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Measurements of Gravel Transport Using the Magnetic Tracer Technique: Temporal Variability Over a Highflow Season and Field-Calibration

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Abstract

The magnetic tracer technique is a surrogate method for measuring gravel bedload transport and detects the passage of naturally magnetic gravels over a detector log. The method was developed in different stages at Squaw Creek, MT, a mountain gravel-bed stream in volcanic terrain. However, this method (like other surrogate methods) has not been properly field calibrated against accurate physical bedload samples, thus its performance and true rates for recorded transport remain unknown. This paper explains different stages in the development of the magnetic tracer technique, shows results obtained over two field seasons, and makes new attempts at field calibrating recorded signal rates.

The magnetic tracer technique provided a high-resolution record of signal rates over 17 days in 1986. Signal rates showed that gravel transport occurred in waves. Bedload activity was typically high near daily peak flow, and bedload waves also occurred during the daily falling limbs. Daily wave patterns changed over the highflow season, suggesting changes in the sources of sediment supply. The relationship of signal rates to flow was moderately well defined, hence in addition to flow, bedload conveyance, nearby sediment supply, bed adjustment to flow, and traveling bedload sheets likely played a major role in determining bedload transport rates.

Signal rates recorded in 1986 and 1991 were field calibrated against gravel bedload samples collected in a net-frame sampler. Improvements in signal filtering, amplification, and data recording considerably increased the 1991 system sensitivity although a general decrease in sensitivity with increasing transport intensity remained. Decreasing system sensitivity can cause large errors in annual load estimates, but is amendable by correction functions developed from intensive field calibration.

In a direct comparison of signal rates recorded in 1991 with sampled gravel transport rates, signal rates matched the majority of bedload samples, suggesting that signal rates could predict gravel transport rates reasonably well. Mismatching signal rates that occurred early in the one-day records hint at problems regarding system sensitivity and field calibration: system sensitivity was likely too high during the initial hours of the recordings, possibly caused by a sensitivity imbalance. A continuous record might have avoided this problem and allowed bedload wave patterns to be evaluated in the context of a season-long record. With respect to field calibration, the locations of signal recording and bedload sampling were too far apart, allowing bedload waves to disintegrate between the two sites. Sampling time was too short for physical samples to integrate over bedload waves, and most bedload

happened to be sampled during wave troughs. More samples should have been collected, using a sampler easier to operate than the one used.

The magnetic tracer technology can provide high-resolution and season-long records of signal rates that, when frequently and continually calibrated against physical bedload samples, can provide accurate accounts of gravel bedload transport. However, before becoming a reliable monitoring and research tool, the magnetic tracer technique needs to become an off-the-shelf product, portable, robust, and operable by people other than experts in instrument technology. Technological advances should permit analyses of signal shape to tease out particle sizes, and thus bedload mass, from a recorded signal.

1. Introduction

Several studies had suggested that the passage of artificially magnetized particles across a detector system could be recorded as a measure of bedload transport (Oldfield et al. 1981, Ergenzinger and Conrady 1982; Arkell et al. 1983; Reid et al. 1984). Studies at Squaw Creek, Montana, USA, showed that naturally magnetic streambed particles could be used as tracers for the automated detection of gravel transport. This opened the opportunity for obtaining a high resolution temporal record of bedload transport for an entire runoff season. Such records are necessary to improve our understanding of bedload transport dynamics in gravel-bed streams and to accurately monitor annual bedload yield. Prerequisite, however, is that recorded signal rates are calibrated against physical bedload samples to ensure that the technology provides reproducible information on bedload transport flux.

The magnetic tracer technique at Squaw Creek was developed in three stages between 1981 and 1991. Each stage improved the technology and provided interesting insights into the temporal and spatial variability of bedload transport. However, neither the Squaw Creek studies nor later studies using the magnetic tracer technique (Tunnicliff et al. 2000; Gottesfeld and Tunnicliffe 2003) provided a successful field calibration of signal outputs against physical bedload samples. Thus, the accuracy of the magnetic tracer technique under field conditions was never assessed, and absolute gravel transport rates and particle sizes remained unknown.

The objective of this paper is threefold: to provide an overview of the magnetic tracer technique used at Squaw Creek; to present the capability of the technique via an example record of temporal variability of signal rates over a highflow season; and to present a new attempt of field calibrating signal rates recorded at Squaw Creek in 1988 and 1991.

2. Methods

2.1 Study site

Squaw Creek is a mountain gravel-bed stream draining the Gallatin Range in southwestern Montana. The 105 km^2 watershed is mostly forested. Fifty-five percent of the watershed area is comprised of tertiary volcanic rocks, much of which are lava flows of porphyric andesites that contain about 7.4% magnetite (McMannis and Chadwick 1964). Sedimentary rocks make up most of the remainder of the watershed.

Squaw Creek has a snowmelt flow regime with pronounced diurnal fluctuations of flow. Daily flows peak around midnight and are lowest between 14:00 and 16:00. The 1.5 year recurrence interval flow is 5.7 m^3/s. At the measuring site near the confluence with the Gallatin River, the stream has lateral gravel bars that become flooded at high flow and increase the stream width to about 20 m. Upstream of the measuring reach, stream morphology is mostly plane-bed. The stream is 6-10 m wide at low flow, often incised into a floodplain, and has occasional pool-riffle sequences. The reach-averaged stream gradient is 0.021. The bed surface and subsurface D_{50} sizes are 45 and 35 mm, respectively; 8% of the subsurface sediment is sand.

A large percentage of the streambed gravels is naturally magnetic and can serve as natural tracers for the magnetic tracer technique. The percentage varies with particle size and increases from 63% for particles 22.6-32 mm in size to 75% for particles 90-128 mm. The magnetic field strength of volcanic particles larger than 32 mm ranges between 40 and 400 gamma and is unrelated to particle mass (Monahan and O'Rourke 1982).

2.2 Magnetic tracer technique at Squaw Creek

The magnetic tracer technique is based on the Faraday induction principle: a magnet that passes a coil (iron bar with copper windings) induces a voltage peak that has the form of a sine wave. These voltage peaks can be amplified, filtered, and recorded. The detection and measuring/registration units used at Squaw Creek were not off-the-shelf products, but were developed step-by-step and improved over the years. The first generation equipment (Ergenzinger and Custer 1982, 1983; Custer et al. 1987) consisted of two small detector logs that housed the coils, and the logs were implanted into the streambed. The registration unit recorded signals and showed wavelike movement of bedload—the magnetic tracer technology basically worked. However, improvements were needed to (1) facilitate signal records across the stream width, (2) increase the signal-to-noise ratio, (3) reduce electronic noise, and (4) achieve a computer-based processing of the recorded signals.

2.2.1 The 1986 system

The next generation magnetic tracer detection system developed by Spieker (1988) included a new coil design, their installation in two parallel rows, coverage of the entire stream width, and a new measuring/registration unit. Each of the 0.7-m long coils comprised 310 chokes that were glued wire-side up into plastic U-profile slots and connected in series. Using a series of chokes instead of a single ferrite bar with copper wire ensured an even sensitivity over the coil length. Two coils were wired together to form a unit 1.55 m long.

The wooden log that housed the coils was 0.25 m wide, 0.15 m high and 8.5 m long to span the stream width. Two parallel notches, about 2.5 cm wide and deep, were cut into the upper side of the log 0.15 m apart. Five coil units were placed end-to-end into both notches that, after all wiring was in place were filled with epoxy (Spieker 1988; Bunte et al. 1987; Spieker and Ergenzinger 1990) (**Fig. 1 a**). The detector log was mantled with aluminum flushing for protection and placed adjacent to a log installed for erosion protection at the upstream side of a vehicle bridge (**Fig. 1b**). The flush position of the detector log with the upstream channel bottom as well as a drop of the bed on the downstream side of the bridge-log accelerated the flow and ensured that bedload particles slid quickly over the log surface. A high particle velocity is essential for generating large signal amplitudes and prevents pebbles from being trapped in interstices close to the detector log where they may vibrate and cause noise signals.

Considerable thought and hand labor went into the design of the measuring/registration unit that had different filters for eliminating noise and different amplifiers to increase the signal strength (Spieker 1988). The entire unit was built from scratch. Examples of the sign-wave voltage peaks that were induced by a magnetic particle as it passed the detector log are shown in **Fig. 1c**. The duration of a bedload signal was 0.2-0.3 s for particles 30-70 mm in size and decreased as particles slid over the detector log more quickly during higher flows. Using two adjacent rows of coils has several benefits. The time difference between two signals recorded at the upstream and the downstream coils makes it possible to calculate particle velocity. Noise signals caused by alternating current in the power supply line, the difference in potentials of electric ground (between the power line, the instrument shed, and the stream), radio reception, lightning strikes, the nearby presence and movement of iron objects and people, or impacts and vibrations of the detector log are detected equally by coils in both rows, thus identical signals on both coils can be identified as noise and eliminated.

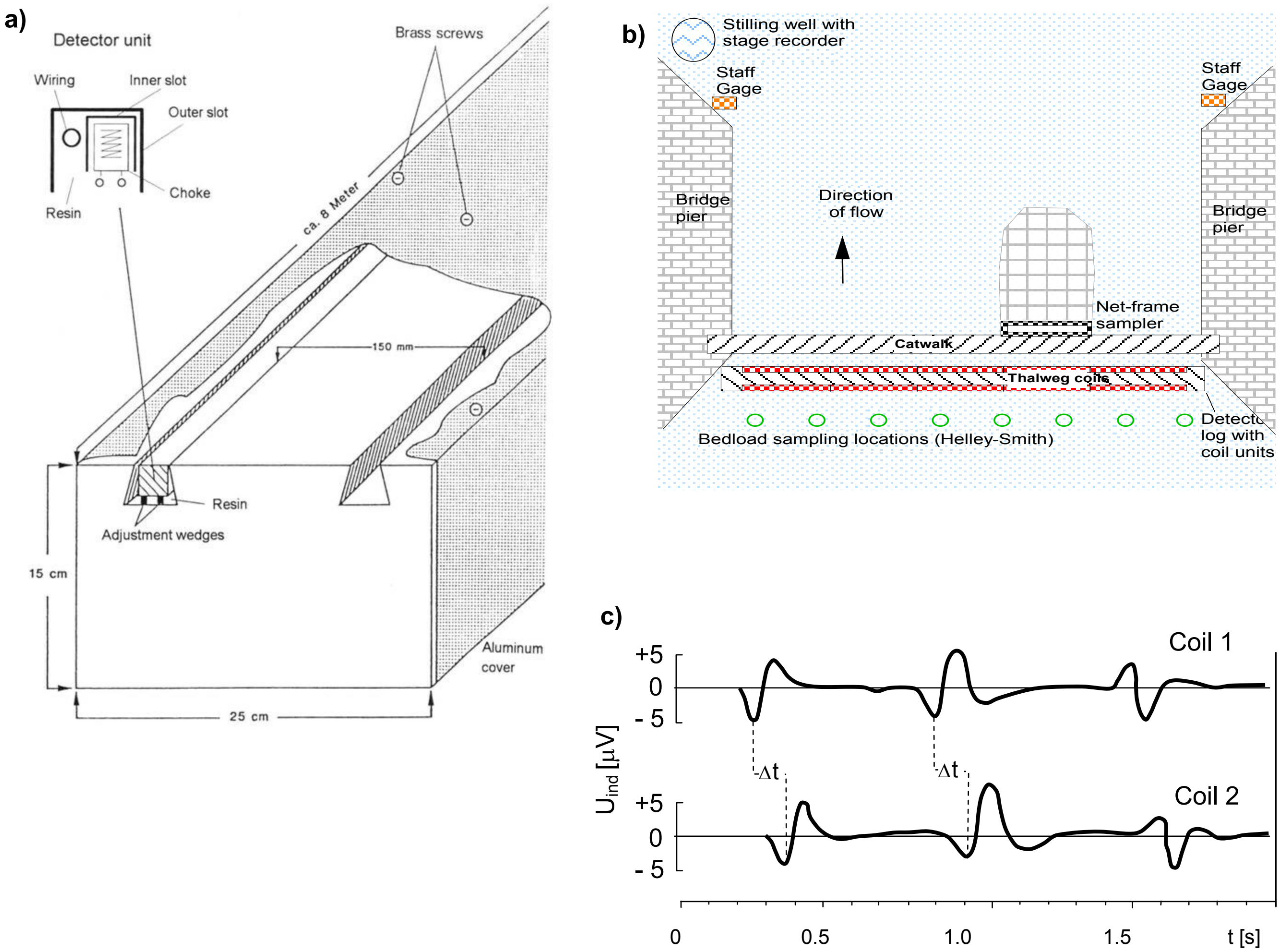

Figure 1. Detector log (cross-section) (a); The 1986 measuring site at Squaw Creek showing the detector log and its coils as well as bedload sampling locations (b); High resolution record of signals created by the passage of magnetic rocks over the detector log (c);(modified, from Bunte et al. 1987).

The 1986 magnetic tracer system was devised to detect particles with field strengths of more than 40 gamma. On average, these are magnetic particles larger than 32 mm, and they represent about 40% of the coarse bedload material at Squaw Creek. Each 1.55 m coil unit could theoretically record the passage of about four particles per second or 160 particles per minute per 1 m width. This capacity exceeded the highest measured transport rate at Squaw Creek and appeared sufficient for recording transport rates expected near bankfull flow.

Signals detected from the five coil units were recorded on a multi-channel strip chart recorder that could be set to different paper advance speeds (**Fig. 2a and b**). The strip charts indicated different temporal patterns of gravel transport (**Fig. 2b**): single-particle motion during low intensity (June 6, 8:00-9:00), wavelike transport (June 6, 6:00-7:00 and after 10:00), and pulse-like motion at high intensity transport (June 6, 1:00-3:00). The majority of all signals was registered on the thalweg coil unit (**Fig. 1b**). Using a magnifier, signals with amplitudes larger than 1 mm on the strip chart were manually counted for 1-hour time intervals over the 17-day highflow season, as well as for 5-minute increments over a three-day period (Bunte at al. 1987; Bunte 1991, 1996). Manual signal counting became problematic when more than 100-200 signals were recorded per hour and signals plotted on top of each other, making small signals invisible. Because test stones dragged over the detector log reliably produced signals, and because signal rates increased steeply with increase in water discharge, it was assumed that signal rates have a positive and persistent relationship to gravel transport, and that recorded signal rates reveal a temporal record of gravel transport.

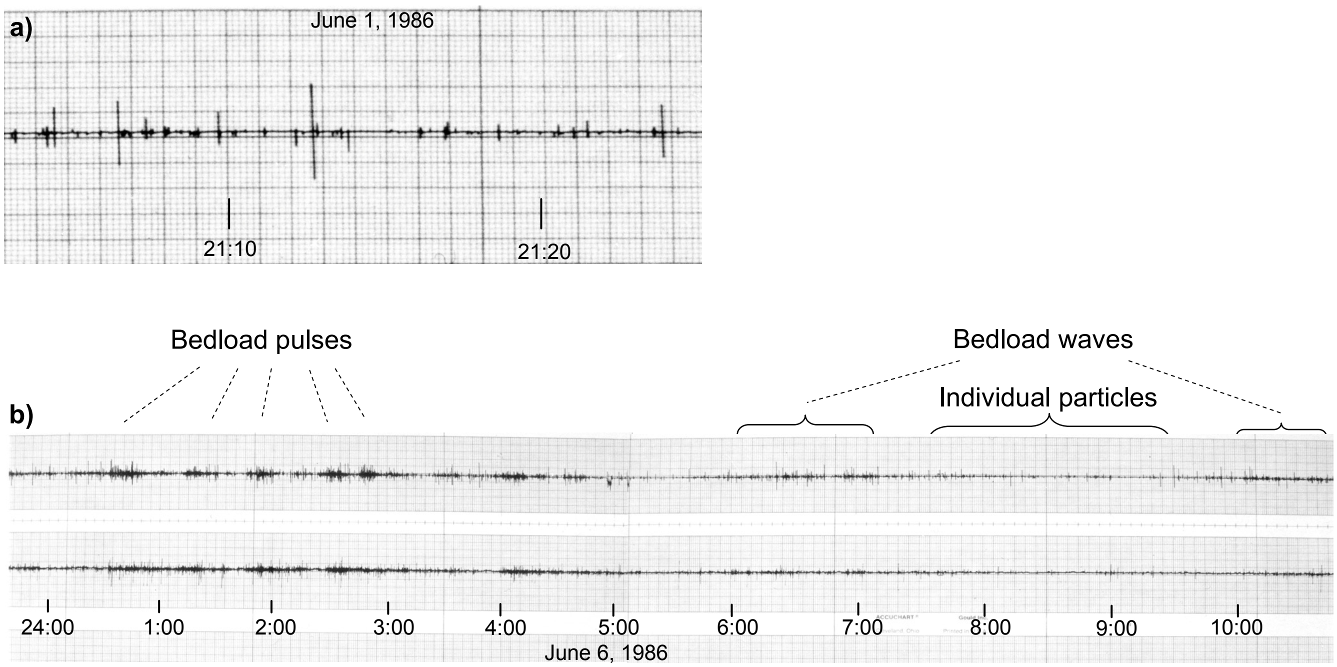

Figure 2. Examples of strip chart records from the magnetic tracer technique, June 1 and 6, 1986; High resolution record on June 1 (a) and low resolution record on June 6 (b). The upper row of signals represents the thalweg coil unit that on average registered 70% of all signals. The lower row represents the stream center coil unit. Very few signals were registered on the other three coil units.

To provide a means for recording signal shape that could be used for further analysis regarding particle velocity and size, Spieker (1988) had experimented with using frequency modulation to transform the signal shape into sound that could be stored on a tape recorder and be demodulated for later analysis. However, the cleverly thought-out features did not reach a workable stage for the continuous registration of bedload signals during the highflow season in 1986, nor was there expertise to analyze particle velocity and signal shapes. The approximate cost of the magnetic tracer technique as built in 1986 amounted to a few thousand US$ for electronic parts, wires, epoxy, the wooden log, truck rental, and other materials, plus a graduate student's salary for about a year during development and field construction of the magnetic tracer technique.

2.2.2 The 1991 system

To increase the signal-to-noise ratio, and to circumvent manual particle counting, a new measuring/registration system was designed in 1990/91 by the department of electronics and instrumentation development at the Technical College, Berlin (Achter and Brüggmann 1991). A second detector log, basically a copy of the first one, was fabricated and placed into the stream bottom about 30 m upstream of the old detector. The new measuring/recording unit consisted of a double auto zero amplifier and an analog multiplexer, a data acquisition controller with digital converter and auxiliary electronics with a micro-controller. The 1986 system had a relatively low amplification that allowed the recording of signals on a strip chart recorder. However, a further increase in the degree of amplification overwhelmed the measuring system and produced electronic background noise signals (i.e., intense buzzing of the strip chart recorder). In the 1991 system, the pre-amplification of signals from each coil unit was much increased. An inbuilt filter reduced low-frequency noise produced by the vibration of the detector log in the stream and the wiring. The data processing unit consisted of a micro-controller with a control program and a PC with corresponding software. The software digitized the amplified output signals and transferred the values to the PC. The software also controlled the analog multiplexers as well as the analog-digital converter and served as the serial interface (Ergenzinger et al. 1994a). The PC displayed bedload signals in their shape on screen as they occurred, sampling each signal 10 times. This sampling rate allowed the computer to identify that a signal had occurred, but not to record the entire signal shape, which required a sampling rate of 34 per signal (Achter and Brueggmann 1991). For each coil unit, the program recorded a signal as an event together with the time of its occurrence. The program counted signal rates for preset time intervals (typically 10 minutes) and stored those data. While the numerical computer output with time series of signal rates was convenient for later analyses, viewing an advancing strip chart with the original data and keeping it for later analyses is a reassurance that the new system did not have.

2.3 Other measurements

A variety of other measurements were taken over the years together with the magnetic tracer technique. Stage was recorded at various locations within the reach and permitted computations of changes in water surface slope over time (Bunte 1991, 1996). Apart from simple discharge measurements, detailed velocity profiles were measured in 1988 and 1991 by Carling et al. (1993, 1998). Berry (1988) and De Jong (1995) took detailed time series measurements of the cross-sectional profiles of the streambed and the water surface elevation and analyzed their change over time. Bedload samples were collected with a 76 by 76 mm Helley-Smith sampler in 1986 and with a net-frame sampler in 1988 and in 1991 (Bunte 1991, 1992, 1996). The net-frame sampler had a wooden frame with a 1.55 by 0.3 m opening to which a 3-m long net with a 10-mm mesh-width was attached (Fig. 3a). The net-frame sampler was installed immediately behind the detector log and extended over the width of the thalweg coil unit (Figs. 1b and 3b). Sampling times ranged between 2.5 and 60 minutes depending on the estimated transport magnitude. Two series of sequential bedload samples were collected with the net frame sampler each in 1988 and 1991. They comprised between 5 and 11 samples and spanned between 6 and 24 hours, respectively.

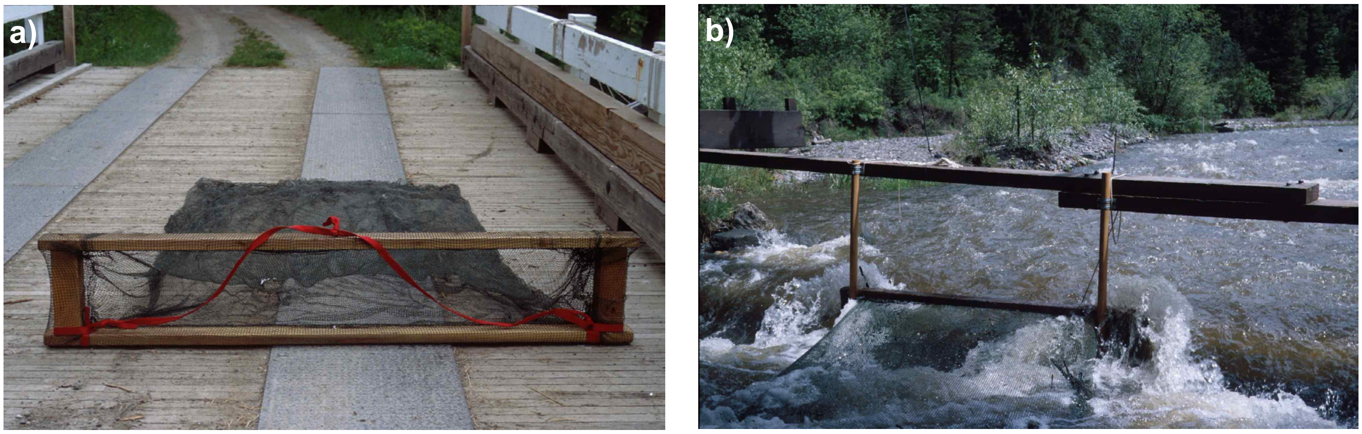

Figure 3. Net-frame sampler (a) and its installation at the thalweg unit of the detector log (b).

3. Results

The Squaw Creek measuring site provided many insights into the intricacies of the magnetic tracer technique as well as the dynamics of gravel transport (see references by Ergenzinger, Custer, Bunte, Spieker, Berry, De Jong, Carling, Achter and Brüggmann). The study presented here focuses on two aspects. It shows the capability of the magnetic tracer technique by presenting a time series record of the temporal variability of gravel transport at Squaw Creek, a relation of signal records to other hydraulic parameters as well as implications for bedload sampling and monitoring. This study also shows results from former and recent attempts of field calibrating signal rates at Squaw Creek and assesses the accuracy of the magnetic tracer technique in recording the passage of magnetic gravel particles over a detector log.

3.1 Temporal variability of signal rates over the course of a highflow season

3.1.1 Daily patterns of bedload waves

Hourly signal rates recorded with the magnetic tracer technique during the 1986 snowmelt highflow season were plotted over 17 days together with daily fluctuating flow. The time series of gravel signals disintegrated into a sequence of bedload waves (**Fig. 4**). Days with flows larger than about 80% of bankfull had three periods of high bedload activity. The largest bedload waves typically occurred on the daily rising limbs, when signal rates increased strongly with flow but dropped considerably soon after peak flow. These primary bedload waves around rising and peak flow were sometimes twin peaked. Secondary bedload waves occurred during the falling limbs 4-6 hours after the peak of the primary bedload wave. A third period of bedload waves followed 4-6 hours after the peaks of the secondary bedload waves. Tertiary bedload waves were also often twin-peaked, with both maxima 4-5 hours apart. Thus, beyond a 24-hour periodicity synchronized with daily discharge peaks, bedload waves at Squaw Creek also occurred at 4-6 hours intervals. The disintegration of gravel transport into large bedload waves near peak flow and a second period of large bedload wave at the end of the falling limb of diurnally fluctuating flow was also observed in the one-day record obtained with the magnetic tracer technique by Tunnicliffe et al. (2000). Similarly, in their week-long records, Habersack et al. (2001) and Gottesfeld and Tunnicliffe (2003) reported bedload waves that peaked either on the rising limb, near peak flow or on the falling limbs of diurnally fluctuating flow.

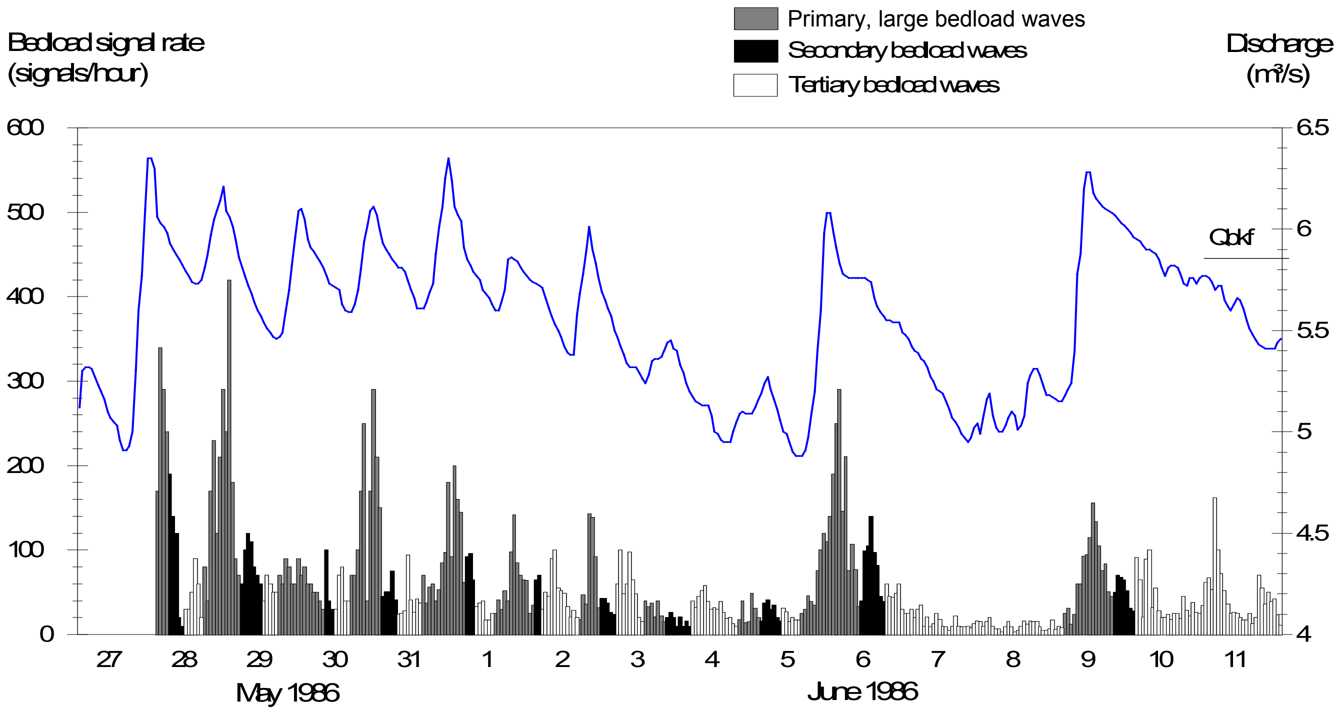

Figure 4. Snowmelt hydrograph and hourly signal rates plotted over a 17-day period from May 27 to June 11, 1986 at Squaw Creek. Note bedload waves that occurred at different times throughout the hydrograph.

The long record obtained at Squaw Creek also showed that the magnitude of bedload waves during the primary, secondary, and tertiary wave periods changed in proportion to each other over the course of the highflow season. Both peak rates and duration, and thus the total number of signals within primary bedload waves decreased with time, while amplitudes and duration of signals within tertiary waves increased (**Fig. 4**). The presence of large primary bedload waves at the beginning of the snowmelt highflow suggests that gravel is stored close to the site during the previous day's falling limb of flow and is ready to be transported on the next day's rising limb. However, over the course of several highflow days with generally decreasing flows, primary bedload waves became less pronounced, while tertiary waves at the end of the falling limbs of daily flow became stronger. This suggests that the main source of gravel was no longer close to the site. Instead, gravel likely originated either from bedload sheets traveling through the fluvial system or from being eroded somewhere and arriving at the site as tertiary waves about half a day after peak flow. Bedload wave pattern recorded during the 1986 highflow season could not be confirmed during the 1991 season because time series of signal rates were only recorded for a few individual 24-hour periods in 1991.

3.1.2 Short-term variability

Analyzing the 1986 data at 5-minute intervals (Bunte 1991, 1996) shows that bedload transport is composed of a series of fluctuations with different durations: small waves lasting about 1.5 hours (Figure 5a), shorter-term bedload waves lasting about 30 minutes, as well as random fluctuations (Figure 5b). The high temporal resolution record by Gottesfeld and Tunnicliffe (2003) likewise shows short-term random fluctuations that appear to overlay bigger fluctuations.

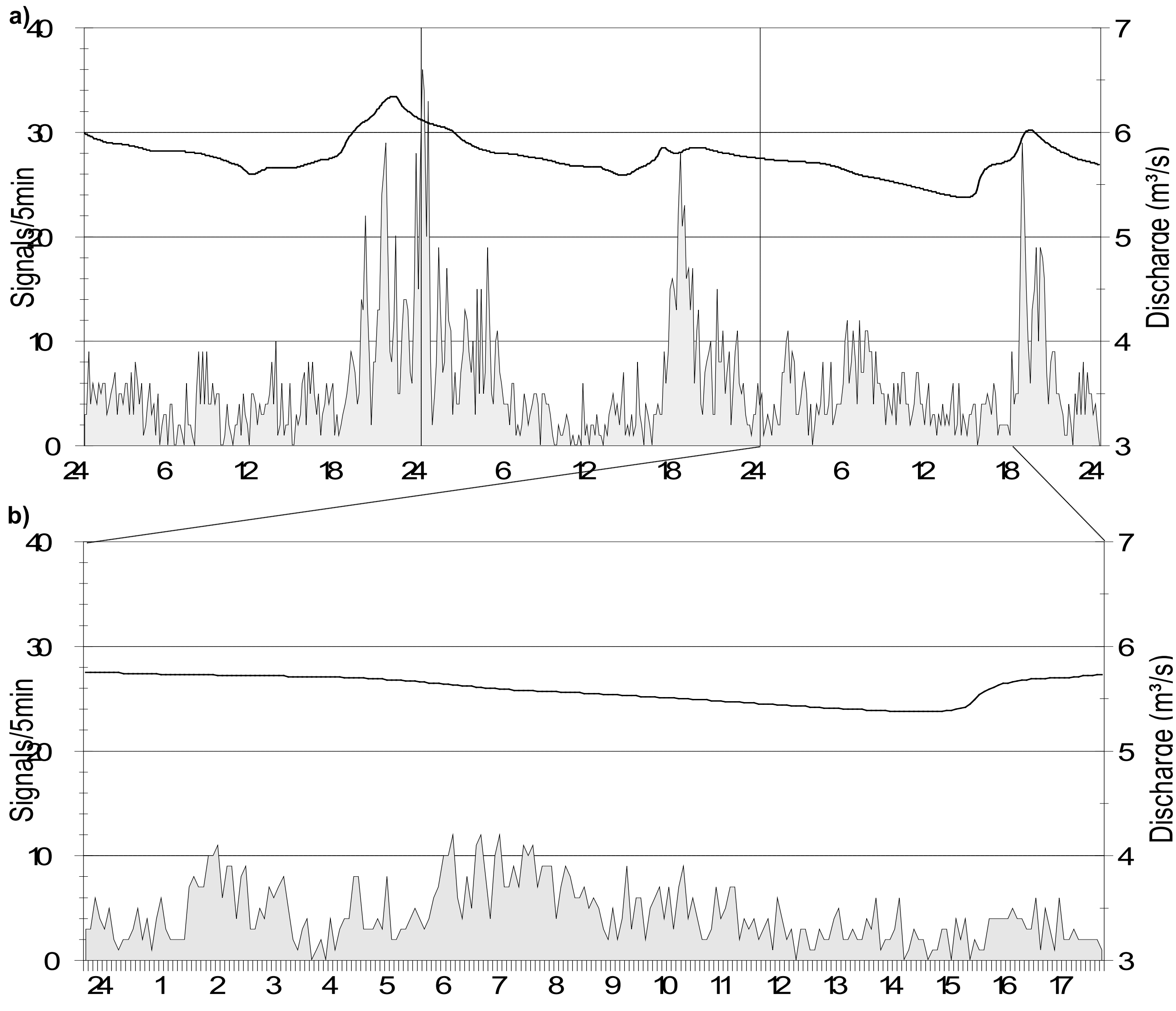

Figure 5. Snowmelt hydrograph and bedload signal rates counted over 5-minute intervals over a 3- day period from May 31 to June 2, 1986 at Squaw Creek. Note signal rates peaking on rising and falling limbs of flow (a). Zooming in on an 18-hour period on June 2. Note short-term fluctuations in signal rates (b).

3.1.3 Bedload waves during two storm flow events

Distinct bedload waves also occurred during two storm flow events on June 5-7 and June 9-12 at the end of the 1986 highflow season. Both events had steeply increasing water discharge, the second event peaking slightly higher and with a longer recession. Similar to the snowmelt days, bedload waves occurred during the recession limbs of the storm event but were spaced further apart (about 8 hours) than those during the snowmelt days. Bedload waves during the storm events also showed the temporal shift from large primary and small tertiary bedload waves to small primary and large tertiary ones later on. A surprising feature during the second storm event was that after long periods of low bedload activity during the long recession limb, new bedload waves unexpectedly passed the site. One arrived 21 hours after the tertiary wave, while another bedload wave occurred 12 hours later. It appears that as long as flow competence sufficed, gravel bedload moved through the fluvial system at Squaw Creek in waves that periodically arrived at the site. Hence, other than flow, bedload conveyance and availability of gravel near the site for transport by newly rising flows played a major role in determining instantaneous signal rates.

3.1.4 Causes of bedload waves

Bedload patterns with waves on the falling limbs of flow have been reported for flood events by many studies (e.g., Jackson and Beschta 1982; Schlatte 1984; Reid et al. 1985; Bänzinger and Burch 1990; Lisle 1989; Rickenmann 1994; De Jong 1995; Bogen and Møen 2003; Laronne et al. 2003; Tunicliffe et al. 2000; Gottesfeld and Tunnicliffe 2003; Mizuyama et al. 2003). All cases were marked by a decrease in high transport rates soon after the peak flow, as well as by one or more (smaller) bedload waves on the falling limb of flow. Several interpretations have been offered. Reid et al. (1985) suggested that the entire upper layer of the channel bottom moves downstream in lobes of different width and velocity that arrive at a site at different times. Jackson and Beschta (1982) suggested that channel change on riffles is the reason for bedload waves. Gottesfeld and Tunnicliffe (2003) attributed observed bedload waves to the passage of bedload sheets. Bedload waves observed at Squaw Creek were attributed to several processes. Based on observations of temporal change of the longitudinal water surface profile over a riffle-pool unit about 30 m upstream from the detector log, Bunte (1991; 1996) related bedload waves to sediment accumulating on a nearby riffle for several hours, and then eroding off rather abruptly just before the passage of a bedload wave on the detector log. Berry (1988), Ergenzinger et al. (1994 a and b), De Jong (1995), De Jong and Ergenzinger (1994, 1998) related the passage of bedload waves to adjustments of the streambed cross-section to changing flows that brought with them changes in flow structure. Carling et al. (1993, 1998) related the Squaw Creek bedload waves to the transport of gravel from flooded upstream bars over an essentially stable coarse armor.

3.1.5 Temporal variability in bedload samples

The series of sequential bedload samples collected with the net-frame sampler at Squaw Creek in 1988 and 1991 are insufficient to analyze pattern of temporal variability, but information on the collected particle sizes was used to infer processes causing the temporal variability of transport rates. Large transport rates comprised all but the very largest particle sizes available in the bed, while small samples lacked either the coarse or the fine portion of the bedmaterial size distribution. Large bedload transport rates occurred at times at which the upstream water surface slope showed an abrupt change, suggesting the arrival and subsequent passage of a sediment body. Differences in bedload transport rates and particle sizes were thus attributed to nearby streambed adjustments to flow, with major adjustments involving all particle sizes and minor adjustments involving fewer particles and not all size classes (Bunte 1991, 1996). However, similar variations in bedload transport rates and particle sizes could be possible during the passage of gravel bedload waves.

3.1.6 Relationships between signal rates and water discharge

Due to the wavelike nature of gravel transport at Squaw Creek, the relationship between hourly signal rates and water discharge measured in 1988 scattered within an order of magnitude ($r^2 = 0.56$) similar to observations by Gottesfeld and Tunnicliffe (2003), and each day had a different hysteretic relationship between signal rates and water discharge. Signals recorded on the daily rising limbs of flow were better correlated to discharge ($r^2 = 0.63$) than those on the falling limbs ($r^2 = 0.35$). The correlation improved when the temporal scale was increased from hours to days. The number of daily signals was well correlated to the daily flow volume ($r^2 = 0.87$), indicating that the amount of bedload transported was generally in proportion to water discharge. Although hourly signal rates S_B increased steeply with flow Q ($S_B = 2.68\text{E-}7\ Q^{10.93}$), the increase was less steep than the one between gravel transport rates Q_B computed from the net-frame sampler and water discharge ($Q_B = 4.43\text{E-}13\ Q^{18.2}$). This has several reasons: one is that for bedload samples both the number and the mass of particles increases with flow, whereas for signals rates only the number of particles increases. Another reason may be that the number of signals recorded by the magnetic tracer system or visually counted at high flow is too low, i.e., the sensitivity of the magnetic tracer system decreased. However, the relationship of signals to water discharge at Squaw Creek did not show a flattening trend as observed by Gottesfeld and Tunnicliffe (2003) or e.g., Mizuyama et al. (2003), suggesting that the problem of underrecording at high transport rates is not limited to the magnetic tracer technique. A flattening of the gravel bedload rating curve is not considered typical of slightly entrenched, coarse-bedded mountain streams, at least it was not observed in eight (now nine) studies in which gravel transport was sampled using bedload traps (Bunte et al. 2008), nor in the gravel bedload samples collected with the net-frame sampler at Squaw Creek (Bunte 1991, 1996), nor in large data sets of Helley-Smith samples compiled by King et al. (2004) and Ryan et al. (2005) for Rocky Mountain streams.

3.2 Field calibration of signal rates with bedload samples

The relationship between the magnitude of a signal and the size of a gravel particle causing the signal is quite complex. Signal amplitude is function of four particle parameters: (1) magnetic field strength—that is basically unrelated to particle size at Squaw Creek, (2) distance to the detector log, (3) velocity with which a particle crosses the detector log and (4) magnetic orientation of the passing particle. Signal duration is a function of three particle parameters: its (1) size, (2) shape, and (3) velocity. Although it can be assumed that (most) signals recorded by the magnetic tracer technique at Squaw Creek represented the passage of magnetic particles, the exact relationship between signal rates and transport rates was unknown because it would have required detailed analyses of signal shapes (and would even then have been difficult). Field calibration was needed to determine this relationship. Several attempts were made.

3.2.1 Bedload samples from a 3-inch Helley-Smith sampler in 1986

Attempts were made in 1986 to calibrate recorded signals rates with bedload samples collected in a 76 by 76 mm Helley-Smith (HS) sampler (Bunte 1991, 1996). Because placing the HS sampler onto the detector log generated noise signals that persisted for a while after the sampler was removed, HS samples could only be compared to signals recorded before the sampler was deployed. Besides this temporal difference, the HS samples also contained only a few gravel particles larger than 32 mm, necessitating a comparison of total transport rates with signal rates. This relationship was poor ($r^2 = 0.32$). The 76 by 76 mm Helley-Smith sampler was unsuitable for calibrating signal rates. A sampler with a larger opening and longer sampling times was needed. Deployment of a 152 by 152 mm Helley-Smith sampler failed because the sampler could not be held at high flow. In the absence of other suitable bedload sampling device, no further calibration was performed in 1986.

3.2.2 Gravel transport rates collected in the net-frame sampler in 1988

The large net-frame sampler (Fig. 3) was built in 1987 to calibrate signal rates at Squaw Creek, but no highflow occurred that year. In 1988, the magnetic tracer technique was not operable, and no help was available from an electronically-versed person. However, the 1988 highflow season had a hydrograph similar to the one in 1986. As a stopgap measure, bedload samples collected with the net-frame sampler in 1988 were compared to signal rates recorded in 1986. In step one of the analyses, two power function relationships were established: 1) the increase in the number of magnetic bedload particles of 32-45 mm and 45-64 mm collected in 1988 with flow and 2) the increase in signal rates with flow in 1986. In step two, signal rates recorded at five discrete discharges between 4.5 and 6.5 m^3/s in 1986 were compared to the number of magnetic particles collected at these flows in 1988, assuming that the amount of bedload transported at specified flows remained unchanged over the two years. Results showed that number of particles collected in the 32-45 and 45–64 mm size classes matched signal rates only for the lowest transport intensity with about 1 signal per 10 minutes (**Fig. 6**). At higher transport rates and above bankfull flows, the number of bedload particles larger than 32-45 mm and 45-64 mm collected in the net-frame sampler per 10 minutes exceeded 10-minute signal rates by about one order of magnitude. Either the relationship between bedload transport and water discharge had changed over the years or the magnetic tracer technique under-recorded transport rates in 1986 by a factor of roughly 10. The possibility of a notable change in the bedload rating relationship cannot be excluded, but under-recording by the magnetic tracer technique and under-counting of signals that had plotted on top of each other were the more likely explanations.

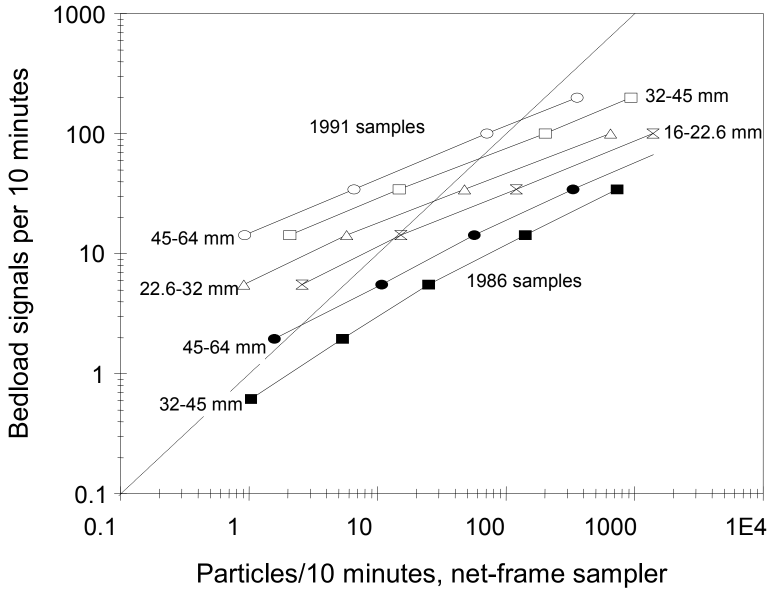

Figure 6. Relationships between bedload signals recorded using the magnetic tracer technique in 1986/1988 (bold symbols) and 1991 (open symbols) and number of magnetic particles collected in the net-frame sampler.

3.2.3 Calibration of the 1991 signal counts with samples from the net-frame sampler in 1991

On May 23/24, 1991 while flows were 100-110% of bankfull, signal rates were continuously recorded at the upstream detector log over a 24-hour period. Every two hours, bedload samples were collected with the net-frame sampler over 30 minutes at the downstream detector log about 30 m downstream from the upstream detector log (**Fig. 7a**). Because it takes time for gravel to travel a 30 m distance, and to account for difference in transport patterns over the 30 m distance, signal rates recorded at the upstream detector log in 10-minute increments were smoothed by a running average over about 3 hours before comparing them to bedload samples. On June 5-6, 1991, signals were recorded continuously at the lower detector at the net-frame sampler while 8 bedload samples were collected (**Fig. 7b**). To average over short-term fluctuations of particles crossing the detector log, signal rates were computed as running averages over 30 minutes before comparison with bedload samples. Water discharge reached 115% of bankfull, and high gravel transport rates required that collection times for the net-frame sampler were short (2-11 minutes). The second sample of the day was unexpectedly large, overfilled the net, and was not retrievable. Knowing that this sample represented a large transport rate, it was assigned a rate 10% higher than the largest recorded rate that occurred a few hours later and marked as "*est.*" in Fig. 7b and 8.

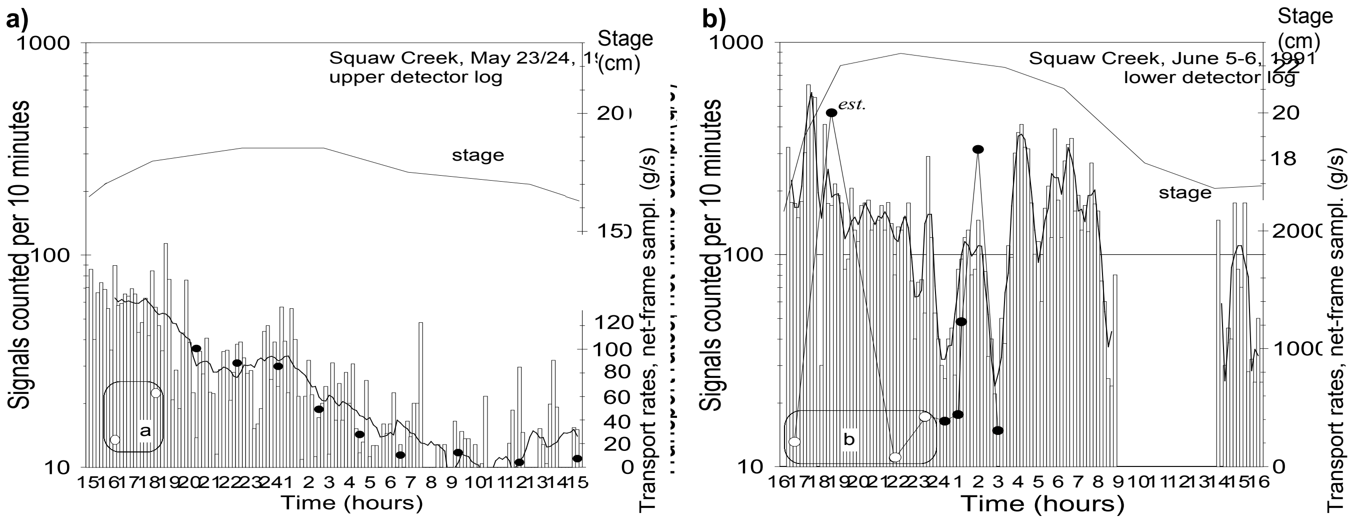

Figure 7. Signal rates counted over 10-minute intervals during two 24-hour periods at Squaw Creek in 1991: May 23-24 (a) and June 5-6 (b). See text for explanation of data point marked "est.". Data points marked *a* and *b* refer to data clusters *a* and *b* in Fig. 8 a and b.

Signal rates from 1991 were also compared to the number of magnetic particles collected in the net-frame sampler and showed that the 1991 magnetic tracer detection system was considerably more sensitive than the 1986 system. For example, when 57 magnetic particles 45-64 mm in size and 142 particles of 32-45 mm were collected in the net-frame sampler per 10 minutes, the 1986 system registered 14 signals in 10 minutes. The 1991 system registered about 90 particles/10 minutes for bedload samples of that size (**Fig. 6**), suggesting that the 1991 system was roughly 6 times more sensitive than the one in 1986. To record more signals, the 1991 system must have detected signals also from particles smaller than 32 mm. What did not improve in the 1991 system was the system stability: similar to the 1986 system, sensitivity decreased with increasing transport intensity. This might be due to the sensor's difficulty of distinguishing between particles when two or more particles pass the detector simultaneously. Further advances in technology to record and analyze signal shapes may enable the measuring system to detect the (near) simultaneous passage of several particles over the sensor. In the meantime, a correction function based on a large number of physical samples needs to be used to account for the decrease in system sensitivity with increasing transport.

In a next calibration step using the 1991 data, signal rates were directly compared to gravel transport rates measured in the bedload samples at the same time. **Fig. 7** shows times series of both signal rates and gravel transport rates. Most of the bedload transport rates collected on May 23-24 and June 5-6 (black symbols in **Fig. 7a** and **b**) matched the temporal trend of the signal rates, but five data points mismatched (white symbols in **Fig. 7a** and **b**). Excluding these five data points, a power function regression fitted between signal rates and sampled gravel transport rates yielded a high correlation (r^2 = 0.89) (**Fig. 8a**), suggesting that transport rates could be predicted from signal rates most of the time. By contrast, the two data points on May 23-24 (cluster *a* in **Fig 7a**) and three data points on June 5-6 (cluster *b* in **Fig. 7b**) had signal rates 2-4 times higher than expected from bedload samples. The fact that those five bedload samples fit the general relationship between gravel transport rates and water discharge (**Fig. 8b**) but not the relationship between signal rates and discharge (**Fig. 8b**) suggests that signal rates rather than sampled bedload transport rates were in error.

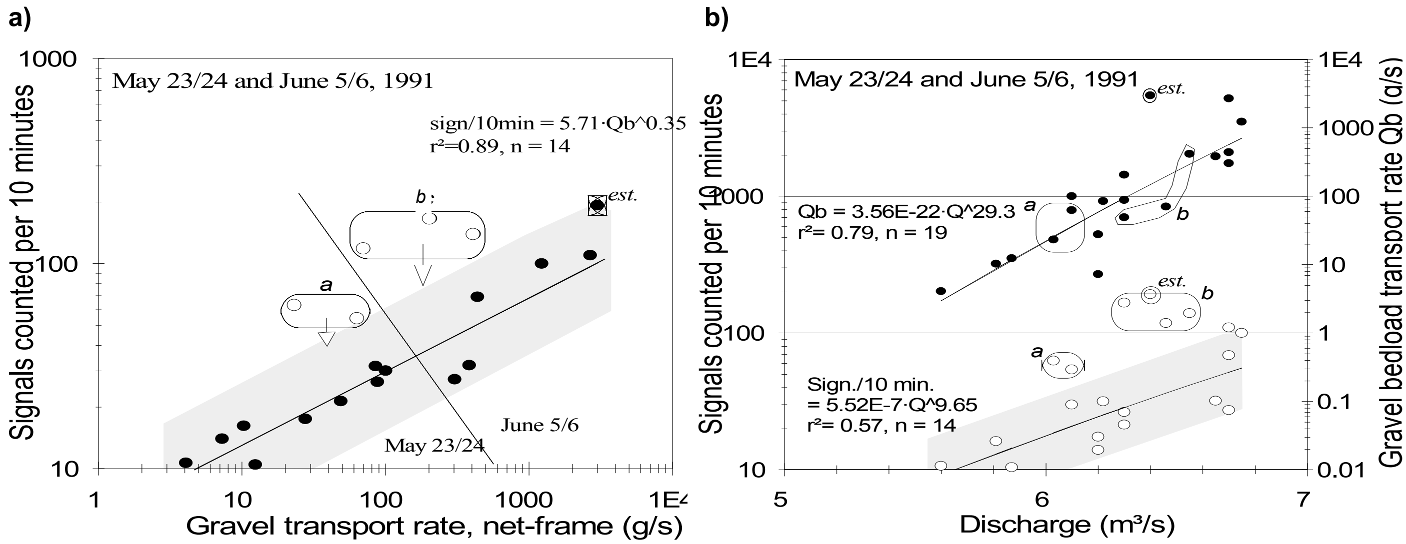

Figure 8. Relationship of signal rates counted per 10 minutes with gravel transport rates obtained from the net-frame sampler (a). Relationship of signal rates and gravel transport rates with discharge (b). Misfitting data points in clusters *a* and *b* are encircled. Arrows indicate direction in which data clusters would have to move for a better fit with sampled transport rates and discharge. See text for explanation of data point noted "*est.*".

Several factors may have contributed to the misfit between recorded signal transport rates and 5 of the 19 bedload samples, and they hint at problems with the magnetic tracer technique in 1991 and with problems of field calibration. One explanation for the misfit between signal rates and gravel transport rates is that recording bedload signals discontinuously for individual days may have caused tuning problems when the recording was started each day, as had been experienced when first starting the 1986 system. Tuning problems in 1991 may have caused an initially altered (i.e., heightened) system sensitivity that then decreased after a few hours. In addition to tuning problems, one-day records fail to analyze signal patterns in their seasonal context. Thus it could not be evaluated whether signal rates on the two recording days in 1991 followed a pattern typical of Squaw Creek in 1991. This information might have helped to validate signal patterns on an individual day. The inability to produce a long-term record in 1991 raises the issue that off-the-shelf electronics require the continued presence of an expert technician to oversee and fine-tune the system.

Even though sampled gravel transport rates were reasonably well correlated to discharge, it is conceivable that field calibration had problems. During May 23-24, 1991, bedload waves passing the upstream detector may have disintegrated within the 30 m long stretch between the upstream detector log and the site of physical sample collection, particularly during the first major daily bedload wave that encountered a bed relatively void of highly mobile gravel. In this case, signal rates recorded at the upstream detector could have been higher than gravel transport rates sampled 30 m downstream and explain the mismatch of the two data points in cluster *a*. During lower transport rates on the falling limb of flow, the 30 m distance may not have caused a spatial difference in transport rates, and similar rates may have occurred at both locations. On June 5-6, 1991, by contrast, the distance between signal recording and bedload sampling may have been too short, and collecting bedload samples directly at the downstream detector log may have disturbed signal registration. The question, however, then would be why those disturbances appear to have vanished after a few hours, and signal rates matched sampled gravel transport rates for the rest of the night. Another sampling problem was that bedload conditions on June 5-6, 1991 were unfavorable high for field calibration. Transport rates reached 300-3000 g/s for gravel > 11.2 mm and were probably 25% higher for total bedload transport rates that includes fine gravel and sand. Unit transport rates exceeding 100 g/m·s suggest that gravel starts to travel in bedload sheet, a state characterized by large and highly fluctuating transport rates. Those conditions make field calibration problematic: sampling times must be kept short in order to avoid overfilling the sampler which, in turn, prevents temporal averaging necessary to compare transport rates measured using two devices during fluctuating transport (see Bunte et al., this volume). It is possible that 3 of the 4 physical bedload samples collected before midnight on June 5 over periods of 5-10 minutes hit bedload sheet tails, while the sample with the overfilled net hit a crest. Many more bedload samples should have been collected, preferably with a less wide sampler that is easier to operate and permits faster sampling intervals. Sampling times should have been longer to average over samples collected in wave troughs and wave crests.

4. Discussion

4.1 Potential of the magnetic tracer technology

If the electronics system is well designed and works properly, and gravel transport occurs, the magnetic tracer technology has the potential for providing high-resolution and season-long time series of relative bedload transport intensity in streams with naturally magnetic particles. Datasets that cover an entire highflow season are still scarce but urgently needed to gain insight into the patterns of temporal variability of bedload transport. Many field studies still rely on only a few annual bedload samples to compute annual load, thus introducing the potential for large errors. However, unless able to provide reliable information on transport rates and bedload particle sizes, the magnetic tracer technique (or other surrogate techniques) cannot become a monitoring tool. Field calibration is absolutely necessary to validate results from the magnetic tracer technique as well as other surrogate techniques, but it needs to overcome several problems (see Bunte et al., this volume).

4.2 Drawbacks of the magnetic tracer technology

The magnetic tracer technique used at Squaw Creek (and elsewhere) had two major drawbacks. One is that it was experimental and not available off-the-shelf. The measuring system required experts in electronics and instrumentation development for construction and required on-site experts to continuously fix, adjust, and fine-tune the system. This precluded a continuous, season-long record of signal rates in 1991 and may have caused temporary shifts in the system sensitivity. Furthermore, unique measuring systems provide measuring results that are not directly comparable to systems of similar kind.

Another drawback of the magnetic tracer technique is its stationarity. The field set-up requires a well-developed site with road access, electricity, and instrument sheds. The success and usefulness of a stationary system funded for a few years by research grants depends heavily on the occurrence of annual highflows large enough to transport gravel within the project period. On average, such highflows occur every other year in Rocky Mountain streams, with marginal transport in most of the other years. To improve the technology and gain full benefits of the results the methodology is able to produce, long-term funding is necessary, but unlikely to obtain. The site at Squaw Creek had sufficient infrastructure and the magnetic tracer technique enough potential that we proposed Squaw Creek as a research site to the Army Corps of Engineers (Custer 1992) and to the U.S. Forest Service as a national bedload transport observatory (Custer 1996). None of the proposals succeeded, and the site was dismantled. Other research sites (e.g., Gottesfeld and Tunnicliffe 2003) had a similar fate.

4.3 Improvements necessary for the magnetic tracer technique

Several improvements are necessary for the magnetic tracer technology before it can become a reliable mainstream surrogate technique used in monitoring and research settings. These include advances in the system electronics, as well as off-the-shelf availability, portability, robustness, and ease of operation. Advancements in the magnetic tracer technique would entail an increase and constancy in the system sensitivity as well as information on absolute transport rates and bedload particle sizes. This means that the shape of each signal would have to be recorded and analyzed to determine the size and mass of magnetic particles causing the signals. This is an immense task in data storage and analysis, but it may become feasible with advances in technical development, increases in computer storage capacity, and new software for signal analysis.

5. Summary and conclusion

The magnetic tracer technique is still experimental and not an off-the-shelf technology. However, when working properly, the magnetic tracer technique used at Squaw Creek provided detailed and long-term records of temporal and spatial distribution of gravel transport over a highflow season—data that are very much needed but that no physical sampling program can provide. The wavelike character of bedload transport and the relatively large scatter in the relationship between signal rates and flow showed that coarse bedload transport is only partially determined by instantaneous water discharge. Other factors such as bedload conveyance through the fluvial system, nearby sediment supply, travel in the form of bedload sheets, and local streambed adjustments play major roles as well. The wavelike patterns of transport that change over the course of a highflow season indicate that any physical sampling program would have to collect a large number of samples per day and extend over the entire highflow season in order to provide a data base for accurate estimates of annual load or for detection of change in bedload transport following natural or anthropogenic watershed effects. Using a surrogate technique together with proper field calibration is an easier and possibly more accurate approach.

However, the magnetic tracer technology (as well as many other surrogate techniques) has not been successfully field-calibrated using an appropriate bedload sampler. Field-calibration in this study suggests that the magnetic tracer technology at Squaw Creek provided accurate results of particles passing the detector log as long as transport intensities were low, but underestimated the number of passing particles when transport was high. Technical improvements in 1991 considerably increased the sensitivity which permitted the detection of smaller particles, but similar to the 1986 system, the sensitivity of the magnetic tracer technique decreased with increasing numbers of particles passing the detector, i.e., too few particles were recorded (and counted) when transport was high. Uncorrected, a decreasing sensitivity of the recording system with increasing transport intensity would lead to large errors in the computation of annual load. However, a persistent change in system sensitivity can be compensated by employing a correction function determined from a large number of bedload samples collected over a range of transport intensities and throughout the highflow season. Of concern are also sudden and temporal shifts in the system sensitivity. To detect those, it would have been useful to record signal rates continuously over the highflow season and evaluate seemingly odd patterns within the context of a season-long record. Continuous recording is also useful to prevent sensitivity imbalances or tuning problems that might occur when the system is started. Short-term shifts in the system sensitivity might not have a large effect on the computation of annual load but lead to a distorted image of the temporal variation of gravel transport.

Field calibration is definitely necessary to validate outputs from the magnetic tracer as well as other surrogate techniques, but is faced with a number of challenges. One is finding an appropriate distance between the recording site and the location of physical samples. The 30-m distance between the location at which signals were recorded and the location at which bedload was sampled was too large when gravel transport occurred in waves or possibly gravel sheets. By contrast, collecting bedload samples directly at the downstream detector log may have disturbed signal registration. The field calibration at Squaw Creek should have collected many more bedload samples for several reasons: to better document changes in the sensitivity of the magnetic tracer with increasing transport intensity, to confirm a sensitivity shift of the recording system, and to average out transport rates obtained from samples collected during a trough or crest of a bedload wave. Collecting more bedload samples requires using samplers that are portable (to place where needed) and easy to use by one or two people (instead of tying up a whole field crew). Field calibration needs to extend over a wide range of transport rates and transport conditions and should be an ongoing activity throughout the highflow season (Bunte et al. this volume).

While the magnetic tracer technology has the potential for providing high-resolution and season-long records of gravel transport, several improvements are necessary. In order to be ready for operational deployment in monitoring and research programs, the technology should be able to analyze signals in their entire shape such that information on particle sizes may be obtained. This, in turn, would provide a more accurate account of transport rates. The technology must become an off-the-shelf product with a data acquisition and logging system that is easy to operate, robust to the elements, and reliable. The detector must be portable and easy to install.

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References Cited

Achter, U. and Brüggmann, J., 1991, Rechnergestütztes Meßdatenerfassungssystem für Kleinsignale [Computer supported data recording system for small signals], M.S. thesis submitted to the Department of Information Sciences at the Technische Fachhochschule Berlin (Germany).

Arkell, B., Leeks, G. Newson M., and Oldfield, F., 1983, Trapping and tracing: some recent observations of supply and transport of coarse sediment from upland Wales, in Modern and Ancient Fluvial Systems, Special Publication of the International Association of Sedimentologists, Blackwell Scientific Publications, Oxford, UK, v. 6, pp. 107-119.

Bänzinger, R., and Burch, H., 1990, Acoustic senses (hydrophones) as indicator for bed load in a mountain torrent, in Hydrology in Mountainous Regions, IAHS Publ. no. 193, pp. 207-214.

Berry, C.T., 1988, Cause of cross-sectional channel change in a gravel bed river at Squaw Creek, Montana, Thesis submitted as an integral part of a Master's degree in Geography with Social Anthropology at the University of St. Andrews, GB.

Bogen, J. and Møen, K., 2003, Bed load measurements with a new passive acoustic sensor, in J. Bogen, T. Fergus and D.E. Walling, eds., Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS-Publication No. 283, pp. 181-192.

Bunte, K., 1991, Untersuchung der zeitlichen Variation des Grobgeschiebetransportes und seiner Korngrößenzusammensetzung (Squaw Creek, Montana, USA) [Temporal variation of coarse material bedload transport and its grain-size distribution (Squaw Creek, Montana, USA.)], Ph.D. thesis submitted to the Dept. of Earth Sciences at the Freie Universität Berlin, Germany, 223 p.

Bunte, K., 1992, Particle number grain-size composition of bedload in a mountain stream, in P. Billi, R.D. Hey, C.R. Thorne and P. Tacconi, eds., Dynamics of Gravel Bed Rivers, John Wiley, Chichester, pp. 55-72.

Bunte, K., 1996, Analyses of the temporal variation of coarse bedload transport and its grain size distribution (Squaw Creek, Montana) [English translation of Ph.D. dissertation submitted to the Dept. of Physical Geography at the Freie Universität Berlin, Germany.] USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-GTR-288, 123 p.

Bunte, K., Abt, S.R., Potyondy, J.P., and Swingle, K.W., 2008, A comparison of coarse bedload transport measured with bedload traps and Helley-Smith samplers: Geodinamica Acta, supplement volume for the Gravel-Bed Rivers VI Meeting, v. 21, no. 1/2, pp. 53-66 (supplement, Gravel-Bed Rivers VI Meeting).

Bunte, K., Custer, S.G., Ergenzinger, P. and Spieker, R., 1987, Messung des Grobgeschiebetransportes mit der Magnettracertechnik [Measuring coarse bedload transport with the magnetic tracer technique]: Deutsche Gewässerkundliche Mitteilungen v. 31, no. 2/3, pp. 60-67.

Carling, P.A., Williams, J.J., Glaister, M.G., and Orr, H.G., 1993, Particle dynamics and gravel-bed adjustments, Final report of a project funded by the United States Army, European research office of the U.S. Army, London, Great Britain, contract no. DAJA45-90-C-0006, 47 p.

Carling, P.A., Williams, J.J. Kelsey, A., Glaister, M.S. and Orr, H.G., 1998, Coarse bedload transport in a mountain river: Earth Surface Processes and Landforms v. 23, pp. 141-157.

Custer, S.G., 1992, A review of natural-gravel-transport-detection experiments at Squaw Creek, Montana, 1981-1991, in M.L. Pearson (ed.), Streams above the Line: Channel Morphology and Flood Control, Proceedings of the Corps of Engineers Workshop on Steep Streams, U.S. Army Corps of Engineers Miscellaneous Paper HL-94-4, pp. 3-1 - 3-28.

Custer, S.G., 1996, A case for a national bedload transport observatory at Squaw Creek's gravel-transport detector in Montana, in Proceedings of the Sixth Federal Interagency Sedimentation Conference, March 10-14, Las Vegas, Nevada, Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, v. 2, pp. V32-V38.

Custer, S.G., Ergenzinger, P.E., Bugosh, N., and Anderson, B.C., 1987, Electromagnetic detection of pebble transport in streams: a method for measurement of sediment transport waves, in F. Ethridge and R. Flores, eds., Recent Developments in Fluvial Sedimentology, Society of Paleontologists and Mineralogists Special Publication no. 39, pp. 21-26.

De Jong, C., 1995, Temporal and spatial interactions between river bed roughness, geometry, bedload transport and flow hydraulics in mountain streams - examples from Squaw Creek (Montana, USA) and Lainbach/ Schmiedlaine (Upper Bavaria, Germany), Berliner Geographische Abhandlungen 59, Institut für Geographische Wissenschaften der Freien Universität Berlin, 229 p.

De Jong, C. and Ergenzinger, P., 1994, Interpreting the temporal and spatial dynamics of bed load transport phases according to FAST (fluid and Sediment Transfer Model), in L.J. Olive, R.J. Loughran and J.A. Kesby, eds., Variability in Stream Erosion and Sediment Transport, IAHS Publ. no. 224, pp. 25-32.

De Jong, C., and Ergenzinger, P., 1998, Dynamic roughness, sediment transport and flow structures in a mountain stream, in P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, eds., Gravel-Bed Rivers in the Environment, Water Resources Publications LLC, Highlands Ranch, Colorado, pp. 39-60.

Ergenzinger, P., and Conrady, J., 1982, A new tracer technique for measuring bedload in natural channels: Catena v. 9, pp. 77-80.

Ergenzinger, P.J., and Custer, S.G., 1982, First Experiences measuring coarse material bedload transport with a magnetic device, in B.M. Sumer and A. Müller, eds. Mechanics of Sediment Transport, Proceedings of Euromech no. 156, pp. 223-227.

Ergenzinger, P.J., and Custer, S.G., 1983, Determination of bedload transport using naturally magnetic tracers: First experience at Squaw Creek, Gallatin County, Montana: Water Resources Research, v. 19, no. 1, pp. 187-193.

Ergenzinger, P., de Jong, C., and Christaller, G., 1994a, Interrelationships between bedload transfer and river bed adjustment in mountain rivers: an example from Squaw Creek, Montana, in M.J. Kirkby, ed., Process Models and Theoretical Geomorphology, John Wiley and Sons, New York, pp. 141-158.

Ergenzinger, P., De Jong, C. Laronne J., and Reid, I., 1994b, Short term temporal variations in bedload transport rates: Squaw Creek, Montana, USA, and Nahal Yatir and Nahal Estemoa, Israel, in P. Ergenzinger and K.-H. Schmidt, eds., Dynamics and Geomorphology of Mountain Rivers. Lecture Notes in Earth Sciences, Springer Verlag, Berlin, pp. 251-264.

Gottesfeld, A.S., and Tunnicliffe, J., 2003, Bed load measurements with a passive magnetic induction device, in J. Bogen, T. Fergus and D. Walling, eds., Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances: IAHS-Publ. no. 283, pp. 211-221.

Habersack, H, Nachtnebel, P.N. and Laronne, J.B., 2001. The continuous measurement of bedload discharge in a large alpine gravel bed river with a slot sampler: Jour. Hydraulic Research v. 39, pp. 125-133.

Jackson, W.L. and Beschta, R.L., 1982, A Model of Two-Phase Bedload Transport in an Oregon Coast Range Stream: Earth Surface Processes and Landforms v. 7, pp. 517-527.

King, J.G., Emmett, W.W. Whiting, P.J., Kenworthy, R.P., and Barry, J.J., 2004, Sediment transport data and related Information for Selected Coarse-Bed Streams and Rivers in Idaho, USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR 131, 26 p.

Laronne, J.B., Alexandrov, Y, Bergman, N, Cohen, H., Garcia, C., Habersack, H., Powell, D.M., and Reid, I., 2003, The continuous monitoring of bed load flux in various fluvial environments, in J. Bogen, T. Fergus and D.E. Walling, eds., Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS-Publication No. 283, pp. 134-145.

Lisle, T.E., 1989, Sediment transport and resulting deposition in spawning gravels, north coastal California: Water Resources Research v. 25, pp. 1303-1319.

McMannis, W.J., and Chadwick, R.A., 1964, Geology of the Garnet Mountain quadrangle, Gallatin County, Montana, Montana Bureau of Mines and Geology, Bulletin 43, Butte, MT., 47 p.

Mizuyama, T., Fujita, M., and Nonaka, M., 2003, Measurement of bedload with the use of hydrophones in mountain torrents, in J. Bogen, T. Fergus and D.E. Walling, eds., Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, IAHS-Publication No. 283, pp. 222-227.

Monahan, S., and O'Rourke, E., 1982, An analysis of the variables influencing the measurements of coarse bedload movement at Squaw Creek, Independent Study report submitted to Prof. Custer, Montana State University.

Oldfield, F., Thompson, R., and Dickson, D.P.E., 1981, Artificial magnetic enhancement of stream bedload: a hydrological application of superparamagnetism: Physics of the Earth and Planetary Interiors v. 26, pp. 107-124.

Reid, I., Brayshaw, A.C., and Frostick, L.E, 1984, An electromagnetic device for the automatic detection of bedload motion and its final application: Sedimentology v. 31, pp. 269-276.

Reid, I., Frostick, L.E., and Layman, J.T., 1985, The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels: Earth Surface Processes and Landforms v. 10, pp. 33-44.

Rickenmann, D., 1994, Bedload transport and discharge in the Erlenbach stream, in P. Ergenzinger and K.-H. Schmidt, eds., Dynamics and Geomorphology of Mountain Rivers: Lecture Notes in Earth Sciences v. 52, pp. 53-66, Springer Verlag, Berlin.

Ryan S.E., Porth, L.S., and Troendle, C.A., 2005, Coarse sediment transport in mountain streams in Colorado and Wyoming, USA: Earth Surface Processes and Landforms v. 30, p. 269–288. DOI: 10.1002/esp.1128

Schlatte, H., 1984, Anwendung einer akustischen Geschiebemeßmethode an der Möll [Application of an acoustic method to measure bedload transport at the river Möll], in Beitrag zur XII. Konferenz der Donauländer über hydrologische Vorhersagen, Bratislava, pp. 4-5.1 - 4-5.9.

Spieker, R., 1988, Entwicklung, Aufbau und Geländeerprobung einer Meßeinrichtunzur Registrierung von Reisegeschwindigkeit und Korngröße natürlicher Grobgeschiebe während der Transportphase

[Development, construction and field testing of a measuring device to register transport velocities and grain sizes of natural coarse bedload during transport], M.S. Thesis submitted to the Dept. of Physical Geography at the Freie Universität Berlin, Germany.

Spieker, R., and Ergenzinger, P., 1990, New developments in measuring bedload by the magnetic tracer technique, in Erosion, Transport and Deposition Processes, IAHS Publ. no. 189, pp. 171-180.

Tunnicliffe, J., Gottesfeld, A.S., and Mohamed, M., 2000, High resolution measurement of bedload transport: Hydrological Processes, v. 14, pp. 2631-2643.