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Article title: The pernicious problem of streambed colmation: a multi-disciplinary reflection on the mechanisms, causes, impacts, and management challenges

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Abstract

The accumulation of fine sediments in rivers is a pernicious problem with wide-ranging consequences for the healthy functioning of rivers throughout the world. It is linked to a range of landuse changes and human activities that have increased sediment inputs leading to elevated fine sediment loads that exceed the sediment transport capacities of rivers. Surficial deposits of fine material can also create the conditions for fine sediment to move into and accumulate *within* the coarser bed substrate, a process known as *colmation* and the focus of this review. Colmation, also referred to as clogging, fine sediment infiltration, fine sediment deposition, ingress, infilling, intrusion of fines, siltation, and the surface-subsurface exchange of particles, is particularly damaging to river habitats and ecosystems. It causes degradation through the physical effects of reduced porosity and flow connectivity and the biogeochemical changes arising from the hydraulic and hydrological impacts and the effects of sediment-bound contaminants, all of which can impact on river ecology. Different aspects of the phenomenon of colmation have been studied across a number of disciplines and over several decades and this paper synthesizes this wide literature to provide a multidisciplinary perspective on the mechanisms, causes and impacts of colmation and discusses some key management challenges.

Keywords: fine sediment deposition, colmation, decolmation, sediment management

Introduction

Fine sediment, defined as inorganic and organic material < 2mm in diameter, plays an important role in the geomorphology, hydrology, and ecology of river systems not least because the healthy functioning of aquatic habitats is dependent upon the delivery of nutrients bound to fine sediments. The varying proportions of sand, silt, and clay in fine sediment will determine whether it is either granular or cohesive, and the organic matter component can comprise particulate organic matter such as seeds and aggregates and/or flocs of organic and inorganic particles[1, 2] including invertebrate faecal pellets[3] or particles with biofilms[4]. In addition to the particulates (solids), fine sediment deposits also contain liquid and gaseous components resulting in a mixture that is physically, chemically, and biologically heterogeneous. Longitudinal, lateral, and vertical fluxes of fine sediment in the fluvial system link hillslopes to floodplains, riparian zones, the active channel, and the hyporheic and groundwater zones. Therefore, fine sediment can provide an important 'connectivity signature' of the river landscape as well possessing a distinctive 'biogeochemical signature' due to its heterogeneous nature[5].

During recent decades, however, many river systems around the world have been experiencing rising inputs of fine sediment[6-8] resulting in fine sediment loadings far exceeding pre-industrial (background) conditions[9, 10]. These increases have been linked to a large number of human activities and catchment disturbances[11-14] and have resulted in a wide range of environmental impacts. The same chemically-active silts and clays that supply vital nutrients to aquatic habitats can also be a vector for pollutant transport because many inorganic and organic micro-pollutants including heavy and trace metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, dioxins and radionuclides, have a high affinity for the fine-grained fraction of sediments[15] with fine sediment entrainment, transport, and deposition dictating the delivery of these sediment-bound contaminants to different parts of the river system and their subsequent residence times[16]. The enhanced sedimentation and accumulated surficial sediments (Figure 1) observed in many rivers[17] reflect elevated fine sediment loads exceeding the ability of streams to transport the material[8]. Permeable, groundwater-dominated streams are particularly prone to fine sediment deposition and colmation due to their distinctive hydrology which reduces the ability of fine surficial sediments to be eroded once deposited on the streambed. These accumulations of surficial fines affect the habitat for aquatic macrophytes[18-20], benthic invertebrates, diatoms[21], and fish[22]. Particles from these accumulated fine sediment deposits can also penetrate into the coarser materials (e.g. gravels and cobbles) forming the streambed and reduce its hydraulic conductivity[23] and also infiltrate further into the hyporheic zone. Thus, several aquatic interfaces will be affected[24]. In particular, the connectivity between surface water, the hyporheic zone[25], and the underlying groundwater may be impeded thus altering the flux of dissolved and sediment-bound substances[26-30].

FIGURE 1: Surficial fine sediments can create the conditions for streambed colmation (Photo Lin Baldock)

There are fewer studies documenting elevated levels of sedimentation *within* streambeds and bed sediment storage compared to those showing increased sediment yields andsuspended loads in rivers. However, studies of the infiltration of fine sediments into streambeds (colmation) and their re-release (decolmation) and an awareness of the environmental impacts can be traced back many decades[e.g. 18, 31-41]. Since this early research, biologists, geomorphologists, hydrologists, and engineers have undertaken field measurements, laboratory experiments, and developed numerical models aimed at understanding how fine sediment enters the river bed, its causes, and its impacts with several terms emerging and being employed interchangeably in the research literature. These include: *siltation*[42]; *ingress*[30]; *clogging*[43-50]; *infilling*[51, 52]; *fine sediment infiltration*[53-58]; fine sediment deposition or sedimentation[8, 46]; *surface-subsurface exchange of particles*[4]; *intrusion of fines*[59]; and *colmation*[60-63] the term used hereafter in this review because it has been used across disciplines and has a clear corresponding term (decolmation) for the reverse process by which fines leave the streambed. A more inter-disciplinary approach to the study of colmation has only started to emerge in recent years[e.g. 4, 63] and, in bringing together the literature on this topic, this paper aims to provide some new perspectives and insights which might help inform the management of fine sediments in rivers. We first consider the processes and key factors controlling colmation before examining the main causes and impacts and concluding with a discussion of some of the challenges for river and catchment management.

Colmation and decolmation: processes and controlling factors

Understanding how, why, and where colmation takes place is critical for assessing the environmental and economic impacts of upstream anthropogenic and natural fine sediment releases into rivers[55]. Streambed colmation has been observed in the field but laboratory studies have been particularly useful in clarifying the mechanisms under different combinations of suspended particles, bed sediments, and hydrodynamic conditions[4] and researchers have also developed theoretical, mathematical and probabilistic models, for example the models by Lauck[64] and Herrero and Berni[58].

The process of colmation encompasses: the entry of finer material into the coarser matrix of the bed (normally sands, silts and clays moving into gravels and / or cobbles; or silts and clays entering a sand substrate); its filtration to the hyporheic zone below; and the formation of a layer which reduces the permeability of a streambed compared to the initial conditions[43, 44, 60]. Colmation is more commonly associated with the intrusion of fine sediments into the coarser bed sediments from surficial deposits (Figure 2(a) *external colmation*) which arises due to increased fine sediment loads in combination with reduced flow velocities and water levels triggering sediment deposition and the subsequent infiltration of fine sediments into the streambed. Interestingly, Lisle[65] found that the largest proportion of infiltrated sediment originated from the finest fraction of the bedload rather than from settled suspended load showing the importance of bed material load and transport. External colmation can also arise due to increased sewage loading in rivers which causes sedimentation of an organic layer on the streambed and the development of dense algal mats[60]. However, the formation of a thin sealed layer below an armour layer (Figure 2(b) *internal colmation*) can occur when surficial fines that have been able to penetrate through a coarse armour layer are unable to pass through the smaller pore spaces of a finer sub-armour layer beneath or when fines move upwards from the underlying hyporheic zone and collect underneath an armour layer[43, 66, 67]. Fines can also penetrate into, and cause the clogging of, an armour layer (as distinct from the entry into a more open and mobile coarse streambed), a process known as *contact colmation*, *intermediate colmation* or *armour layer colmation* [44, 62].

All three forms of colmation are dependent on a number of interconnected physical, chemical, and biological variables[37, 43, 68] including: the flow velocity and shear stress of the river; the hydraulic gradient of the seepage flow and its direction; suspended sediment concentrations; grain size distributions and particle shapes of the infiltrating material and the bed substrate; the presence of algae and biofilms[4]; and the type and concentration of dissolved substances. Early experimental work by Beschta and Jackson[38] was valuable in showing the importance of the flow condition (as represented by the Froude number) as a key hyraulic parameter affecting fine particle infiltration, in combination with sediment input rate and its particle size distribution. They also showed how turbulent pulses generated at higher velocities inhibited fine sediment deposition. Subsequently, Carling[69] demonstrated, not surprisingly, that mean flow data have limited value in understanding a process that takes place on and within the streambed by showing how pore water velocity distribution and substrate porosity are important in controlling the movement of fine sediment into the gravel substrate. A macro analysis by Huston and Fox[50] of ten recently-published studies also provided further insight by showing that whilst bed-to-grain ratio (defined as the grain size distribution of the bed sediments relative to those of the infiltrating grains) is reliable in predicting the initiation of colmation, the depth of ingress is determined more by the substrate porosity, roughness, and Reynolds number since together these better reflect the control of pore water velocity distribution on how fine sediment moves (infiltrates) into the gravel substrate.

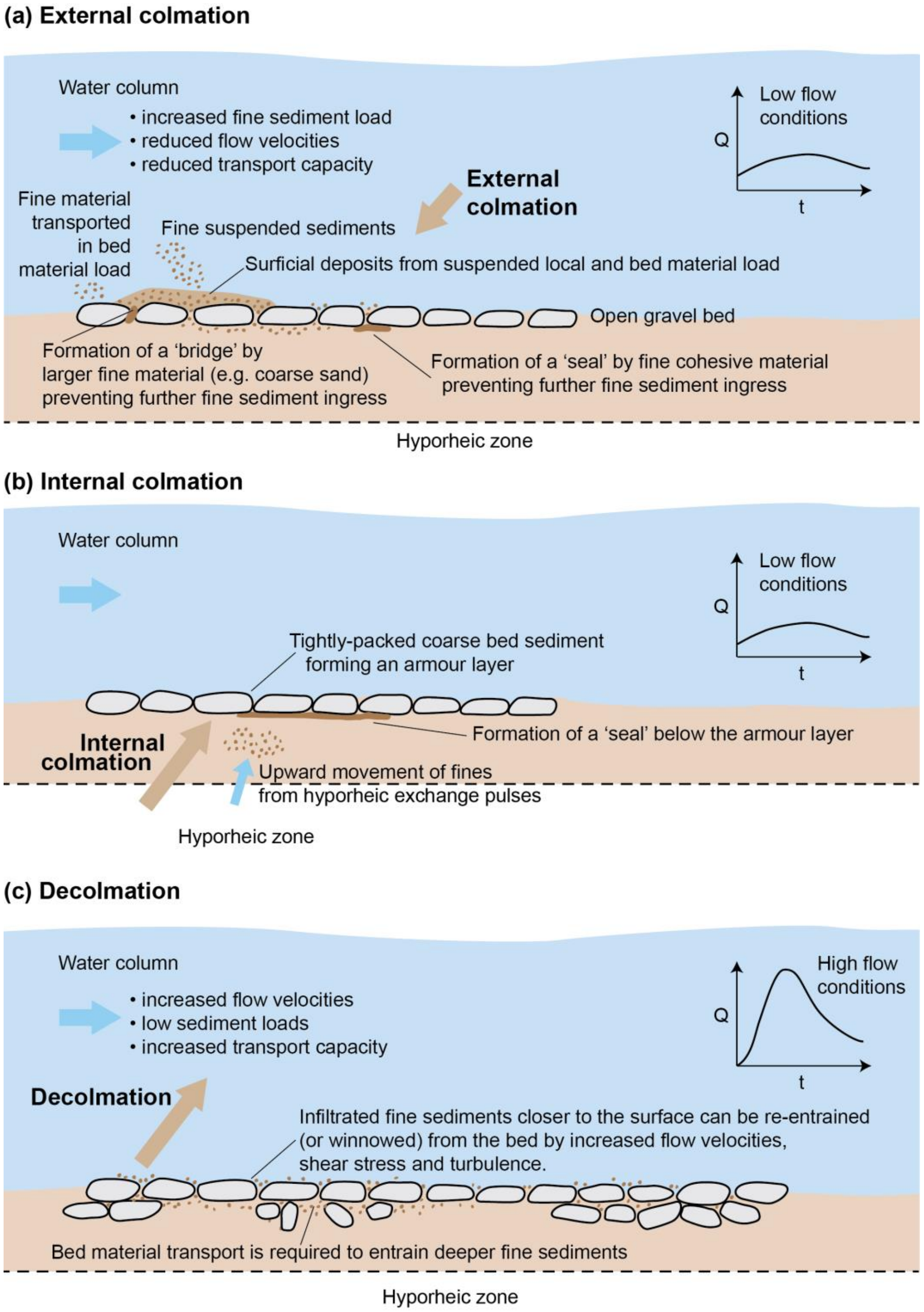

FIGURE 2: Conceptual diagram showing the mechanisms of colmation and decolmation.

Early detailed studies of the mechanism of infiltration[e.g. 37, 70] identified a *mechanical filtration* that occurs with larger fine particles (diameters > 30 µm) where particle size and shape are the most important factors; and a *physicochemical filtration* for smaller particles (< 1 µm) where the surface charge of the particle and adhesion of colloidal particles and bacteria play a role. For medium-sized fine particles (diameters 3 to 30 µm) both mechanisms can determine particle entry and retention. For example, deposition of small biological particles into streambeds is increased if associated with larger inorganic particles or organic / inorganic aggregates and benthic and hyporheic biofilms increase particle retention[71]. Further research is thus needed on the role of biological factors and, in particular, the mechanism of particle capture in biofilms and how particles are released back to the water column[4].

Streambeds that suffer from colmation are characterized by a more consolidated texture, and a reduced porosity and hydraulic conductivity[61] and an important consideration is the depth of ingress. Observations in the field have shown that there is a limit to the depth of fine sediment infiltration within gravel beds[43, 69, 72] with the grain size distribution of the streambed an important control. Cui and Parker[73] reported that the fine sediment fraction within gravel deposits is negatively correlated to the standard deviation of the particle diameters within the gravel matrix (which is a surrogate measure for available pore space). The grain size distribution of the bed sediments influences the available pore space of the substrate which in turn exerts a major control on the size of the particles that can infiltrate and the amount and depth of colmation[43, 57, 74]. Grain size distribution has been shown to be more important for initial particle intrusion[38] whereas pore sizes are critical in determining infiltration depth[66]. A further important recent finding[57] is that larger grain sizes in a streambed offer more pore space to receive smaller infiltrating grains but a streambed with a wider range of particle sizes will have less available pore space because voids can be filled by variably sized particles. This supports earlier work by Wooster et al.[55] on the importance of the relative grain sizes of the substrate, the infiltrating material, and the pore spaces in the bed material and explains how silts and clays can still infiltrate a gravel bed already saturated or over-saturated with sand. And building on this, a new method has been proposed to predict the grain size distribution for a saturated gravel bed and the reduced porosity taking into account the changing characteristics of the bed and the supplied sediments during the filling process[75].

Complementing the field observations and laboratory studies, theoretical and probabilistic models, for example, the Lauck[64] model, have reproduced the general observations of Einstein[32] that fine sediment fills the pores in the gravel matrix from the bottom up when the size ratio of the bed material to fine sediment is large and the bed material is shallow. The Lauck[64] model has also reproduced the key observations from other studies[38, 43, 65, 66, 69] that fine sediment can only infiltrate to a finite depth if the bed material is sufficiently thick. Subsequently, Cui et al.[56] developed a theory to describe the processes of colmation based on Lauck[64] and this states that the highest possible fine sediment fraction resulting from fine sediment infiltrating an immobile clean gravel deposit is an exponential decay function with depth into the bed material. Thus, well-sorted gravels with large pores are conducive to deeper colmation whereas in poorly-sorted streambed sediments with smaller pore sizes the colmation depth is relatively shallow, although the presence of macropores can enable the movement of fines through poorly-sorted sediments to deeper layers[61].

During the process of colmation, larger infiltrating grains can also become trapped among the pore spaces of large bed grains near the surface of the bed substrate creating a “bridge” or the accumulation of fine cohesive material can create a “seal” both of which block further infiltration (Figure 2 (a) and (b)). Seals and bridges have been observed in both field and laboratory studies. Gibson et al.[76] suggest that they form when the ratio D_{15} substrate / D_{85} infiltrating sand is below 12-14, although a mobile bed substrate will limit seal formation and persistence even under conditions of high sand supply[57]. And laboratory flume experiments of clay infiltration into a sand bed[45] showed that clay particles caused the clogging of the surface of the streambed which isolated deeper sections of the bed from the streamflow. Thus, when seals or bridges form, streambeds do not always fill from the bottom upwards and even relatively low suspended sediment loads can degrade the habitat by reducing or preventing surface – subsurface exchanges)[77]. Recent progress which will contribute to a growing understanding of the physics of streambed colmation has also been made in the develoment of a mathematical model which reproduces the two main infiltration mechanisms ("bridging" and "unimpeded static percolation" i.e. the infiltration of fines to an impermeable layer and subsequent filling)[58]. In addition to the variations in bed substrate, spatial patterns of bed morphology (e.g. pool-riffle sequences), flow types, and suspended sediment characteristics along a river, can create "a three-dimensional mosaic of differentially colmated areas within the streambed"[61]. For example, Diplas[78] recorded how pools and the downstream side of bars were the first locations to experience colmation. Furthermore, temporal changes in flow and sediment conditions that arise, for example, during periods of reduced river flow may exacerbate infiltration in locations of the streambed that are already prone to colmation including pools or low velocity areas in and around vegetation or large wood[20, 30, 79].

In contrast, the higher flow velocities and shear stresses, and turbulent pulses experienced during flood conditions or the upwelling of groundwater[44, 80] may not only inhibit the first stages of colmation[38] but may trigger site-specific *decolmation* (Figure 2(c)). Decolmation, also known as *declogging* or *exfiltration*, locally re-establishes the permeability of the streambed as fines are flushed from the pore spaces[81]. Early work by Milhous[36] observed that during low flows the gravel bed acts as a sink for fine sediments (a "silt reservoir") but during high flows the gravel bed becomes a source and releases fines into suspension. And a recent modelling study showed a doubling in the retention of clay particles within the streambed during low flow conditions[82].

Schälchli[43] proposed four main phases to the decolmation process related to increasing dimensionless shear stress and this provides a valuable conceptual framework and starting point for understanding decolmation mechanisms. In Phase I, bedload transport is initiated as the shear stress increases and reaches a threshold level that triggers a partial decolmation. This is followed in Phase II by a further flushing out of fines and an increase in the hydraulic conductivity of the top layer of the streambed. In Phase III the armour layer breaks up locally and the hydraulic conductivity increases up to a maximum level. Finally, at peak flow (Phase IV) the whole riverbed is mobilized and previously consolidated channel beds are broken up. As with the process of colmation, the spatial variations in streambed morphology and hydraulic conditions create areas with different levels of susceptibility to decolmation and those areas most prone to colmation (e.g. pools and the downstream side of bars) are the least prone to decolmation[78]. The colmation-decolmation cycle has also been linked to scour and fill events[65] with fill events leading to colmation but scour events responsible for both decolmation by winnowing fines from the bed but also colmation by exposing deeper portions of the bed to fine sediment infiltration.

Thus, decolmation of the upper layers can be achieved through increased flow velocities and shear stress[60], but bedload movement is needed to open deeper interstices to allow the flushing of fines from lower layers[83] without which *permanent colmation* will occur. More recently, Venditti et al.[84] and Evans and Wilcox[57] have linked the residence time of fine sediment in the bed to the frequency and depth of bed mobilization. A "mortar effect" from the addition of fines has also been observed[85] which could reduce decolmation through the increased strength of the streambed. However, the mobility of coarse surface layers and associated feedbacks with infiltrated fines remain poorly understood[86] and further research is needed.

Building on the studies focusing on the hydraulic controls of decolmation,[e.g. 43] there is growing evidence from more recent research of the importance of biological processes and controls on colmation and decolmation. For example, bioturbation by fish, crayfish, and benthic invertebrates can be a pre-conditioning agent that promotes decolmation by increasing the exposure of sediments to increasing shear stress[87] and Nogaro et al.[88] in an experimental study showed how invertebrate bioturbation can reduce the clogging of sediment. In contrast, Extracellular Polymeric Substances (EPS), such as those produced by diatoms[89] and biofilms[90], may bind and strengthen ingressed sediments and thus slow both the rate of decolmation and the total amount of fine material flushed from the streambed. And the colonization of nutrient-rich fine sediments by filamentous green algae can also encourage the depostion of fine sediments[91]. Further research is thus needed to consider the interplay of physical, chemical, and biological controls which may also have a seasonal dimension as with the preliminary observations of temporal patterns in the erodibility and, therefore, the residence times of surficial fine cohesive sediments[92].

Finally, it is important to emphasize that alternating phases of colmation and decolmation, linked to a river's flow regime and fluxes of fine sediment, are natural cyclical processes of sedimentation and erosion in streambeds[44, 61] that contribute to habitat heterogeneity and the healthy functioning of river systems by giving rise, for example, to the turnover of sediments and replenishment of sediment-bound nutrients. However, anthropogenic activity in many catchments has altered the natural flux of fine materials and resulted in elevated fine sediment loads, enhanced sedimentation, and thus the conditons for colmation that has led to a wide range of environmental impacts[61]. The causes and effects of colmation are now discussed in more detail.

Causes of colmation

A situation of sediment surplus in rivers arises when more sediment is present than can be transported by the available flow and this creates the surficial sediment deposits from which colmation may occur. Those processes and activities which increase the sediment loads of rivers and / or reduce the flow velocities or discharges are thus the triggers for colmation. Numerous studies have reported increasing sediment loads in river systems and enhanced sedimentation. For example, sediment yields in the Danube catchment have risen by 30% to 50% in the period 1950 to 1980[93, 94], annual sediment loads for the River Lech in Bavaria increased after 1965[95], and future increases of 250% are anticipated in the annual sediment supply of the Rhine[e.g.96]. These elevated fine sediment loads have been linked to a large number of in-stream and catchment-wide human activities, many of which have a long history and create a legacy effect (see Wohl[14] for a detailed review of the history and causes of enhanced sedimentation in river systems).

The main causes of elevated sediment loads in rivers have been changes to the catchment land use such as deforestation[97] and logging[98], clearance of native vegetation in association with grazing or cropping[12, 99-102], and changes in agricultural practice, in particular a shift from grazing to tilled agriculture, and an increase in the amount of tillage, all of which have increased runoff and erosion of top soil[10, 12, 103-106]. Different types of crop production have also been linked to elevated fine sediment loads, for example the switch from grain to potato cultivation documented by Klimek[107], as have farming practices, such as those that have led to overgrazing, trampling, and poaching by cattle. And increases in fine sediment production and delivery have been linked to the intensive cultivation of cereals and high livestock numbers during the second half of the twentieth century in the River Frome Catchment, Dorset, UK[108]. Although the agricultural sector is a significant contributor to the fine sediment delivered to rivers, estimated to contribute ca. 76% nationally to the watercourses in England and Wales[109], the urbanization of catchments increases runoff and can lead to increases in fine sediments from road deposited sediment[110, 111]. Further inputs of solids can derive from sewage treatment plants, with Carter et al.[112] estimating approximately 40% of fine sediments in urban rivers coming from sewage or road dust. A large number of in-stream human activities have also resulted in enhanced sedimentation including mining activities[113, 114], sediment "flushing" from hydro-electric power plants[77, 115, 116], and the release of sediments in the construction phase of channelization schemes[19], and as a consequence of dam removal[117]. A few studies have also shown increases in the bed storage of fine sediments in addition to the accumulation of surficial deposits linked to higher fine sediment loads and ultimately changes in catchment land use and agricultural practices, for example the studies of the chalk streams of the Frome and Piddle catchments by Collins and Walling[104] and Heppell et al.[30].

Climate change will clearly have an impact on the sediment dynamics in rivers and therefore streambed colmation but there is currently limited evidence available and it is difficult to isolate the influence of climate change from all the other changes that affect the condition of the catchment [6]. Furthermore, there is no clear emerging pattern in the changing sediment loads of the world's rivers [6]. For the alpine Rhine catchment, sediment supply is estimated to increase by 250% based on future scenarios of climate and landuse change [84]. However, large decreases have been reported in the sediment load delivered from the Huanghe (Yellow River) to the sea and the yield now represents only 14% of the widely cited estimate of 1.08 Gt/yr[118]. This sharp reduction has been explained by decreased precipitation combined with human activities in the river and catchment. In addition to the challenge of isolating the effects of changes in climate and landuse, and understanding the response of different regions and catchments to climate changes, there is also a gap in research linking increases in sediment supply and load to surficial fine sediment deposits and streambed colmation. However, some insights into the effects of climate change on sediment inputs and streambed deposition with links to fish habitat and have been provided by a few studies of deglaciation in alpine countries[82]. This research has shown how rising air temperatures have indirectly affected river sediment loads through changed precipitation patterns, a decline in permafrost, snow melting and rising snow lines [82] and changes in snowmelt dynamics [108]; changes which are known to leave unconsolidated deposits exposed and result in increased runoff and erosion[119]. Further research is needed to establish clear cause and effect relationships between changing climate and catchment conditions, increases in sediment loads and sedimentation both on and within riverbeds, and how this impacts on river ecology.

Alongside the many human activities that increase the supply of sediments to rivers are those that modify river flows and therefore affect the sediment transport capacity. Widespread reductions in groundwater levels and river discharges have occurred due to human consumptive uses with abstractions for drinking water supply, agriculture and industry. In natural streams where the bed is permeable, exchanges (upwelling and downwelling) between surface and subsurface flows take place[61, 120, 121]. Lowering of groundwater levels reduces river baseflow and weakens these exchanges and promotes the development of a colmation layer[122-124]. Hydropower schemes have major impacts on the magnitude and timing of river flows (hydropeaking effects) and river water temperatures (thermopeaking effects)[125] and as a consequence sediment regimes and sediment deposition. Significantly, some studies have shown temporal variations in the deposition and colmation of fine sediments downstream of dams which differ from natural cycles[126] and the promotion of biocolmation processes due to the higher temperatures of the released water[127]. And with a global boom in dam building activity[128] the extent of these impacts is anticipated to increase.

Impacts of colmation

Although colmation causes a relatively slow and insidious change to streambeds[7] because it is triggered in part by the frequent lower flows in contrast to the more dramatic changes that occur as a result of high magnitude discharges, the impacts are wide ranging and have been linked to the severe degradation of river environments. Colmation changes: the composition and structure of streambeds, which in turn modifies the flow conditions in the surface waters above the bed; the interconnections between surface water, interstitial pore water, the hyporheic zone and groundwater and the biogeochemical functioning in each of these zones; and the connectivity between the instream environment and the riparian and floodplain zones. In this section we focus on the impacts of colmation on stream ecology as a result of the direct and indirect effects of these hydrological, hydraulic, and biogeochemical changes operating both vertically and laterally in the fluvial system.

The infilling of streambeds by fine sediments causes the compaction of the stream substratum and an increase in cementation[129], which gradually alters the bed structure and morphology. Experimental studies have demonstrated how this has a significant impact upon the flow structure and turbulence[130-132] above the streambed by reducing the bed relief and effective roughness and Kuhnle et al.[133] have shown how the roughness geometry function[134] reduces abruptly with increments in sand level. Furthermore, even if the streambed is not completely infilled and smothered with fines the protrusion of some coarse particles can create a hiding effect which will reduce fine sediment transport[135]. These studies indicate that sharp thresholds in flow structures may characterize areas of the streambed suffering from colmation and further research is now needed to consider the effects of streambed colmation upon vertical and streamwise velocity distributions and turbulence to inform understanding of fine sediment deposition and entrainment.

The physical changes to streambed structure and composition will have several direct effects on stream ecology by altering the function of different species and competition between them. In turn this will affect species composition and diversity[47, 87, 136] and impacts have been observed on fish[e.g. 22], macro-invertebrates[e.g. 21], diatoms[e.g. 91], and macrophytes[e.g. 20] which comprise the biological elements used to assess the ecological quality of freshwaters under the EU Water Framework Directive[137]. Overall, colmation produces a more homogeneous streambed which reduces habitat and species diversity[60] and community composition can also be altered depending upon how different species respond and adapt to the changes caused by colmation. For example, the increased presence of fine sediments within the uppermost layers of the bed increases the possibility of abrasion which can damage unprotected, fine and fleshy body parts such as gills and filter-feeding apparatus[21]. Blackfly (*Simuliidae*) and caddis fly larvae are also sensitive to receiving particles[21, 138] with blackfly larvae ingesting large amounts of inert material and the nets of caddis fly larvae becoming clogged with fine sediments necessitating increased energy expenditure on cleaning activities. Bivalave molluscs and Cladocera cope better in being able to reject unwanted particles from their gills and filter combs but in so doing they also spend time and energy cleaning these structures[21, 139].

Burial, and sometimes abrasion by fine sediment, can also be a problem for fish eggs in the streambed[22] and smaller individuals and certain life stages of invertebrates can be particularly vulnerable[21]. Additionally, the nymphal stage of species such as mayflies will be impacted because they prefer coarser, more stable, substrates for gripping[21, 140]. The ingress of fine sediments also restricts the space for the movement and growth of macro organisms such as mussels and reduces the ability of invertebrates to penetrate to deeper layers of the substrate to seek refugia from high flows and predators[141]. Non-motile diatoms can also be buried by fine sediment causing diatom assemblages to become dominated by motile taxa where the rates of deposition and ingress of fine sediments are high but benthic diatoms can also thrive in the nutrient-rich deposits[91]. In contrast, some species, such as certain Chironomidae and Ephemeridae that perform bioturbation, are able to move sediment and create enough space for their continued survival and can thrive under colmation[21, 142]. Bioturbators also increase water-sediment interactions which can initiate beneficial biogeochemical and microbial processes[88] which further helps in adapting to colmation.

Colmation can have several direct and indirect effects on macrophytes with the level of impact determined by the rate of fine sediment deposition and ingress and the nature of the ingressed material[20]. For example, fine sediment ingress reduces the grain size distribution of the bed which potentially increases its erodibility and also encourages shallow rooting, both of which increase the likelihood that plants will be uprooted during high flow events. Fine sediment ingress will also smother seeds, turions, tubers, and other reproductive propagules, and affect the ability of macrophytes to establish. The composition of macrophyte communities can also be altered by colmation depending on the different levels of adaptability. For example, fast growing emergent species (e.g. *Rorippa nasturtium-aquaticum*) can continue to grow through the fine sediment and thus competitively replace species such as *Ranunculus penicillatus* subsp. pseudofluitans which are unable to cope with being smothered[18] and the competitive ability of *Elodea nuttallii* (Planch.) St. John and *Myriophyllum spicatum* L. has been observed to increase in more nutrient-rich fine sediments[143]. But the benefits of growing in a more fertile substrate is eventually balanced by the negative aspects of being rooted in an unstable, anoxic medium[20].

Colmation is particularly damaging to the health of rivers because the reduced hydraulic conductivity of the streambed[61, 144] disturbs the spatial and temporal patterns in the exchanges of water, dissolved substances, and fine suspended particles between the surface water, interstitial water, the underlying hyporheic zone[145] and groundwater. This in turn alters the physical and chemical conditions and gradients important for supporting a healthy riverine flora and fauna with significant implications for stream metabolism and nutrient cycling. Thus, colmation will restrict the supply of oxygen to fish eggs buried in the streambed[22] and organisms in the streambed will be excluded from up-welling nutrients and down-welling oxygen with impacts observed on the taxa in the hyporheic zone[87, 144, 146, 147]. Lowering of dissolved oxygen levels leads to reductions in oxic processes such as respiration and nitrification but an intensification of bacterial activity and anoxic processes and a greater prevalence of denitrification and fermentation[88, 144, 146, 148, 149] stimulating the growth of biofilm and heterotrophic microbial processes[144, 150]. These conditions also increase the reproduction of nitrate-reducing bacteria[147] which accelerates the process of biological colmation. The chemical conditions of the streambed are often further altered by the ingress of sediment-bound contaminants such as fertlizers and pesticides which can accumulate over time[62] and reduce species diversity[90, 105]. However, this reduced vertical connectivity and increased resistance can sometimes helpfully prevent pollutants entering the groundwater and also improve purification by bank filtration processes[60, 80, 151].

River temperature regulation is also affected by colmation which has an impact on benthic and hyporheic habitat conditions[25, 60, 152]. Without up-welling groundwater the river is not able to benefit from the injection of cooler water in summer, especially important in counteracting the daytime heating of surface water [153] nor the flow of warmer water in winter. Water temperature has been shown to be critical for fish reproduction[154], invertebrate development, and microbial activity in the hyporheic zone[60, 155]. For example, the earlier than predicted hatching and alevin emergence of brown trout eggs reported by Acornley[154] was explained by the warmer river gravels because colmation weakens the intragravel temperature gradients and produces a more uniform spatial thermal distribution.

Finally, the effects of reduced surface-subsurface connectivity can extend beyond the instream and hyporheic zones to the riparian and floodplain environments since colmation can induce lower groundwater levels[60, 156] and sometimes change a perennial river to an ephemeral one[121]. The riparian zone is an important area for biodiversity and productivity and lower groundwater can have detrimental effects on the riparian vegetation[121, 157] which can have further impacts on other biota[152].

Challenges for management and future directions

Fine sediment is a natural and important component of fluvial systems but in recent decades a range of land use changes and human activities in combination with some reported climate change effects have caused it to become a major ecosystem stressor. The increased delivery of fine sediments to rivers and reductions in sediment transport capacity have elevated suspended sediment loads far beyond background (pre-industrial) levels[9] and led to the accumulation of surficial fine deposits and streambed colmation with impacts on the physical, chemical and biological condition of rivers (Figure 3). In England and Wales for example, the total loss of sediment in excess of the target modern 'background' sediment delivery to rivers has been estimated at an alarming 1389, 818 t yr^{-1}, equating to environmental damage costs of up to £523 M yr^{-1} [158]. Contaminants bind to fine sediments further degrading river habitats and fine sediment is now classified as a diffuse pollutant in Europe under the Water Framework Directive[126] and responsible for 23% of water bodies in England at risk of failing to reach good ecological status[96] (Environment Agency, 2015). A key management challenge is thus to address these sediment quantity and quality issues and meet legislative requirements[159] without undermining the positive effects of fine sediment in sustaining ecosystem functions and services[160]. But the lack of routine monitoring of sediment runoff or in-channel siltation means there is limited regional to national data to inform decision making and assess the effectiveness of implemented management options[161]. Data on streambed colmation are particularly limited but hydraulic conductivity, which is highly correlated with the percentage of subsurface fines, has been identified as an accurate and robust method that could be used for large scale and long term colmation monitoring programmes[162].

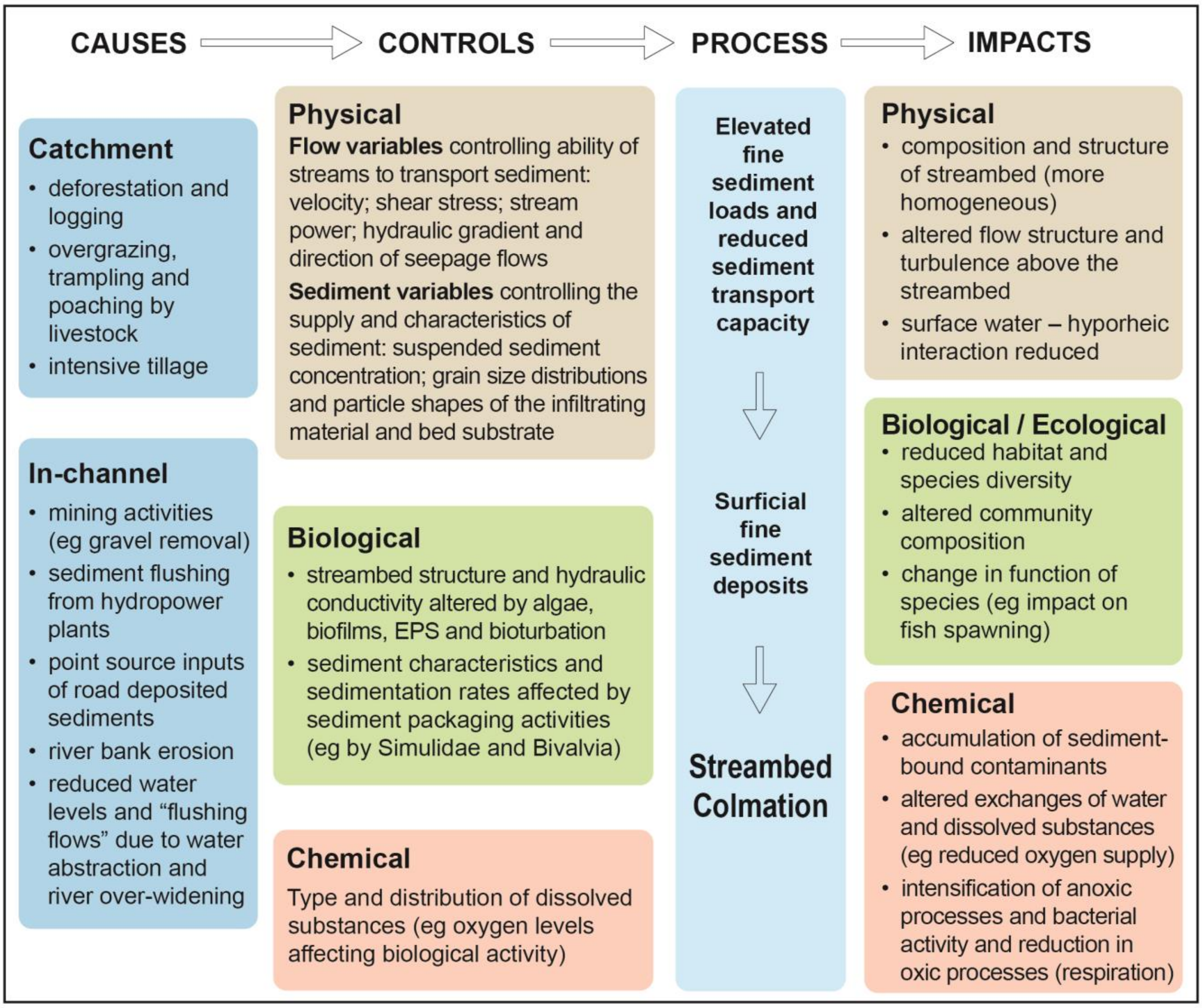

Figure 3: Summary of the main causes, controls and impacts of streambed colmation

Instream approaches to remediate excessive fine sediments in streambeds, such as mechanical removal (vacuuming) of fines from fish spawning beds or the use of clean 'flushing' flows[163], can be prohibitively expensive, may impact on other biota, and are not sustainable because they treat the reach-scale symptoms of degradation rather than the causes. Thus, management and restoration strategies need to shift towards integrated solutions from the river through to the catchment scale[158] that seek to reduce the production of fine sediment and its delivery to rivers and promote the mobilization and removal of fines from the bed. Such source control methods, as part of strategic sediment management regimes[8] should be underpinned by sediment targets[164] (such as Total Maximum Daily Loads) which account for the ability of streams to transport or retain fine sediment[8] and quality guidelines[165, 166]. Furthermore, the control measures should be informed by improved estimates of the nature and extent of fine sediments not just in the suspended load of rivers but also *on* and *within* streambeds. The latter is particularly difficult to identify and quantify if it is not accompanied by surficial deposits, for example if colmation is caused by internal mechanisms or if fines have penetrated to deeper layers in the bed.

Fine sediment ingress is particularly damaging to river ecology but, despite recent advances in understanding the processes of colmation, further research is still needed to achieve a more comprehensive understanding of what sized sediment infiltrates into the subsurface under different sediment supply and shear stress conditions and the role of biological processes and controls[57]. Understanding the mechanism of fine sediment infiltration will also help develop more environmentally-sensitive management operations such as sediment flushing operations from hydropower schemes[58]. To improve the prediction of contaminant transport for the protection of human and aquatic health, Droppo et al.[159], have also called for the suspended and bed sediments to be combined with the biological components and stream energy. This could support the development of risk-based management approaches with river reaches or segments at risk of colmation identified from a combined knowledge of suspended sediment characteristics relative to the bed material characteristics set within the context of the energy conditions of the reach. As a starting point, more studies are needed to determine the spatial and temporal extent of bed sediment storage in rivers with river substrate metrics that capture substrate composition and embeddness, mirroring calls for a rapid, cost effective method for assessing the extent of surficial fine sediment deposits[167]. Furthermore, to begin to predict the residence times of ingressed sediments, a better understanding is needed of the mobility of coarse surface layers and associated feedbacks with infiltrated fines which are still poorly understood.

Another key challenge in managing fine sediment loads in rivers through the implementation of source control measures, such as catchment-sensitive farming, is determining an acceptable level of input and critical sediment yields from catchment and sub-catchment sources[168] that take into consideration the amount of fine sediment required for the healthy functioning of the system. Thus, targets need to recognise the dynamic nature of fine sediment transport, including colmation and decolmation, and be related to demonstrable impact based on biological effect data[168]. This approach should be based on new analyses of the linkages between fine sediment pressures and a range of freshwater biota and life stages for different river types. A desired outcome would be generic modelling toolkits that couple sediment stress and impacts on a range of biological quality elements to support a weight-of-evidence approach in fine sediment management[91]. Such toolkits have been proposed within a pressure-impact modelling framework[109] that could explore the expected benefit of sediment mitigation options in relation to improved targets for sediment compliance.

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