (that report relevant details) are conducted.

This investigation also highlights the need for more thorough reporting of statistical measures for both significant and non-significant results so that meta-analyses such as this can provide the greatest quantitative insight into well-studied conservation issues. This requires authors to explicitly reporting all analytical methods used, all sample sizes used each analysis (e.g., regressions using subsets of experimental groups), resultant critical values from each test, directionality of any relationships (including when non-significant) and most importantly the reporting of exact *P*-values for both significant and non-significant results. Adopting this practice would not only increase efficiency of meta-analysis but also further increase transparency of research and allow for more consistent and standardized statistical methodology within similar research fields.

Sediment fences were demonstrated to provide the most effective control measures when properly installed. While current mandates in many jurisdictions require the installation of sediment-control devices during development activities, we believe that more stringent post-installation monitoring of deployed sediment controls will improve overall efficiency. Our review also identified a clear need for rigorous experimental studies contrasting different sediment-control devices and strategies given that much of the existing work is descriptive and is not published in peer-reviewed outlets. That alone is remarkable given that sediment-control devices are often a requirement of regulators for riparian development activities, yet the evidence-base to identify effective mitigating strategies is weak; without such knowledge it is unclear whether mitigating strategies are sufficiently effective. Relatedly, there is a need to better link endpoints from sediment-control measure studies (i.e., % effectiveness) with biological endpoints. For example, what level of percent effectiveness is suitable for a given sediment source or lotic system? Or what are the factors that influence the level of effectiveness? Clearly there is a great need and ample room for additional rigorous study related to sediment-control measures.

5. Conclusions

While attempting to quantify the effect of fine sediments on lotic fish and the efficiency of sediment-control devices, this study has identified issues in statistical reporting and major gaps in research. Results indicate an overall negative impact of increased sedimentation on fish embryo development, feeding behavior and species richness, and though lack of homogeneity between studies may have influenced the accuracy of estimated effect sizes, the overall trends identified are consistent with previous research. The lack of peer-reviewed research on sediment-control devices is startling and identifies a clear need for rigorous scientific testing to identify and confirm best management practices. A strategic framework would aid in guiding future research on these topics and increase the accuracy of future meta-analyses, a factor that may promote the use of research in guiding management decisions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.watres.2014.02.047.

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