Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances

Volume of Extended Abstracts
from the International Workshop in Oslo, Norway
19 – 21 June 2002

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Preface

Due to a growing awareness of the important role of fluvial sediment in a wide range of environmental problems, there is an increasing need for a better understanding of the processes of erosion and sedimentation and their relationship to the transport of sediment in rivers. Despite the need for better and more consistent information, data collection in this field still lags behind other areas of hydrology. New problems also call for new approaches, new strategies and new methods in order to develop an improved understanding of cause and effect relationships for different activities within a river basin.

This workshop focuses on new sediment measurement technologies and presents a review of the status of current research and development in this field.

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Erosion and Sediment Transport Measurement: Technological and Methodological Advances. Workshop in Oslo 19 – 21 June 2002.

Extended abstracts:

Perspectives in bed load measurements.
Peter Ergenzinger (Freie Universitet Berlin, BD)

Submitted papers

Testing and improving the reliability of volumetric estimates of hydrogeomorphic features derived from LiDAR data.
Graeme R. Aggett (Central Washington University, USA)

Sampler size and sampling time affect measured bedload transport rates and particle sizes in gravel-bed streams.
Kristin Bunte and Steven R. Abt (Colorado State University, USA)

A new instrument to record sediment movement in bedrock channels.
Carling, P.A., Benson, I. & Richardson, K. (Southampton University, UK)

Long-term close-interval monitoring of suspended sediment transport in meltwaters draining from an Alpine glacier.
David N. Collins (University of Salford, UK)

Bed load measurements with a passive magnetic induction device.
Allen S. Gottesfeld & Jon Tunnicliffe (Gitxsan and Wet'suwet'en Watershed Authorities, Canada)

Recent development in sediment monitoring of glacial rivers in Iceland.
Jorunn Hardardottir (National Energy Authority, Iceland)

Grain size distributions of fluvial sediment mixtures: Indicators for sequential dependent hydraulic control of bedload transport.
Daniel Hartmann (University of Bremen, Germany)

Turbidity-controlled sampling for suspended sediment load estimation.
Jack Lewis (USDA Forest Service, USA)

Accuracy of sediment yield measurements in small catchments.
Jussi Baade & Claudia Liese (Friedrich-Schiller-University Jena)

areas.
Examples from the National Agricultural Environmental Monitoring Programme.
Lillian Øygarden, Johannes Deelstra & Stine Vandsemb & Hans Olav Eggestad (Centre for Soil and Environmental Research, Ås, Norway)

Submitted posters

Development of a conceptual soil erosion model for Ghana.
Mark Bambury (School of Engineering & Applied Science, UK)

Suspended and Bedload Sediment Transport Dynamics in Two Lowland UK Streams - Storm Integrated Monitoring.
D.J. Evans (Queens University Belfast, UK)

Bedload measurements in periglacial environments - examples from Svalbard.
Thomas Glade (Friedrich-Wilhelms-University Bonn, Germany)

The intelligent pebble: A new technology for tracking particle movements in fluvial and littoral environments.
Sear, D.A., Lee, M.W.E., Collins, M.B. & Carling, P.A. (University of Southampton, UK)

Bandsaar as a traditional method for soil conservation and flood cultivation in Khorasan province.
Shahriary, A., Kelarestaghi, E., & Javadi, M. (Teheran University, Iran)

Adequacy of current methods of suspended sediment monitoring for recent European Legislative requirements.
Barnaby P.G. Smith, David M. Cooper, Pamela S. Naden & Michael J. Dunbar (Centre for Ecology and Hydrology, Wallingford, UK)

The character and concentration of the fluvial transport in the karst area of Lublin Upland.
Swieca Andrzej & Tucki Andrzej (Maria Curie-Sklodowska University, Poland)

The Influence of Hydraulic Load and Aggradation on Sedimentation of Soil Particles in Wetlands.
Braskerud, B.C. (Centre for Soil and Environmental Research, Ås, Norway)

Laser diffraction Sensors measure Concentration and Size Distribution of Suspended Sediment.
Yogesh C. Agrawal & H.C.Pottsmith (Sequoia Scientific, Inc., USA)

A new definition of suspended sediment: Implications for the measurement and prediction of sediment transport

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Extended Abstract

While it is now well documented that cohesive suspended sediment is commonly transported in a flocculated/aggregated form (Figure 1) (Bale and Morris, 1987; Walling and Moorehead, 1989; Droppo and Ongley, 1994; Phillips and Walling, 1999; Droppo *et al.*, 2000; Droppo, 2001), research into sediment transport issues, still relies on traditional sedimentological techniques. That is, the chemically dispersed mineral fraction (absolute particle size) is measured to characterize particle size and for input values to models for the prediction of sediment and contaminant source, fate and effect. This implicit or explicit assumption of single grain particles is motivated by a lack of a standard defining equation, which can explain the formation and interaction of flocs/aggregates with their surrounding aquatic environment, and the lack of a standard method for sampling, observing, and measuring such particles. Regardless, most rivers possess significant proportions of cohesive (fine-grained) sediments, and as such, for the reasons stated below, a knowledge of the particle structure is imperative for sediment/contaminant transport related studies.

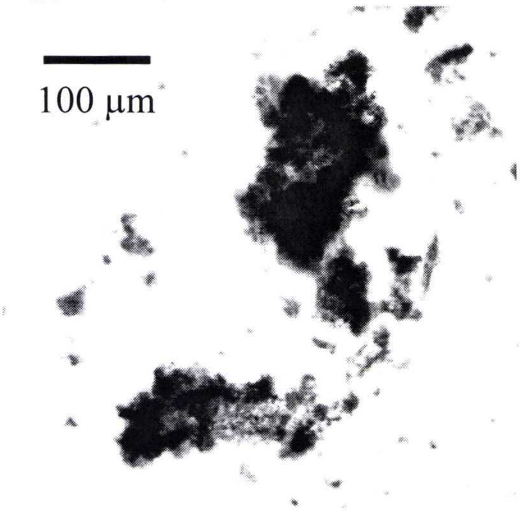

Figure 1. Example of typical fluvial flocs.

Flocs/aggregates are heterogeneous, composite structures composed of an active biological component, a non-viable biological component, inorganic particles, and water held within or flowing through pores (Walling and Woodward, 1993; Droppo and Ongley, 1994; Liss *et al.*, 1996; Droppo *et al.*, 1998, 2000). Flocs are formed within the water column or on the surface of the bed by a variety of complicated physical, chemical and biological means. Alternatively, aggregates are generally considered to form outside of, and be transported to, the aquatic system as water stable soil aggregates. Aggregates transported in a water column will possess many of the same physical, chemical and biological characteristics as flocs (although denser with a concomitant higher settling velocity), and are generally optically indistinguishable from flocs (particularly when the two flocculate together). As such, for the purposes of this work, the terms floc/flocculation and aggregate/aggregation will be used interchangeably. The most significant impact of flocculation in terms of sediment and contaminant transport is that it alters the downward flux of sediment by changing the hydrodynamic properties of the sediment. This is brought about by flocculation increasing the effective particle size by orders of magnitude over the absolute particle sizes and, as such, also changes the effective particle shape, density, porosity and composition of the characteristic particle (suspended or bed sediment) within a system (Li and Ganczarczyk, 1987; Nicholas and Walling, 1996; Droppo *et al.*, 2000; Phillips and Walling, 1999). A typical relationship of floc size to settling velocity, porosity and density is provided in Figure 2.

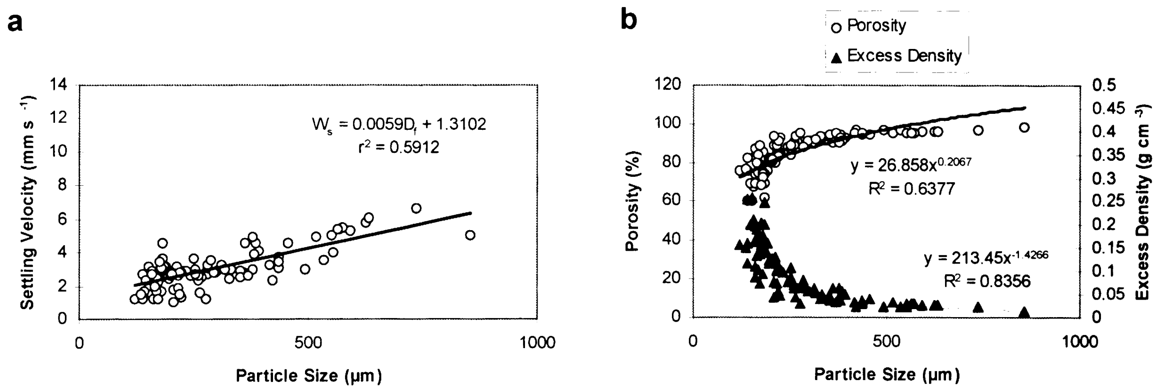

Figure 2. Examples of the typical relationship of floc size to a) settling velocity (note the increasing settling velocity with particle size) and b) density and porosity (note the increasing porosity and decreasing density with particle size).

A flocculated/aggregated particle is in continuous interaction with its aquatic surroundings, as the medium in which it is transported provides the floc with further building materials, energy, nutrients and chemicals for biological growth, chemical reactions and morphological development. While flocs can regulate their own characteristics, they are also known to be able to contribute to the regulation of their surrounding water quality through their physical, chemical and biological activity (Liss *et al.*, 1996). Given the complex composition of flocs and the complicated physical, chemical and biological interactions within flocs and within the systems where they occur, a new definition of suspended sediment particles (flocs) is required. Given the importance of the biological system within the particles, a floc definition is suggested as follows:

> A floc is an individual microecosystem represented as a composite particle composed of a complex matrix of water, inorganic and organic particles, with autonomous and interactive physical, chemical and biological functions or behaviours operating within the floc matrix (modified from Droppo et al, 1997; Droppo 2001).

While there are many studies of flocculation (e.g. Hunt, 1982; Kranck, 1984; Bale and Morris, 1987; Walling and Moorehead, 1989; Fennessy *et al.*, 1994; Droppo *et al.*, 1998, 2000) which focus on many different aspects of flocculation from a variety of different environments, very few papers have attempted to link the physical, chemical and biological aspects of flocculation together in a simple manner to enhance our understanding and learning of such an important phenomenon in our aquatic ecosystems. Furthermore, few papers have attempted to explain the impact that particle structure will have on our traditional measurement of sediment transport. This paper provides a comprehensive conceptual model with supporting documentation for the explanation of the linkage between floc structure and floc behaviour (transport) within aquatic environments. Given the realization that the majority of cohesive sediment is not transported as single particle but rather as flocs or "microecosystems", it is important that we gain a better understanding of what constitutes cohesive suspended sediment and its transport within aquatic ecosystems.

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Modelling and monitoring flow and suspended sediment transport in lowland river floodplain environments

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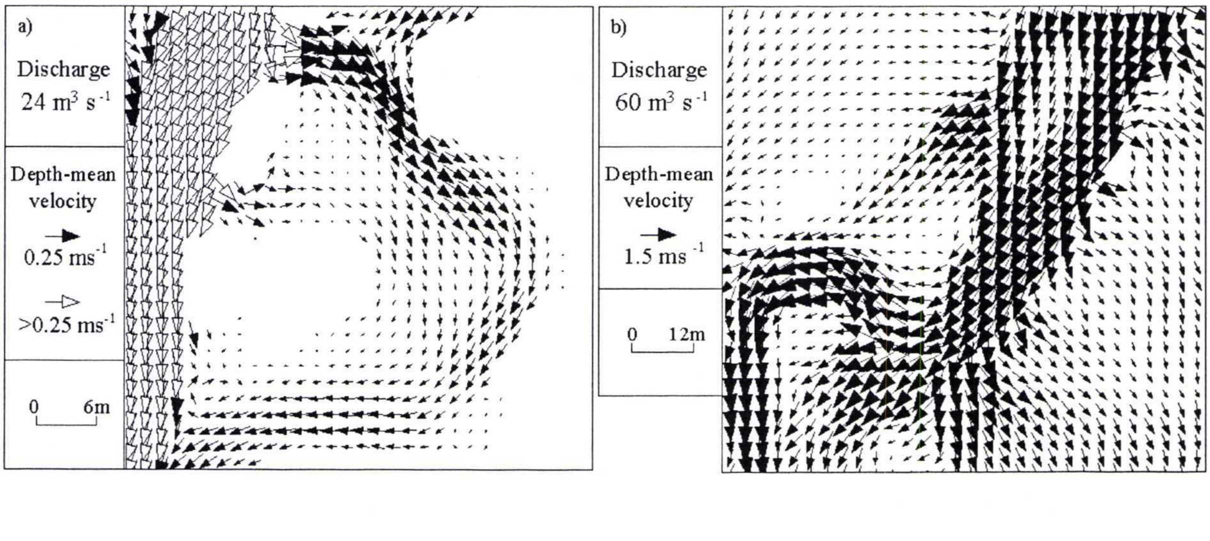
Introduction

Recent research has lead to greater awareness of the role of lowland floodplains as suspended sediment sinks and demonstrated the complexity of relationships between floodplain morphology and rates and patterns of medium-term overbank deposition (Walling and He, 1997). This relationship undoubtedly reflects the interactions between topography, hydraulics and sedimentation. However, to date most research into these processes has been conducted in compound channel laboratory flumes that are characterized by simplified geometry and surface roughness. In contrast, relatively little progress has been made in understanding the mechanics of overbank flow and suspended sediment transport on natural floodplains. This situation can be attributed to the difficulty of obtaining representative spatially-distributed data during floods, a problem which stems in part from the obvious logistical constraints, and also from the complexity of natural floodplain topography and boundary roughness. Computational Fluid Dynamics (CFD) models may provide an alternative means of investigating process interactions in these environments (e.g. Nicholas and McLelland, 1999; Nicholas, 2002). However, model validation and interpretation require data quantifying three-dimensional mean and turbulent flow characteristics and suspended sediment concentrations. This paper examines recent developments in these areas and considers the prospects for investigating flow and sedimentation processes using combined modelling and monitoring approaches.

Overbank hydraulics

Two-dimensional hydraulic models that solve the shallow water equations have been used to simulate floodplain flows in a range of environments (Hervouet and Van Haren, 1996; Connell et al., 2001). Such models provide distributed information quantifying flow depths and depth-averaged velocities in two horizontal directions, although they necessarily incorporate a simplified representation of surface roughness and turbulence. A higher level of process representation can be achieved using CFD models that solve the three-dimensional Reynolds averaged Navier-Stokes equations. However, such models are not easily applied to natural floodplains since the majority do not predict the position of the water surface. Instead this must be specified as a model boundary condition. Three-dimensional models that do predict water surface elevation (and hence inundation extent) generally fall into one of two categories. Either they use procedures that are not suitable for natural floodplain applications, where boundary conditions are complex, or they assume a hydrostatic pressure distribution leading to the prediction of spurious vertical velocities. One way to overcome these problems is to adopt an approach that involves a combination of two-dimensional and three-dimensional modelling. For example, distributed predictions of inundation extent and water surface elevation from a two-dimensional model can be used to specify boundary conditions in three-dimensional CFD simulations.

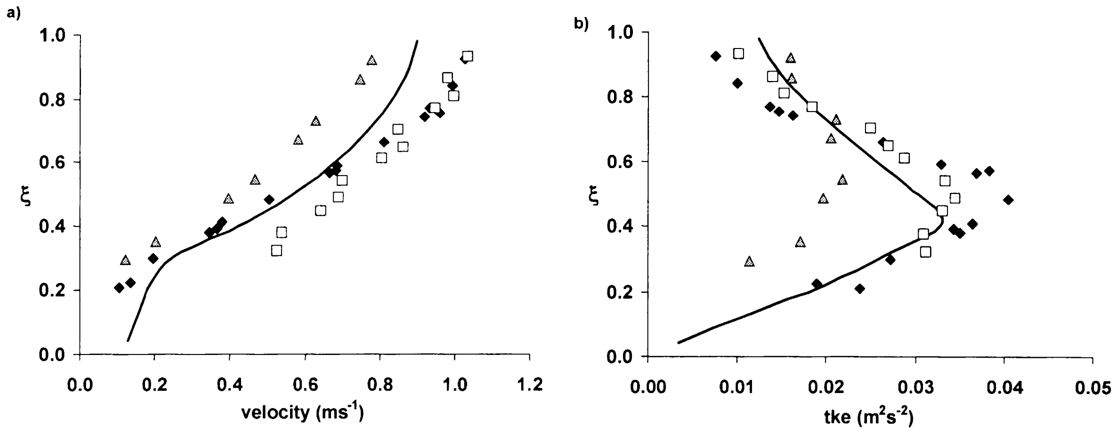
A combined two- and three-dimensional modelling approach was applied to an 800 m reach of the floodplain of the River Culm, Devon, UK. Output from three-dimensional CFD simulations conducted in this way is shown in Figure 1 for selected regions within this site. These results illustrate complex flow patterns that are representative of lowland floodplains in general and are a function of topographic controls operating over a range of spatial scales. During the initial stages of flooding, inundation is confined to low-lying areas within the channel belt (Figure 1a). Velocities are typically low, ponding is common and flow directions are determined by topographic features with spatial dimensions similar to the active channel (i.e. 10-20 m in the case of the Culm). Such features continue to influence flow patterns at higher discharges when the majority of the floodplain is inundated. However, larger-scale topographic controls become increasingly important (Figure 1b), as illustrated by the vectors perpendicular to the channel indicating flow down a pronounced levee on the true left bank of the



channel.

Figure 1: Modelled depth-mean velocity vectors illustrating flow structures at two spatial scales; a) Within a floodplain cutoff (white channel vectors have fixed length for clarity); b) Within a channel meander belt (the river flows from top right to bottom left where it rounds a sharp bend).

Model validation has been accomplished using measurements of mean and turbulent flow characteristics obtained with an array of Acoustic Doppler Velocimeters (ADVs). The ADVs determine three-dimensional velocities at frequencies of up to 100 Hz by measuring the phase shift in the acoustic reflections from scatters in a small sampling volume located 0.05 m from the probe head. These data allow the calculation of all Reynolds stress components and the turbulent kinetic energy. Figure 2 shows an example of modelled and measured flow profiles from a location on the levee back-slope on the left of the channel. Velocity profiles exhibit strong shear at a relative depth of approximately ξ = 0.2-0.3, and a relationship between velocity and height above the floodplain surface that is approximately linear over the central 50% of the profile (most notably in the case of the field data). Turbulent kinetic energy profiles exhibit a clear peak at ξ = 0.4-0.5. These trends contrast with those observed for two-dimensional open channel flows where velocities generally fit the logarithmic 'law of the wall' and peak turbulence intensities occur near the bed (Nezu and Nakagawa, 1993). These differences reflect the role of floodplain surface vegetation and micro-scale topography, both of which contribute to hydraulic roughness that acts within a layer that typically occupies the lower 20-30% of the water column for the shallow flows considered here. In the CFD model a sink term is added to the momentum equation at cells within the vegetation layer to simulate these effects. Figure 2 illustrates that this approach successfully replicates the shape of both velocity and turbulent kinetic energy profiles monitored in the field. However, measured flow characteristics exhibit substantial local variability over distances of a few metres that is not reproduced by the model. This reflects the existence of subgrid-scale topographic variability on the natural



floodplain surface and its influence on local flow characteristics.

Figure 2: Modelled (lines) and monitored (symbols) velocity and turbulent kinetic energy profiles for three floodplain locations within 3m of one another.

Clearly, hydraulic flow structures on natural floodplains are influenced by topographic controls that act at spatial scales covering at least 3-4 orders of magnitude. While CFD models have the potential to generate accurate spatially-distributed predictions of flow characteristics in these environments, they are not yet able to simulate the effects of topographic roughness at all scales. These issues of process representation and subgrid-scale roughness parameterization can only be addressed with the aid of three-dimensional hydraulic data sampled at an appropriate spatial resolution. ADVs appear to provide an effective instrument for obtaining these data in overbank flows.

Suspended sediment transport

Several studies have developed models that solve two-dimensional advection-diffusion equations to simulate suspended sediment transport and deposition processes on lowland floodplains (e.g. Nicholas and Walling, 1997; Middlekoop and Van der Perk, 1998). Such approaches have also been extended to three dimensions (e.g. Tsujimoto *et al.*, 1994; Fang and Wang, 2000), although to date this work has concentrated mainly on in-bank and compound channel flows. This situation probably reflects the difficulties noted earlier that are experienced when applying three-dimensional flow models to natural floodplains. Implementation of a combined two- and three-dimensional hydraulic modelling approach goes some way towards solving these problems.

Output from the CFD simulations described above were used within a new three-dimensional suspended sediment transport model to investigate the relationships between floodplain morphology, overbank flow structures and sediment dispersion and deposition. Figure 3 shows patterns of simulated depth-integrated suspended sediment concentration within the study reach for a single sediment size fraction (63 μm) at an intermediate flood discharge. Sediment concentrations decline with distance from the channel at rates that vary with local flow characteristics. The latter control both the relative importance of advective and diffusive sediment transport mechanisms and rates of sediment deposition. Previous theoretical and flume based research has emphasized the role of sediment diffusion driven by turbulent vortices at the main channel-floodplain interface (James, 1985; Pizzuto, 1987). However, simulation results suggest that suspended sediment transport on natural floodplains is dominated by advection (as illustrated in Figure 3 by sediment plumes along major flow paths). Diffusive mechanisms are less significant except where advective currents are weak and turbulence intensities are high (e.g. at ponded sites that are separated from the main channel by well developed shear layers).

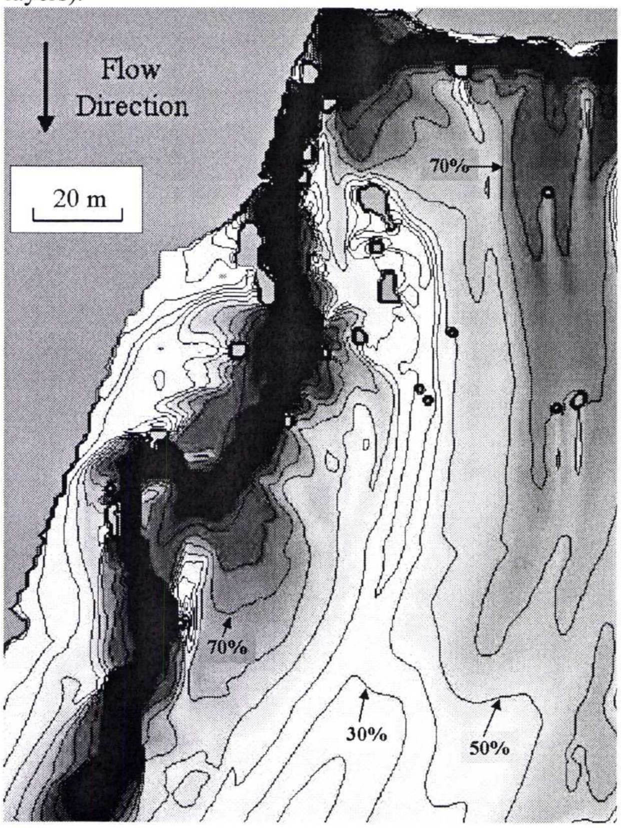
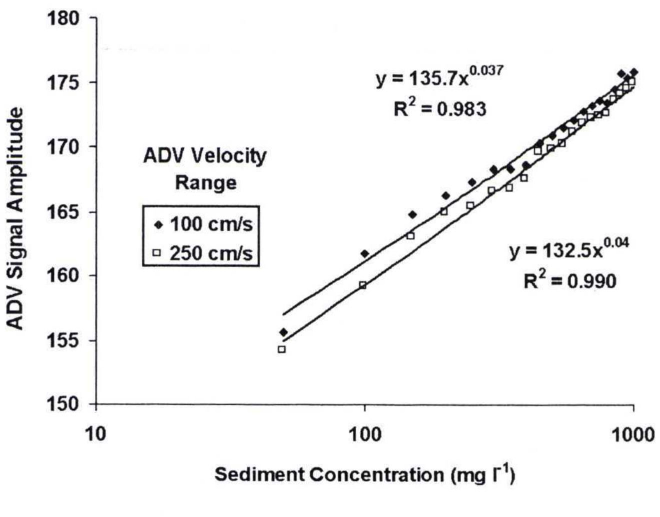


Figure 3: Modelled patterns of depth-integrated sediment concentration (63 μm size fraction) as a % of main channel value (10% contour interval).

Comparison of modelled and monitored flow characteristics with theoretical threshold conditions for sediment deposition illustrate that three-dimensional models have clear advantages over depth-averaged approaches. For example, depth-averaged velocities and turbulence intensities appear, in general, to be sufficient to prevent deposition over the majority of the floodplain. However, estimates of deposition rates derived using Caesium-137 illustrate that most floodplain areas experience net sedimentation. This observation is consistent with the fact that previous applications of depth-averaged suspended sediment transport models have identified a need to use relatively high values of the critical shear for deposition in order to optimize model performance (Middlekoop and Van der Perk, 1998) or have neglected the role of threshold flow conditions (Nicholas and Walling, 1997). Although such models have the potential to generate realistic predictions of sedimentation rates and patterns, they clearly provide a limited representation of the mechanics of fine sediment deposition. Vegetation plays an important role in controlling these processes, both by trapping sediment (Elliott, 2000) and promoting reduced mean and turbulent velocities within the vegetation layer (Figure 2). Three-dimensional sediment transport models are able to simulate both of these effects, while also incorporating vertically-distributed representations of flow and settling processes. Consequently, they provide greater physical realism and offer the prospect of an improved quantitative understanding of flow-sediment-vegetation interactions.



Validation of the numerical model has been accomplished with sediment concentration estimates obtained using Optical Backscatter Sensors. There is also some prospect for obtaining sediment concentration data using the ADV (see Figure 4). This technique has the advantage that flow and sediment data are obtained at the same points in time and space. However, the relationship between sediment concentration and ADV signal amplitude is

also a function of the instrument configuration and sediment characteristics.
Figure 4: Relationship between suspended sediment
concentration and ADV signal amplitude.

Future progress

Preliminary results suggest that three-dimensional models provide a realistic, near physically-based framework for investigating flow and sediment transport processes in natural floodplain environments that are characterized by complex boundary conditions. Consequently, they can be viewed as offering a solution to the problems inherent in monitoring these processes during floods. Despite the prospects for modelling natural floodplains, many issues require further attention. These include choice of turbulence closure, calibration of spatially-variable boundary roughness, representation of dynamic aspects of floodwave propagation, and parameterization of sediment-vegetation interactions. Furthermore, model results highlight a need for high resolution, three-dimensional measurements of flow and sediment concentration. These data are required to assist model calibration and validation, quantify small-scale variability in model variables, and evaluate the extent to which parameterization schemes provide a realistic representation of subgrid-scale processes.

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Monitoring of bed load transport by use of acoustic and magnetic device

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The high energy and active morphodynamic environment associated with mountain streams introduce important technical constraints in the application of classical techniques to measurements of bed load transport. Direct classical methods for investigating bed load transport are for the most part expensive to apply, in terms of both equipment and manpower requirements. As a result, most studies applying such methods have addresses very limited objectives and involving short periods of records. In addition, it is difficult to use short-term monitoring in the interpretation of longer-term sediment yield and contemporary fluvial system changes. Most attention has centred on bed load versus suspended load because this determination is important to subsequent evaluations of transport rates. Studies of sediment transport indicate, that bed load constituting a substantial part of the total load and is generally much more important than suspended load in forming and changing the channel system of a mountain stream.

Direct measurements particularly during floods are extremely difficult because of many problems such as high flow velocity, large quantities of sediment, the wide range of grain size and dangerous field conditions. Any sampler placed in the flow may perturb local hydraulics conditions. Numerous studies have attempted to measure bed load using acoustic device (e.g. Bedeus & Ivicsics, 1964; Tywonivk & Warnock, 1973; Richards & Milne, 1979; Froehlich, 1982; Bänzinger & Burch, 1990; Rickenmann, 1994). Geomorphologists and hydrologists are constantly seeking improved methods for measuring bed load transport in order to more accurately quantify sediment yield from drainage basins. Field studies are difficult to compare because of a variety of measurement techniques and sampling procedures. Therefore it is necessary to develop appropriate techniques to monitoring bed load transport in the mountain streams.

The work reported was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where different monitoring techniques of sediment transport have been applied over the past 30 years. The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes. Fluvial processes are dominant, and the channel network is being actively deepened. The extreme floods has a decisive determines the formation of the fluvial system, being a geomorphologically effective event. The armoured surface layer consists of grain sizes with a D_{50} of 55 mm. The coarsest fractions (> 600 mm) of the bed material only becomes mobile during extreme floods. But transport rate and mechanisms of this material are still poorly understood. Little is currently known about large particles moving through the drainage system of catchment basins of different scales.

Grain sizes that normally move as bed load are transported at high rates during extreme flood as part of the suspended load. During low and intermediate magnitude flood events, when a stream is not competent to transport the coarser fractions of the bed material, the finer, mobile fractions are selectively removed from the active layer. When the tractive force is larger than the critical value for the maximum grain size, all fractions are transported.

In instrumented catchment of Homerka stream bed load transport is measurement using the acoustic and magnetic methods. The Homerka stream draining a catchment area of 19.6 km^2 with a longitudinal slope of 53,3 ‰, mean discharge of 0.350 $m^3 s^{-1}$, annual flood discharge of 9.15 $m^3 s^{-1}$ and a mean annual rainfall of 909 mm. Diverse bed load transport along the Homerka stream is associated with differing sediment supply developing in response to bedrock erosion, bed armouring and hillslope mass movements.

The acoustic device was made by author and has been installed at gauging station of Bacza stream, which is tributary of Homerka stream. It enables the continual detection of coarse particle movement during flood events as indicator of the magnitude of bed load movement. Early experimental investigations started in 1972 and an upgraded recording system has been working since 1975. In the past 29 years, 75 events have been recorded.

The acoustic device consists of a three steel-pipes with a microphones placed horizontally on a bed channel, a signal processing unit, oscilloscopes, recorders and a computer. These recording systems have been installed in a straight reach in the lower part of the stream. This type of sensor does not interfere with the natural hydraulic conditions. Each steel-pipe has 6 m in length and 42 mm diameter and have been installed on bed channel at 10 m distance from each other. Each microphone is a small capacitive one and has a flat frequency response from 20 Hz to 35 kHz. Author tested different microphones as also different diameter of pipes both steel and plastic.

The microphones catches sound (acoustic waves) transferred through the pipes after its generation due to percussion of gravels. The acoustic noise has a frequency in the range from 20 Hz to 60 Hz. The signal-processing unit have a low frequency amplifier and six noise filters. Data logging system are based on the recording current signal whose amplitude is a measure. Power is supplied from external high-capacity lead-acid batteries connected to power. The above device is still experimental and has their own advantages and disadvantages.

The relationship between water discharge and rate of bed load transport is analysed from the continuous recording of water discharge and the continuous measurement of acoustic signals of coarse sediment. In general, sound intensity increases with transport rate and the frequency of sound is inversely proportional to the diameter of the moving particles. The pattern of signals has a complicated hierarchic system reflecting bed load transport pulsed nature and noise. The initiation of sediment particle movement is an important factor of the bed load transport process. There were observed different threshold discharge, the passing of which causes initial motion of bed load.

The transport rate increases rapidly and achieves its maximum value very soon after an increase in the magnitude of the flow renders the bed unstable. The threshold discharge varies during each flood events. It is possible to recognise the discharge threshold for initiation motion of the bed load transport during the rising limb of flood and the second one, during the falling limb, which sediment transport stops. In general, bed load transport reaches a peak more rapidly than the discharge. For a given flood discharge, intensity of bed load transport vary according to whether they are associated with the rising or the falling stage. This is reflected in the shape of the loop describing the discharge and bed load transport relationship (e.g. Froehlich, 1982; Schöberl, 1991; Rickenmann, 1994; Moog & Whiting, 1998). Each flood is characterized by a loop with a different shape in a manner similar to the hysteresis curve analogous as suspended sediment load (Froehlich, 1982). The device also has a possibility of estimating the amount of discharge of bed load. Calculation of the amount of bed load moved it be bases on periodic surveying or emptying of the sedimentary basin on above concrete weir and drop dam. The particle size distributions of the sediment were determined using large sieve.

Usually more bed load was transported by discharges preceding the first annual occurrence of a threshold rate of initial motion. A very important role is played by the sequence of floods and interarrival time. The role of the relaxation time has still been poorly understood.

Applications of the magnetic tracer technique allow to obtain the fractional bed load transport rate, in compliance with the grain fractions, transported during flood (e. g. Ergenzinger & Conrady, 1982; Ergenzinger & Custer, 1983; Hassan et al., 1984; Reid, et. al., 1984; Ergenzinger, et al., 1994;). The first continuous measurement of the passage of naturally magnetic coarse material bed load transport was done by Ergenzinger and Custer (1982).

Coarse material bed load transport is measured at Homerka stream at use magnets cemented into holes drilled into gravels and an electromagnetic device that acts like as a classical metal detector. The system was made by author and has been installed at gauging station of the Homerka stream. Early experimental investigations started in 1982. The device consists of a two elongate magnetically sensitive coils (copper windings on an iron core), each of 4 m length. Coils have been installed across bed channel at 30 m distance from each other. The motion of traced gravels during a flood is registered by their passage over the coil, which affects the magnetic field causing a change in the inductance of the coils. According to the Faraday principle a voltage peak is induced and the signal is detected, amplified and transmitted to a receiver and then to recorder. The median bed material in the experimental reach is 64 mm in size. Different size of magnets are inserted to different sizes of gravels and protected with epoxy. A paint cover helps to visually identify the traced coarse particles on the stream channel. After every flood gravels were searched with a portable metal detector and reseeded**.** Recovery rates range from 12 to 85%.

Transfer of gravel particles through the Homerka channel system appeared to be influenced by flood magnitude and duration. The first event after the injection of the traced gravels into the channel may not representative. It is almost not possible to relocate labelled particle in the exactly identical position it had occupied prior to treatment. The transport distances of single traced gravels range from 5 - 140 meters during annual flood. The small gravels have significantly lower transport lengths than the larger particles.

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Continuous monitoring of suspended sediment in rivers by use of optical backscatterance sensors

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Oceanographers began to commonly use optical sensors for measuring turbidity or suspended-sediment concentration (SSC) in the 1980s on the continental shelf, in nearshore waters, and in estuaries (Sternberg 1989). Optical sensors transmit a pulse of light and measure the intensity of light transmitted, scattered 90°, or backscattered 180°, depending on sensor design. The sensor processes the signal so that its output is in units of turbidity or is proportional to SSC if the particle size and optical properties of the sediment remain fairly constant. Calibration of the sensor output voltage to SSC will vary according to the size and optical properties of the suspended sediment; therefore, the sensors must be calibrated in the field or a laboratory using suspended material from the field. If the optical window is fouled by biological growth or debris, the sensor output is invalid.

Use of optical sensors in rivers for continuous monitoring of suspended sediment is becoming more common in the United States and a workshop on the topic was held in spring 2002 (Glysson & Gray 2002). The primary reasons for increased continuous monitoring are regulatory requirements of the U.S. Clean Water Act and improved technology for real-time monitoring for environmental, drinking water, and public health needs.

The purpose of this abstract is to demonstrate that optical backscatterance sensors (OBS, Downing *et al.* 1981) successfully can monitor suspended sediment in rivers if the effects of particle size do not preclude sensor calibration. The issue of the effects of particle size on OBS is addressed first, followed by an example calculation of suspended-sediment discharge with an OBS. This abstract updates a previous paper on this subject (Schoellhamer 2001).

PARTICLE-SIZE EFFECTS

The relationship between SSC and sensor output is dependent on particle size, which can confound calibration of a sensor. In estuaries like San Francisco Bay, particle size is fairly constant and sensor calibrations are remarkably invariant with time (Buchanan & Ruhl 2001). In channels with a variable suspended particle size, however, sensor output depends on particle size and SSC. Finer sediment has more reflective surfaces per unit mass, so, for constant SSC, sensor output increases as the suspended sediment becomes finer. Particle-size effects on OBS were minor in the Sacramento River at Freeport, California, but were more pronounced in the Colorado River at Cisco, Utah.

Freeport

Flow at Freeport is unidirectional but is affected by tidal backwater during low discharge. An OBS was installed to measure the effect of tidal fluctuations and flood pulses on suspended-sediment discharge and, therefore, sensor output was calibrated to discharge-weighted, cross sectionally averaged SSC. Point OBS measurements have been collected continuously near the right bank of the river every 15 minutes at 3 feet above the bed beginning in July 1998. The sensor was cleaned every 1-8 weeks. The linear equation for SSC, as a function of sensor output (fig. 1), was determined using the robust, nonparametric, repeated median method (Buchanan &

Ruhl 2001). Scatter of the calibration data is caused by comparing a point OBS measurement with a cross sectionally averaged SSC, particle-size effects, and any other source of error including possible effects of water and sediment color, bubbles, plankton, and organic sediment.

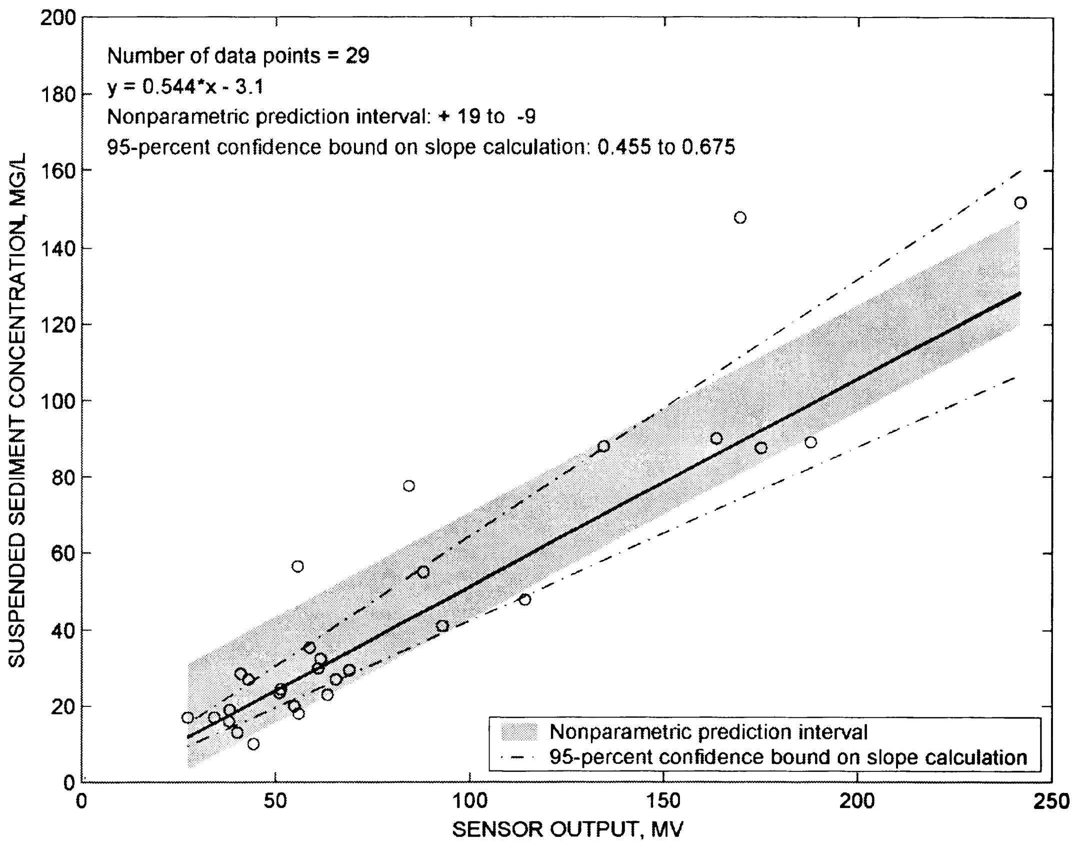

Figure 1. Calibration of an OBS at Freeport, Sacramento River, California, water years 2000 and 2001. Mg/L, milligrams per liter; mV, millivolts.

Particle-size variations had only a small effect on the calibration of the OBS at Freeport. The output of an OBS is virtually zero when SSC is zero, so the ratio of concentration to voltage (C/V) for any data point is approximately equal to the slope of a calibration line through that point. At Freeport, the fraction of fine sediment ranged from 49 to 98 percent and C/V decreased slightly as the fraction of fine sediment increased, but with considerable scatter (fig. 2).

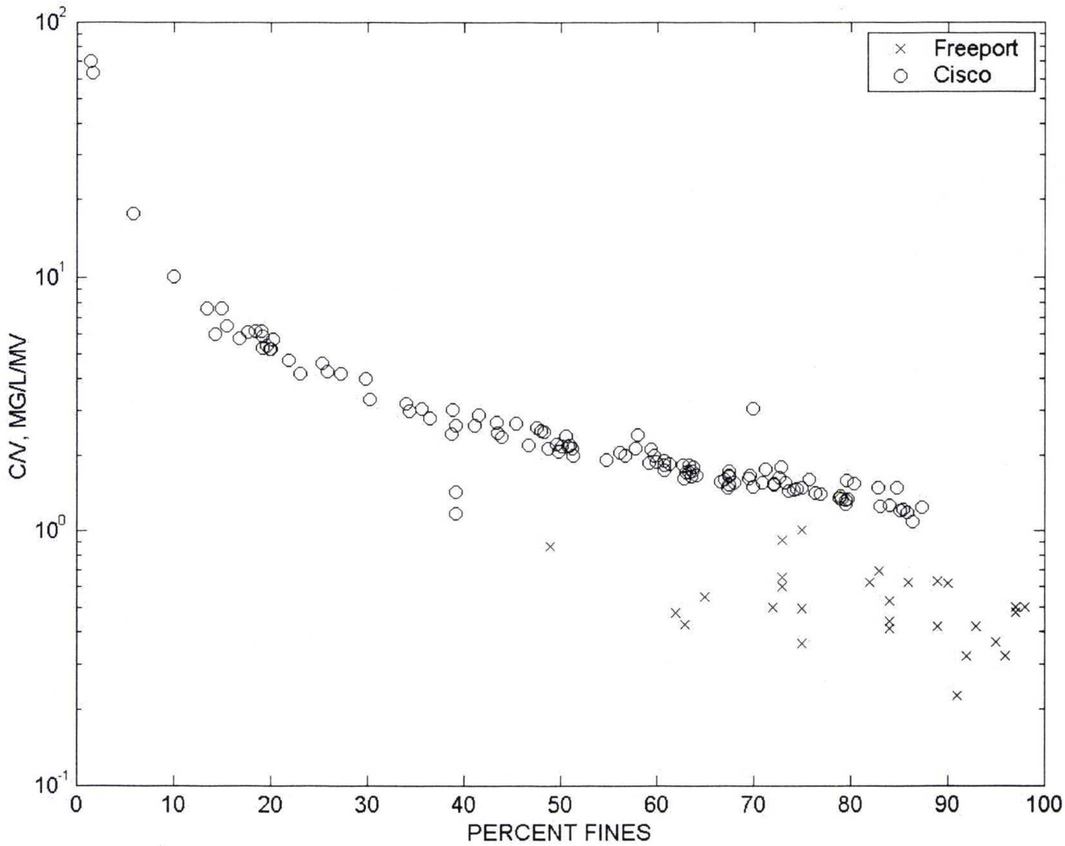

Figure 2. Ratio of suspended-sediment concentration to voltage (C/V) as a function of the fraction of fine sediment, at Freeport, California, on the Sacramento River and Cisco, Utah, on the Colorado River. C/V for any data point is approximately equal to the slope of a calibration line through that point. A different OBS was used at each site and each OBS has slightly different optical characteristics, so the difference in the trend of C/V should be compared between the two sites, not the absolute value of C/V. Mg/L/mV, milligrams per liter per millivolt.

Cisco

Vertical profiles of OBS measurements and suspended sediment were collected from the Colorado River near Cisco, Utah, from May 10-12, 1995. While measuring vertical profiles at 3 stations, 118 pairs of point OBS measurements and suspended-sediment samples were collected from near the bed to near the water surface with an OBS attached to the side of a US P61 suspended-sediment sampler (Edwards & Glysson 1999) close behind the nozzle. Near the bed almost all of the suspended sediment was sand, and very little suspended sand was near the surface. SSC ranged from 480 to 40,000 mg/L.

Particle-size variation precluded successful calibration of the OBS at Cisco. As the fraction of fine sediment increased from 1 to 87 percent, C/V decreased exponentially by almost two orders of magnitude (fig. 2). The Cisco data have less scatter than the Freeport data because the Cisco OBS was very close to the nozzle of the point sampler, whereas the Freeport OBS was near the right bank and the samples were collected over the entire cross section.

CALCULATION OF SUSPENDED-SEDIMENT DISCHARGE

The calibrated OBS on the Sacramento River at Freeport has been used successfully to measure suspended-sediment discharge. Output from the sensor was converted to a time series of discharge-weighted, cross sectionally averaged SSC and the calibration line is shown in figure 1. This concentration is multiplied by the water discharge measured hourly by a calibrated ultrasonic velocity meter (Anderson *et al.* 2001) to calculate the suspended-sediment discharge.

The hourly suspended-sediment discharge from the OBS compares well with daily suspended-sediment discharge from a sediment station operated by the U.S. Geological Survey at Freeport (fig. 3, Anderson *et al.* 2001). Thus, the output of the OBS can be used as an index value that is calibrated to cross sectionally averaged SSC and multiplied by discharge to determine the suspended-sediment discharge.

The primary advantage of optical sensors is better temporal resolution, compared to a typical daily sediment station. The primary disadvantage of optical sensors is fouling, as only 52 percent of the Freeport OBS data were valid due to fouling. More frequent cleaning and self-cleaning sensors can reduce the effect of fouling. Despite fouling, the OBS made 50 times more successful measurements than the daily station, providing the ability to monitor sediment pulses on the order of hours rather than days.

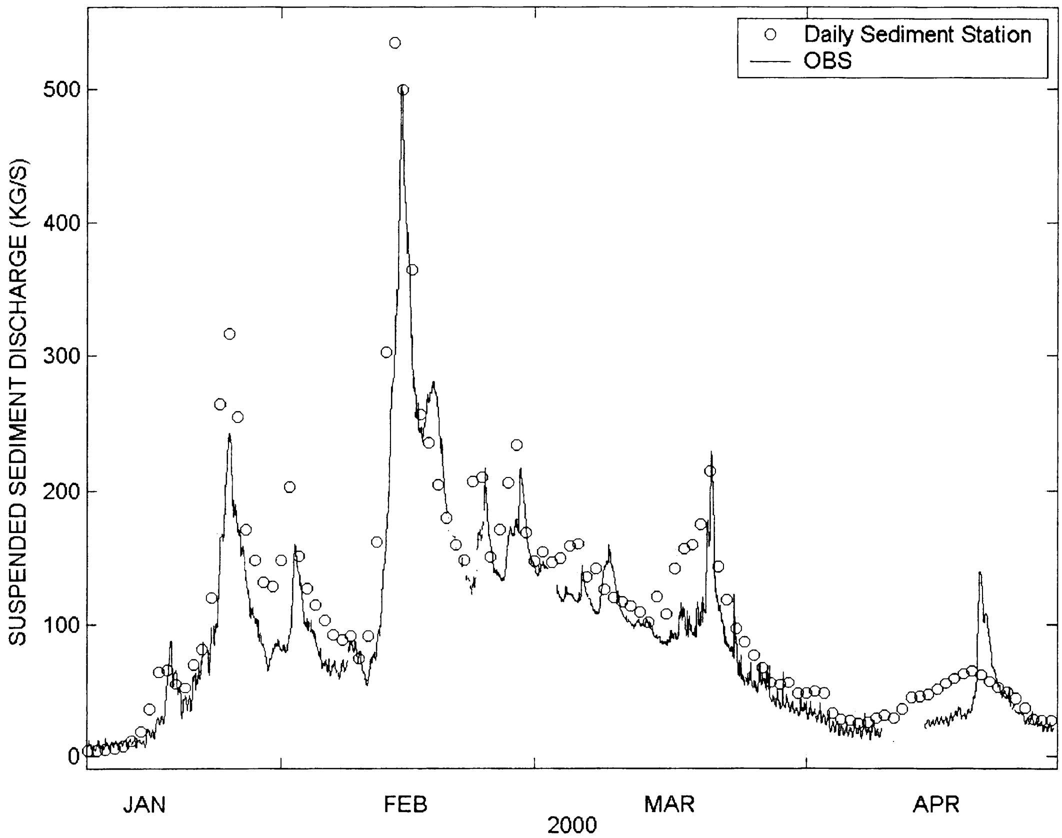

Figure 3. Suspended-sediment discharge at Freeport, Sacramento River, California, January - April 2000. Sediment station data are daily (Anderson *et al.* 2001) and optical backscatterance sensor (OBS) data are hourly. Kg/S, kilograms per second.

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Using environmental radionuclides as tracers in sediment budget investigations

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INTRODUCTION

The use of fallout or environmental radionuclides to trace and quantify the mobilisation, transfer and deposition of sediment in catchments can be traced back to the 1960s and to work such as that reported by Rogowski & Tamura (1965). In this early work, attention focussed on the mobility and fate of radioactive fallout from weapons testing from a health or radioecological perspective. Such work demonstrated that radionuclides such as caesium-137 (^{137}Cs) were rapidly and firmly fixed by the surface soil and that their subsequent mobilisation and transfer were effectively controlled by the erosion and transport of soil and sediment particles. The potential to exploit this feature of radionuclide behaviour to trace and quantify sediment movement was soon recognised by workers such as Ritchie and McHenry and their co-workers (e.g. Ritchie et al., 1970, 1973) who successfully used ^{137}Cs to estimate rates of soil loss from agricultural land and sedimentation rates in lakes, reservoirs and wetlands. Since that early work, ^{137}Cs has been successfully used in soil erosion studies in many areas of the world. The approach has also been extended to include other radionuclides, such as beryllium-7 (^{7}Be) and unsupported or excess lead-210 ($^{210}Pb_{ex}$) and to embrace various sediment budget components including, for example, floodplain sedimentation. Such work has increasingly demonstrated the potential for using fallout radionuclides as an essentially unique tool in sediment budget investigations.

THE BASIS

The fundamental basis for using environmental radionuclides in sediment budget investigations is that over a relatively small area their fallout input, which will be largely associated with rainfall, can be assumed to be effectively uniform. In most environments, this fallout is rapidly and firmly fixed by the surface soil and subsequent redistribution of the fallout input will therefore reflect the redistribution of soil and sediment particles in the landscape. Measurements of the distribution of the radionuclide within the landscape and its activity levels in sediment moving through the landscape can thus be used to derive estimates of rates of sediment redistribution and to trace the source of mobilised sediment. In this way, it is possible to obtain spatially distributed information on soil and sediment redistribution within the landscape and to use a common or integrated approach to investigate several components of the catchment sediment budget.

To date, most studies involving environmental radionuclides have focused on the use of ^{137}Cs, but increasing attention has been given to the use of alternative radionuclides, and more particularly $^{210}Pb_{ex}$ and ^{7}Be. Each of these fallout radionuclides is characterised by a different origin, fallout record and half-life and thus offers different opportunities for use as a tracer. Caesium-137 is an artificial radionuclide, originating primarily from nuclear weapons testing, and thus its fallout has varied markedly through time. Fallout was first detected in the early 1950s, reached a peak in the early 1960s prior to the Nuclear Test Ban Treaty, and rapidly declined to very low levels by the mid 1970s. In some areas of Europe and adjacent regions, significant further short-term inputs were received in 1986 as a result of the Chernobyl accident. This time variable input represents an important characteristic in many applications of ^{137}Cs measurements, for example in establishing the chronology of sediment deposits and thereby estimating sedimentation rates. Caesium-137 fallout is also characterised by significant spatial variability at the global scale, reflecting control by both location in relation to the nuclear weapons tests and global stratospheric circulation patterns and the magnitude of annual precipitation. Fallout inventories in some equatorial areas and throughout much of the southern hemisphere are almost an order of magnitude less than in the northern hemisphere, where most of the early work in developing the potential of ^{137}Cs measurements was undertaken. These reduced inventories introduce some constraints on the potential for using ^{137}Cs measurements in different areas of the world. With a half-life of 30.2 years, ^{137}Cs is relatively long-lived, although in the absence of further significant fallout, existing inventories will necessarily decline through time, making measurements increasingly difficult or unreliable in areas with low inventories.

In contrast to ^{137}Cs, $^{210}Pb_{ex}$ is of natural geogenic origin, being a natural product of the ^{238}U decay series, with a half-life of 22.3 years. It is derived from the decay of gaseous ^{222}Rn, the daughter of ^{226}Ra. Radium-226 occurs naturally in soils and rocks and will generate ^{210}Pb that will be in equilibrium with its parent. Upward diffusion of a small quantity of the ^{222}Rn from the soil introduces ^{210}Pb into the atmosphere and its subsequent fallout provides an input of this radionuclide to the soil surface that is not in equilibrium with its parent ^{226}Ra. This fallout component is commonly referred to as 'unsupported' or 'excess' ^{210}Pb, since it cannot be accounted for (or supported by) decay of the in-situ parent. Again in contrast to ^{137}Cs, the fallout input of $^{210}Pb_{ex}$ is essentially constant through time, and, by virtue of this contrasting behaviour, $^{210}Pb_{ex}$ frequently offers a useful complement to ^{137}Cs in many applications. Much less is known about the global pattern of $^{210}Pb_{ex}$ fallout, but the magnitude of fallout inputs are known to reflect both the magnitude of the annual precipitation and location on the continental land masses in relation to the prevailing winds. In some locations where ^{137}Cs activities are low due to low fallout receipt, $^{210}Pb_{ex}$ activities may be significantly higher and this radionuclide could therefore provide an alternative to ^{137}Cs in areas with low ^{137}Cs inventories.

Beryllium-7 is also of natural origin, but unlike $^{210}Pb_{ex}$, its origin is cosmogenic and it is produced in the upper atmosphere by cosmic ray spallation of nitrogen and oxygen. In contrast to ^{137}Cs and $^{210}Pb_{ex}$, the half-life of ^{7}Be is very short (53.3 days) and it therefore offers considerable potential for investigating soil and sediment redistribution over much shorter time periods (i.e. days rather than decades).

SOME EXAMPLES

In order to demonstrate the potential for using environmental radionuclides in sediment budget investigations, several examples can be usefully introduced. These relate to, firstly, quantifying rates and patterns of erosion and soil redistribution on catchment slopes and estimating sediment delivery ratios, secondly, quantifying rates and patterns of overbank deposition on river floodplains and estimating the associated conveyances losses, thirdly, establishing the relative contribution of different sources to the suspended sediment output from a catchment, and, finally, the synthesis of such results to construct a catchment sediment budget.

Quantifying rates and patterns of erosion and soil redistribution on catchment slopes

The results of using ^{137}Cs and ^{7}Be measurements to quantify both short- (i.e. several events) and longer-term (i.e. ~ 45 years) rates of soil erosion and redistribution within a 6.7 ha cultivated field at Higher Waltham Farm near Crediton, Devon, UK (cf. Walling et al., 1999), provide a useful example of the potential to document both rates and patterns of erosion within small areas. By focusing attention on an individual field, it is possible to assess the gross and net erosion from the area and to thereby estimate the sediment delivery ratio. The ^{7}Be measurements were used to investigate the erosional response of the field under relatively extreme conditions, when a period of heavy rainfall coincided with the field being bare and compacted after the maize harvest. The resulting estimate of net soil loss for this short period (2.5 kg m^{-2}) was substantially greater than the longer-term mean value based on ^{137}Cs measurements (0.48 kg m^{-2} $year^{-1}$), although the associated sediment delivery ratios were very similar at 0.80 and 0.83 respectively.

Results such as those illustrated above require a dense network of sampling points and equivalent information is unlikely to be available for even a relatively small catchment. It is therefore necessary to devise sampling strategies capable of generating representative data that can be extrapolated to an entire catchment. A simple approach was used by Walling et al. (in press) to derive estimates of soil redistribution rates on the slopes of a 63 km^2 catchment in southern Zambia. In this case, representative transects were used to characterise sediment redistribution on the slopes under three contrasting land use types, namely, commercial cultivation, communal cultivation and bush grazing. Caesium-137 inventories are low in this region of Southerm Africa, and measurements of both $^{210}Pb_{ex}$ and ^{137}Cs were used to establish these sediment budgets, both as a means of validating the two approaches and to obtain additional information on medium-term changes in erosion rates. Since $^{210}Pb_{ex}$ fallout can be considered to be essentially constant through time, whereas that of ^{137}Cs occurred primarily between the late 1950s and the mid 1970s, comparisons of the results provided by the two radionuclides can provide information on changes in erosion rates through time.

Quantifying rates and patterns of overbank deposition on river floodplains and estimating conveyance losses

Measurements of the ^{137}Cs or $^{210}Pb_{ex}$ content of a sediment core collected from a river floodplain afford an effective and reliable means of estimating the sedimentation rate at that point (cf. He & Walling, 1996; Walling & He, 1997). Collection of a substantial number of cores from a floodplain reach in turn provides a means of investigating the spatial pattern of deposition and the influence of such factors as distance from the channel, depth of inundation and the local microtopography (cf. Walling & He, 1998). Since the estimates of sedimentation rate derived from ^{137}Cs measurements relate to the past ca. 40 years, whereas those based on $^{210}Pb_{ex}$ measurements relate to a longer period (e.g. ca. 100 years), it is also possible to investigate changes in sedimentation rates over the recent past (cf. Walling & He, 1999). Use of ^{137}Cs and $^{210}Pb_{ex}$ measurements to document rates and pattern of overbank sedimentation within a short reach of the floodplain of the River Severn at Buildwas, UK showed a close relationship between the microtopography and the sedimentation rate. The estimated mean sedimentation rate for this site over the past 40 years was 0.28 g cm^{-2} $year^{-1}$, whereas the equivalent rate for the past 100 years was 0.33 g cm^{-2} $year^{-1}$. This suggests that the sedimentation rate at this site has decreased towards the present. Collection of cores from representative sites on the floodplains of 21 rivers in the UK has permitted a more wide-ranging comparison of estimates of recent sedimentation rates provided by ^{137}Cs measurements with the longer-term values provided by ^{210}Pb measurements. In this case floodplain sedimentation rates estimated from the ^{137}Cs measurements ranged between 0.04 and 1.22 g cm^{-2} $year^{-1}$, whereas those based on $^{210}Pb_{ex}$ measurements ranged between 0.04 and 1.42 g cm^{-2} $year^{-1}$. By comparing the two estimates for each site, it was found that sedimentation rates have remained relatively constant over the past 100 years, although evidence of decreasing sedimentation rates was found at 11 sites, increasing rates at four sites and stable rates at six sites.

Although information on the detailed pattern of overbank deposition rates will be of value in many sediment budget investigations, in some case a more general estimate of the magnitude of the conveyance loss associated with overbank deposition within the floodplain system may be required. In this case there will be a need to extrapolate the findings from individual reaches or cross sections to the entire main channel system. This approach was adopted by the author and his co-workers on the Rivers Ouse and Wharfe in Yorkshire, UK (cf.

Walling et al., 1998). More than 250 sediment cores were collected from 26 representative transects located along the main channel systems of the Yorkshire Ouse and River Wharfe for ^{137}Cs analysis. The estimates of average sedimentation rate for the individual transects were extrapolated to the reaches between adjacent transects and the mean annual deposition flux or conveyance loss associated with overbank deposition on the floodplain bordering the main channel system was calculated. By comparing these losses with the mean annual sediment loads of the rivers, it was possible to establish the relative importance of floodplain storage in the sediment budget of the main channel system. In the case of the River Ouse, floodplain deposition was seen to account for ca. 40% of the total suspended sediment load delivered to the main channel system over the past 40 years. The equivalent value for the River Wharfe was ca. 49%.

Tracing suspended sediment sources

Growing recognition of the many environmental problems associated with fine sediment in river systems has focused attention on the implementation of sediment management strategies. Information on sediment source is of critical importance in developing such management strategies and in identifying and targeting key source areas where control measures should be applied. Sediment source fingerprinting procedures have been shown to possess very considerable potential for providing such information (cf. Walling & Woodward, 1995). The successful application of sediment source fingerprinting procedures relies heavily on the availability of fingerprint properties, which are able to discriminate potential sources. Environmental radionuclides offer considerable potential for discriminating sediment derived from different source types, for example cultivated land, grazing land and channel banks and gullies (e.g. Walling & Woodward, 1992). Because of their fallout source, ^{137}Cs, $^{210}Pb_{ex}$ and ^{7}Be accumulate at the soil surface and their concentrations in mobilised sediment provide an effective means of discriminating between surface and subsurface (e.g. channel bank) sources. Furthermore, because concentrations will be lower at the surface of cultivated land (by virtue of mixing into the plough layer), they also afford a means of discriminating sediment mobilised from cultivated and pasture land. In most current applications of sediment source fingerprinting procedures, composite fingerprints comprising a range of fingerprint properties are used, but environmental radionuclides are frequently included in such fingerprints as a key, if not sole, source indicator. The use of ^{137}Cs to discriminate sediment sources is usefully illustrated by the work of Zhang et al. (1997) in the 3.86 km^2 catchment of the Zhaojia Gully in the rolling loess plateau region of Shaanxi Province, China. In that study, ^{137}Cs concentrations were used to discriminate sediment derived from the rolling plateau and the gully areas and to establish the relative importance of these two sources to the sediment output from the catchment. The results emphasised the importance of the gully areas as the main sediment source and the need to target these areas in any attempt to reduce downstream sediment yields through the implementation of soil conservation and sediment control measures.

Establishing catchment sediment budgets

By providing information on erosion rates and sediment delivery from the slopes of a catchment, sediment source areas and transmission losses associated with overbank deposition on the floodplains bordering the main channel system, results such as those presented above can be integrated with measurements of sediment yield at the catchment outlet to establish a catchment sediment budget. Thus, for example, Walling et al. (2002) were able to construct sediment budgets for two small catchments in Central England and Walling et al. (2001) established a sediment budget for the 63 km^2 Kaleya catchment in southern Zambia. In the latter case, separate sub-budgets were constructed for the slopes under communal cultivation, bush grazing and commercial cultivation and these, along with erosion of channel banks and gullies, accounted for the inputs to the channel system. Conveyance losses of sediment passing through the main channel system were associated with reservoir deposition and overbank sedimentation on the floodplains and the overall sediment delivery ratio from the catchment was estimated to be 9%.

PERSPECTIVE

Traditional monitoring techniques employed for assembling information on catchment sediment budgets possess many limitations in terms of spatial and temporal sampling. Environmental radionuclides offer the potential to overcome many of these limitations. Some key advantages include the following:

1. Provision of spatially-distributed data on sediment redistribution, which are compatible with recent advances in physically-based distributed modelling.
2. Generation of estimates of longer-term average rates avoids the problems of representativeness frequently associated with event-based or short-term data.
3. No major disturbance of the landscape is involved.
4. Estimates of sediment redistribution rates can be obtained on the basis of a single site visit and the need for costly instrumentation and monitoring is avoided .
5. Estimates of sediment redistribution rates based on contemporary sampling are retrospective and data are available immediately rather than after a long period of monitoring.
6. Source fingerprinting data provide spatially integrated results for the entire catchment.

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Automated monitoring of bank erosion dynamics: new developments in the Photo-Electronic Erosion Pin (PEEP) system

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INTRODUCTION

Bank erosion processes are still not well understood or specified in river dynamics and sediment flux models. The field is particularly complicated by the operation of both fluvial and non-fluvial erosion processes in channel systems, the change in bank material erodibility over different timescales which induces complex bank responses to similarly-sized flow events and - the specific focus here - the lack of bank erosion data *at the event timescale.* The main aims here are to: (1) describe recent developments in the Photo-Electronic Erosion Pin (PEEP) automatic erosion monitoring system; (2) demonstrate its potential to establish more clearly the timing of individual bank erosion events, including the concept of *thermal consonance timing* (TCT); and (3) outline the general importance of automatic erosion and deposition monitoring within the fluvial sciences and geomorphology more generally; (4) call for further research to address the outstanding process monitoring challenges.

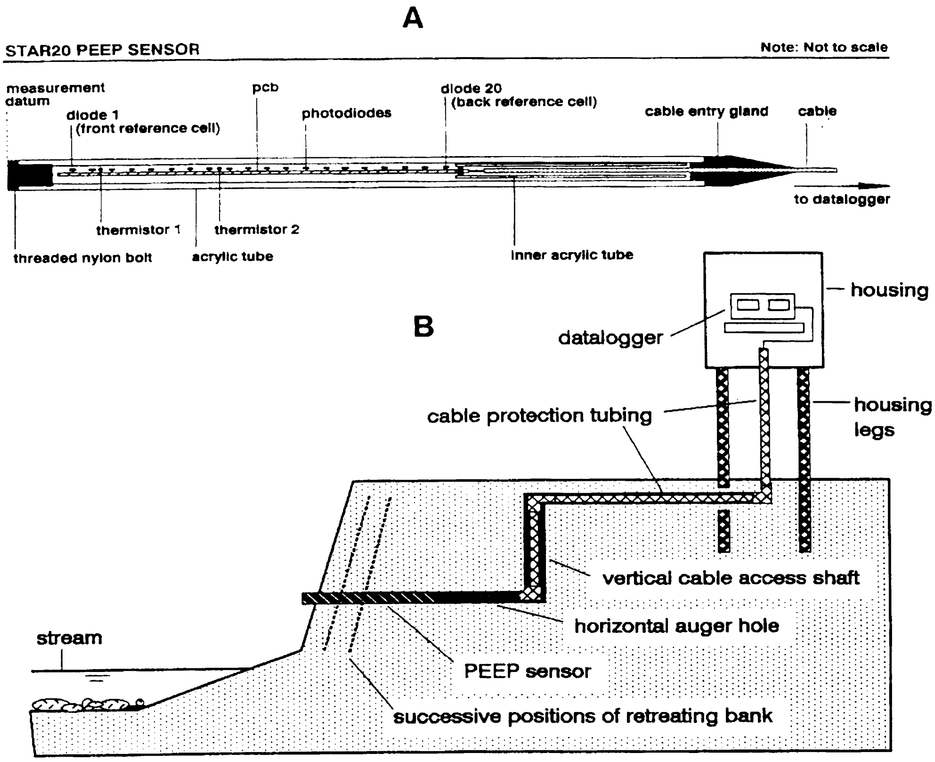
RATIONALE

For the interpretation of contemporary erosional patterns and processes, hydrologists commonly rely on continuous, automatically-monitored data on stage, discharge, precipitation intensity and turbidity, recorded with pressure transducers, automatic raingauges and turbidity meters. However, the erosion and deposition time series themselves are likely to form the weakest part of the investigation. This is because conventional, *manual*, field monitoring methods, typically erosion pins, cross-section resurveys or terrestrial photogrammetry (Lawler, 1993), merely reveal *net* change in the position of a bank or gully surface since the previous measurement. They do not quantify the precise *temporal distribution* of that change. This means that erosion event *timing,* and the precise bank response to *individual* flow or meteorological events, is generally uncertain. Because of the limitations of existing measurement methods, little knowledge has yet emerged of the *dynamics* of bank erosion and deposition *events* at a time resolution comparable to that available for flow and sediment transport rates (Lawler, 1992; 1994). Clearly, bank erosion process explanations and model development and testing will be more securely based when (a) the full episodicity of bank change is detected, including event *timings* and (b) magnitude/timing information for specific erosion and deposition events can be related to continuous information on the temporal fluctuations in the suspected driving forces.

THE PHOTO-ELECTRONIC EROSION PIN (PEEP) SYSTEM

To help address these measurement problems, the Photo-Electronic Erosion Pin (PEEP) system was developed in the early 1990s (e.g. Lawler, 1991, 1994). The PEEP sensor is a simple optoelectronic device containing a row of overlapping photovoltaic cells connected in series, and enclosed within a waterproofed, transparent, acrylic tube of 12 mm I.D. and 16 mm O.D. (Fig. 1A). The sensor generates an analogue voltage proportional to the total length of PEEP tube exposed to light. A reference cell adjusts outputs for variations in light intensity (Fig. 1A). Small networks of PEEP sensors are normally inserted into carefully pre-augered holes in the bank face, and connected to a nearby datalogger set to record PEEP mV outputs at 15-min intervals, though any frequency is possible (Fig. 1B). Most dataloggers are compatible. Subsequent retreat of the bank face exposes more cells to light, which increases sensor voltage output (Fig. 1B). Deposition reduces voltage outputs. Data recovered from the logger thus reveal the magnitude, frequency and timing of individual erosion and deposition *events* much more clearly than has been possible before (Lawler, 1992, 1994).

Figure 1: The Photo-Electronic Erosion Pin (PEEP) erosion monitoring system: (A) The PEEP sensor, which is now extended to 660mm length (200mm active) and includes two reference cells and two thermistors; (B) typical installation of a PEEP sensor and datalogger at a river bank site



Various PEEP designs are possible to suit the application (e.g. bank, gully wall, channel bar, hillslope, cliff, dune, beach).

Laboratory calibration establishes relationships between PEEP outputs and exposed tube lengths. These relationships are encouragingly strong: the position of the sediment surface is generally known with 95% confidence to within $\pm$ 2-4 mm (Lawler, 1992), although low light levels can reduce confidence. Further details of PEEP system measurement principle, design, calibration, installation and applications can be found in Lawler (1991; 1992; 1994; 2001), Lawler et al. (1997a), Prosser et al. (2000) and Stott (1999). Advantages and potential of the PEEP system are listed in Table 1.

Table 1. Advantages and potential of the Photo-Electronic Erosion Pin (PEEP) sensor

Advantages	Potential
* No power needed; PEEP based on solar cells	* Temporal distribution of erosion established more clearly
* Reference cells normalise for light level changes	* Process inference and model testing stronger
* Easy to connect to dataloggers	* Threshold identification more definitive
* Simple and reasonably robust	* Magnitude-frequency analysis more comprehensive
* Temperature and light monitoring capability	* Relation of erosion to sediment dynamics possible
* Sufficiently inexpensive for networks (e.g. 4-8)	* Erosion-warning capability via telemetry systems viable
* Applicable to many erosion/deposition contexts	* Real-time monitoring for research or management

Research is proceeding, however, to address certain limitations of PEEP systems. For example, being a visible-light system, nocturnal events are not detected until the following morning, although temporal resolution is still much better than with traditional manual methods. Data gaps at night can be plugged with programmed bursts of artificial light. Also, as with traditional erosion pins, PEEPs are invasive (although their small size minimises this), and they may be less suitable for gravel materials or for large mass-failure situations. The addition of data transmitters to PEEP sensors will obviate the need for cabling and backfilled access holes (e.g. Fig. 1B). Some PEEP data are occasionally degraded in low-light conditions, or when the bank is covered by snow, snagged vegetation or highly turbid water.

PEEP DESIGN DEVELOPMENTS

The early generation of PEEP sensors were 0.40m long, and were equipped with an array of 10 photovoltaic cells to provide an active length of ~90mm. The PEEP sensors were redesigned in 1996 and 2001 as follows (Fig. 1): (a) sensors were lengthened to 200mm active length and 660mm total length to allow for higher bank retreat rates; (b) a second reference cell was added to permit inverted installation, and to confirm minimum erosion magnitudes for large events; and (c) two thermistors were incorporated to generate bank temperature data at the sediment surface and at 68 mm depth, to help evaluate bank freeze-thaw, desiccation and biological (e.g. vegetation growth) processes. For example, two freeze-thaw events are detected in the bank temperature time series of Fig. 2. Thermistors also allow erosion events to be better timed through the use of *thermal consonance timing* (TCT), as discussed below.

METHODS

Study Area

The bank erosion results reported here derive from the UK Land-Ocean Interaction Study (LOIS) study, 1994 - 2001. The aims of LOIS were to understand the fluxes and dynamics of sediments, contaminants and nutrients from the land surface to the ocean (North Sea) (e.g. Leeks et al., 1997). We focused bank monitoring on the fluvial and estuarine part of the Swale-Ouse-Wharfe river system in northern England from January 1996 - April 1998. This paper concentrates mainly on the R. Wharfe PEEP site at Easedike in Yorkshire, for which flow and suspended sediment concentration data are available from Tadcaster, 2 km downstream. At Tadcaster, the Wharfe drains an area of 818 km^2 (Webb et al., 1997), and it is a largely rural, cool, humid temperate basin (Jarvie et al., 1997). Average annual precipitation (1961-1990) is 1139mm, rising to over 1500mm in the headwater areas. Banks here are high (>2.5 m), very steep and are formed from fine-grained sediments.

Monitoring techniques

A total of 26 representative fine-grained eroding bank sites (16 fluvial; 10 estuarine) were established for bank monitoring. Grid networks of ~30->100 erosion pins were installed and re-read at ~20-day intervals for between 1 and 2.25 years. Repeat survey was used to quantify major changes in bank position. For a clearer picture of erosion events, we deployed the Photo-Electronic Erosion Pin (PEEP) *automatic* erosion-monitoring system at up to six strategic points at eight key bank sites near LOIS Core Monitoring stations (5 fluvial; 3 estuarine). All sensors, including PEEPs, were connected to Campbell-Scientific CR10X dataloggers programmed to scan at 1-minute intervals and store data as 15-minute means. An Automatic Water Sampler was used within the LOIS Core monitoring programme to assess temporal changes in suspended sediment concentration (SSC) and for turbidity meter calibrations (Leeks et al., 1997). Flow and meteorological data were obtained from nearby UK Environment Agency stations. All timings are in GMT (Greenwich Mean Time).

EXAMPLE BANK EROSION EVENT SEQUENCES

Erosion dynamics

This is believed to be one of the most detailed river bank erosion investigations ever undertaken, in terms of the holistic basin approach adopted, the number of sites and points monitored, and the temporal resolution of measurement achieved. Around 15,000 manual erosion pin measurements were made over the 2.25-year monitoring period, plus 15-min PEEP readings. Some early data are published in Lawler et al. (1999, 2001) and Mitchell et al. (1999).

Much bank erosion took place in discrete, episodic events, rather than as a slower, continuous process. Moreover, in most cases, these bank erosion events were virtually instantaneous, and generally took less than 15 minutes to be completed (i.e. the logger scan interval). This underlines the need to adopt an automatic (quasi-) continuous approach to the monitoring of erosion in fluvial and other systems. Focus here is on bank erosion event sequences at Easedike to illustrate the how the PEEP system can clarify bank erosion event timings with respect to the hydrograph.

November 1996 Event

Fig. 2 illustrates a typical PEEP diurnal data sequence. The sudden increase in PEEP series outputs, with respect to a largely constant reference cell signal, clearly reveals that a large (>150 mm) erosion event occurred during a flow rise in early November 1996. Maximum readings for the PEEP back reference cell also confirm that the complete active length of the sensor has been exposed by bank retreat. In addition, the pattern of PEEP outputs indicates that the erosion event took place within an 18-hour 'window' between 14.15 h on November 6 and 08.15 h on November 7 (Fig. 2), i.e. around the time of the flow and suspended sediment concentration peaks.

THE CONCEPT OF THERMAL CONSONANCE TIMING (TCT)

Although defining the 'erosion event window' as above is very useful, and a significant improvement over conventional methodologies, the moment of material removal can be further fine-tuned through what I have called *thermal consonance timing* (TCT). PEEP sensors now include two thermistors, one at the bank surface and one at 68 mm depth (Fig. 1B). Under normal conditions, micrometeorological theory and empirical data suggest that thermal regimes at the soil surface (which acts as a radiation exchange surface) are much more extreme than at depth.

This is precisely what is recorded. Note how, before the November 6 flood, bank surface temperatures tend to be higher during the day and lower during the night than the bank interior (e.g. November 1-6, Fig. 2). However, once erosion 'exposes' both thermistors so that they experience very similar microclimates, minimal thermal differences and hence *thermal consonance*. The time when sustained thermal consonance is first established, therefore, reveals the moment of material removal. This is especially useful for those periods when PEEPs do not produce strong signals (e.g. when in nocturnal 'sleep' mode or if inundated by turbid water). The simple plot of the temperature difference time series in Fig. 2 reveals when *thermal consonance* has been established, i.e. when thermal differences become low (< 0.4 deg C) and constant.

For example, TCT in Fig. 2 suggests that the bank erosion event which exposed both thermistors occurred on November 6 at 15.00 GMT. This was 1.5 hours after inundation, 1 hour before the suspended sediment concentration peak, and 2 hours before the flow peak. In this case, therefore, at least 68 mm (the inter-thermistor distance) of the 150 mm bank erosion recorded was achieved as a *rising limb* event. Data on the timing of material removal with respect to the hydrograph can help to clarify the minimum stresses required for entrainment.

A further example is discussed of a triple-peaked hydrograph event in February 1997. Here, PEEP data themselves show that bank erosion was a *delayed retreat* incident, occurring *at least* 6 hours after the flow peak of 12.45 h on 18 February. TCT evidence suggests that the main bank retreat occurred towards the end of this window, within a 6-hour period between 02.15 h and 08.15 h on February 19.

Delayed retreat events, well after the discharge peak, suggest that direct *fluid entrainment* is not the main erosion process. Instead, such delays are usually taken as the signature of *a mass failure* or bank collapse process, and reflects either the removal during or following the hydrograph recession of transient lateral buttressing support to the bank provided by the flood waters themselves, or time-lags in the attainment of the critical pore-water pressure conditions necessary for geotechnical instability (e.g. Lawler et al., 1997b). Although there is some anecdotal evidence in the literature to suggest that delayed bank retreat events can occur, it is significant that the PEEP data are able to confirm that the phenomenon exists and also quantify the magnitude of delay. Thus, PEEP data on erosion *timing* can help to advance or eliminate certain controlling processes. Future parallel investigations of the variables driving such mechanisms should therefore provide a method of evaluating competing hypotheses, and testing erosion and sediment transport models.

DISCUSSION AND CONCLUSIONS

This application of the PEEP system has demonstrated that bank erosion event details can be determined much more clearly than was possible hitherto - especially the magnitude, frequency and timing of erosional and depositional activity in relation to fluctuations in river flow and hydrometeorological conditions (e.g. Fig. 2). The study has also yielded new information on the time-dependent behaviour of bank erosion. Erosion sequences presented show how the PEEP system can (a) quantify the impact of *individual*, rather than aggregated, forcing events, (b) reveal the full complexity of bank response to flow sequences, and (c) help to identify likely driving processes. The occurrence of *delayed* bank retreat events, up to 19 hours after the flow peak, indicating mass failure processes rather than fluid entrainment mechanisms, has been confirmed and quantified.

PEEP techniques have been used to improve the temporal resolution of erosion and deposition monitoring on other river systems (e.g. Lawler, 1991, 1994; Lawler and Leeks, 1992; Lawler et al., 1997a, 1997c). PEEP systems are now also being applied by other research teams to different contexts, including snow ablation and accumulation, beaches, tidal systems, drainage ditches and artificial channels (e.g. Mitchell et al., 1999; Prosser et al. 2000; Stott, 1999).

Such high-resolution information on the temporal distribution of bank erosion is vital to a sound process understanding of: the mechanics of bank instability, the fate of failed material, operation of basal clean-out cycles, and the delivery and storage of bank sediment to river systems, especially time-lags between hydrograph peaks, erosion events, and sediment injection to rivers. In particular, given the importance of data on the *timing* of inputs and outputs, coupling PEEP systems with concurrent flow and turbidity monitoring should help in future studies to evaluate the relations between erosion, sediment supply and sediment transport in fluvial systems and other geomorphological contexts.

There is an urgent need for further research, however, to refine *existing* techniques and to develop *new* methods for the continuous monitoring of erosion and deposition events in many geomorphological contexts. Such research could usefully exploit recent developments in micro-electronics, communications and data acquisition systems.

ACKNOWLEDGEMENTS

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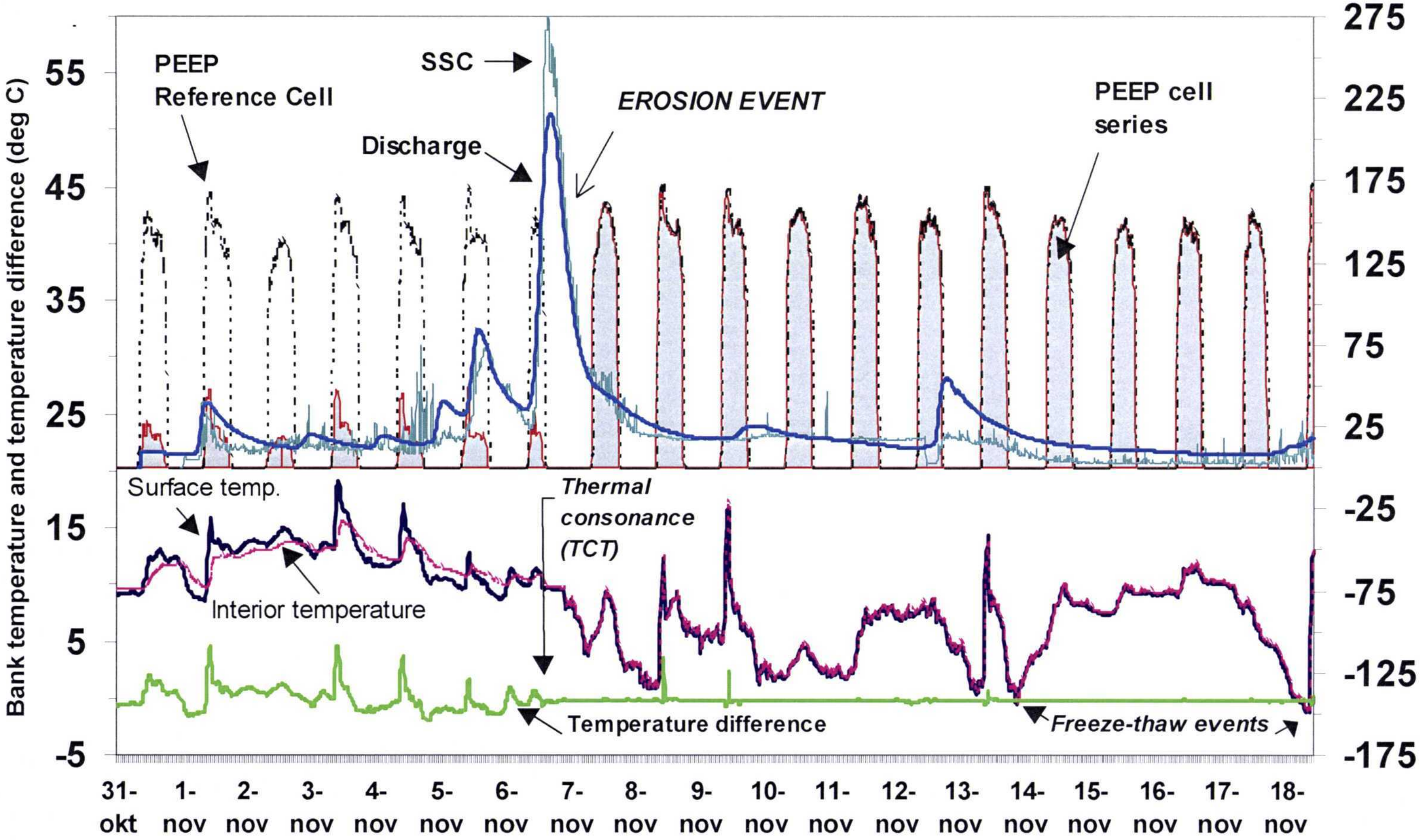
Figure 2. PEEP series showing bank erosion event, flow, suspended sediment concentration (SSC) & bank temperature series: the R.Wharfe at Easedike, UK, October 31 - November 18 1996



Stochastic nature of bedload transport – results from radio-tracking gravel particles

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ABSTRACT This paper aims to analyse the stochastic nature of bedload transport on the basis of radio-tracking gravel particles in the field. The Lagrangian technique of radio-tracking offers the opportunity to investigate the stochastic elements of transport from erosion to final deposition after a flood. These results demonstrate the interaction between flow turbulence and initiation of motion, bed particle dispersion, distribution of step lengths and rest periods as well as the interaction between morphology and transport paths. Following Einstein´s pioneering work on a probabilistic view of bedload transport field data are analysed and discussed in relation to theoretical considerations and concepts.

Keywords bedload transport, gravel bed rivers, river morphology

INTRODUCTION

In general two different approaches exist concerning bedload transport modelling:

- determinisitic concepts
- stochastic concepts

The first concepts describe processes by using a deterministic approach to investigate the responses of hydraulic systems in terms of various parameters. A system is said to be deterministic if its response at any time due to a given input is uniquely determined. Stochastic concepts describe and analyse processes and phenomena by the methods of probability theory.

Researchers and practitioners are familiar with the difficulties in making reliable estimates of bed-load transport rates. Since 1873, when Du Boys introduced his bed-load equation, there have been a large number of bed-load equations put forward in the technical literature.

Einstein, 1937, was the first to introduce a probabilistic view with respect to sediment transport, obtaining a compound Poisson distribution. The following processes of bedload transport reveal a stochastic nature:

- initiation of motion
- transport path
- transport rates
- river morphology
- sediment budgets and catchment-wide aspects

Our lack of understanding of some of the basic interactions between flow and moving sediment is, in a large part, due to the difficulty we have had in making reliable observations of the underlying physics. Einstein (1937) assumed that the mean step length of the particles with average sphericity in a uniformly-sized sediment is about 100 grain diameters. At the time few data were available to justify this assumption or provide insight into how it might be improved. Over the succeeding decades numerous investigators have questioned it but even today we have not reached a consensus about how the mean step length depends upon the flow velocity. This uncertainty presents a major obstacle to the development of a bed-load transport equation securely based on the physics of the processes (McEwan et al., 2001).

The uncertainty concerning the parameterisation of the bed-load transport rate equation faced by Einstein can be resolved by employing new technologies to the sediment transport research. In this paper one field technique, active tracers, is discussed. Here the results of radio tracking gravel particles in the large braided gravel bed river Waimakariri in NZ are presented.

TRACER MEASUREMENT TECHNIQUE

The most commonly used bed-load transport measurement techniques (e.g. basket samplers, traps or acoustic methods) are based on the Eulerian measuring concept, where the measurement takes place at a stationary point. In contrast tracer particles are a Lagrangian technique as they examine particle motion along the river course. Einstein (1937) used a Lagrangian concept as a basis for his transport rate formula when he described the motion of individual particles in terms of step lengths (length between consecutive points of deposition made by rolling, sliding or saltation) and rest periods (particles stay deposited until the instantaneous lift force overcomes the particle weight).

Passive tracer techniques have given insight into the cumulative travel lengths of individual particles, the effect of grain size, weight and shape on travel length (e.g. Hassan *et al.*, 1984) and transport probability, the dispersion of particles, the influence of varying hydraulic conditions, the initiation of motion (Ashiq & Bathurst, 1999) and vertical mixing of coarse particles in gravel bed rivers (Hassan & Church, 1993). The first active-tracer technique was the radioactive tracing method (e.g. Hubbell & Sayre, 1964, Stelczer, 1981) but mainly due to environmental concerns and high costs this method is not applied anymore in the field.

Chacho *et al.* (1989) and Ergenzinger *et al.* (1989) independently undertook the first experiments with radio tracers with similar size and frequency (150 MHz, Ergenzinger and Schmidt, 1995). A development of this system has recently been used by an Austrian research group to collect data in Austria and New Zealand.

The basic part of the technique is a radio-transmitter, that is either implanted in a natural or artificial pebble (Fig 1). A swinging quartz, which is mounted in a water-proof, shock-resistant cover, sends a signal of a frequency of about 150 MHz at an impulse interval of 450 to 600 ms. A mercury switch is triggered whenever the pebble is turned through 180° about a given axis (with an accuracy of 11 ms). This means that a maximum theoretical temporal resolution of about 650 ms can be assumed for the measurement of an individual pebble. Based on the described impulse interval and a pulsing time of 13 ms the life-time of one transmitter is between 3 and 10 months, depending on the battery capacity. The length of the regular transmitters varies between 4.5 and 8.0 cm, so that the long lasting transmitters can only be used for coarse gravel material. Newly developed mini-transmitters of cylindrical shape (length and diameter both 1 cm) are available but have a life of only a few weeks.

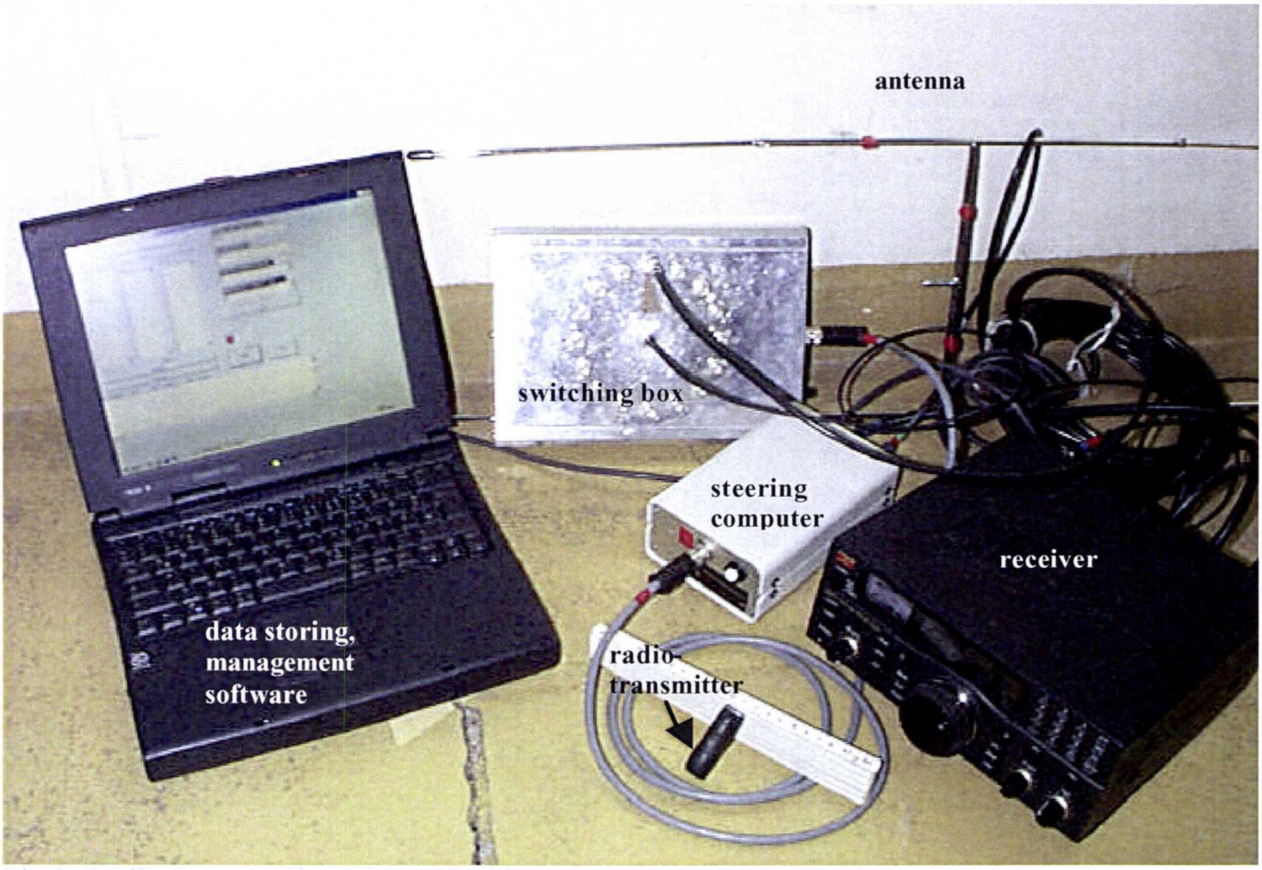

Fig 1. Radio-tracer equipment, used at the IWHW / Austria

The Austrian system can use a maximum of 16 antennas, which are sequentially interrogated for the frequencies of the transmitters by a computer controlled switching box. The signal from the transmitters (~ 1 milliwatt) reaches a receiver (Fig. 1) via the antennae that are positioned along the measuring reach. If several transmitters are used simultaneously the frequencies differ by at least 20 MHz. Software on the computer stores the data and enables management of the measurements.

RESULTS

At the 1 km wide braided section of the Waimakariri river at Crossbanks, New Zealand, the transport path of individual, artificially produced gravel particles, was monitored during various floods of different magnitude. It was found that the rest periods followed an exponential distribution whereas the step lengths were modelled by the use of a gamma distribution with the density function.

In general the results of the work at the Waimakariri River suggest that combining the exponential and gamma-distributions should give an appropriate model for the migration process of bed load particles in a large braided river as well (Habersack, 2001).

Einstein assumed an average travel distance of 100 grain-diameters for any bed-load particle between consecutive points of deposition, but larger values of 6.7 m or 150 grain-diameters and 6.1 m or 120 grain diameters were measured for two test particles sizes. Together with other available large scale field data a dependence of the mean step length on particle diameter relative to the D_{50} of the bed surface was found (Habersack, 2001). During small floods the time used for movement represents only 2.7 percent of the total time from erosion to deposition. The increase of the percentage of time being used for transport means that it then has to be regarded in stochastic transport models. Tracing the flow path of bed load particles between erosion and deposition sites is a step towards explaining the interactions between sediment transport and river morphology.

Both theoretical and experimental studies in mechanics have not produced data which verify the complete movement of particles in the system. The radio-tracked particle was naturally eroded and transported towards the thalweg (deepest point in a cross section) of the channel. The final location marked the position of the stone after the flood, where it was deposited in an aggraded, extended bar. Similar flow paths were observed from other particles used in the same flood.

The flow path of gravel particles is a composition of invidividual steps, interrupted by rest periods. On their way through the fluvial environment particle dispersion takes place.

The *local range* corresponds to ballistic particle trajectories between two successive collisions with the bed (Fig 2). The *intermediate range* corresponds to particle trajectories between two successive rests or periods of repose. The (intermediate) trajectories from this range consist of many local trajectories and may include tens or hundreds of collisions with the bed. The stream-wise component of the straight line connecting the ends of the intermediate particle trajectory is equivalent to the "quick length step" in the Einstein's (1937, 1942) theory of bedload. The *global range* of scales corresponds to particle trajectories consisting of many intermediate trajectories just as intermediate trajectories consist of many local trajectories. This three-range conceptual model was verified by the analysis of video camera observations in an irrigation canal in NZ (Nikora et al., 2002). In this paper large scale data from the radio tracking of gravel particles in the Waimakariri river will be analysed.

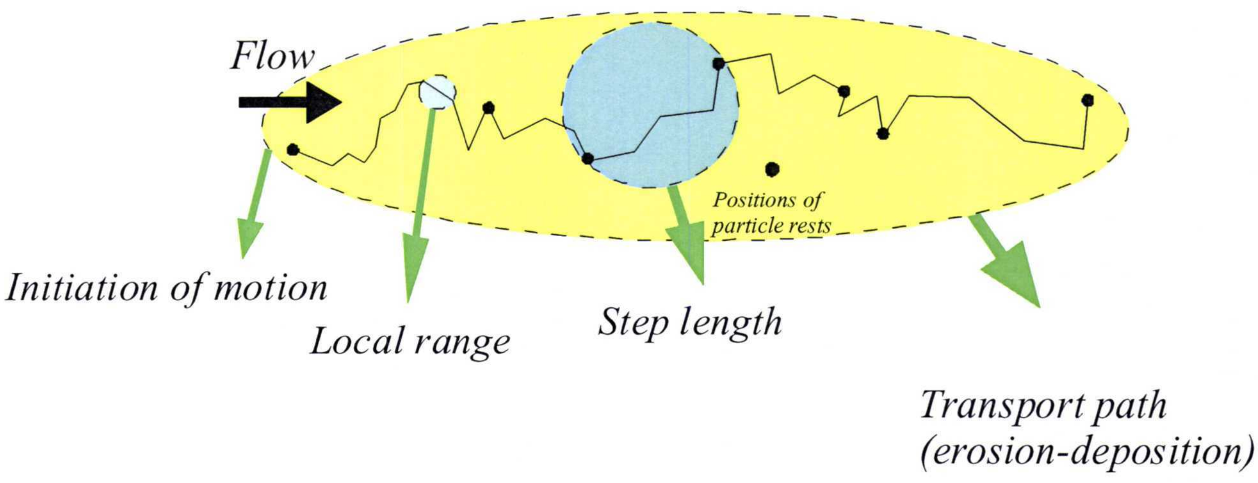

Fig 2. Stochastic elements of bedload transport at various scales (modified after Nikora et al., 2002)

Knowledge of the actual transport path of gravel particles helps us to understand important processes in river morphology at several scales, extending the analysis of stochastic transport components, which was introduced by Einstein. At a point scale we have the interaction between turbulence and initiation of motion. The use of a modified Pitot tube and radio tracers allowed the analysis of the interrelation between turbulence and bed particle erosion for the Waimakariri and demonstrated a significant correlation, which will be analysed in future research. At a local scale we have the stochastic nature of bed load transport. At larger scales, we have the development of bars and other bed forms and the relation between erosion and deposition zones.

In future, combining field studies of "Einstein-parameters" and hydraulic as well as morphological boundary conditions will allow the stochastic behaviour of bed load transport to be further investigated.

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The continuous monitoring of bedload flux in various fluvial environments

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ABSTRACT We present detailed advantages and limitations of an accurate, reliable, durable and relatively cheap means of continuously monitoring bedload flux and texture using Birkbeck-type slot samplers based on almost a quarter of a century of data. These have been derived from alpine, mid-latitude perennial, Mediterranean, semiarid, and arid fluvial settings in single and multi thread rivers 1 - 40 m wide that have a characteristic surface bed materials in the sand-granule to cobble-boulder range. Methods of construction and principles of operation, calibration, data handling as well as ranges of flux rates and textural characteristics of bedload are discussed.

KEY WORDS bedload flux, sampling, incipient motion, cessation of motion, texture

INTODUCTION

Slot (also termed pit) samplers do not affect the flow and are, therefore, more accurate than other bedload samplers, unless the latter can be shown to have hydraulic and sampling efficiencies of 100%. Slot samplers are of various types, utilizing either a vortex tube (Milhous, 1973) a continuous conveyor belt (Leopold & Emmett, 1976) or a local weighing device (Reid *et al.* 1980). The Birkbeck sampler has become the preferred method (Lewis, 1991; Kuhnle, 1992; Laronne *et al.*, 1992; Harris & Richards, 1995; Garcia *et al.*, 2000; Cohen & Laronne, 2000; Sears *et al.*, 2000; Habersack *et al.*, 2001; Powell *et al.*, 2001). Several other methods have been used to sample bedload without unduly affecting the flow (Ashida *et al.*, 1976; Lenzi *et al.*, 1999), but these have not been used widely.

With a growing need for high quality, continuous bedload datasets from automatically activated samplers, we offer observations and provide operational principles of relevance to deploying the Birkbeck sampler in various environments. Further details will be included in the manuscript to be published in the IAHS red book series.

PRINCIPLE OF OPERATION

The Birkbeck bedload sampler operates on the principle of weighing the mass of bedload that enters a slot. Variations in water stage are accounted for by independently monitoring water stage (Reid *et al. 1980)*. The sampler has a hydraulic efficiency of 100% when sediment fill is small, it is 90% at a fill of 60% and it decreases to 66% at a fill of 80% (Habersack *et al.*, 2001). The bedload sampling efficiency is likely to decrease accordingly. The decrease in efficiency derives from the generation of recirculation flow cells within the sampler as it fills. At least four such cells, the velocity of which increases with extent of fill, have been identified (Habersack *et al.*, 2001). Due to the separation between the channel flow and the water column within the sampler, slot samplers are excellent separators of bedload and suspended sediment (Poreh *et al.*, 1970). The latter is deposited only at very low stage.

To ensure that the bed does not scour downstream of the samplers - the cover of which is smooth, thereby decreasing friction and causing the flow to accelerate - a cement apron has been installed. Anabranches change location and bed elevation varies considerably in braided rivers. We have dealt with a rising bed elevation in the Rahaf anabranch by attaching an increasing number of 'spacers' to the sampler.

CONSTRUCTION

Slot orientation, width and length

Photographs of etch marks made by moving particles on the sampler cover indicate that the direction of movement is essentially downstream. This is expected in straight reaches of single thread and relatively narrow streams. In wider streams, at meander bends and especially in multi-thread systems, local near bed flow direction may differ considerably from the downriver direction. As a precaution, small vanes have been used to ensure that bedload enters only from the upper slot entrance (Sears *et al.*, 2000).

The choice of an appropriate slot width depends on the grain size distribution (gsd) of the riverbed and expected flux of bedload in the context of sampler volume. In order to capture all clasts, it is axiomatic that slot width should be larger than the coarsest clasts (Hubbell *et al.*, 1981). Our samplers have slots that can be varied in width (0 - 180 mm) to suit individual river reaches and sampling objectives. In perennials, where bedload fluxes are typically very low (Reid & Laronne, 1995), slot width can be increased considerably, and values as high as 200 mm have been deployed. However, in ephemerals, with bedload flux several orders of magnitude larger than in perennial counterparts over the same range of flow conditions (Laronne & Reid, 1993), increasing the slot width significantly decreases the length of the record. Hence, planning an appropriate slot width depends on the local gsd, on the extent of armour development (Laronne *et al.*, 1994), and on expected bedload fluxes, which are themselves dependent on hydraulic and hydrologic factors. In the Eshtemoa we have used a slot width of 110 mm and presently also a slot width of 165 mm, 50% larger. This will allow us to determine more accurately when the coarser material of the channel bars is mobilized – i.e., when equal mobility is attained (Powell *et al.*, 2001).

Slot length should be larger than the maximum hop length of saltating particles. Because the truncation of gsd is commonly undertaken at a fixed size, the calculation of the slot length may be based on this a lower truncation. The maximum hop length is calculated from the Shields parameter, a hiding factor and a ripple factor (Habersack *et al.*, 2001).

Inner box dimensions and box hauling

Sampler volumes are either 0.24 or 0.48 m^3 at all our sites except the Drau (0.75 m^3), where the sampler and logger remain underwater during the entire spring and summer freshet. Other reported sampler volumes are similar except the smaller boxes used by Sears *et al.* (2000) and recently by Powell at Jornada and Walnut Gulch (see below). Small sampler boxes may be lifted manually. Larger ones require either a fixed davit (Turkey Brook, Yatir and Eshtemoa) or a fixed I-beam (Tordera), a portable beam where channel width makes a fixture impractical (Rahaf) and where fixed installations are environmentally detrimental (Qana'im); in wide channels hauling may be accomplished from a bridge if this is sited appropriately (Drau).

PRESSURE SENSING

Neoprene pillows have been used at the Eshtemoa continuously for over a decade. Pillows rarely puncture. Puncture repair is simple, though some have contended otherwise and provided a design modification (Harris & Richards 1995). Pillow response is linear when the water fill does not contain much soluble gas. However gas may evolve within the pillow and a bleeder should be attached to the top. In order to maximize sensitivity; the pressure transducer should at the same elevation as the pillow. Standard errors of estimates of bedload are typically +/- 0.3 kg for small (0.24 m^3) samplers and +/- 0.6 kg for those twice this capacity.

Load cells are another means of monitoring pressure. In a Birkbeck sampler, the load cell is mounted on the floor of the outer box and supports the inner box in such a way that the weight of the accumulating load is transmitted entirely and directly to the cell's strain element. Load cells are less prone to temperature effects, function independently of water stage and simple ones cost as much as locally made pressure pillows. Lewis (1991) used a single, centrally located load cell, whereas a more uniform distribution of pressure on a single load cell is attained by utilizing a stainless steel 'scissor' cradle (Sears *et al.*, 2000). Birkbeck-type samplers are currently being used by Mark Powell to study sediment transport in small rills at the Jornada, New Mexico and in a first order gully at Walnut Gulch, SE Arizona. At Jornada and Walnut Gulch, each inner box is supported by three load cells to ensure sampler stability in the event of uneven filling. The load cells are connected in parallel to provide a single voltage output proportional to the accumulating load.

CALIBRATION

Loading and unloading calibration regression equations are essentially identical, indicating that pillow response is linear and non-hysteretic (Laronne et al., 1992; Harris & Richards, 1995). Summarizing the annual variation in the slope of pillow calibration regressions, all the coefficients of determination exceeded 0.99 and response of the transducers remained linear.

Sampler calibration varied, often by about 5% between years. In some instances sampler calibration remained essentially constant. That the calibration factors did not consistently increase with time indicates that the manufacture of pillows by rubber vulcanization is sufficient and that it is not essential to provide a metal frame (see Harris and Richards, 1995). A change in pillow response may derive from a number of factors such as minor but variable air content within the water in the pillow, variable temperature during calibration and a change in the response of the transducer. Whatever the reasons may be, the changes indicate that long term use of pressure pillow-based Birkbeck type samplers requires repeat calibration, a maintenance routine common to all scientific instruments.

DATA ANALYSIS

Record termination and time averaging

Record termination takes effect when sampling efficiency decreases, often occurring abruptly. Terminating a record before the sampler is entirely full also implies that the sediment accumulated thereafter should not be incorporated in textural analyses.

The nature of the bedload record depends in part on the interval chosen to compute flux. As the averaging period increases, the response is dampened and lacks the high peaks and low fluxes that are characteristic of the smaller interval data. The spikiness of response is removed at progressively shorter time intervals as the average bedload flux increases.

Initiation, cessation of motion and hysteresis in bedload flux *vs* water depth relations

Close-up view of bedload records reveal that initiation of motion occurs at considerably higher stage (and shear stress) than cessation of motion, as documented by earlier observations using Birkbeck samplers. Indeed the Birkbeck system is sufficiently sensitive to determine these thresholds. However, incipient motion cannot be determined with this system in bores (sudden flash floods), particularly where the sampler is not primed. The Birkbeck can determine whether hysteresis occurs, allowing a description of the direction of the relation, whether clockwise or anticlockwise.

Extending the bedload record

Continuous bedload records are notoriously short due to the limited volume of samplers. Record extension has been achieved by periodically pumping a slurry of water and sediment from the sampler (Lewis, 1991). When flux rates are not too high, record length can be considerable if sampler volume is appropriately large. Indeed, the voluminous sampler employed in the Drau has allowed us to continuously monitor bedload for a period of up to an entire week (Habersack *et al.*, 2001). Bedload records may also be prolonged if one or more among a group of samplers deployed at a reach are uncovered after others have been filled. We have successfully used this method at the Eshtemoa. During the Oct. 26, 2000 flood, a covered sampler began collecting bedload 7 min after others, at which time the other 4 samplers had variously accumulated 18-91 kg.

Coping with small pressure fluctuations within the sampler

As sediment accumulates inside a sampler, it falls and thereby creates a fluctuation in pillow pressure, which dampens within few to several dozen seconds (Harris & Richards, 1995). We have utilized two distinct methods to deal with these fluctuations. Initially we disregarded all negative, admittedly small values, and assumed them to represent zero flux. A more advanced means of treating the fluctuations is to delete the erroneous small negative values, as well as the small succeeding positive values. Moreover, only continuous traces of bedload are utilized. When flux rates are very low, they can be calculated only for intervals over which the cumulative deposited sediment weighs more than the confidence limit of the system.

BEDLOAD FLUX AND BEDLOAD SAMPLING FOR TEXTURAL ANALYSES

Bedload flux

The Birkbeck system has been utilized to monitor a very wide range of bedload fluxes. These have ranged from a reported 0.000 001 kg/sm in a perennial armoured lowland river (Sears *et al.* (2000) to 60 kg/sm in the unarmoured, steep (2%) and braided Rahaf (Cohen & Laronne, 2000). That one relatively simple monitoring system can handle a sevenfold order of magnitude range is exceptional. Self evidently, the monitoring conditions in such diversely distinctive rivers are not only hydrologically and sedimentologically distinct, but the monitoring and calculation steps also differ markedly. For instance, the Rahaf-Qana'im samplers are logged the average of five 2 s data. Longer logging time spans have enabled us to determine the conditions of incipient motion even when flux rates are low, such as in the Mediterranean Tordera, allowing us to determine the origin of the bedload from the patch-dominated, armoured bed (Garcia et al., 1999; Laronne *et al.*, 2001). Birkbeck bedload flux records may also be used to evaluate bedload equations (Reid *et al.*, 1996).

Bedload texture

In small samplers the entire deposit can be sieved and otherwise studied. To sample the trapped bedload in larger (> 0.1 m^3) samplers, we have installed a door in the inner box to view stratification. This allows slicing of samples according to stratification, rather than some arbitrary method. Stratification is best viewed after the deposit has been dewatered. To achieve a fresh, undisturbed view of stratification, it is necessary to incline the sampler away from the door before opening it.

Morphology and texture of accumulating deposit: implications for sampling strategy

Unlike in the Drau we have observed and documented in the Rahaf and Qana'im a distinct and large sideways increase in texture. The symmetric span-wise variation of texture requires that representative sediment layers be taken from the centre to either left or right wall of a sampler. The shape of the deposit was often cross-sectionally symmetric, attested by small difference in angle between the right and left side slopes. This implies that horizontally sliced samples represent a synchronous accumulation only for the bottom deposits. So in layer sampling the accumulated deposit, either allowance is made for the varying angle of stratification or one accepts that the material cannot all be attributed to a single time-slice.

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Bed load measurements with a new passive ultrasonic sensor

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Introduction

Sound generated by particle impacts has been employed for detecting bed load movement for some time (Mulhofer 1933), but the development of this approach has been slow in spite of its advantage in producing a continuous record.

Richards and Milne (1979) applied a piezo-electric transducer to convert acoustic energy to electric signals. They concluded that the method was potentially useful for identifying bed load transport thresholds.

Banziger and Burch (1991) and Rickenmann et al. (1997) describe a system where impacts caused by bed load passing over a metal plate are detected by a hydrophone. Impacts above a certain threshold amplitude are recorded by a pulse counter. The volume of material deposited in an adjacent sediment trap was found to correlate with the number of pulses counted per minute.

The present paper discusses the results of experiments and field work carried out to test the suitability of a passive ultrasonic sensor recording in a narrow frequency band. It had initially been developed to monitor the amount of sand carried in suspension by oil pumped up from reservoirs below the Norwegian continental shelf. The sensor detected the sound of particles impacting the pipeline wall at a bend. These collisions generate a characteristic frequency pattern which was analysed to estimate the total mass of sand.

Clampon (1998) adapted this pipeline instrument for NVE so that it could also record the impact of gravel- and cobble-sized material. The first generation model of the resultant bed load sensor was installed and tested in three rivers in Norway.

Sensor design and mode of operation.

The sensor consists of an acoustic sensing device, a signal amplifier and, a low-pass / high-pass filter and a digital signal processor (DSP). The signal filter removes all frequency components outside a narrow ultrasonic frequency band. The remaining signal is integrated over a period of one second and the amplitude value output in digital form as a numeric string. The water turbulence generates very little acoustic energy in the selected frequency band. The processed data thus almost entirely represents variations in bed load transport with very little ambient noise present in the record. The sensor is fitted onto the underside of a 500x500x10 mm steel plate which is fixed to the riverbed. Particles sliding or rolling over the plate create a vibration, which in turn is picked up by the sensor.

The sensor has been connected to a Sutron 8210 datalogger (RTU). To conserve data storage space and reduce communication time when downloading, one random sample in every 5 second interval is recorded; the remainder are discarded. In addition to the bed-load reading, the logger measures water stage at 5 minute intervals. The stored data is transmitted to the office once a day, using a combination of line-of-sight radio and fixed line modems. Of the two sites operational today, one is solar powered and the other uses mains power.

The sensor runs on a 12V power supply using 300 mA and communicates readings through an RS-485 serial interface. The cylindrical sensor-head is 20 cm high and 10 cm in diameter. All electrical components are mounted in a robust and watertight stainless steel housing.

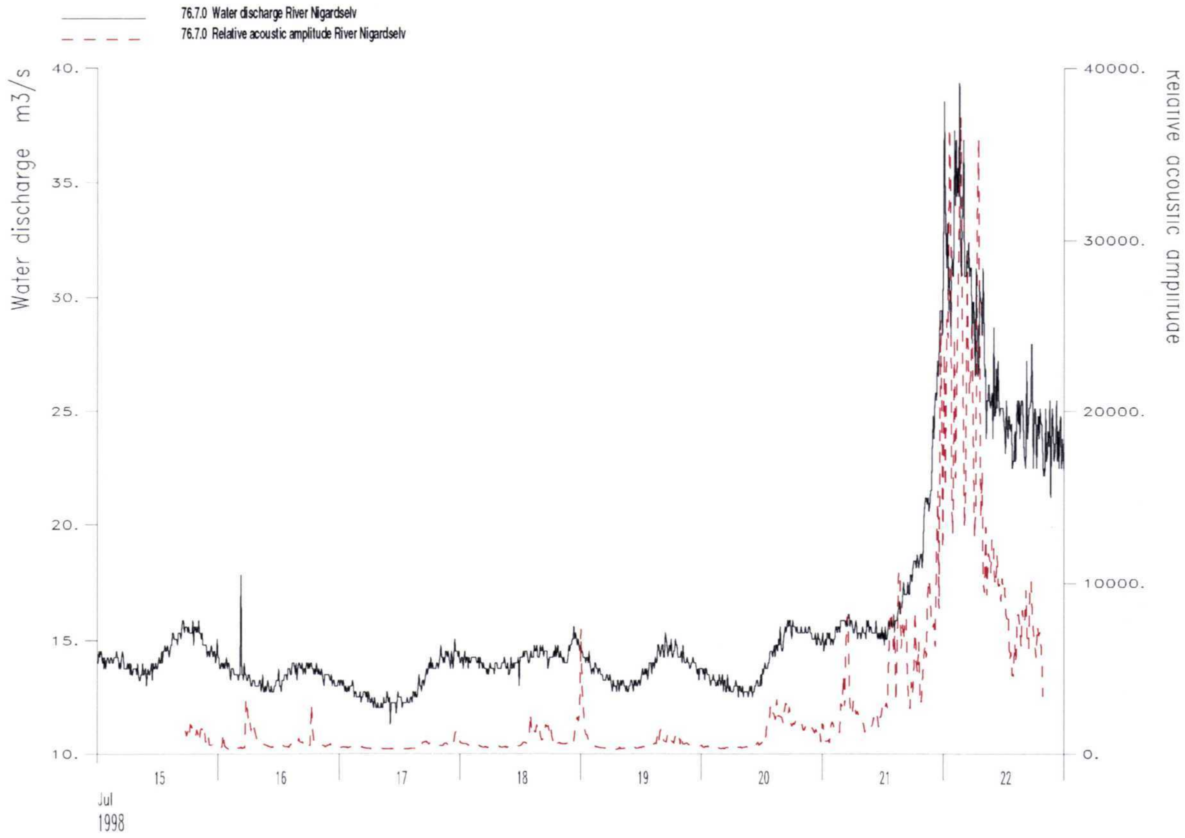

Fig. 1 Maximum relative acoustic amplitude and water discharge in river Nigardsbreelv 15 – 22 July 1998.

Nigardsbreelv

Nigardsbreelv is the meltwater river from the Nigardsbre glacier and its flow is characterised by a high degree of turbulence. The river occupies a bedrock channel and the bed load carried by the river is derived from sediments supplied by the glacier. The bed load is composed of relatively coarse material; gravel fractions dominate but there is also a large proportion of cobbles and boulders. Clasts are often well rounded.

The annual transport rates have been calculated from measurements of the annual rate of deposition on the delta in lake Nigardsvatn, 0.6 km downstream from the glacier terminus. The mean annual transport rate amounts to 8000 t/yr, though up to 20 000 t/yr have been measured during years with particularly intense runoff.

In May 1998 a sensor was installed in a rock surface cavity on the riverbed ca 0.5 km downstream from the glacier. The cavity was covered with a steel plate, connected to the datalogger by a cable.

A record covering 15-22 May 1998 is shown in Fig 1. This indicates mean values during successive 5 minute periods. During the first seven days, the discharge was subject to daily fluctuations of around 12-15 m3/s because of snowmelt. The acoustic record shows little bed load activity, except for some minor peaks triggerd by short term blocking of subglacial tunnels. The acoustic activity increased considerably, however, during a flood at the end of the period of measurement but fell back to a low level during the recession phase even though discharge remained high for some time. No direct sampling of bed load was carried out. However a high transport rate of cobbles and boulders during the flood is indicated by the fact that the cable was heavily abraded, and eventually broken.

Gråelva

In November 1999 a sensor was installed in the river Gråelva, a lowland river in Trøndelag in central Norway. The sensor and the corresponding plate were built into the weir of the water discharge monitoring station. Gråelva represents a low energy environment when compared to Nigardsbreelv . The bed load is derived from a layer of gravel and cobbles on the river bed upstream of the monitoring station.

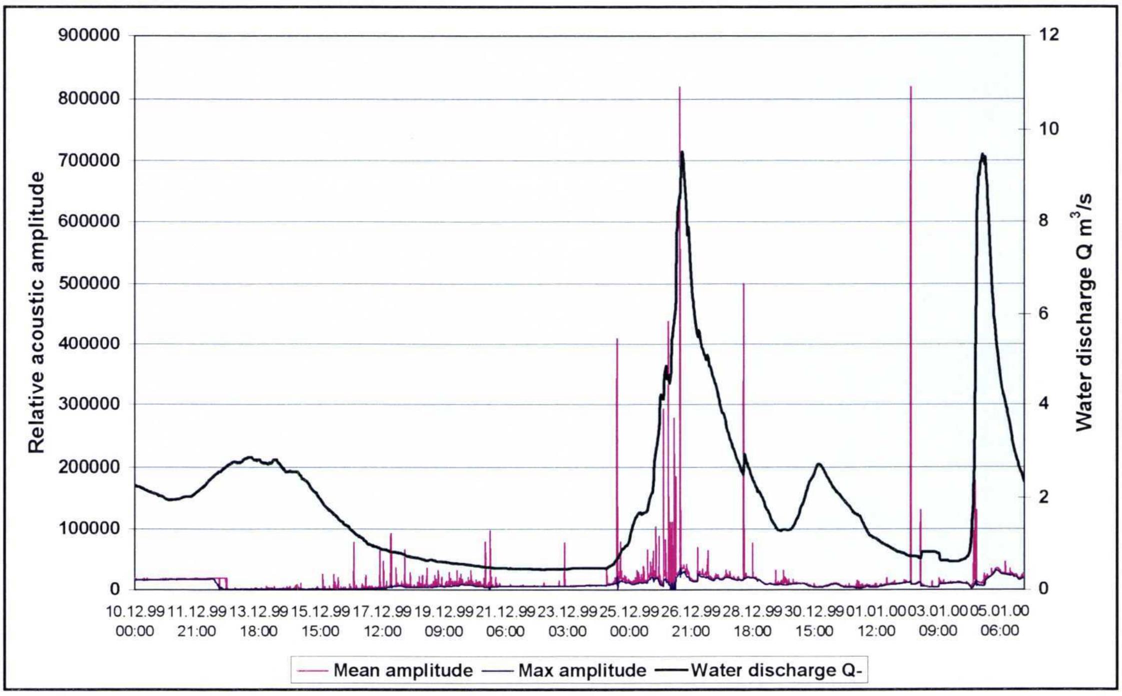

Fig. 2 Relative acoustic amplitude and water discharge in river Gråelva 10 December - 5 January 1999.

A record covering the period 10 December 1999 to 5 January 2000 is shown in fig 2. The measurements reveal a transport pattern essentially in agreement with general bed load observations. The bed load passes in pulses, but these do not always correlate with high water discharge.

If we exclude the anomalous measurement of 2 January the largest maximum amplitudes were recorded during the rising water stage of the flood event on 25 og 26 December. During the falling stage of the same flood there is apparently little bed load activity except on the 28 December when a small rise in discharge was accompanied by a major acoustic peak. The mean amplitude, however, remained low throughout the whole measurement period. In contrast, during the flood on 4 January there was only a small increase in acoustic amplitude. No high amplitude events were registered after the flood had culminated.

Bayelva

Bayelva is located near Ny Ålesund on Svalbard in the high Arctic. Most of the sediments are supplied by the Austre and Vestre Brøggerbre glaciers and erosion in the glacier forefield.

Sediment transport and water discharge are measured at a composite Crump weir near the river outlet in the fjord. Between the the monitoring station and the glaciers the river passes through several sandurs. The sediments on the riverbed are dominated by gravel and cobble fractions. They are derived from sandstones and are in general more angular than the clasts in the two other rivers.

Results from the acoustic record for 14 – 25 July 2000 are given in Fig.3 Water discharge variations during the period were mainly caused by temperature fluctuations giving rise to variations in snow and glacier melt. The highest acoustic amplitudes were recorded during the rising stage of the 17 June flood event. A similar pattern occurs during each of the daily discharge fluctuations during the period. However, the amplitude of the acoustic peaks does not always match the water discharge amplitudes. During low discharges of 3 – 6 m3/s for 24 – 27 July, the acoustic amplitudes are higher than the ones of the preceeding days despite significantly lower water discharges.

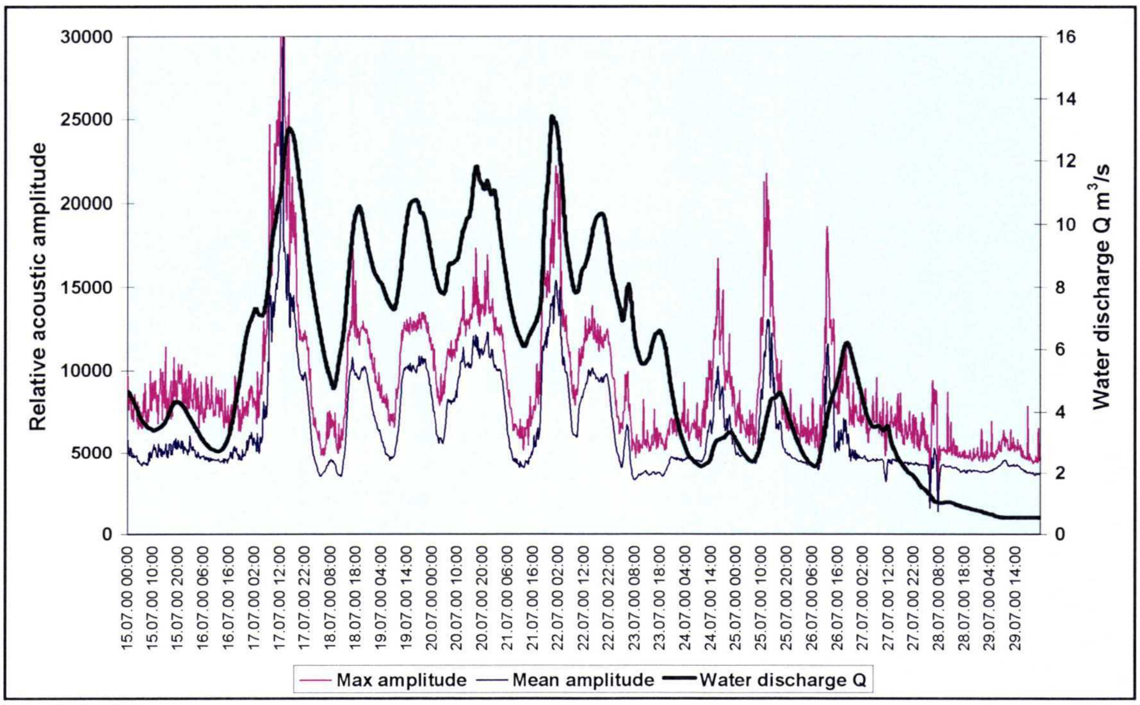

Fig. 3 Relative acoustic amplitude and water discharge in river Bayelva 15 – 29 July 2000.

A plot of bed load samples obtained with a Helley–Smith sampler vs acoustic amplitude is shown in Fig. 4. More data need to be collected to confirm this correlation. It is however apparent that the amount of bed load trapped by the sampler increased when the acoustic amplitude peaked.

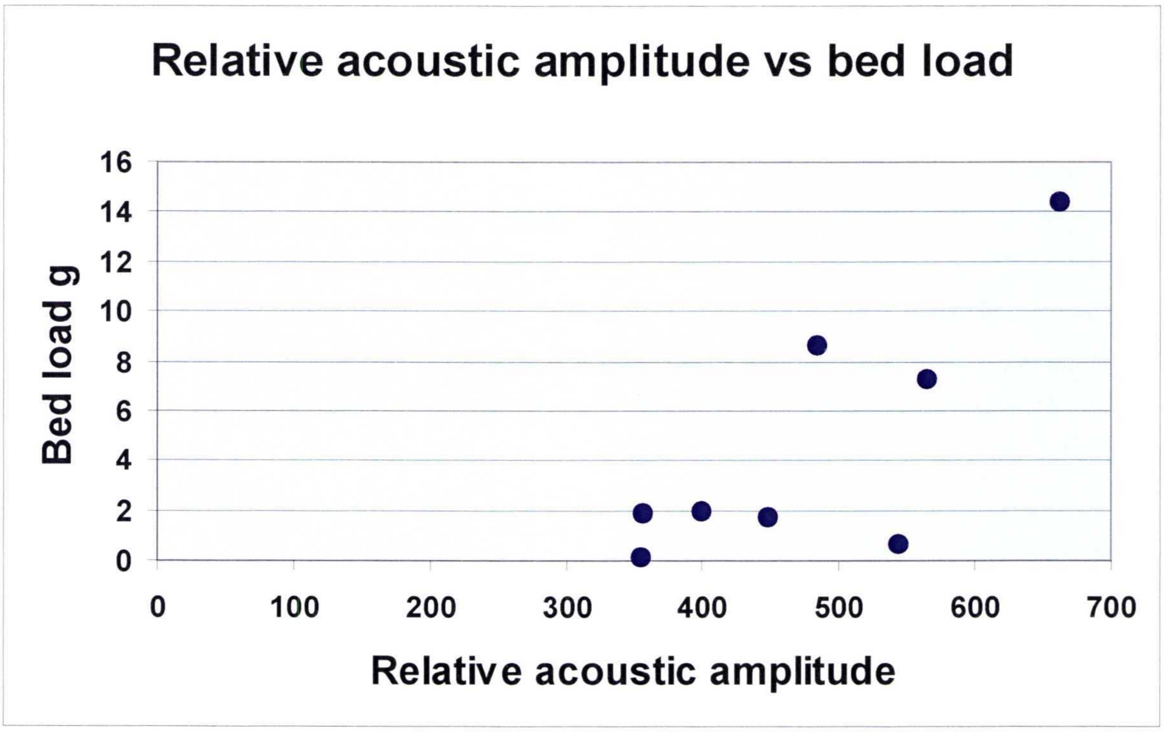

Fig 4. Relative acoustic amplitude vs bed load trapped by Helley – Smith sampler for 20 min.

Conclusions

The experiments and field tests of the acoustic bed load sensor indicate that this system successfully monitors temporal variations in the rate of bed load transport.

The system must be calibrated to direct samples of bed load for each measuring site.

The field measurements reveal a markedly irregular pattern of bed load transport rates in the studied rivers. There is some similarity to suspended load transport in the way that an hysteresis effect is present, namely the transport rate is much larger on the rising stage than on the falling stage of a flood.

The small difference between max and mean acoustic amplitudes recorded in the high energy rivers Bayelva and Nigardsbreelv most probably indicates continuous movement of fairly coarse bed load. In the quieter river Gråelva there is a very large difference between the mean and max amplitudes. This probably represents a continuous flow of small amounts of sand with only sporadic transport of cobbles or boulders during the observation period.

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PERSPECTIVES IN BEDLOAD MEASUREMENTS

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Extended Abstract

Over the past decade, considerable developments have been made in bedload measurement techniques for floods and debris flows in mountain areas. While suspended sediment still remains the more common fraction measured, bedload remains a problem since it is not only more difficult to determine but also has the largest impact in terms of geomorphological change. Little is known for example on sediment transfer rates during sediment sluicing below dam sites. Developments in bedload measuring techniques are essential and need to be adapted to function efficiently in different environments. Optimally, bedload measuring techniques should be non-intrusive, flexible and representative for different types of transport.

In the Schmiedlaine, Upper Bavaria, bedload was measured between 1995-1997 using VICOM (Video Cobble system), a bedload separation system (Krause 1997). An inclined steel grid system allowed water to be separated from the bedload fraction during floods and enabled coarse particles to be filmed and digitally stored during motion by means of a video camera system. The system was not totally satisfactory since bedload mobility was dependent on a certain threshold flood and too much turbulence made measurements obsolete.

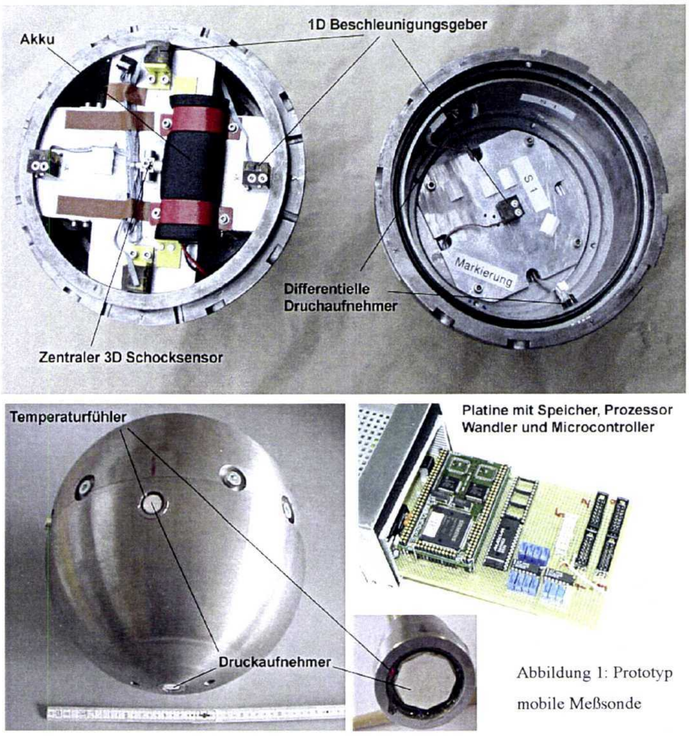

Fig. 1 Prototype of mobile measuring probe

Following the successful development of COSSY (Ergenzinger and Jüpner 1992), a special instrumented boulder, KNÖDELI, was developed in order to monitor the internal fluid dynamics of debris flows at the Chemolgan test site in Kazakhstan, including particle movement, pressure, kinetic energy and the impact of other moving particles (Fig. 1). Inside the two steel hemispheres, the sensors installed include those for 3-dimensional acceleration, differential pressure, temperature and radio signal. The data is captured at a sampling rate of 100Hz and transmitted via radio. KNÖDELI is 30 cm in diameter and 37 kg in weight. The advantages of instrumented boulders are their direct measurement of internal flow, the transmission of complex information at distinct points in the flow, the mobility and flexibility of the system and the possibility for measurement under natural conditions. Fig. 2 gives an indication of how KNÖDELI works under natural conditions, both in cross-section and long profile. An ultrasonic device together with an antenna and video camera system allow the instrumented boulder to be tracked during a debris flow.

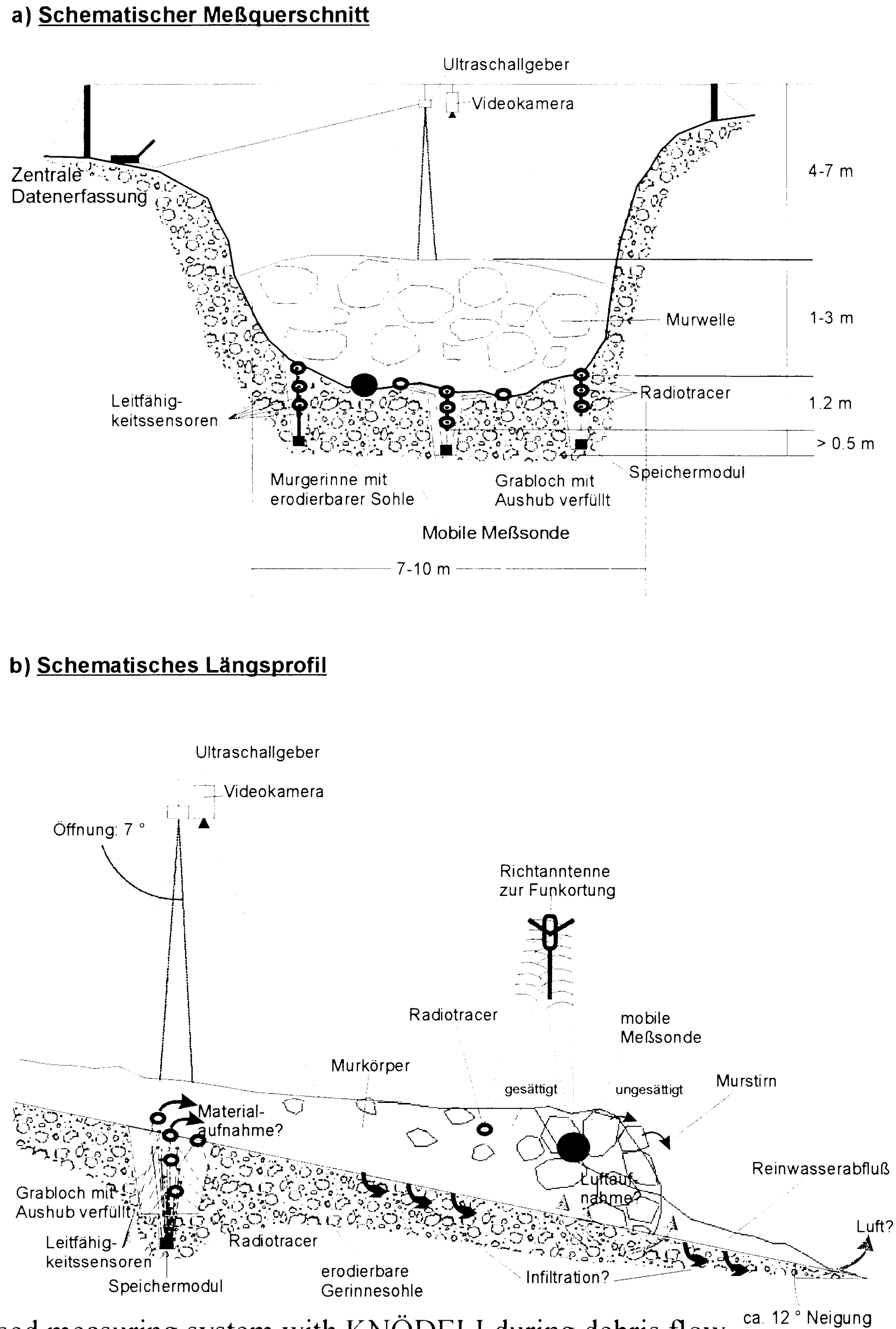

Fig. 2 Proposed measuring system with KNÖDELI during debris flow.

The idea of taking aerial photographs of river beds to monitor sediment size and change led to the development of a remotely controlled, helium-filled balloon system. By means of a digital camera, the river bed could be analysed from a height of up to 10 m and the images processsed digitally. Similar work has been carried out by Church et al (1998). The advantage of the system is that a such a scale, the interpetation of the river bed is not confined to single particles, but instead whole entities, such as ring structures and step-pool systems can be identified (Ergenzinger 2000). The disadvantage of such systems is their vulnerabilty in steep, forested catchments.

Recently, high resolution image data from the HRSC-A (High Resolution Stereo Camera-Airborne), flown by light aircraft from the German Aerospace Centre (DLR) has enabled new insights into bedload transport rates and size (Fig. 3). The multispectral optoelectronic digital stereo scanner has a focal length (grid size) of 17.5 cm, including 5 stereo CCD lines, a stereo angle of 18,9° and 12,8°, 4 multispectral CCD lines, a field of view of 11,9° and a data rate of 80MBit per second (Lehmann 2001). The colour images can be geometrically corrected and a high-resolution DEM created with the help of GPS controlled orientation data. Such high resolution images allow detailed, non-destructive analysis of sediment size above 17.5 cm in diameter, arrangement and imbrication of coarse-grained alpine river beds pre- and proceeding flood events. A detailed, simultaneously constructed DEM enables the determination of changes in sediment volume.

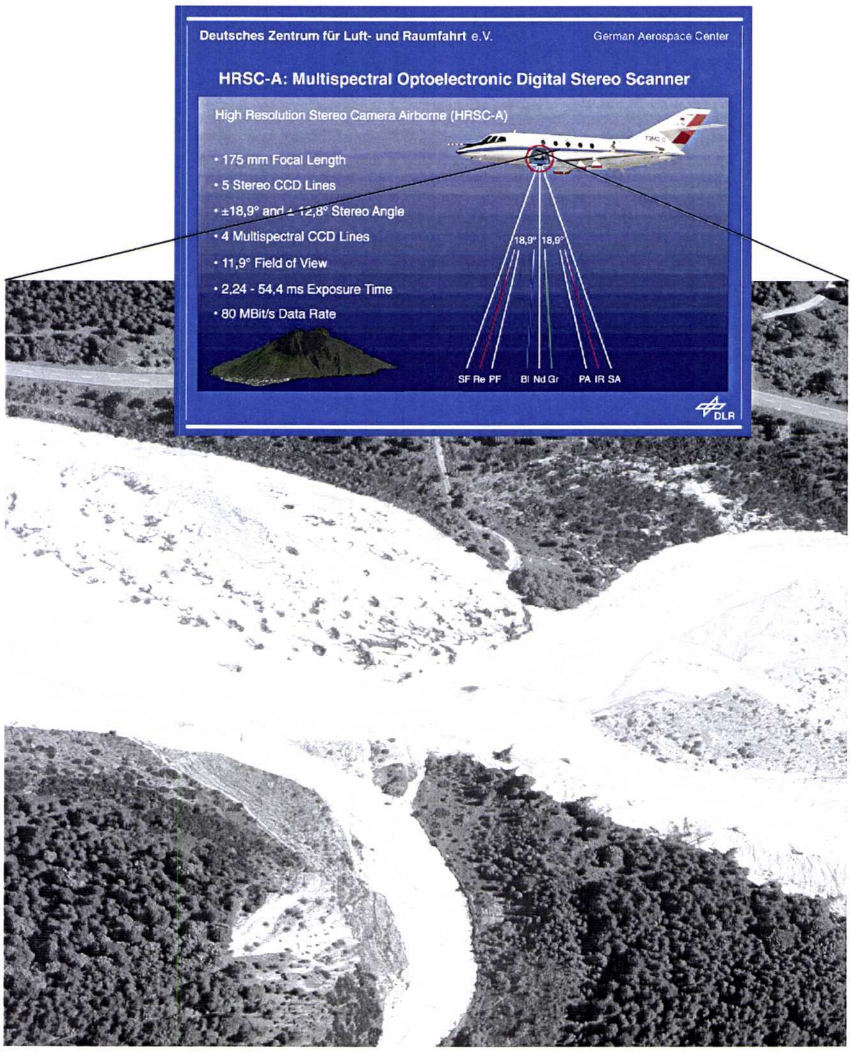

Fig. 4 Detailed analysis of sediment size, arrangement and volume changes of river beds based on HRSC image analysis with a grid size of 17.5 cm.

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Testing and improving the reliability of volumetric estimates of hydrogeomorphic features derived from LiDAR data

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key words: fluvial geomorphology; DEM's of difference; LiDAR;

Bedload transport provides the major process linkage between river channel form and hydraulic conditions. It is a phenomenon that is both temporally and spatially variable and thus very difficult to measure. Recent developments in the monitoring of changes in river channel form using geospatial technologies have improved things significantly, and accurate and dense DEM's of features such as gravel bars may be collected quite rapidly using photogrammetry, total station, and GPS. Repeat survey enables DEM's of a difference to be used to visualize spatially distributed information on river channel erosion and deposition patterns, and also to quantify the volumes of change, thus providing an alternative means for the estimation of bedload.

Light Detection and Ranging (LiDAR) is a scanning and ranging laser system that can yield enough data points to create a highly accurate digital terrain model (DTM). LiDAR provides the potential to collect morphological data over a complete river system at relatively low cost, affording more detailed monitoring of channel change and sediment transport than previously possible. It is essential that the reliability of LiDAR for this method be thoroughly evaluated before it is used in this type of river study. This paper utilizes data from several gravel-bed river bars surveyed using a total station and survey grade GPS. Surfaces were fitted to this data and used as 'ground truth' to validate volumetric estimates derived from DEM's obtained using LiDAR data. Results indicate LiDAR will provide an invaluable tool for monitoring river channel change and sediment transport estimates in large gravel bed river systems.

Sampler size and sampling time affect measured bedload transport rates and particle sizes in gravel-bed streams

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INTRODUCTION

The transport frequency of gravel particles of the size class that is just beginning to move is very low, exactly how low is a matter of observer definition (or patience) (e.g., one particle per m width per hour). For accurate samples of marginal transport rates of gravel and cobbles (4 to 256 mm in size), the sampling duration must be equal to or larger than the presumed transport frequency of the largest mobile particle size to be collected. Other prerequisites for accurate sampling of gravel and cobble bedload are a sampler opening large enough for cobbles to enter, while the sampler bag must have a sufficiently fine mesh to retain small gravel particles. The bag size must be large enough to hold the large quantity of smaller bedload particles that accompany cobble transport at the onset of motion. Bedload samplers with those criteria are not standardly available. We therefore developed bedload traps that have those attributes as initial motion samplers for gravel and cobble bedload (Fig. 1).

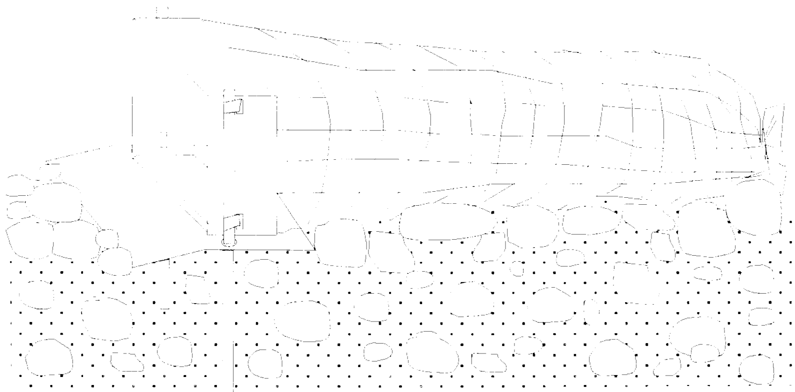

Fig. 1 Bedload trap for collecting gravel and cobble bedload.

METHODS

The bedload traps (Fig. 1) consist of a 0.3 by 0.2 m aluminum frame onto which a net 0.9 m long with a 3.9 mm mesh width is attached. For the 1-hour duration of each sample, the frame is fastened onto a ground plate anchored on the stream bottom. This arrangement frees the operator from holding the traps and avoids unwanted particle pick-up during trap setting or retrieval. Several bedload traps are deployed across the stream in 1 - 2 m increments (Fig. 2). Bedload was sampled with these bedload traps in four mountain gravel-bed streams with plane-bed or step-pool morphology (Table 1). At each stream, bedload was also collected with a 3-inch Helley-

Smith sampler (7.62 by 7.62 cm opening) using a standard sampling scheme (2 minutes per location spaced at 0.5 - 1 m increments across the stream).

Fig. 2 Bedload traps with ground plates at East St. Louis Creek in low flow (a); Emptying bedload traps at Little Granite Creek in bankfull flow. The open squares indicate the positions of 4 of the 6 bedload traps which are completely submerged by flow (b). Using a 3-inch Helley-Smith sampler at Little Granite Creek in bankfull flow (c). Arrows indicate flow direction.

SAMPLING INTENSITY

In order to quantify the differences in sampling duration and sampled width by the two samplers, we defined a relative sampling intensity I_r as

$$I_r = \frac{w_s \cdot n_s \cdot \Delta t}{w_{act} \cdot t_{tot}}$$

where w_s and n_s are the width and number of traps (or sampling locations for the Helley-Smith sampler) per cross section, and Δt is the sampling time. w_{act} is the active stream width and t_{tot} is the total time increment allotted to one sample. This time is set to one hour, since it usually takes about one hour to collect a bedload sample with a Helley-Smith sampler and 1 hour is a time period for which discharge can be assumed constant in a snowmelt highflow. Using 4 to 6 bedload traps across streams 6 to 12 m wide resulted in sampling intensities of 15 - 30%. Sampling the entire stream width continuously over the entire time period equals 100%. Sampling intensities reached 0.4 - 0.5% for the Helley-Smith sampler; a difference of a factor of about 50.

RESULTS

The long sampling duration facilitated by temporarily mounting the bedload traps onto ground plates permits collecting very small samples. The smallest possible transport rate obtained from collecting 1 particle of 4 mm per hour equals 0.1g/hr or 0.00003 g/s. When transport rates are high, the large opening size of the bedload traps and a large bag size permit collecting very large samples as well (e.g., 20 kg of gravel and cobbles per 6 minutes = 56 g/s). These attributes, a long sampling duration, a large sampler opening and a large bag size facilitate the collection of bedload samples that appear to accurately represent gravel and cobble transport rates. These transport rates span 6 or more orders of magnitude between lowest and highest flow. Transport rates measured with the bedload traps therefore increased steeply with discharge and the data scatter was comparatively low. Power function rating curves fitted to the bedload data were well-defined ($0.76 < r^2 < 0.91$) for all four streams (Table 1) and had high exponents between 8 and 16 (Fig. 3). High rating curve exponents between 5 and 20 have likewise been observed by other researchers who measured gravel bedload transport using long sampling times and large sampler openings.

Table 1 Characteristics of the four streams sampled and exponents of bedload rating and flow competence curves.

Stream	Drainage Area (km^2)	Q_{bkf} (cfs)	w_{bkf} (m)	Surface D_{50} (mm)	Surface D_{84} (mm)	Stream gradient	Stream type & morphology	Rating curve exponent trap	Rating curve exponent HS	Flow competence curve exponent traps	Flow competence curve exponent HS
Little Granite	55	200	14.3	69	141	0.017	B4, plane-bed	16.7	3.2	3.5	0.87
Cherry Cr.	41	109	9.5	49	152	0.025	B4, plane-bed	11.5	1.7	2.7	0.67
St. Louis Cr.	34	141	6.5	53	120	0.017	B4, plane-bed	9.0	3.2	2.4	1.01
East St. L. Cr.	8	26	3.7	108	258	0.093	A3, step-pool	8.4	3.6	1.5	1.03

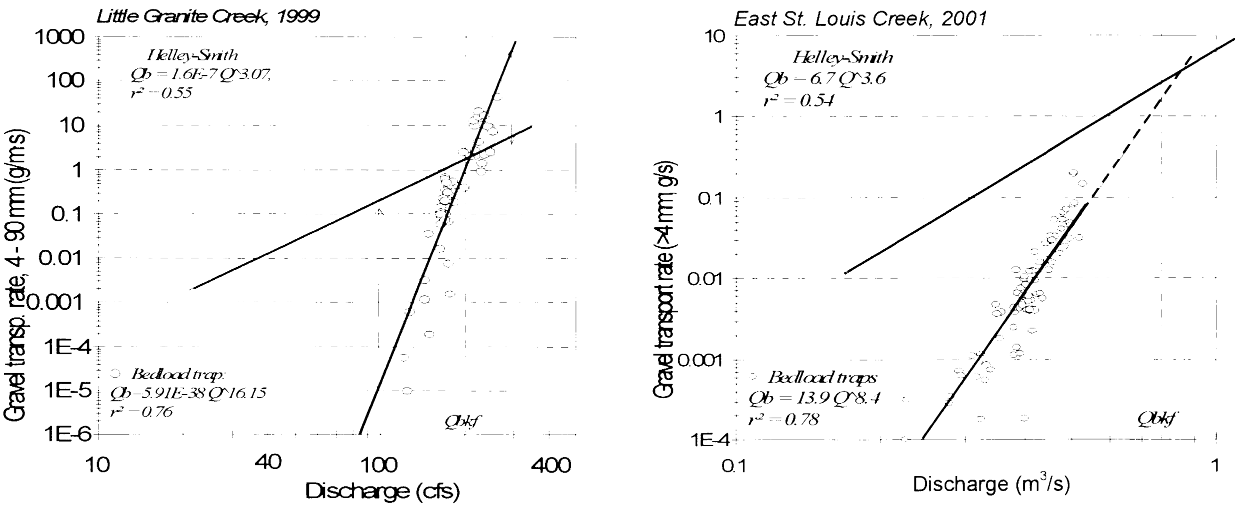

Fig. 3 Bedload transport rates and rating curves obtained from samples collected with bedload traps and a 3-inch Helley-Smith sampler at two gravel-bed streams. The gray-shaded areas in both plots represent the envelop of bedload transport rates computed from samples collected with the Helley-Smith sampler (320 samples for Little Granite Creek, 211 for East St. Louis Creek).

Gravel transport rates obtained from a 7.62 by 7.62 cm opening Helley-Smith samples had larger data scatter ($0.35 < r^2 < 0.59$) and lower rating curve exponents (1.7 to 3.6) (Table 1). For any given stream, the rating curves from the two samplers crossed between 1 and 1.3 times bankfull discharge (Fig. 3). At 0.5 of bankfull flow, the bedload trap rating curves were up to 4 orders of magnitude lower than the Helley-Smith rating curves, but up to 2 orders of magnitude higher at 1.5 of bankfull flow. Bedload rating curves for individual particle size classes and flow competence curves obtained with the bedload traps (Fig. 4) also had higher exponents than those from the Helley-Smith samples as well as less data scatter (higher r^2).

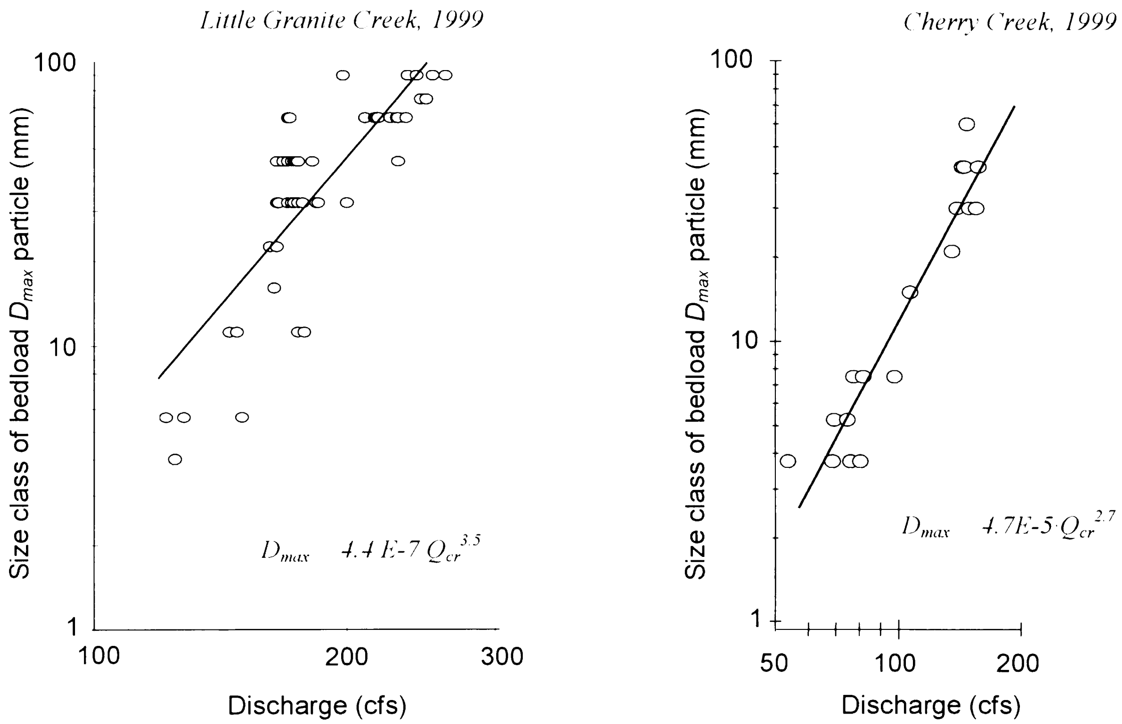

Fig. 4 Flow competence curves determined from samples collected with the bedload traps for two gravel-bed rivers.

Sampler dimensions and sampling durations affected not only transport rates and flow competence, but also the particle-size distributions of sampled bedload. Bedload collected with the bedload trap coarsened more pronouncedly with increasing discharge and the coarsening was more regular than for samples collected with a Helley-Smith sampler.

IMPLICATIONS

The sampler-dependent differences in sampled transport rates and particle-size distributions have implications for all subsequent computations that are based on measured bedload transport rates. The point of initial motion computed from transport measurement varies markedly between data sets obtained from samplers of different sizes and with different sampling durations. Critical discharge for gravel mobility is higher when computed from bedload trap samples than for

Helley-Smith samples.

Annual load computations are also affected by sampler differences. Annual bedload discharge computed from bedload trap samples is smaller for years of low flow and higher for years with high flows than annual bedload discharge computed from Helley-Smith samples. Effective discharge, which is calculated from a magnitude-frequency analysis and determines the flow that transports the majority of bedload in a given streams over the long run, if affected by the rating curve steepness as well. Effective discharge which seems to be in the neighborhood of bankfull flow in mountain streams when computed from bedload rating curves with exponents around 3 shifts to higher flows as exponents increase.

A new instrument to record sediment movement in bedrock channels.

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Introduction

Measurements of initial motion and bedload transport are difficult in alluvial streams but pose a particular problem in high-energy bedrock rivers. Not only is expensive instrumentation at risk of being destroyed, but suspension cables and support frames are usually inadequate to allow successful deployment. In addition there is a considerable risk to the safety of researchers in such environments. These problems may be addressed by the development of instrumentation which is robust during high-flows but which is deployed safely during low-flows. A long sampling period, with a high-frequency sampling interval, is required as sediment transport will not occur immediately after deployment, but only when a floodwave passes through the system. Finally the system needs to be cheap to allow for replication and for inevitable instrument losses in such hostile environments.

Instrument Details and Limitations

An instrument has been developed to detect the acceleration of a steel plate fixed to a rock riverbed upon being struck by a clast. A counting data logger is attached to the underside of this plate within a recess chiselled into the bedrock. Small commercially available rock-fixings are used to anchor the steel plate to the bedrock. The acceleration sensor itself is placed within the water-tight datalogger and it uses the same battery supply. The device is limited by the need to install it in low-water conditions and by its insensitivity to clast size. We have yet to properly calibrate the detection threshold of the device, but clasts as small as a few mm are detected. Importantly, it has shown to be reliable and rugged in the extreme environment presented by bedrock channels in flood. The device is relatively small; the dimensions of the logger being 8 x 6 x 3.5cm, whilst the impact plate is 15 x 13 cm and is 6mm thick (Fig. 1).

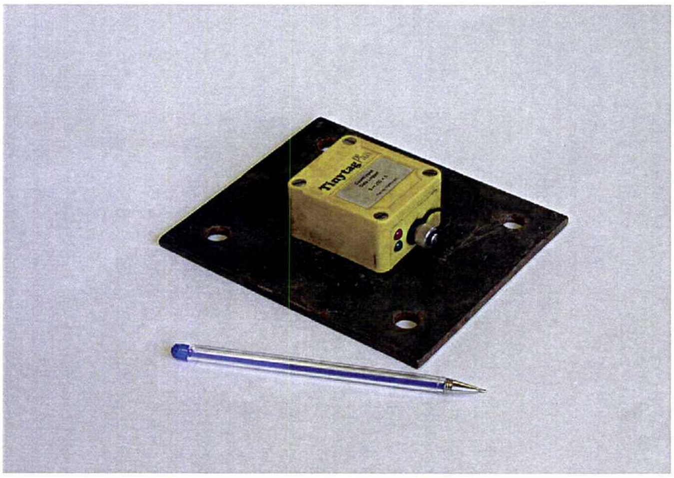

Figure 1. Impact sensor and impact plate shown in inverted position.

The internal battery is replacable and can power the unit for over six months. A version with a small external sensor is also under development for laboratory-flume experiments with sand size particles. At the time of writing the cost of the field unit is around £400.

There are some limitations to the sensors currently in use which need to be considered when interpreting data-charts. The sensors can record a maximum of 3 counts per second, and impacts which occur less than 1/3 second after the previous one are not recorded. This works out at 1800 counts in a

10 minute interval. The highest recorded count in the results presented below is 1850. This recording, and others of similar magnitude, therefore are probably saturated. In addition, the response of the sensors is not linear, as the likelihood of two impacts occurring less than one third of a second apart increases with transport rate.

Preliminary Results

To date, the main uses of the device has been (a) the detection of the thresholds of sediment motion and cessation, (b) relative intensities of transport through time and (c) comparison of simultaneous differences in transport intensities in different regions of a channel. Some recent results from the field (in Birk Beck, Cumbria, UK) are presented below for an 'extreme' flood during which flow velocities of 3.5m/s were measured directly and in which velocities commonly reach 4m/s. During this event, coarse gravel including large cobbles and rounded boulders up to 1m in diameter were moved through the test section. The largest tabular block known to have moved measured 1.5m x 1.0m x 0.5m. An uncalibrated pressure sensor, deployed in the same manner as the inpact sensors, initially produced useful results but was later destroyed. However all three impact sensors which were deployed, survived and gave excellent results (Fig. 2). In Figure 2 the main bedload transport occurred along the left side of the channel (left track) with a additional contribution along a central track. A further minor bedload track occurred near the right bank but transport intensities were too low to be visible in this figure. In view of the failure of the single pressure sensor, additional water depth data are reported, which were obtained from two non-invasive ultrasonic water level sensors mounted above the river. Depth was then determined from knowledge of the distance from each sensor to the bedrock surface.

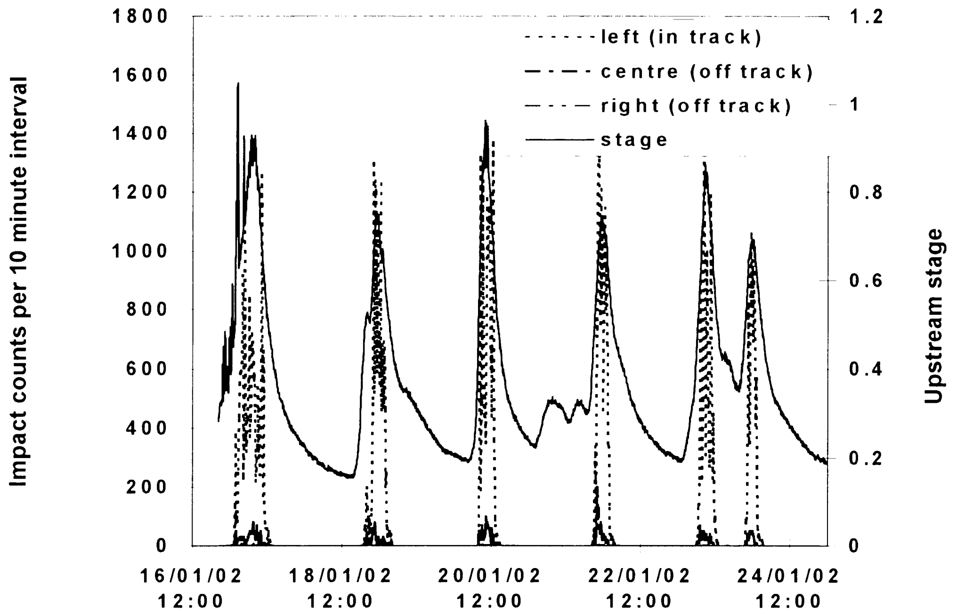

Figure 2. Variation in number of bedload impacts during the passage of six flood peaks.

Discussion

Bedload is routed along well-defined and narrow pathways within the channel, as shown by the distinctly different records of the three sensors. This conclusion is supported by qualitative observations. Specifically, during the prolonged summer low-flows, the bedrock surface becomes covered by algae. The first autumn floods scours the algae completely from distinct bedload tracks, leaving several visually distinct 'clean' ribbons of bedrock separated by algal-covered areas. There is a well-defined critical shear stress for bedload transport that is detectable by the sensors of 40 - 50 Nm^{-2}. Using a Shields' parameter of $\theta = 0.045$ within the well-known Shields' threshold entrainment equation a minimum detectable grain size of 55 - 70mm is indicated. Nevertheless, the critical shear stress for initiation of transport (as detected by the sensors) is variable between events, and occurs between 40 and 100 Nm^{-2}. In contrast, the critical shear stress for the cessation of transport is more constant at 40 – 50 Nm^{-2}. Consequently, during any single event, the graph of recorded bedload impacts versus shear stress shows a hysteresis of bedload transport, in which transport persists at lower shear stresses than those required to initiate it (Fig. 3).

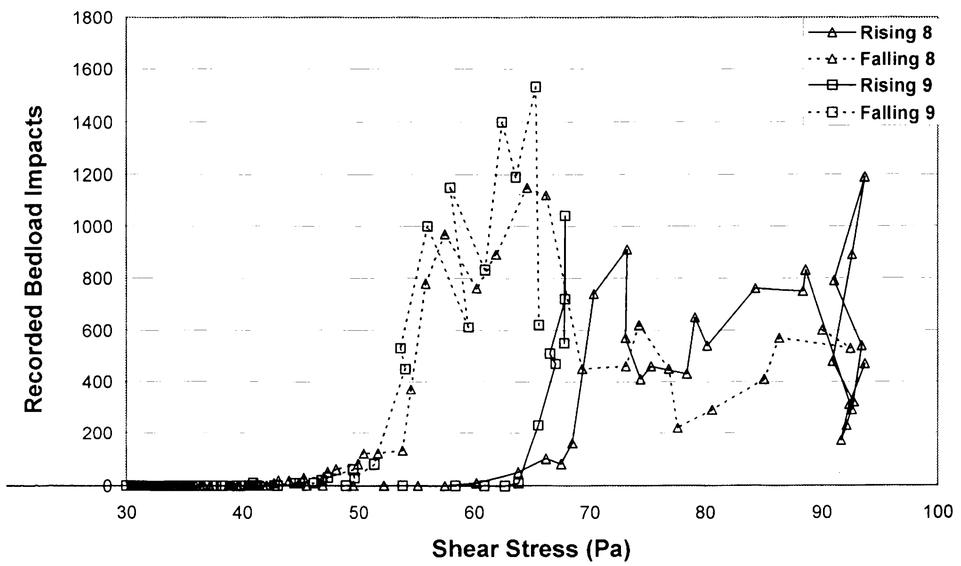

Figure 3. Hysteretic behaviour of bedload transport intensity for flood events 8 and 9.

Although the curves are variable in shape, they generally indicate increasing bedload transport with increasing shear stress above the threshold. During falling stage, transport rates show a gradual decrease at first, followed by a more rapid decrease as the threshold is approached from above. The peak transport rate may even occur during falling stage. In fact, although the curves during rising stage are variable, the falling stage curves often overlie each other. Some few events, for example 8 and 9 (Fig. 3) are very similar in behaviour. Although transport rates show an increasing trend with stage above the threshold, transport rates are highly stochastic and illustrate the pulsing nature of bedload. No clear trends over the period of the record can be identified, nor do the very large events appear to have an effect on the subsequent events. However these latter two observations may reflect the length of the period of monitoring. A longer study period might indicate seasonal or event-by-event exhaustion effects (see Carling and Hurley, 1987).

Conclusion

I new robust bedload sensor has been developed for deployment in high-energy bedrock channels. The instrument has provided high-quality data on initiation and cessation of motion of bedload. In addition, the variation of relative transport intensity during individual flood events has been recorded at a fine time-resolution enabling the detection of pulsing in bedload motion and distinct hysteretic behaviour when comparing the waxing and waning limbs of hydrographs.

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Long-term close-interval monitoring of suspended sediment transport in meltwaters draining from an Alpine glacier

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BACKGROUND

Suspended sediment concentrations and fluxes in meltwater rivers draining from mountain glacierised basins vary considerably at a range of temporal scales, from hour to hour, day to day, month to month during the annual cycle of runoff, and from year to year. These variations are influenced both by changing hydrometeorological and climatic conditions, and by interactions between evolving characteristics of the subglacial drainage network and the glacier bed. Irregularity of sediment flux through time results from residual winter flow through remaining small pathways having inadequate velocity to entrain even fine sediment. Rising discharge in spring and early summer transports disproportionately large quantities of sediment by comparison with higher flows later in the ablation season (e.g. Østrem 1975, Collins 1990). This seasonal pattern of sediment flux is punctuated, particularly in the earlier part of the season, by pulses lasting for hours through several days, as rising discharge, initial increased water pressure in subglacial hydrological pathways and concomitant glacier motion develop subglacial drainage pathways. Evolution of the drainage network beneath a glacier each year follows the timing, quantity and seasonal pattern of discharge, which in turn reflect climatic conditions. Winter snow accumulation interacts with summer energy conditions for melt to generate the seasonal discharge cycle. Measurements of sediment content of meltwaters, together with discharge, have to be sufficiently closely spaced in time to capture pulses which provide glaciologically-relevant information about sudden changes in, and seasonal development and evolution of the subglacial drainage network, as well as indicating seasonal and year-to-year variations in suspended sediment flux associated with climatic variation at the scale of tens of years.

MEASUREMENT PROGRAMME AT GORNERGLETSCHER

Samples of meltwater and suspended sediment have been collected from the Gornera, the only river draining from Gornergletscher, Pennine Alps, Switzerland, at the gauging station located ~750 m from the glacier portal, every hour, 24 h d^{-1}, from as early in the ablation season as practicable until mid-September, every year for 28 years, since 1974. Initially, this close-interval sampling programme was designed with a view to determining sediment concentration-discharge dynamics in order to provide information on subglacial processes and conditions. The measurements have continued, providing estimates of sediment concentration and flux in the Gornera from year to year through almost three decades. In that period, mean summer air temperature at Grächen, about 20km north of the basin, increased by 1.7°C, and annual total discharge of the Gornera varied in the range -40 % to +30 % of the period mean, being generally lower in the 1970s than subsequently (Collins *et al.* (in press)).

Since 1983, a Manning S-4050 automatic pumping sampler has been programmed to draw up samples of meltwater and suspended sediment. The samples have been collected from the same position in the cross section with the orifice at the same fixed height above the base of the gauging structure. Until 1982, samples were collected using a mechanical North Hants Engineering Company Mark 4 automatic liquid sampler, which was initially located about 400 m upstream of the gauge, with the aim of collecting samples as close as practicable to the glacier terminus. Subsequently the sampler was repositioned on the gauging structure, with the sampler hose intake nozzle at the same position as that subsequently occupied by the Manning sampler. All samples were filtered under pressure or vacuum through individually pre-weighed Whatman No. 1 papers and the quantity of sediment retained determined gravimetrically. Suspended sediment flux (kg s^{-1}) was obtained as the product of sampled sediment concentration (g L^{-1}) and hourly average discharge (m^3 s^{-1}), and daily total suspended sediment load was calculated from the 24 hourly suspended sediment flux values. The aims of this paper are to examine characteristics of the dataset assembled for the Gornera with respect to long term homogeneity, and to compare estimates of sediment concentration obtained from samples collected by Manning and North Hants instruments.

LONG-TERM SUSPENDED SEDIMENT FLUX DATA

Examples of suspended sediment data collected for the Gornera, resolved as daily total sediment fluxes, are shown in Fig. 1 for the five years 1990 through 1994. Salient features of the annual pattern of suspended sediment flux result from the interaction of the developing glacier drainage system with glacially-abraded sediment stored beneath the glacier sole.

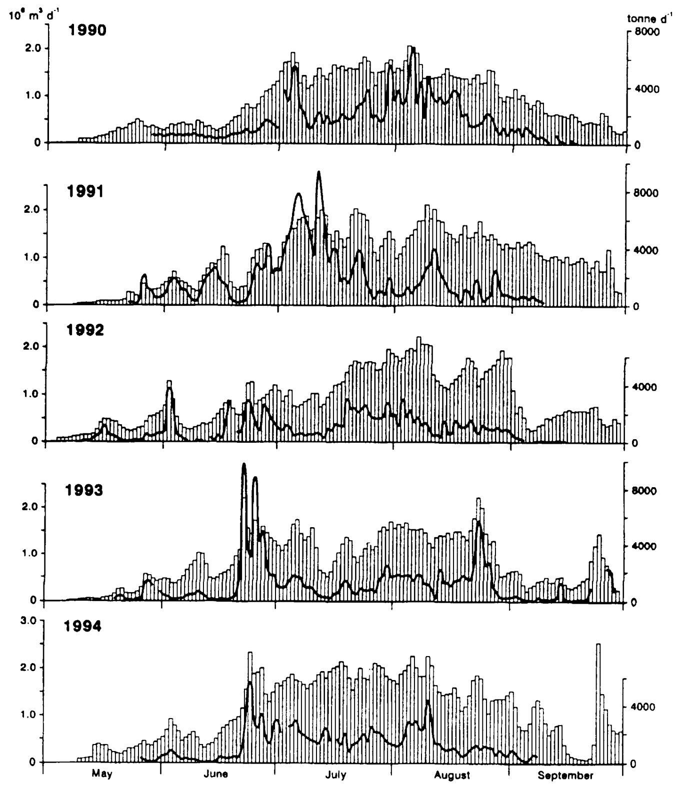

Fig. 1 Daily total discharge (columns) and daily total suspended sediment flux (curves) in the Gornera, in the months May-September in the years 1990 through 1994.

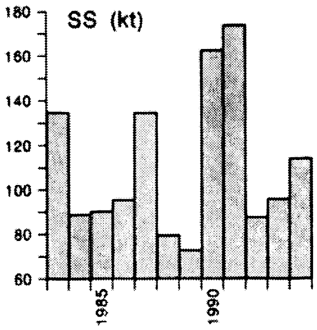

Fig. 2 Suspended sediment flux (SS) in the Gornera between 27 June and 11 September for the years 1983 through 1994.

Major instabilities in the subglacial drainage network are indicated when sediment flux rises for a few days above the background level for a particular part of a season. Almost all the major sediment flux events occurred during times of generally rising discharge, and were more frequent and often larger at the start of summer. Later in the season, flux events were usually associated with rainfall events. Significant flux events occurred each time discharge exceeded levels not previously reached for some time, as meltwater penetrated areas of glacier bed formerly hydraulically isolated, on which sediment remained stored (Collins 1996). Interpolating for missing data, considerable variation occurred from year to year in total suspended sediment flux in the Gornera for the period 27 June through 11 September each year (Fig. 2).

Mean annual suspended sediment flux for the period was 117 kt (1.427 kt km^{-2} yr^{-1}), and the range –35% to +45% of the mean. There appears to be no simple relationship with annual discharge and climatic conditions. In the years illustrated, 1994 had the largest annual

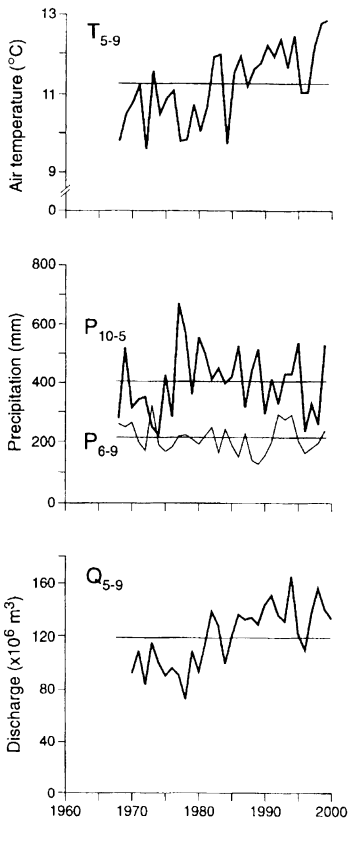

Fig. 3 Year to year variations of T_{5-9}, P_{10-5}, P_{6-9} and (Q_{5-9}), 1970 – 1999.

discharge in the period 1970-2001 (but was only the third warmest summer), 1991 and 1990 third and fourth, respectively, and 1989 thirteenth. Variations in mean summer air temperature (T_{5-9}) and winter (P_{10-5}) and summer (P_{6-9}) precipitation at Grächen, and total summer runoff in the Gornera (Q_{5-9}), between 1970 and 1999 are shown in Fig 3.

DATA HOMOGENEITY

Samples from which suspended sediment concentration data for the Gornera have been derived were collected by a Manning pumping sampler operating under standard conditions since 1983. The samples collected, of between 150 and 230 ml, are unlikely to be representative of sediment concentration throughout the cross section. With the intake a fixed distance from the bed, samples are collected at varying fractional depths of changing water surface levels in the gauging structure. Hence, sampled sediment concentrations between warmer years, with higher discharge, and cooler are likely to be influenced by nozzle position. Experiments to compare sampled suspended sediment with nozzles suspended at a fixed depth and a depth varying with water surface level fluctuations have been undertaken.

Before 1983, and without an overlap period with the Manning sampler, a vacuum North Hants sampler was used for 9 ablation seasons. An experiment to compare suspended sediment concentration obtained by simultaneous collection by the two instruments from the same depth throughout a range of discharge levels has been undertaken, with a view to assessing relative sampling efficiency. Aliquots of between 450 and 750 ml of meltwater and sediment were collected by the North Hants sampler, fired in a parallel hourly sampling programme alongside the Manning.

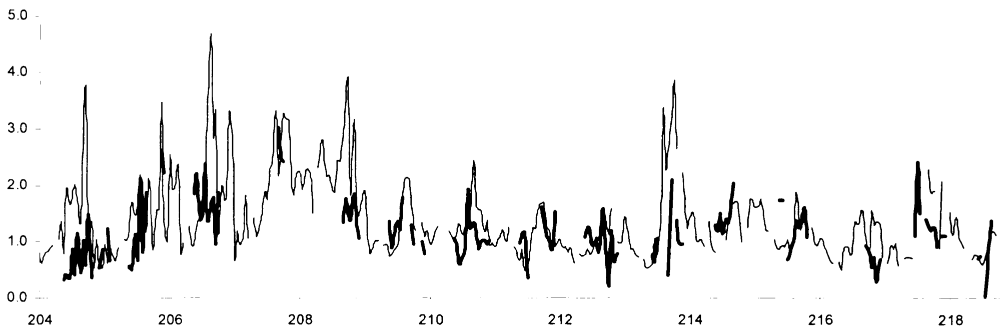

Fig. 4 Sediment concentration (g l^{-1}) in simultaneous pairs of samples collected from the Gornera by Manning pumping sampler (thin) and North Hants (thick) during 15 days from 23 July to 6 August.

The North Hants sampler appears to collect samples which generally imply lower suspended sediment concentrations in the Gornera than those drawn up simultaneously by the Manning. At times when sediment concentration in the Gornera is relatively low, however, the North Hants can outperform. A plot of the pairs of sediment concentration estimates obtained from the two samplers indicates poor association, the correlation coefficient being 0.33 (Fig. 5). Intra-sampler variability is great, and individual pairs of estimates can differ 4 fold. Sediment pulses are identifiable using both samplers. Estimation of suspended sediment flux is more problematic. However, comparison of estimates of sediment concentration provided by replicate samples collected by the Manning sampler (actually not

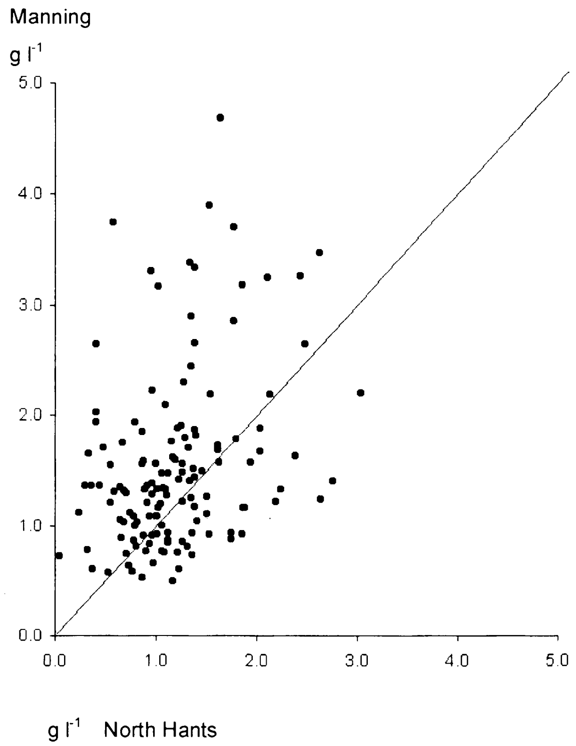

Fig. 5 Plot of paired estimates of suspended sediment concentration obtained from Manning and North Hants samplers. The diagonal line indicates equal estimates from both samplers.

simultaneously but over three minutes at xx.59 h, xx+1.00 h and xx+1.01 h for logistical reasons) suggest precision may be low. Analyses are presented of how precision and intra-sampler variation are influenced by discharge.

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Bed load measurements with a passive magnetic induction device

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Bed load movement was monitored from 1993 to 1999 on a small stream in the headwaters of the Fraser River in northern British Columbia Canada, as part of the Stuart-Takla Fish-Forestry Interaction Project. The investigation entailed three components: (a) tracer studies, to obtain information on the distance of travel and depth of burial of clasts (b) repeated topographic surveys, to develop volumetric estimates of nival and summer flood events and (c) a passive-magnetic bed load detection device spanning the channel to record the passage of coarse clastic material. This paper will discuss the results of the Bedload Movement Detector (BMD) from the 1999 nival flood event.

In 1997 the Bedload Movement Detector device was installed in the riffle section of a small forest channel. The device consists of an array of 82 magnetic sensors set in an aluminum housing, mounted on an adjustable frame that may be raised or lowered to compensate for changes in streambed elevation. The sensing surface is set flush with the streambed. The sensors are disk-shaped (4 cm high x 8 cm diameter) and spaced 2 cm apart along the 8 m length of the device. Ferromagnetic minerals in particles passing over the sensors induce small electrical currents. Sufficient magnetism is found in most sedimentary and metamorphic rocks, that moving particles of pebble and cobble size, can be detected. The apparent lower size limit of detectable particles, under laboratory conditions, is 1 to 2 mm. The signal duration is proportional to the size of the clast and the velocity of transport. The signals generated from passing particles are sampled at 100 hz by a data acquisition system and stored on a computer hard drive. Further details of the construction and calibration of the BMD can be found in Tunnicliffe *et al.* (2000) and Tunnicliffe (2000).

The Bedload Movement Detector is installed on O'Ne-ell Creek at a site 8 m wide with a slope of 0.013, a peak discharge about 20 m^3 sec^{-1}. The channel has a forced pool-riffle morphology with an abundance of large woody debris. The sampled reach has a coarse gravel bed with a mean grain size of 42 mm. The largest clasts are approximately 300 mm. Clast lithologies and thus magnetic properties are extremely variable.

Bed load movement occurs annually during the peak of the snow-melt flood in May or June. O'Ne-ell creek has relatively little suspended sediment transport. At the sample site the streambed could be visually observed from a catwalk for much of the 1999 flood. At the peak of the 1999 nival flood sediment movement, approximately $3x10^5$ particle passages per hour were detected (Fig. 1).

The 1999 flood was unusual. A cool cloudy spring and high snow accumulations resulted in the snowmelt period being prolonged over about six weeks. Peak discharge was relatively low. Stream flows were just below that sufficient to initiate bed load movement from May 25 to June 9. During this time sporadic movement of only single particles and bursts of finer material was observed. Between June 10 and June 12 the rate of entrainment increased, and sensors detected "batches" of larger-sized material crossing the device. Sampling with a small basket net yielded maximum particle sizes of 20 to 30 mm. Particle counts ranged from 0 to 35 per second. As the stage rose during the afternoon and evening of June 12, increasingly intense waves of sediment passed over the device. Inter-granular collisions, and the sheer volume of material in motion, often blurred the distinction of passing particles. Peak particle counts exceeded 100 to 150 per second. At times, the material seemed to pass in steady sheets. The activity continued until about mid-day on June 13, when the amount of material in transit subsided for a few hours and then resumed and reached a maximum on the evening of June 13. There was clearly an abundant supply of material entrained by the high flows, and the bed load discharge continued even as the stage level dropped during the mid-day period of June 13.

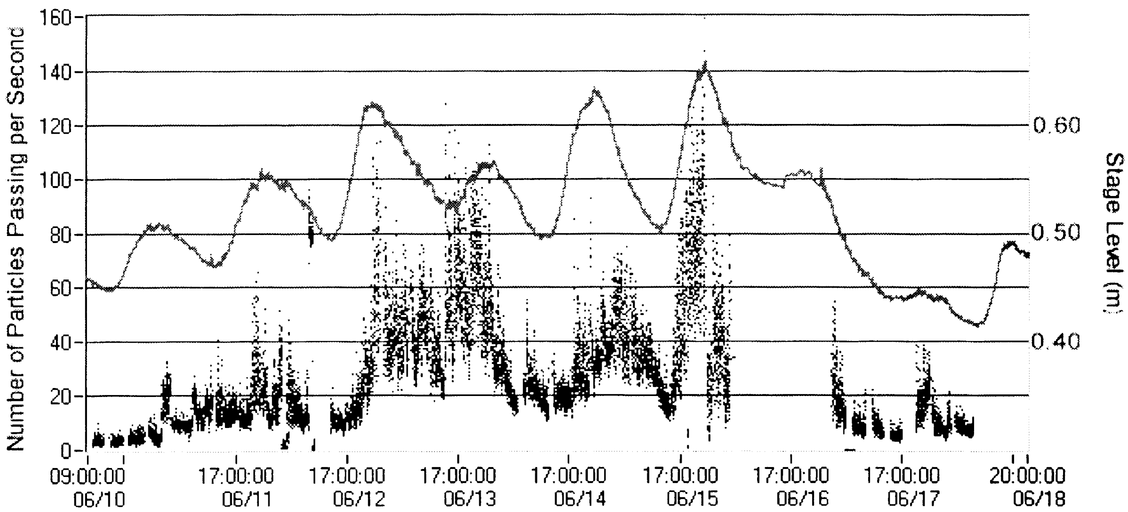

Fig. 1. Rates of particle transport (number of events per second) over the course of the flood.

With the ample availability of material for transport, the batch effect becomes less pronounced, and we observed the onset of pulses of multi-minute duration. In the intervals between pulses, the transport rate drops substantially. A condensed record of 24 hours at this peak stage is shown in Fig. 2.

The final portion of the bed load transport interval, June 14 to 17, features one or two narrow transport zones, 1-2 meters wide, which migrated laterally by about one meter. Material in transport was sand to small pebble size.

Temporal variation in transport rates

Pulses of sediment movement occurred during the flood at a variety of scales. Snowmelt flows in O'Ne-ell Creek show a clear diurnal discharge cycle. As flows reached competent velocities each evening from June 12 to June 17, high rates of coarse bed load movement commenced. The transport commences abruptly (Fig. 3), presumably as clusters and patches of the stream bed disassemble and are entrained (Kuhnle and Southard (1988), Brayshaw *et al.* (1983)).

Within the frame of this daily cycle, the transport rate vacillates considerably on a time scale measured in minutes, independent of channel flows. There appears to be no dominant cyclic period, though the interval between pulses ranges from 5 to 20 minutes. Although previous authors (Gomez et al., 1989, Kuhnle and Southard, 1988, Whiting et al., 1988) have attributed this kind of variation to the migration of bedform elements such as bed load sheets, bars or ripples, it is not clear from our limited observations of upstream conditions that this is the operating mechanism in the forced pool-riffle morphology of O'Ne-ell Creek. The reach is in an approximate equilibrium, with no marked tendency for aggradation or degradation. Fig. 3 shows a summary of an hour and a half of bed load activity, with at least 10 distinct surges in bed load activity. The data are plotted assuming a transport velocity of about 1m sec^{-1}, to show that the length of the passing pulses is comparable to their width.

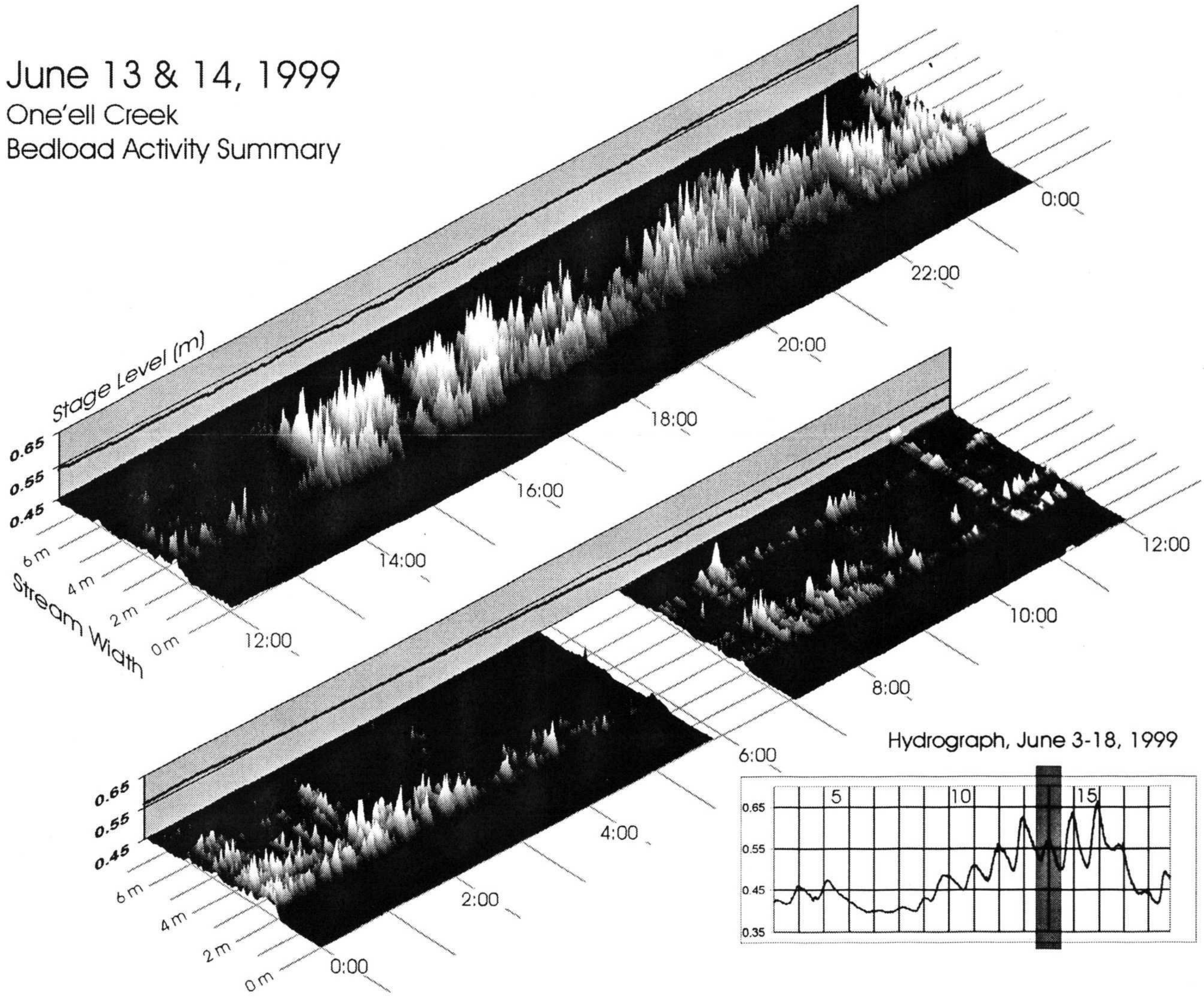

Fig. 2. Summary of bed load movement June 13-14 1999. Bed load movement commences abruptly with increase in stage at about 14:00 on June 13. Pulses of sediment movement of variable intensity and duration continue to 00:30 on June 14. As the overall sediment flux declines in the early morning, bed load movement is confined to one to three streets.

On the finest scale, that of seconds, particle movement is concentrated into batches. At high sediment discharge rates, velocity and size of individual particles becomes difficult to determine because batches of sand and gravel particles are moving across each sensor simultaneously. This is due mostly to the stochastic nature of bed load transport, related to near-bed turbulence, obstacles along the transport path and breakup of clusters.

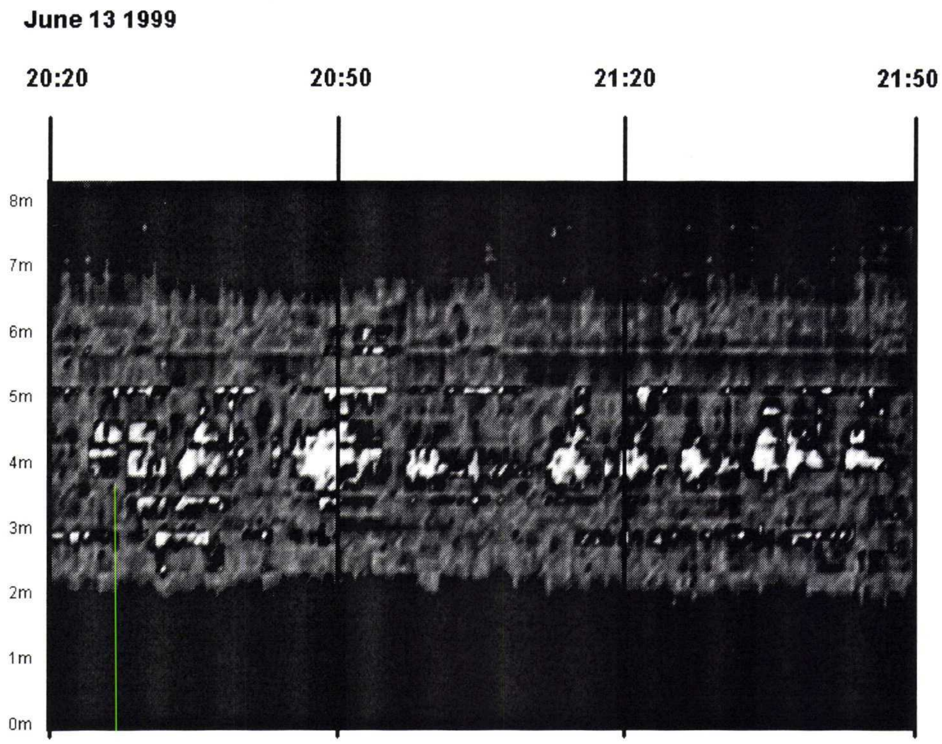

Fig.3. Transport of pulses of sediment past the Bedload Movement detector during an interval of high transport rates.

Lateral instability in the transport record

Over the course of the 1999 flood, bed load movement involved nearly all of the streambed. Total signal intensity for each sensor channel was summed for each sampling period, generally about three hours. The point of maximum bed load transport activity in the stream cross-section, the locus of transport, is shown in Fig.4. Early and late in the flood, when small volumes of bed load were in motion, transport was concentrated close to the deepest portion of the channel, the thalweg. During the peak of the nival flood, most of the channel was simultaneously active; however the point of greatest transport migrated widely across the channel and back. The 1999 nival flood produced little change in the streambed. Previous studies of nearby reaches, using repeated total station surveys (Poirier, 2002), show modest alteration of nearly all of the streambed during nival floods, with complex patterns of scour and fill averaging one to two clasts thick.

During the flood, 14.41×10^8 particle signals were recorded by the BMD at O'Ne-ell Creek. We attempted to estimate the volume of transport making a number of simplifying assumptions, including: that the variation in magnetic intensity is uniform for various size clasts, and is similar in character to the bed material; that the material in transport has the same composition and size distribution as the streambed; that 30% of the moving particles are detected, that only particles >4 mm are detected, and that intervals of peak sensor response represent single sediment particles. With these assumptions the estimated volume is 7.88 m^3 Independent estimates for transport rates on this stream and an adjacent similar stream were determined in previous years by repeated detailed mapping of the stream bed and by magnetic marker studies (Gottesfeld (1998), Poirier (2002)). These estimated transport volumes agree within a factor of two.

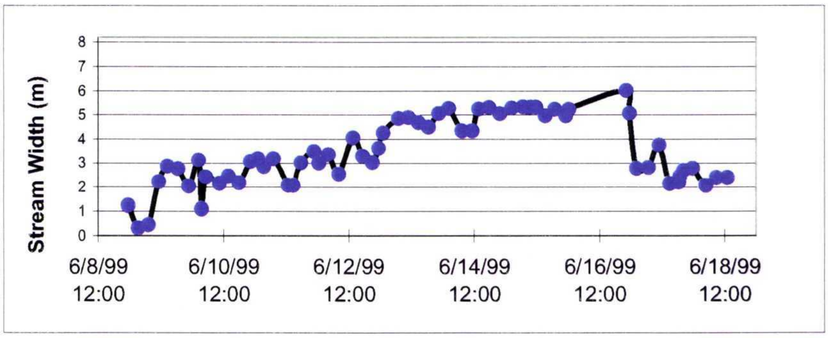

Fig.4 – The wandering locus of transport in the 1999 nival flood. The locus of transport moved substantially throughout the event, starting within roughly 1 m of the right bank (June 9) and drifting to within 2 m of the left bank (June 15-16).

The problem of identifying single grains with assurance complicates calculation of apparent velocity. At present we are unable to separate the velocity and size components in the sediment passage record. In a stream with simpler lithology the amplitude of the voltage response of the sensor would provide a scale for clast volume and permit calculation of apparent velocity.

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Recent development of sediment monitoring of glacial rivers in Iceland

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INTRODUCTION AND METHODS

Water resources are of great abundance and importance in Iceland. Much of the water within the hydrological cycle, both groundwater and surface water, originates from glaciers, which cover approximately 10 percent of the land surface. Hence, most of the largest rivers in Iceland are glacially derived and transport great amount of sediment within their course from the glaciers towards the ocean.

The extreme sediment transport within the glacial rivers raises numerous technical and environmental questions, many of which are related to hydroelectric development of the rivers. Therefore, sediment sampling in Icelandic rivers has been an integrated part of the river monitoring carried out by the Hydrological Service in Iceland during the last 50 years. Throughout this time samples of suspended sediment have been obtained predominantly from rivers with potential for hydroelectric power generation, or rivers subject to glacier outburst floods (jökulhlaups). Since 1963 measurements of grain size and total dissolved sediment have been made on over 10.000 suspended sediment samples, in addition to measurements of total suspended sediment concentration that were started in 1949 (Fig. 1). During the decades, the continuous data set has expanded greatly and today it comprises the basis of all evaluations of sediment transport in Icelandic rivers.

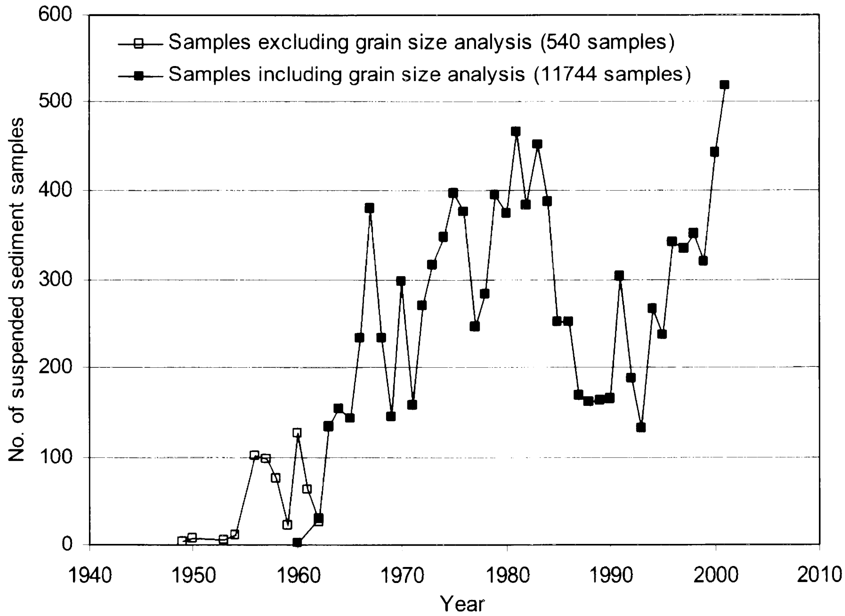

Fig. 1 Number of suspended sediment samples collected in Iceland at the Hydrological Service.

Figure 2 shows the sampling locations of the suspended sediment program in effect during the year 2001. During that year, over 500 suspended samples were obtained from 41 locations. The number of samples at each station (1–95) and quality of the samples ranged greatly among the stations as in some instances they were a part of a detailed integrated sediment study, but in other cases a part of an annual sediment monitoring program.

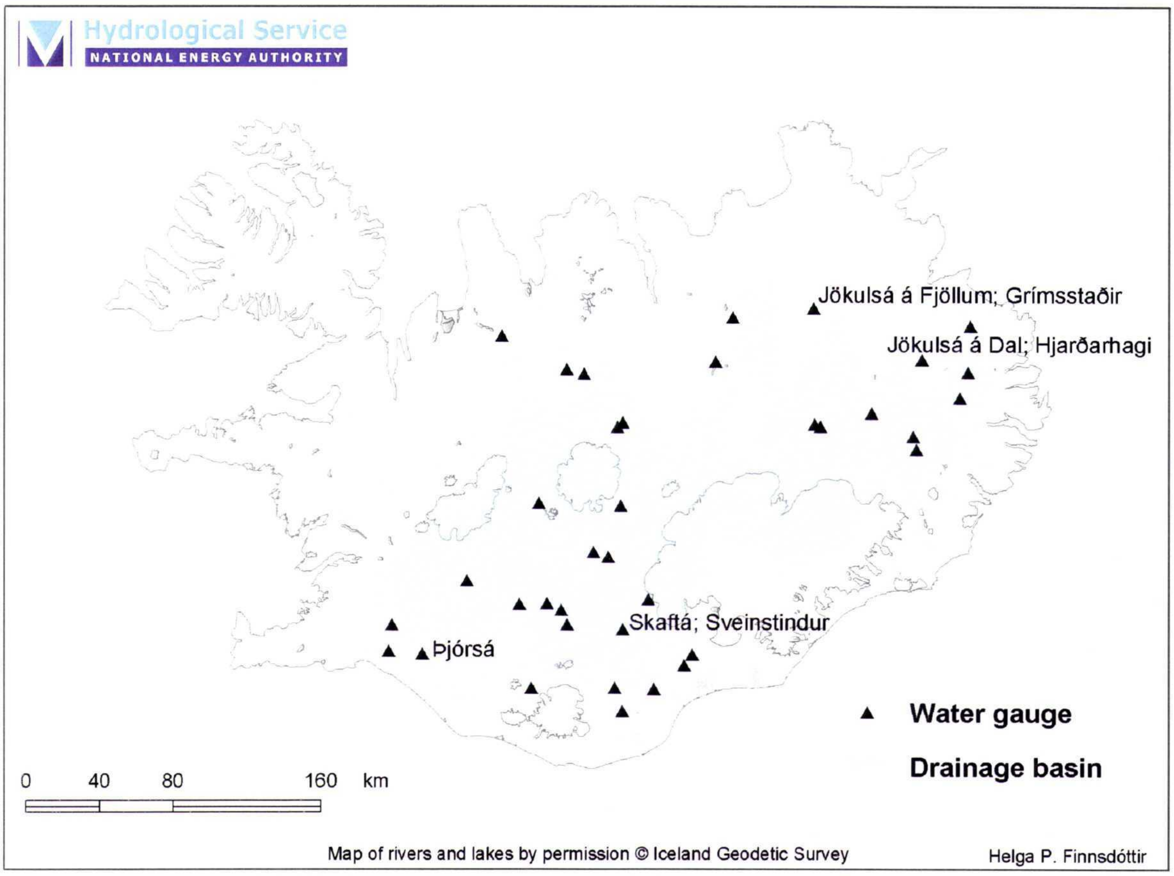

Fig. 2 Suspended sediment sampling sites in 2001.

Bed-load sampling has on the contrary been a negligible part of the sediment monitoring of Icelandic rivers (Palsson, 2001). A major step forward was taken in 2000 when a pilot bedload sampling program was initiated in Jökulsá á Dal, a river in Northeast Iceland studied for possible hydroelectric development (Fig. 2)(VST & Orkustofnun 2002). Bedload sampling had not been employed in any detail at the Hydrological Service before, as the great current speed in the Icelandic glacial rivers was thought to prevent such measurements. Results from the pilot study in Jökulsá á Dal proved very satisfying, despite the loss of one sampler, and subsequently extensive total sediment programs were established in three other glacial rivers that are presently studied as possible hydroelectric projects.

During the year 2001, bed-load samples were taken from cableways on four of the largest glacial rivers in Iceland, i.e. Jökulsá á Dal, Jökulsá á Fjöllum, Thjórsá, and Skaftá (Fig. 2, Table 1).

Table 1 Number of bed-load samples collected and analysed in 2001 at the Hydrological Service.

River and location	No. of trips	No. of weighted samples	No. of grain size measurements
Jökulsa a Dal, Hjardarhagi	3	300	30
Jökulsa a Fjöllum, Grimsstadir	2	176	32
Thjorsa, Krokur	9	745	76
Skafta, Sveinstindur	2	109	40

The samples were collected with a Helley-Smith cable-suspended bed-load sampler on 5–10 locations on each river transect during 2–9 sediment campaigns carried out at each river. Two types of samplers were used, the 105 lbs (47.7 kg). Helley Smith sampler with a 3" x 3" opening and a 3.22 expansion ratio, and the heavier 167 lbs (75.8 kg) sampler with the 6" x 6" opening, but the same expansion ratio.

All the samples were weighted on location, but selected samples from each river were dry-sieved to establish grain-size distribution of the bed-load material. After collecting 10 or more samples at each location on the river transect during each trip, the total mean bed-load transport was calculated in several steps. First the bed-load transport of each sample at each station was calculated by dividing the weight of each sample (in grams) by the time interval the sampler sat at the riverbed. The mean transport at each station was then calculated by:

Mean transport at each station j
$$q_{b_j} = \frac{1}{n_j}\sum_{i=1}^{n_j}\frac{M_i}{t_i d}$$

where M_i is the mass of sample i (in grams), t_i is the sampling time (in seconds) for sample i, d represents the width of sampler opening (0.0762 m), and n_j is the total number of samples at station j.

Total transport through cross section
$$Q_b = \frac{q_{b1}}{2}x_1 + \frac{q_{b1}+q_{b2}}{2}x_2 + \ldots + \frac{q_{bn-1}+q_{bn}}{2}x_n + \frac{q_{bn}}{2}x_{n+1}$$

where Q_b is in g/s and x represents the distance between sampling points, between a marginal point and the edge of the water surface, or that of the moving strip of stream bed (World Meteorological Organization, 1994).

If the discharge varied greatly over the sampling period, the procedure above was carried out in steps for each discharge interval, which were finally added together.

CASE STUDY –THJÓRSÁ RIVER, SOUTHERN ICELAND

The most extensive study was done at Krókur on Thjórsá river, southern Iceland (Fig. 2), where bed-load samples were taken at variable discharge values during nine sediment campaigns in 2001, and during a 10-year-flood in January 2002 (Table 2). Close to 800 bed-load samples were collected with the Helley-Smith 47.7 kg cable-suspended sampler at 7–10 stations during each campaign.

Great difference is seen in bed-load transport among the stations within the river channel (Fig. 3). Most of the bed load is transported in a narrow gully between 50 and 70 m distance from the house, which is situated *ca.* 18 m from the river bank. In contrast, only a minor fraction of the bed load is transported at other stations closer to the river banks. Furthermore, grain size measurements of the bed-load samples show that the coarsest sediment is transported at the 50–70 m stations, or at the same locations as where the transport is greatest.

Table 2 Results from bed-load sampling at Thjórsá in 2001 and the January flood in 2002.

Campaign date	Station locations m from house	Mean discharge ($m^3 s^{-1}$)	Total integrated bedload transport ($g s^{-1}$)
11–14 July 2001	40.50.60.70.80.90.100.130.160.180	351	4706
23–25 July 2001	40.50.55.60.65.70.80.100.140.180	320	4992
31–1 August 2001	40.50.60..65.70.80.140	326	8716
8–9 August 2001	–	327	9523
13–14 August 2001	–	326	9281
23–24 August 2001	–	442	13076
29–30 August 2001	–	342	9787
18–19 September 2001	–	352	8689
19–20 December 2001	–	352	5603
10 January 2002	–	1326	134331
11 January 2002	–	1066	36999
12 January 2002	–	550	11148

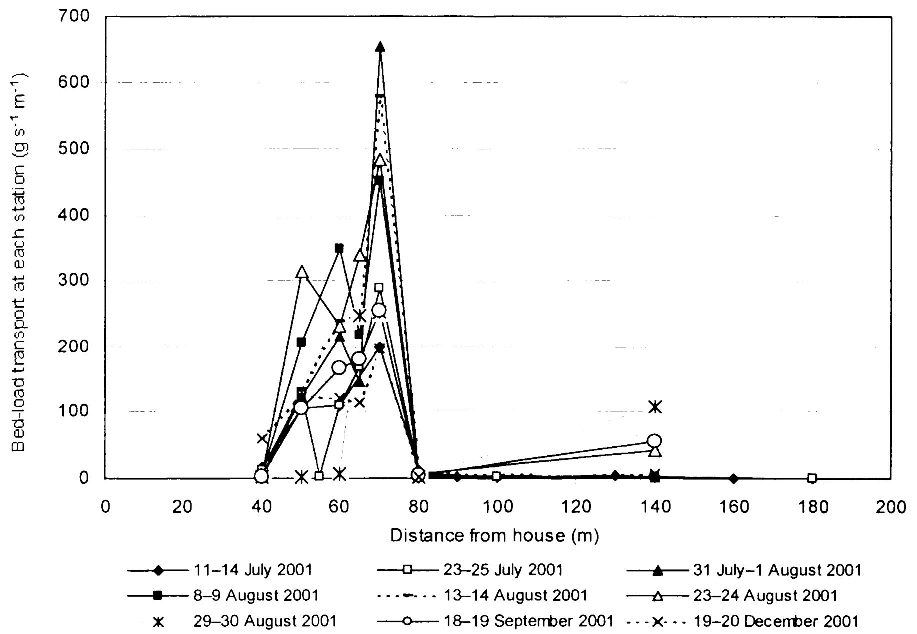

Fig. 3 Mean bed-load transport at each station in Thjórsá during sediment campaigns in 2001.

Total bedload transport ranges from *ca.* 4700 to 13000 g s^{-1} during sediment campaigns in 2001, but is greater than 134000 g s^{-1} during the peak of the 10-year-flood in January 2002 (Table 2, Fig. 5). The flood was triggered by a winter rainstorm with heavy precipitation melting fresh snow cover on frozen ground.

The correlation between total bedload and discharge for the sampling campaigns in 2001 is poor as we have large distribution of total transport at the same discharge interval. The poor correlation is probably to some extent related to the narrow distribution of discharge values during the year 2001 and shows that we especially lack data from low and high discharge periods. Hence, the three values obtained in the January flood 2002 extended the curve considerably and suggest a semi-exponential correlation between the discharge values and bed-load transport. However, more transport values at high and low discharges have to be determined before the correlation between these parameters can be evaluated with greater certainty.

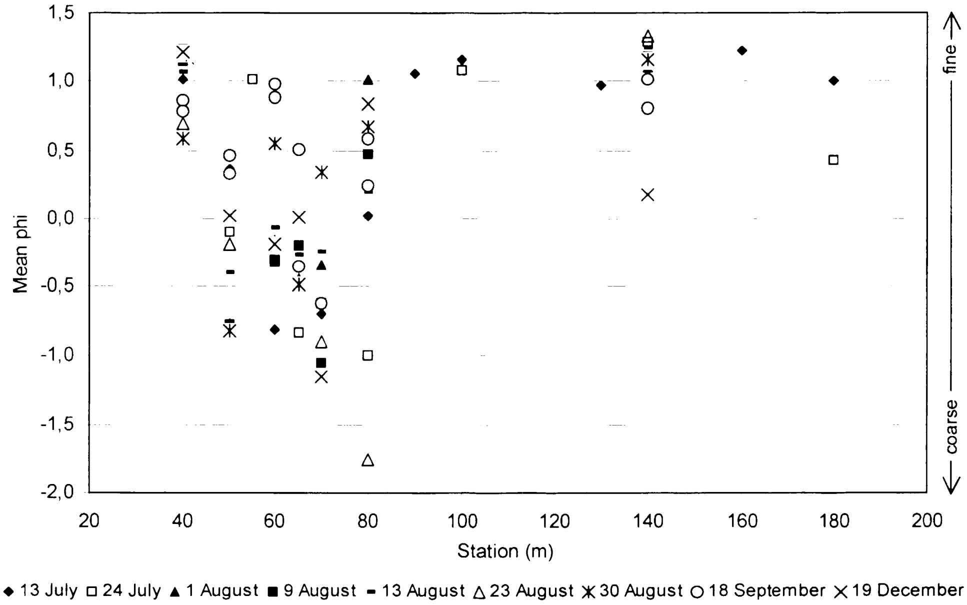

Fig. 4 Mean grain size (in phi values) of sieved bed-load samples collected in Thjórsá in 2001.

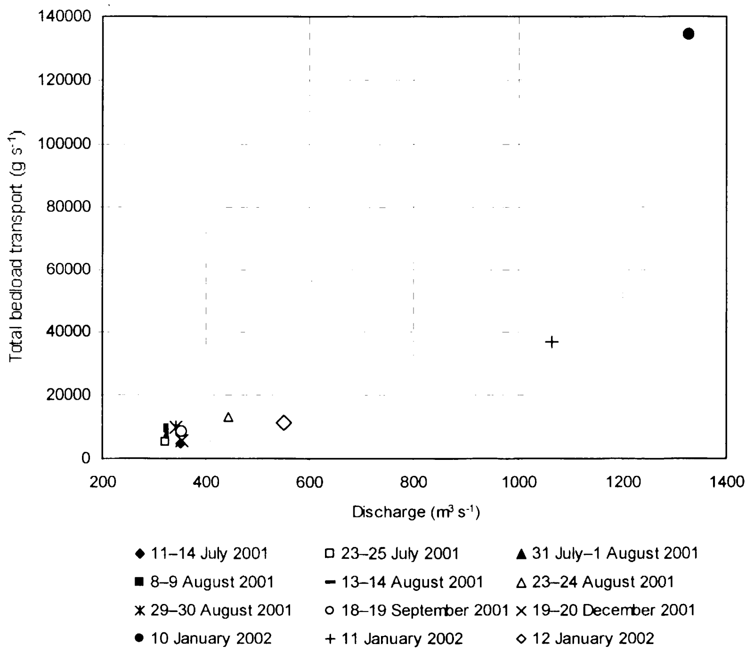

Fig. 5 Total bed-load transport in Thjórsá during sediment campaigns in 2001 and January flood in 2002.

The wide distribution of bedload transport values shows well the stochastic nature of bed-load transport, as bed load is transported in pulses rather than in a semi-continuous stream-flow like the finer suspended material. Hence, one of the best ways to minimize errors in bedload calculations is to sample frequently and calculate the average transport. For this we need to collect numerous samples over a broad discharge spectrum.

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Grain size distributions of fluvial sediment mixtures: Indicators for sequential dependent hydraulic control of bedload transport

Daniel Hartmann

A recent trend in fluvial sand and gravel sediment mixtures studies has been an attempt to relate hydraulic control to some statistical parameters of grain size distributions. A common method is to compare grain size parameters to flow parameters in a general way. Another common idea is that in a fluvial system, two 'end member' theoretical grain-size distributions exist and any best-fit relation to them can explain the dynamical fate of the sampled empirical distributions.

A fluvial sedimentary system is composed of three elements, which are forces, morphology, and sediment grains and it builds together a process-response system evolving in time. However, many monitoring programs do not deal adequately with the problem of an appropriate time scale that is sufficient to integrate all processes responsible for the net erosion, transport and deposition of sediments.

The studied data set from Oak Creek consist of grain size distributions taken over 56 days from January to March 1971. The data set is very popular among scientists and was studied and reanalyzed often over the last three decades. In our approach, we divide the sampled period to seven dynamical phases beginning each time with a peak flow followed by flow decay. The paper looks at the time dependency of the sediment grain-size evolution, reflected in the parameters of the log-hyperbolic Probability Density Function (PDF), under specific flow regime pattern from peak flow to decay and examines how it changes with time. The results show that under the same flow regime, but with different bed source material, the resulting pattern of particle size distributions will evolve in a different way. Such a sequential analysis, together with the descriptive statistical power of the log-hyperbolic process related model, will expose the true relationship between the flow and the sediment in any time phase. The paper will show that the most suitable statistical tools to study the above-mentioned processes are the log-hyperbolic PDF and the hyperbolic shape triangle. These tools posses the highest descriptive power to represent a wide variety of grain size distributional forms and the ability to connect it to process-oriented approach.

The morphology of the investigated Oak Creek has been chosen to be very simple and 'flume like' and is easy to quantify and the same goes for the flow measurements taken by Milhouse. The sediment's grain-size distributions are the element of the system that remembers best the dynamic processes and their directions and conserves the integrated information in their hydrodynamical acquired attributes. Any attempt to relate hydraulic forces to sediment grain-size distributions should consider few fundamental aspects:

a. What is the available grain-size distribution in the active layer as reflected by the entire sampled field population? The scientific respond is the 'super sample' approach.

b. What should be the approach, knowing the fact that although momentary hydraulic forces posses an accurately measurable potential energy, the bed sediment is, in most cases, not in equilibrium with that energy? A common characteristic of fluvial dynamics is the fact that the erosive and transport capacity of such hydraulic systems is not saturated. The scientific respond is a sequential analysis approach in the relation between grain size characteristics and hydraulic measurements.

c. What is the relation between the grain size distributions of a sequence of samples and the relation between source material and its sorting products? The scientific respond is a use the best available PDF for the characterization of grain size distributions. The PDF's parameters should posses a proven process relationship.

Turbidity-controlled sampling for suspended sediment load estimation

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INTRODUCTION

Accurate measurement and estimation of suspended sediment transport is dependent on the timing and frequency of data collection. It is common in streams and rivers for most of the annual suspended sediment to be transported during a few, large runoff events. Automated data collection is essential to effectively capture such events. Although it is possible to rely solely on manual measurements, important flows are infrequent, unpredictable, and when they do occur, trained personnel may not be available to collect the required information.

There is currently no practical method to directly measure total (submicron to 2 mm) suspended sediment concentration (SSC) in the field. Pumped or manual samples must be transported to a laboratory for analysis. However, a number of companies offer turbidity sensors that can be deployed on a continuous basis in streams. While turbidity cannot replace SSC, it can be of great benefit as an auxiliary measurement. The continuous turbidity record can reveal sediment pulses unrelated to flow, providing information about the timing and magnitude of sediment inputs. And turbidity can be used in an automated system that makes real-time sampling decisions to facilitate sediment load estimation. Such a system, called Turbidity Threshold Sampling (TTS) has been used at a growing number of gaging stations in northern California since 1996 (Lewis and Eads, 2001). Its design objectives are to:

(1) Facilitate accurate estimation of suspended sediment loads at a reasonable cost.

(2) Provide an adequate number and distribution of physical samples to

   (a) validate every significant rise in turbidity, and

   (b) calibrate turbidity against SSC for each period being estimated.

(3) Provide a continuous estimate of sediment concentration and flux based upon turbidity.

The algorithm ensures that a wide range of SSC is sampled in each transport event, so that reliable turbidity-SSC relations can be developed. These are then applied to the near-continuous turbidity data to produce a corresponding time series of estimated SSC.

While turbidity is virtually always a better SSC surrogate than flow, its quality is less consistent due to fouling from biological organisms, detritus, and waterborne debris. Mechanical wipers can prevent fouling from small contaminants such as fine organics and sediment, algae, and macroinvertebrates, but larger debris must be manually removed. Data affected by fouling is in many cases difficult to distinguish from episodes of sediment transport. Some types of fouling can be readily identified on graphical displays with experience. However, fouling that occurs during storm events can often be identified only by plotting the turbidity against SSC from corresponding physical samples, or by comparing the turbidity with independent readings from a second sensor. By activating a pumping sampler during each significant change in turbidity, TTS provides physical samples that can be used to validate the turbidity.

SAMPLING PROTOCOL

The TTS algorithm attempts to collect physical samples at specific turbidity thresholds. The scaling of thresholds is designed to adequately define loads for small storms without oversampling large storms. This is most often accomplished by evenly spacing the square roots of thresholds so that threshold density decreases with increasing turbidity. A programmable data logger instructs an automatic pumping sampler to collect a sample when a threshold is crossed. To avoid sampling ephemeral turbidity spikes caused by passing debris, a threshold must be met for two intervals before signalling the sampler. Because more sediment is discharged while turbidity is in a recession mode, more thresholds are needed while turbidity is falling than when it is rising. Reversals are detected when the turbidity drops 10% below the preceding peak, or rises 20% above the preceding trough. In addition, the change must be at least 5 NTU, and the new course must continue for at least two intervals before declaring a reversal. At the time a reversal is detected, a sample is collected if a threshold has been crossed since the preceding peak or trough unless that threshold has already been utilized in the past five intervals. The program has been implemented on two brands of data loggers. The specific thresholds and sampling parameters described above are all set by the user.

The above rules provide reasonable assurance of avoiding extraneous sampling in the presence of normal turbidity fluctuations. However, it will not prevent oversampling when debris snags on the sensor or its mounting apparatus, causing extended fluctuations. Oversampling due to fouling can cause a pumping sampler to quickly reach its bottle capacity and fail to sample the next important event. Sites experiencing fouling require more frequent field visits. Telemetry provides the most effective means of detection. A warning can be issued remotely from the gaging station when sampler capacity is approached.

SIMULATIONS

Lewis (1996) simulated the above sampling protocol with varying threshold scales, fitting procedures, and sample sizes to evaluate the effectiveness of TTS and associated regression models for load estimation. The sampled populations consisted of five Caspar Creek (north coastal California) storm events for which both turbidity and SSC were measured at 10-min intervals. Sampling based on a square-root threshold scale generally produced more accurate results than cube-root or logarithmic scales; and regression variable transformations (square root, cube root, and logarithm) tended to increase estimation errors. But there was not a great deal of sensitivity to either the threshold scale type or the choice of regression model. The most important result was that root mean square errors (r.m.s.e.) were small, less than 10% in nearly every combination simulated, with mean sample sizes of 4-13 per storm. For samples sizes of at least five, r.m.s.e. was generally no more than 5% of the load. Estimates based on log-linear discharge-SSC rating curves had r.m.s.e. 1.9-7.5 times larger than those based on linear turbidity-SSC regressions when a single curve was fit to each storm.

In one of the storm events, applying separate turbidity-SSC regressions to periods of rising and falling turbidity significantly improved the estimation. In another storm, quadratic regression had a slight 1-2% edge over linear regression. But, in most cases, a single linear regression performed nearly as well or better than other methods, and caution should be exercised in applying nonlinear fits or multiple fits, particularly in the presence of outliers.

Extrapolating nonlinear curves can lead to large errors and dividing the data is inefficient unless there clearly are multiple relations.

Power functions based on log-linear fits were less prone to extrapolation error than polynomials. Log-linear models performed nearly as well as linear models in estimating sediment load; and they have two advantages over linear models: (1) predictions are always positive, and (2) the residuals are often more homoscedastic. This last feature can improve variance estimation.

The variance of the load estimate can be estimated without bias if the regression model assumptions are satisfied. Formulas are given for the linear regression model by Lewis (1996) and for log-linear regressions by Gilroy *et al*. (1990). Lewis investigated the errors associated with applying linear regressions to realistic SSC data generated from log-linear models and concluded that, for typical TTS sample sizes of 4-11 samples per storm, variance estimation was unreliable regardless of the model applied. The variance estimator associated with the log-linear model had little bias, but its r.m.s.e. ranged from 52 to 110%. The variance estimator associated with the linear model performed even worse, with r.m.s.e. from 73 to 244%. In contrast, both models produced very good load estimates, with r.m.s.e. from 5.2 to 7.9% for log-linear models and 5.6 to 8.3% for linear models fit to the log-linear data. For larger sample sizes, variance estimation would improve, and the log-linear model should produce reliable estimates if the residuals can be normalized by log-transformation.

EXAMPLE

The TTS method is illustrated by a February 2000 storm event at Caspar Creek. The range of turbidity measured during the 5.5-day storm was 14-199 NTU. Thresholds were 20, 77, and 170 NTU during rising turbidities and 159, 105, 62, and 30 NTU during falling turbidities. During the course of the event turbidity rose and fell four times, resulting in 12 samples. SSC was well-correlated with turbidity on both natural ($r^2 = 0.98$) and log-transformed ($r^2 = 0.97$) scales. The untransformed model predicts a sediment load of 24 519 kg, with an estimated coefficient of variation (CV) of 5.2%. However, the model predicts negative SSC at the beginning and ending of the storm (Fig. 1). If the negative predictions are set to zero, the estimated load increases to 24791 kg. The difference is small, but a log-linear model that avoids negative predictions seems preferable. The log-linear model predicts a sediment load of 23 343 kg with estimated CV of 7.3%. For comparison, a discharge-SSC rating curve predicts a sediment load of 28 447 kg with an estimated CV of 13.2%. The TTS sample selection likely improved the rating curve estimate considerably (relative to, say, sampling at 12-hour intervals). The rating curve was unusually good for this stream ($r^2=0.92$), but inferior to the turbidity models. Standard errors in predicting SSC were 46% for the discharge-SSC rating curve versus 25% for the turbidity model. To aid interpretation, the standard errors from these log-linear regressions are expressed as percentage errors, $s\% = 100(\exp(s) - 1)$

PARTICLE-SIZE INFLUENCE ON TURBIDITY

It is well-known that turbidity is strongly influenced by particle size (e.g. Foster *et al*., 1992), among other factors. Therefore, when particle sizes are changing, one might expect the usefulness of turbidity as a surrogate for SSC to be limited. But how much error is acceptable in

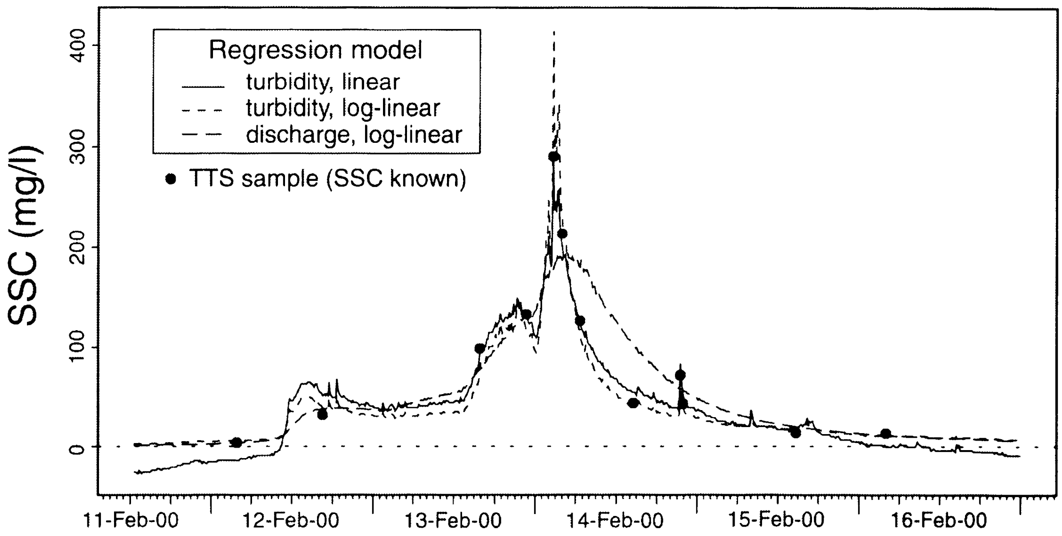

Figure 1. Estimated SSC from 3 models derived from TTS sample data

a given SSC estimate? Historically, the only available surrogate for SSC has been flow, and ranges of variability as high as 100:1 for a given flow have been routinely accepted.

To evaluate the influence of particle size on the relation between SSC and turbidity, historical data sets that included turbidity, SSC, sand fraction, and flow were obtained from five streams in northern California (Table 1). Variability in sand fractions (*sand*) and turbidity (t) for a given SSC (c) were related using the residual standard errors, s, of linear regressions of *sand* and $\ln(t)$ on $\ln(c)$. Although the sample size of five stations is small, a 0.88 correlation between the two standard errors suggests that the variability in *sand* and $\ln(t)$ may be related.

Also compared were variability in SSC for a given turbidity (t) or flow (q), again using standard errors from log-linear regressions (Table 1). The percentage error (s%) was 1.8-4.2 times greater using flow as a surrogate than using turbidity.

If the particle size distribution coarsens with increasing SSC, then one would expect to see an increase in the slope of the relation between SSC and turbidity at higher turbidity and SSC levels. None of the streams exhibited a strong trend in *sand* versus $\ln(c)$ (Table 1, maximum r^2=0.502). Minor upward curvature was apparent at Caspar and Freshwater Creeks, the two streams with the strongest relations between sand fraction and SSC. But linear models perform quite well in estimating loads from slightly nonlinear data when the variance of the relation is low. For example, at Freshwater Creek in water year 2000, a linear regression resulted in a load estimate only 1.7% higher than a loess model developed from the same 181 samples.

While the relation between SSC and turbidity depends on several factors, it is typically nearly linear with low variance. There is growing recognition (Glysson & Gray, 2002) that optical sediment surrogates have the potential to improve sediment load estimation. By controlling sampling using TTS, very accurate load estimation is possible with a moderate number of physical samples. Because it collects samples during each rise in turbidity, TTS also overcomes the difficulty of interpreting turbidity spikes that may be caused by fouling. The TTS method should work well in any stream where a pumping sampler can collect samples that are representative or can be reliably adjusted to cross-sectional mean SSC.

Table 1. Characterizations of variability in relationships among sand fraction (*sand*), SSC (*c*), turbidity (*t*), and flow (*q*) in five streams in northern California

	Miller	Caspar, NF	Mad, NF	Freshwater	Panther
Data source	RSL	RSL	RSL	SF	RNP
Basin area (km^2)	2.3	3.8	104.6	34.4	15.7
Water year	1982	1986-1988 1998[a]	1986	2000	2000
Turbidity sensor	DRT, lab	OBS, in situ	DRT, lab	OBS, in situ	Hach, lab
Mean sand fraction	0.25	0.24	0.24	0.30	0.32
r^2: *sand* v. ln(*c*)	0.137 (203)	0.502 (29)	0.010 (69)	0.391 (50)	0.005 (298)
s: *sand* v. ln(*c*)	0.093 (203)	0.126 (29)	0.042 (69)	0.106 (50)	0.118 (298)
s: ln(*t*) v. ln(*c*)	0.190 (203)	0.241 (173)	0.117 (80)	0.195[b] (181)	0.299 (38)
s%: ln(*c*) v. ln(*q*)	67.0 (169)	122.8 (171)	42.3 (80)	111.1 (181)	126.6 (272)
s%: ln(*c*) v. ln(*t*)	26.9 (203)	45.1 (173)	21.9 (80)	61.3[b] (181)	30.0 (38)

Data sources: RSL=U.S. Forest Service, SF=Salmon Forever, RNP=Redwood National Park
Turbidity sensors: Fisher model DRT-1000, D&A Instruments Co. model OBS-3, Hach model 2100-P
Parenthetical numbers indicate sample sizes
[a]At Caspar Creek, the sand fraction data were from 1986-1988, turbidity data from 1998
[b]Loess regression was applied to curvilinear relations

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Accuracy of Sediment Yield Measurements in small Catchments

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Key words: suspended sediment yield, event based sampling, small drainage basins, accuracy of data, Germany

ABSTRACT

The most common used methods to determine sediment yield from small catchments (≈ 10 km²) are based on water sampling strategies, as flow depths are often too small and irregular to use optical sensors. In several sediment yield studies automatic sampling devices triggered by water stage recorders were used to determine sediment transport. Based on two field studies in a small loess-covered catchment in southwestern Germany (Kraichgau) and a former uranium-mining area in eastern Germany (Thurengia) we discuss several factors determining the accuracy of sediment yield data. These factors include accuracy of discharge measurements, timing of sampling, water sampling intervals and methods, as well as selected sediment concentration measurement techniques.

INTRODUCTION

Parallel to the progress in the mitigation of river pollution from point sources concern about so called diffuse sources of pollution has grown in the public and in science. Increasing awareness of the damages caused by sediment laden, muddy waters, calls for a better understanding of the processes involved in sediment mobilization by soil erosion and channel erosion as well as the sediment delivery problem.

In this context field observations and sediment yield data from small catchments are necessary to quantify relevant processes and to test models. In model testing exercises modeling results are compared with measured values and deviations are discussed. But quite often, no information is given on the accuracy of the measured values. In this paper factors determining the accuracy of suspended sediment yield data from small catchments will be discussed.

FACTORS DETERMINING SEDIMENT YIELD DATA ACCURACY

In many cases suspended sediment yield from small catchments (≈ 10 km²) in temperate environments is determined from continuous discharge data and sediment concentration data based on some kind of intermittent sampling strategy. This combination of continuous water level recordings and intermittent water sampling takes into account the high temporal variability in discharge and sediment transport in small catchments. Accuracy of resultant sediment yield data is determined by the accuracy of the runoff data and the accuracy of the sediment concentration data. In this context temporal resolution is a very important factor.

ACCURACY OF DISCHARGE DATA

The accuracy of discharge data depends on (a) the temporal resolution of water level records, (b) the accuracy of the water level readings and (c) the accuracy of the calibration curve for the gauging station.

(a) Using present day technology (data loggers and some kind of electronical water level recording device) water level records with a high temporal resolution are readily available. Therefore, temporal resolution of water level records from small catchments should always be better than 15 minutes. Longer time intervals (≈ 60 min) between water level measurements could yield errors in total storm runoff volume of up to 100%, depending on (i) the size of the catchment, (ii) land use characteristics in the catchment, and (iii) season. Therefore, highest temporal resolution is necessary for unforested first order basins with immediate response to rainfall events during summer conditions.

(b) At carefully planed and maintained gauging stations the accuracy of water level records should be in a range of 5 mm to 10 mm. But, under turbulent flow conditions accuracy of water level readings might drop to a few centimeters. A better than 5 mm accuracy of water level readings seems unrealistic because of the difficulties in determining the water level at the reference meter used to calibrate and check the continuous water level recording device.

(c) Assuming a consistent accuracy of water level readings, accuracy of discharge measurements depends on the type of weir used and the corresponding calibration curve. Figure 1 compares the relative error of discharge (in %) and discharge for four different types of weirs used in a 3-years nested catchment monitoring program, with catchments varying in size from 0,04 to 7,7 km². In general, the relative error of discharge measurements decreases with increasing water level and discharge. This means that accuracy of total storm runoff volume will be higher for large events, as compared to small events. In addition to this, total storm runoff volumes from larger catchments can be measured more precisely than runoff volumes from smaller catchments. Due to the changing accuracy of discharge measurements with flow level, mean accuracy for an individual runoff event is strongly depended on the

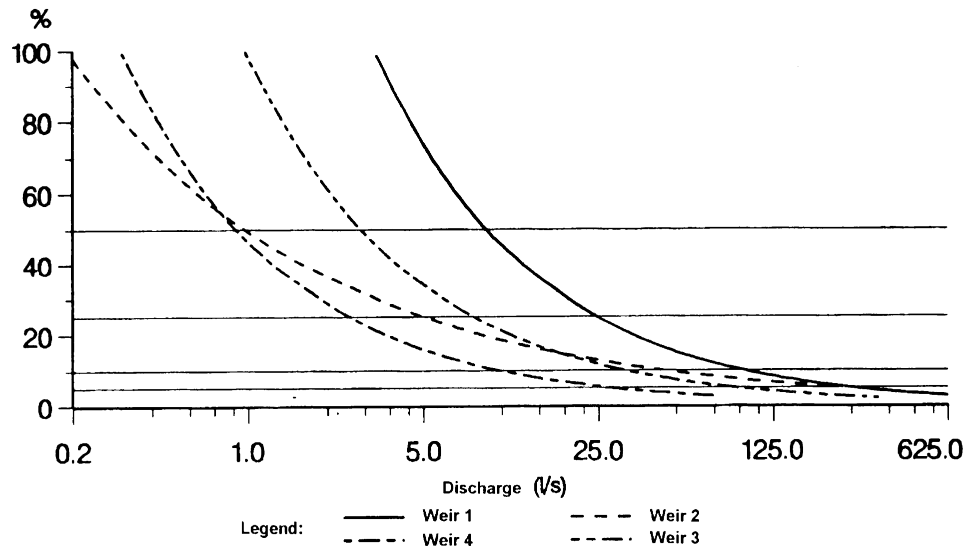

Fig.1: Relative error of discharge measurements for four different types of weirs

characteristics of the event, i.e. previous level, time and intensity of rise, peak flow, and post event level of flow. Previous and post event level of flow determine the lower level of accuracy, while peak discharge determines the upper level of accuracy. Because of the skewed distribution of flow levels within an event, the median of flow level should be used to characterize the overall accuracy of storm discharge data. Nonetheless, as mean flow is more easily calculated, it is suggested, that the accuracy for the mean flow could as well be used to express the accuracy of discharge data for a given event. Based on the experience from a 3-years study in a loess-covered catchment in southwest Germany one thus can estimate the over all error for storm runoff volume to be < 10 % for small catchments (< 10 km^2) and from 22 to 7 % for very small catchments (< 1 km^2).

ACCURACY OF SEDIMENT CONCENTRATION DATA

The accuracy of sediment concentration data depends on (a) the temporal resolution of water sampling, (b) the variability of sediment concentrations within a given stream cross section (not dealt with in this presentation) and (c) the methods used to determine sediment concentration in the lab.

(a) It has been long recognized, that temporal resolution of water sampling is the most important factor when discussing accuracy of sediment yield data. The results from the 3-years sediment yield monitoring scheme showed that over 90% of the total amount of sediment (860 t) leaving a small catchment in southwestern Germany was transported in the course of only 9 events, lasting less than 2% of the total investigation period. Therefore, continuous, fixed interval sampling is usually of little help in measuring sediment yield from small catchments, because this either creates numbers of samples far exceeding handling capacities or has a good chance to miss the times when stream flow and sediment concentrations are high. Under conditions limiting the amount of samples to be handled, some kind of intermittent, event based sampling strategy using an automatic sampling device connected to a water level recorder or a flow meter should therefore be applied. Nonetheless, even with these devices, some adjustments are necessary in order to accommodate seasonal variations as well as differences in runoff generation within catchments of different size and land use characteristics and thus ensure high quality sediment yield data. Due to lower baseflow during the summer, the benchmark for triggering the sampling device needs to be set at a lower level as compared to the winter time. In addition to this, sampling frequency needs seasonal adjustment. Based on our experience, during the winter time a sampling interval of 30 min in very small catchments (< 1 km^2) and 60 to 90 min in small catchments (< 10 km^2) is sufficient. During the summer, sampling intervals should be around 15 min for very small catchments, although this might already be too long to get representative samples from intense summer thunderstorms, and around 30 min for small catchments.

(c) Further minor errors in determining the sediment concentration can occur due to deviations from what might be regarded as a standard method, i.e. vacuum filtration of water samples using membrane filters with a pore size of 0,2 and 0,45 µm. With high sediment concentrations (> 1,000 mg l^{-1}) filtration tends to become a very time consuming procedure, specially if silt and clay contents are high. In order to deal more time efficiently with these samples two alternative methods were used to divide suspended solids from water and determine sediment concentrations. Depending on availability of man power water samples were either left to settle down for a certain amount of time or suspended sediment was settled using a large centrifuge (5,000 rpm). Afterwards, the excessive, macroscopic clear water was pored away and the reminder was dried at 105 °C. In order to determine the loss from poring away the excessive water, several samples of excessive water were filtrated using 0,2 µm filters. Results show that both, centrifugation and settling over several weeks, introduces only minor errors (<1 to 3% of the sediment content measured in the dried samples). But, when settling time is in the order of one week only, excessive water can still contain up to 100 mg l^{-1} of solids, and the error can rise up to 6%.

Conclusions

Due to the high temporal variability of discharge and sediment concentration in runoff, data with a high temporal resolution are a prerequisite for accurate sediment yield measurements in small catchments. Automatic sampling devices connected to water level recorders or flow meters provide the necessary technique. But, when setting up representative sampling schemes the size of the catchment and the season should be considered. With a proper temporal resolution for discharge measurements and sample collection and with the equipment properly working, sediment yield from small catchments can be determined with an error of less than 10 %.

Prediction of sediment delivery to watercourses from land

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Introduction

The accelerated erosion of soil in England and Wales has been an issue of some concern to researchers and policy makers alike for several years (Morgan, 1995; Robinson and Blackman, 1990). The impacts of accelerated soil loss include decreased fertility, a loss of viable agricultural land, sedimentation in reservoirs and rivers, decreased fish stocks and water quality (Butcher *et al.*, 1992; Theurer *et al.*, 1998). An understanding of sediment sources, movement and delivery is a crucial first step in the design and implementation of efficient management strategies (Higgitt and Lu, 2001; Walling *et al.*, 2001). This research was initiated to identify the risk of sediment delivery to rivers and streams in England and Wales by investigating the connectivity between erosion and watercourses.

Experimental method: erosion from arable, grassland and upland soils

Data on the rates and extent of erosion from land under upland, grassland and arable soils were derived from a series of objective and nationally-representative field monitoring programmes.

Erosion vulnerability and risk on arable soils was described using topsoil texture, which defines the stability of the soil, and gradient. Topsoil texture was determined from the proportions of sand, silt and clay within the uppermost soil horizon (McGrath and Loveland, 1992) and the presence of calcareous material, which confers greater aggregate stability to topsoils (Harrod, 1998). Coefficients of amounts of erosion from arable soils were then applied, using data from a study of 270 field sites.

For upland soils, erosion vulnerability was defined using soil hydrological status from HOST (Hydrology Of Soil Types; Boorman *et al.*, 1995) and slope (Morgan, 1995; McHugh, 2002). Quantitative data on erosion from upland soils was provided by a study of over 400 field sites.

The risk of erosion on grassland soils, which can suffer structural degradation following trampling by livestock or by untimely vehicle movements, can also be defined by hydrology and land management. Quantitative data on erosion from grassland soils were collected from 135 grassland field sites (Harrod, 1998).

Experimental method: Connectivity Index and Connectivity Ratio

The efficiency of sediment delivery from land to watercourses, which reflects the connectivity between the land surface and the river system, was characterised using a

Connectivity Index, which represents the relative efficiency of sediment transfer and Connectivity Ratio, which represents a quantitative measure of the efficiency of sediment transfer. Algorithms for estimating the connectivity index from existing datasets and a dataset providing national scale coverage of values of the Connectivity Index were derived. The Connectivity Index was then calibrated to provide values and national scale coverage of the Connectivity Ratio.

The key factors controlling the efficiency of sediment delivery to watercourses were identified as runoff potential, slope steepness, slope shape, drainage pattern, land use and sediment characteristics, each of which was parametrised using a variety of nationally-representative spatial data sets. Arc/Info GIS was then used to generate secondary data layers, to integrate different data layers and to up-scale data to the required spatial resolution of 1 km grid cells.

Experimental method: combining erosion risk and sediment connectivity using GIS

In the third and final phase of the research, ESRI's *ArcView GIS*© including the *Spatial Analyst*© extension software, was used to portray the erosion vulnerability and connectivity of land and watercourses in England and Wales. The quantitative assessments of soil loss were combined with the Connectivity Ratio to provide graphical illustrations of the sediment input to watercourses from arable, lowland grassland and upland soils.

Discussion

This project has progressed some way towards producing a robust, national-scale tool to identify areas of England and Wales at risk of sediment delivery to watercourses, and has also identified key areas where additional work, particularly the provision of additional data and the validation of indices, would be of benefit. Specifically, additional data on erosion are required to develop a fully robust and adaptable tool capable of identifying the risk of sediment delivery to water. Also, the basic framework for the characterisation of slope-channel connectivity established could be refined through further parameterisation of the controlling factors, improved calibration of the weighting factors and validation of the results obtained using erosion rate and catchment sediment yield data. In the longer-term, the limited understanding of sediment delivery processes and of the factors influencing the efficiency of slope-channel sediment transfer could be addressed.

Conclusion

The GIS maps of sediment delivery provide useful indications of where erosion and sediment control should focus. In addition, the research has considerably furthered our understanding and appreciation of erosion and sediment movement processes in a variety of landscapes in England and Wales, although further research is desirable in order to be able to produce a fully validated end product.

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Testing laser-based sensors for continuous, in-situ monitoring of suspended sediment in the Colorado River, Arizona

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The Grand Canyon Monitoring and Research Center (GCMRC) was established in 1995, following completion of a major environmental impact statement on the operation of Glen Canyon Dam. The GCMRC supports the Glen Canyon Dam adaptive management program (AMP) by providing research and monitoring data on a variety of Colorado River ecosystem resources within Grand Canyon National Park (fig. 1). Resources of special concern include native fishes, cultural and recreational resources, as well as numerous eroding fine-grained sediment deposits located along the river's margins. Owing to the ecosystem's supply-limited sediment-transport behavior (Rubin et al. 1998, Topping et al. 2000a), intensive monitoring of fine sediment below Glen Canyon Dam is an AMP requirement for environmental management (Rubin et al. in press). One objective of the GCMRC's monitoring program is to measure the enrichment and depletion of the ecosystem's fine-sediment supply. This is done by estimating the system-wide sand mass balance between influx from tributaries, such as the Paria and Little Colorado River and efflux downstream to Lake Mead. Daily or near-daily measurements of suspended-sand concentration and grain size using standard suspended-sediment sampling methods is currently required to estimate monthly to seasonal sand flux below the dam. The current mass-balance protocol is logistically complicated, costly and provides limited spatial and temporal resolution. In-situ, laser-based sensors are being investigated as an alternative for measuring sand flux downstream to Lake Mead.

RESULTS OF 2001-2002 LISST TESTING

Initial point data collected at a fixed-depth, near-shore site were obtained by averaging 16 measurements at 2-minute intervals during a 24-hour deployment starting at 16:00 on July 19, 2001. These data were collected using a LISST-100 "Type-B" sensor (Laser In-Situ Scattering and Transmissometry). The Type-B is a laser-diffraction based sensor designed to detect suspended particles over a size range of 1.3-250 microns. The LISST can also determine suspended concentrations over a variable range, depending on grain size and adjustment of the instrument's sample-path length. The standard sample path of the LISST-100B is a cylindrical volume with a diameter of 0.6 cm and a length of 5.0 cm. Additional description of this technology is reported by Agrawal & Pottsmith (2001). The LISST-100B used during the July 2001 test was previously evaluated under laboratory and field conditions and its performance is reported by Gartner et al. (2001). The 720 LISST point measurements collected at the Grand Canyon gage in July 2001, compare very well with cross-sectionally integrated suspended-sand and silt & clay data collected at a cableway near the test site using a D-77 bag sampler. During the July test, fluctuating releases from Glen Canyon Dam ranged from about 320 to 480 cubic meters per second (typical summer pattern of discharge related to hydropower generation at the dam). In addition to accurately tracking the sand concentration, the LISST-100B also recorded the physically expected increase in sand-concentration variance as flow increased, with peak values ranging from 60 to 140 mg/l (fig. 2a). As predicted, concentrations of silt and clay obtained by the LISST-100B were a factor of two less variable, ranging from about 50 to 90 mg/l (fig. 2b). It is worth noting that the highest concentrations of fines occurred during the daily minimum discharge, which at this location occurs at night.

A second field test was conducted from September 22, 2001 to February 8, 2002 to explore performance characteristics of both the LISST-100B and a LISST-25 during longer, continuous deployments. Both the LISST-100B and the LISST-25 measure only the volumetric concentration and grain size of suspended particles. However, mass concentration can be estimated by the user once a suitable density conversion is gravimetrically determined. Our LISST-25 had a size range similar to the LISST-100B, however, the standard LISST-25 provides only a Sauter mean grain size (see Agrawal & Pottsmith 2001) rather than the full size distribution provided by the LISST-100B. During fall 2001, the LISST-100B was fitted with a path-reduction module (PRM) to expand the instrument's concentration range by a factor of four (optical path of 5 cm reduced to 1 cm). Although the PRM allowed for higher-concentration measurements, introduction of this optical accessory in the beam path altered the raw data in ways that were not trivial to resolve. The PRM's influence was most pronounced on scattering related to the sand-sized particles (inner rings of the detector). Use of a PRM with LISST is therefore not recommended on the basis of our tests. In contrast to the LISST-100B with the PRM, the LISST-25 (with a standard 2.5 cm optical path) measured higher concentrations of suspended sediment with no discernable complications over the four-month long test. Despite complications introduced by the PRM, the January 10-18, 2002 concentration data obtained from the LISST-100B also compared well with cableway samples for sand (fig. 3a) and silt & clay (fig. 3b) collected with the D-77 bag sampler.

Suspended-sediment grain size is an important component of the Grand Canyon monitoring protocol. For the July 2001 test, the LISST-100B provided median grain size data for sand that closely matched sand sizes obtained using the D-77 sampler (fig. 4a). Grain-size data for sand from the January 2002 test also compared well with the D-77 data (fig. 4b). Our five-week deployment of the LISST-25 provided the most compelling results about how well these optical instruments perform during continuous deployments (fig. 5). Even during September 2001, when the LISST-25 was technically out-of-range (less than 0.2 transmission), these data generally tracked the D-77 samples. Preliminary results from these field tests indicate that in-situ, laser-based sensors can provide continuous suspended-sediment point data in fluvial settings with appropriate maintenance, albeit under a limited range of grain-sizes and concentrations.

Monitoring sediment supply using LISST and *beta*

Our previous work has shown that suspended-sediment concentration and grain-size data can be used to back-calculate grain size of sediment on the bed upstream (Rubin & Topping 2001). The ***beta*** value, derived by the above method, is a surrogate for how enriched a river segment is in fine sediment, and thus provides an indirect, reach-integrated measure of a river's sediment mass balance (in non-armored conditions). The approach can also be applied to other sediment transport environments. Within a period of less than 24 hours on January 11, 2002, the LISST-100B recorded about a factor of seven increase in sand concentration and about a 50 percent decrease in median grain size of sand. This abrupt change in sand-transport occurred in response to enrichment of the river's sediment supply following tributary inputs (figs. 3a and 4b), rather than a change in discharge. Preliminary results such as these suggest that LISST data will be suitable for calculating ***beta*** at higher spatial and temporal resolutions than those that are presently obtained using conventional suspended-sediment sampling methods.

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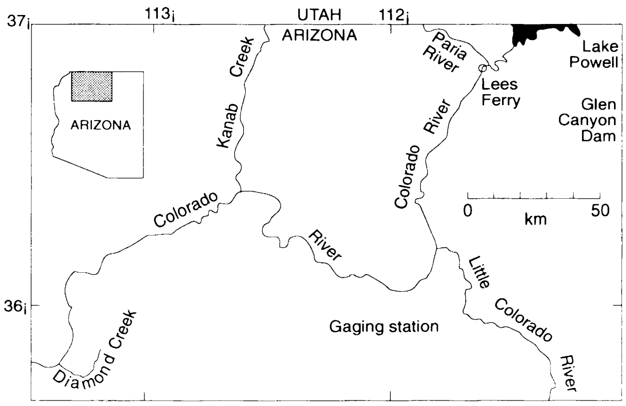
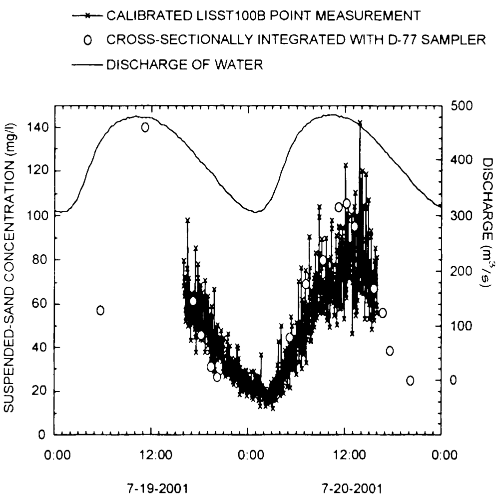


Figure 1. Map of the Colorado River downstream from Glen Canyon Dam.



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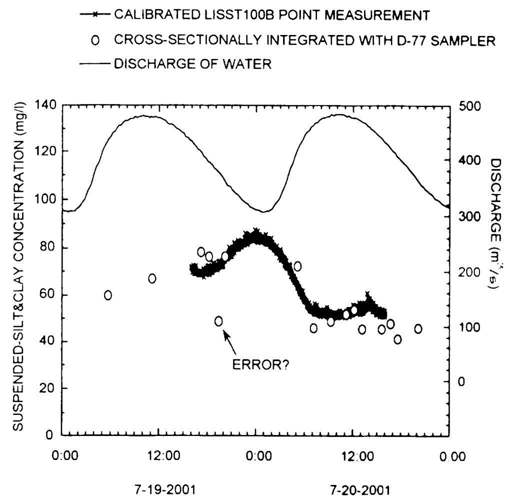
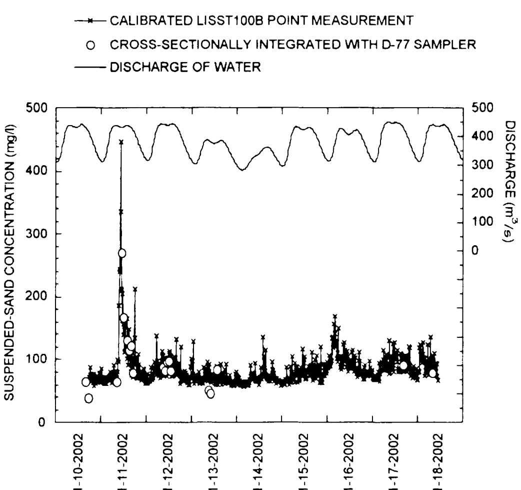


B.

Figure 2. **A.** Comparison of sand concentrations and **B.** Silt & clay concentrations measured at the Grand Canyon gage using LISST-100B and a D-77 bag sampler during the 1-day July 2001 test. Discharge data are from the Grand Canyon gage.



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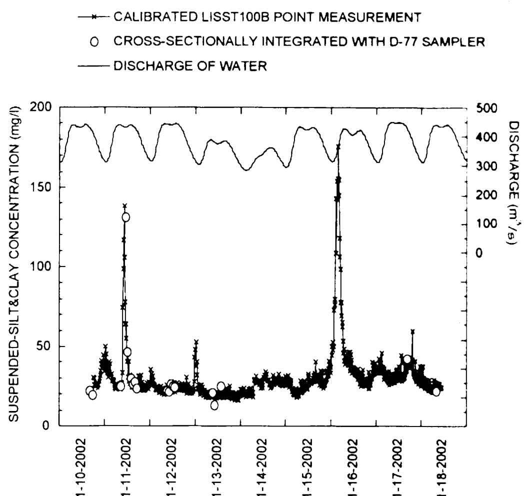

B.

Figure 3. **A.** Comparison of sand concentrations and **B.** Silt & clay concentrations measured at the Grand Canyon gage using LISST-100B (with 80% PRM) and the D-77 bag sampler during the multi-day January 2002 test. Discharge data are from the Grand Canyon gage.

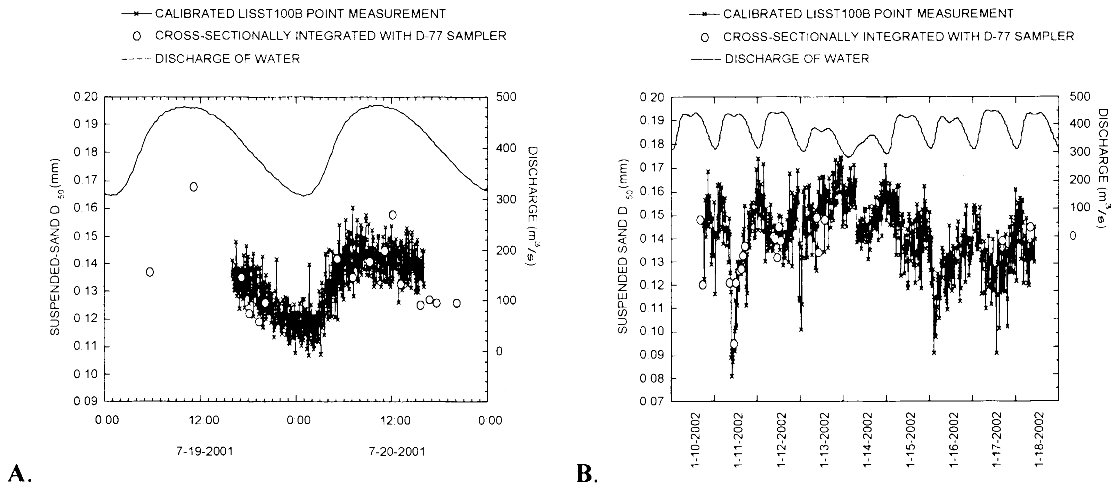

Figure 4. Comparison of median grain size (D_{50}) of sand measured at the Grand Canyon gage using LISST-100B and the D-77 bag sampler during **A.** the 1-day July 2001 test, and **B.** the multi-day January 2002 test. Discharge data are from the Grand Canyon gage.

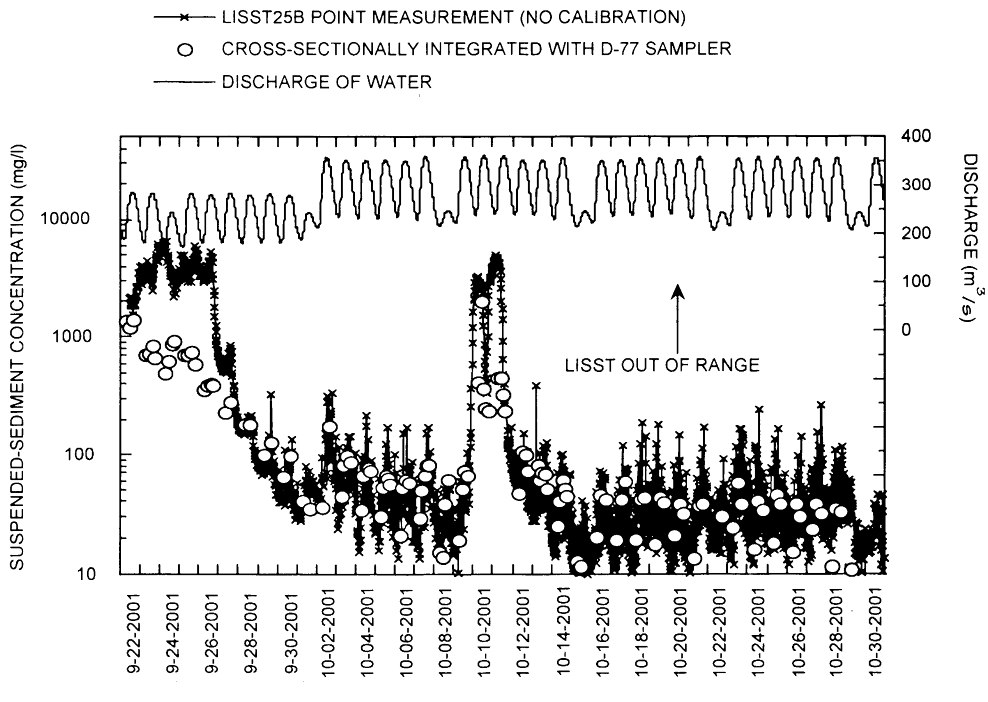

Figure 5. Comparison of total suspended-sediment concentrations (1-250 micron sizes) measured at the Grand Canyon gage using LISST-25 and the D-77 bag sampler during the multi-day fall 2001 test. Discharge data are from the Grand Canyon gage.

MEASUREMENT OF BEDLOAD WITH THE USE OF HYDROPHONE IN MOUNTAIN TORRENTS

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INTRODUCTION

Actual sediment outflow rate depends not only on the sediment transport capacity of the flow but also the movable sediment volume produced in mountain streams. In most cases the amount of sediment on to torrent beds and banks is limited. Torrent beds are often covered with an armor coat. When the discharge rate is small, the actual sediment transport rate is less than the sediment transport capacity that is given by sediment transport equations for the sediment grain size, torrent gradient and flow discharge rate of flow depth. When the flow discharge rate exceeds the critical condition of the incipient motion or the rainfall exceeds its critical one creating landslides or the occurrence of debris flow, sediment is produced and supplied to the torrent. The sediment transport rate increases sharply and approaches the sediment transport capacity. The actual sediment transport has to be observed to determine a reasonable sabo (erosion and sediment control) plan. Monitoring of the sediment transport rate is necessary to operate the sediment control gates of sabo dams being developed. Suspended load is relatively easy to measure with samplers or suction tubes. The measurement of bedload on the other hand is difficult. Some bedload samplers have been used for mountain streams. It is actually difficult to set the samples on the torrent bed, because the bed is rough, has large rocks, and the flow velocity is high. Hydrophones counting the impacts or sound of sand and gravels against plates or pipes are appropriate in mountain torrents. They measure not absolute sediment transport rate but rather the relative sediment transport rate (intensity). Hydrophones with pipes and microphones were developed for isolated mountain torrents and they were installed on the bed of slit sabo dams. The system and data observed using hydrophones are reported in this paper.

HYDROPHONE SYSTEM

A slit sabo dam has one or more vertical slits several meters wide. It dams up water during high water and makes the sediment inflow deposit temporally at an upper reach of the dam. When the discharge rate decreases the degree of dam-up disappears and the trapped sediment is eroded and released. The behavior of slit sabo dams have been known through flume experiments and computer simulations although the actual function must be verified in the field. The hydrophones were applied to measure the actual sediment which flowed out from slit sabo dams.

A block diagram of the hydrophone system is illustrated in Figure 1. A hydrophone was installed at the Tsuno-ura-Karyu slit sabo dam (Figure 2) constructed by the Tateyama Sabo Work Office in the Joganji River. The sabo dam is 13.5 meters high and has two slits, each 16.0 meters wide and 7 meters deep. The water level is also measured using a pressure gauge. The water level can be converted into the flow discharge rate. Measured data is stored in the data logger and also transmitted to the work office through a cellular phone every five minutes. The hydrophone system is powered by solar batteries.

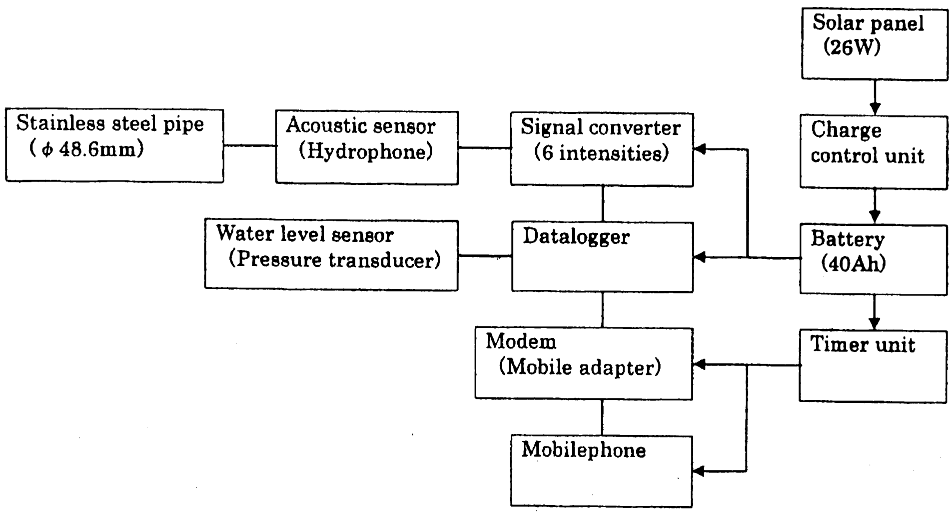

Figure 1 A block diagram of the hydrophone system.

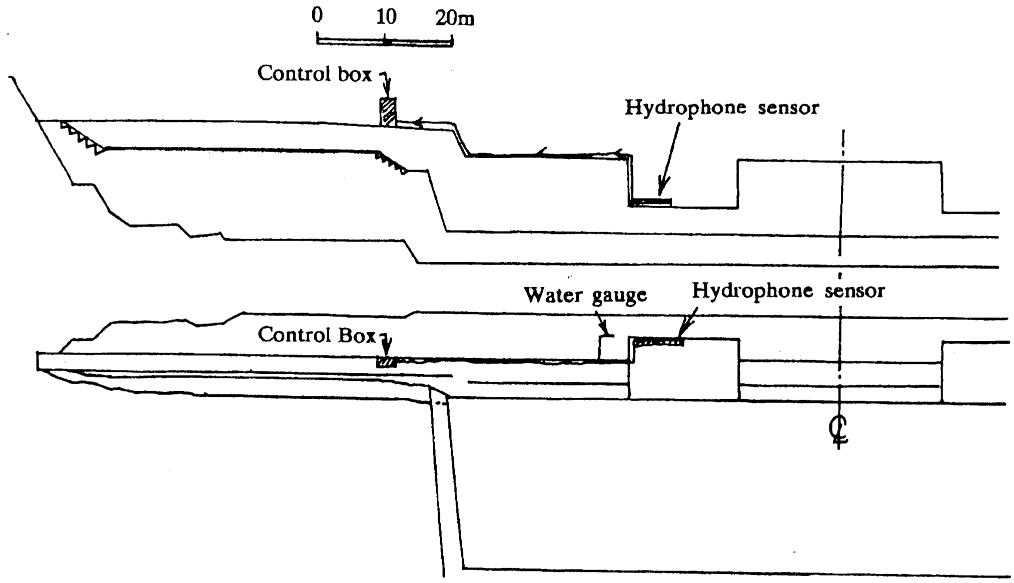

Figure 2 Installation of a hydrophone at the Tsuna-ura-Karyu slit sabo dam.

RESULTS OF MEASUREMENTS

Measurements using the hydrophone system started at the Tsuno-ura-Karyu slit sabo dam on June 16, 2001. They have been continued to date except during snow seasons. The gain of the hydrophone was set 2 times (L5), 4 times (L4), 8 times (L3), 16 times (L2) and 32 times (L1). Measured data of incoming signals and the water level of a storm in 2001 is shown as an example (Figure 3). The storm was not large enough to dam up the flow. Recorded data indicates that sediment was transported with a small flow discharge during the rising stage of the storm and disappeared rather early in the falling stage. The movable sediment which was produced before the storm was not large enough to be transported by the flow. It is expected that more information can be obtained from an analysis of this kind of data.

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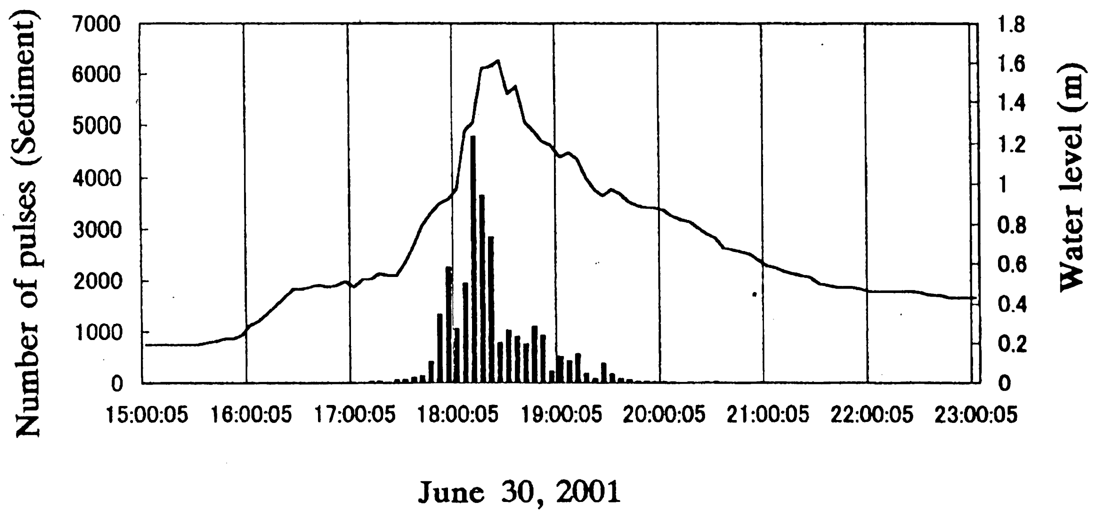

Figure 3 An example of the recorded data of hydrophone and water level

Gully erosion measurement in loess hilly area

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Abstract

Gully erosion is one of the most important kinds of soil erosion that causes soil degradation. Also sediment yield of eroded gully causes many problems in downstream areas. Loess is one of the erodible soils that have wide distribution in Golestan province. Because of the erodibility of these soils all of kinds of erosion can be seen in loess area. Also because of enough depth of soil gully erosion is common over these soils.

For studying of gully development trend in loess hilly area of Gorgan, Golestan province three typical gully selected with 40-50 cm depth, 90-110 cm width and 300-500 cm length. The slope of study area is 12%. Average of annual rainfall is 700 mm. To measure the surface area of gully cross sections and changes from cutting back or bank collapse a rectangular grid of erosion pin was set out at an appropriate interval. After each rainfall the dimensions of gully measured again. From 43 rainfall event in one-year study only 6 of them had measurable changes in gullies. In each rainfall event intensity, depth and time of rainfall data was collected from Hashem Abad station in 3 km far from study area. The results of this study showed that after each rainfall the amount of degraded soil was between .0.1 – 0.5 m^3. The total of soil eroded in one-year study was about 0.6 m^3 for each gully. The amount of gully development from head and two sides in one year was 10 and 7 cm respectively. Statistical analysis showed that volume of eroded soil has significant relationship with depth of rainfall.

This survey also showed that depth of gully after each rainfall doesn't increase necessarily and usually because of head cutting and side bank collapse, depth of gully decrease. But after washing and transporting of eroded soil depth of gully increase again. It must be mentioned that amount of rainfall and volume of runoff and also duration of rainfall has important role in cycle of increasing and decreasing of gully depth.

Key words: gully erosion, erosion measurement, and loess soil

Introduction

Gullies are relatively permanent steep-sided watercourse, which experience ephemeral flows during rainstorms. A headcut and various steps or knick-points along their course characterize gullies. (Morgan 1986). Gullies are almost always associated with accelerated erosion and therefore with landscape instability.

Numerous studies record the formation of gullies by pipe or tunnel collapse. Tunnels develop particularly where the clays are of low permeability and sodic. Loess is one of the most erodible soil that great part of Golestan province in hillslope is covered by it.

Surface, rill and gully erosion is different type of erosion in loess hilly area of Golestan provience. Because of improper land use and also farming operation in downslope direction soil erosion in this area is very high. Gully initiation and development is very typical and must be studied for better management.

So this study carried out for better underestanding of gully erosion processes.

Description of study area

The study area located in 36°, 46′, 49″ N latitude and 54°, 26′, 40″ E longtitude with 160 m high above sea level. This area is located in south of Gorgan, capital of Golestan province in loess hilly area.

Average slope of this area is 22.12 % and its land use is range with 50-60% vegetation cover. The soil of study area is loess with 61-74% silt, 14% clay and sand and 15-25% lime. Average of annual rainfall is 750mm. Ttable 1 show soil characteristics of study area.

Table 1- soil characteristic of study area

	Gully 1	Gully 2	Gully 2
texture	Silty-clay	Clay	Clay
Ph	7.2	7.25	7.3
Ec	0.7	0.58	0.9
Organic material	3.45	3.01	3.00
So	54	55	59
Na	21	15	12

Material and method

For monitoring of gully development in loess hilly area 3 typical gully has selected with 40-50 cm depth, 90-110 cm width and 300-500 cm length.

To measure the surface area and changes from cutting back a rectangular grid of erosion pin was set out at an appropriate grid interval. After each rainfall event the dimensiones of each gully measured again. Six-rainfall event that had runoff and was enough for gully erosion occurred in one year. For each rainfall event depth, intensity and time has recorded. Meteorological data has collected from Hashem Abad synoptic station with 3.5 km distance from study area.

First, cross section of each headcut mesaeured and after each rainfall event new cross section at the same location mesaured again.

Figs 1-3 show cross section of each gully for 6 rainfall events. Then with comparison of different cross section the amount of removed soil volume was determined. Table 2 show volume of removed soil for each gully.

Fig 1- Gully 1 cross section

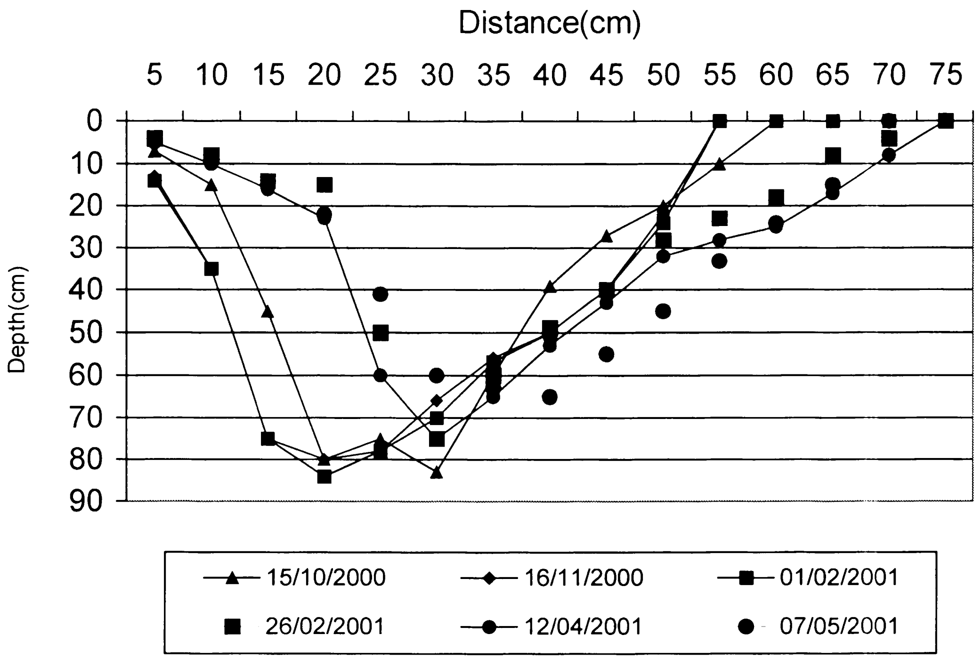


Fig 2- Gully 2 cross section

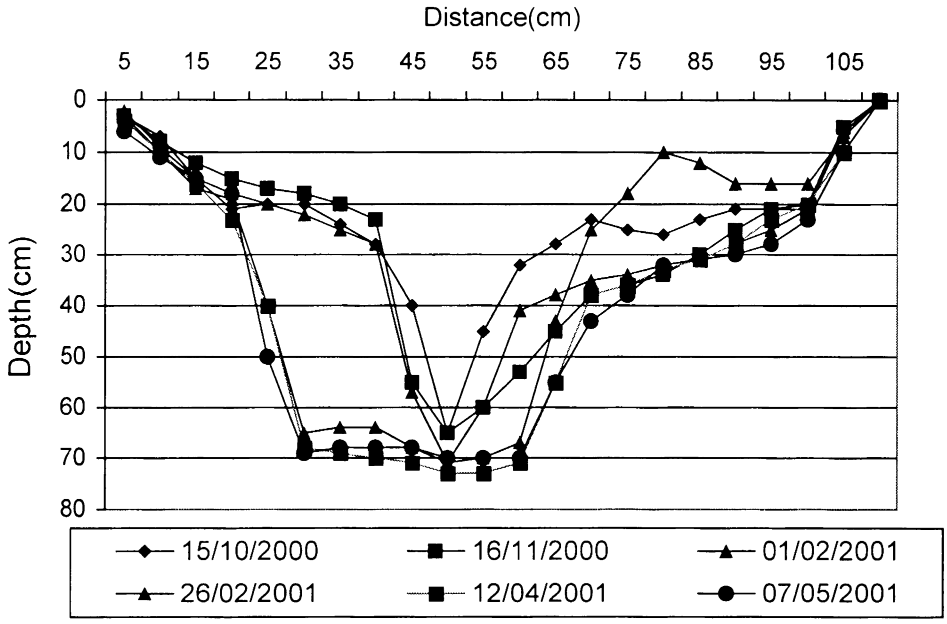
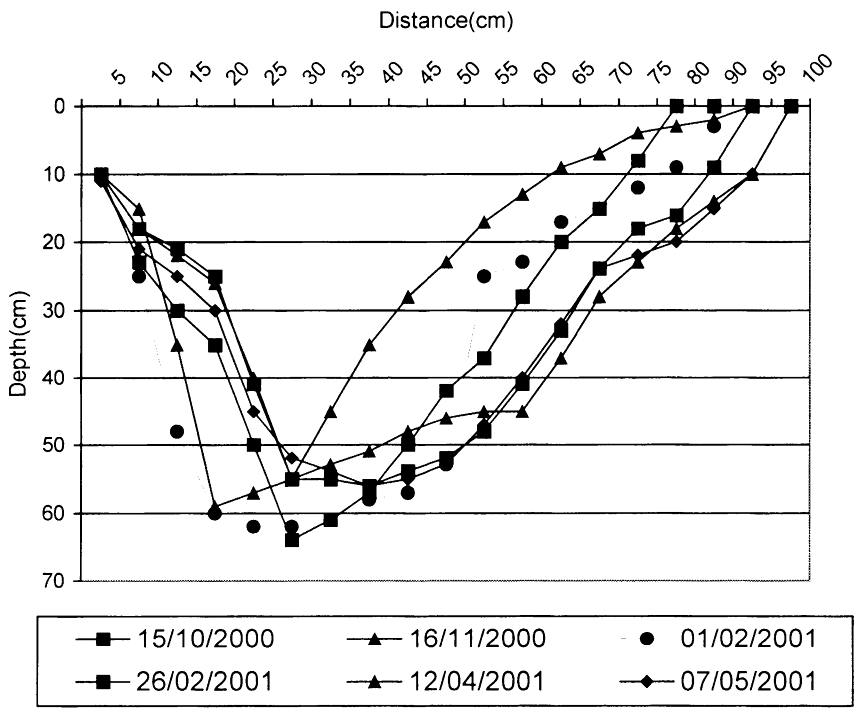


Fig 3- Gully 3 cross section



Results

Results of this study show that after each rainfal event that can generate runoff ,gully head-cut develop. In this study the amount of removed soil was between .1- .5 m^3. Statistical analysis shows that volume of eroded soil has significant relationship with amount of rainfall. This study also shows that depth of gully in each rainfall not only increases necessarily but also usually because of headcutting and side bank collapse decrease. . But after washing and transporting of eroded soil depth of gully increase again. It must be mentioned that depth of rainfall and volume of runoff and also duration of rainfall has important role in cycle of increasing and decreasing of gully depth.

Table 2. Amount of rainfall and volume of soil removed

		Gully 1	Gully 2	Gully 3
date	Rainfal amount(mm)	Volume diference(m^3)	Volume diference(m^3)	Volume diference(m^3)
16/11/2000	64.4	0.05	0.121	0.037
01/02/2001	14.4	0.123	0.067	0.075
26/02/2001	75.6	0.116	0.118	0.69
12/04/2001	4.85	0.076	0.254	0.44
07/05/2001	65.1	0.004	0.036	0.58

This study will continue for 3 years for collection more data.

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Two technological advances in continuous monitoring of suspended sediment transport and particle characteristics

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EXTENDED ABSTRACT

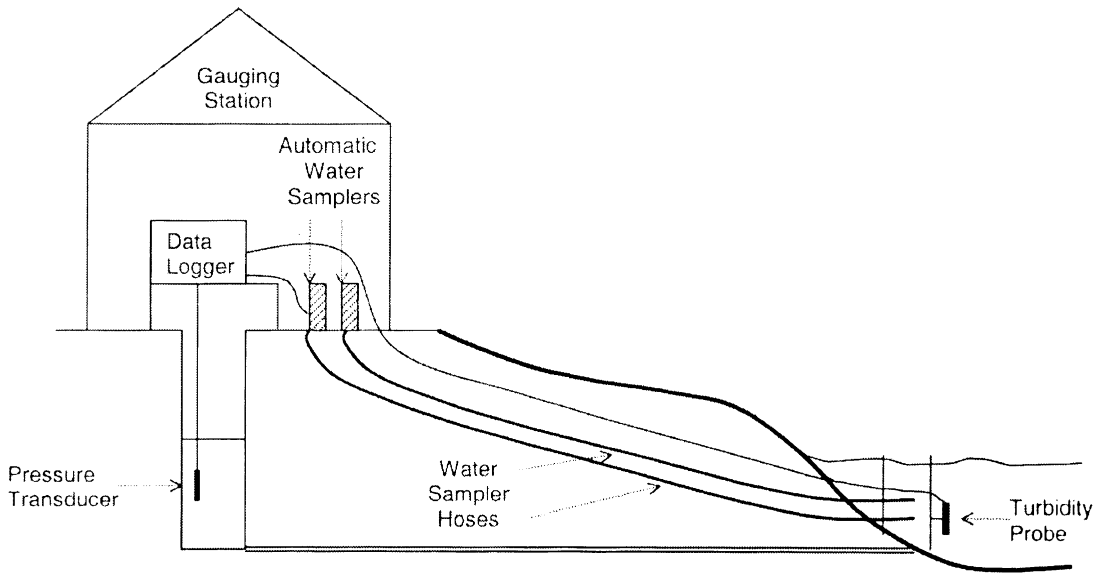
This paper describes two instrumental developments in the field of fluvial suspended sediment monitoring and describes the significance of their data outputs to understanding sediment dynamics. The technologies are: (1) WISER (Wallingford Integrated System for Environmental monitoring in Rivers); and (2) OPTIMO (Optical Technology for Intelligent Monitoring Online). This paper focuses on the WISER system and its application in extreme urban environments where the extremely rapid flow and sediment transport response to rainfall necessitates the use of an intelligent sampling strategy.

Most studies of suspended sediment transport adopt a continuously recording turbidimeter; an optical device determining turbidity from the scattering of light. However, as well as reflecting the suspended sediment concentration, turbidity is also influenced by the size distribution and optical properties of the suspended particles and the water colour (e.g. Foster *et al.*, 1992; Gippel, 1995; Lawler, 1995). Therefore, turbidity is usually calibrated to suspended sediment concentration determined from a concurrent river water sampling programme on a site by site basis. Water and sediment samples are often taken from the river using an automatic water sampler.

The WISER system was developed to allow the adoption of a range of efficient sampling strategies (Evans *et al.*, 1997). The technology enables manual and time triggered automatic water sampling to be supplemented by sampling usually triggered in response to stage and/or turbidity threshold values being exceeded. This allows water samples to be collected during short lived flow events when significant sediment transport occurs (90% of a river's annual sediment transport usually occurs in less than 25% of the time e.g. Old *et al.*, 2002; Wass & Leeks, 1999). It is essential to sample high sediment concentrations during flow events to allow the calibration of the full range of turbidity measurements. However, the WISER system can accommodate a wide variety of online sensors that may be used to trigger an automatic water sampler.

The WISER technology has been used successfully in a two year study (1999 to 2001) of fine sediment transport in Bradford Beck, UK. This research was part of the Natural Environment Research Council's Urban Regeneration and the Environment (URGENT) thematic programme. Bradford Beck drains the small (58 km^2), steep and highly urbanised catchment of Bradford. In this application the WISER technology, integrated a range of commercially available equipment as shown in Fig. 1. It included a pressure transducer, a turbidity sensor, two automatic water samplers and a data logger.

Fig. 1. Wallingford Integrated System for Environmental monitoring in Rivers (WISER)



An example of the rapid response of flow and sediment transport, in Bradford Beck, to rainfall is shown in Fig. 2. River flow and sediment transport data are presented for Shipley Weir; a site close to the catchment outlet. The rainfall data on Fig. 2 were recorded at Lister Park which is approximately 2 km from Shipley Weir. Frequent fouling of turbidity sensors with algae, litter and sanitary products resulted in many false triggers of samplers when turbidity activation was used. However, samplers triggered on a river stage basis operated successfully and this is recommended for urban streams. Fig. 3 illustrates successful sampling of an extreme flow event that occurred in Bradford Beck in response to an intense summer rainfall event (15 June 2001). Flow rose from 0.4 $m^3 s^{-1}$ to 34.6 $m^3 s^{-1}$ in just 15 mins and receded to 3.3 $m^3 s^{-1}$ within 1.25 hours. Unless field scientists are on site, it is unlikely that samples would be collected throughout such extreme and short duration flow events that are typical of many urban river systems.

Sampled suspended sediment concentrations are used to calibrate the continuous turbidity record. Fig. 4 illustrates the relationship between sampled suspended sediment concentration and turbidity in Bradford Beck (Shipley Weir) using data from January to June 2001. Although useable relationships are found in most river systems, significant scatter normally occurs about the regression line (Fig. 4). This is largely due to ambiguity in the interpretation of turbidity data as a result of temporal variability in the size distribution and optical properties of suspended particles.

A major aim of the OPTIMO technology is to contribute towards resolving this ambiguity in turbidity measurement. The technology measures characteristics of particulate suspensions using an optical sensor head with a series of multi-wavelength light sources and multi-angle detectors. Neural networks are used to calibrate OPTIMO output data to suspended sediment concentration (0-1000 mg/l) and the proportions of 4 particle size classes (0-3, 3-10, 10-20 and 20-120 μm). Although this new technology is at an early stage in field trials it is potentially a significant contribution to continuous, and more direct, monitoring of fluvial suspended sediment concentration and particle size.

Therefore, WISER and potentially OPTIMO represent significant developments in monitoring sediment transport. WISER has proven to be reliable and particularly useful in harsh urban environments where river flow and sediment transport are extremely responsive to rainfall. OPTIMO has the potential to contribute to resolving the ambiguity in turbidity measurements. It is likely that it will provide continuous suspended sediment concentration data with the added value of an indication of its particle size distribution.

Fig. 2. Rapid response of flow and sediment transport to rainfall in Bradford Beck (Shipley Weir) from January to June 2001

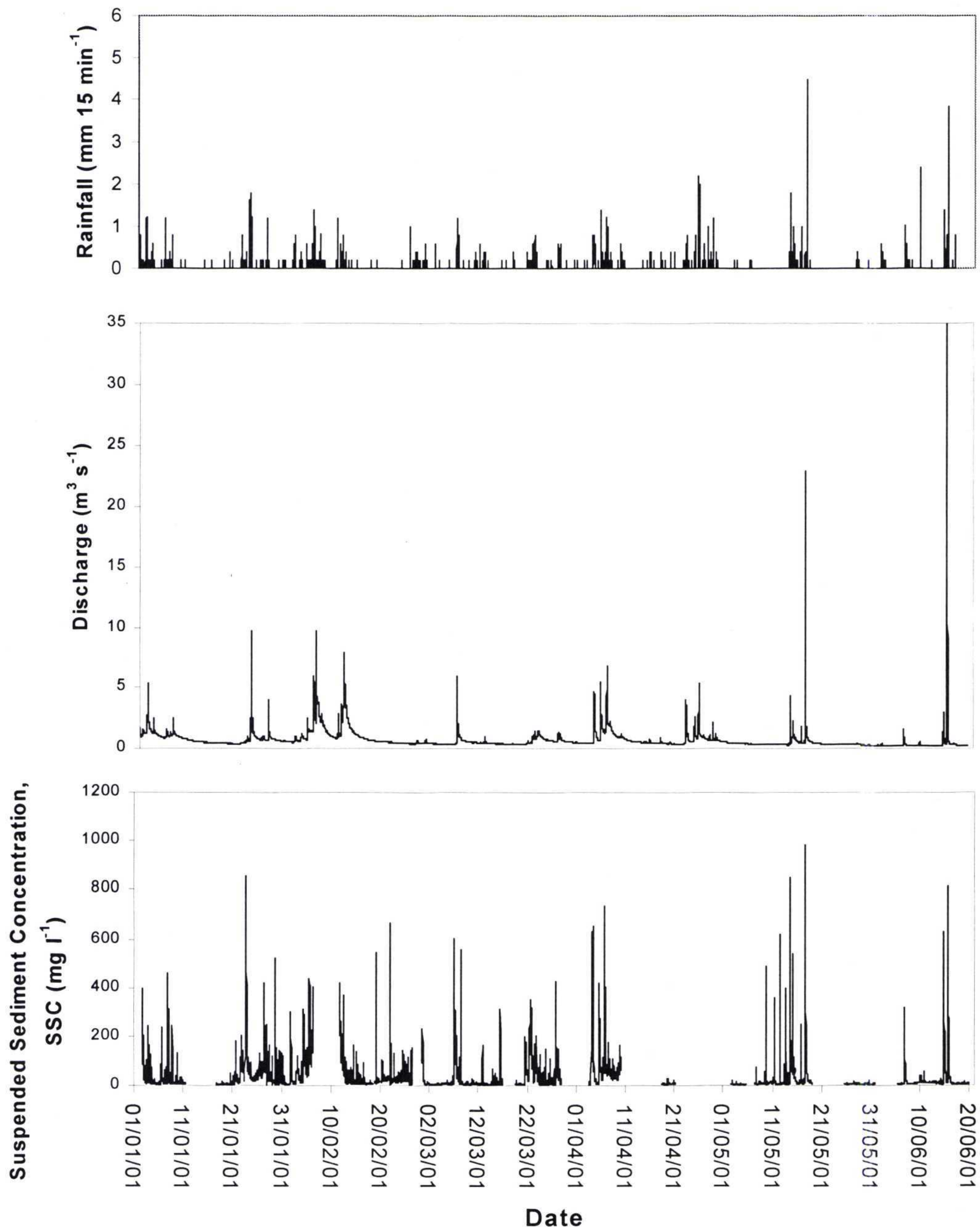


Fig. 3. Suspended sediment samples extracted from Bradford Beck (Shipley Weir) using the Wallingford Integrated System for Environmental monitoring in Rivers (WISER) during an extreme, short duration, summer flow event (June 15th 2001)

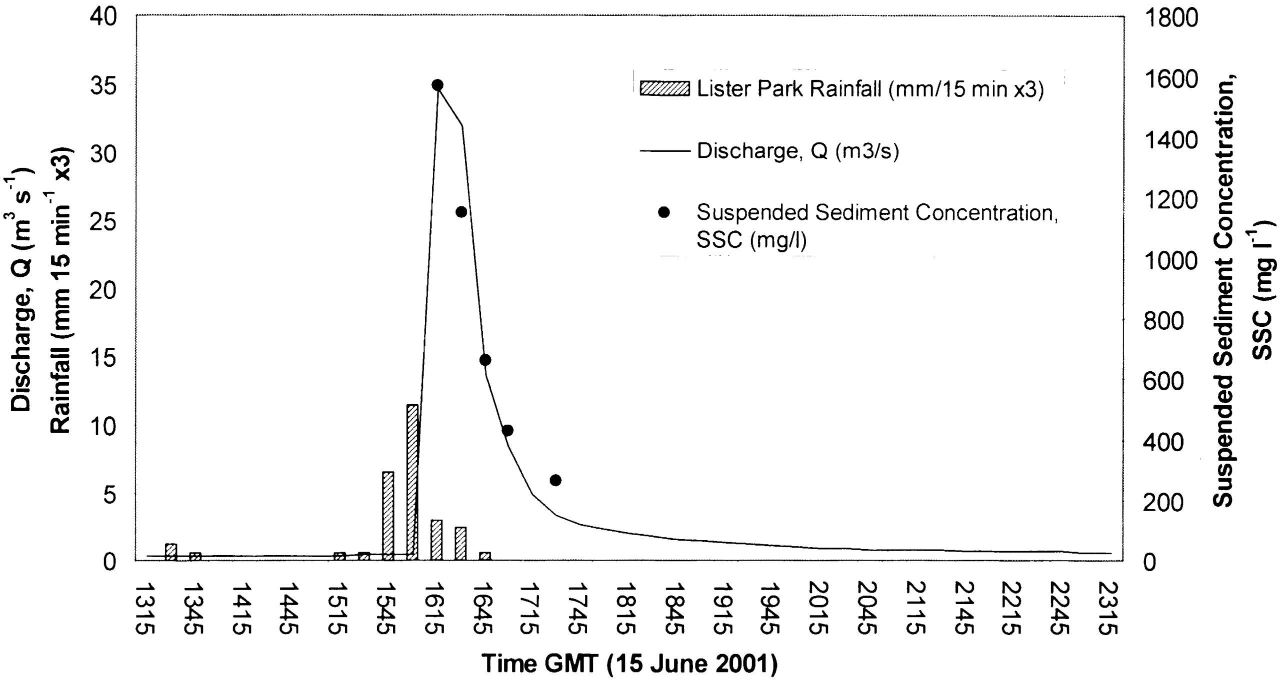
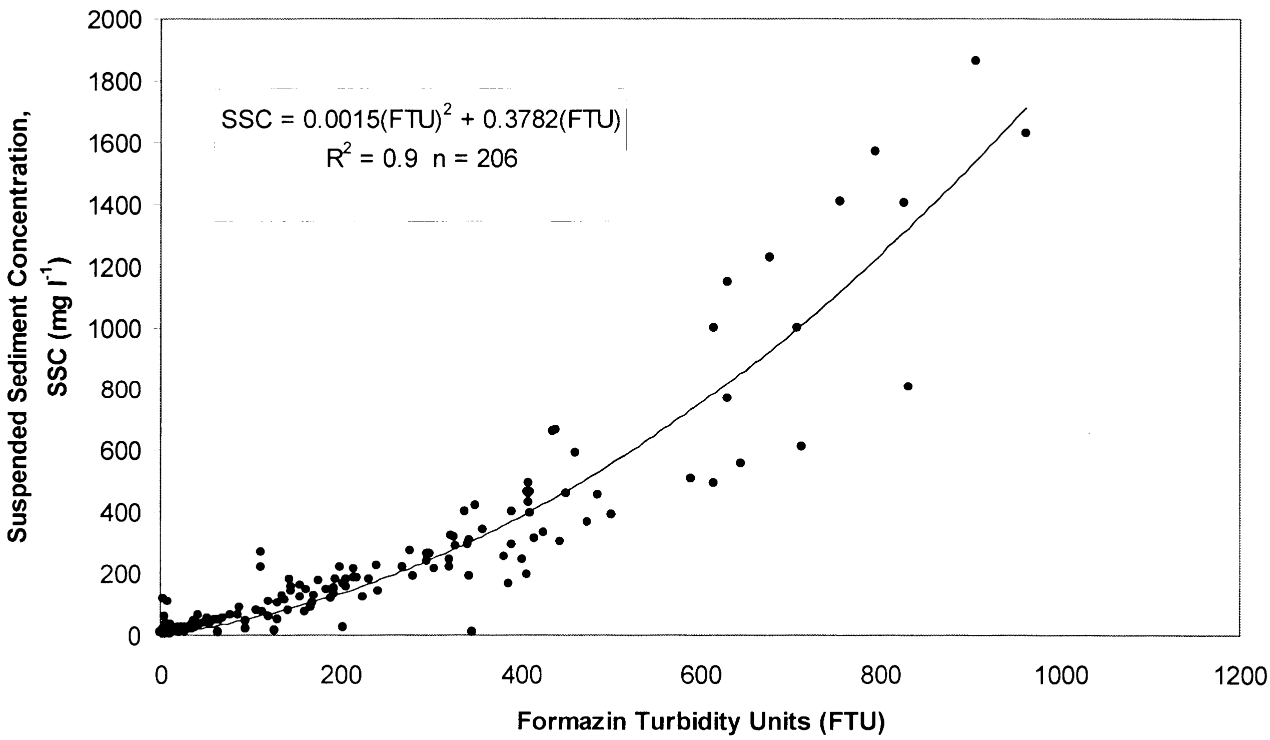


Fig. 4. Relationship between turbidity and sampled suspended sediment concentration in Bradford Beck (Shipley Weir) from January to June 2001



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Bedload transport rates and the stream hydrograph: results from a new type of load cell bedload trap

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Introduction

Bedload transport is known to be highly unpredictable. At the fundamental level, bedload transport is a function of the entrainment and the movement of individual grains on a stream bed (Hassan & Church, 1992). To date, most studies have attempted to derive physically-based or empirical models of entrainment, and where transport rate is to be calculated, between transport rates and section averaged or even local estimates of driving force. One of the main stumbling blocks to the modelling of bedload transport arises from the fluctuations in rate caused by time varying passage of sediment from upstream. The supply of sediment available to be transported is known to be a function of both temporal and spatial variations in entrainment characteristics (cluster , armouring and patches) of the river bed (Larrone et al 2000). Stream beds dilate, or become more packed under marginal transport conditions, affording higher resistance to transport. In supply limited rivers, the sudden availability of new sources of bedload from armour break-up, bar mobilisation or bank collapse, may become locally important. Such variability is reflected in the high degree of scatter recorded in bedload transport datasets, although it seems particularly pronounced in supply limited humid-temperate streams (Reid & Frostick, 1986).

An important element in the process of bedload transport is the extent to which local vs. remote sources of supply interact with the sequence of flows to create temporal and spatial variability in transport at a section. We can hypothesise that sediment will be available at different times (flows) and in different places during an event. As flows rise, new sources are accessed, the significance of which will depend on the geomorphology of the channel; for example, channels with relatively high bar amplitude will only access sediment on the bar tops relatively infrequently. Similarly, wide shallow channels, may access most of the channel bed relatively rapidly. An additional factor influencing the temporal patterns of bedload at a section, will be the distance over which bedload can travel to supply material to the point of measurement. Most tracer studies of particle movement indicate an average event travel distance of < 4 channel widths, with maximum average values of < 17 channel widths for high magnitude floods. An important factor affecting the connectivity of the measurement point with upstream sediment supply must therefore be the duration of flow over the critical threshold for transport, together with some consideration of where the sources of sediment are within the upstream reach. Set alongside this aspect of the flood hydrograph (the event duration) is the event magnitude, as this conditions the proximity to thresholds of entrainment, armour break up, and access to vertical change in sediment source area. Long term, high resolution bedload data is rare, since most trapping studies tend to be project specific, or are undertaken in environments where the number of transport events is limited (Powell et al. 1992). However, if we are to better understand the processes of bedload transport it will be important to extend the data sets over longer periods of time.

This paper takes a holistic look at the influence of the flood hydrograph on bedload transport yield measured at a downstream station using a dataset of 60 individual bedload events collected over the period 1998 – 2002.

Study Site and Methods

Four bedload samplers were installed across a section in a straight reach of the Highland Water, a small gravel-bed channel located in a 12.5km^2 semi-natural wooded catchment in southern England (Booker et al 2001). The Highland Water Bedload Sampler (HWBS) is a load-cell based continuous recording pit-trap (Sear et al. 2000). Annual re-calibration has proven the system to be stable, with some drift accounted for by accumulation of sediment around the load cell cradle. The traps have functioned without the need for maintenance for over 75 bedload events. Flows have varied up to floods of 1:50 year Recurrence Interval.

Results

Bedload transport is dominated by material in the coarse sand – medium gravel ranges (D_{16} 1.3mm, D_{50} 3 – 7mm, D_{84} 7-22 mm), typically the same composition as upstream bar material, and somewhat finer than surface armour found on riffles and in pools. Considerable scatter is shown in the relationship between specific stream power and transport rate (Figure 1). Transport rates are low compared to Desert Flash floods, but are of similar magnitude to those observed in the Turkey Brook, a stream with similar geology and sedimentological properties (Reid & Larrone, 1995). In accounting for the scatter observed in their transport rates, Reid et al. (1985) suggested that the thresholds of initiation of transport and cessation were often different, with lower thresholds for final motion. A similar result is found in the Highland water, but is interpreted not as representing the difference in static vs. dynamic resistance to movement, but rather a due to the temporal variability in the supply of material from upstream sources. Similarly, Reid et al (1985) observed a temporal variation

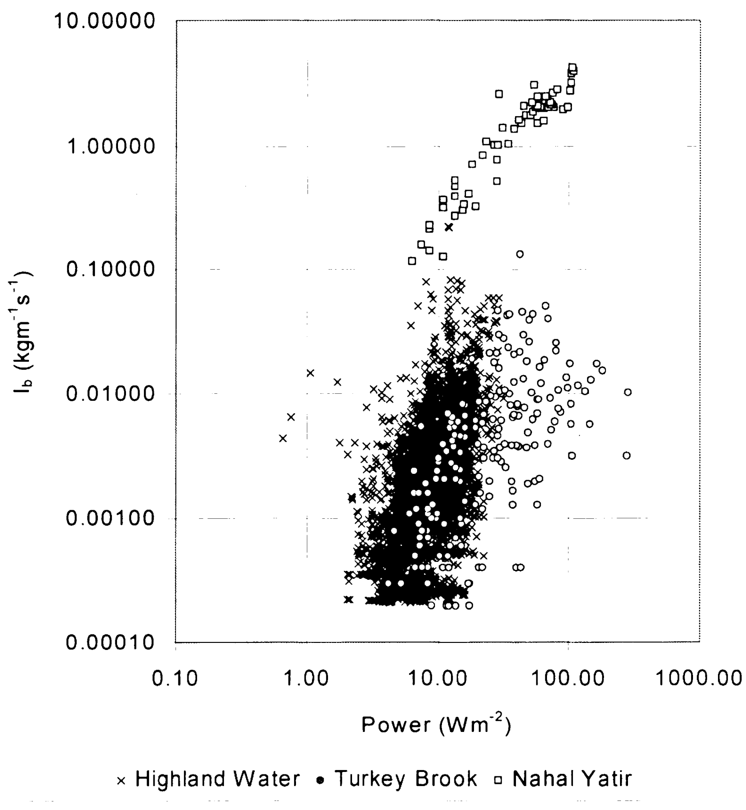

Figure 1: Scatter in the relationship between specific stream power and bedload transport rate for Highland Water and selected streams.

in entrainment thresholds associated with prolonged periods of bed stability. This was not observed in the Highland Water, rather as the period between bedload events increased subsequent entrainment thresholds tended to reduce. This is interpreted as representing the difference in dominant sediment sources; the Highland Water largely deriving bedload from upstream patches of fine material stored in bars and pools.

One of the main goals of sediment transport research is to be able to predict the volume or mass of material transported by floods. The dominance of discrete upstream sources of bedload, suggests that much of the variability in observed transport rates, relate to the ability of upstream sediment to make it to the traps on an individual event. This is more closely associated with the duration of bedload above the threshold for transport than event magnitude. However, the magnitude of the event is still significant because it determines not only the power available to initiate transport, but also conditions event duration, and the access to vertically segregated sediment sources. A measure of the total event power above the threshold for sediment transport can be derived with units in Mjm^{-1}. The relationship between total event power and total event yield is given in Figure x. Over 70% of the variation in event yields is explained by this term, compared to 52% and 54% for maximum stream power or event duration respectively. Factors contributing to the unexplained variation include the presence of stochastic supply from bank collapse, the exhaustion of upstream sources and the suspected influence of turbulence in conditioning sediment transport rates particularly at lower flows.

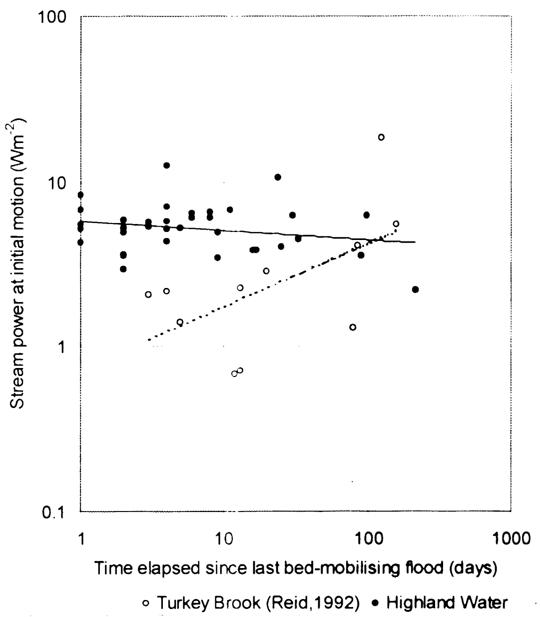

Figure 2: Variation in the threshold of transport with time between bedload events for Highland Water and Turkey Brook (after Reid & Frostick 1986))

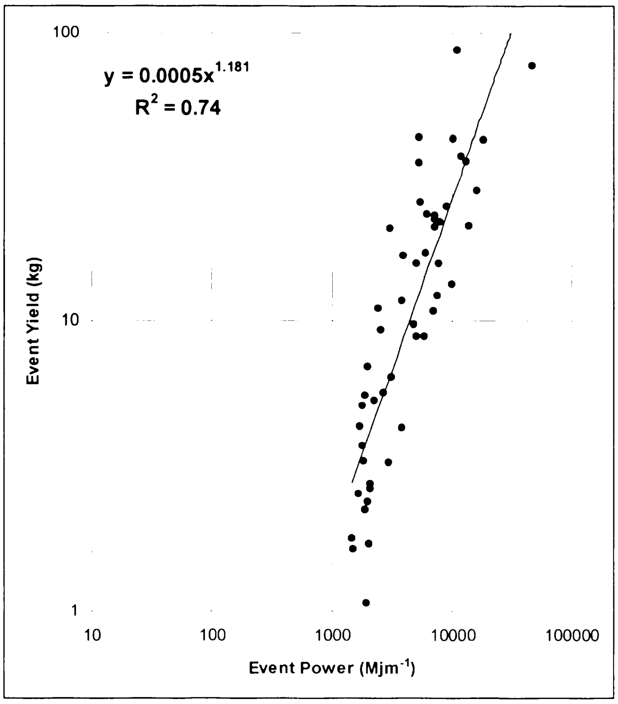

Figure 3: Relationship between total event power and event yield, for 60 floods in the Highland Water.

The influence of event duration and magnitude on sediment transport rates has been previously suggested as a means of classifying the effectiveness of extreme floods (Costa & O'Connor, 1995). Three types of flood were discerned,; A) those that have high magnitudes, but short duration, B) those that have long duration but are below or at the threshold of motion and C) those that are of high magnitude and duration. The latter were considered to be the most geomorphologically effective since these had the largest total available energy for sediment transport. Using the database of 60 floods covering events up to 1:50 year RI, it is possible for the first time to test this conceptual model (Figure x). In Figure x, the circles scale in proportion with total event yield (a measure of geomorphological effectiveness). Geomorphological effectiveness is maximised for events of high magnitude and long duration (B), but also for those of long duration and moderate magnitude (C). Short duration high magnitude events (A) owe much of their effectiveness to the

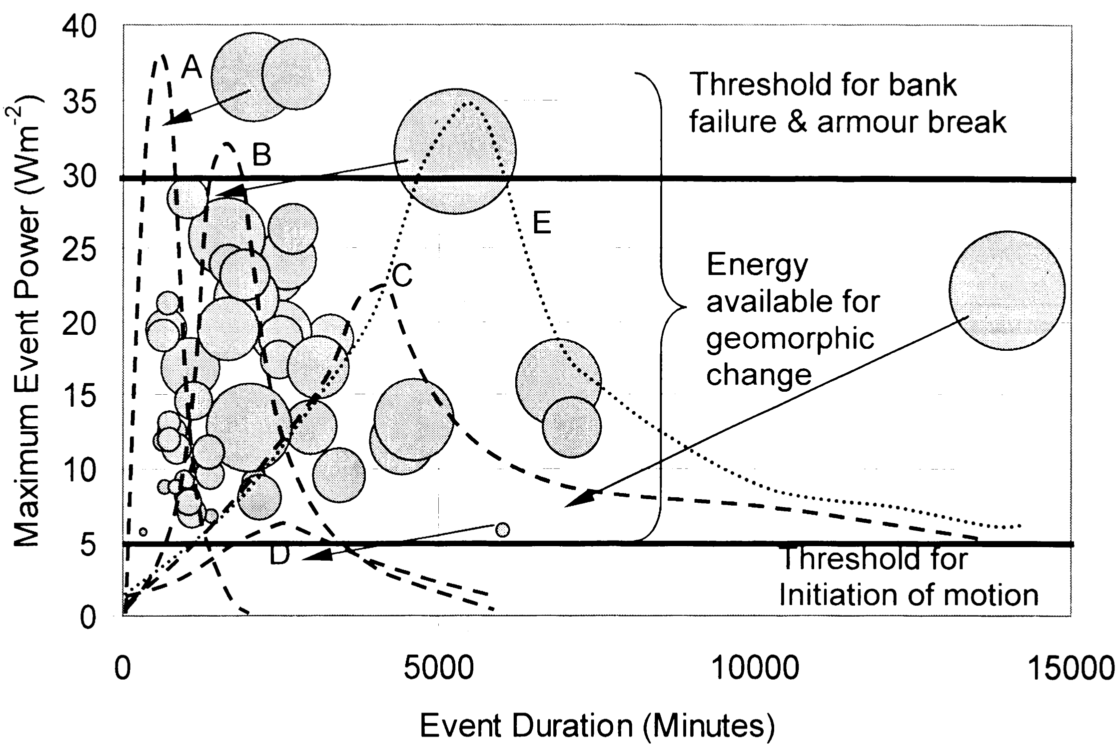

Figure 3: Classification of floods in terms of geomorphological effectiveness after Costa & O'Connor (1995). Circles are scaled according to event yield for 60 floods on the Highland Water.

collapse of the river banks, and break up of the Armour layer, creating new local sources of bedload. Conversely, events that fail or are close to the threshold of transport of whatever duration (D), generate only limited movement. The reason for the effectiveness of Type (B) is that they not only access new sources through armour break-up and bank erosion, but they also establish connectivity between sediment sources over much longer reaches of channel. The identification of the significance of the form of the flood hydrograph on bedload transport has implications for interpreting the impacts of land management activity and climate change on channel morphology. Conditions that increase flood magnitude but reduce flood duration may be associated with sedimentation since transfer of material will occur over relatively short distances. Conversely, longer duration events of higher or similar magnitude to present, may result in much more significant channel activity as longer reaches of the river network become connected.

Conclusions

A new portable and cheap load-cell based continuos recording bedload trap has been successfully deployed and run for four years, over which time 75 bedload events have been recorded for flows up to 1:50 year RI. Sediment transport rates are of comparable magnitude to those reported in similar streams, but there are significant differences. Thresholds for initiation of bedload transport do not increase with time between events, rather these remain stable or reduce. Similarly, events are characterised by negative hysteresis. Both these factors point to the importance of upstream sources in controlling temporal variations in event yield. It is demonstrated that for predictive purposes, total event power, a variable that includes duration as well as magnitude, explains over 70% of the variability in event yield. A model of the effectiveness of different flood types is tested. Four types of event are identified in the highland water. Those of high magnitude and long duration are associated with maximum effectiveness because they not only access new sources through armour break-up and bank erosion, but they also establish connectivity between sediment sources over much longer reaches of channel.

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Assessing the accuracy of the Spatial Integration Method (S.I.M.) for estimating coarse bedload transport using passive tracers.

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Introduction

The evolution of morphology and physical habitat in river environments is linked intrinsically to the processes of sediment transport. In many cases, these environments are dominated by coarse sediments (here, defined as particles having a diameter of 8 mm and greater), (Leopold, 1992). Understanding coarse sediment transport processes has direct economic and ecological benefits,via improvements in the prediction of changes in physical habitat and the location and magnitude of erosion and deposition; the latter accounting for substantial costs in terms of land loss and disruption of infrastructure (Sear et al, 2000).

The study of sediment transport processes has become increasingly sophisticated (McEwan et al, 2001; Habersack, 2001), with progress in fluvial research converging on the prediction of sediment transport rates; this has taken place through improvements in the physically-based understanding of entrainment, transport and deposition . Sediment tracing provides a non-invasive, cost-effective approach to the determination of sediment transport rates (Haschenburger & Church, 1998; Habersack, 2001). A major review of this published literature has been undertaken (Sear et al., 2000). The principle behind tracer studies is to introduce material that is easily distinguishable from the natural sediment, but behaves similarly, into an environment, and to monitor its behaviour. In practice, several types of tracer study exist (Madsen, 1989): the present study focuses upon the Spatial Integration Method (SIM). This approach is the most widely and simply deployed method, in both littoral and fluvial tracing studies (Lee et al, 2000; Sear et al, 2000). Three quantities need to be measured during a SIM tracer study: (1) the distance travelled by the tracer's centre of mass or volume (centroid), during a given time period (allowing the virtual velocity of downstream or longshore movement (v_b) to be determined); (2) the thickness of the active layer (d_s) (deVries, 2001) and (3) the width of the active layer (w_s) (Ashiq, 1999). The relationship is represented mathematically as:

$$Q_b = v_b.\, d_s.\, w_s \qquad (1)$$

where Q_b is the bulk transport rate (downstream or longshore). Typically, estimates of sediment transport rates have been empirically related to certain hydrodynamic variables; in fluvial environments, maximum stream power (Haschenburger & Church 1998); whilst on beaches, the longshore component of wave power (Lee et al, 2000).

Methods & Field site

Two field sites were used to test the SIM method. The Highland Water and the River Lune, represent contrasting coarse sediment fluvial environments (Table 1). Two passive tracer technologies were used; cast aluminiun "forms", and Aluminium foil covered natural clasts. These latter tracers, provide a cheap tracer that enables 3-D detection to 0.25m burial at low cost, and with high grainsize/shape representativeness.

Field Site	Basin Area (km^2)	$Q_{bankfull}$ (m^3s^{-1})	Slope	Width (m)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
Highland Water	11.5	2.80	0.0073	3.5	9.9	32.8	46.3
River Lune	26.0	22.5	0.0048	10.6	9.9	57.2	137.2

Table 1: Field site characteristics used in SIM experiments

Theoretical advances focussed initially on manufacturing tracers that represented the indigenous material in terms of size and shape. The accurate measurement of bulk grainsize was undertaken, for each study site, using the ISO lower precision curves published by Church et al, (1987). Sizes that represented the 16th, 50th and 84th percentiles were identified and manufactured where tracing technology allowed. A new, methodology for the determination of representative tracer shape was developed (Oakey et al, in review). This methodology can be used to measure the shape of tracers in any percentile size class; as such it is reproducible, statistically representative of the river bed material and has minimal bias.

Error analysis from this research and others (Haschenburger & Church, 1998) demonstrate that over 50% of the total error in SIM estimates of sediment transport rate in fluvial environments, are derived from the estimation of travel distance v_b and d_s. Thus a statistical approach to the estimation of the tracer numbers required to obtain a given level of accuracy about the mean was undertaken for the derivation of travel distance, L (Lee et al, in review). Analysis of all the tracer experiments show that for the conditions studied, in order to acquire an accuracy L to within 10% of the mean value, required tracer numbers are typically in the order of 700. There was no correlation with event magnitude, but as tracers become more dispersed by successive events, progressively higher number of tracers will be required. This methodology can be used to check the minimum accuracy of estimates after a tracer study. In all the experiments in this project, accuracy was to within +/- 20% of the mean L, with 3 attaining </= 10%.

The third area of tracer theory explored the methodology for the SIM estimates of virtual velocity (v_b), burial depth (d_s) and active width (w_s). Different measures were used, and tested against measured transport yields recorded from traps installed in the Highland Water fluvial site.

The fourth area of tracer theory explicitly tackled in this research were the effects that tracer size, shape and deployment location (cross-stream or cross-shore) had on the estimation of transport rates. In each environment, tracer forms were constructed that represented the 16th, 50th and 84th percentile diameters wherever possible. In addition 3 shapes were scaled so that each form in each percentile had the same volume and mass. The resulting 9 forms were deployed in three injection beds located at 25%, 50% and 75% of the channel width, each containing the same numbers and distribution of forms.

Results

The compilation of field datasets, on this project, may be summarised as follows:

- 51 fluvial tracer studies, including summary data for each deployment and incorporating (wherever possible) hydrodynamic, together with sediment transport measurements (Sear et al, 2000).
- Data obtained on tracer movement, for 11 events of contrasting magnitude and duration, from two different fluvial environments; these include simultaneous hydrodynamic, topographic and sedimentological information.

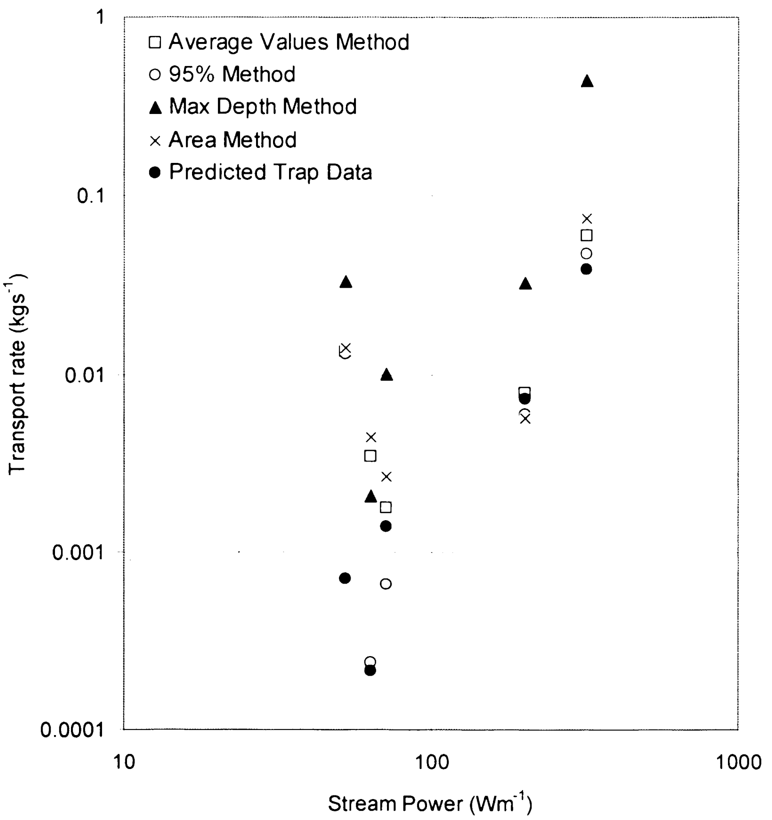

Figure 1: Variation in SIM calculated transport rates with method of estimating active width, virtual velocity and active depth.

Figure 1, demonstrates the variability in calculated transport rates arising from the different methods used to estimate v_b, d_s or w_s. Three points emerge from this analysis: (1) there is up to 3 orders of magnitude variability in transport rate depending on the Spatial Integration methods used; (2) assuming the trapped data is the real value, then the Average Values Method (AVM) provide the most consistent, and accurate predictions of "observed" transport rates. The 95% Method (95M), modified from Bray, (1996), also consistently performs better than other methods. The Maximum Depth Method (MDM), which is based on maximum d_s and averages of all other values, over-predicts in all cases. In subsequent analysis of data, AVM was applied; (3) The values predicted by the AVM and 95M are close to the measured values, demonstrating that the SIM method, when applied carefully is a valid method for estimating sediment transport rates across a range of stream powers in fluvial environments. Encouragingly, application of the AVM to existing published literature collapses transport rates onto a single, well defined power-law relationship with stream power (Figure 2).

Tracer form (size and shape) and injection Bed were tested in a 2-Way ANOVA for significant effect on the two dominant determinants of transport rate v_b and d_s.. The main results may be summarised as follows:

1) Tracer Injection position is a significant control on both travel distance and burial depth in both rivers studied and is independent of event magnitude.
2) Tracer form (size and shape) is a significant control on both travel distance and burial depth in both rivers studied and appears less significant at near threshold conditions. This latter finding is unexpected, and inexplicable. The behaviour of forms was not significantly different between injection beds.

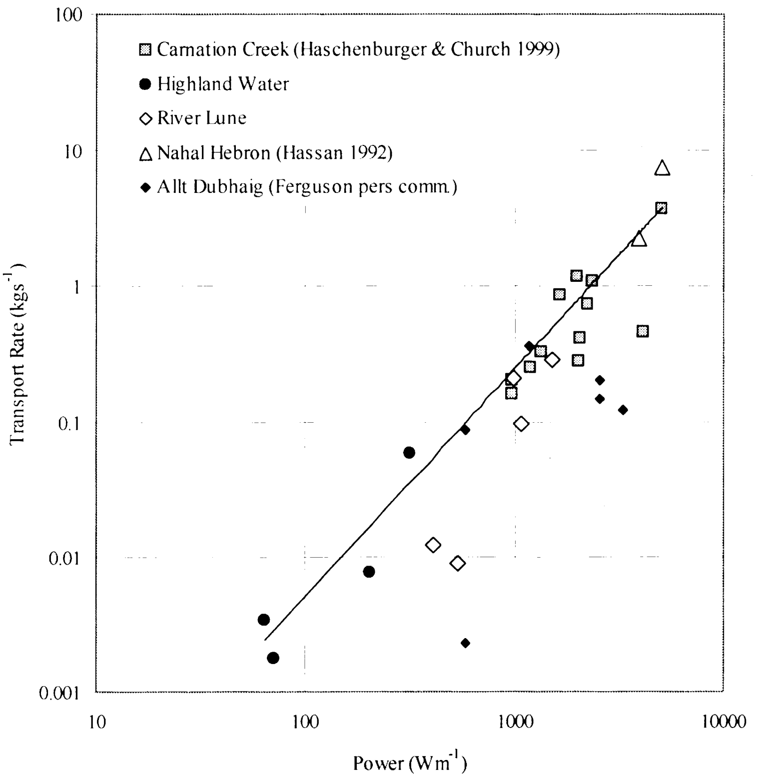

Figure 2: Comparison of SIM estimated transport rates for a range of fluvial environments and stream powers.

These results are directly comparable with previous tracer theory studies undertaken on beaches (Lee et al, 2000, Bray, 1996).

Conclusions

The Spatial Integration Method of transport rate or yield determination can provide values that approach those measured using simple Pit traps. The advantages of the Tracer based approach, is that data can be obtained for high magnitude events, where other methods of monitoring fail. However, the SIM results are sensitive to the precise method of estimating the main variables v_b, d_s or w_s. In this assessment, Average Values Methods, 95% Methods and Area methods all performed consistently across the different magnitude events. Use of Maximum Depth Methods over-estimate transport rates in the study stream. A method for the assessment of number of tracers (n) necessary to acquire a given accuracy in the estimation of the main variable L, has been developed. Application of this method to a range of tracer datasets derived from contrasting environments indicates that tracer deployments should use 700 tracers to be reasonably certain of attaining an accuracy of +/- 10% of the mean value of L.

The use of SIM for determination of sediment transport rates must replicate not only the size, but also the shape and spatial controls on transport distance and burial depths, regardless of event magnitude. The use of Aluminium foil-coating of natural clasts, provides a cheap passive tracer with 3-D detection, capable of replicating the size and shape distribution of the indigenous grainsize population. Deployment of tracers in patches across the channel represents a balance between the ideal representation of the full cross-section, and pragmatic limitations of working in large rivers. Deployment of tracers should also seek to represent the active layer depth, in order to provide over-estimation of L.

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A Critical Analysis of the Application of a Single Frequency Acoustic Doppler Current Profiler to the Measurement of Suspended Sediment Fluxes in Rivers and Estuaries

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Determination of sediment flux is critical to many estuarine and river engineering and scientific applications. At the largest scale sediment flux controls the morphological evolution of the channel whilst at smaller scales it impacts on the design of ports and harbours and other engineering structures through it's impact on siltation rates and hence the requirement for maintenance dredging.

Today Acoustic Doppler Current Profilers are widely used to measure the variation of flow field and although these instruments were primarily developed for the measurement of current profiles a number of workers have attempted to derive sediment flux estimates from inversion of the backscattered pressure field recorded by these instruments.

In this paper we evaluate the results of such an analysis using data acquired using a single frequency broadband Doppler Profiler. The instrument was deployed on a vessel running repeated transects across the Thames Estuary over two 25 hour periods on a Spring and Neap tide.

Suspended sediment concentration data determined from gravimetric analysis of water samples and profiles of the optical transmission and backscatter are compared against the estimates of suspended sediment load obtained from inversion of the backscattered acoustic pressure field measured by the ADCP and a error budget calculated the results of which we present here.

Measurement of suspended sediment characteristics in an embanked flood plain environment of the River Rhine

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Introduction

During the last years, flood plains have increasingly become acknowledged as major sinks for both sediments and pollutants (e.g., Walling, 1999). Attempts to quantify the amount of (sediment-associated) pollution of lowland flood plains often proceed through modelling. However, data on suspended matter characteristics in flood plain environments are scarce, yet important for the calibration of flood plain sedimentation models and the assessment of the fate of sediment-associated pollutants in riverine environments.

Therefore we deployed a portable particle sizer and settling tube during two discharge peaks of the River Waal, which is the major distributary of the River Rhine in The Netherlands (mean discharge of 2400 m^3/s at the Dutch-German border). The fieldwork area at the flood plain of the Afferdensche & Deestsche Waarden in the east of The Netherlands (Fig. 1) was inundated two times in Spring 2002 (Fig. 2). From 27–02 to 21–03 (rendering the 'March' data) and from 24–03 to 03–04 (the 'April' data), the instrument was deployed in its steel construction located in a meadow at about 100 m distance of the minor embankment.

The aim of this paper is to outline the use of the device, give an overview of the recent data gathered in the field campaign and discuss the opportunities for further use of the data in near future research.

Fig. 1. Location of the fieldwork area within The Netherlands.

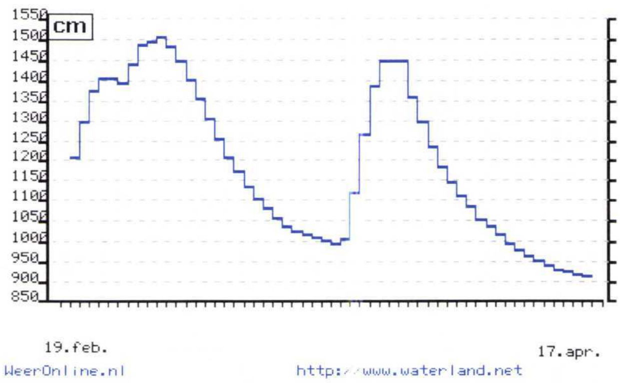

Fig. 2. Stage in cm a.s.l. of Rhine at Dutch-German border during March and April 2002.

Description of the measurement device

The portable particle sizer/settling tube we used is the LISST-ST Type C manufactured by Sequoia Scientific, Inc. (Redmond, WA, USA) (Fig. 3). This instrument has been used in several marine, coastal and estuarine studies but has not often been deployed in a riverine environment. The LISST-ST measures particle sizes and settling velocities of particles ranging from 2.5 to 500 μm using laser diffraction principles following the 'exact Mie theory'. In addition, a photo-diode measures the transmissivity (clearness) of the water. At the beginning of each experiment, the settling tube is opened for four seconds and water with suspended matter is taken in. Next, the suspended matter settles within the settling tube and the grain size distribution is measured 71 times during 12 hours at logarithmically spaced time intervals. The settling velocity is calculated from the decrease of the volume concentration of the different particles fractions in time. For a more comprehensive description of the LISST-ST device, we refer to Agrawal & Pottsmith (2000).

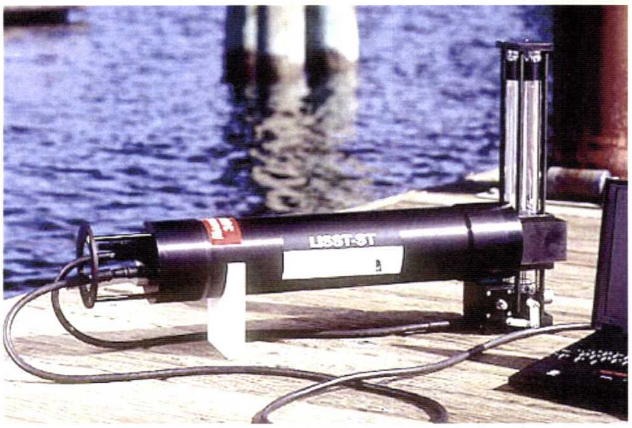

Fig. 3. The LISST-ST combined particle sizer and settling tube measures 86.36 × 48.90 cm. The horizontal tubing holds the laser. The settling tube can be seen on the right. Photograph: Sequoia Scientific, Inc.

Transmissivity data

It can be seen in a transmissivity graph (Fig. 4) that there is progressive clearing of the water as particles settle. However, 100 % transmissivity is not reached, because the finest particles have not settled yet after 12 hours (i.e., the measuring period we used) and still attenuate the laser beam. On the one hand, this means that we did not measure the characteristics of the smallest particles, i.e., those particles that have a diameter up to about one micron. On the other hand, it allows more insight in the temporal variation during a flood event because of a larger amount of data than in the case of the use of e.g. 24-hour periods.

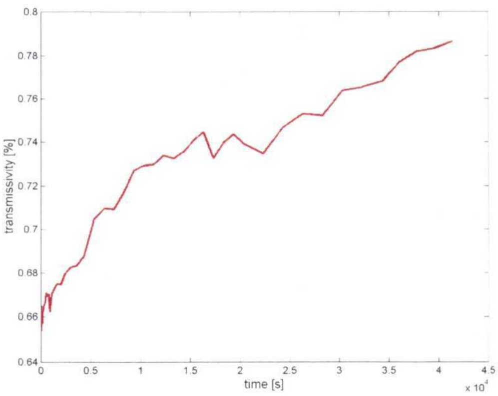

Fig. 4. Transmissivity graph for experiment 9 (out of 9) of the April data set.

Volume concentration data

During a settling experiment, the volume concentration of particles in each of the 32 size classes is measured. This is resampled afterwards to eight size classes for convenience. An example of the development in time during one experiment of the volume distribution of these eight classes is depicted in Fig. 5. The concentration of the three classes that include the smallest particles is considerably higher than that of the particle classes including the largest particles. The concentrations of all classes decrease during the experiment due to gradual settling. These concentrations can be summed up in order to obtain total suspended sediment concentration.

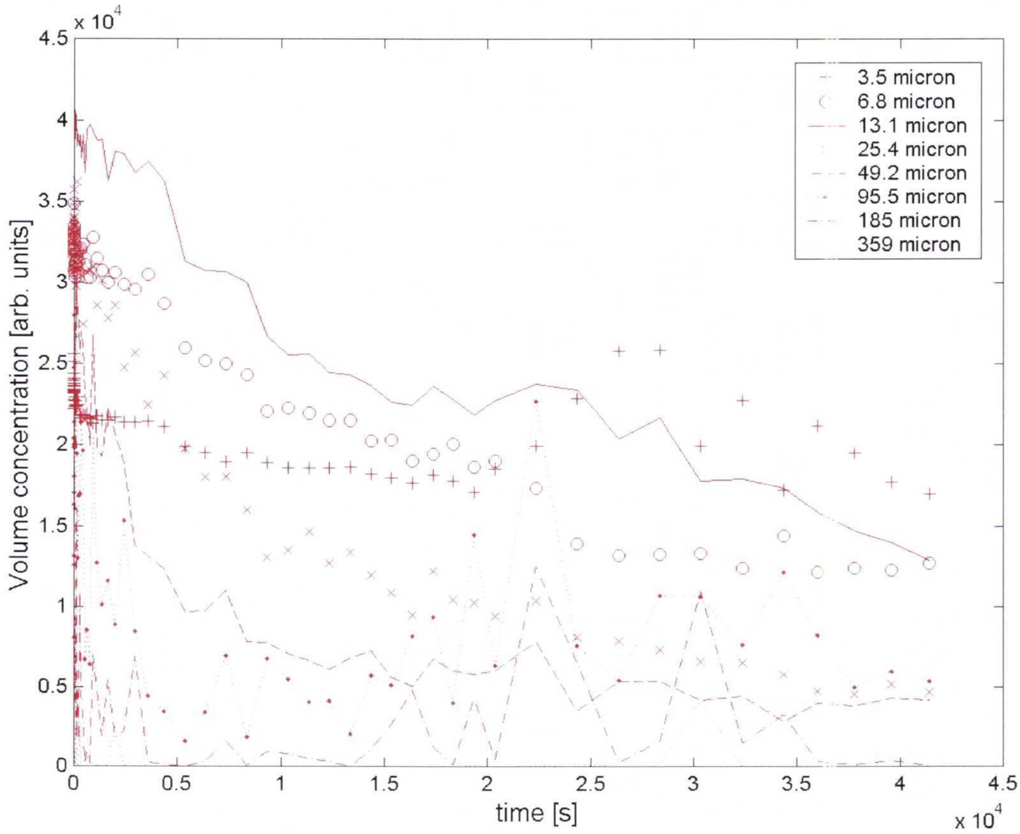

Fig. 5. Volume concentrations of the eight resampled size classes (named after their class mean) during the ninth and last experiment in the April data set.

Settling velocity data

In Fig. 6, an example of the relation between settling velocity and particle size is depicted. The settling velocity for larger particle sizes strongly deviates from the theoretical particle size/settling velocity relationship, depicted here as 'Gibbs settling velocity'. This is most probably due to the fact that the larger particle sizes largely consist of flocs (i.e., sediment and organic matter that have coagulated). These are known to have a much lower density than 2.65 g/cm^3 (the density with which the Gibbs settling velocity was calculated) because of a high degree of porosity (Droppo *et al*. 1997). This causes the settling velocity to be lower than the theoretically derived velocity.

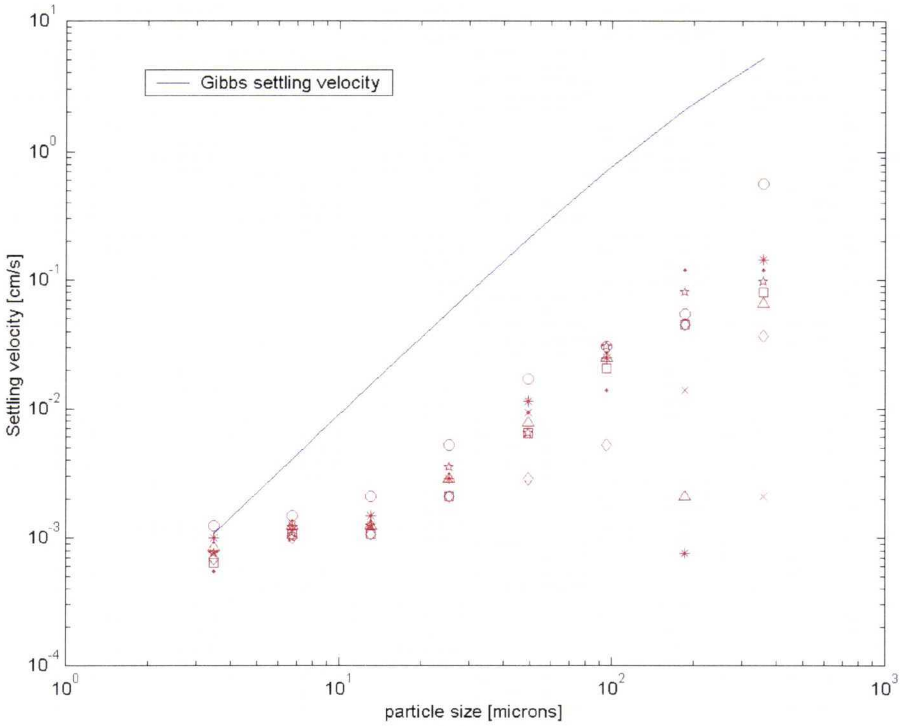

Fig. 6. Relation between particle size and settling velocity for the eight resampled particle size classes. Each point symbol represents measurements derived during one 12h experiment from the April data set. Note the deviation from the theoretical relationship for quartz sediments (Gibbs settling velocity). Also note the increase in standard deviation with particle size.

Perspective

Using a combined portable particle sizer/settling tube, several important particle properties such as volume concentration and settling velocity could be measured in an inundated flood plain environment. Here, mainly data for one out of nine measurements during the deployment in April have been presented. In the near future, the settling velocities and particle sizes will be used to calculate the particle density variations during a flood event. The temporal variation of the sediment concentrations, particle size distributions, and particle densities during a flood event will be further explored to assess the effect of discharge, influx of sediment, hydraulic conditions during the different inundation stages in the floodplain environment. The data from the March and April deployments will be mutually compared to assess the differences in particle characteristics as a result of flood magnitude and duration. In addition, the sediment characteristics will be related to turbidity and stream velocity measurements that were carried out during the April deployment using an Optical Backscatter Sensor (OBS) and Electromagnetic Field current meter (EMF), respectively. The particle size distributions will be compared to the grain size distributions of suspended sediment from a 60 litre water sample collected during peak discharge of the March flood event, and of deposited sediment collected from sediment traps in the study area during both flood events. The total suspended sediment concentration data will be compared to the sediment concentrations in 500 ml water samples taken at various places on the flood plain during the March deployment.

Acknowledgements

We are greatly indebted to Chris Roosendaal for his many hours of technical support. We also would like to thank Sander Wijnhoven for the under water-installation of the LISST-ST, thereby making the March deployment possible.

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Sediment transport in agricultural catchments- the need of methods for tracing sediment sources from agricultural areas . Examples from the National Agricultural Environmental Monitoring Programme.

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ABSTRACT

In the Agricultural Environmental Monitoring Programme in Norway losses of sediments and nutrients have been measured since 1991 in ten agricultural catchments of sizes between 1-30 km^2.

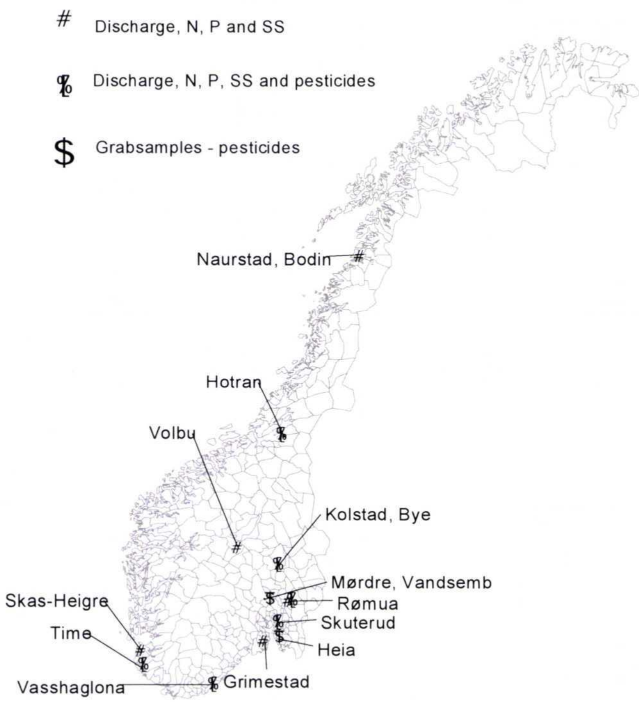


Figure 1. Catchments in the Norwegian Monitoring Programme

One of the major objectives of the Monitoring Programme is to document the effect of different agricultural production systems and site – specific characteristics on erosion and nutrient losses to surface waters and give advice to the policymakers about agricultural production systems and their environmental effects.
Annual variations in weather conditions have a significant influence on the losses while also political decisions concerning subsidies etc. may also influence on cropping systems and thereby influence erosion. During the last ten years new subsidies, with the objective to

change tillage systems from autumn tillage to spring tillage in addition to subsidies for catch crops, buffer zones and sedimentation ponds have lead to changes in agricultural practices. Within the Agricultural Environmental Monitoring Programme, information concerning agricultural practices is collected yearly for individual fields in the catchments and any changes in practices are thereby recorded.

Although there has been a reduction in the areas being autumn ploughed (Fig.2), there has not been documented a high reduction in the measured annual soil losses. This is partly due to large variations in weather conditions and runoff between the years. But it might also be that other sources than agriculture contribute to the soil losses.

The focus in this paper is on two small agricultural catchments Skuterud and Mørdre which are situated in the south east of Norway. Site characteristics are given in Table 1. Discharges are measured continually using a Crump weir while runoff water is sampled on a volume proportional basis. A composite sample is collected bi-weekly and among others analysed for suspended solids in addition to total nitrogen and phosphorus. On the basis of the total runoff volume and the analysis results the total loss is calculated.

Table 1 Site characteristics of the catchments Skuterud and Mørdre included in the Agricultural Environmental Monitoring Programme in Norway. Temperature and precipitation expressed as 30 year annual means (DNMI, 1993).

Catchments	Total area (ha)	Farm-land (%)	Arable land (% of farmland)	Manure animal units (mau/ha)	Temp. (°C)	Prec. (mm)	Soil type	Major crops	Study start
Skuterud	449	61	93	0.2	5.5	785	Silty loam	Cereals	1993
Mørdre	680	65	95	0.2	4.3	665	Silt and clay	Cereals	1991

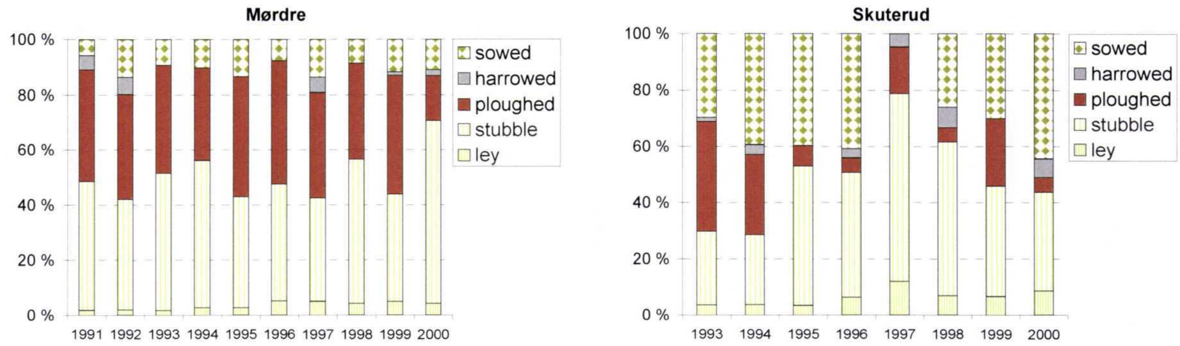


Fig.2 Land management in the autumn for the Mørdre and Skuterud catchment.

Soil losses have varied from around 100 $kgha^{-1}$ to nearly 3000kg ha^{-1} (Fig. 3). Highest erosion is measured in catchments with a large area ploughed during the autumn. Detailed erosion pattern on each field in the catchments are registered after major runoff events and after snowmelt periods during the winter season. Erosion patterns are dependent on agricultural practices, runoff condition and the winter conditions with frozen or unfrozen soils.

These field investigations have also documented that in some years there is an active bank erosion in the catchment. Also erosion around hydrotechnical equipment like inlets for surface water, outlets from drainage pipes into the river bank etc. has been observed. This leads to concentrated erosion and particle transport from the agricultural landscape.
Field investigations (event studies) have documented particle transport through drainage pipes. It is assumed that the process with transport through macropores and cracks, preferential flow is more important than earlier assumed for these catchments. In the autumn of 2000 the south-eastern part of Norway received 2-3 times higher precipitation than normal. Runoff in the Skuterud and Mørdre catchments was respectively 5 and 3 times higher than average for the whole monitoring period.Compared to earlier autumn periods the soil losses in Skuterud and Mørdre catchments were 6 times higher even though less area than normal had been autumn ploughed. This autumn there was also an increase in area with catch crops. Field investigations did not document especially much visible erosion, and not rills and gullies which are more usual after winter runoff events. It is assumed that erosion was dominated by sheet erosion and especially by preferential flow through soil profile. In the following spring 2001 significant landslips were registered along the streambanks and over drainage pipes in these catchments. This might be due to oversaturation and instability caused by the unusual wet previous autumn period.

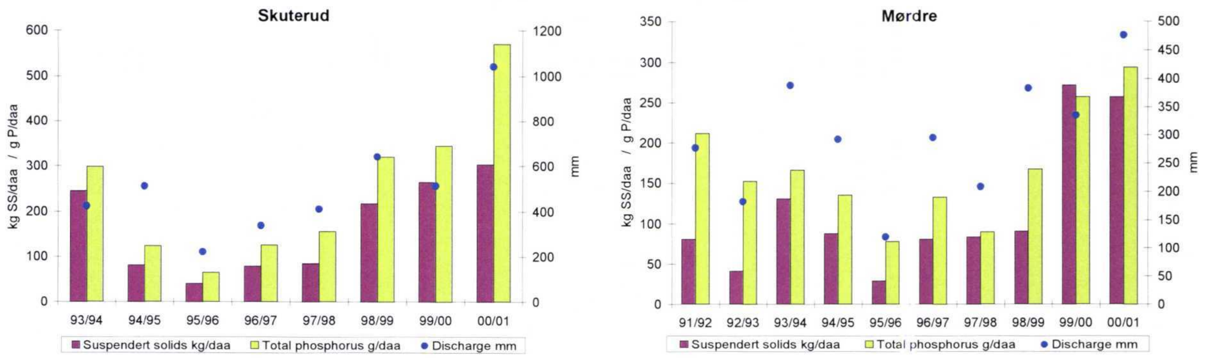
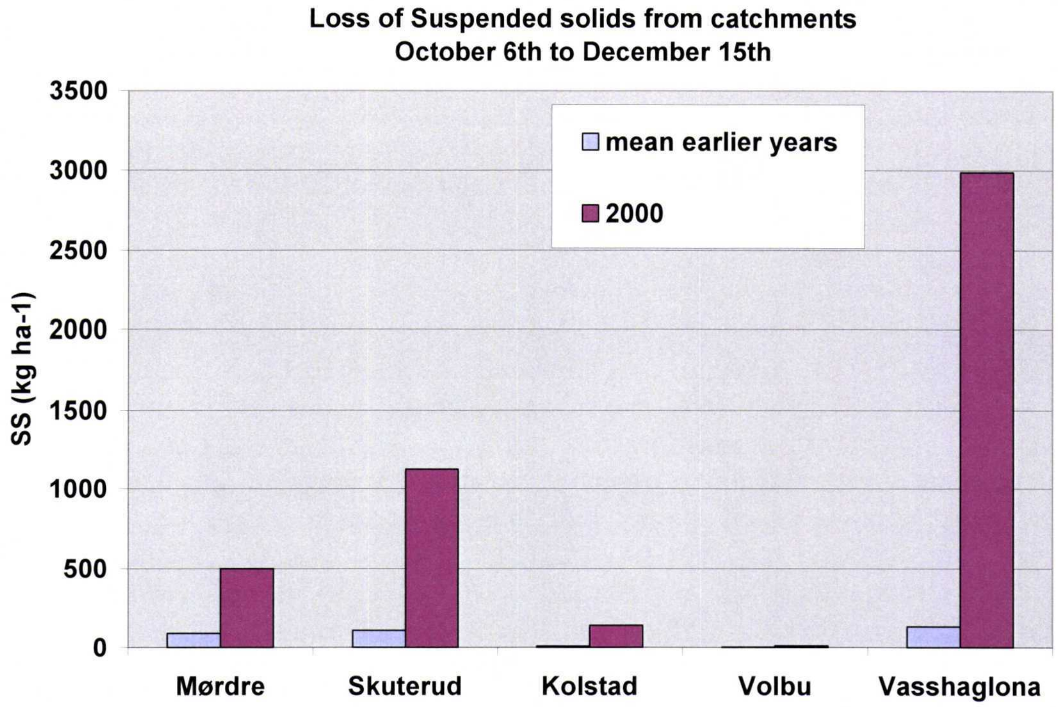


Fig.3 Losses of suspended solids (kg/daa), total phosphorus (g/daa) and discharge (mm) for agrohydrological year (May 1. – May 1.) for the Mørdre and Skuterud catchment.

For planning further measures to reducing erosion from agricultural areas it is important to have methods that document whether the particles are coming from bank erosion or from the agricultural areas. Such studies are now planned to take place in selected catchments in the Agricultural Environmental Monitoring programme. There is a need for methods for tracing the sediment sources from agricultural areas.



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Development of a Conceptual Soil Erosion Model for Ghana

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Extended Abstract

Soil erosion is one of the most pressing issues facing developing countries. In these countries, the need for soil erosion assessment is greatest as a successful and productive agricultural base is necessary for economic growth. However, the greatest importance on soil erosion modelling is placed by developed countries due to a lack of education and prioritisation by developing countries to the problem of land degradation. In Ghana, a country with an exponentially expanding population and high potential for economic growth, agriculture is a vital resource. In the study area most of the crop production is low technology and restricted to slash and burn agriculture with most units effectively being self-sufficient smallholdings, which trade the surplus in the large urban areas and towns. Small-scale cash crop production, such as cocoa beans, is also undertaken. The high intensity seasonal rainfall coincides with the early growing period for many of the crops such as maize, cassava and yam. This means that the plots are very susceptible to high erosion rates especially when combined with farming areas on steep-sided valleys in the regions around the south half of Lake Volta.

The success of soil erosion models is largely determined by the availability and quality of the calibration data and the type of model used. There are two main model categories; empirical models and physically based models, a third category; conceptual models describes those that are somewhere between the two, i.e. they contain some parts that are empirically derived and some that are based on mathematical representations of the physical processes.

The two main types of model have distinct advantages and disadvantages inherent to the structure of those models, especially in relation to their use in developing countries. Empirical models, due to their simplistic nature, require only a few input parameters. However, the data sets for each of the parameters need to be recorded over long periods to reliably calibrate the model. Physically based models require only a fraction of the amount of input data for calibration, but generally have a much larger range of parameters. These can both cause problems when trying to apply the models to developing countries, where either long data sets or the equipment to record data for complex parameters are not available. One possible solution to attempt to overcome the problems encountered with using either a empirical or physically based model, is to develop a conceptual model that incorporates the best features of the empirical and physically based models with a view to eliminating the drawbacks of both. The model being developed and tested on a small basin in Ghana is a conceptual model incorporating features of the Calibrated Simulation of Transport Erosion model (CALSITE) (Bradbury et. al., 1993) and the Agricultural Non-Point Source pollution model (AGNPS) (Young et. al., 1989)

The model is being tested on a small 14 km^2 basin, containing a tributary of the river Pompom, south west of Lake Volta. One immediately noticeable problem of this basin, and probably many other similar ones, is that the effects of soil erosion are intensified by the network of paths throughout the basin used by the local villagers. These pathways effectively act as man-made gullies that aid the routing and transport of runoff and eroded sediment down to the basin outlet.

USLE (Wichsmeier & Smith, 1978) estimates had already been calculated for the whole of southern Ghana and this provided a basis for the selection of the study basin. The most basic form of the USLE was used, A = R C K LS, where R is the rainfall erosivity factor, C is the crop cover factor, K is the soil erodibility factor, and LS the slope length factor. The management factor P is taken as 1, and has therefore not been included. Figure 1 shows the results for the USLE over the southern half of Ghana with the study basin highlighted, and Figure 2 shows the USLE results for the study basin.

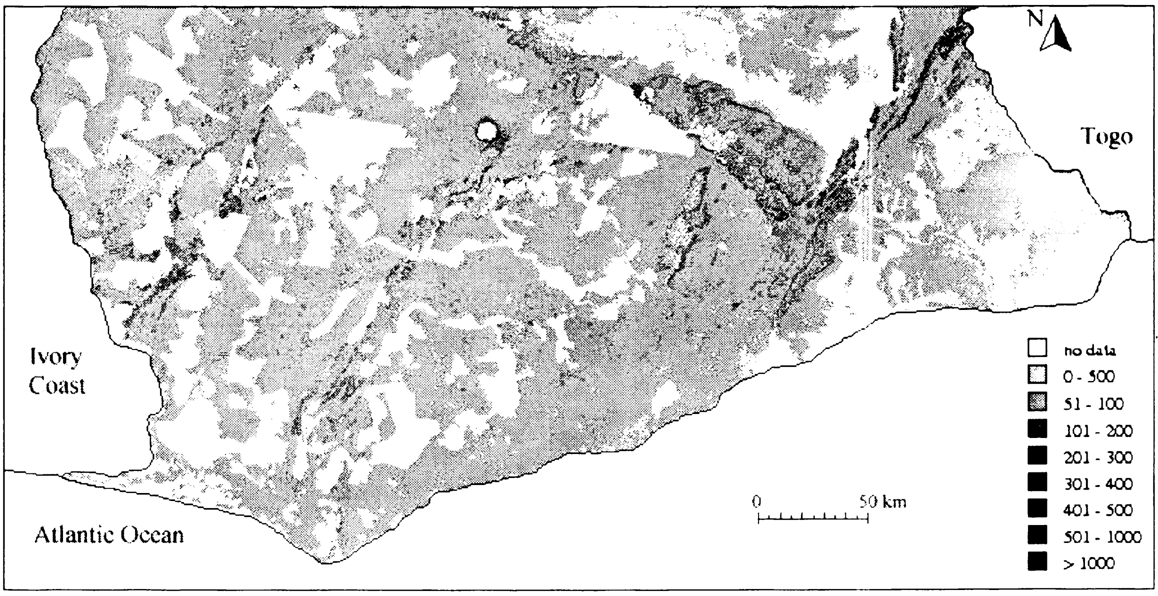

Figure 1 Estimated Annual Soil for Southern Ghana in t/ha/year

The figures show estimated annual soil loss in t/ha/yr per pixel. The estimated total annual soil loss for the study basin was 109 230 t/year, based on the whole basin being used for agriculture.

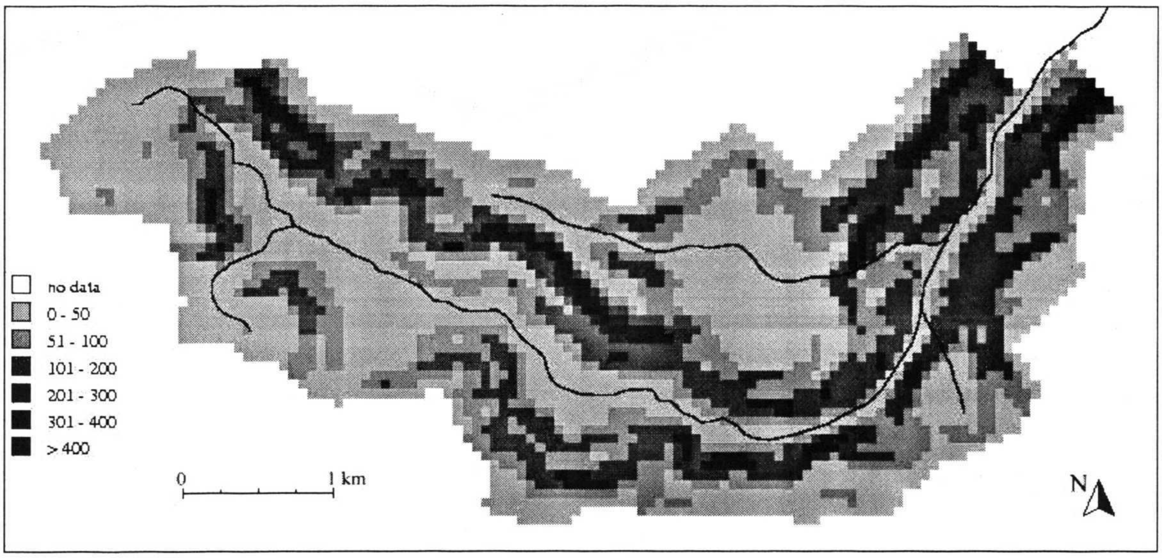

Figure 2 Estimated Annual Soil Loss for Study Basin in t/ha/year

AGNPS is an event based, distributed parameter simulation model that calculates the sediment yield for a basin for single storms. The CALSITE model is an empirical model that calculates sediment yield for a basin on an annual basis. The CALSITE model's main advantage is that it employs a very simple but effective aspect driven routing structure that utilises the concept of a delivery ratio, however, it is restricted by the need for long data sets for calibration. The model does not comprehensively cover the processes of deposition and detachment within the flow of runoff. The main advantage of the AGNPS model is that it can be calibrated using only short data sets, but its drawbacks are its poor modelling of channel scouring and bed-load transport and the use of updatable parameters. The model also utilises many components that have been developed within the US, such as the SCS curve numbers and hydrologic soil group classifications, that may not be portable to other areas of the world especially Africa.

The conceptual model under development for Ghana utilises the CALSITE model especially the routing algorithm as a base but adapts the delivery ratio to incorporate equations and factors to cover better sediment transport, deposition and detachment phases and peak flow so that it can cover single storm modelling and calculate sediment yield as well as soil erosion. The model is to be implemented using the open-source GRASS (Geographical Resources Analysis Support System) GIS software package, which allows new modules to be written and added in the C programming language.

During the summer of 2000, a field trip to Ghana was undertaken to collect daily rainfall, streamflow, soil properties and sediment monitoring data. Data were collected for the 14 km^2 basin during September and included a range of storms from 5 to 61 mm, September 21st and 19th respectively. Other long-range data were also provided for some of the larger rivers and basins within the area by the Ghanaian Water Resources Research Institute (WRRI).

Key Words: Soil erosion; sediment yield; Ghana; CALSITE; AGNPS; conceptual modeling.

Suspended and Bedload Sediment Transport Dynamics in Two Lowland UK Streams – Storm Integrated Monitoring

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INTRODUCTION

There is little information on the role of channel storage and remobilisation in determining sediment transport dynamics in lowland streams (Walling, 1996). In particular the response to macrophyte cutting and storm events has not been well quantified.

A one-year monitoring programme was conducted at two contrasting tributaries of the River Kennet, in Southeast England to address these issues. The River Lambourn sub-catchment lies on chalk and groundwater is the dominant source of baseflow. A shallow, rapid flowing channel with low seasonal variation in discharge (2-year range 0.725 – 2.77 m^3s^{-1}) and extensive macrophyte beds results from these conditions. The River Enborne sub-catchment is overlain by low permeability sands, silts and clays. The river has sluggish flow within a deeper channel. During high intensity rainfall events, generation of overland flow pathways led to peaky, variable flow (2-year range 0.116 to 25.3 m^3s^{-1}). Submerged macrophytes are usually sparse due to water depth, turbidity and instability in the bed sediment.

METHODS

Suspended sediment concentrations were determined using two automatic watersamplers on each river reach (upstream and downstream stations) set on a 24-hour collection cycle. At the onset of storm events, an additional sampler was triggered to collect samples every 60-minutes by a float switch. Bedload material transported along the streambed of the river was sampled using two 25x25cm pit type sediment traps on each river reach (upstream and downstream stations). The boxes were emptied weekly.

SUSPENDED SEDIMENT TRANSPORT

Suspended sediment concentrations in the Enborne were high (means 29-39 mg l^{-1}) and very variable (Figure 1a). Suspension of bed sediment and bank erosion were postulated as the main sources of sediment. Concentrations increased during high flow periods in the winter. This was probably due to the activation of overland flow and drainage ditches pathways that delivered considerable quantities of sediment to the channel during storm events. Strong, linear relationships between suspended sediment and flow were observed at the two sampling stations (r^2 0.63 and 0.78). Varied response times to increases in flow, displaying multiple peaks in concentration, indicated the variety of sediment sources to the channel. The period between December 1998 and January 1999 exemplified the effect of sediment exhaustion in the River Enborne channel (Figure 1b). A clockwise, cyclical loop in suspended sediment response to storm events indicated that concentrations were higher on the rising than on the falling stage of the hydrograph.

In the Lambourn, suspended sediment concentrations (means 8-9 mg l^{-1}) were lower, and year round variations were less marked (Figure 1c). Suspension of bed sediment and bank erosion were probably the only sources of sediment to the channel. Although increasing suspended sediment concentrations were generally associated with high flows, the relationship between the two parameters was much weaker than on the Enborne. Notably high suspended sediment concentrations also occurred on the Lambourn during low flows (see Figure 1d). Periodic flushing of fine material during macrophyte clearance or livestock disturbance of bed sediment at the time of sampling might have caused this.

BEDLOAD SEDIMENT TRANSPORT

Bedload transport weights were far lower in the Lambourn (weekly means 12.7 and 19.7g) than the Enborne (weekly means 87.2 and 102g) (Figure 2). This was thought to be a function of hydrologic behaviour, sediment supply and in the Lambourn macrophyte sediment trapping and bed armouring. River Enborne bedload had a stronger relationship to flow (e.g. r^2 0.84 for 5.00 – 0.250mm size fraction) than in the Lambourn.

ENTRAINMENT THRESHOLDS

The competence of flows throughout the sampling period to mobilise bed sediment of different calibres was investigated. In the Enborne, bedload was dominated by fine sand-sized particles (0.250 – 0.063mm). Preferential transport of finer material (<0.038mm) occurred during storm events. In the Lambourn however, a more even distribution of particle sizes were transported with fine material transported in baseflow conditions. These contrasts were thought to be a function of different critical shear velocities for the two rivers.

Table 1 Estimating shear velocity (μ_*) in the Rivers Lambourn and Enborne (Julien 1995)

Flow conditions	**Lambourn μ_* (ms^{-1})**	**Enborne μ_* (ms^{-1})**
Low	0.0596	0.0027
High	0.0646	0.0065

Fine sand, silts and clays were transported irrespective of flow conditions in the Lambourn. However, movement of granules and coarse sand was restricted at low flows indicating the higher entrainment threshold required. A decrease in silt and clay-size material in the bedload during high flows suggested that these particles were resuspended into the water column.
In the Enborne, lower shear velocities explained the absence of coarse material in traps during baseflow conditions. However, larger rates of change in shear velocities and bedload transport to increasing flows implied that particles were more responsive to changes in flow than in the Lambourn. Reasons for this were threefold:

- Absence of macrophytes/bed armouring which protect fine bed material from transport by retarding flow and sheltering in the Enborne
- Supply of additional particles into the channel via overland flow pathways in the Enborne
- Steeper and larger magnitude rising limbs on hydrograph in the Enborne

CONCLUSIONS

Principal research findings were that suspended and bedload transport varied on both a temporal and spatial scale. Factors affecting sediment dynamics included sub-catchment geology, flow delivery pathways, flow magnitude, physical retention devices (macrophyte growth, bed armouring) and readily available sediment within the catchment/river channel.

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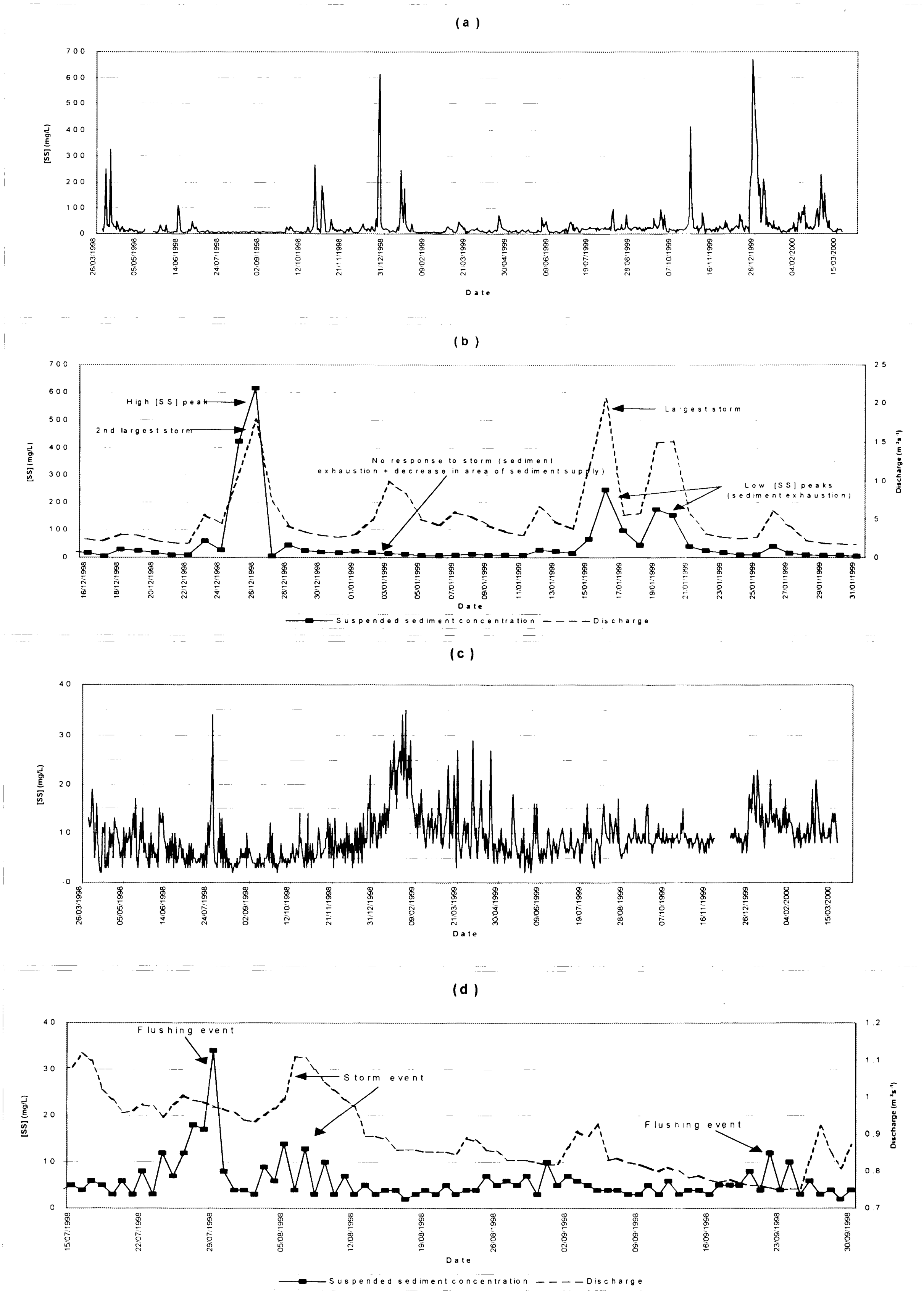

Figure 1 Suspended sediment concentrations (a) River Enborne 2-year record (b) River Enborne during storm event (c) River Lambourn 2-year record (d) River Lambourn during storm and flushing events

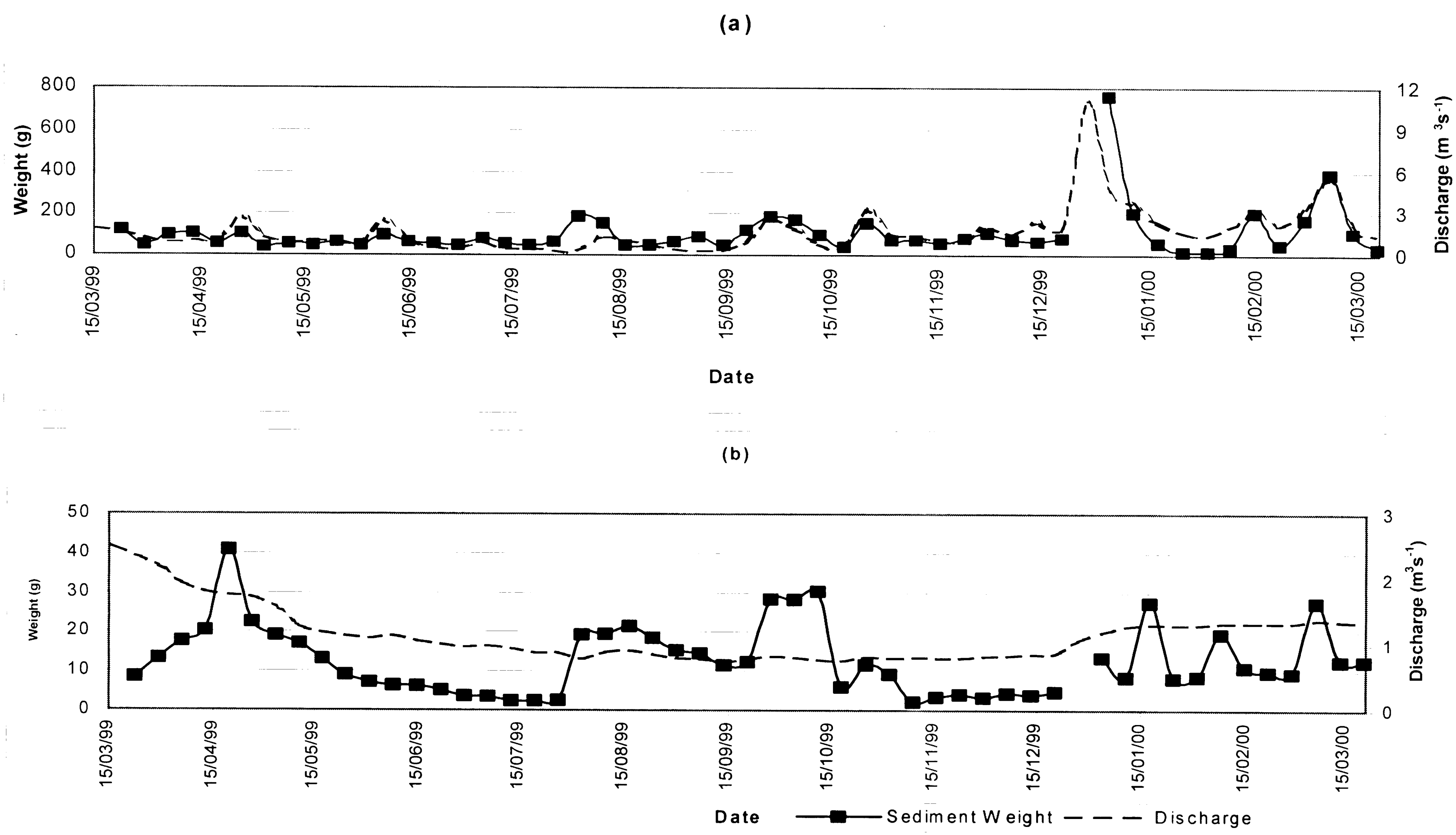

Figure 2 Bedload weights transported in (a) River Enborne upstream station (b) River Lambourn upstream station

Bedload measurements in periglacial environments - examples from Svalbard

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Abstract

Bedload transport in periglacial streams differs significantly from other environments. In periglacial environments, surface is frequently covered by ice. As a consequence, shear resistance on channel beds is low due to reduced surface roughness. This leads to increased runoff, accompanied with low infiltration into the ground. This effect has been studied in more detail with respect to bedload transport in the Kvikkåa and Beinbekken catchments, Liefdefjorden in Northwest Svalbard.

Bedload movement including sliding, rolling, and saltation processes was measured through fixed installed baskets samplers and sediment traps to approximate grain size distribution and loads for specific events and through sediment basins to determine total sediment load in a given period. Painted and numbered stone tracers allowed an approximation of travel distances at different locations within the river profile. Changing river courses on the active fluvial fan were observed during melting periods using coloured stone lines. These techniques have been applied to the Kvikkåa catchment at various locations, e.g. above the junction of the two tributaries of Småbreen and Kvikkåabreen, in the main river stream before reaching the fluvial fan, on the fan and at the outlets to Liefdefjorden. In addition, sediment baskets have been positioned in the Beinbekken catchment. Stream stage measured at gauging stations have been calibrated using NaCl-tracer and current meters to determine flow velocities and subsequent discharge, both available for comparisons with bedload measurements.

In the Kvikkåa catchment, clasts larger 2cm were not supplied from Småbreen during the observation period. From the Kvikkåabreen tributary, some sediment > 2cm has been supplied to the Canyon. It is assumed that most of the sediment reaching the fluvial fan has been mobilized in the Canyon. Comparison of total sediment collected in sediment basins, basket samplers, and sediment traps indicate, that both latter techniques underestimate total sediment transport by approx. 82%. Nevertheless, measurements on the outlet of the Kvikkåa to the Liefdefjorden showed, that only 3% of the bedload sediment supplied to the fan is transported into the Fjord. Coloured stone lines indicate a continuous change of the river course on the fluvial fan during melting periods. Transport distances of single stones from different painted stone lines is up to 28m on the fan during melting period. Coloured and numbered stone tracers have been transported of up to 405m in the Canyon, 317m on the Canyon base, and 32m on the fan. Largest travel distance is independent on pebble form and size and has been reached during frozen ground conditions. As a consequence, if sediment is available and not frozen to the ground, even low river discharge is able to transport large clasts over long distances.

Comparisons of sediment transported by slush flows and fluvial processes indicates, however, that slush flows contribute significantly to the overall sediment transport. It is suggested, that during the observation period, slush flows are more important for sediment delivery than fluvial processes.

The intelligent pebble: A new technology for tracking particle movements in fluvial and littoral environments.

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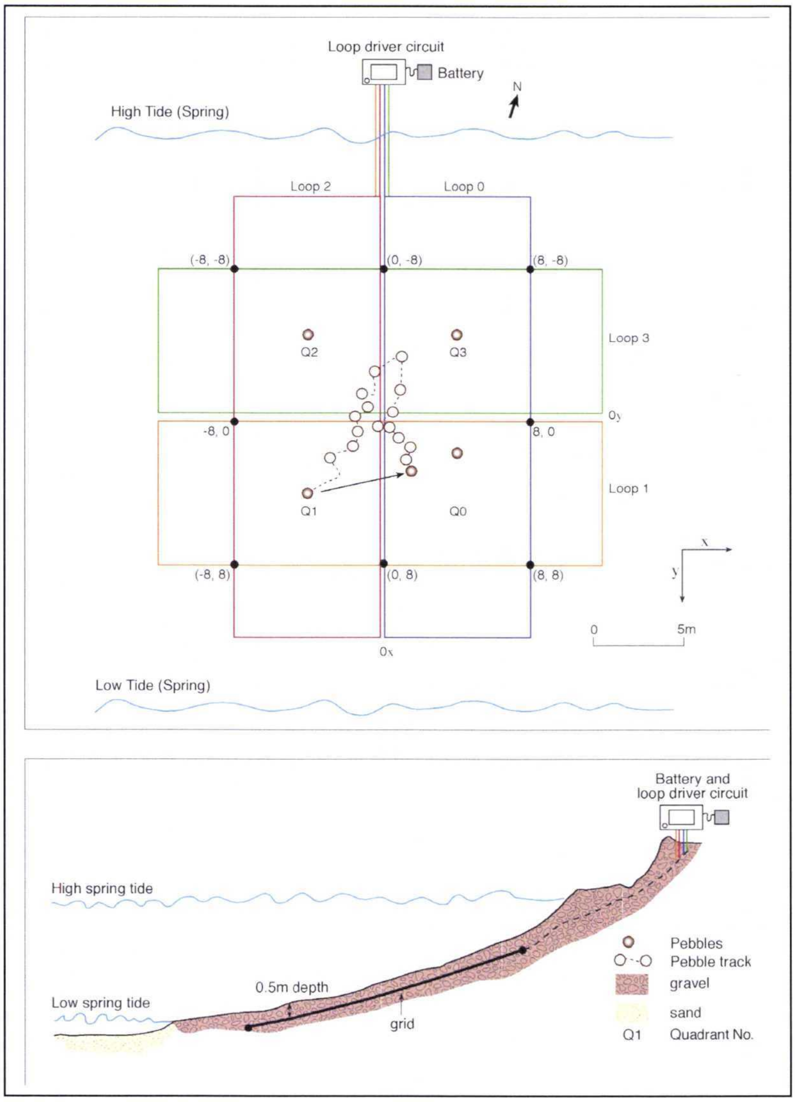
Introduction

To achieve a more detailed, physically-based understanding of the relationship between hydrodynamics and particle movement requires improvement in the resolution of particle location in time and space. This can be achieved through the development of particle tracking technology (Habersack, 2001, Ergenzinger et al, 1989). To date, tracking technology has been limited to relatively few (< 10) particles, with limited spatial resolution (+/- 1-2 m) almost exclusively in fluvial environments. However, a limited experiment in acoustic particle tracking has been undertaken in estuarine environments (Dorey et al, 1972). On the basis of the above, the primary objectives of the present research project were to develop a multiparticle tracking technology, for deployment in littoral and fluvial environments that was capable of producing finer spatial and temporal resolutions, and that was not limited to small numbers of particles.



The project has developed and deployed a novel multi-particle tracking system, suitable for use in littoral and fluvial environments. The results provide data on the *first ever* tracking of coarse gravel/cobbles from within swash, surf and breaker zones, over a tidal cycle. Unlike previous methodologies (Ergenzinger et al, 1989; Habersack, 2001; Dorey et al, 1972), the technology is based upon the pebble receiving and storing transmitted signals from a grid of wires buried within or suspended above the beach / river bed (Figure 1).

This arrangement has the advantage of minimising the requisite on-board power supply within the pebble (size reduction), whilst allowing considerable power to be supplied to the transmitting coils. The methodology permits the deployment of an infinite number of particles.

Figure 3: Logging pebble components, illustrating from R-L, Circuitry and receiving coils, encapsulated circuitry, data download jig.

The system, as developed, is based upon the generation of magnetic fields, by loops of wire buried within the beach or river bed. If the power supplied to a wire loop is known, then it is possible to calculate the electro-magnetic field at any position and use this to estimate the location of an object that records field strength. The tracking system uses four independent, rectangular, wire transmitting loops (Figure 1). These transmit, in sequence, with a pause between sequences. The total sequencing takes 2.88s. The logging pebble detects the transmitted field, using 3 orthogonally-mounted receiving coils of 0.03m diameter (Figure 2). Field strength, time, battery output and tilt-switch output (a measure of whether the pebble is moving or not) are recorded to non-volatile EPROM memory circuits and downloaded via a resin-covered serial port on the pebble. The logging pebble was configured to record every 6 s; this provides a memory life of 8 hours, and a battery lifetime of 180 hours. The pebble could be re-programmed, to provide different logging sequences; these could extend operational lifetime to over 1 month. This approach is most suitable for use in fluvial deployments, where flooding may occur on an irregular basis.

Once downloaded, the data are filtered (usable data are only recorded when the pebble is stationary for a whole loop sequence); and processed via a custom-built MATHCAD programme, which converts stored data into electromagnetic field strength. The pebbles position is then calculated via a series of sub-routines. The data are exported subsequently as a single file, containing time (s), and calculated x, y position (m). A full description of the software processing protocols and hardware are available upon request from the P.I.'s.

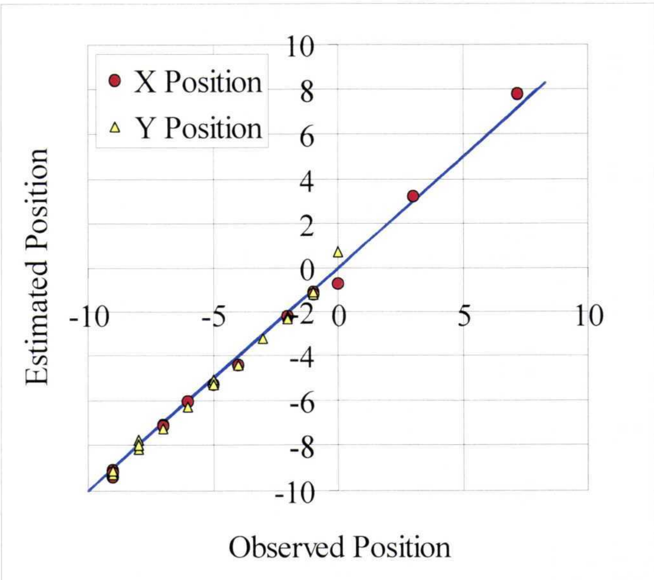


Figure 4: Positional accuracy for logging pebble field test.

Field trials were undertaken initially on land. The prototype circuit was moved to fixed locations, within and outside of the transmitting loop, with the signal strength recorded. These trials demonstrated the feasibility of the system, recording positional errors of +/-0.08m, at a transmitting loop. Subsequent land-based tests, using 4 loops and a 3-coil detecting pebble, gave rms errors of 0.1m and 0.07m, in x and y directions, respectively (Figure 4).

Beach trials were undertaken on 4 separate occasions using, initially, a single loop/coil set-up. Initial tests undertaken at Hordle Beach (Southern UK) were affected significantly by the presence of buried metal, or cabling. Subsequent tests using a circuit fixed, in place within a single transmitting loop, demonstrated that at peak immersion by sea water (1.0m depth), the field magnitude was increased by 1%, resulting in an 0.04m change in the estimated position. The results of both theoretical and field tests were considered satisfactory in terms of positional accuracy and proof of concept; subsequently 20 logging pebble circuits were constructed, of which 14 were deployed in field trials; the remaining seven became non-functional during encapsulation. The final pebbles used two coil configurations, in order to achieve spherical and discoid-shaped particles. The circuit and receiving coils were coated in waterproof resin, and wrapped in protective film. A mixture of barytes ($BaSO_4$) powder and a waterproof modelling material was used to encapsulate and mould the pebble shapes, before coating with fibreglass and resin. The pebbles had a density of 2.60-2.73kgm^{-3}; this is similar to that of the indigenous material at the field sites (2.65 kgm^{-3}).

Two field trials were undertaken, using 6 and 7 pebbles, respectively. During the first test undertaken at Shoreham-by-Sea, no useful data were logged; this was related to the signal power being set too low by the operators. However, the tests demonstrated: (a) that the transmitting grid could be installed between tides and operate for at least two full tidal cycles; (b) the pebbles logged the transmitted signals and that these data could, after a full tide, be downloaded to a PC; and (c) that the pebbles could be deployed and recovered successfully. The second deployment, used 7 pebbles. Data were recorded by all of the pebbles, but two only operated intermittently due to minor circuit faults. The remaining 5 pebbles had full data logs.

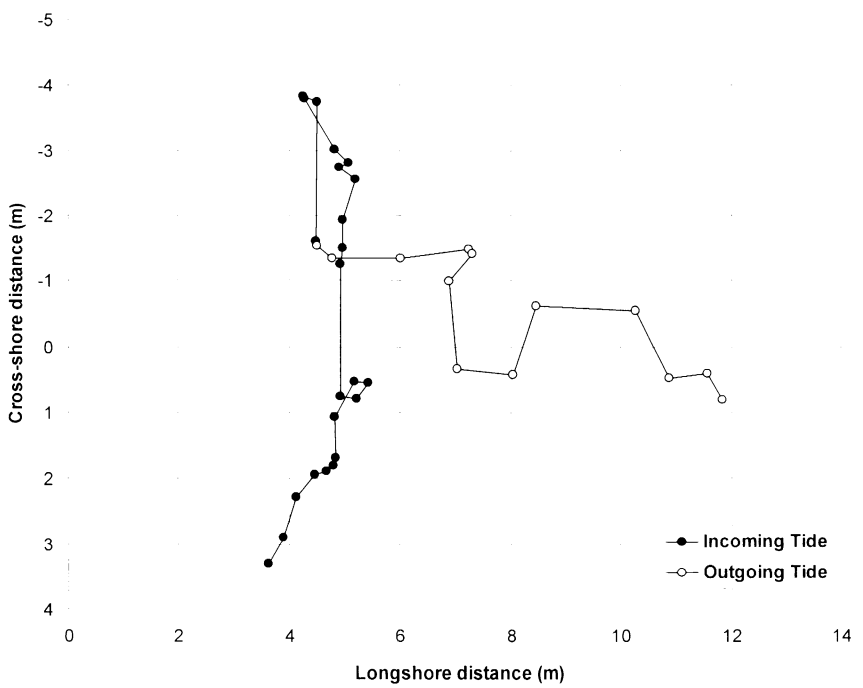


Figure 5: Movement of a single pebble during a tidal cycle.

The diameter of the pebbles deployed in this experiment are similar to that of radio-tagged pebbles deployed in fluvial environments (72mm B-axis). The top 1.5% of the indigenous beach material was represented. Scope for improvements using the existing circuitry and batteries, could reduce tracer size to 50mm diameter (top 8% of indigenous material), and with AMIC circuit design, a reduction down to 20mm (top 35%) is possible. However, costs of the latter would probably be prohibitive. Note the representativeness would be improved at coarser sites.

During the second Shoreham experiment, hydrodynamic conditions changed between the incoming and outgoing tides. This is reflected in the behaviour of the logging pebbles (Figure 5). During the flood tide, the movement of all Logging Pebbles (LP's) was onshore and to the East as would be expected from the angle of wave approach to the shore. Typical flood tide net transport distances average 2m longshore, but were much more varied cross-shore, depending on pebble position on the beach. During the ebb tide, net transport is again east but changes to offshore and the transport distances increase. This is consistent with a change in longshore component of wave power recorded during this period.

Net transport distances, as would be measured by standard tracer experiments, were consistent with those observed using foil and electronic tracers at the same deployment. Those pebbles that were positioned or moved higher up the beach during the flood tide, experienced much longer step lengths and transport distances. This is consistent with the Electronic (transmitting) pebble experiments undertaken at the same time. None of the LP's were buried during the tidal cycle. Data on particle velocity, rest periods and step lengths are available at a 6s resolution for all five particles. These indicate that particle motion is limited to relatively short periods when the pebbles are in the Swash, Surf or Breaker zone, with no transport outside of these zones (Figure 6).

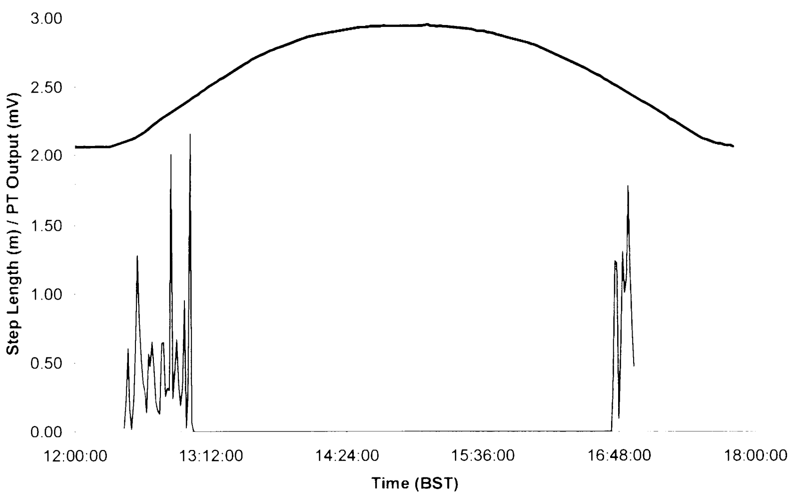


Figure 6: Particle step lengths in relation to the tidal cycle

In fluvial research, particle step length is typically modelled using exponential or 2-parameter Gamma function distributions (Einstein, 1942, Ergenzinger et al, 1987, Habersack, 2001). These assumptions form the basis of stochastic sediment transport models such Einsteins (1942). The logging pebble technology provides, for the first time, the ability to test this assumption applied to coarse particle movements on shingle beaches.

Conclusions

A new particle tracking system has been developed that enables high spatial and temporal resolution to be acquired for any number of particles. Although the system has been deployed in littoral environments, it is equally suited to fluvial systems. Instead of burial of the transmitting cables, these could be suspended above the channel. The technology used in these prototypes currently restricts particle diameters to > 50mm, but there is potential to reduce these still further.

Field trials of the logging pebble have provided the first ever data on individual particle movements from within the dynamic swash, surf and breaker zones. Predicted particle movements accord with coincident passive tracer experiments. The total time in transport is much shorter than those assumed by current models of sediment transport.

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Bandsaar as a traditional method for soil conservation and flood cultivation in Khorasan province

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Abstract

Iran, having a mean annual rainfall of 240mm is one of semi-arid countries of the world. The people of arid and semi-arid regions have to store rainwater and collect floodwater for agricultural use. In central and southern part of Khorasan province, flood agricultural lands called Bandsaar are constructed, Which provides water for agricultural need. Bandsaar is composed of a Small stream that conducts water from Ephemeral River to Bandsaar inner Area, decreasing of water Speed as a result of vertical and parallel embankment Infiltrated. This traditional method has many benefits such as, soil moisture Increasing, Improvement of physical and chemical characteristic, erosion decreasing, modification of barren lands to farmlands and groundwater artificial recharge.

Keyword: Bandsaar, soil conservation, Khorasan province, sedimentation

Introduction

Iran is one of the arid and semi-arid countries because of its geographical Situation. From ancient years, people of Iran have invented different methods for defending versus aridity. One of these methods accomplished in Khorasan province (north eastern of Iran) called Bandsaar. In this method, natural location of floodwater spreading formed on alluvial fan area. Bandsaar is a plot or pond that formed by embankment construction in direction of water flow and flood waters retained, until water infiltrated.

Brief Background

Kowsar (1991) argued, ground waters recharging have carried out in Iran From 3000 years ago until now .He appointed residences of northeastern part of Iran have been recharging ground waters by alluvial fan irrigation.
Water collecting for agricultural goals have accomplished in Iran, Pakistan And India from many years ago. There are many methods in Iran, such as Bandsaar, khoshab, dashtyari and degar. In all probability different methods of water collecting and its use for agriculture has transmitted from Iran to Adjacent countries.

Parts of Bandsaar

Bandsaar relatively simple construction and are usually made of following parts: ephemeral stream or kal (shallow-water drainage with temporal flow), Tarkehband (a check-dam made of river sediment), embankment (the main wall of the dam), Mewband (parallel subsidiary walls for balanced water spreading) and Gooshband (a waterway for overflow of water). Figure1. Shows a Bandsaar and its parts. Running flood in ephemeral streams (a), conducted into dam by Tarkehband (b). For discharging of excess water and avoiding of dam overflow, the end of embankment used to spillway that known as Gooshband (f). A Bandsaar has different area, for example from 1000 m in valleys until 30 ha in low slope lands .In large dams, there are secondary dams constructed vertical or parallel with main dam that distributed water uniformly, named Mewband (d,e) .Embankment height (c) is between 1-2m .Flood flow subsided when it has contact with embankment and infiltrated gradually .In alluvial fans , the land has situated between two stream is suitable area for Bandsaar construction.

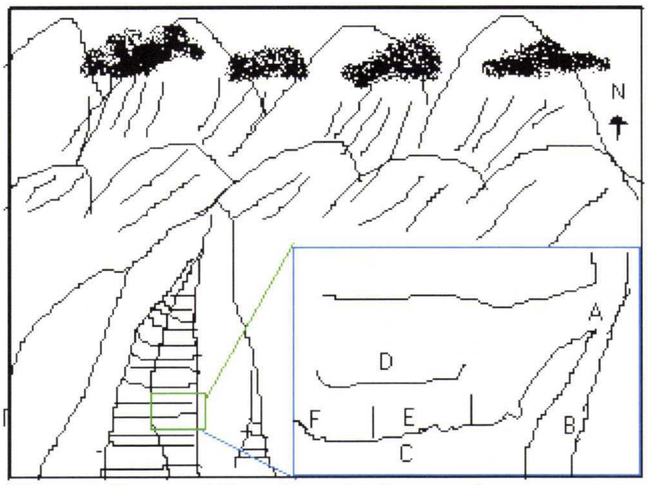

Figure1.Parts of Bandsaar.Ephemeral stream (A), Tarkehband (B), Embankment(C), Mewband (D, E) And Gooshband (F).

Bandsaars distribution in Khorasan province

The most of Iran bandsaars have situated in central and southern parts of Khorasan province that have minimum precipitation during the year such as Birjand, Nehbandan, Qaien, Gonabad and Sabzevar cities that their mean annual precipitations are less than 200 mm. For example mean annual precipitation is 135mm in Sabzevar (filehkesh, 1991) and 169.3mm in Birjand (Arabbkhedri 1994).

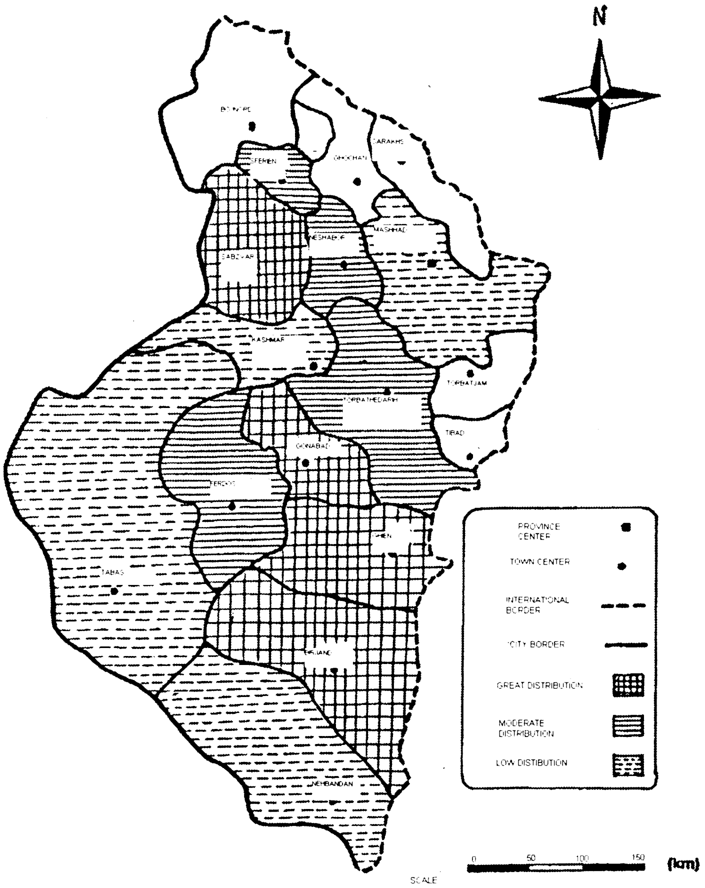

Figure2.Bandsaar distribution map in Khorasan province

Sedimentation condition in Bandsaars

Sedimentation in Bandsaars change physical and chemical characteristics of soil, in comparison physical characteristics more affected that improve soil texture. Also chemical characteristics such as organic and mineral matter increase. When flood entered Bandsaar, created stilling cause sedimentation and contact of ephemeral stream flow speed, and bed load subsided. But suspended load moved and subsided into dam. When speed decrease gradually, at first coarse suspended grains subsided and then fine suspended grains. Consequently Coarse suspended grains such as pebble and sand subsided in dam entrance but fine suspended grain such as silt and clay subsided at the end of dam that is deepest part. Sediments being deposited in Bandsaars are usually fine-grained Which decrease the permeability of sediments through time, but annual plowing, cultivation of diverse plants, root infiltration into soil, micro-organism activity and manure carried by flood water all improve permeability
This is the main difference between traditional flood spreading system (Bandsaar) and modern artificial recharge systems.

General benefit of Bandsaar

Bandsaars have many benefits such as:

I.soil conservation aspects:

a) Increase of soil moisture and lowering limitation of plant product
b) Fertility of Bandsaar soil
c) Improvement of soil structure
d) Prevention of water wasting to Kavir and saline lakes
e) Artificial recharge of ground aquifer

II. Economical aspects:

a) Income of crops selling
b) Provide employment
c) Prevention of migration to cities
d) Production of diverse agricultural products

In addition to simplicity of design and operate, low cost of construction , use of local material, reliance on family man power make the advantages of these traditional flood water spreading system twice.

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Adequacy of current methods of suspended sediment monitoring for recent European legislative requirements

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INTRODUCTION

Recent European environmental legislation has been combined with an increasing focus on the use of suspended sediment monitoring in pro-active catchment management strategies. These factors have prompted a review of the adequacy of current widely accepted methodologies for suspended sediment monitoring. This paper discusses the impact that two recent EC Directives, namely the Habitat and Species Directive (92/43/EEC) and the Water Framework Directive (2000/60/EC) may have on the techniques and strategies used for suspended sediment monitoring within European rivers in future years. An example is provided of the application of current thinking on suspended sediment measurement and sampling strategies to a proposed set of monitoring requirements for a freshwater Special Area of Conservation as designated under the EC Habitat and Species Directive (92/43/EEC).

THE HABITAT AND SPECIES DIRECTIVE

The EC Habitat and Species Directive (92/43/EEC) prompts member countries to identify Special Areas of Conservation (SAC), and report on the condition of these SACs every six years. The Directive designates specific species as worthy of conservation, and encourages countries to establish conservation measures, undertake surveillance of conservation status and partake in necessary research and scientific work. To report on the condition of SACs it may be sufficient to report on species status but it may be preferable to report additionally on habitat status.

In undertaking surveillance monitoring of habitat status to see if favourable conditions exist for relevant species, conservation objectives may be set which can be couched in statistical terms. With regard to sediment, examples may include limits for mean annual suspended sediment concentrations or particular quartiles such as the median and 90th percentile. If this is done there is a corresponding requirement for rigorously designed monitoring strategies that will allow the assessment of compliance with these objectives as well as any change in status over the six year reporting time frame.

Much of the existing operational monitoring of freshwater suspended sediment concentrations is carried out at a monthly frequency using bottle sampling (The major exception to this is in response to pollution incidents, when a small number of high time frequency bottle samples may be collected). Table 1 shows data from a set of research catchments which illustrate the variability in suspended sediment concentrations. From this information it is possible to calculate the number of samples required to characterise the mean suspended sediment concentration in these drainage basins. For example, Fig. 1 outlines the number of samples required to estimate the mean for different levels of variability, represented by standard deviation, to within various levels of precision. At low levels of variability, for example the Cyff basin, annual means can be successfully characterized using nine samples, a level of sampling already achieved in most operational monitoring schemes.

However in other catchments, much larger numbers of samples are required to achieve the same purpose. In many cases, given typical levels of variability detected during high resolution suspended sediment monitoring in UK rivers, the number of samples required is in most cases well above that currently collected. The large numbers of samples needed suggest that the use of flow-stratified sampling or proxy methods of instrumented monitoring such as sample calibrated turbidity probes may be needed.

Clearly, the application of new approaches to measurement techniques and monitoring strategies are required. However, such initiatives are constrained by the limited resources under which many national regulatory authorities and conservation agencies operate. These agencies often prefer simple monitoring solutions which give rapid answers, a task for which "research-level" methods are often not ideally suited. In response to the above points, an example is given of a proposed monitoring strategy suitable for a freshwater SAC designated under the Habitat and Species Directive. This example is intended to provide a compromise between research level activity and the constraints under which day to day monitoring operates. Relevant lessons from a long term event-based and annual suspended sediment study in mid-Wales are applied to allow the creation of the proposed strategy. The reasons for choice of measurement technology, and important issues regarding possible implementation of this strategy are outlined.

Table 1 Suspended sediment concentrations in three example UK rivers[†].

	Catchment type	Catchment size	Mean SSC (mg l^{-1})	Std. dev. SSC (mg l^{-1})	No. of samples required*
Tanllwyth	Forest	<1 km^2	8.9	12.7	138
Cyff	Moorland	3 km^2	1.8	3.0	9
Swale at Catterick	Mixed agriculture, 10% urban	500 km^2	23.2	77.9	Approx. 6000

[†]Data from intensive monitoring using 15 minute frequency recording of turbidity probe output, routinely recalibrated using suspended sediment concentrations determined from storm and low flow samples.
*no of samples required is the number to determine annual mean to a precision of 2 mg l^{-1}. This is a reasonable required precision for assessment of year to year change and compliance with threshold objectives.

THE WATER FRAMEWORK DIRECTIVE

The EC Directive (2000/60/EC) is establishing a framework for community action in the field of water policy. It is commonly known as the Water Framework Directive (WFD) and came into force on the 22nd December 2000. Consequently, implementation of this Directive is not as far advanced as the implementation of the Habitat and Species Directive. The overriding goal of the Directive is that Member States should aim to achieve at least "Good Ecological Status" in all bodies of surface water (lakes, rivers, estuaries and marine) and groundwater, and also aim to prevent deterioration in the status of those water bodies. It will eventually repeal and subsume all previous EU water directives. In common with the Habitat and Species directive it works on a six year planning cycle. Key implementation dates are listed in Table 2.

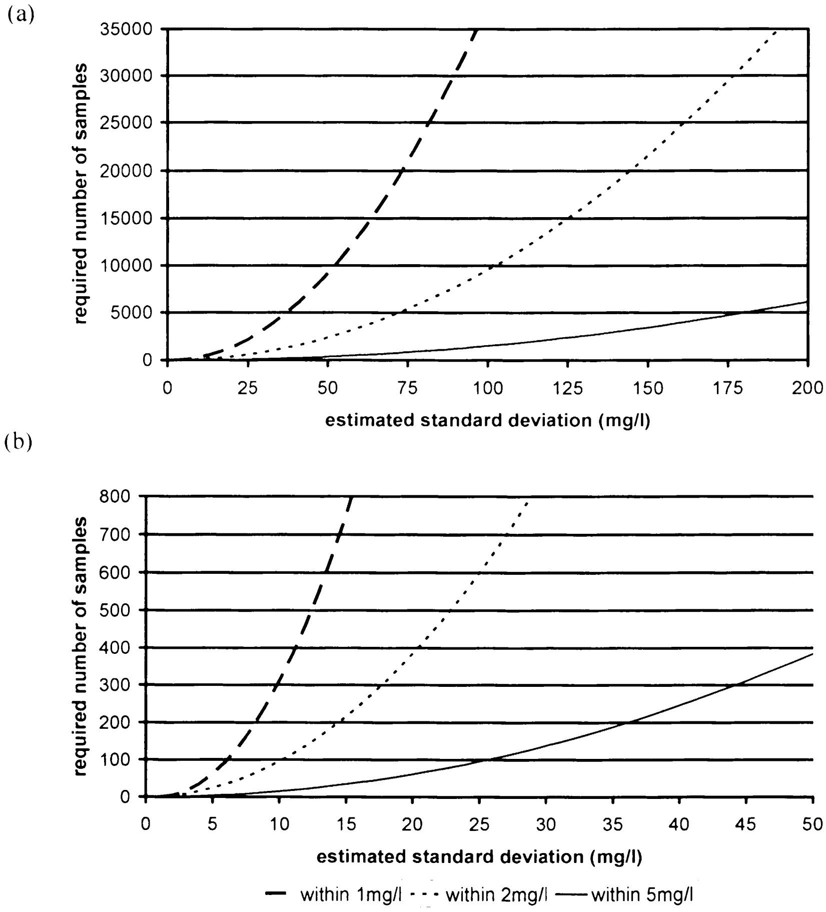

Fig. 1 Number of samples required to estimate the mean to within a specified precision (1, 2 or 5 mgl^{-1}) given the sample standard deviation (a) Standard deviation range 0 to 200 mgl^{-1}; (b) Enlargement of Fig. 1(a) for standard deviation range 0 to 50 mgl^{-1}.

The WFD has a broad scope does not just cover chemical water quality. Ecology is judged the key measure of status, although final status is judged to be the lower of ecological and chemical status. Status is measured by comparison to "type-specific" reference conditions. There is a strong emphasis on monitoring, for example status assessments are intended to be based on monitoring. The Directive distinguishes between operational monitoring – to define current status, and investigative monitoring – when good status requirements are failed.

Table 2 Key dates for WFD implementation.

Date (end of)	Action
2004	Initial characterization of river basin districts
2006	Monitoring programmes established
2006	Timetable for River Basin Management Plans (RBMPs)
2008	Draft RBMPs
2009	Final RBMPs including objectives and programmes of measures
2012	Operational programmes of measures
2015 (and every six years thereafter)	Review and update plans

The need for sediment monitoring to comply with the WFD is unclear. There are obvious links between sediment transport and river morphology, and "hydromorphology" is a supporting status element. Sediment transport is more clearly acknowledged elsewhere, such as in its link with river continuity, and by the recognition that differing sediment regimes may contribute to water body typology. Pollutant association with sediment is also specifically acknowledged, and must be monitored. However the role and monitoring of sediment loads in themselves is unclear. It is also surprising that suspended sediment is not included as a physico-chemical element requiring monitoring and assessment.

CONCLUSIONS

The two Directives described here are currently having, and will continue to have, a major influence on the suspended sediment monitoring requirements of regulatory and conservation agencies across Europe. In many cases, existing methods and strategies may struggle to provide fit for purpose results, and innovative solutions may be required in future. Implementation of the Habitat and Species Directive is at a relatively advanced stage, but the full impact of the Water Framework Directive is as yet unclear. Consequently the final implications of the implementation of these two Directives for sediment transport monitoring across Europe have still to emerge.

The character and concentration of the fluvial transport in the karst area of Lublin Upland.

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The content of this assignment concerns the studies conducted on the waters of the Uherka catchment – the tributary of the middle Bug river (Fig. 1). The basin of the Uherka river is situated in the northern and eastern parts of Lublin Upland (Chełm Hills, Grabowiec Height) and Southern Polesie (Dubienka Plain). The Uherka catchment situated higher than the gauging station of the Meteorology and Water Management Institute in Ruda Opalin (Fig. 2) is 433 km^2 which is 75 % of the Uherka catchment. This is a region which is conspicuous in the Lublin area by the register of karst forms.

In the basement complex there are lithologically differential Upper Cretaceous rocks; the outcrops of the soft limestones of chalk type are related to spread depression, whereas more resistant rocks of the same age (marl and marly opokas) are related to inselberg heights, being characteristic element of landscape of Chełm Hills. The highest point reaches the height of 156 m above sea level.

The research was conducted during the period, which was significantly colder and more humid than in the average year; average discharges of the Uherka river in Ruda Opalin were 2,25 m^3/s and which was 41% higher than multiannual average statistics.

Two additional gauging stations (on the upper Uherka at Pokrówka and on the Garka at Staw) enabled the authors to extract partial catchments, where valley depressions furrowed in the soft limestones of chalk type were very visible. The valley depressions were strewed with Quaternary deposits with the prevalence of mineral and organic.

In the examined area the domination of the solution sediment to the suspended load was ascertained (91% of the water load was the solution transport).

The concentration of dissolved matter in the river waters of the upper Uherka and Garka was found between 381 – 440 mg/dm^3, the water was found as a hard water (6.4 – 7.4 mval/dm^3), they were also distinguished by low concentration of Mg^{2+} (0,0 – 5,0 mg/dm^3).

In river waters the concentration of dissolved matter (Cd) distinctly depends on the discharge (Q); for Cd = f(Q) a high correlation coefficient was found on a significant level. The highest coefficients of correlation and determination are calculated for a polynominal function (Cd = aQ2 + bQ + c), illustrated by the parabola (Fig. 3A). In both catchments the coefficient "a" is below 0 (parabola is open downwards), so the function indicates an increase of dissolved matter concentration with discharge increase up to the limit value; over this value the concentration decreases which can be connected with a greater dilution of solutes. Discharges about 1.0 m3/s at Pokrówka and Staw are limit values (Fig. 3A).

A significant relationship between the dissolved load (Ld) and discharge (Q) is also calculated. It is linear relationship Ld = aQ + b, illustrated by the straight line with high coefficients of correlation (Fig. 3B)

The proportion of the suspended sediment load to the dissolved (Ls/Ld) in the analysed hydrometric river cross-sections (at Pokrówka and Staw) is between 0,1 – 0.01 (Fig. 3C), which causes from 10 to 100 advantage of dissolved sediment load over suspended. When the water is high dissolved sediment load is ten times bigger than suspended (Fig. 2). The average indices of solution discharge in the examined part of the Uherka catchment flactuated between 66 to 75 ton/km^2 a^{-1}, whereas the indices of suspension discharge between 6,5 – 7,7 ton/km^2 a^{-1}.

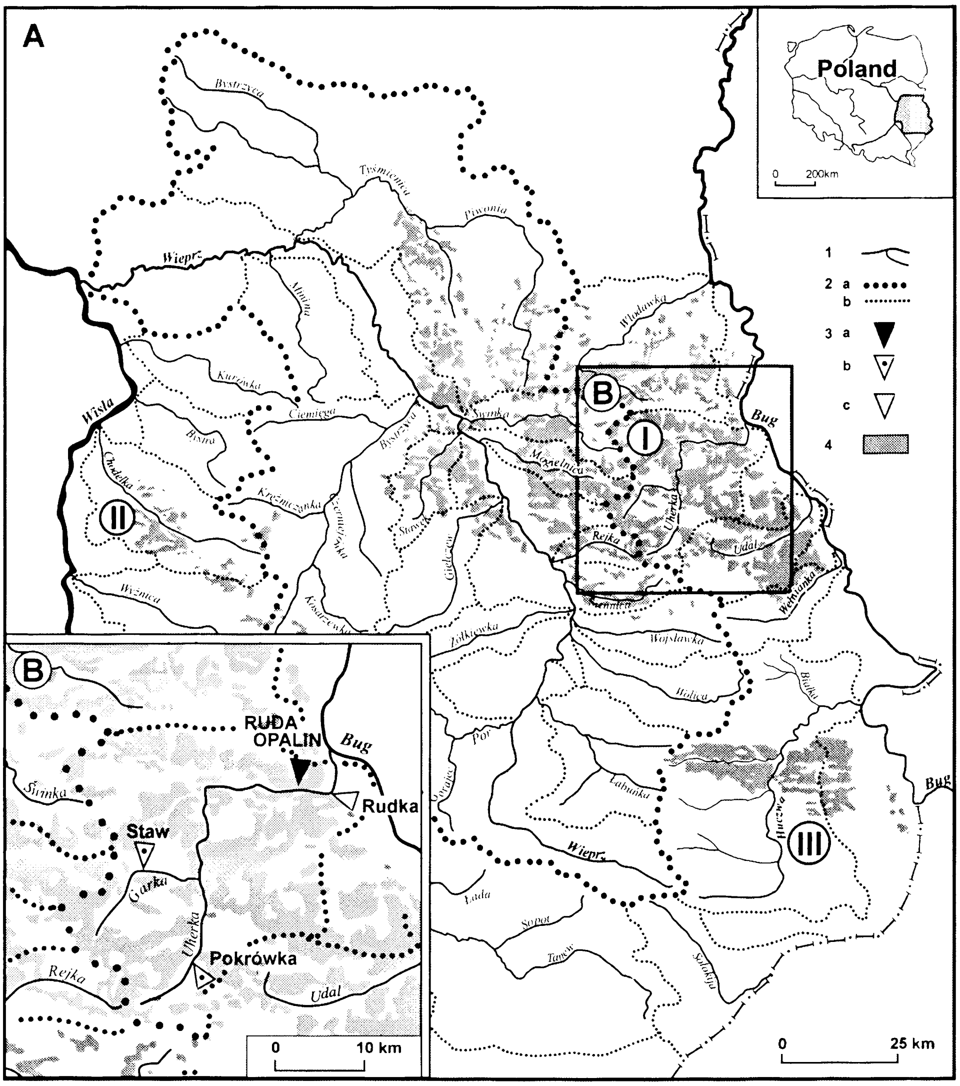


Fig.1A. Areas with the karst forms developed in the Upper Createcous carbonate rocks of the Vistula and Bug interfluve *(compiled by authors on the basis of the H.Maruszczak 1966)*
Fig. 1B. Location of the Uherka river in relation to the occurence of areas of karst forms.

1 - river network; **2** - watersheds: higher rank (a), lower rank (b); **3** - sampling sites of river water: gauging stations of the Meteorology and Water Management Institute (a), additional gauging stations (b), other points (c); **4**- areas of occurence of karst forms (I, II, III)

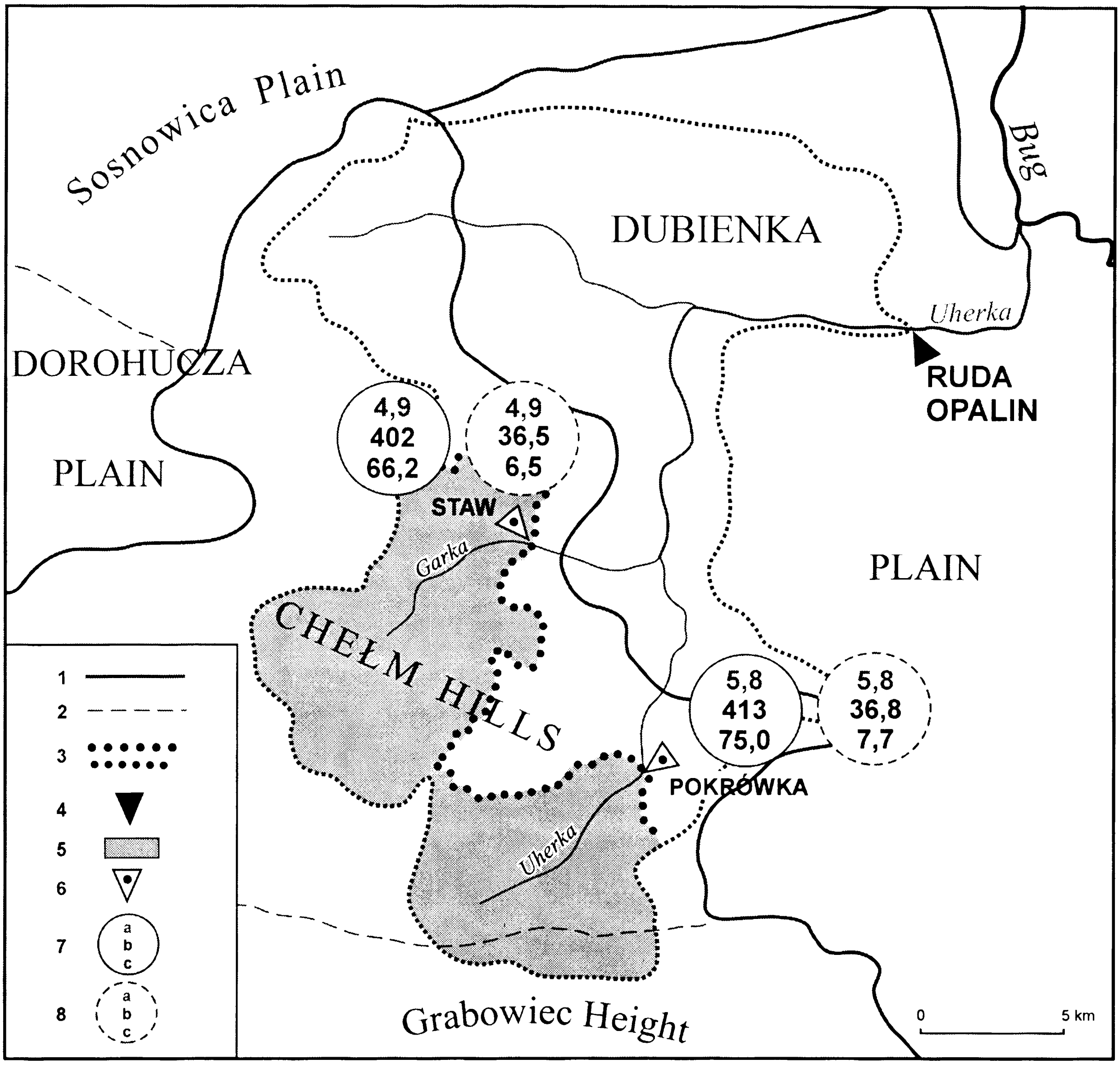


Fig. 2. The concentration of the river transport in the catchment of the upper Uherka river (Pokrówka) and its tributary Garka (Staw) in the years 1978-1987

1 - boundaries of geomorfological regions; **2** - boundaries of geomorfological subregions; **3** - watershed; **4** - additional gauging stations; **5** - examined catchment; **6** - gauging station of the Meteorology and Water Management Instiitiut; **7** - indices of solution transport: a - specific river yield ($dm^{-3}*s^{-1}*km^{-2}$), b - solute load ($mg*dm^{-3}$), c - specific solution yield ($t*km^{-2}*a^{-1}$); **8** - indices of suspension transport: a - specific river yield ($dm^{-3}*s^{-1}*km^{-2}$), b -sediment yield ($mg*dm^{-3}$), c - specific suspension yield ($t*km^{-2}*a^{-1}$)

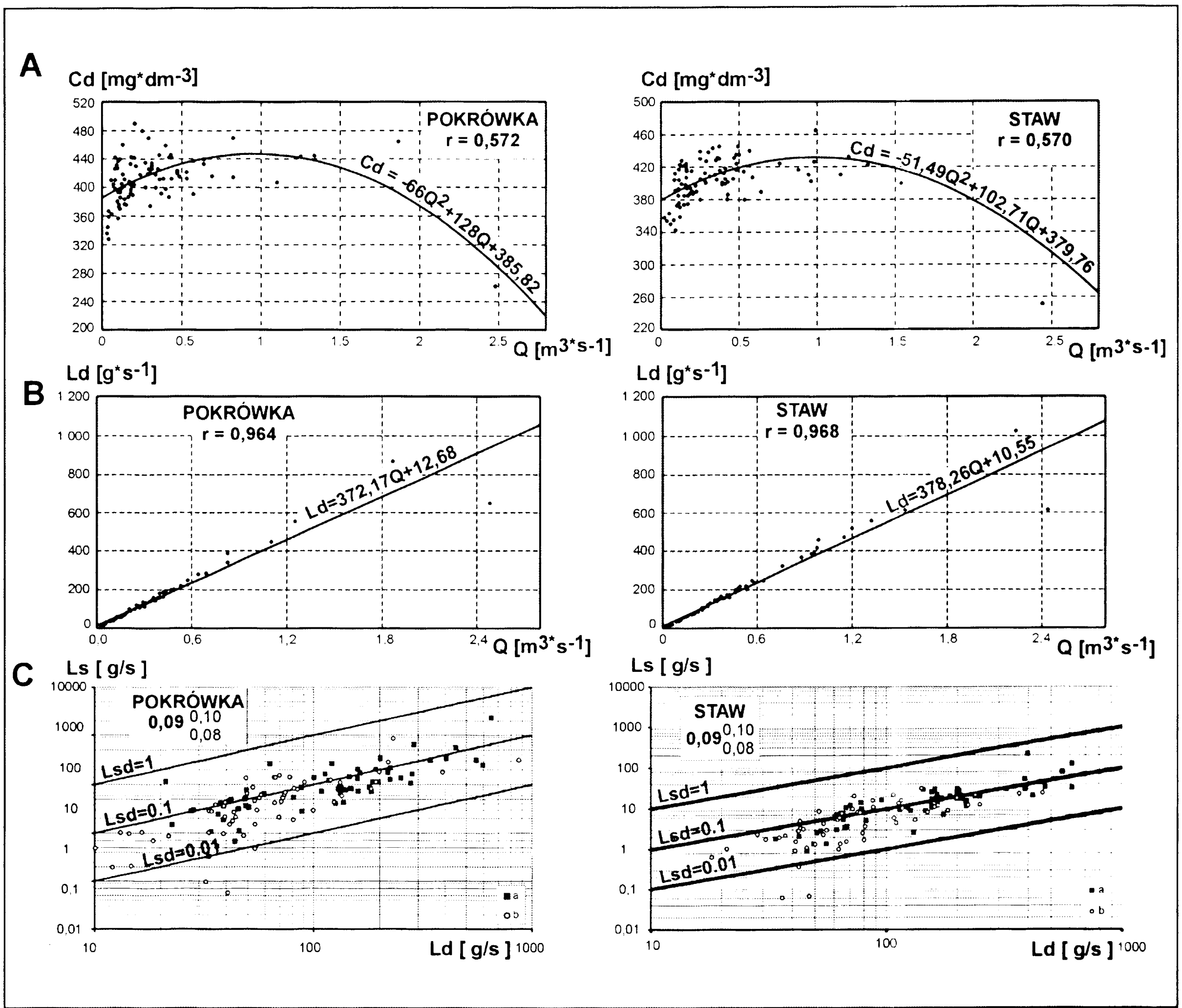


Fig. 3. Statistical relationship between the discharge and some elements of river sediment in the upper Uherka river (Pokrówka) and its tributary Garka (Staw) in the years 1978-1981

A. Relationship between the dissolved sediment concentration (Cd) and discharge (Q) in the guaging stations on the Uherka river and its tributary Garka

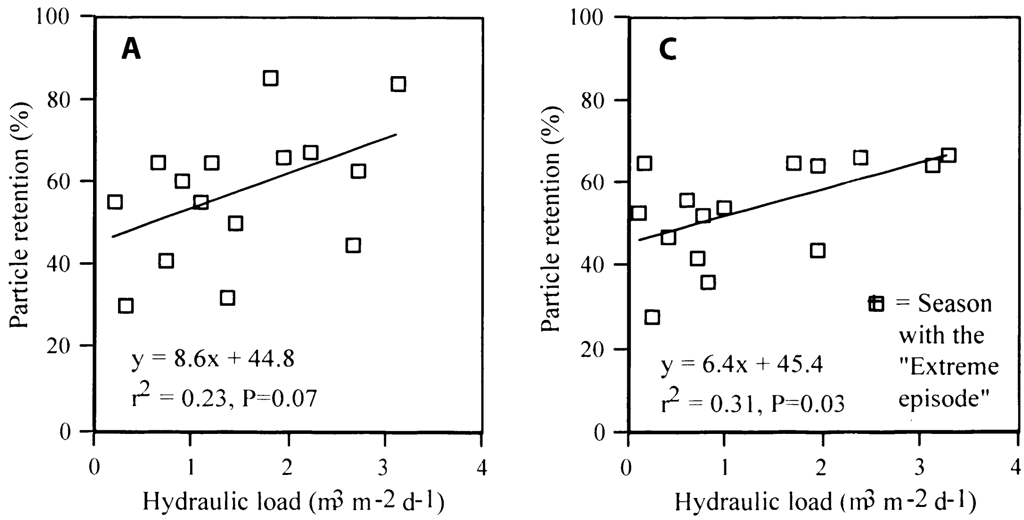
B. Relationship between the dissolved sediment load (Ld) and discharge (Q) in the guaging station on the Uherka river (Pokrówka) and its tributary Garka (Staw)

C. Relationship between the suspended sediment load (Ls) and the dissolved (Ld) in the Uherka river (Pokrówka) and its tributary Garka (Staw)during the winter half-year (a) and the summer half-year (b)

The Influence of Hydraulic Load and Aggregation on Sedimentation of Soil Particles in Wetlands

Abstract - Loss of soil particles from arable land to streams and lakes negatively affects water quality. When initiatives to mitigate soil erosion are insufficient or fail, constructed wetlands (CWs) could be a *last buffer* to mitigate pollution. The objectives in this study were to determine the influence of aggregation on clay sedimentation in CWs, and evaluate the prediction performance of two commonly used retention models, based on hydraulic load and particle sedimentation velocity. Retention was measured three ways. with (i) water flow proportional sampling systems in the inlet and in the outlet, (ii) sedimentation traps and (iii) sedimentation plates. Surface area of the wetlands was 0.03 to 0.07 % of the watershed, which consisted of silty clay loam (18-33 % clay). Some runoff episodes, usually at high runoff rates, accounted for a relatively high proportion of total sedimentation. Thus 80 % of the particles were retained from less than 44 % of the total runoff. Constructed wetland performance increased with increased hydraulic load or decreased detention time. The clay content in the CW sediment reflected the clay content in the arable soil. Actual CW sediment exceeded model estimates 2.5 to 8.2 times, depending on wetland size and runoff. The probable reason for the prediction error is clay particles entering the wetlands as aggregates. Constructed wetlands should be located in small streams to avoid break up of aggregates, and a reduction in retention efficiency.

Reference: Braskerud, B. C., H. Lundekvam and T. Krogstad, 2000. *The Impact of Hydraulic Load and Aggregation on Sedimentation of Soil Particles in Constructed Wetlands*. Journal of Environmental Quality 29 (6): 2013-2020.



Seasonal sedimentation of soil particles as a function of hydraulic load in Constructed Wetlands A and C. Increased runoff did not result in decreased particle retention, as expected.

The retention of soil particles is a key factor, since phosphorus and many other pollutants are mainly particle bound. It is a general agreement that particle sedimentation velocity, runoff and pond or wetland surface area influence the retention performance. This can be expressed in a commonly used model. For fully developed turbulence, the relative retention, E (%), is (e.g., Chen, 1975):

$$E = 100\,[1 - \exp(-w\,AQ^{-1})] \qquad [1]$$

where w is the particle settling velocity (m s^{-1}), A is the constructed wetland (CW) surface area (m^2), and Q is the runoff from the pond (m^3 s^{-1}), and exp is the value of e (2.718..).

Sedimentation velocity is estimated by Stoke's Law for water temperature 7 °C, and specific gravity of particles 2.65 g cm^{-3}. As an example, Fig. 2 shows that the predicted average retention of 2 µm particles, which is the largest clay particle, should have been 17 % for the average AQ^{-1}-value 76000 m^2 m^{-3} s. The hydraulic load decreases to the right hand side in the figure. Observed retention of clay particles in composite sample events are points in Fig. 2.

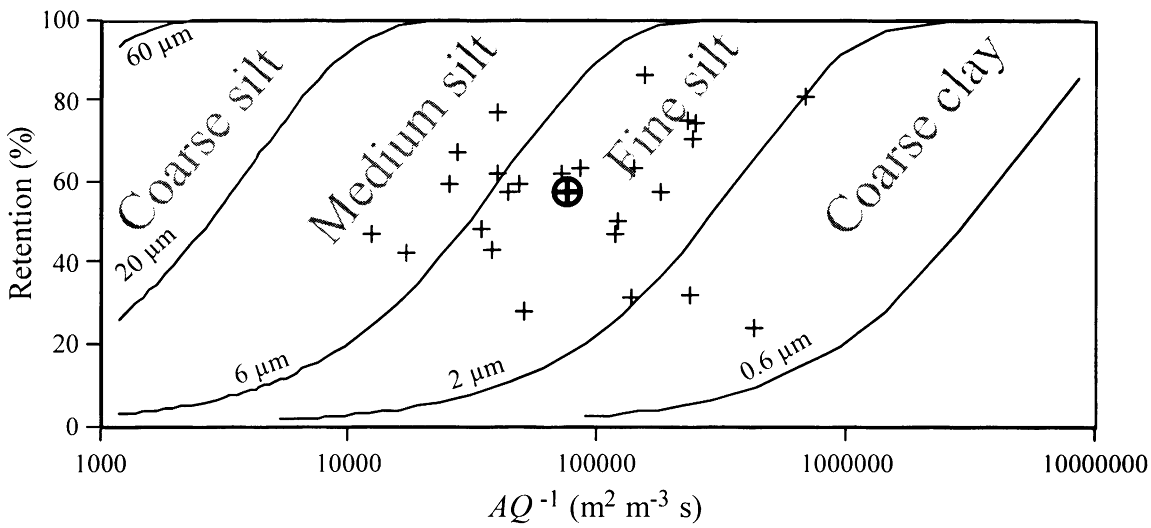


Fig. 2. Predicted retention of five grain sizes (lines) and observed retention of clay (+) in CW-A as a function of inverse hydraulic load. Large symbol gives average observed AQ^{-1} and average observed clay retention.

The average observed clay retention was 57 %, which is more than three times higher than predicted by [1]. Since average A, Q and E is known in every composite sample, [1] can estimate w. The data in Fig. 2 show that the clay particles behaved as fine silt and medium silt with respect to sedimentation velocity. Several investigations show that particles in streams and rivers are transported as flocs or aggregates (e.g., Droppo and Ongley, 1994; Eisma, 1993). Floc and aggregate are often used synonymous, because they may be difficult to distinguish (Droppo and Stone, 1994). However, their origin is different: aggregates are formed as a result of processes in the soil, while flocs are formed in the watercourse.

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Laser Diffraction Sensors measure Concentration and Size Distribution of Suspended Sediment

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Abstract: Optical turbidity sensors, transmissometers, and acoustic backscatter sensors have been well entrenched in the monitoring of suspended sediments. However, results published recently by (Sutherland, et al. 2000) note the two difficulties with turbidity sensors: the calibration changes with grain size changes, and with particle color. Similarly, (Davies-Colley & Smith, 2001) noted that transmissometers also change calibration with grain size, and have upper size cut-offs, (Voss, 1993). Acoustics usually operate at frequencies where $a\ \lambda << 1$, (a is grain radius and λ is acoustic wavelength) where scattering varies as $\int a^6\, da$, again not suitable for a mixture of grain sizes. In contrast to these 3, **laser diffraction** methods measures multi-angle scattering at small angles from which size-distribution and concentration is computed, with only a minor error due to changes in particle composition. In this paper, we describe the fundamentals of the technology, we describe a new instrument that permits measuring suspended sediment concentration in a *size-subrange*, and we provide a preview of an *isokinetic* version of the instruments, the LISST-SL.

Keywords: size distribution; suspended sediment; Sauter mean diameter; LISST; sediment monitoring.

Introduction to Laser Diffraction: Laser diffraction is a technique pioneered in the 70's (Swithenbank et al., 1976). At the time, it was widely known from light scattering physics (Mie theory) that when angular scattering from a particle is examined in small forward angles, it appears identical to the diffraction pattern from an aperture of equal diameter . There is a simple conceptual reason for it, see Figure 1. A particle blocks light waves. Some enter the particle, others are diffracted *around* the particle. The diffracted rays appear in the small-angle region. The rays that enter the particle are scattered over the full π angle range, so that their contribution to the small-angle region is minimal. As a result, diffraction dominates the small-angle scattering signal. Particle composition and color, which are represented by the refractive index as a function of light wavelength[1], became irrelevant. From the diffraction signature, which has a characteristic shape termed the Airy function (Born and Wolf, 1975), particle size and concentration can be determined by inversion of the small-angle light scattering data. In other words, if the small-angle scattering signature is observed, it leads via inversion to the size-distribution. When the size-distribution is summed, one has the total concentration. The mathematics of interpreting the multiple-small-angle scattering are briefly reviewed by us in our Marine Geology paper (Agrawal and Pottsmith, 2000).

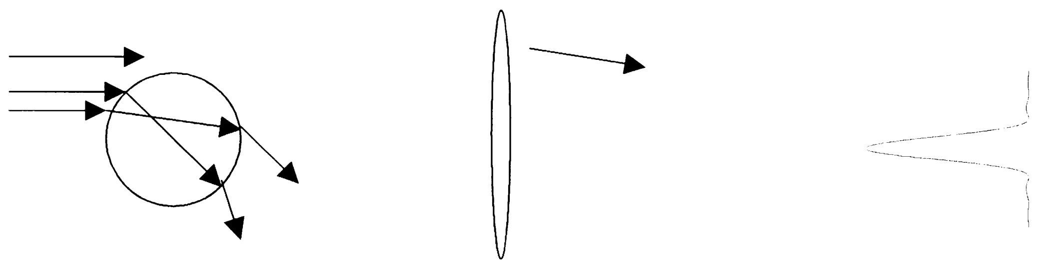


Figure 1: This sketch shows a parallel beam of light striking a spherical particle. The light that enters the particle – and that therefore feels its composition – exits at large angles to the original beam. It makes a very small contribution to the very small angle scattering. Only rays diffracted around the particle appear at the small angles, producing the Airy pattern shown on right. This is why the name: *laser diffraction*.

Thinking of particles as same-size apertures, clearly, is a great convenience. For this reason, the method was called laser diffraction. Due to its ability to size particles regardless of their composition, it is now widely

[1] e.g. a red particle has an imaginary component in its refractive index that has a minimum at red wavelength

used in diverse industries – from chocolates, paints, cements, to pharmaceuticals and controlling coffee grinding. In 1994, we published the first use of this technology in the sea from an autonomous instrument, fully equipped with a computer and datalogger, running on battery (Agrawal and Pottsmith, 1994). Later, refinements to the idea of pure diffraction occurred for 2 reasons. First, there is indeed a small sensitivity in small-angle scattering to refractive index. Thus the desire for better accuracy was behind replacing the pure diffraction approximation with the full Mie theory model for scattering. The second such factor was the use of larger angles, reaching all around to 170 degrees as extensions of laser diffraction. At such large angles, it became essential to abandon the diffraction approximation, and use Mie theory.

Size Distribution measurement with LISST-100: Refer now to the optics shown in figure 2. A collimated beam illuminates particles. A receiving lens of focal length *f* collects scattered light. A detector is placed at the focal plane of the receiving lens. All rays originating at a particle at an angle θ, regardless of its location in the beam, arrive at the detector at a distance from center *r* such that $\theta = \mathrm{atan}(r/f)$. For mathematical reasons of inverting the measured scattering to get size distribution, instead of measuring the scattered light at single points (representing single angles), ring detectors are used. These *rings* integrate all light scattered into a cone of angle centered on θ. The radii of the rings increase in fixed proportion, i.e. the radius and width of each

ring is a constant multiplier times the corresponding value for the previous ring. This *logarithmic* spacing of the rings also corresponds to a logarithmic spacing of particle sizes in the inversion. In other words, the size-distribution represents the concentration of suspended sediment in logarithmically spaced size bins. Logarithmic size-bins are familiar to geologists as sizes that are linearly spaced in φ units. This is our **LISST-100** instrument. A growing list of scientific publications using the LISST-100 can be found at http://www.sequoiasci.com/publications.asp.

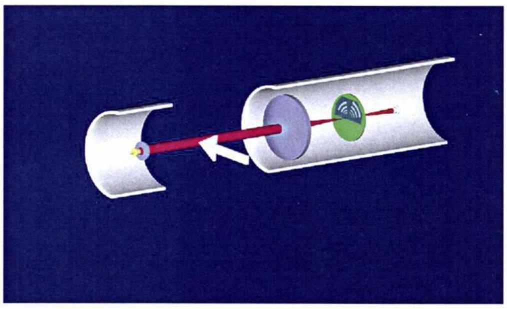


Figure 2: This is the **LISST-100.** A collimated laser beam emanates from left. Particles in the flow scatter light. A receiving lens collects the scattered light, which is detected by the *ring detector.* A hole in the center of the ring detector permits the focused laser beam to pass through, where its power is sensed. This constitutes a transmission measurement. This measurement corrects for attenuation of the scattered light that is sensed by the rings.

New Developments, LISST-25: As a precursor to the newest developments, we note first the development of the **LISST-25** sensor. The principle of the **LISST-25** is based on ideas from laser diffraction, as follows. According to diffraction, the scattered light energy falls at larger angles on the ring-detector plane for finer particles, and *vice versa.* To measure suspended sediment concentration (SSC), the sensed scattered light energy per unit sediment concentration should be identical for any size. Thus, crudely speaking, if the width of a ring at a large

angle is proportional to the scattering per unit volume for the corresponding fine particle, and so on down to all rings, then the sum of these *modulated* rings would represent the true SSC. These rings can be joined together to form a single detector. Such a detector takes the shape of a *comet (lower form, right)*. The comet detector accomplishes an angle-weighted sum of scattering, which is directly proportional to SSC. Thus, unlike the old turbidity sensors or transmissometers, the LISST-25 responds directly to SSC, and since it too is grounded in laser diffraction

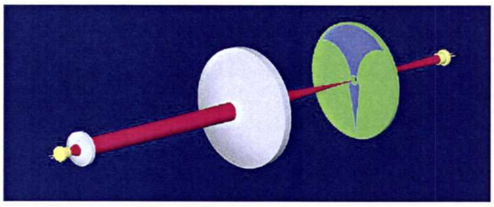


Fig.3: The use of shaped focal plane detector in LISST-25 for direct TSS measurement.

principles, its calibration is held for all sizes and colors of particles. The upper, wedge-shaped detector senses total particle area. From these two detectors, the Sauter Mean diameter (SMD) is computed as the ratio of volume/area concentrations. A change in SMD by a factor *n* implies a change in calibration of area-based sensors such as optical backscatter, by the same factor *n*.

LISST-25X: This instrument was designed in response to a need of USGS Flagstaff scientist Ted Melis, who required SSC but *excluding* fines below 63 micron in size. In response to this need, a family of new focal plane sensor geometries was invented. This family of geometries permits measuring the concentration in any sub-range of sizes. For example, one may measure concentration of particles greater than a threshold (*high-pass*), smaller than a threshold (*low-pass*), or within a band of sizes (*band-pass*). These detectors, replacing the comet shape of the LISST-25, take the shape of truncated comets for high-pass, or *blobs* for low-pass. The first of these instruments was tested in the Grand Canyon (see Melis, this Workshop).

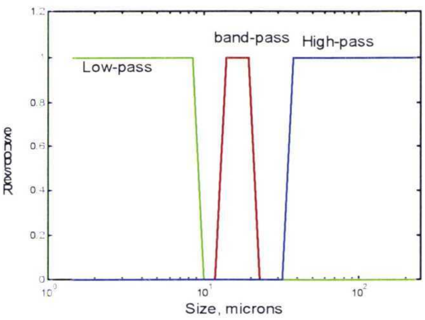


Figure 4: The **LISST-25X** embodies specially shaped focal-plane detectors that can permit the user to select the size-range over which SSC is to be measured. As example, a user may choose to ignore the wash-load in a stream, or use the LISST-25X to measure the wash-load only.

LISST-SL: The newest development underway at Sequoia is a streamlined, low-drag vehicle that encloses an isokinetic withdrawal LISST-100 instrument. This device includes pressure transducers to record depth of sampling. It actively equalizes the free-stream velocity and the withdrawal speed into the nose of the vehicle using a tiny pump. The device will run on external power and will use 2-wire communication protocol. Isokineticity is assured by measuring the free-stream velocity and adjusting an in-built flow-assist pump to control withdrawal rate. The LISST-SL will have the full size-distribution measuring capabilities of the LISST-100, although the housing can enclose the LISST-25 or 25X. Field trials are scheduled for summer of 2002. The LISST-SL will also be available for towed use.

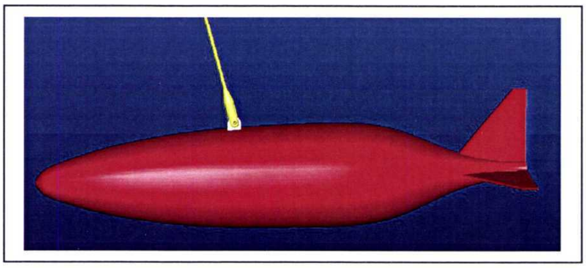
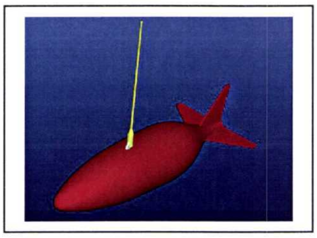


Figure 5: Two *artist's views* of the **LISST-SL**. A 2.5cm diameter opening at the nose draws water in.



Studies on Effect of Particle Shape: New research underway uses the LISST-100 to observe small-angle scattering properties of random-shape grains sorted by settling velocity. The shape effect is such that when small-angle scattering from natural grains is inverted with a model for spheres, a change in calibration is found, and fines are invented by the inversion. Consequently, future inversion will employ a suitable model.

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