Colmation and Depth Filtration within Streambeds: Retention of Particles in Hyporheic Interstices

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key words: colmation, depth filtration, sediment, fine particles, streambed

Abstract

Colmation refers to the retention processes that can lead to the clogging of the top layer of channel sediments and decolmation refers to the resuspension of deposited fine particles. Internal colmation, clogging of the interstices directly below the armor layer, may form a thin seal that disconnects surface water from hyporheic water by inhibiting exchange processes. The settling of particles under low flow conditions can cause external colmation. Colmated channel sediments are characterized by reduced porosity and hydraulic conductivity as well as by a consolidated texture. The term 'depth filtration' refers to the transport and storage of fine matrix sediments in interstitial layers. Depth filtration is of significance for the transport of colloidal and fine particulate inorganic as well as organic matter within the hyporheic interstices and into the alluvial aquifer. The role of depth filtration is assessed for the content (given in mg per liter) of matrix fine particles retained in the coarse framework sediment of a gravel-bed river in Switzerland. Sediment samples were taken by freeze-coring with liquid nitrogen down to 70 cm depth and by piezometers down to 150 cm depth. Seventy-two percent of the mobile matrix fine particles were smaller than 0.1 mm and 50% were smaller than 0.03 mm. The content of fines tended to increase with depth, although higher accumulations were found at intermediate depths in sediments influenced by exfiltrating ground water. Interstitial detrital particles >90 μm showed vertical distribution patterns opposing those of total particles. These relationships revealed a differential significance of import, storage, and transport within three types of hydrological exchange zones (infiltration, horizontal advection, exfiltration) in the cross-section of the stream.

1. Introduction

Hyporheic interstices are the connecting ecotone between river and groundwater ecosystems and mediate the exchange processes between both of them. The permeability of this ecotone depends on the hydraulic conductivity of the sediment layers (BRUNKE and GONSER, 1997). The sediment of gravel-bed rivers can be separated into two components, the framework gravel and the fine inorganic matrix particles (PETTS, 1988). The proportion of these fine inorganic particles (<2 mm: sand, silt, clay; PETTS, 1988; LISLE, 1989), henceforth referred to as 'fines', is decisive for the hydraulic conductivity.

Fines suspended in the flowing surface water may intrude into stable gravel-beds and progressively reduce pore spaces, thereby causing decreasing seepage rates. This affects the metabolism of fluvial hydrosystems and the habitat quality for fish and aquatic invertebrates (BRUNKE and GONSER, 1997; MILAN and PETTS, 1998).

The local retention and transport of particles <2 mm in rivers are determined by flow conditions (shear stress, depth, kinematic viscosity, density, hydraulic gradient), by properties of the suspended load (grain size distribution, concentration, shape, settling properties, cohesivity), and by the channel sediment structure (grain size distribution, texture; Geldner, 1982; Reynolds *et al.*, 1990; Bettess, 1992; Carling, 1992). According to Jobson and Carey (1989) it is usually assumed that a freely flowing stream is capable of transporting all particles <62 μm which are imported to it.

Sediment in suspension can interact with the streambed in several ways (Fig. 1):

1 Sediment may settle on the top of the streambed in areas of low water velocity (e.g. in pools, or between coarser gravels) under low flow conditions. Silt may be trapped within the structural matrix of epilithic periphyton even in turbulent water (Graham, 1990).

2 A thicker layer of fine particulate matter, that reduces the permeability of the streambed (external colmation), may develop after an extended period of low current velocity (Beyer and Banscher, 1975). These clogging processes can also be induced by algal mats in eutrophic streams as well as by cohesive depositions in rivers receiving sewage effluents (Kustermann, 1962; Beyer and Banscher, 1975).

3 Fine sediment that passes the coarse armor layer may accumulate beneath the armor layer; if low discharge continues a compact layer that reduces the porosity and hydraulic conductivity of the streambed may develop and stabilize the streambed against erosion (internal colmation) (Beyer and Banscher, 1975; Schälchli, 1993).

4 Fine particles that penetrate the armor layer but do not contribute to the clogging of the top layer may undergo alternating phases of deposition and resuspension within the interstices (depth filtration).

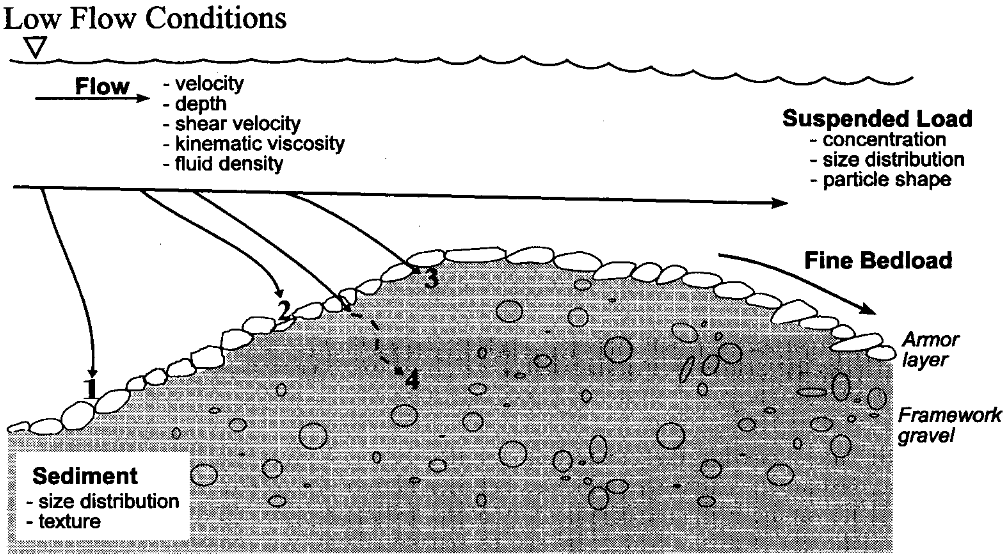

Figure 1. Factors that influence the retention of fine particles in streambeds. Numbers 1–4 are described in the text.

The objectives of this article are two-fold. The first part provides an overview on the ecological significance of fine matrix particle transport within fluvial sediments and on the mechanisms underlying deposition and transport processes. The second part focuses on the characterization and distribution of mobile matrix fines subjected to depth filtration within the interstices of the Töss River, Switzerland.

1.1. Ecological Significance of Colmation and Depth Filtration

1.1.1. Colmation

In general, colmation lowers the exchange processes between a river and the adjacent ground water. The alternating phases of colmation during low flow conditions and the decolmation induced by a high discharge are natural processes of sedimentation and erosion. However, the balance between colmation and decolmation may be altered anthropogenically towards an enhanced siltation, e.g. by flow regulation (PETTS, 1988). In the Rhine River a mechanical opening of a colmated reach near a drinking water filtration site induced a 1 m rise of the ground water table near the river, but after a few weeks the opened section was sealed again (GÖLZ *et al.*, 1991). River bank storage is a component of the ground water budget as well as of the riverine discharge regime (BAUMGARTNER and LIEBSCHER, 1990; SQUILLACE, 1996). Therefore, if infiltration is inhibited, floodpeaks that cannot erode consolidated channel beds (REID *et al.*, 1985) are not diminished. A sealed bed can act as an intrusion barrier that prevents the contamination of ground water by polluted surface water (YOUNGER *et al.*, 1993; KOMATINA, 1994).

Increased clogging threatens the reproductive success of fish spawning on gravel (BERKMAN and RABENI, 1987; CHAPMAN, 1988; ZEH and DÖNNI, 1994). Sealed interstices cannot function as nurseries for aquatic insects (GAMMETER, 1996). Furthermore, siltation reduces the refugial space available to invertebrates, and thus the impacts of natural and anthropogenic disturbances, such as urban stormwater runoff, are magnified (BORCHARDT and STATZNER, 1990). Increased loads of sand may affect the components of benthic communities differentially. It has been shown that small sized animals and the taxonomic groups Ephemeroptera, Diptera, and Coleoptera exhibit stronger declines in abundance compared to other taxa as the proportion of sand increases (ALEXANDER and HANSEN, 1986).

1.1.2. Depth Filtration

The fine matrix sediment proportion of total bed sediments is increased by depth filtration. The fines enlarge the surface area that can be colonized by a biofilm. On the other hand, the interstitial throughflow and the concomitant delivery of resources, as well as the usable pore space for the interstitial fauna can be reduced. Excessive siltation has impacts on the colonization dynamics of interstitial animals (RICHARDS and BACON, 1994; GOVEDICH *et al.*, 1996; MARIDET *et al.*, 1996).

Colloidal particles contribute significantly to subsurface transport processes as carriers (DVWK, 1992) since they are important adsorbents for metals, phosphates, humic acids and organic compounds (EGGLESTON *et al.*, 1991). Trace metals adsorped to particles may accumulate in the interstitial habitat (PETTS *et al.*, 1989; GIBERT *et al.*, 1995). Suspended bacteria may be interpreted as living colloids (VAN LOOSDRECHT *et al.*, 1990). Their transport and initial adhesion is controlled by the structure and physicochemical characteristics of the surfaces, especially by the hydrophobicity (LINDQVIST and BENGTSSON, 1991; BOSMA and ZEHNDER, 1994). Algae that are transported into the subterranean water may remain viable; they are protected during unfavorable periods and may even reproduce in some cases (POULÍCKOVÁ, 1987; WASMUND, 1989).

1.2. Overview of Colmation and Depth Filtration

1.2.1. Mechanism of Filtration

According to HERZIG *et al.* (1970) and BEYER and BANSCHER (1975) two types of filtration can be defined in natural systems: Large fine particles with diameters >30 µm are subjected to a mechanical filtration, whereby size and shape prevail in importance over surface phenomena such as positive and negative charges. Smaller particles (diameter about 1 µm) are mainly subjected to physicochemical filtration; surface phenomena prevail over volume phenomena. Medium size particles between 3 and 30 µm are retained by both filtration mechanisms. Adhesion of colloidal particles and bacteria is exclusively due to physicochemical processes (HERZIG *et al.*, 1970; VAN LOOSDRECHT *et al.*, 1990) (Tab. 1).

Table 1. Mechanisms of filtration according to HERZIG *et al.* (1970) and BEYER and BANSCHER (1975).

Particle Size	>30 µm	~1 µm	<0.1 µm
Filtration Type	mechanical	physicochemical	colloidal
Retention Sites	constrictions, crevices, caverns,	surface sites	surface sites
Retention Forces	friction, fluid pressure,	Van der Waals forces, electrokinetic forces,	Van der Waals forces, electrokinetic forces, chemical bonding
Capture Mechanism	sedimentation, interception,	interception	interception, diffusion
Remobilization	alterations in flow direction	increase in flow rate	increase in flow rate

The following formula describes the effectiveness of mechanical depth filtration in relationship to the *effective pore diameter* of a filter medium, which is about *D15/5*[1]:

$$\mathrm{D15}_{\mathrm{particle}} < D15_{filter}/5 < \mathrm{D85}_{\mathrm{particle}}$$

For a retention of fine particles the effective pore diameter of the filter must be smaller than D85 of the fines, otherwise fines will pass through the filter. Furthermore, for a retention within the filter column, the effective pore diameter must to be larger than D15 of the fines (SOWERS and SOWERS, 1970; SHERALD *et al.*, 1984). If the effective pore diameter is smaller than D15 of the fines, they would accumulate on the top of the filter.

1.2.2. The Evolution of Colmation

The formation of clogged interstices depends on the size distributions of suspended sediment, fine bedload, and channel sediments. SCHÄLCHLI (1993) developed a model of the evolution of colmation in which he distinguished three phases by using the different filtration mechanisms of HERZIG *et al.* (1970) (Tab. 2). During each of these phases the retention of

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[1] D15 represents the particle diameter for which 15% of the sediment is smaller

a different particle size fraction is decisive for the process. Larger fine particles (>30 µm) are essential for an initial bridging of the pores, but during this first phase the hydraulic conductivity remains largely unaffected. This phase can be rapidly completed. Fine sand may be under-represented during low flow conditions with a minor transport capacity, and therefore a depth filtration of particles may prevail. However, in most streambeds a sandy fraction exists, which has been deposited contemporaneously with coarser framework particles (Lisle, 1989).

Table 2. Processes and phases of internal colmation according to Schälchli (1993).

	Large Particles (∅ > 30 µm)	Medium Particles (∅ 3–30 µm)	Small Particles (∅ < 3 µm)	Permeability of the Streambed
Phase **I**	*decisive process:* clogging of larger pores directly between and below the gravels and stones of the armor layer	deposition mainly in the pores of the upper subarmor layer; transport into deeper strata is possible (depth filtration)	partial deposition on surfaces due to physicochemical interactions; transport into framework gravel (depth filtration)	minor reduction of hydraulic conductivity
	↓	↓	↓	
Phase **II**	filling of some voids, limited deposition on the armor layer; role of large particles is largely terminated	*decisive process:* mechanical clogging of fine pores; sedimentation in voids with low current	attachment on substrate of the filter layer effects further narrowing of pore channels	substantial reduction of hydraulic conductivity
	↓	↓	↓	
Phase **III**	only minor deposition	lessoned deposition between larger particles	*decisive process:* further attachment effects a reduction of the interstitial velocity to a lower limit due to a decreased import of particles into the filter layer	hydraulic conductivity reaches a minimum value

Commonly fluvial sediments have a bimodal grain size distribution (Petts *et al.*, 1989) characterized by the absence of the fine gravel and coarse sand. The fine material is generally missing in unimodal open framework gravel (Huggenberger *et al.*, 1988), e.g. of fresh spawning redds (Kondolf *et al.*, 1993). Such sediments are rapidly filled by fines from the bottom up (Einstein, 1968; Beschta and Jackson, 1979; Carling, 1984).

During the second phase the straining and sedimentation of intermediate sized particles (3–30 µm) effects a significant reduction of the streambed's hydraulic conductivity, while the contribution of larger particles on the clogging process decreases continuously. The small particles (<3 µm) still penetrate the sediment layers in which larger particles are strained (filter layer) or may adhere to surfaces due to physicochemical interactions. Below this filter layer the small particles are subjected to depth filtration.

In the third and final stage of colmation the small particles settle in the filter layer and the pore spaces are reduced to a minimum. Then the hydraulic conductivity reaches a certain minimum value (BANSCHER, 1976), due to an inhibited import of fines in the filter layer by lowered advection. The minimum value of hydraulic conductivity is maintained by an equilibrium of deposition and resuspension of particles at the top of the filter layer (SCHÄLCHLI, 1993).

1.2.3. Factors that Influence Colmation

The temporal development of colmation, the clogging depth, and the lower limit of the decreased hydraulic conductivity are influenced by interactions of several factors (Tab. 3). Low flow conditions, suspended particles and fine bedload are requirements for the clogging process. A key parameter is the *dimensionless shear stress* (Θ, Theta) (often termed Shields factor) (SCHÄLCHLI, 1993) as the force ratio between shear stress promoting entrainment of particles and the particle size, density and gravity resisting entrainment (CARLING, 1992):

$$\Theta = \tau / (p_s - p)\ g\ D$$

and

$$\tau = p\ g\ R\ S$$

where Θ is the dimensionless shear stress; τ is the shear stress; p_s is the density of the sediment; p is the density of water; g is the accelaration due to gravity; D is the grain size; R is the hydraulic radius and S is the slope.

A dimensionless shear stress below a *critical* dimensionless shear stress (Θ_k of the beginning of decolmation, which is about 0.05) is a prerequisite for the occurrence of colmation. If Θ is below a certain minimum value, all suspended particles will be deposited. When Θ is above this minimum value only a small fraction of the fines will settle and the rest remain in suspension. At a Θ near the Θ_k, colmation converts to decolmation. Thus, for a theoretically constant Θ the concentration of suspended particles and their deposition attain an equilibrium. Below a Θ_k increasing Θ effect a more dense packing of the sediment due to higher turbulent pulses and vibrations of the framework gravel (SCHÄLCHLI, 1992, 1993). Therefore, higher Θ (below Θ_k) accelerate the development of sealing and lower the minimum of the hydraulic conductivity.

The grain size distribution is of overriding relevance for the intrusion of fines into the bed sediments (BESCHTA and JACKSON, 1979). The transport into the interstices of large and medium sized particles, once they have passed through the surface, is largely determined by the pore sizes (FROSTICK *et al.*, 1984). Well-sorted gravel with large pores promote a deep intrusion of fines into the bed sediments, and thus more matrix sediment can accumulate increasing the clogging depth and lowering the minimum of hydraulic conductivity (BEYER and BANSCHER, 1975). In contrast, poorly sorted framework sediment is characterized by small pore sizes, which induce a straining of fines within a thin layer. Therefore, in such sediment less fine material is deposited, the clogging depth is comparatively shallow and the minimum of hydraulic conductivity is not raised compared with well-sorted gravel (SCHÄLCHLI, 1993). However, even in poorly sorted sediment macropores may exist which can enable the transport of fines into deeper layers. In streams with a coarse armor layer and a finer subarmor layer internal colmation develops directly below the armor layer in a thin stratum due to clogging of the small pore spaces of the subarmor layer (FROSTICK *et al.*, 1984; CUNNINGHAM *et al.*, 1987).

Table 3. Summary of factors that influence the temporal course of colmation, the clogging depth, and the minimum value of decreased hydraulic conductivity (after (BEYER and BANSCHER, 1975; SCHÄLCHLI, 1993) (C is the concentration of suspended particles, Re is the Reynolds number).

Primary Influence	Variable	Key Parameter	Relevance
Flow	– current velocity – dimensionless shear stress	Θ	requirement: $\Theta < \Theta_{k;}$ low
Suspended Particles	– concentration – size distribution – shape – adhesion, cohesion	C/p_w	requirement: $C > 0$
Sediment	– size distribution – armor layer – texture	d_{10}/d_m	high
Hydraulic Gradient	– infiltration – exfiltration	– VHG + VHG	medium decolmation at $+\text{VHG} > +\text{VHG}_k$
Temperature	– kinematic viscosity	Re	low
Secondary Influence	**Variable**		
Morphology	– riffle-pool sequences – longitudinal and cross profile – zones of preferential bedload movement	VHG, Θ, D_{10}/D_m	variable

In the study by CUNNINGHAM *et al.* (1987) the suspended particle concentration in a range of 200–1600 ppm did not have a significant effect on the degree of colmation. This is because the particle concentration does not influence the location of deposition within the filter layer (SCHÄLCHLI, 1993). However, suspended particles and fine bedload are a prerequisite for the clogging process and higher concentrations of such material can accelerate the temporal development of colmation (BANSCHER, 1976; CARLING, 1984; DIPLAS and PARKER, 1992).

Compared with other factors the vertical hydraulic gradient (VHG) is of intermediate relevance for the development of a colmation (SCHÄLCHLI, 1993). Influent conditions induce higher interstitial current velocities and particles may be transported deeper into the bed sediment. Thus, more fines can be deposited resulting in a thicker colmated layer, and thereby effect a low hydraulic conductivity (SCHÄLCHLI, 1993). Effluent conditions reduce the deposition of very fine particles and only large particles intrude into interstices, which exert a minor effect on hydraulic conductivity. However, the permeability of an already clogged streambed can only be re-established locally when the exfiltration reaches site-specific threshold levels, whereby fines are flushed out from local pore channels (BANSCHER, 1976).

Increasing water temperature affects colmation in a similar way as infiltration; the reduction of the cinematic viscosity promotes higher interstitial velocities. However, the relevance of temperature for colmation is comparatively low (SCHÄLCHLI, 1993).

In conclusion, the colmation depth depends mainly on the grain size distribution of the bed sediment. SCHÄLCHLI (1993) derives an empirical formula from his flume experiments, which can be used to roughly estimate the depth of the clogged layer (D_c) in gravel-bed streams:

$$D_c = 3D_m + 0.01 \ [\mathrm{m}]$$

where D_m is the mean grain size.

A variable fluvial geomorphology integrates all these factors on a reach scale. Riffle-pool sequences induce variable flow patterns with alternating local up- and downwelling zones (SAVANT *et al.*, 1987; HARVEY and BENCALA, 1993), and heterogeneous grain size distributions and textures (CARLING, 1992). Complex flow patterns with high variability due to discharge fluctuations create different scour and depositional areas in a longitudinal and cross-sectional profile (CHURCH, 1992). Thus, siltation may be highly variable locally resulting in a three-dimensional mosaic of differentially colmated areas within the streambed. The import of larger fine particles is increased in areas of preferential bedload movement and higher surface velocities (FROSTICK *et al.*, 1984), presumably because of fine bedload (i.e. larger fine particles) that has a higher probability of intrusion into the interstices than the suspended load (LISLE, 1989) and an increased flushing of small particles relative to areas not situated in the thalweg (FROSTICK *et al.*, 1984). However, the effect of imported larger fine particles may be small, since the hydraulic conductivity of the streambed is not reduced significantly.

Low flow conditions enable external colmation processes, characterized by a deposition of fines directly on the streambed. External colmation prevents an intrusion of fines into the channel sediments and thus constrains the development of internal colmation (BANSCHER, 1976).

1.2.4. Decolmation

Decolmation refers to all processes that contribute to an increase of hydraulic conductivity and to a breaking up of the bed sediment structure. SCHÄLCHLI (1992, 1993) distinguished different phases of decolmation according to dimensionless shear stress: (I) At $\Theta > 0.05$ fine bedload transport begins, which may induce a partial decolmation by jostling deposited fines and removing them or, depending on the stage of colmation, fill up larger pores, e.g. of open framework gravel. (II) During a transitional phase of Θ values between 0.06 and 0.072 the hydraulic conductivity of the top layer can increase by a factor of 10 due to a flushing out of fines below and beside the coarser gravels of the armor layer and by removing individual components of the armor layer. (III) During the flushing phase (Θ between 0.072–0.078) at high flow conditions the armor layer breaks up locally and hydraulic conductivity increases to a maximum value. However, the development of new colmation is possible when discharge remains constant and the suspended load is high. (IV) At peak flows when $\Theta > 0.08$ the whole river bed is mobilized and consolidated channel beds are broken up.

1.2.5. Depth Filtration

Depth filtration refers to particle separation by selective straining and transport within porous media. In riverine sediments and aquifers it means transport and retention of fine inorganic and detrital particles. Moreover, fine inorganic particles may be colonized by microorganisms and contain adsorbed compounds on their surfaces. The mechanisms underlying depth filtration correspond to those occurring during colmation. It must be stressed that the role of the cohesive properties of organic matter for filtering are difficult to assess and have rarely been addressed in experiments. Since organic layers have a porosity of about

90% (Characklis, 1984), they can increase the particle size of fines enormously. However, organic layers on fines and detrital particles may have a high plasticity in form and thereby pass pore channels differentially depending on interstitial throughflow.

2. Distribution of Fine Particles within the Interstices of a Calcareous Gravel-Bed River

Very little ecological research has been conducted on fine matrix sediments, regarding their influence on interstitial organic matter and organisms, even though they constitute the ecologically most important inorganic sediment fraction in gravel-bed rivers (Jobson and Carey, 1989; Bretschko, 1991; Ward *et al.*, 1998). For example, in two gravel-bed streams in Austria and Switzerland particles smaller than 1 mm contributed to only 6–9% of the total sediment, yet up to 88% of the total organic carbon (TOC) and total organic nitrogen (TON) content was associated with this component (Leichtfried, 1988; Eglin, 1990). The percentage of particles <1 mm can be used as an indicator of habitat quality (Adams and Beschta, 1980).

For a characterization of the mobile matrix fines the size distribution of this fraction must be examined separately from the total bed sediment. Theoretically, the interstitial content of the mobile matrix fines should increase with sediment depth simply because of gravity. It is hypothesized that the proportion of large particles (>30 μm) should decrease with depth due to a straining in the topmost layer of the streambed, whereas the content of small particles (<2 μm) should not change with depth, because similar physicochemical surface properties of the sediments were assumed. Therefore, the proportion of small particles should increase with depth.

Interstitial detrital particles >90 (DPs) of allochthonous origin (i.e. mostly plant material) were used as tracers of interstitial transport of organic matter. It was predicted that the interstitial content of DPs decrease with depth, because of continuous mineralization and ingestion by interstitial animals. Furthermore it was tested if the DP content differs between three types of hydrological exchange between the stream and the interstices, i.e. infiltration of surface water, exfiltration of ground water, and prevailing subsurface flow along the channel (horizontal advection).

2.1. *Objectives*

Specific objectives were: (1) to characterize the mobile matrix fines by their grain size distribution, (2) to examine the vertical distribution of three grain size classes differing in their type of filtration, (3) to examine the vertical distribution of detrital particles, and (4) to test the influence of infiltration, horizontal advection, and exfiltration on the vertical distribution of detrital particles and all fine patricles.

3. Study Site, Materials and Methods

The study was carried out in a transect across a calcareous prealpine gravel-bed river (Töss River, 460 m a.s.l., Switzerland). Due to hydro-engineering the former braided channel has been straightened and no riffle-pool morphology exists; the present channel width is about 20 m. At the study site distinct exfiltration zones (EZ) are located on the stream's left side, whereas on the right side surface water infiltrates into the alluvial sediments (infiltration zone; IZ). In midstream neither infiltration nor exfiltration prevail, but a horizontal advection dominates the throughflow within the sediments (horizontal advection zone; HZ).

Interstitial water was extracted by steel piezometers (internal diameter = 50 mm), from 4 sediment depths (20, 50, 100, 150 cm). Piezometers were spatially organized as clusters located in each of the three hydrological exchange zones. The piezometer nests within the IZ were located 3 m from the right bank, those within the HZ were 10 m from both banks in midstream and those within the EZ were 3 m from the left bank. Total matrix particles (i.e. inorganic fine particles and particulate organic matter, given as total particle content in mg per liter of interstitial water) were collected with a submersible electric pump after taking a sample with a hand pump for faunistic investigations (Bou and Rouch, 1967; HUSMANN, 1971). Sampling dates were on 15 occasions between May 1995 and November 1996. The samples were filtered through Whatman GF/F filters. The filters were dried to constant weight at 60 °C and weighed. The grain size distribution of the fine particles from 12 samples were measured with a SediGraph 5100 (Micrometrics). The detrital particles (DPs) were collected on 3 occasions in July, September and November 1996. Ten liters of interstitial water were taken with the hand pump and filtered through a 90 μm net. The DPs were extracted from the sample by a flotation technique along with the interstitial animals (DANIELOPOL, 1976; DOLE-OLIVIER and MARMONIER, 1992a). In another step DPs and animals were separated by removing the animals individually. The DPs were separated into size classes >300 μm and 300–90 μm. The allochthonous origin of the DPs from plant material was determined by means of cellular structures with a microscope. The DPs were measured as ash free dry mass by loss on ignition at 500 °C for 3 hours.

Additionally, 9 freeze cores (BRETSCHKO and KLEMENS, 1986) were taken on November 1996, three of them in each hydrological exchange zone to measure the size distribution of framework gravel and to assess sediment porosity and hydraulic conductivity. Cores were taken to a sediment depth of 70 cm and cut into 10 cm sections. Framework grain size distribution was determined for each depth layer by passing the sediment through a set of seven sieves (mesh sizes >20, 12.5, 8, 6.3, 2.5, 1, 0.063 mm). Rocks greater than 50 mm were excluded from the analyses as recommended by ADAMS and BESCHTA (1980) to reduce the effect of extreme values for relatively small sediment samples. The sorting coefficient $(D75/D25)^{-0.5}$ was calculated according to SCHWOERBEL (1994). Porosity was calculated as (total volume – grain volume) × 100/(total volume) according to EGLIN (1990). Hydraulic conductivity was calculated according to BEYER (1964) and HÖLTING (1989). A few depth layers did not freeze on some cores presumably due to high interstitial currents. Therefore, it was not possible to statistically compare framework characteristics of depth layers between hydrological exchange zones. The grain size distribution of the armor layer was assessed with two methods: (a) by measuring the intermediate axis (b-axis) of 200 mineral particles >1 cm along a straight line in flow direction in three replicates according to FEHR (1987) and (b) by taking 6 sediment samples down to a depth of 10 cm using a Surber sampler (400 cm^2) with a 90 μm net.

4. Results and Discussion

4.1. Bed Sediment Characteristics

The porosity of the bed sediments of the Töss River tended to increase with depth (Fig. 2), though this was not statistically significant. Porosities ranged between 6.2% and 32%, with an average of 18.8% (± 6.6 SD). The Thur and Neckar Rivers, two other calcareous gravel-bed rivers in Switzerland, had similar sediment porosities (EGLIN, 1990; NAEGELI, 1997). In the Lunzer Seebach (Austria) porosity is about 24% (BRETSCHKO, 1991).

The D50 of the surface sediment (i.e. the grain diameter at which 50% of the sediment in weight is smaller) was 31.0 mm (±2.6 SD) measured by b-axis and 32.2 mm (±6.1 SD) measured by sieving. It was coarser at the stream margins than in midstream (Tab. 4). Not shown by the grain size analyses was that the grains in midstream tended to be more rounded and those at the margins tended to be flatter. The reason for this difference was probably that the midstream sediments were more often affected by bedload movement, where water velocities were highest in the straightened channel. Furthermore, the layering of the flatter gravels at the margins resulted in a more erosion resistent armor layer. River engineering and lateral embankments in the whole catchment of the Töss River have reduced sediment supply, which leads, in conjunction with an increased transport capacity by the straightening of the river course, to a deficiency of bedload. In flume experiments DIETRICH *et al.* (1989) found that a reduction in sediment supply resulted in an expansion of lateral coarser 'inactive' zones in which little or no transport took place compared to finer 'active' zones in midstream. In the Töss River this is presumably a self enhancing process, since the longer a surface layer is not mobilized, the more it consolidates and becomes erosion resistent (REID *et al.*, 1985).

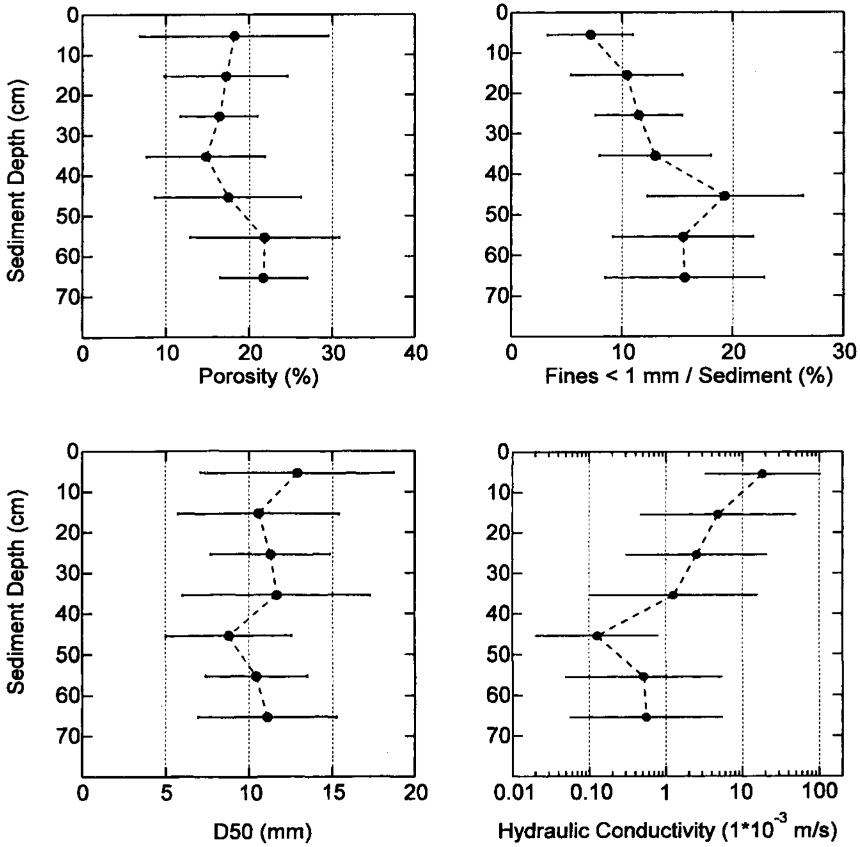

Figure 2. Depth profiles of sediment porosity, the proportion of fine particles <1 mm in the sediment, the D50 (mm) and the hydraulic conductivity. Means (±SD). n = 38.

Table 4. Sediment characteristics of the three positions within the channel cross-section. Means (±SD) for three freeze cores in each zone. Grain size metrics in mm.

	Infiltration zone (right margin)	Horizontal advection (midstream)	Exfiltration zone (left margin)
$\text{D50}_{\text{surface}}$ (b-axis)	36.5 ± 2.9	24.9 ± 1.8	32.2 ± 2.8
$\text{D50}_{\text{surface}}$ (sieving)	38.5 ± 6.3	26.5 ± 0.7	31.5 ± 0.7
$\text{D75}_{\text{subsurface}}$	16.5 ± 2.7	15.5 ± 2.3	16.2 ± 2.5
$\text{D50}_{\text{subsurface}}$	11.0 ± 3.6	10.3 ± 3.1	10.9 ± 4.1
$\text{D25}_{\text{subsurface}}$	3.4 ± 3.4	3.1 ± 1.4	4.4 ± 2.9
$\text{D15/5}_{\text{subsurface}}$	0.41 ± 0.33	0.21 ± 0.16	0.31 ± 0.45
So $(\text{D75/D50})^{-0.5}$	2.4 ± 1.0	2.3 ± 0.45	2.9 ± 1.6
Porosity (%)	18.8 ± 7.8	19.7 ± 6.9	18.0 ± 5.7
$\text{kf}_{0-70\,\text{cm}}$ $(1 \times 10^{-3}$ m/s)	16.9 ± 34	3.7 ± 6.8	11.2 ± 28
$\text{kf}_{0-20\,\text{cm}}$ $(1 \times 10^{-3}$ m/s)	48.5 ± 63	9.2 ± 6.4	29.3 ± 51
$\text{kf}_{20-50\,\text{cm}}$ $(1 \times 10^{-3}$ m/s)	6.2 ± 8.4	5.5 ±10.6	1.3 ± 1.4
vertical $\text{vf}_{0-20\,\text{cm}}$ $(1 \times 10^{-3}$ m/s)	−0.92 ± 63	0.12 ± 6.4	0.44 ± 51
vertical $\text{vf}_{20-50\,\text{cm}}$ $(1 \times 10^{-3}$ m/s)	−0.94 ± 8.4	−0.09 ± 10.6	0.04 ± 1.4

The subsurface sediment showed a finer grain size composition than the surface sediment, with a D50 = 11 mm (±3.6 SD), but ranging between 4.5 and 17 mm. The difference in D50 values between midstream and marginal sediments is reduced (Tab. 4), due to a higher proportion of sand in the subsurface sediments. SCHÄLCHLI (1993) collected larger amounts of sediment with a different technique from an upstream site of the Töss River and calculated a D50 of 16 mm, presumably for a mixture of surface and subsurface sediment. The technique of freeze coring underrepresents the coarse fraction where there are cobbles and gravels (discussion by G. E. PETTS in CHURCH *et al.*, 1987). SCHÄLCHLI (1993) calculated a porosity of 25% and hydraulic conductivities ranging between kf = 1.5×10^{-3} and 2.5×10^{-4} m/s. In this study, hydraulic conductivities ranged between 1.5×10^{-5} and 1.2×10^{-1} m/s and changed significantly with depth (Kruskal-Wallis test, $p < 0.05$) (Fig. 2). Hydraulic conductivity decreased continuously down to the 40–50 cm depth stratum, thereafter it increased again. On average the sediment down to 40 cm was 'highly permeable', whereas the deeper strata were 'permeable' according to HÖLTING (1989). The specific flux (vf) was calculated for the upper sediment strata by using the average kf-values and the average vertical hydraulic gradients measured between April 95 and November 96 on 22 occasions (BRUNKE and GONSER, in prep.) (Tab. 4). These calculations indicate that in the IZ water can infiltrate down to a depth of 20-cm with an average velocity of 5.5 cm/min and in the EZ water can exfiltrate with an average of 2.6 cm/min. Therefore, by using the porosities for the IZ and EZ, 10 liters per minute could infiltrate and 4.7 liters per minute could exfiltrate on a square meter. At the sampling site the IZ and EZ are both approximately 4 m x 24 m in size, each. Therefore, about 47 liter m^{-1} s^{-1} are exchanged throughout the sampling site, contributing to 0.67% of the annual mean surface discharge of 7 m^3/s. Assuming hydrological exchange along the river course is the same as at the study site, the entire stream water would be exchanged on a channel length of 3.57 km. With an average flow velocity of 0.67 m/s complete exchange would take 1.5 hours. However, these calculations are just rough estimations, since they are based on averages and approximate calculations of hydraulic conductivity. Data from the HZ were not included in the calculations, though it contributed actively to the exchange since temperature variations can be detected down to a depth of 150 cm. Therefore, these estimates are likely to underestimate the water exchange between the stream and the subsurface water.

According to SCHÄLCHLI's (1993) formula a thin colmated layer of the topmost streambed would be located at a depth of about 10 cm. Severe colmation only occurred at the channel margins that were rarely affected by bedload movement.

The proportion of fines <1 mm in the sediment increased with depth, from 7.3% (±3.2 SD) at 10 cm to 16% (±6.7 SD) at 70 cm (Fig. 2). ADAMS and BESCHTA (1980) and MILAN (1996) also found lower levels of fines near the bed surface. ADAMS and BESCHTA (1980) assumed that this might reflect a paucity of fines or the presence of an armor layer. In their study they had an average of fines of 17.4% at 0–10 cm, 22.3% at 10–25 cm, and 22.2% at 25–40 cm sediment depths, which were clearly higher percentages of fines than in this study. The vertical trend for fines was not reflected in the porosity; porosity and fines were not correlated. MARIDET *et al.* (1992) concluded in their study, that only a high content of fines always leads to a low porosity, whereas porosity may be high or low when the content of fines is low. However, if the infiltrated sediments are a clay then the porosity can remain high.

The sorting coefficient was highly correlated to the percentages of fines <1 mm and <2 mm ($r_s = -0.86$, $p < 0.001$ and $r_s = -0.95$, $p < 0.001$, respectively). Therefore, the depth profile of the sorting coefficient resembles the depth profile of the percentage of fines <1 mm in the sediment (Fig. 2).

4.2. Characterization of Mobile Matrix Sediment

For various reasons the interstitial fines fraction is a critical factor for hyporheic biota in the Töss River (Brunke and Fischer, in press.; Brunke and Gonser, in prep.). On average it contributed 13.9% (± 6.0 SD) of the bed sediment down to a depth of 70 cm. About 72% (±23 SD) of these fines were smaller than 0.1 mm and the median size was 0.03 mm (Fig. 3a).

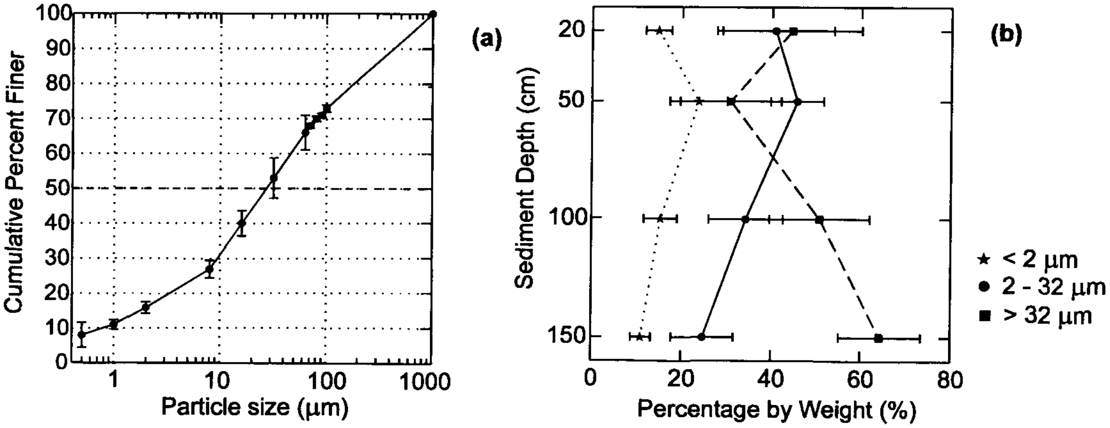

Figure 3. (a) Cumulative size distribution curve for mobile matrix fines. (b) Depth profiles for three size classes which are differentially subjected to physicochemical and mechanical filtering (see text and Tab. 1 for further explanations). Means (±SD). n = 12.

The distribution of particles <2 μm, which is exclusively filtered by physicochemical forces, did not change much with depth except for slightly higher portions at 50 cm depth (Fig. 3b). Its proportions ranged between 8.5% and 32.7% with an average of 14.5 (±6.6 SD). The depth profile of the size fraction 2–32 μm was similar in shape to the depth profile of the fraction <2 μm ($r_s = 0.88$, $p < 0.001$), but it contributed to higher proportions ranging between 16.7% and 60.4% with an average of 36.4% (±12.9 SD). Consequently, the proportions of the fraction > 32 μm were inversely related to the fractions of 2–32 μm and < 2 μm ($r_s = -0.82$, $p < 0.001$ and $r_s = -0.81$, $p < 0.001$, respectively). The proportions of this fraction ranged between 5.1% and 74.9% with an average of 43.7% (±6.4 SD). The hypothesis that the proportions of the large size fraction are greater in upper sediment strata, because of an exclusive filtering in the top layers by mechanical straining is not supported. Instead, this fraction might be responsible for the general trend that fine particles accumulate with depth (Leichtfried, 1988, 1994; Panek, 1994). In this study the content of the fine particles also increased with depth, though strong temporal variations occurred (Fig. 4). Only in the 50-cm depth stratum of the exfiltration zone was the content of fine particles higher than in deeper strata. This is probably due to the upwelling forces of exfiltrating ground water, which likely prevented the sedimentation of particles into the deeper strata.

As discussed above, bedload movement was more frequent in midstream than at the margins because of the straightening of the channel and bedload deficits. In these midstream sediments the content of total mobile fine particles tended to be lower. In contrast, the vertical patterns of the detrital particles (DPs) (Fig. 5) were opposed to those shown by the content of total fine particles (Fig. 4). Considering the continual degradation of DPs, higher contents of DPs in sediment depths below 50 cm in midstream sediments indicate higher import of fine particles in these sediments. Therefore, it appears that the transport of fines within

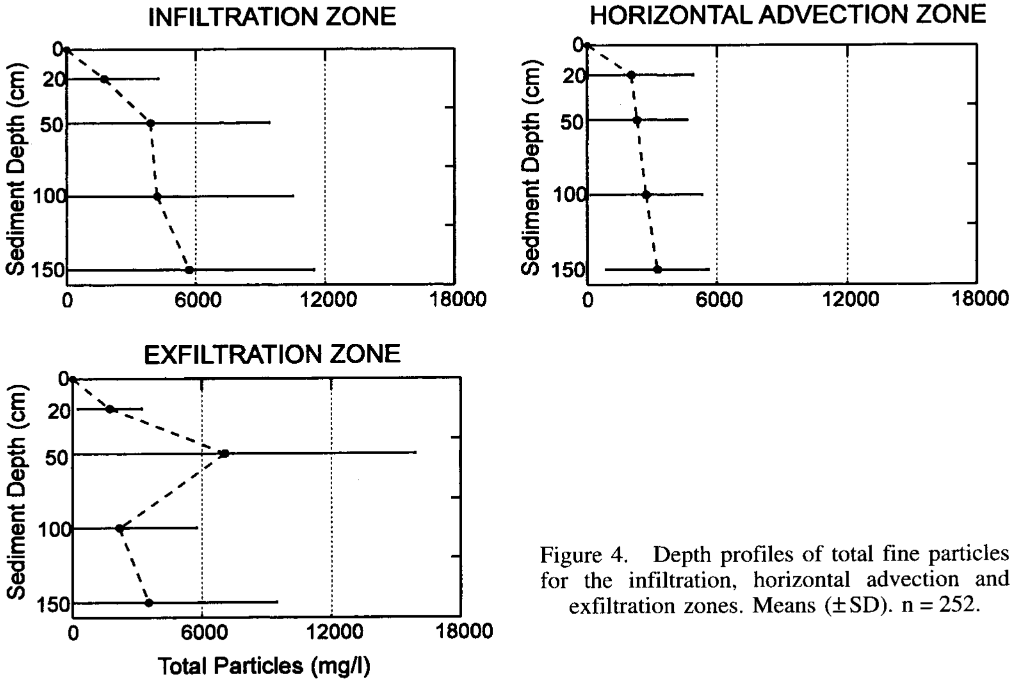

Figure 4. Depth profiles of total fine particles for the infiltration, horizontal advection and exfiltration zones. Means (±SD). n = 252.

midstream sediments is increased relative to the deposition when compared with sediments at the margin. In a similar way FROSTICK *et al.* (1984) found a higher ingress of matrix fines in thalweg sediments in a field experiment. Higher interstitial currents promote the transport of fines, provided there is no straining effect (HERZIG *et al.*, 1970). In contrast, in marginal areas where flow is reduced accumulation may prevail until the next flood that breaks up the sediment across the entire channel. In this context, the contrasting low contents of DPs in the exfiltration zone at a depth of 50-cm compared with the high contents of total particles are remarkable (Figs 4, 5). This relationship supports the interpretation that the import of particles to this stratum is reduced, but the temporal accumulation is of long duration.

The proportion of DPs > 300 µm to DPs > 90 µm ranged between 22% and 60% and showed no clear trend with depth (Fig. 5). This suggests that the straining of DPs >300 µm was not affected differentially by pore size than that of DPs >90 µm. The DPs were certainly flushed (and not deposited during bedload movements) into the sediment down to depths of 100-cm and 150-cm and probably also into the upper strata, because bedload movement of a magnitude which could have buried the DPs to depths below 100-cm would have removed the piezometers.

Calculations using the formula by SOWERS and SOWERS (1970) demonstrate the potential mobility of most matrix fines in the Töss River streambed. The D15/5 of the subsurface sediment (Tab. 4) is about the size of the D85 of the fine particles ($D85_{\text{fines}}$ = 0.28 mm) and much higher than the D15 ($D15_{\text{fines}}$ = 0.002 mm).The grain size distribution of the matrix fines reflects the absolute sizes of particles. It is likely that the effective grain size distribution is somewhat coarser due to formation of aggregates. However, even with an estimated median grain size an order of magnitude greater (i.e. about 0.3 mm), most particles could still pass the framework. This becomes even more evident considering the sampling method which in general underrepresents the gravels and cobbles, the exclusion of rocks greater than 50 mm, and the fact that the sand and silt fractions were also included in the grain size analysis of the freeze core samples.

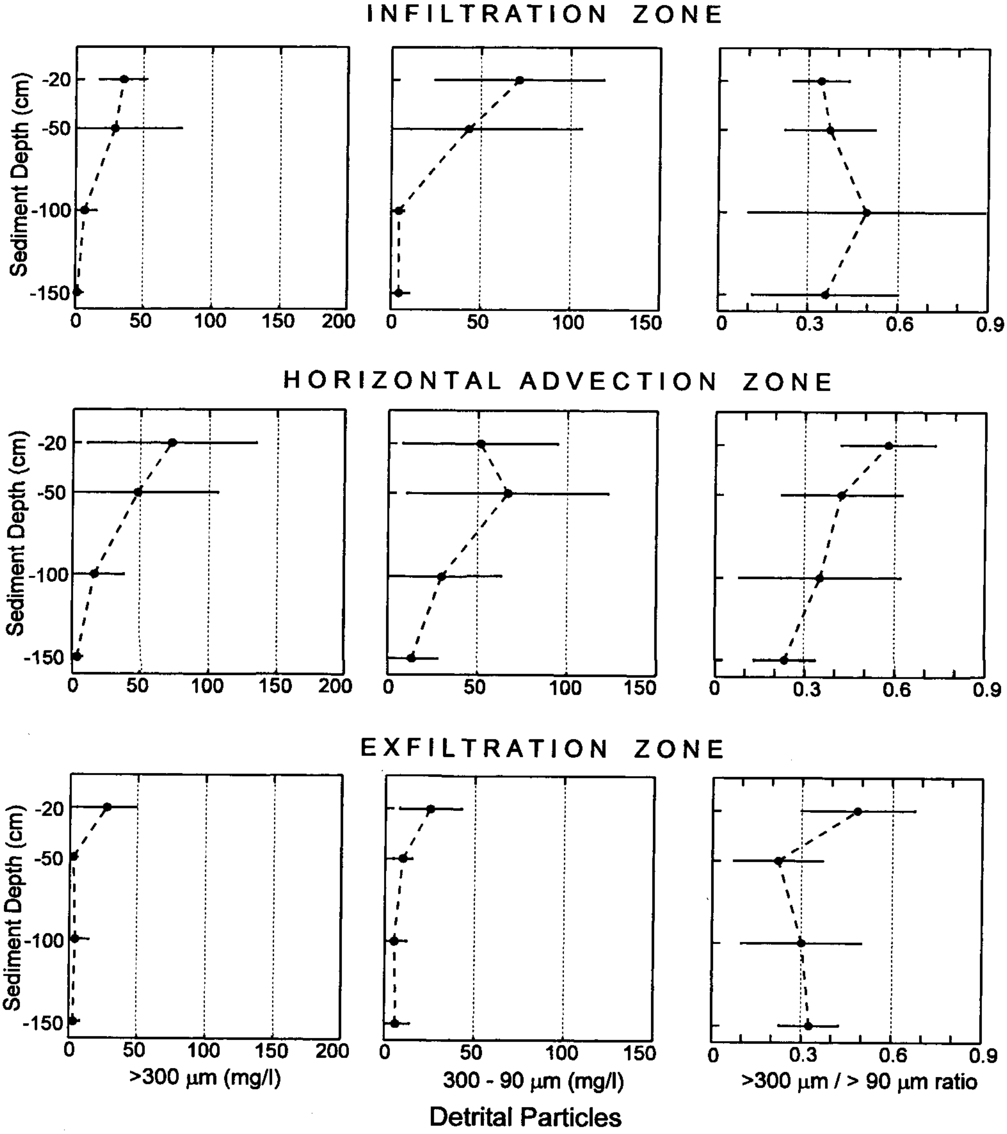

Figure 5. Depth profiles of detrital particles >300 µm, 300–90 µm, and the proportion >300 µm to DPs > 90 µm for the infiltration, horizontal advection and exfiltration zones. Means (±SD). n = 74.

5. Conclusions

Field studies in gravel-bed rivers with unregulated discharge regimes (LEICHTFRIED, 1988; 1991; PANEK, 1994; NAEGELI *et al.*, 1995; PUSCH, 1996; MILAN and PETTS, 1998; this study) do not support the results from flume experiments in which fine particles were retained exclusively in the topmost layer of the channel bed and that further transport into deeper layers was negligible (e.g. BEHNKE, 1969; BESCHTA and JACKSON, 1979; DIPLAS and PARKER, 1992; SCHÄLCHLI, 1992). The presence of detrital particles >300 μm even at sediment depths of 150 cm demonstrated the importance of transport by interstitial throughflow and the interconnectedness of voids. In the Töss River the large pore sizes of the framework sediment probably limited the significance of mechanical straining of mobile fine particles. Rather, the interplay between direction and intensity of interstitial throughflow with sedimentation in subsurface dead zones and particle inertia, as described by HERZIG *et al.* (1970), appear to be more important for depth filtration. Finally, the intrusion of fines appears to be influenced by the location in the channel relative to the frequency of bedload movement, since it controls the composition and shape of framework gravel.

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