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Review

On the apparent failure of silt fences to protect freshwater ecosystems from sedimentation: A call for improvements in science, technology, training and compliance monitoring

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ABSTRACT

Excessive sedimentation derived from anthropogenic activities is a main factor in habitat and biodiversity loss in freshwater ecosystems. To prevent offsite movement of soil particles, many environmental regulatory agencies mandate the use of perimeter silt fences. However, research regarding the efficiency of these devices in applied settings is lacking, and fences are often ineffective due to poor installation and maintenance. Here, we provide an overview of the current state of research regarding silt fences, address the current culture surrounding silt fence installation and maintenance, and provide several recommendations for improving the knowledge base related to silt fence effectiveness. It is clear that there is a need for integrated long-term (i.e., extending from prior to fence installation to well after fence removal) multi-disciplinary research with appropriate controls that evaluates the effectiveness of silt control fences. Through laboratory experiments, *in silico* modelling and field studies there are many factors that can be experimentally manipulated such as soil types (and sediment feed rate), precipitation regimes (and flow rate), season, slope, level of site disturbance, fence installation method, type of fence material, depth of toe, type and spacing of support structures, time since installation, level of inspection and maintenance, among others, that all require systematic evaluation. Doing so will inform the practice, as well as identify specific technical research needs, related to silt fence design and use. Moreover, what constitutes "proper" installation and maintenance is unclear, especially given regional- and site-level variation in precipitation, slope, and soil characteristics. Educating and empowering construction crews to be proactive in maintenance of silt fencing is needed given an apparent lack of compliance monitoring by regulatory agencies and the realities that the damage is almost instantaneous when silt fences fail. Our goal is not to dismiss silt fences as a potentially useful tool. Instead, we question the way they are currently being used and call for better science to determine what factors (in terms of fence design, installation and site-characteristics) influence effectiveness as well as better training for those that install, maintain and inspect such devices. We also encourage efforts to "look beyond the fence" to consider how silt fences can be combined with other sediment control strategies as part of an integrated sediment control program.

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1. Context

As a result of human activities freshwater biodiversity around the globe is in crisis (Dudgeon et al., 2006; Strayer and Dudgeon, 2010). Although there are many factors that contribute to the degradation of freshwater ecosystems, landscape alteration is regarded as one of the most insidious (Allan, 2004; Dudgeon et al., 2006). Human-driven landscape alterations (e.g., development, agriculture, mining) leads to dramatic changes in hydrology, water quality, and habitat configuration even when activities occur in the terrestrial realm away from water sources (Schlosser, 1991; DeFries and Eshleman, 2004; Allan, 2004). Changes to physicochemical characteristics of the environment (such as water temperature, flows, silt, and nutrients) alter biotic elements, including population abundance and community structure in aquatic systems (Paul and Meyer, 2001; Allan, 2004; Dudgeon et al., 2006). Of particular concern is the introduction of fine sediment from terrestrial sources that run off into lotic and lentic systems and have the potential to cause direct and indirect negative effects on aquatic biodiversity.

In aquatic systems, excessive sedimentation – herein inclusive of suspended sediment, siltation, and turbidity - has been named the most detrimental form of aquatic habitat degradation and its effects on aquatic wildlife is the subject of numerous comprehensive reviews (e.g. Newcombe and Macdonald, 1991; Waters, 1995; Henley et al., 2000; Robertson et al., 2006; Kemp et al., 2011). Land-use alterations change natural sedimentation processes, increasing fine sediment suspension and deposition (Waters, 1995), and the effects on aquatic ecosystems are extensively documented and generally undisputed. Increased inorganic sediment loading changes the physical habitat of aquatic ecosystems by altering water pH (Lemly, 1982), water clarity, and decreasing oxygen flow through substrate by in-filling of interstitial space between larger substrate materials (Beschta and Jackson, 1979). Such changes to the abiotic aspects of aquatic ecosystems have great implication for the biotic: suspended sediment decreases photosynthetic activity by blocking light (Newcombe and Macdonald, 1991; Madsen et al., 2001), limiting primary production, and can limit feeding at higher trophic levels (Zamor and Grossman, 2007), increase foraging demands (Gregory and Northcote, 1993; Utne-Palm, 2004), physically harm sensitive oxygen exchange tissue (Redding et al., 1987; Lake and Hinch, 1999) and alter filter feeding behaviour (Rundle and Hellenthal, 2000) in aquatic organisms, potentially increasing metabolic demands (du Preez et al., 1996). Once settled, deposited sediments can cause substrate to be unsuitable for spawning (Chapman, 1988), directly smother eggs (Greig et al., 2007), prevent emergence of fry (Jennings et al., 2010), and bury food sources for invertebrate species (Suren, 2005; Kent and Stelzer, 2008).

The amount of sediment transport increases dramatically during construction compared to pre- and post-construction levels (Cleveland and Fashokun, 2006). To minimize the movement of sediment off site, regulatory agencies require the use of sediment mitigation techniques during construction activities (Kerr, 1995; Harbor, 1999). Although there are a variety of sediment control measures and tools, silt fences are among the most commonly used. These geotextile systems consist of semi-permeable fabrics and/or composites that filter sediment. Silt fences are widely used because of their low cost, versatile application, and ease of installation and removal (Robichaud et al., 2001). Fences can also be easily customized in design and installation to best suit the conditions of the site, such as changes in type and placement of support stakes and type of geotextile used (Kouwen, 1990; USEPA, 2012). For any sediment control devices deployed, proper design, installation, and maintenance is key to their efficiency (Kouwen, 1990; Barrett et al., 1998; Gogo-Abide and Chopra, 2013).

Here we argue that silt control fences, despite being widely adopted, have failed to prevent silt from entering aquatic ecosystems. We submit that the science behind silt control fences is limited and that there are few rigorous assessments to identify the extent to which such controls actually reduce aquatic sediment mobilization. We also discuss the role of improper use and maintenance of silt control fences and limited compliance monitoring on silt mobilization. Given the manifold negative effects of silt on aquatic systems and our ability to pinpoint the source (i.e., largely point source – or at least identifiable), it would seem that we should be better able to address this pressing issue contributing to the degradation of aquatic ecosystems around the globe. To that end, we identify a number of improvements needed to advance the science, technology and practice of silt control.

2. The science of silt control

As new materials and designs emerge, studies on the performance efficiencies of silt fence installation design and fabrics are crucial. Generally, laboratory testing consists of a flume in which a portion of geotextile is drawn across tightly and secured (e.g. Barrett et al., 1998; Keener et al., 2007) and samples are collected pre- and post-material to assess efficiency of sediment concentration removal and changes in turbidity. Flow through-rate – the amount of time for sediment-laden water to pass through the material – is also measured: prolonged retention leaves silt fences vulnerable to failure due to overtopping, undermining or sediment diversion (Harbor, 1999; Keener et al., 2007). Under laboratory conditions, studies often report high removal efficacies compared to field studies (Crebbin, 1988; Kouwen, 1990; Chapman et al., 2014). For example, Barrett et al. (1998) found that flow through was two orders of magnitude less than values reported by manufacturers due to clogging of pores in the materials. The way geotextiles are installed in test flumes prevents any overtopping or undermining of the material, meaning that any efficiency results are only applicable when fences are perfectly installed and maintained. Indeed discrepancies between laboratory and field tests have been indicated by paired study designs (Barrett et al., 1998).

More testing of silt fence sedimentation rates in field settings is vital to assess realized efficiencies of this widely applied mitigation device. In applied settings, a number of contributing factors (soil type, particle size, precipitation, slope, vegetation type, etc.) results in data gathered at a particular site that must be extrapolated to other locations (Strecker et al., 2001). Further, studies may not report data vital for interpretation such as rainfall (Barrett et al., 1998) or have controls (Horner et al., 1990). Both sedimentation rates and silt fence integrity are directly affected by soil consistency (Sansone and Koerner, 1992), precipitation rates (Gogo-Abite and Chopra, 2013), UV exposure (Suits and Hsuan, 2003), and other environmental qualities that vary regionally and seasonally (Harbor, 1999; USEPA, 2012). Consequently, long-term field studies (i.e., prior to fence installation to long-after fence removal) of installed fences are critical. Further, inconsistent reporting of variables leaves interpretation difficult; studies may report changes in total suspended solids, turbidity, or total mass of sediments using a variety of measurement techniques. Overall, while perhaps present within industry, systematic testing of sediment fences in applied field studies has not been made available through peer review.

3. The practice of silt control

Sustainable development is the stated goal of many development projects and the construction phase is one of the most important phases to target to reduce human impacts and work towards sustainability (Hostetler, 2010). *In silico*, laboratory, and controlled field tests of silt fences may clearly demonstrate the ability of these materials to reduce sediment input into aquatic systems. In practice, however, scaling up from the computer or lab bench to large-scale, onsite applications of technology are rarely straight forward and few studies exist on the efficacy of silt fencing in real-world applications (Chapman et al., 2014). The goal of silt fencing is to limit erosion and prevent fine-sediment on human-disturbed land (e.g. construction sites) from entering lakes and rivers, until the land is re-vegetated and naturally stabilised. In order for sediment fencing to work there must be sufficient fencing, constructed of appropriate material, and properly installed. The United States Environmental Protection Agency lays out five criteria for effective silt fencing installation including: 1) proper placement of the fencing based on site contours; 2) sufficient amount of fencing without long runs that may cause excessive water pooling and overflow; 3) use of a heavy porous fabric; 4) metal posts driven to at least 0.6 m depth and spaced at appropriate intervals to support the fabric; and 5) tight soil compaction on both sides of the fence (USEPA, 2012). Although the majority of construction sites today employ some form of sediment fencing, at many sites the fencing is not effective due to improper design installation, or maintenance (USEPA, 2012).

Unfortunately, it does not take long when visiting most construction sites to note multiple failure points in silt fence installation and maintenance. Typical problems observed with silt fence installations include tearing, broken or bent support poles, insufficient fencing, uncompacted soil near the base, material piled on or against fencing, and vandalism (Fig. 1). These failures in the silt retention strategy likely reflect a lack of training on the importance, maintenance, and upkeep of silt fencing, and a lack of resources dedicated to the proper installation and continued maintenance of the fencing. It often appears that regular inspection and maintenance of silt fencing is not a high priority. This is most evident at sites where active construction has ceased but the ground remains susceptible to erosion and perimeter controls such as silt fencing are still required to prevent off-site movement of sediment and consequent damage to aquatic ecosystems. All too often it would appear that the practice of silt fencing is to “set it and forget it”. In order to limit the impact of human activities on aquatic ecosystems and make best use of the time and money invested into erosion control by industry it is important that we have effective sediment control based on sound scientific research. Silt fencing needs to be more than window dressing.

4. Opportunities for improvement

To address what we regard as long-standing and persistent failure of sediment fences to control sediment inputs in freshwater ecosystems, we outline opportunities for improvement related to the science and practice of sediment control with a focus on sediment fences.

4.1. Generate credible science

As noted above, there is relatively little research that has been published on the science of silt fences and the work that has been done suffers from a number of issues. There is a dire need for credible science (Kaufman, 2000). We don't presume that we can identify all the necessary opportunities, but we do identify a number of priority questions and approaches. For example, a key research priority is to determine the factors that influence the ability of silt fences to effectively trap silt while enabling filtered water to pass. That research priority is superficially simple yet there are so many factors that can be manipulated such as soil types (and sediment feed rate), precipitation regimes (and flow rate), season, slope, level of site disturbance, fence installation method, type of fence material, depth of toe, type and spacing of support structures, time since installation, level of inspection and maintenance, among others. Also important is research on different strategies for removing fences (when their use is no longer required) and the sediment that they have captured and remediating the site (i.e., does one simply yank the fence and drive away?). From a conceptual perspective, there is a need for research that spans the laboratory (Barrett et al., 1998; Zech et al., 2009), field (both real construction sites and test plots; Faucette et al., 2005; Zech et al., 2009; Gogo-Abite and Champa, 2013) and *in silico* (modelling; Britton et al., 2001) realms to provide a comprehensive understanding.

Moreover, engineers, soil scientists, geographers, and biologists need to collaborate to conduct holistic, integrated research with a variety of relevant endpoints. When studies occur in the field they should extend beyond being observational where researchers simply travel from site to site to examine silt fence performance. Instead, experiments should be designed making use of a before-after-control-impact approach with adequate replication (see Conquest, 2000). Variables such as soil conditions, installation methods, fence materials, among others, should be systematically manipulated (or selected) to design experiments with the ability to identify causal relationships. Indeed, much of the existing literature is based on correlations (e.g., Paterson, 1994). We also call for researchers around the globe to collaborate to evaluate regional differences in silt fence performance. We recognize that the characteristics of a given stream and landscape as well as its biota will dictate the level of silt control needed. Clearly not all silt fence materials are created equal so replication in the face of different soil characteristics and water flows seems prudent. The advent of various sensors, automated water samplers and digital cameras (video or still) provide great opportunities to document fence performance through time and thus across various precipitation events, seasons (including winter) and time since fence installation. To improve understanding of maintenance regimes and the culture surrounding sediment control within industry, there is a need for social science studies directed towards inspectors and those that install silt fences. Use of non-obtrusive cameras (Struthers et al. in press; notwithstanding privacy issues) could provide fascinating

Fig. 1. Common problems with silt fence installation and maintenance observed in Ottawa, Ontario, Canada. All of these problems can lead to unnecessary silt deposition into aquatic ecosystems. a) Fencing that has fallen over with broken wooden support poles, b) Sediment piled upon and over silt fencing, c) Wooden support poles removed causing fence to collapse, d) Insufficient fencing, e and f) Loose and ripped fencing.

insight into silt fence monitoring and maintenance.

4.2. Train, educate, and empower site crews

As noted above, silt fences often fail entirely due to improper installation or maintenance. There are clearly a number of opportunities for improvement in this regard. For example, there is a need for the development of training courses for developers and contractors (i.e., those that hold the shovels) to learn about proper installation and maintenance. There are training courses available but they tend to be focused on environmental consultant and compliance monitoring staff (e.g., Florida Stormwater, Erosion, and Sediment Control Inspector Training and Certification Program; http://www.dep.state.fl.us/water/nonpoint/erosion.htm) rather than crews that are on-site daily and would be doing the physical installation and maintenance. It can be effective to show examples (with photographs) of both proper installation as well as failed examples with reasons for their failures rather than only showing technical engineering diagrams or line drawings. Video footage showing silt fence performance during precipitation events could also help site crews to understand the forces that act on the silt fences. Given differences in soil/site conditions, slope and precipitation among sites and regions, generic training materials should be coupled with regionally-relevant content. We found some examples of "guidelines" or "best management practices" developed by natural resource management agencies but they tended to be written as legal edicts rather than providing meaningful "how to" advice (e.g., Manitoba, https://www.gov.mb.ca/mit/mateng/apl/152_1.pdf; Bellevue, Washington, http://www.ci.bellevue.wa.us/pdf/Development%20Services/CG_DevStds2010_BMPC233.pdf). There is also an attempt to generate a global "standard" for silt fence installation (see http://www.astm.org/Standards/D6462.htm) but it lacks regional context. We did identify some progressive training courses (e.g., Nova Scotia Transport Ministry; http://novascotia.ca/tran/works/enviroservices/ESCCourseMaterial/2_ESC%20Principles%202013.pdf) where there was emphasis not only on silt control but on minimizing erosion. Included in training should be educational materials that emphasize the negative consequences of silt on aquatic systems in an attempt to empower site crews to actively monitor silt fences and fix them when needed – a concept known to change learner behaviour (Hungerford and Volk, 1990; Steg and Vlek, 2009). Such empowerment should lead to more consistent silt fence function rather than only fixing fences when problems are identified during compliance monitoring (if such monitoring occurs).

4.3. Conduct meaningful compliance monitoring

In contemporary society where regulations and policy are enacted to protect the environment, compliance monitoring is essential (Shimshack and Ward, 2008; Gray and Shimshack, 2011). There is little research or information on the extent to which compliance monitoring related to silt control occurs. Burby and Paterson (1993) revealed that in one study developers failed to install 27% of the control measures specified in the approved plans while in a another (Loew et al., 2004) approved silt fences at construction sites were commonly missing or installed improperly. Clearly compliance monitoring is needed for silt fences. Moreover, if compliance monitoring is to occur it is worthwhile to do so during precipitation events to determine if the silt fences are performing as intended. Compliance monitoring does not necessarily have to be punitive. Rather, it should be viewed as an opportunity for inspectors to educate site staff and empower them to conduct their own monitoring. Indeed, in the long-term it would be desirable if such compliance monitoring efforts were somewhat redundant with monitoring conducted by trained and empowered on-site workers that deal with the installation and management of the silt fences.

4.4. Build the evidence base

There is a growing movement towards evidence-based conservation and environmental management (Sutherland et al., 2004). Rather than relying on "gut feelings" or "experience" to determine the best conservation intervention (which is common in environmental management; Pullin et al., 2004), an evidence-based approach relies on rigorous evaluation of diverse evidence sources and synthesis (in the form of a systematic review; Pullin and Stewart, 2006) to determine the best evidence-based course of action. From meta-analyses it is clear that keeping sediment out of aquatic systems should be a priority (e.g., Chapman et al., 2014). However, the evidence-base supporting the best means of achieving that target is limited. Silt fences remain a core (if not the primary) tool in silt control despite the fact that scientific evaluations of their effectiveness or the factors that influence effectiveness are limited. There is a paucity of peer reviewed literature on the topic – so much so that a recent meta-analysis (i.e., Chapman et al., 2014) was unable to amass sufficient data from the literature to evaluate effectiveness of silt fences. There is a need to publish research in credible and accessible outlets rather than obscure technical reports that are difficult to obtain and are not subject to peer review. We also suspect that practitioners serve as a rich source of knowledge if their experiences and perspectives could be extracted and synthesized. Social science studies could be used to identify research priorities (e.g., Brown et al., 2010) for silt controls as well as identifying aspects of silt fences that are regarded as particularly effective, which would help address the science-policy gap related to sediment and erosion control (Kaufman, 2000). There is also room for case reports from practitioners that summarize successes and failures. In this context, failures are particularly important as there is likely a "file drawer" effect (Rosenthal, 1979) whereby there is a tendency to not publish failures which could leave the impression that silt fences are more effective than they are. Perhaps the paucity of peer reviewed literature on silt fences (whether success story or failures) is a reflection of the broad failure of silt fences? We submit at this point the evidence-base is sufficiently shallow to know whether silt fences are of any benefit in real world applications. We hope that this paper will stimulate research (with appropriate controls and replication) that will enable proper meta-analysis in the context of a systematic review in the coming years.

4.5. Beyond the fence

Here we have focused on silt fences given that they are arguably the most common approach to sediment control, which is not surprising given that they are a relatively simple and inexpensive technology. Nonetheless, they represent just one of the possible sediment mitigation tools available. There is relatively little work on the comparative effectiveness of different sediment mitigation strategies so it is not possible to provide specific direction here other than to note the need for comparative studies. There are a growing range of materials (i.e., geotextiles) that can be used for fencing that have been tested (e.g., Barrett et al., 1998; Risse et al., 2008; Gogo-Abite and Chopra, 2013), however, equally important may be new means of installation that will require less maintenance. There would also seem to be a need for more direct interaction between practitioners that install and maintain silt fences and those that design such tools. It is unclear the extent to which the various industry partners seek input from practitioners to refine and enhance the effectiveness of sediment controls. It is difficult to know exactly where the industry stands in terms of new innovations but a search of patents reveals developments related to installation (Whitener, 2000; Wheeler et al., 2000; Vreeland, 2004). We also encourage efforts to develop more combined approaches that use multiple strategies simultaneously to minimize sediment mobilization. Some of the other strategies that appear to be equally "simple" in design and low in cost are compost filter berms (Tyler, 2001) and erosion control rolls (Allard, 2003). What is clear is that current fences, partly due to improper installation and insufficient maintenance, do not appear to be overly effective at preventing sediment from entering freshwater systems so the status quo must change. Looking "beyond the fence" would seem prudent should the challenges identified here not be surmountable without combining tools.

5. Conclusion

In the face of development activities, regulatory bodies have enacted policies (see Mertes, 1989; Alsharif, 2010) in an attempt to reduce the input of sediment into aquatic systems given that it has been long (see Ellis, 1936) and widely accepted that such inputs are deleterious to environmental quality and aquatic biodiversity (e.g., Ryan, 1991; Wood and Armitage, 1997; Bilotta and Brazier, 2008;

Chapman et al., 2014). Accompanying such policies is a suite of tools (or best practices) that are available to practitioners known as silt or sediment controls. By far the most common and visible is the silt fence (Kouwen, 1990). One doesn't have to venture far in developed countries to see them deployed adjacent to most construction activities that have the potential to mobilize sediment. Although presumably used with good intentions, there is surprisingly little research that evaluates the effectiveness of silt fences and the factors that modulate success when properly installed and maintained. What constitutes "proper" installation and maintenance is unclear, especially given regional- and site-level variation in precipitation, slope, soil characteristics, etc. We presented a candid critique of silt fences. Our goal was not to dismiss silt fences as a potentially useful tool. Instead, we question how they are being used and call for better science as well as better training for those that install, maintain and inspect such devices, as well as more rigorous compliance monitoring. From our perspective, the jury is still out regarding the effectiveness of silt fences with many opportunities (as we outlined here) to improve the science and practice of sediment control via silt fences. Quite simply, with insufficient literature/data to conduct a systematic review and meta-analysis on the utility of silt fences for protecting aquatic ecosystems from sedimentation, their widespread use is not consistent with an evidence-based approach to environmental management (Sutherland et al., 2004).

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