

Intrusion of fine sediments into low mountain creeks and associated influence on benthic invertebrates

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Abstract

Hydromorphological deficits of European rivers and creeks are a major reason for not reaching the good ecological status according to the European Water Framework Directive. One of these hydromorphological pressures is the clogging of river beds by fine sediments (colmation) and its deleterious effects on benthic ecology.

The mitigation of these effects requires the assessment of colmation levels by analysing temporal and spatial variations on a river basin scale. The aim of this study is to formulate a colmation assessment approach based on a combination of hydrological / hydraulic modelling, sediment sample taking and colmation mapping. We tested the reliability of these methods by comparing their outputs with invertebrate samplings.

The combination of sampling site selection through interpretation of a pollution-runoff-model, freeze core sampling, sediment traps and colmation mapping provided appropriate information to assess the colmation level on a river basin scale aiming at the prioritization of mitigation measures.

Notwithstanding, the lack of standardized sampling methods and missing quality guidelines regarding colmation levels impede appropriate assessment of fine sediment pressure on benthic invertebrates. Great effort is still needed to set these standards and provide river basin managers with adequate hands-on tools to assess colmation.

Keywords

colmation, sediment sampling methods, benthic ecology

INTRODUCTION

One of the central objectives of the European Water Framework Directive (EC-WFD) is to achieve a 'good surface water status' by the end of 2015 with deadline extensions until 2021/2027 (Directive 2000/60/EC). A surface water body fulfils this objective when both its ecological status and its chemical status are at least 'good'. The ecological status of a water body is assessed via four biological quality elements: fish fauna, benthic invertebrate fauna, macrophytes and phyto-benthos. The herein presented work focuses on benthic invertebrates.

At present only 10 % of surface water bodies in Germany are in a good status. One major reason for failing to achieve the EC-WFD objective is their anthropogenic altered hydromorphology (UBA 2010). Morphological alterations, such as stream bed colmation, change habitat characteristics and hence impede the presence of stream type-specific biota (e.g. benthic invertebrates) that can be found in the potential natural state (reference state) of these waters (Ehlert *et al.* 2002).

The colmation of a river bed occurs when suspended solids either deposit on the surface layer or intrude into the porous system of the gravel matrix. This results in both a reduction of the hydraulic conductivity and a cementation of the structure of the river bed (Schälchli 1992). The consequence of this clogging effect mainly caused by very fine particles of the silt and clay fractions is an oxygen deficiency and in consequence a deterioration of the interstitial habitat (Schälchli 1993).

Numerous studies have quantified sediment intrusion and storage within the channel of permeable rivers (Betscha and Jackson 1979, Walling and Amos 1999, Collins and Walling 2006). Colmation has repeatedly been shown to degrade benthic ecology resulting in reductions in invertebrate populations, changes of macrophyte communities and the reduced health and reproductive impairment of game fish (Erman and Erman 1984, Berkman and Rabeni 1987, Waters 1995, Wood and Armitage 1997, Acornley and Sear 1999, Bo *et al.* 2007, Omesová and Helesic 2009, Kefford *et al.* 2009).

The deposition of suspended solids and subsequent colmation of gravel-bed rivers have been recognised as a major cause for the reduced development and survival of salmonid eggs and larvae within salmonid redds. This is because the deposited fine sediment blocks the pores in the gravel matrix, preventing the sufficient exchange of dissolved oxygen and carbon dioxide between the respiring eggs/larvae and the flowing water (Lisle 1989, Greig *et al.* 2005, Walling *et al.* 2003).

Also the distribution patterns of benthic invertebrate communities are highly dependent on substrate characteristics like stability, heterogeneity and compactness (Beisel *et al.* 1998, Buss *et al.* 2004, Reice 1980, Beauger *et al.* 2006). Previous studies have consistently found that the biodiversity of invertebrates has positive correlations with the heterogeneity and stability of the streambed (Beisel *et al.* 2000, Evans and Norris 1997), and is higher in a loose bed than in a compact bed (Cobb *et al.* 1992). Verdonschot (2001) and Jowett (2003) reported that benthic macroinvertebrate assemblages were greatly dependent on the streambed stability at the reach scale. In general, one can state that more complex substrata generally support more species (Minshall 1984).

Despite the great knowledge of the negative effects of colmation on benthic ecology no assessment standards or quality guidelines are set for identifying and quantifying a potential colmation problem in a river or creek. Several water quality guidelines for concentrations of suspended solids in freshwater systems (Bilotta and Brazier 2008) and gravel quality criteria for salmonids (Iwamoto *et al.* 1978, Milan *et al.* 2000) have been set, but no benchmark particle-size distributions for assessing levels of colmation in regard to benthic invertebrates are defined.

The herein presented study addresses this lack of knowledge by testing an colmation assessment approach to support river basin managers in mitigating negative effects on benthic ecology. This assessment approach consists of a combination of different fine sediment sampling and mapping methods and a comparison of these results with benthic invertebrate samples.

Freeze core sampling (Petts *et al.* 1989, Thoms 1994, Hill 1999) at strategic sites in a river basin were taken and analyzed to provide a first overview of the colmation situation. Sediment traps (Zimmermann and Lapointe 2005) were taken to differentiate spatial and temporal variations of the colmation phenomena. Colmation mapping (Schälchli 2002a) was conducted to extrapolate and verify the information about spatial and temporal colmation variations at the sediment trap sites to entire river sections.

A comparison of invertebrate samplings (Meier *et al.* 2006, Hering *et al.* 2004) – especially their interpretation according to organic fine sediment pressure (Wupperverband 2008) – with the colmation level at the sediment trapping sites was applied to provide indications of the effect of colmation on benthic invertebrates.

METHODS

Study area and sampling site selection

The above described approach of colmation assessment was applied the watershed of the creek Morsbach. This 16 km long creek is a tributary of the river Wupper which in turn flows into the stream Rhine at the city of Leverkusen. The Morsbach watershed (47 km²) is located in a low mountain range of siliceous bedrock in the German state of North Rhine-Westphalia (Figure 1).

The Morsbach creek and its major tributaries are classified as 'small coarse substrate dominated siliceous highland rivers' according to the German stream typology (Ehlert *et al.* 2002, Pottgiesser and Sommerhäuser 2004). The creeks under consideration (Morsbach, Gelpe, Leyerbach and Klausener Bach) have a width of 2 to 6 m and a valley slope of 2.5 to 6.0 %. The average total annual precipitation rates range from 1,100 to 1,400 mm.

The study area in its entirety is dominated by urban areas (approx. 40 %). The sub-catchments of the creek Gelpe and Klausener Bach are in a near-natural state with predominant forests and relatively unchanged water bodies whereas the sub-catchment of the Leyerbach mainly comprised urban areas and altered waters (e. g. bank fixation, canalization).

The Morsbach watershed possesses 7.2 km² paved areas which are drained to equal parts by separate and combined sewer systems. According to the pollution-runoff-model of the Wupper Water Association the annual input of 1,200 tons of suspended solids into the Morsbach system is divided into 630 t/a coming from separate sewer systems, 257 t/a from combined sewer systems and 313 t/a from erosion (Zumbroich *et al.* 2011).

All water bodies except the creek Gelpe fail to achieve the EC-WFD goal of a good ecological status. In all cases the deficits of the biological quality element 'benthic invertebrates' and 'fish' are decisive for a moderate to bad ecological status (Figure 1).

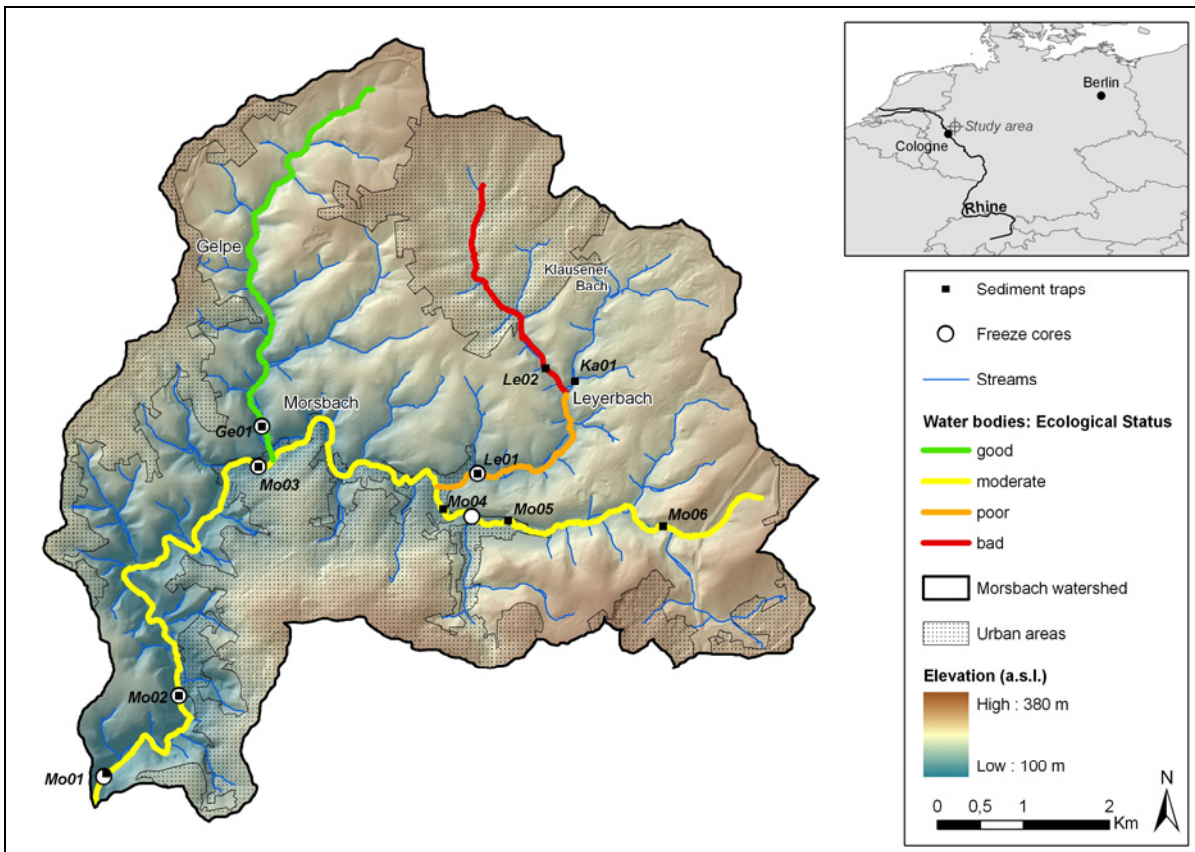


Figure 1: Location of the study area and sampling sites.

The selection of the sampling sites (Figure 1) bases on the interpretation of average annual concentration levels of suspended solids [mg/l] and average shear-stress levels [N/m²] derived from the pollution-runoff model of the Water Association 'Wupperverband' (Wupperverband 2008). By intersecting both parameters the potential sedimentation resp. colmation level of a specific location along the creeks could be derived. The assumption was that the sedimentation resp. colmation level is high if the suspended solid concentration is high and at the same time the local shear stress is low (vice-versa for low sed. / col. level). Based on quality guidelines for suspended solids (Bilotta and Brazier 2008, MUNLV NRW 2006, European Council 1978) five concentration classes were defined. Based on the critical shear stress for the underlying stream type (BWK 2008, Wupperverband 2008) five shear stress classes were defined. The combination of both parameters resulted in the sedimentation / colmation potential (Figure 2). Neglecting the sampling site Mo02 we installed two sampling sites with very high sed. / col. potential, three sites with high potential, three sites with medium potential and one site with low potential for colmation (see also Table 6).

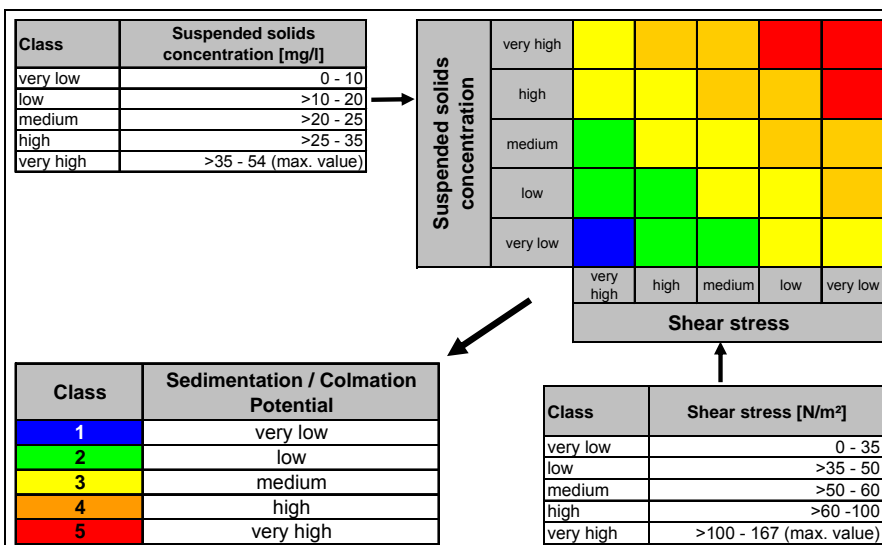


Figure 2: Classification scheme for sedimentation / colmation potential.

Freeze cores

Six freeze cores were taken at selected sampling sites along the Morsbach (Mo01 - river mouth, Mo02 - lower reach, Mo03 - middle reach and Mo04 - upper reach), Gelpe (Ge01 - river mouth) and Leyerbach (Le01 - river mouth) to obtain a general overview of the colmation situation of the Morsbach and its major tributaries (Figure 1). The freeze-sampler used for this study consists of a rigid and hollow 3.0 cm diameter standpipe which is driven into the river bed (Figure 3). Liquid nitrogen, inserted into the standpipe, causes the surrounding substrate and intra-gravel water to freeze (freeze core). A detailed description of the freeze core sampling apparatus and methodology can be found in Petts *et al.* (1989), Thoms (1994) and Hill 1999.

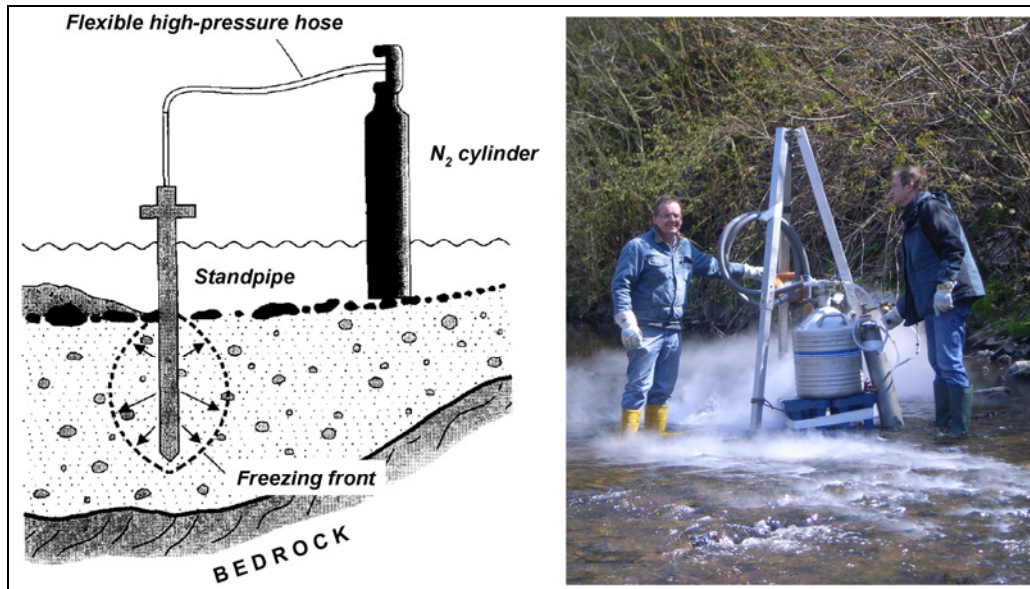


Figure 3. Freeze sampling device (Thoms 1994) and sample taking at the Morsbach creek.

The columnar frozen cores of about 30 cm length, 15-20 cm diameter and a total weight of 9.0 to 16.7 kg were extracted, oven dried and subsequently passed through 2.0, 0.6, 0.2 and 0.06 mm sieves (Table 1).

Table 1. Analysed grain-size fractions (EN ISO 14688).

Grain size fraction	Diameter limits [mm]
Stones / cobble	> 2.0
Coarse sand	> 0.6 - 2.0
Medium sand	> 0.2 - 0.6
Fine sand	> 0.06 - 0.2
Silt / Clay	≤ 0.06

The resulting percentages of weight for the grain-size fractions <2.0 mm were compared to the threshold of 15 % fine sediment <2.0 mm for river bed substrata suitable for trout spawning grounds as suggested by Milan (2000) and Iwamoto *et al.* (1978). Although this comparison is not indicating a negative effect of fine sediment on benthic invertebrates, it still allows for a first evidence of a potential fine sediment problem within the Morsbach river basin.

Sediment traps

At the ten above mentioned sampling sites sediment traps were buried into the river bed (Figure 1). The traps were sampled twelve times between March and November 2010 with a three weeks exposure per sampling period. The aim was to gain information of spatial and temporal variations of fine sediment intrusion into the river bed. The aspect of the temporal variations mainly addresses the fine sediment intrusion in relation to the discharge levels during the sediment trap periods (Figure 4).

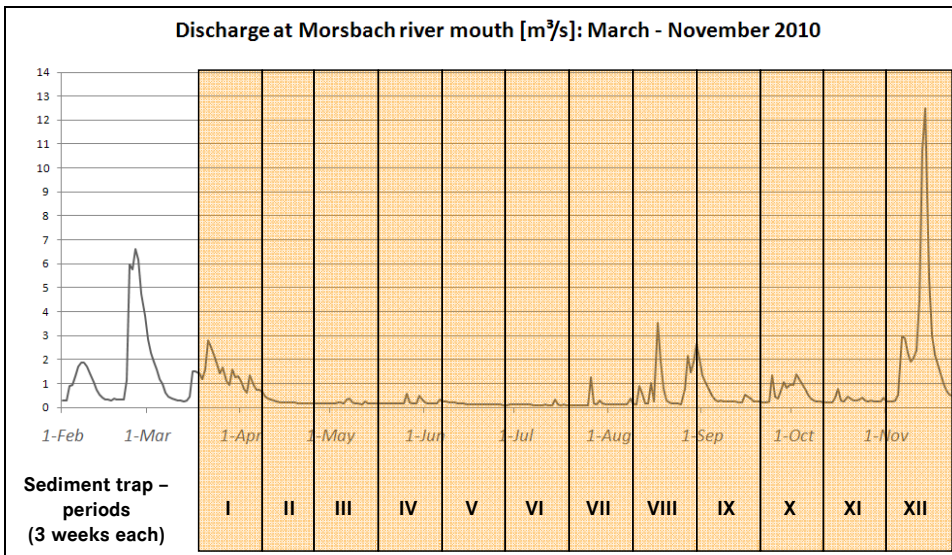


Figure 4. Discharge during sediment trap periods.

The sediment traps consist of two cylindrical buckets (16 cm diameter, 2.5 litres) set inside of each other. Both the inner and outer bucket have 1-2 cm holes that enable water to pass through them. The inner bucket is filled with 63-20 mm cleaned substrate before being buried into the river bed (Zimmermann and Lapointe 2005). During the exposure period of three weeks the inner bucket fills up with infiltrating bed load material. After removing the trap and drying the material the fine sediment (<2 mm) is separated from the coarser material and analysed according to the grain-size fractions in Table 1.

The organic shares of the grain size fractions <2.0 mm were derived from the glowing residue after processing the samples in the muffle furnace. In this paper the interpretation of the sediment trap results is limited to the accumulated percentage by weight of the grain size fractions < 2.0 mm and <0.2 mm.

Due to trap losses the sediment trap Mo02 and the traps from the sediment trap period II had to be excluded from further analysis and interpretation.



Figure 5. Sediment trap inserting, trap after three weeks exposure in river bed and grain-size analysis in laboratory.

Colmation mapping

At each of the ten sampling sites a mapping of the colmation level was conducted to extrapolate and verify the punctual information about spatial and temporal colmation variations at the sediment trap sites to 100 m long river sections. The colmation mapping bases on the survey method for hydromorphological quality developed by the German Working Group on water issues of the Federal States and the Federal Government – LAWA (Zumbroich et al. 1999, Raven et al. 2002). Besides general parameters regarding water course development, longitudinal profile, cross-section and bank structure the colmation mapping focuses on river bed structures. The main bed structure parameters 'substrate compactness', 'substrate composition' and 'pore system' (Table 2) are assessed by visual inspection and manual sample taking (Schälchli 2002a, Schälchli 2002b, Brandhuber 2004, Strohmeier *et al.* 2005).

The aggregation of the general parameters and the special bed structure parameters result in a classification of the colmation level for 100 m sections, ranging from no colmation to complete colmation (Table 2).

Table 2. Main evaluation criteria of the applied colmation mapping method (Schälchli 2002a).

Colmation level	Substrate compactness	Substrate composition	Pore system
no colmation	very loose	stones, gravel, few sand	coarsely pored, no adherence, loose
low c.	loose	stones, gravel, sand	coarsely to fine pored, very little adherence, loose
medium c.	slightly compacted	sand and little cohesive accumulation of silt, clay and/or detritus	fine pored, little adherence partially clogged
high c.	clearly compacted	sand and cohesive accumulation of silt, clay and/or detritus	fine pored, good adherence, heavily clogged
complete c.	heavily compacted	Comprehensive accumulation of silt, clay and/or detritus	good adherence, completely clogged

**Figure 6:** Complete colmation (left), medium colmation (manual sample, middle) and no colmation (shovel sample, right).

Invertebrate sampling

In order to assess the local ecological status at the ten sampling/mapping sites we applied to invertebrate samples which were provided by the Water Association 'Wupperverband'.

The samples were taken according to the standardised method PERLODES (Hering *et al.*, 2004; Meier *et al.*, 2006) and processed with an indication method developed by the Umweltbüro Essen (ube 2008). This method identifies and evaluates the relative importance of partial pressures on benthic invertebrates based on habitat requirements, flow velocity preferences and feeding characteristics of invertebrate indicator species. Among the identifiable pressures are organic fine sediments, reduced base flow, hydraulic stress, lacking bank vegetation and reduced habitat diversity (Wupperverband 2008).

The partial pressure caused by organic fine sediments is derived from comparison of the composition and abundance of invertebrate species of specific feeding types in a hypothetical natural reference state with the actual feeding type composition and abundance of invertebrate species. A description of the evaluation procedure is provided in Wupperverband (2008).

The classification of the pressure caused by organic fine sediments is given in Table 3. The actual organic fine sediment pressure at the ten sampling sites based on this evaluation method is given in Table 6.

Table 3. Classification of organic fine sediment pressure on benthic invertebrates (Wupperverband 2008)

Class	Scale range (score)	Pressure specification
I	0 - <243	no to very low pressure
II	243 - <627	low pressure
III	627 - <1160	medium pressure
IV	1160 - <1841	high pressure
V	>1841	very high pressure

FINDINGS AND DISCUSSION

General colmation level (freeze core analysis)

At most of the freeze core sampling sites the fine sediment percentage within the river bed exceeds the threshold of 15 % suggested by Milan (2000) and Iwamoto et al. (1978). Especially in the middle and upper reaches of the Morsbach (Mo03 and Mo04) and in the tributaries (Ge01 and Le01) the substrate composition of the river bed is not suitable for serving as trout spawning ground. Freeze core sampling within the close-by Bröl watershed show similar results with fine sediment percentages reaching from 10 to 22 % (Dirksmeyer 2002, p. 76).

Considering the trout (*S. trutta*) as umbrella species one can take these results as a first indication of a potential problematic fine sediment situation in regards to benthic invertebrates.

Table 4: Percentage by weight of size fractions in freeze cores.

Freeze Core	Mo01	Mo02	Mo03	Mo04	Ge01	Le01
Size fraction						
Sand (>0.06 - 2.0 mm)	13.7%	9.4%	17.1%	20.3%	21.1%	19.3%
Coarse sand (>0.6 - 2.0 mm)	8.6%	6.1%	11.7%	13.9%	10.4%	8.7%
Medium sand (>0.2 - 0.6 mm)	4.5%	2.6%	4.0%	5.5%	9.1%	5.4%
Fine sand (>0.06 - 0.2 mm)	0.6%	0.7%	1.4%	0.9%	1.5%	5.1%
Silt and Clay (≤0.06 mm)	0.7%	0.8%	2.0%	1.1%	1.5%	10.9%

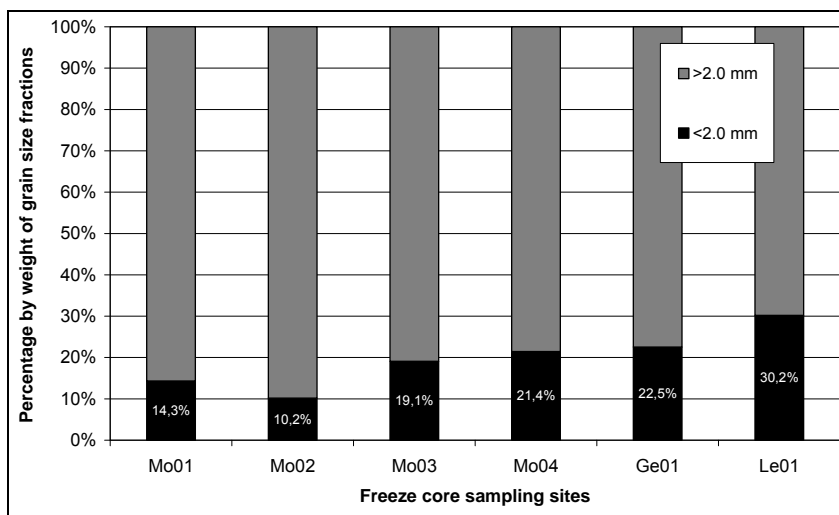


Figure 7: Fine sediment (<2.0 mm) share of the freeze cores.

Temporal variation of fine sediment intrusion into the river bed (sediment trap analysis)

The intrusion of fine sediments <2.0 mm correlates positively with the discharge pattern during the single sediment trap periods ($r = 0.77$, $p = 0.005$). Especially the great differences between the periods I and III, VI and VII, VIII and IX, and XI and XII reflect the correspondence between fine sediment intrusion and discharge (Figure 8).

The difference between the periods VI and VII indicate the importance of single events of high discharge after long dry periods regarding the amount of fine sediment transported along the water body and intruded into the river bed. The discharge sum of the period VII (0.35 million m³) is only slightly elevated in comparison to the discharge sum of period VI (0.20 million m³). The average fine sediment content measured in the sediment traps of period VII (804 g) however is considerably higher than the content in the period VI (314g). This indicates the importance of the single event of high discharge, which occurred during the period VII (see also Figure 4).

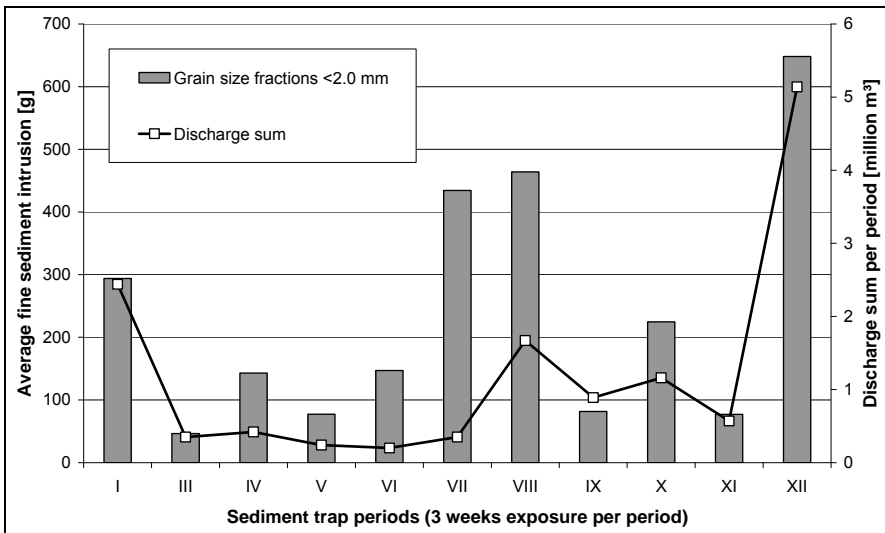


Figure 8: Comparison of fine sediment intrusion and discharge during sediment trap periods.

The organic share of the fine sediments <2.0 mm corresponds negatively with the discharge sum during the sediment trap periods ($r = -0.64$, $p = 0.035$). During the periods with low discharge values the organic share is considerably high (Figure 9). Whereas the total fine sediment intrusion drops down during low discharge periods the organic fine sediment intrusion remains stable in general (Table 5).

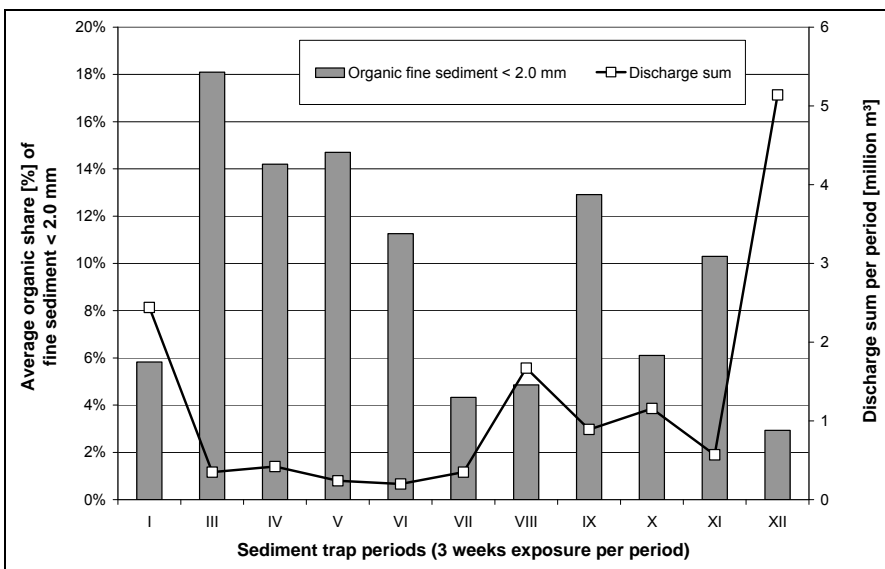


Figure 9: Organic share of the fine sediment <2.0 mm intruded during the sediment trap periods.

Table 5. Average intrusion of organic and inorganic fine sediment < 2.0 mm into sediment traps.

	Sediment trap periods											
	I	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
organic fine sediment [g]	17	8	20	11	17	19	23	11	14	8	19	
inorganic fine sediment [g]	277	38	123	66	130	415	441	71	211	69	629	
sum [g]	294	46	143	77	147	434	464	82	225	77	648	

Spatial variation of fine sediment intrusion into the river bed (sediment traps / colmation mapping)

The fine sediment intrusion into the river bed is elevated at the lower reaches of the creeks under investigation (Mo01, Mo02, Le01 and Ka01) with exception of the near-natural creek Gelpe (Ge01) (Figure 10). This pattern indicates an accumulation of fine sediments during periods of high suspended solids concentration and low discharges at the anthropogenic altered creeks.

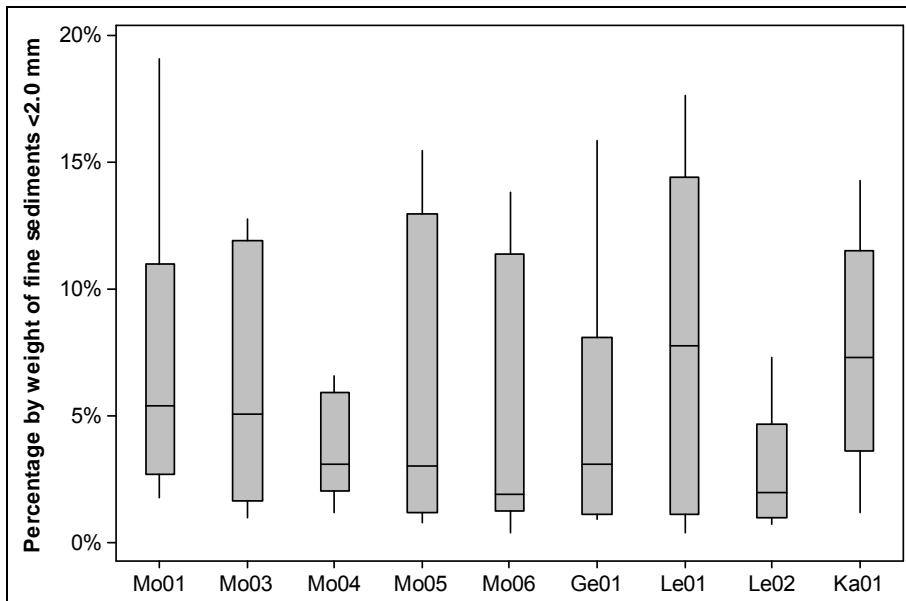


Figure 10: Fine sediment share (percentage by weight) in the sediment traps.

The intrusion of organic fine sediment <2.0 mm during the three weeks sampling periods ranges between 1.9 g (Le01) and 37.0 g (Ge01). The organic fine sediment intrusion varies considerably at the mouths of the near-natural creek Gelpe (Ge01) and at the anthropogenic altered Leyerbach (Le02). None of the sediment traps show exaggerated organic fine sediment intrusion (Figure 11).

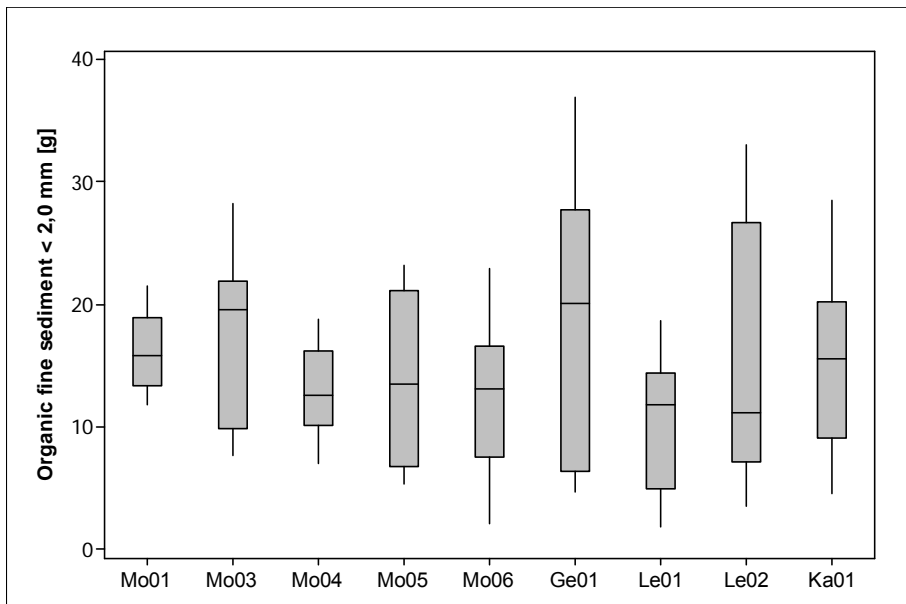


Figure 11: Absolute organic fine sediment content in the sediment traps.

The colmation mapping showed medium colmation levels on average. Only at the mouth of the near-natural Gelpe (Ge01) there could be detected no colmation at all (Table 6).

Comparison of colmation level and invertebrate status

The investigated parameters correspond only in parts to the organic fine sediment pressure on benthic invertebrates derived from biological sample evaluation (Wupperverband 2008).

The colmation potential derived from the pollution runoff model only shows some coincidence with the scores of the organic fine sediment pressure derived from invertebrate sample evaluation at four sampling sites (Mo05, Mo06, Ge01 and Le02). A considerably good correspondence exists between the theoretical colmation potential and the actually measured fine sediment share within the sediment traps.

The colmation mapping results correspond generally to the organic fine sediment pressure scores at six of the nine sampling sites (Mo03, Mo04, Mo06, Ge01, Le01 and Ka01).

No clear correlation between fine sediment intrusion into the riverbed derived from the sediment traps and the organic fine sediment pressure (Wupperverband 2008) could be detected.

Table 6. Comparison of organic fine sediment pressure on invertebrates derived from invertebrate sample evaluation (Wupperverband 2008), theoretical colmation potential (Pollution runoff model), total and organic fine sediment content (sediment traps) and colmation level (mapping).

Aspect	Parameter	Unit	Sampling / Mapping Sites								
			Mo01	Mo03	Mo04	Mo05	Mo06	Ge01	Le01	Le02	Ka01
Sedimentation / Colmation -potential (Pollution runoff model)	Suspended solids concentration	mg/l	27.0	21.0	17.0	6.8	8.2	7.0	16.9	18.6	10.3
	Shear stress	N/m ²	25.8	11.1	12.0	32.4	35.3	24.1	23.5	60.1	30.9
	Colmation potential	-	very high	high	high	medium	medium	medium	high	low	very high
Organic fine sediment pressure on invertebrates (Wupperverband 2008)	Class (score)	-	II (492)	III (844)	II (422)	I (118)	I (56)	I (71)	III (678)	II (295)	I (212)
	Pressure specification	-	low	medium	medium	very low	very low	very low	medium	low	very low
Average fine sediment share in river bed (Sediment traps)	Fine sediment <2.0 mm (org. & inorg.)	%	5.3	5.1	2.0	3.0	1.3	1.2	7.8	1.0	7.3
Average organic fine sediment content in river bed (Sediment traps)	Organic fine sediment <2.0 mm	g ^(MEAN)	16.2	17.6	12.9	13.7	12.3	18.5	10.6	15.5	15.6
		g ^(MED)	15.9	19.6	12.7	13.5	13.2	20.1	11.9	11.2	15.5
	Organic fine sediment <0.2 mm	g ^(MEAN)	4.9	6.9	6.4	4.7	4.4	5.8	4.2	5.2	7.9
		g ^(MED)	5.3	5.4	6.9	5.2	4.4	3.6	4.4	5.2	6.9
Colmation level (Mapping)	-	-	medium - high	medium	medium - high	medium	low - medium	no	low - medium	medium	low - medium

As an example for the non-correlation of fine sediment content in the sediment traps and organic fine sediment pressure on benthic invertebrates the relation between the average organic share of the grain-size fractions <0.2 mm and the organic fine sediment pressure score derived from invertebrate samples is shown in Figure 12. One has to state that the model presented in Figure 12 is not statistically significant due to a low number of samples (n = 9) and hence its interpretation can only be a first lead for formulating further research questions.

At the two near-natural creeks Gelpe (Ge01) and Klausener Bach (Ka01) the amount of measured organic fine sediment <0.2 mm is much higher than the score of the organic fine sediment pressure derived by invertebrate samples is indicating. At the same time the organic fine sediment amount at the highly anthropogenic altered Leyerbach (Le01) is very low in comparison to the actual fine sediment pressure on invertebrates. This pattern leads to the assumption that rather the origin resp. the energetic value of the organic fine sediment may be of relevance for its effects on the composition and abundance of invertebrate communities than the amount of the organic fine sediment. The assumption is strengthened by the fact that the organic fine sediment in the Leyerbach is mainly of anthropogenic origin coming from overflows of the combined sewer systems.

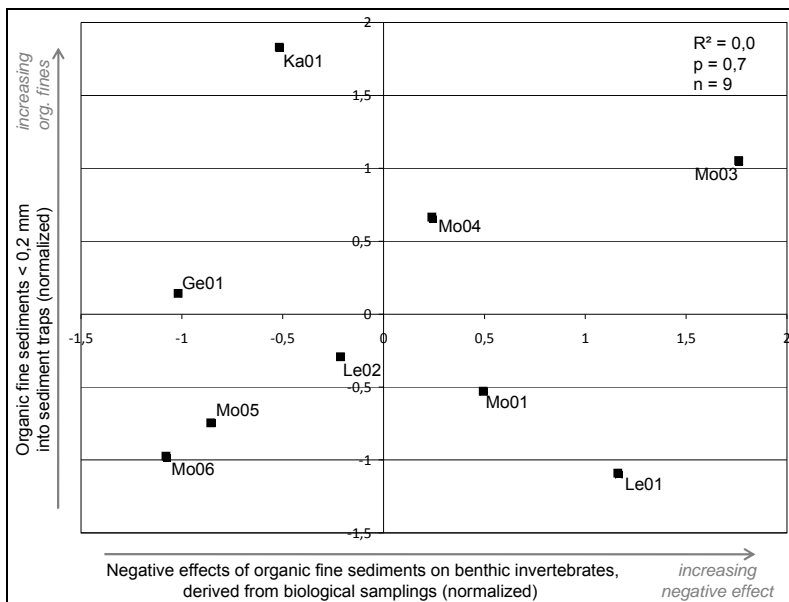


Figure 12: Correlation between measured organic fine sediment and organic fine sediment pressure scores derived from invertebrate sample evaluation.

CONCLUSIONS

Three sampling resp. mapping methods were applied to detect and quantify colmation levels within a river basin. Through a combination of freeze core sampling, sediment traps and colmation mapping a medium colmation problem could be identified and hence mitigation measures for reducing fine sediment intrusion could be formulated (e.g. reduction of organic fine sediment from overflows of combined sewer systems). However, none of the methods tested show a satisfactory correlation with benthic invertebrate sample interpretations regarding fine sediment pressure. Further research is needed to set quality guidelines and thresholds for evaluating colmation phenomena influencing benthic ecology.

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