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The use of fine sediment fractal dimensions and colour to determine sediment sources in a small watershed

Andreas Krein[a,*], Ellen Petticrew[b,1], Thomas Udelhoven[c,2]

[a] *Hydrology Department, University of Trier, Trier D-54286, Germany*
[b] *Geography Program, University of Northern British Columbia, Canada*
[c] *Remote Sensing Department, University of Trier, Trier D-54286, Germany*

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Abstract

As many particle-associated contaminants and nutrients are supply controlled, the question of particle source is crucial. In addition, sediment storage has important implications for the delivery and fate of pollutants. Increased accumulations of fine sediment (< 63 μm) in gravel beds not only modify benthic habitat but also increase the retention time of sediment-associated contaminants in these biologically active areas of river systems. It is of overriding importance to determine the origin of the fines and the amount, location and process of storage. There is little doubt that the characteristics of particles can be used to derive this information. There is no general agreement, however, about the characteristics that should be considered in such investigations. Furthermore, scientists have a great demand for simple methods, especially for routine use under dry weather conditions when suspended particle concentrations are low. This investigation shows that, in addition to loss on ignition, the determination of fractal dimension and particle colour also provide a fast and easy approach. After filtering the suspensions through glass microfibre filters, the dried filter residues are scanned by a colour scanner. Particle-bound cations and heavy metals were analysed by atomic absorption spectrometry after material decomposition with nitric acid. Fractal dimensions were obtained from measurement of the digital pictures using standard methods of digital image analysis. The fractal dimension decreases, indicating an increase in the regularity of particle

Abbreviations: A, Particle area; *b*, Linear regression coefficient; *D*, Perimeter–area fractal; D_{20}, Particle size for which 20% of the material is finer; D_{50}, Median particle size; LOI, Loss on ignition; *P*, Particle perimeter.

* Corresponding author. Tel.: +49-651-201-2235; fax: +49-651-201-3978.

E-mail addresses: krein@uni-trier.de (A. Krein), ellen@unbc.ca (E. Petticrew), udelhove@uni-trier.de (T. Udelhoven).

[1] Tel.: +1-250-960-6645; fax: +1-250-960-5538.

[2] Tel.: +49-651-201-4594; fax: +49-651-201-3815.

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morphology as one moves from gravel-stored sediment to surface-stored sediment to suspended sediment. Generally, flocs with high organic content exhibit more irregular morphology while single mineral particles have a more regular shape. In this study, the dominant factor for variable particle morphology was determined to be the mechanical forces influencing the flocs. An increase in shear associated with high flows and the impact of colliding with the channel bed appears to result in less flocculated, more regular particles at the surface. In addition, the morphology of particles shows that the exchange of particles in the gravel bed takes place during and shortly after flood events when the armoured layer is broken up and the sediment down to a depth of several centimetres is disturbed. Deposition onto the sediment surface was observed during the falling limb of every event. Surface sediment and suspended sediment show similarities in loss on ignition and particle morphology, particularly in low flow conditions when the stored amount of 25 mg/cm^2 is not exceeded. The exchange between suspended sediment sources over the course of a year can be described using colour variation of the fine sediment. Along with particle-bound manganese, it can be shown that during both the winter month, which exhibit a high baseflow, and flood events, distant sediment sources predominate. In summer low flow conditions, in-channel sources are more important. Furthermore, the use of colour values can allow prediction of the sediment chemical properties as, for example a significant linear correlation between particle colour and particle-bound manganese was found.

Keywords: Gravel bed river; Fine sediment; In-channel storage; Fractal dimension; Particle colour

1. Introduction

River sediments are a major potential sink for hydrophobic pollutants in the aquatic environment (Voice and Weber, 1983). As biogeochemical storage depots for contaminants, fine particles have a considerable influence on the water quality. The occurrence of organic pollutants in river sediments has been correlated with the abundance of particles smaller than 63 μm (Karickhoff and Brown, 1978). Storage sites may act as a source of sediment and contaminants. In addition, the storage of fine-grained sediment represents an important component of the suspended matter budget of a drainage basin. Mobilised sediment can be stored at different locations within a basin—especially on flood plains and in the sediment—in amounts that can be of magnitudes many times greater than the suspended sediment export from the basin (Phillips, 1991; Owens et al., 1997). The interpretations of downstream sediment yields in terms of upstream material mobilisation are therefore complicated.

In addition, the role of fine sediment as an agent of habitat degradation has been documented in numerous field and laboratory experiments. It has been demonstrated that high levels of fine sediment in gravel bed rivers have a deleterious effect on the survival of the incubating embryos of trout and salmon or macroinvertebrates (Soulsby et al., 2001). This indicates the importance of the sediment source and availability in the process of infiltration. Results from laboratory flume studies generally agree on the predictive importance of suspended sediment concentration on infiltration rates (Beschta and Jackson, 1979) but differ on the usefulness of gross flow hydraulic parameters such as velocity, shear stress and Froude number. In natural waters, small mineral particles are commonly observed to be bound with particulate organics in the form of flocs or aggregates. As these larger aggregated particles exhibit increased settling rates and decreased densities their mobility towards and within the gravels is modified from their original behavior as individual mineral particles (Droppo et al., 1998). While floc structures are more transitory and fragile than sands the fact that they can move into the gravels enables the storage of both the associated contaminants and the organic matter. This is problematic for organisms inhabiting the gravels as the biological and chemical oxygen demand on the interstitial water can be increased. Therefore, the presence of fines can exert chemical, biological and physical changes to the gravel habitat. The objective of the work was to determine the origin and characteristics of fine sediment (< 63 μm) stored in riverine gravels in comparison to the characteristics of surface-stored sediment and suspended sediment.

A common procedure for the detection of particle source uses suspended particle characteristics, including physical, chemical and, more recently, biological properties. These are utilised in the classical fingerprinting approach (Walling and Kane, 1984). There is no general agreement as to which particle characteristics are most important in terms of the particle-associated contaminant load, because many theoretical and experimental approaches do not hold under natural conditions. For example, the generally accepted theoretical influence of particle size and particulate organic carbon on the load of organic contaminants (Karickhoff, 1979), could not be identified by Umlauf and Bierl (1987) in field investigations.

In addition, there are major methodological problems in dealing with suspended solid concentrations in the range of only a few milligrams per litre, especially if you are interested in a chemical characterisation. There is a need for easy and efficient techniques for routine examination. Examples of commonly applied physical methods include measurements of turbidity, loss on ignition, particle size, particle shape and microscopic techniques. The use of loss on ignition as a measure of a sample's organic content is, however, especially problematic in calcareous drainage basins.

One characteristic that has been more or less neglected until the present, is the quantitative description of the colour of suspended sediments. Furthermore, the morphology of the fine sediments and its significance for locating sources and investigating storage in channels has been only incompletely taken into consideration. In this study, the colour and shape of the suspended as well as the gravel-stored and surface-stored fine sediment in the Olewiger Bach are described in detail.

2. The study area

The study area is the 25 km^2 drainage basin of the Olewiger Bach, which is located to the south of Trier in the western part of Germany (Fig. 1). Devonian shales of the Hunsrück Mountains with quartz and diabase veins dominate the geology. Pleistocene terraces of the River Mosel overlie the solid geology in the northern part of the drainage basin. Land use is predominantly agriculture with grassland and arable farming. Residential land use covers about 10% of the basin. In summer, multi-peaked flood waves, which can be traced to consecutive contributions of tributaries, are characteristic in the

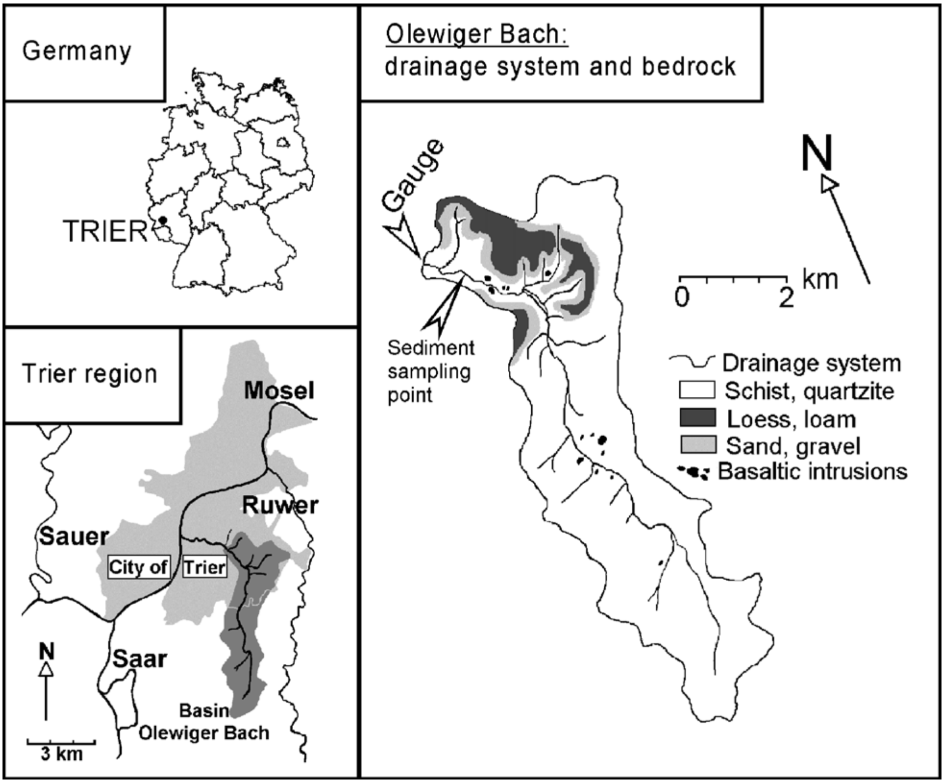

Fig. 1. Field area location.

catchment. The tributaries typically have a steep gradient and a relatively short channel length. The long lasting, low intensity winter precipitation causes a singular broad discharge maximum, which is primarily composed of laterally flowing soil water and groundwater. During the high drainage winter half, predominantly dense, mineral-rich components will thus be deposited. The less dense particles, in contrast, remain in suspension and are transported away. Runoff from several roads, effluents from small industries and untreated waste water from solitary farms influences river water quality. Detailed information about stream bed morphology and sediment characteristics is given by Krein and Schorer (2000) and De Sutter et al. (2000).

3. Methods

3.1. Suspended sediment sampling and analysis

Investigation of suspended sediment took place from 1996 to 1998 with daily water samples at the gauge identified in Fig. 1. The sampling and analysis programme covers the aspects of hydrological condition, conductivity, suspended sediment concentration, particle characteristics (loss on ignition, colour) and the particle associated solids manganese, iron and magnesium. The significance in the choice of these parameters is described by Symader and Bierl (1998). Due to the low suspended sediment concentrations, up to 120 l of water were collected into polyethylene tanks. Each of these daily samples were filtered through two glass fibre filters. One of the filters was used to determine the suspended sediment concentration by filtering a known volume of river water through a pre-ashed and pre-weighed 0.45 μm filter (Whatman GF/F, 47 mm, No. 1825047), which was dried and weighed following filtration. Afterwards, the filter was scanned with a colour scanner (HP Scanjet 5300C, 500 dpi) and placed in an oven for 5 h at 500 °C. After cooling and re-weighing, it was scanned again. Using this method, the colour of the mineral residues can be determined without organic coatings on the mineral sediment. A discussion of the colour scanning processes is given in Section 3.4. Simultaneously, the loss on ignition can be calculated. The temperature during heating must not exceed 500 °C, in order to avoid a transformation of the minerals, especially the coloured aluminium, manganese and iron hydroxides and oxides.

The second filter with the sample material was decomposed for 6 h under pressure at 170 °C with concentrated nitric acid. Cations and heavy metals were analysed with an atomic absorption spectrometer (SPEKTRA A 640, VARIAN). A detailed description of the analytical methods is provided by Krein and Schorer (2000). The particle size distribution was determined from a sub-sample of the original water sample. The sediment suspension was analysed using an in situ laser technique, the GALAI CIS-1 (Aharonson et al., 1986), that was linked via computer to a camera to determine particle morphology. Values of particle area and perimeter are obtained from the digital images and stored in ASCII format.

3.2. Bed sediment sampling and analysis

The three types of sediment samples were collected weekly from November 2000 to March 2001 at two selected riffles approximately 600 m above the gauge site (Fig. 1). The grain size distribution of the coarse sediment matrix at the sampling points had a D_{20} of 6 mm and a D_{50} of 16 mm. A more detailed description of the sediment characteristics in the Olewiger Bach is provided by De Sutter et al. (2000).

Sampling of the riffle gravel was undertaken to determine the characteristics and amount of fine sediment stored both on the surface of the gravels and within the interstitial gravel space. This was done by pushing a tube of known diameter about 2 cm into the gravel to form a seal. Following this, the water above the gravel was stirred to resuspend the sediment stored on the gravel bed surface. When stirring ceased, a 10-s settling period was allowed before the water was sampled using a wide mouth Nalgene bottle. This 10-s delay allowed the sands to settle out of the surface waters so that only material less than 63 μm was sampled. We were able to confirm the upper boundary of 63 μm with our laser measurement tool GALAI CIS-1 via multiple measurements. The measurement of sediment concentration in combination with the total volume of water in the tube above the gravel allowed for the determination of total fine sediment mass stored on the surface and of the gravels. Following the surface resuspension, the gravels were mixed to a depth of 10 cm using a steel ruler. The fines stored to this depth in the gravels were maintained in suspension by stirring and again a sample of suspended sediment was collected following a 10-s wait to allow for settling sands. These measurements of gravel- and surface-stored fine sediment mass associated with the riffle bed were taken in three locations in both of the riffles. Immediately following the sampling of stored sediment, a suspended sediment sample was collected from the water column. Stored sediment and suspended sediment samples were taken to the laboratory for chemical and morphological analysis.

3.3. Determination of the fractal dimension

Many methods have been developed to describe and quantify the morphology of individual particles using techniques such as fractal approaches or Fourier analysis (Kaye, 1989; Orford and Whalley, 1983; Whalley and Orford, 1989). The applications of fractal dimension analysis in geosciences are shown by Korvin (1992) and Lam and De Cola (1993). This work follows the approach of quantifying the morphology of particle populations using fractal dimension as described by Logan and Kilps (1995) or Li and Ganczarczyk (1989). Natural objects like fines have been found to have perimeter–area relationships described by the power function $A \propto P^{2/D}$, where P is the perimeter, A is the area and D is the fractal dimension of the collection. According to De Boer (1997) and Mandelbrot (1983), Euclidean objects like squares and circles have a D of 1. Values of D greater than 1, have been found for synthetic fractals and for objects such as clouds ($D = 1.35 \pm 0.05$; Lovejoy, 1982), lakes ($D = 1.5 \pm 0.18$; Kent and Wong, 1982) and snow patches during melt ($1.536 < D < 1.684$; Shook et al., 1993). De Boer (1997) used four different fractal dimensions to quantify visually observed changes in the morphology of fluvial suspended sediments during baseflow conditions. The dimensions were consistent with, and allow quantification of, observed changes which coincided with an increase in primary production in the form of algae.

To calculate the perimeter–area fractal according to Mandelbrot et al. (1984), areas and perimeters of single particles were saved from the CIS-1 into ASCII-files. In order to rule out device artefacts (bubbles; drop shadow), only particles whose smallest diameters were greater than 6 μm and less than 150 μm were measured. The areas of all the selected particles are between 20 and 1000 μm^2, while their perimeters are between 20 and 200 μm. The fractal dimension can be directly derived from a log–log plot of particle circumference and area. Fig. 2 illustrates the derivation of the perimeter–area fractal from a sediment sample taken on January 4, 2001. The average fractal dimension of the sample can be derived from the linear regression coefficient b, with $b = 2/D$. Should the particles under investigation be precisely spherical, then the slope of the regression line is 2.0 and D is given a value of 1. In general, the value of D is between 2 and 1, where higher values represent open and irregular floc structures. According to De Boer (1997), the physical interpretation of values of D greater than 1 for many natural objects is that it indicates that as the objects become larger, i.e. as A increases, the perimeter increases more rapidly than for Euclidean objects, so that the boundary becomes more convoluted. A validation of the values resulted from triple testing of the samples using the laser particle sizing instrument, the GALAI CIS-1. The deviations between replicates of the fractal dimensions of the samples were at all times less than 3%.

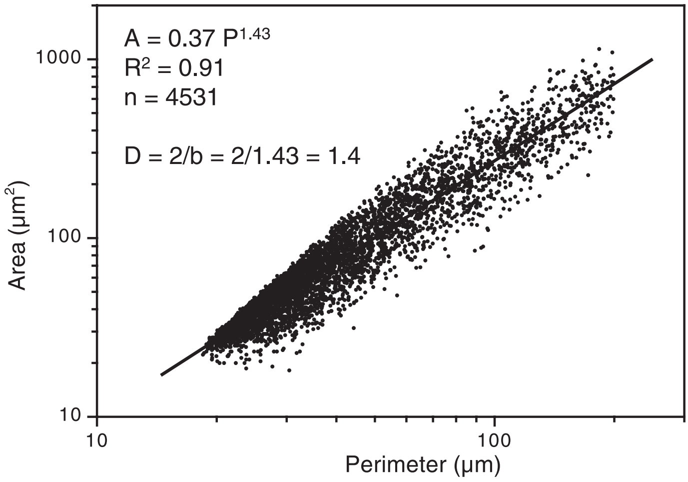

Fig. 2. Perimeter–area fractal of particles in a fine sediment sample (January 4, 2001).

3.4. Colour measurement

In the literature of hydrological remote sensing, there are many examples of applications of spectral pattern measurements. They range from examination of spatial and temporal variations in suspended particle concentration to the identification of chlorophyll, phaepigments and organic substance in oceans and lakes (Farmer et al., 1983; Horne and Wrigley, 1975; Kondratyev and Pozdniakov, 1990). For this study, a known volume of river water was drawn through a glass microfibre or membrane filter. All filters were dried for 1 h at 105 °C. The dried filter residue contains information about the suspended particle concentration and also its colour. Different residue colours are as obvious as the colour changes observed during flood events, which indicate the activation of different particle sources (Grimshaw and Lewin, 1980). The colour of the residue was measured by scanning the dried filters with a colour scanner (HP Scanjet 5300C, 500 dpi). The digitised colour values, which contain the red, green and blue colour information and the luminosity value for the residue, were stored using one of the common graphic formats. During scanning, the integrated light source of the scanner with a defined colour temperature illuminates the sample. A special filter system separates the reflected light into its three component colours, and leads the focused light beams to a CCD-element. The measured voltage values are converted by an analogue/digital converter, using a nonlinear calibration equation, into discrete number values. An 8-bit resolution for each colour, that is a total colour depth of 24 bit, provides $256 \times 256 \times 256 = 16.8 \times 10^6$ colours. In contrast, the human eye can only differentiate 200,000 colours.

To compare colour information for different suspended particle samples, the measurement conditions must be held constant. The scanner must work with a fixed adjustment and, furthermore, filter type and residue weights should be always the same. A validation of the measurement conditions resulted from the multiple scanning of a test sheet parallel to the single scanning procedure of the samples. This sheet consists of a table with

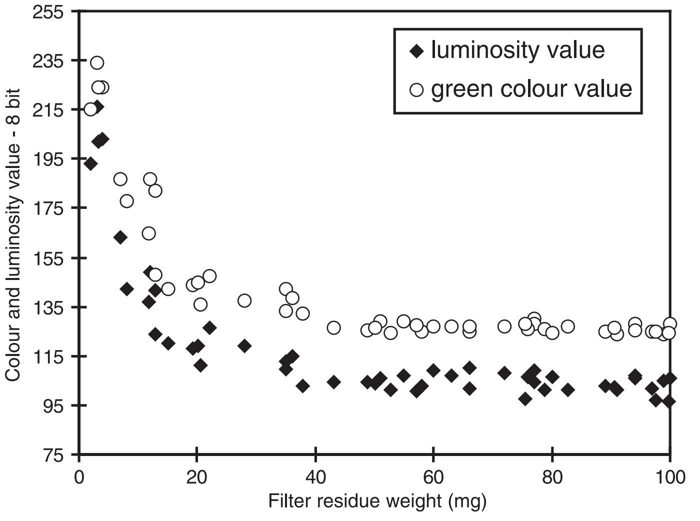

Fig. 3. Relationship between mean green colour values, luminosity, and filter residue weight. All residues are from the same sediment sample.

differently coloured surfaces. The results were deviations in the colour values of less than 1% between the individual control measure. The consistency of the measurement conditions is thus ensured and no calibration of the scanner was essential.

For colour scanning, 0.45-μm Sartorius cellulose nitrate and polyamide membrane filters as well as Whatman GF/F glass microfibre filters with a mean pore size of 0.6 μm were used. For similar particle weights up to 45 mg, the membrane filters always provided darker colour values. However, the glass fibre filters were preferred because they do not wrinkle during the drying procedure. All filters where scanned with a HP Scanjet 5300C scanner with 500 dpi and stored in the BMP format. The software package Photoshop 5.5 was used to extract the colour features of the digitised filters.

Fig. 3 illustrates the relationship between the values for green colour, luminosity and residue weight for a single suspended particle sample. It is obvious, that the relationships change as residue weigh changes. For filter residue weights less than 45 mg, the colour measurement is influenced, in a nonlinear manner, by the underlying white filter. For this reason, the scan procedure for a suspended particle sample at a given concentration always provides a relative rather than absolute colour measurement. In the subsequent analysis, only filters coated with more than 80 mg of material are considered.

4. Amount and characteristics of stored sediment and suspended sediment

Fig. 4 shows the changing amount of fine sediment which accumulated on the channel bed and was stored down to a depth of 10 cm for the winter of 2000/2001. The amount stored in the gravel bed is approximately 20 to 25 mg/cm^2. Flood events with a peak discharge greater than 1.5 m^3/s result in a decrease in the amount stored in the gravel bed.

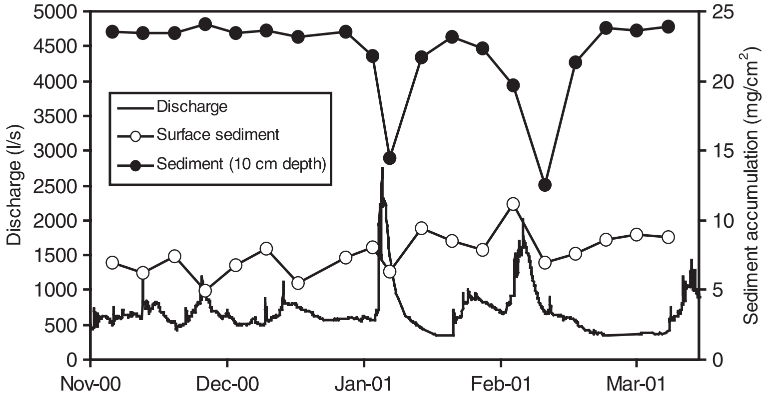

Fig. 4. Amount of stored fine sediment in 10 cm depth, amount of surface sediment and hydrological conditions in the Olewiger Bach.

During such events, the armoured layer is broken up. The upper 10 cm of the sediment is disturbed and a part of the fine material is eroded. The stored amount thus decreases to 12 to 15 mg/cm^2. During the falling limbs of the flood events, the freed up storage space is replenished, and 1 to 2 weeks later the pre-storm amounts have been reached again. This observation confirms the work by Sear (1993) who concluded that accumulation rates and variations in the grain size distribution of fines into a gravel bed are complex and relate in particular to the local hydraulics. In addition, however, the supply of sediment, the transport mechanism (i.e. suspended or bedload), the dimension of interstices between the framework gravels, scour and fill sequences during floods and the reach morphology are also controlling factors. However, in our investigation these parameters were not taken into consideration. Smaller events have little effect on the sediment stored deep within the gravel bed as there is not enough energy to break up the armoured layer. A reduction in the amount of stored surface sediment, which is not protected in the interstices of the gravel during the small flood events is observed. The total mass of stored fine material on the river bottom surface varies, depending on the discharge, between 5 and 10 mg/cm^2. New sediment from flood waves accumulates during the falling limbs.

Fig. 5 shows that the surface stored fines contain organic-rich compounds. The variability of the loss on ignition of the surface fines is similar to the variability of suspended sediment. After flood events, the LOI drops from ~ 0.6 to between 0.2 and 0.3 indicating that predominantly mineral material is deposited on the river bottom. During the winter month (October–March), these particles originate for the most part from the exposed arable land susceptible to erosion (Krein, 2000). The LOI of the gravel-stored fines (10 cm) is lower than in the other fine sediment samples being ~ 0.2%. The variability of the loss on ignition in the gravel-stored sediment remains both very constant and low. Note in Figs. 4 and 5 that the effect of the two flood events which modified the quantity and LOI of both the suspended and surface-stored fines is not apparent on the LOI of the gravel-stored fine sediments. So while inorganic contributions and losses are noted over this winter sampling period in the deeper gravel-stored samples, the proportion of

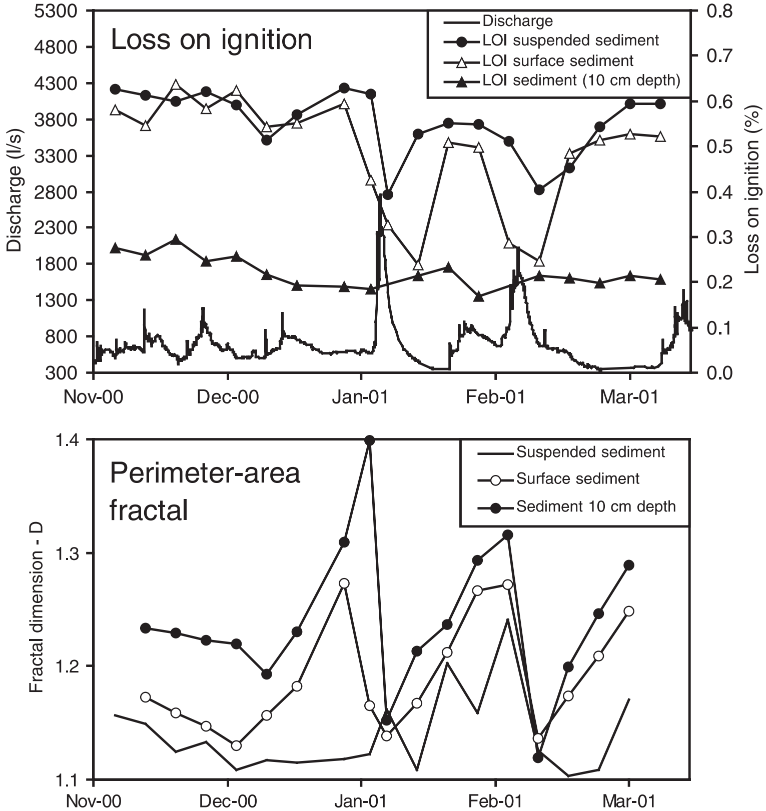

Fig. 5. Loss on ignition and fractal dimension of stored sediment, surface sediment and suspended sediment.

organic matter does not fluctuate in response to storm events as it does in the surface-stored fine sediments. During the high drainage winter half, predominantly dense, mineral-rich components will thus be deposited. The less dense particles, in contrast, remain in suspension and are transported away.

Nevertheless, the fractal dimension shows that the more gravel-stored fine sediment is influenced by winter drainage conditions. While the loss on ignition values are relatively constant during the period of storm events, the fractal dimension of these gravel-stored fines varies from 1.4 to 1.15 (January), and 1.3 to 1.1 (February). The changing morphology of the gravel-stored sediments shows a time sequence similar to the surface-stored fines. The particles of the surface sediment, however, are more regularly shaped, or rounded. Both large flood waves reduce all sample types to lower values of the fractal dimension indicating more regular shapes. For a short period following flood events, morphologically similar, and more regularly shaped material can be found on the channel bed, in the gravels and in suspension. During base flow, the irregularity of both sediment types (surface- and gravel-stored) again increases. The images captured by the GALAI CIS-1 system indicate the presence of flocs during these low flow periods. These form when there is no hydraulic disturbance to separate the loosely aggregated particles (Petticrew and Droppo, 2000). Therefore, flocculation in flow-protected sediment interstices may occur, although the organic portion is small. After heavy flood waves, the flocs are also destroyed and the samples exhibit more regular shapes as indicated by the lower fractal dimensions. On the whole, suspended sediment shows smaller fractal dimensions. As suspended sediment is mechanically stressed in the turbulent water flow during the larger winter discharges, few flocs are formed, although the organic portion is comparatively high. Overall, the fine sediment particles are observed to be more regularly shaped in the following order: gravel-stored, surface-stored and suspended sediment. In this system, the morphology appears to be determined less by the concentrations of organic substances and more by the mechanical stress (turbulent water flow, particle collisions) on the particles.

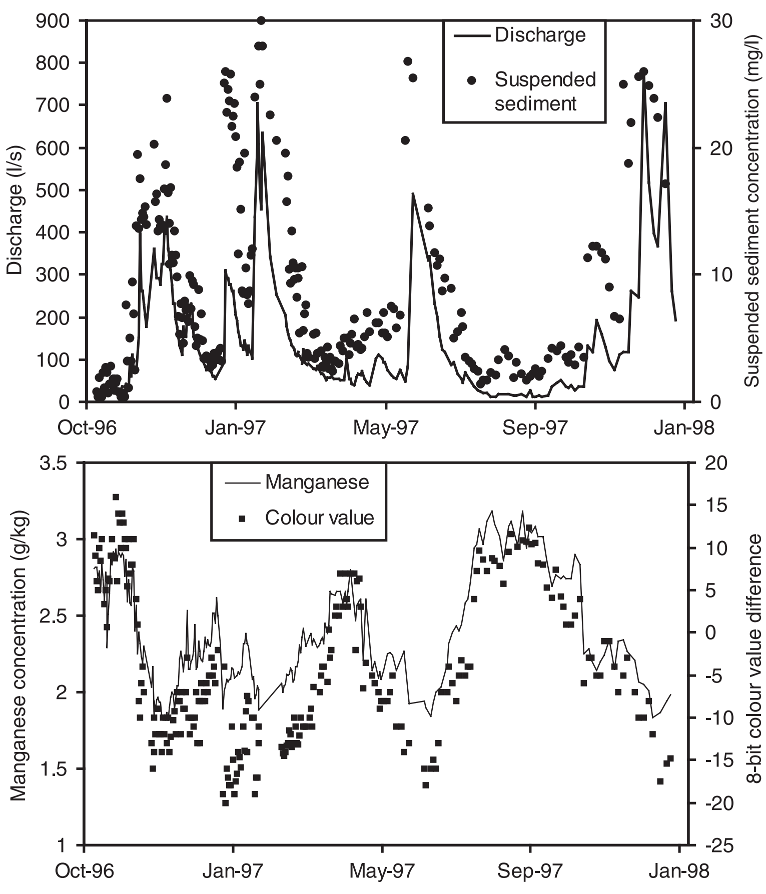

Fig. 6. Time series of discharge, suspended sediment concentration, particle-bound manganese and difference of green colour values before and after material combustion by heat.

5. Determining suspended sediment sources by particle colour

Fig. 6 shows the annual variation of the suspended sediment concentration, particle-bound manganese as well as the difference in green colour values before and after combustion. As expected, suspended particle concentrations increase with rising discharge. The concentrations of the daily samples however are small, with a maximum of 30 mg/l, as sampling was not carried out during floods. Flood events may contain up to 5000 mg of suspended particles per litre of water. The colour values consistently show a decrease when the suspended particle concentrations are high, contrastingly, during low flow phases they increase. The course of the colour curve directly reflects that of particle-bound manganese. This observation is not only true for the winter of 1996/1997 and 1997/1998, but also for the wet summer of 1997 when a change of the sediment sources was observed. A rainy period results in an extension of the source area. This is shown by lower manganese concentrations and an increased proportion in mineral elements such as magnesium (Krein, 2000). Fig. 7 illustrates the maximum concentrations of manganese in individual flood waves at the Olewiger Bach. These were plotted against the highest 10-min precipitation intensity of the events. Particle-bound manganese, whose origin is predominantly the channel sediment (Krein and Symader, 1999) is diluted by allochthonous substances from the soils being delivered from the terrestrial portion of the watershed during heavy precipitation events. The increased rainfall intensity reflects the greater erosive power of storms but also implies an expansion of the source area for sediment delivery. With increasing rainfall intensity and amount, there is an increase in the influx of material from sources that are located further away from the stream channels. In these situations, eroded soil minerals become dominant and mask the fingerprints of anthropogenic sources or of river channel and bank sediment. This dilution effect of large storms on particle-bound manganese is also shown in Fig. 6 and support the hypothesis for changing source areas.

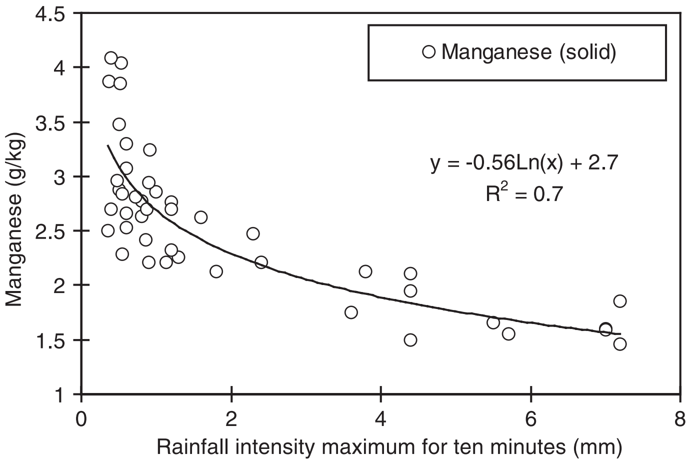

Fig. 7. Olewiger Bach—highest 10-min precipitation intensity versus maximum concentrations of particle-bound manganese of individual flood events (Krein, 2000).

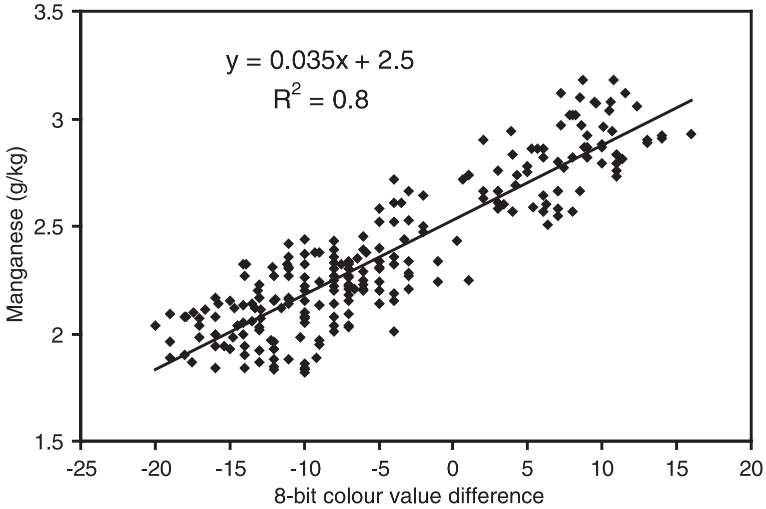

Fig. 8. Difference of green colour values before and after material calcination in relation to particle-bound manganese.

Therefore, to characterise diverse sources, colour measurements prove suitable. Here, the method involved subtracting the colour values from the untreated filters, which included the organics, from the ashed filter values, which included only the mineral components as colour.

In addition, the concentration of some particle-bound solids can also be derived from the colour values. Fig. 8 shows the linear relationship between particle-bound manganese and the difference between colour values (green) before and after sediment combustion. This correlation is, however, valid only for manganese and only for the catchment area of the Olewiger Bach. Magnesium and iron show no relationship to the colour values. Further work needs to be done to determine the relationship of colour with other chemical substances, and as well, the use of other measures of colour as a predictive variable.

6. Conclusions

Suspended particle characteristics show a high spatial and temporal variability during floods and also in dry weather conditions. The temporal variability can be related to changes in the composition of suspended solids caused by seasonal changes in hydrological and climatological conditions. A dominant factor for the variable particle morphology is the physical impact on the particles. The intensity with which the particles collide amongst themselves and with the channel bed appears to regulate the shape of the aggregated particles. The higher intensity energy environments result in more regular, rounded particles, implying that the loosely bound flocs have been broken down into smaller more regular structures. In the lower flow regimes of the gravel matrix, the stored particles are more irregularly shaped. Interestingly, these more irregularly shaped gravel-stored fine sediments are also very low in organic matter whereas the flocs or aggregates with higher proportions of organic components appear more regular. These results do not agree with findings of Petticrew and Droppo (2000) who found that smaller and more rounded particles were found stored in the gravels while suspended sediments were more irregular and floc-like. The differences may result from their sampling a highly productive salmon spawning stream following die off when much higher organic matter was available in the system and streamflows or shear conditions were low during the sampling period. The fractal dimension, and the irregularity of particle shape was found to increase in the order: suspended, surface-stored and gravel-stored sediment. The exchange of fine sediment between the gravels and the water column takes place predominantly during and immediately after storm events when the armoured layer is broken up and the gravel bed is disturbed down to a depth of several centimetres. Deposits onto the gravel surface are observed on the falling limbs of the investigated events. Surface fines and suspended sediment appear to be in a state of dynamic equilibrium, especially during periods of low water flow. In the conditions, sampled both components act interchangeably as source and sink material. The amount of fine sediment stored on the surface of the gravels does not exceed 10 mg/cm^2 over the winter sampling period.

Particle colour is a useful parameter for examining variations in suspended particle characteristics even at very low concentrations. The change of suspended sediment sources during the course of a year can be described with the aid of a colour differentiation of the material. Along with the behaviour of particle-bound manganese, it can be illustrated that during the winter season and more so during flood events sources that are located further from the streams are active. During summer low flow conditions, in-channel sources become more significant. Furthermore, using colour, conclusions as to the chemical properties of elements containing colour can be drawn, as shown by the linear correlation between the fine sediment colour and particle-bound manganese.

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