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Predicting spawning bed erosion and longevity: a case study in tributaries to river Vindelälven, northern Sweden

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Erosion och livslängd på lekbottnar: en fallstudie i biflöden till Vindelälven, norra Sverige

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ABSTRACT

Timber floating operations in Scandinavia during the 19th and 20th centuries has contributed to severe negative impacts on riverine ecosystems. Increase in water velocity and lack of stream bed heterogeneity as a result of stream channelization lead to increased bed load transport. Since availability and recruitment of new suitable spawning substrate in Scandinavian watercourses is sparse, spawning habitats for salmonids has become a scarce commodity. Lately, increasingly more attention has been given to the recreation and improvement of brown trout (Salmo trutta) spawning habitats in restoration projects. While much of the research on spawning habitat has been focused on evaluation of the influence that the constructed spawning grounds have on fish populations, few studies have been conducted to evaluate the persistence of these constructions over time.

I evaluate erosion of constructed spawning beds as an effect of sediment transport attributable to water discharge. Two easily applicable sediment transport prediction models are applied to spawning beds in restored tributaries to river Vindelälven. I evaluate these as a method to determine suitable locations for construction of spawning beds. I also evaluate erosion of constructed spawning beds attributable to spawning activities by female brown trout by deploying PIT-tag marked pebbles over spawning beds in tributaries to River Vindelälven and use received data to develop a model describing the erosion process.

Analyses of erosion attributed to water flow suggest that both models tested in the study needs refinement to be reliable for prediction of erosion in the water systems investigated in this study. The results highlight the complexity of near-bed shear stress and water velocity.

The evaluation of spawning bed erosion attributed to spawning activity suggests that there is a spatial heterogeneity in erosion probabilities over a spawning bed. Erosion differed in magnitude between central-, downstream- and upstream sections, though no difference in movement between pebbles deployed along the edges of the bed compared to pebbles deployed in the middle of the stream could be proven. A longevity model, based only on the bed erosion caused by female digging activity, suggests that a spawning bed have a lifespan in the range of 13 to 35 years, depending on gravel depth.

The prediction tools developed in this study can offer guidance for fisheries managers and significantly improve and facilitate restoration efforts, provided the user of the models understand their limitations. I give suggestions for improved data collection approaches and bring forth alternative methodologies.

SAMMANFATTNING

Timmerflottningsverksamheten under 1800- och 1900-talet förde med sig förödande konsekvenser för ekosystem i rinnande vatten i scandinavien. Rensning av block och stenar resulterade i ökade vattenhastigheter och en omfattande sedimenttransport. Då tillgång och rekrytering av grus i lämplig storlek för fisklek i scandinaviska vattendrag är låg, har lekområden för laxfiskar blivit en bristvara. Under senare år har allt mer uppmärksamhet riktats mot återuppbyggnad och förbättring av lekområden för öring (Salmo trutta) inom restaureringproject i Sverige. Medan stor del av forskning kring lekområden har haft fokus på hur restaurerade lekbottnar påverkar fiskpopulationer, få studier har utvärderat hållbarheten av dessa konstruktioner över tid.

Här utvärderar jag erosion av konstruerade lekbottnar som en effekt av sedimenttransport som kan tillskrivas vattenflöde. Två lättillämpliga prediktionsmodeller för sedimenttransport är applicerade på lekbottnar i restaurerade biflöden till Vindelälven. Jag utvärderar dessa som en metod att för bestämma lämpliga lokaler att konstruera lekbottnar på. Jag utvärderar även erosion av konstruerade lekbottnar som en effekt av sedimenttransport som med kan tillskrivas lekaktivitet av öringhonor, genom att placera ut lekgrus försedda med PIT-märkning över lekbottnar i biflöden till Vindelälven och använder erhållen data för att utveckla en modell som beskriver erosionsprocessen.

Analyser av erosion som kan tillskrivas vattenflöden tyder på att modellerna behöver justeringar för att prediktera erosion i vattensystem utvärderade i den här studien på ett tillförlitligt sätt. Resultat i den här delstudien belyser komplexiteten av vattenflöden och skjuvspänning på botten av rinnande vattendrag.

Utvärdering av erosion på lekbottnar som kan tillskrivas lekande öring tyder på att det finns en rumslig heterogenitet i sannolikheten för erosion över en lekbotten. Storleksorningen på erosion skillde mellan centrala- uppströms- och nedströms delar av lekbottnar, men det kunde inte påvisas någon kanteffekt.

En livslängdsmodell baserad enbart på bädderosion som följd av öringhonors lekaktivitet visar att en lekbotten har en livslängd på mellan 13 och 35 år, beroende på initiellt djup på lekgruset minsta medeldjup på lekgrus i de centrala delarna av lekbottnen som en öring behöver för att kunna leka.

Genom att använda och tillämpa mina prediktionsverktyg med försiktighet och genom att förstå deras begränsningar kan de ge vägledning för fiskeriförvaltare och därmed underlätta och förbättra restaureringsåtgärder. Jag ger förslag på förbättringar i metodik för datainsamling och för fram alternative metoder för datainsamling.

INTRODUCTION

Native populations of salmonids all over the world have declined due to human impacts on riverine ecosystems. The four most important factors for the decline in stocks are believed to be overfishing, migratory barriers, aquaculture impacts and reduction in habitat (WWF 2001; Montgomery 2003). In Scandinavia, timber floating operations has specifically contributed to loss of habitat (Nilsson 2007).

History and negative impacts of timber floating

During the 19th and 20th centuries a majority of Swedish watercourses were channelized to facilitate timber floating (Östlund 2000; Törnlund and Östlund 2002; Ahlbäck and Albertsson 2006). The channelization had great negative impacts on the riverine ecosystem (Poff et al. 1997; Nilsson 2007). Increase in water velocity and the lack of impounding structures following the stream channelization lead to spawning gravel being flushed downstream, often ending up in less suitable spawning environments (i.e. calm, deep sections of a river) (Poff et al. 1997; Nilsson et al 2007; Palm et al. 2007). As the importance of timber floating decreased (Embertsén 2000; Ahlbäck and Albertsson 2006) and with an increased understanding of the importance of heterogeneity in streams (Cooper et al. 1997; Brown 2003), numerous river and stream restoration projects have been undertaken the last three decades, often with focus on the rehabilitation of salmonid populations (e.g. Näslund 1989; Palm et al. 2007; Palm et al. 2009).

Restoration of spawning habitats

Availability of suitable spawning habitats seems to limit salmonid populations in many streams (Allen 1969; Palm et al. 2007; Sear et al. 2008). Thus in recent years increasingly more attention has been given to the recreation and improvement of salmonid spawning habitats (Nilsson et al. 2005; Nilsson 2007). While much of the research on spawning habitat has been focused on evaluation of the influence that the constructed spawning habitat have on fish populations (e.g. Palm et al. 2006; Palm et al. 2007; Svensson 2012), relatively few studies have been done to evaluate the persistence of these constructions over time. Although initial studies suggests positive effects of reconstructed spawning beds on trout populations (Palm 2007; Palm et al. 2007), such effects may decline over time as the spawning bed erodes. Construction of spawning beds is often a work intensive and expensive restoration action (Roni et al 2002). Commonly, river restoration projects are on a limited budget, and have to prioritize between different restoration actions based on a cost-benefit analysis. By not knowing the longevity of restoration measures, it will be difficult to make such priorities.

Transport of spawning substrate in streams primarily is a result of high water velocities during flood events (Kondolf et al. 1996; Gottesfeld et al. 2004; Macdonald et al. 2010) and spawning activities of salmon and trout females (Gottesfeld et al. 2004; Hassan et al. 2008; Macdonald et al. 2010). By excavating spawning redds, salmonids move sediment downstream and change the spawning bed morphology and physical conditions (Montgomery et al. 1996; Gottesfeld et al. 2004; Gottesfeld et al. 2008). In small stream with a sufficient amount of spawners they contribute to gravel transport to a great extent. Several case studies have concluded sediment transport attributable to spawning fish to be comparable with, or even greater than, sediment transport attributable to snowmelt flood events (Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008).

In this paper, hydrological and biological factors which influence persistence of constructed spawning beds in tributaries to River Vindelälven are considered. Erosion as a result of the snowmelt flood during the spring of 2012 and of spawning activity of female brown trout (*Salmo trutta)* during the fall of 2012 is evaluated and predictions of sediment movement and bed longevity are modeled in two separate case studies.

Study 1: Erosion due to water discharge

A variety of formulae are available to predict bed load transport in gravel bed rivers (Gomez and Church 1989; Martin 2003). The common aim for all these formula is to model the relationship between various environmental variables and gravel bed erosion. The majority of gravel bed erosion models have not been developed for river restoration per se, but rather to be used for various engineering purposes. Thus, many of the models available today are parameter intensive, requiring a lot of data on many different variables to predict erosion probabilities. However, since fisheries restoration projects commonly are on a limited budget regarding time and funding it is important to achieve bed load transport predictions using simple and easy applicable models. For the models to be easily applicable, they need to require few input parameters. Although such simple models are quick and easy to apply in the field (i.e. few variables to measure), they risk to produce poor predictions due to sparse input data. This study aim to evaluate the prediction accuracy of two simple gravel bed erosion models to see whether these models could function as an easily applicable method for fisheries managers to determine suitable locations for constructing spawning beds in small streams. The first method is to compare shear stresses on stream beds to the critical shear stress for entrainment of specified gravel grain sizes (NRCS 2007a). The second method is to compare water velocities to critical water velocities for entrainment of specified gravel grain sizes (NRCS 2007b). Usage of these models has been proposed for planning and designing restoration actions (Kondolf et al. 1996; Wheaton et al. 2004), though no evaluations of the practical accuracy of predictions made with these models have been done on spawning beds in natural streams.

It is unlikely that these sediment entrainment models will give completely accurate predictions of erosion due to the great spatial and temporal variability of streams and substrate properties and the stochastic nature of climate events, which are not included in the calculations.

Study 2: Erosion due to trout digging activity

Spawning bed erosion can be measured by using tracer gravels to determine grain entrainment rates and gravel displacement lengths (Gottesfeld et al. 2004; Carré et al. 2007; Gottesfeld et al. 2008; Hassan et al. 2008). The tracer gravels are well suited to evaluate the spatial and temporal variability of erosion in streams and the stochastic nature of climate events (Wilcock 1997). In this study, to evaluate the erosion and predict longevity of constructed spawning beds attributable to female trout spawning activity, individual clasts of spawning substrate were equipped with passive integrated transponder (PIT) tags. This way each marked clast received its own identification signal and their movement could be traced and modeled. Although dispersion of spawning substrate by salmonid spawning activities previously has been described with similar methods (Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008), no study has used this data to test the spatial heterogeneity in erosion over a constructed spawning bed. Neither has the data previously been used to predict the longevity of spawning beds.

The objectives of this study was (1) to evaluate erosion of constructed spawning as an effect of sediment transport attributable to water discharge and to apply two sediment transport prediction models to spawning beds in restored tributaries to river Vindelälven, this to evaluate these as a method to determine suitable locations for construction of spawning beds and (2) to evaluate erosion of constructed spawning beds attributable to spawning activities by brown trout by deploying PIT-tag marked pebbles over spawning beds, and to use received data to develop a model describing this process. The report discusses the findings of this study and its applicability to fishery managers.

MATERIAL AND METHODS

Study area

This study was conducted in tributaries to the Nature-2000 catchment of River Vindelälven. The river arises in Scandinavian mountain range and flows in a south-easterly direction through Västerbotten County and ends up joining river Umeälven approximately 42 km upstream where river Umeälven drains into the Gulf of Bothnia on the east coast of Sweden, adjacent to the city of Umeå.

The water flow in Vindelälven follows a snowmelt-dominated flow regime. The maximum discharge occurs in June during snowmelt and is measured up to approximately 1000 m^3/s. Average flow throughout the year is 180 m^3/s and minimum is 40 m^3/s. The composition of fish species consists mainly of Atlantic salmon (Salmo salar), brown trout (Salmo trutta), European grayling (Thymallus thymallus), northern pike (Esox lucius), Eurasian perch (Perca fluviatilis), Euroasian minnow (Phoxinus phoxinus) and burbot (Lota lota).

The study is based on two different sub studies. Study 1 (Erosion of spawning beds caused by water flow) was carried out in 8 different tributaries to river Vindelälven in Västerbotten County; Abmobäcken, Beukabäcken, Falåströmsbäcken, Hjuksån, Mattjokkbäcken, Mösupbäcken, Olsbäcken and Rågobäcken (Figure 1). Study 2 (Erosion of spawning beds caused by spawning activity) was carried out in Storkvarnbäcken (Figure 1), also a tributary to river Vindelälven. All tributaries host resident brown trout. Storkvarnbäcken serves as spawning area for lake dwelling trout that spawn downstream of lake Storsandsjön. The body mass of the lake dwelling spawning females range between 1-5 kg. All tributaries are surrounded by cultivated boreal coniferous forests, dominated by Scots pine (Pinus sylvestris) and Norwegian Spruce (Picea abies). The riparian zones consist essentially of deciduous trees such as birch (Betula spp.), grey alder (Alnus incana) and willow (Salix spp.).

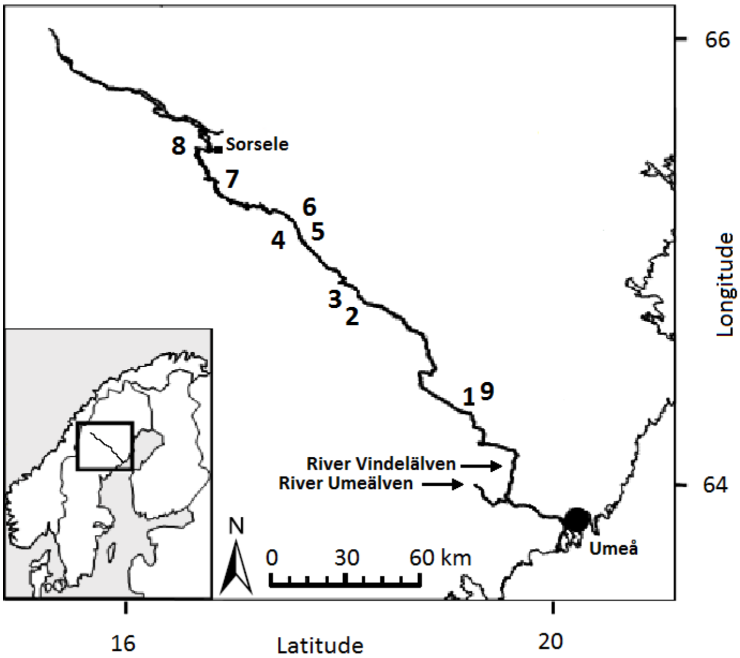

Figure 1. Map showing the location of River Vindelälven and tributaries in which the study took place. The numbers, 1-9, refers to the tributaries Hjuksån (1), Falåströmsbäcken (2), Mösupbäcken (3), Rågobäcken (4), Mattjokkbäcken (5), Beukabäcken (6), Abmobäcken (7), Olsbäcken (8), Storkvarnbäcken (9).

Spawning bed construction

All studied spawning beds were constructed during summer and fall of 2011, thus had at the time of fieldwork for this study only experienced one snowmelt flood.

The spawning beds were constructed by placing boulders in horseshoe like shape (Figure 2). Externally acquired gravel in the size range of 1 to 5 cm in diameter was dispersed over the stream bed between the boulders, over an area of approximately 2X5 meters. The function of the boulders is to prevent gravel from dispersal downstream and increase the current velocity and hyporheic flow through the gravel. Spawning mainly occurs in between the larger boulders located at the downstream end of the spawning bed (Svensson 2012).

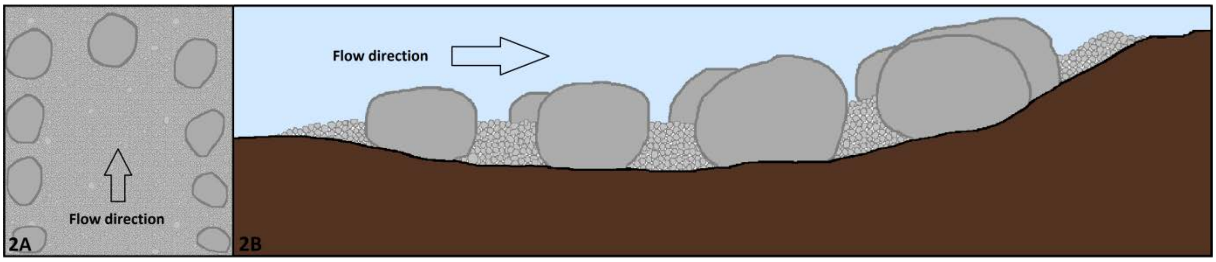

Figure 2. Illustration of a reconstructed spawning bed. 2A illustrates the bed from above. 2B illustrates the bed from the side.

Study 1: Erosion of spawning beds caused by water flow

To evaluate prediction of erosion caused by water flow two hydraulic models were tested.

Model 1

In a first attempt to predict erosion on spawning beds in this study, the allowable shear stress approach (NRCS 2007a) was used. In this approach applied shear stress (the force of which the water act on the bed material in the downstream direction - τ_0) is compared to the critical shear stress (the shear stress of which particles on the spawning beds with a specific D_{50} are set in motion - τ_c). To obtain the applied shear stress of the streams in this study the following equation was used (NRCS 2007a):

$$\tau_0 = \gamma_w RS$$

Here, τ_0 is in N/m^2, γ_w is specific weight of water (N/m^3), R is hydraulic radius (m) and S is the energy slope, dimensionless. S was measured at each reach where spawning beds were constructed using a laser clinometer (Vertex Laser L402, Haglöf Sweden AB). R was calculated using this formula describing the radius of a parable formed channel (Kling, J. pers. com. 2012):

$$R = \frac{(W^2 \times D)}{(1{,}5 \times W^2) + (4 \times D^2)}$$

Where W is stream width and D is stream depth, both in meters.
To obtain the critical shear stress of which particles on the spawning beds are set in motion this equation was used (NRCS 2007a):

$$\tau_c = \tau_c^*(\gamma_s - \gamma_w)D_{50}$$

Here τ_c is in N/m^2, D_{50} is the median spawning bed substrate diameter (m), γ_s is specific weight of the bed material (N/m^3). τ_c^* is the dimensionless critical shear stress (or Shields parameter). The commonly used Shields curve (Shields 1936) was applied in my study to provide τ_c^* -values for spawning substrate on beds which ranged from 0,057 for particles on the bed with the smallest median pebble diameter, to 0,058 for particles on the bed with the largest median pebble diameter.

Shields curve is expressed as the following equation (NRCS 2007a):

$$\tau_c^* = 0{,}22\,\beta + 0{,}06 \times 10^{-7{,}7\beta}$$

$$\beta = \left(\frac{1}{v}\sqrt{\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right) \times gD_{50}^3}\right)^{-0{,}6}$$

where v is kinematic viscosity of water (m^2/s) and g is the acceleration due to gravity (m/s^2). The median spawning bed substrate diameter D_{50} was obtained by measuring the b-axes (Figure 3) of 30 random pebbles at each bed.

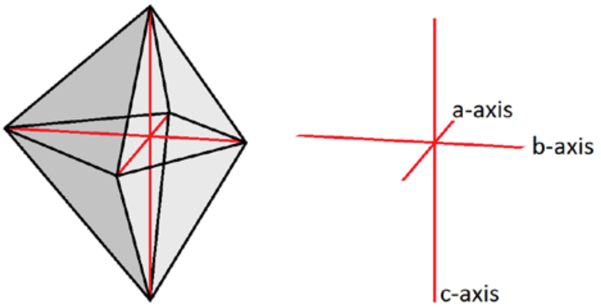

Figure 3. Illustrates the three axes of a pebble. The c-axis is the longest of the three, the a-axis is the shortest and the b-axis is the axis of a pebble with intermediate length.

Analyses

To evaluate the erosion predictions the computed erosion was compared to actual erosion. Actual erosion was determined by observations at the end of the study. The definition of an eroded bed was a bed which was determined to no longer be functional for spawning by brown trout due to absence of spawning substrate. If the prediction did not coincide with the true observation the model was considered to fail.

Model 2

In a second attempt to predict erosion on spawning beds in this study, the Isbash method (NRCS 2007b) was used. In this method near-bed water velocity (V_c) is compared to the critical near-bed water velocity (the water velocity of which particles on the spawning beds with a specific D_{50} are set in motion - V_c). To obtain the critical water velocity of streams in this study the following equation was used (NRCS 2007b):

$$V_c = \left(C \sqrt{\left(2g * \left(\frac{\gamma_s - \gamma}{\gamma}\right)\right)} \times \sqrt{D_{50}} \right)$$

Here V_c is in m/s, C is the Isbash constant, which range from 0,86 for high turbulence level flow to 1,2 for low turbulence level flow (here 0,86 was used) D_{50} was calculated according to the same method as mentioned above.

True near-bed water velocity (m/s) was measured at a depth of 92 % of total depth using an electromagnetic flow meter (Valeport 801, Townstal Industrial Estate). Water velocity was measured at 1-3 spots, depending on bed size, on each spawning bed at a minimum of three different discharge levels between the fall of 2011 and 2012. The flow meter recorded one velocity value per second for 10 seconds, from which a mean was achieved. Data loggers were deployed in all reaches were spawning beds had been constructed to continuously record air and water pressure throughout the study. By combining air and water pressure data with water velocity data from each spawning bed at different discharge levels, a “Discharge level/ True water velocity” model was generated for each spawning bed. By calculating if the true water velocity exceeded the critical water velocity at any 24 hours period predictions of erosion for each spawning bed, were made. If the critical water velocity was exceeded at least one 24 hour period the spawning bed was assumed to be eroded. Discharge (m^3/s) was measured by using an Acoustic Doppler Current Profiler (StreamPro ADCP, Teledyne RD Instrument). By combining air and water pressure data with water discharge data from each tributary at different discharge levels, discharges for every 24 hour period throughout the study were estimated.

Analyses

To evaluate the erosion predictions the computed erosion was compared to actual erosion. Actual erosion was determined by observations at the end of the study. The definition of an eroded bed was a bed which was determined to be no longer functional for spawning by brown trout due to absence of spawning substrate. If the prediction did not coincide with the true observation the model was considered to fail.

Study 2: Erosion of spawning beds caused by spawning activity

In order to measure the substrate transport, attributed to trout spawning activities, pebbles were equipped with passive integrated transponder (PIT) tags and deployed on spawning beds in Storkvarnbäcken, Västerbotten County. The b-axes (Figure 3) of 30 pebbles from each bed were measured in order to get the median diameter (D_{50}) of spawning substrate, all pebbles pooled. Pebbles which were in the range ±5 mm of the median diameter in all axes were then selected. Thus, the largest and the smallest gravel did not differ with more than 10 mm in any of the three axes (Figure 3). An angle grinder was used to make a slot in each pebble, in where a ⌀ 4mm x 23 mm half-duplex PIT-tag (Texas instrument) was placed (Figure 4). Epoxy glue was used to fixate the PIT tags. White dots were painted on two sides of each pebble for better visual detectability under water. In late September 2012 (approx. two weeks before spawning), 373 PIT-tag equipped pebbles were deployed over 5 different spawning beds in grids with spacing of approximately 60 cm in the flow direction and 30 cm perpendicular to the current direction (Figure 4). Each pebble was given a gentle push into the gravel bed in order to get them in level with surrounding pebbles, to avoid the risk of the deployed pebbles to lie on top of the gravel mixture, thus be more prone to move than native top layer pebbles.

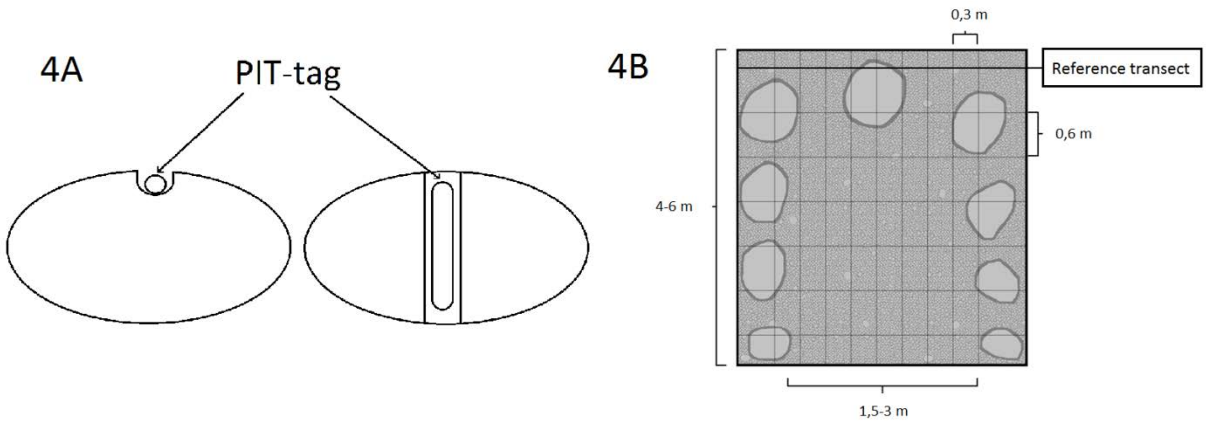

Figure 4. Pebble equipped with a ⌀ 4mm x 23 mm half-duplex PIT-tag (A) and illustration of a spawning bed with a grid (B). Pebbles where placed in each available intersect. No pebbles where placed onto a boulder.

The position and identity of each pebble were noted. In late October (approx. two weeks after the spawning period), the position of each pebble were again observed, by scanning the beds with a stick reader (RS320, Allflex). The stick reader was capable of reading the transponders at a minimum of 30 cm, 360º in radial and axial planes with respect to the end of reader enclosure. The position of marked pebbles was measured as the distances to a perpendicular reference transect downstream the spawning beds, using a laser distance meter (LDM-100, CEM-Industry CO.) with 1 mm as the smallest unit displayed and an accuracy of ±1,5 mm. The laser distance meter was mounted onto a stick equipped with two spirit levels to keep it vertical to the ground. Most PIT-tagged pebbles could be located by sight and on these occasions the laser meter stick was placed on top of the pebbles while distance to the reference transect was measured. When pebbles were buried and could not be located by sight, although detected by the stick reader, distance to the reference transect was estimated. Maximum possible error in this estimation was 30 cm, although most likely a lot less since the position of the pebble was triangulated with the reader. For each perpendicular transect, average near-bed water velocity was measured at two depths (at 92 % and 85 % of total depth). Two depths were decided to be measured to cover the magnitude of vertical movement of pebbles when being flicked by fish. Velocity was measured by using a Valeport 801 velocity meter. All five spawning beds were constructed with an inclined plane where water depth at the most upstream transects were in general 2,8 greater than at the most downstream transects and there was in general a strong negative correlation (R^2= -0,59) between depth and water velocity over beds. Discharge was 0,87 m^3/s at the time for measurement (approximately two weeks prior to spawning) and the loggers showed no significant fluctuations during the spawning period.

Analyses: Spatial heterogeneity in erosion

Observations during spawning suggested that trout utilized the central sections of a bed more than the outer perimeters, and hence that the spawning bed material mobility caused by spawning would differ in magnitude spatially over a spawning bed. In order to investigate spatial heterogeneity in erosion over a spawning bed, difference in movement between pebbles deployed along the edges of the bed compared to pebbles deployed in the middle of the stream was tested. Two tests were made, 1) difference between the middle section and the edge sections parallel to the direction of the stream current (edges) and 2) difference between the central section and the upstream or downstream-sections of the beds (ends). The parallel sections had a width of 30 cm on either side of the bed, whereas the upstream/downstream section each had a depth of 60 cm (Figure 5). Each bed was used as a replicate in the analysis. As the absolute distance in average pebble movement differed between the beds, it was necessary to standardize the movement data (subtracting the bed average from each observation and dividing by the standard deviation) for every bed, so that each of the five beds would contribute equally in subsequent analysis. Normal distribution of the standardized dataset was concluded by visual inspection of the data when plotted using a histogram. To avoid pseudo replication, mixed models were used in where "bed" was treated as a random factor (i.e. correcting for observational dependence within spawning bed). The two models were specified as follows:

Model 1 (the effect of bed "edge" on erosion probability):
Standardized movement ~ edges (a factor with two levels; middle and edge), random = bed.

Model 2 (the effect of bed "ends" on erosion probability):
Standardized movement ~ ends (a factor with three levels; middle, upstream, downstream), random = bed.

For model 2, there were big differences in variance between the three levels of the factor (i.e. heteroscedasticity). To account for this, a variance structure was added to the model that allowed for different spread among levels.

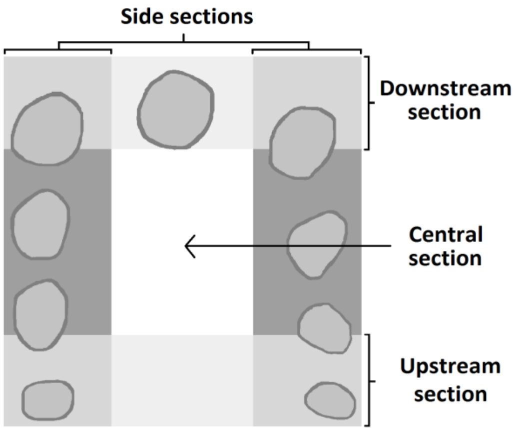

Figure 5. Two tests were made to test for spatial heterogeneity in erosion, 1) difference between the middle section and the edge sections parallel to the direction of the stream current (edges) and 2) difference between the central section and the upstream or downstream-sections of the beds (ends).

Longevity model

To describe the process of erosion on and to estimate the lifetime of a spawning bed as a result of female trout spawning activity, a longevity model was constructed. The model was based on a hypothetic spawning bed with a size that corresponds to the average dimensions of the five studied spawning beds (bed dimension: 410 cm long, 350 cm wide). From the PIT-tag data I could calculate the proportion of PIT-tagged pebbles that had moved certain distances. For example, if six out of ten pebbles in a transect had moved after spawning, 60% of the pebbles of that transect were considered to have eroded. As I also knew the distance each pebble had traveled, I could calculate the probabilities of a pebble to move certain distances, based on where on the bed the pebble was located (see table X). Given the dimensions of the bed, the size of the pebbles, and the depth of the gravel bed, I could derive the number of pebbles that was contained within a bed, including the number of pebbles in the top layer (the layer of the bed that was under erosion). By combining data on probabilities of movement with the number of pebbles exposed in the top layer I could construct a model that would describe the erosion process over time, given that the same erosion dynamic were to be repeated every year. Below follow a more detailed description of how the model was constructed.

Detailed description

The model was based on the probability and distances of downstream movement for pebbles in a bed. Since there was a varying number of transects and pebbles deployed over each bed the model could not be based on the probabilities and distances of movement for neither each pebble location nor each transect location for all beds. Therefore a bed was divided in the sections, and an average of probabilities and distances of movement for all pebbles located within a section was used. The bed was divided into three sections (upstream = 60 cm, central = 290 cm, downstream = 60 cm). This since the spatial heterogeneity in the erosion test (described above) showed differences of pebble movement distances between upstream, central and downstream bed sections, and the assumption was made that also probabilities of movement followed a similar pattern. The model hence accounted for that the proportion of the top layer pebbles that moved downstream, as well as the distance they traveled, differed between sections. All pebbles within a section had the same average movement probability and average distance of movement.

The hypothetic spawning bed was then divided into rectangular prisms, so that the entire bed consisted of a number of prisms standing side by side, their long side facing the flow direction (Figure 6). Thus, the length of the prisms was the same as the width of the entire spawning bed (3,5 m) and their height was the same as the depth of the bed (for example 15 cm). Their width was set to 5 cm, since that was the shortest range of motion that was considered measurable with accuracy (i.e. pebbles that have moved 5 cm or less were not considered to have moved at all). By estimating bed material porosity to 30 % (Porosity for gravel and sand mixtures range between 20-35 % (Fetter 1994) and 30 % was assumed to be a reasonably estimate for gravel beds) and by knowing the median diameter of spawning gravel (31 mm), the amount of pebbles within each prism was calculated, as well as the number of pebbles at the top layer of each prism. After dividing the hypothetic bed up into 82 prisms (or movement distance intervals), each 5 cm wide, the frequency of pebbles that moved a specific distance (a distance within a certain interval) was calculated, thus how many pebbles from the top layer of each prism would travel a certain distance (within a certain interval) and end up in each downstream prism (or distance intervals) or leave the bed altogether, during one spawning period (i.e. every year) was calculated. Every year, a prism would hence give away a certain amount of pebbles through erosion (based on in what section the prism was located), and also receive a certain amount of pebbles from prisms upstream. The number of pebbles a prism would receive depended not only on in what section the prism was located, but also on the position of the prism within that section. For example, the prism located at the uppermost position of the upstream section would never receive new pebbles, as it did not have any prisms upstream. Similarly, a prism located at the most downstream position in the downstream section would continue to receive pebbles for a very long time, as all other prisms in the bed were located upstream. Based on a probability matrix of pebble movement and prism location, the longevity model hence distributed the eroded pebbles across the prisms. The model then repeated this several times, each time equals one year.

The amount of pebbles in the middle section was considered being the critical variable in bed longevity, since this was where most of the spawning activity occurred (according to the spatial heterogeneity in erosion test). By providing the model with different magnitudes of initial bed depth (i.e. depth at the start of erosion) and average middle section depth which could be considered a minimum for a bed to be utilized for spawning (i.e the depth when the bed no longer could be used for spawning), a range of predicted longevities, depending on chosen attributes, could be achieved. Here I test the model with two different initial bed depths; 15 and 20 cm combined with with two different minimum depths for a bed to be utilized for spawning; 10 and 5 cm. To illustrate how erosion changed the morphology and structure of a bed over time, a 3D rendition was made in which erosion was simulated during 30 years. All analysis, plotting and animation were made in the statistical program R, and Microsoft excel.

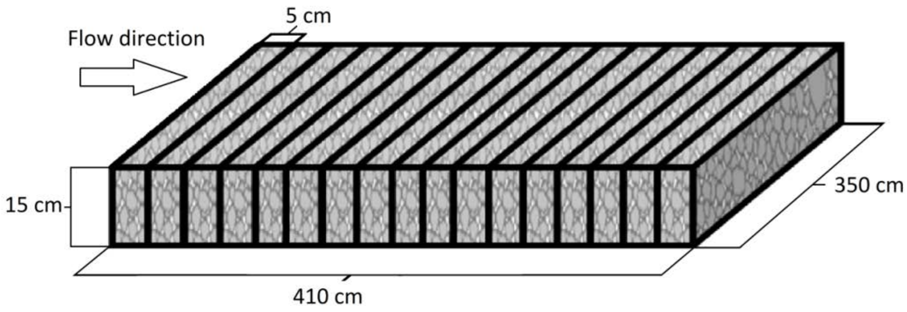

Figure 6. The figure illustrates a hypothetic spawning bed divided in to rectangular prisms, which was used to construct a model predicting longevity of this specific bed. Each spawning period, a proportion of the top layer pebbles of each prism leaves and ends up in another prism further downstream or leaves the bed altogether. The figure is not to scale.

Table 1. Example of the proportional distribution of top layer pebbles moving downstream in steps of 5cm (one prism) for each of the three sections of the bed. The table is intended as an example of the data generated by PIT-tag pebbles, and hence only gives data for the first 10 steps. Based on information on probability of downstream movement, as well as the knowledge of the number of pebbles in a bed, a longevity model was constructed to predict the erosion process over time.

	Upstream section	Central section	Downstream section
	(%)	(%)	(%)
5 cm	82,9	40,7	61,1
10 cm	12,2	7,9	2,8
15 cm	2,4	4,0	0,0
20 cm	2,4	2,4	0,0
25 cm	0,0	0,8	0,0
30 cm	0,0	1,6	5,6
35 cm	0,0	1,2	8,3
40 cm	0,0	1,2	8,3
45 cm	0,0	1,2	5,6
50 cm…			

To study the relation between water velocities and travel distance of pebbles, the average water velocities derived from all perpendicular transects on each bed and the average distances travelled by pebbles on respective bed was linearly regressed.

RESULTS

Study 1: Erosion of spawning beds caused by water flow

In intermediate discharge, median midstream depths of study streams ranged from 0,25 m to 0,72 m and average widths range from 11,2 m to 18,8 m. Slopes of study streams ranged from 0,006 m/m to 0,032 m/m and median diameter (D_{50}) of spawning bed substrate ranged between 23,5 and 41 mm. Lowest estimated discharge in any stream during the study period was 0,03 m^3/s and highest discharge estimated in any stream during the study was 25,82 m^3/s

(Table 2). A total number of 32 beds were included in the study. The number of beds that was observed to be eroded was 9, which is 28 % of the total number of studied beds.

Table 2. Width, depth and discharge for study streams. Discharges (Q) was estimated from logger data and ADCP-measurements recorded from 2011-08-27 to 2012-08-27 except discharges in Mösupbäcken which was estimated from logger data and ADCP-measurements recorded from 2011-08-31 to 2012-08-31. All studied spawning beds were constructed during the summer and fall of 2011, thus have during the study only experienced one snowmelt flood. Discharge estimates were not available for Hjuksån.

Tributary	Width (m)	Depth (m)	HQ (m3)	MQ (m3)	LQ (m3)
Abmobäcken	15,15	0,25	4,40	0,90	0,15
Beukabäcken	11,22	0,43	3,70	0,73	0,04
Olsbäcken	18,83	0,57	25,82	2,82	0,03
Rågobäcken	11,52	0,43	3,57	0,77	0,13
Falåströmsbäcken	15,79	0,53	5,20	2,06	0,85
Mösupbäcken	11,37	0,48	2,96	1,48	0,56
Hjuksån	16,69	0,72	-	-	-
Mattjokkbäcken	11,79	0,49	4,70	2,06	0,56

HQ = Estimated discharge during peak flow
MQ = Estimated discharge during median flow
LQ = Estimated discharge during low flow

Model 1

25 out of 30 beds were computed to be exposed to a bed shear stress exceeding the critical bed stress at intermediate discharge levels (Table 3). 14 beds (47 %) had a prediction of erosion that coincided with observed erosion. Out of 25 predicted erosions, 9 beds was observed to be eroded, thus the degree of explanation when predicting erosion with this model was 36 %.

Model 2

The percentage of days (24 hours) where true water velocity could not be estimated due to lack of field measurements ranged between 2 and 20% of the total study period. Two out of 32 beds were computed to be exposed to water velocities greater than their critical velocities at least at seventeen 24hour periods during the study (Table 3). 23 beds (72 %) had a prediction of erosion that coincided with observed erosion. Out of 9 observed erosions only 1 (11 %) could be predicted with the model. In addition, erosion was predicted on one bed where no erosion was observed.

Table 3. Data achieved from water velocity measurements and calculations of critical water velocities, bed shear stresses and critical shear stresses.

Serial Nr.	Tributary	Bed ID	τ_0	τ_c	$\tau_0 > \tau_c$	V_c	Days $V > V_c$	Days $V < V_c$	Days $V_{n/a}$	Days tot.	$V > V_c$	Erosion
1	Abmobäcken	1	46,2	31,4	Yes	0,89	0	378	14	392	No	No
2	Abmobäcken	2	46,2	26,8	Yes	0,83	0	378	14	392	No	Yes
3	Abmobäcken	3	46,2	31,9	Yes	0,90	0	378	14	392	No	No
4	Abmobäcken	4	46,2	29,8	Yes	0,87	0	378	14	392	No	No
5	Beukabäcken	3	34,8	35,5	No	0,95	0	362	21	383	No	No
6	Beukabäcken	5	34,8	32,9	Yes	0,92	0	362	21	383	No	No
7	Beukabäcken	6	34,8	26,8	Yes	0,83	0	362	21	383	No	Yes
8	Beukabäcken	7	17,7	29,8	No	0,87	0	362	21	383	No	No
9	Beukabäcken	8	17,7	26,8	No	0,83	0	362	21	383	No	No
10	Beukabäcken	9	17,7	31,9	No	0,90	0	362	21	383	No	No
11	Beukabäcken	10	17,7	37,5	No	0,98	0	362	21	383	No	No
12	Falåström	1	-	-	-	0,92	0	249	17	266	No	No
13	Falåström	2	-	-	-	0,97	0	249	17	266	No	No
14	Hjuksån	1	64,2	36,0	Yes	0,96	0	148	28	176	No	Yes
15	Hjuksån	2	64,2	41,1	Yes	1,02	0	148	28	176	No	Yes
16	Mattjokkbäcken	1	62,7	26,8	Yes	0,83	0	201	30	231	No	Yes
17	Mattjokkbäcken	3	82,9	30,9	Yes	0,89	0	201	30	231	No	Yes
18	Mattjokkbäcken	4	62,6	37,5	Yes	0,98	30	159	42	231	Yes	Yes
19	Mattjokkbäcken	5	95,3	29,8	Yes	0,87	0	201	30	231	No	Yes
20	Mattjokkbäcken	6	70,3	37,0	Yes	0,97	0	201	30	231	No	No
21	Mösupbäcken	2	39,7	27,3	Yes	0,84	0	206	18	224	No	No
22	Mösupbäcken	3	39,7	30,4	Yes	0,88	0	206	18	224	No	No
23	Mösupbäcken	4	39,7	23,7	Yes	0,78	0	206	18	224	No	No
24	Olsbäcken	1	60,4	35,0	Yes	0,94	0	376	17	393	No	No
25	Olsbäcken	2	43,2	27,8	Yes	0,84	17	368	8	393	Yes	No
26	Olsbäcken	3	43,2	25,7	Yes	0,81	0	376	17	393	No	No
27	Olsbäcken	4	51,1	33,9	Yes	0,93	0	376	17	393	No	No
28	Rågobäcken	3	91,1	29,8	Yes	0,87	0	331	84	415	No	No
29	Rågobäcken	4	91,1	36,0	Yes	0,96	0	331	84	415	No	No
30	Rågobäcken	5	58,8	29,8	Yes	0,87	0	331	84	415	No	Yes
31	Rågobäcken	6	58,8	30,9	Yes	0,89	0	331	84	415	No	No
32	Rågobäcken	7	58,8	35,5	Yes	0,95	0	331	84	415	No	No

Model 1 **Model 2**

τ_0 = Computed bed sheer stress (N/m^2)
τ_c = Computed critical bed sheer stress (N/m^2)
V_c = Computed critical Water velocity (m/s)
Days $V > V_c$ = Number of days the water velocity was estimated to be higher than the critical water velocity
Days $V < V_c$ = Number of days the water velocity was estimated to be lower than the ctitical water velocity
Days $V_{n/a}$ = Number of days we dont have an estimate of the water velocity
Days tot. = Number of days from which we have obtained logger data.
$V > V_c$ = Bed exposed to water velocities higher than computed critical water velocity at some point during the study.
Erosion = Observed erosion

Study 2: Erosion of spawning beds caused by spawning activity

As a result of brown trout spawning activity, 55 % of the PIT-tagged pebbles travelled downstream, 24 percent was not displaced (i.e. pebbles that have moved 5 cm or less were not considered to have moved at all), 8 % of the pebbles travelled upstream and 13 % of the PIT-tagged pebbles could not be found after the spawning period.

There was a spatial heterogeneity in pebble travel distance over spawning beds. Pebbles with the initial location in the center sections moved a significantly further distance compared to pebbles deployed in the downstream and upstream sections of the beds. (Linear mixed effect models: $F_{2,324}$= 63.7, p= <0.001) (Table 4). Pebbles initially located in the upstream sections also moved significantly shorter distances than pebbles located in the downstream sections (Table 4; Tukey Post-hoc tests). No evidence for difference in movement distance between pebbles located along the edges parallel to the direction of the stream current compared to pebbles located in the middle of the stream was found (Linear mixed effect models: $F_{1,325}$= 0.2, p= 0.6520) (Table 4). Models that included pebbles that had been estimated by triangulation produced very similar results as models that excluded estimated pebbles, hence concluding low influence of estimation error on model results. All results were hence based on the full dataset (i.e. including estimated pebbles).

Table 4. Results from the statistical tests.

	F-value	p-value	numDF	denDF	Tukey post-hoc
Side/Middle	0.20	0.6520	1	325	
Up/Down/Centre	63.66	<.0001	2	324	Centre>Down>Up

	Centre	Downstream	
Upstream	z= -11.12 p= < 0.001	z= -3.31 p=	0.003
Centre		z= -5.15 p=	<0.001

Histograms of the movement distribution for all beds showed a distinct trend in the frequency of movement over distance. The major proportion of pebbles moved a distance up to 10 cm. The frequency decreased with increased distance up to about 15 cm. At distances exceeding 15 cm the profiles leveled off, after which no apparent correlation between frequency of pebbles and distance of motion could be found (e.g. see bed #1 in figure 7). The average distance moved in the downstream direction, for all pebbles pooled, was 38,3 cm (pebbles which had moved upstream was included and contributed to a lower mean value. The average of pebbles which had only moved downstream was 48,4 cm). The maximum distance travelled by a pebble was 326 cm.

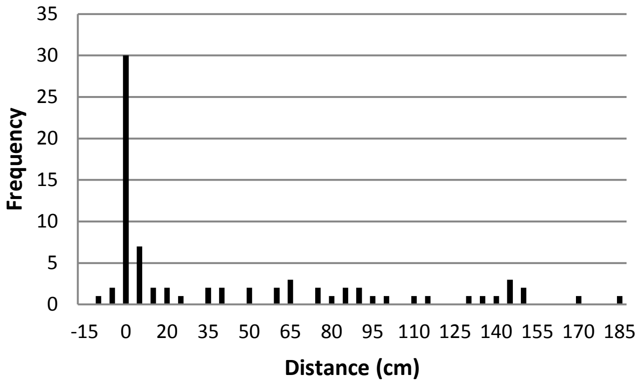

Figure 7. Histogram depicting the frequency of pebbles regarding travel distance. The figure represents data from spawning bed number 1.

There was a big variation in the magnitude and spatial pattern of gravel movement between different spawning beds, as is exemplified in figure 8.

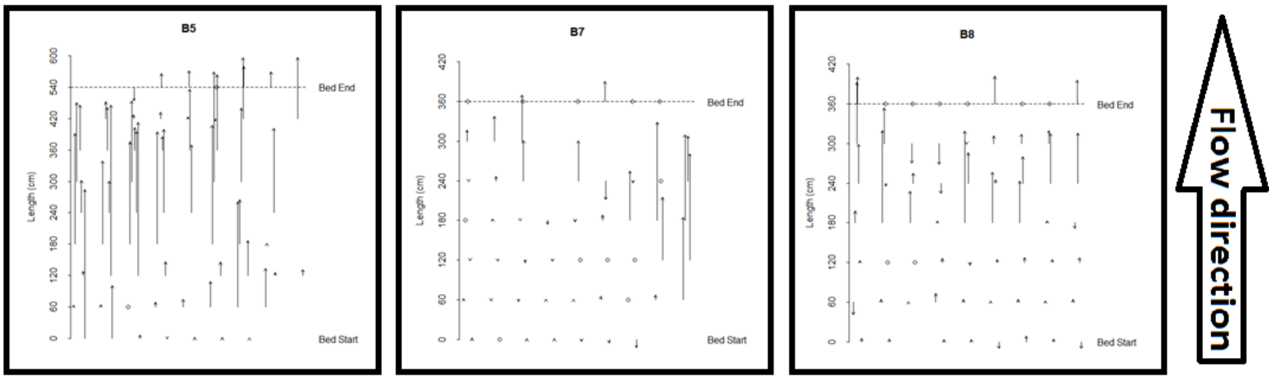

Figure 8. This plot illustrates three spawning beds seen from above, similar to the illustration of a spawning bed in figure 2A, except the graphics. In the illustration the beds lay side by side, though in reality the beds were spread out over the stream reach. The base of the plots illustrates the upstream ends of the beds. The reference transect is the downstream end of the beds. The direction of the water flow goes from the bed start toward the reference transect. Arrows illustrate start and end positions and direction of movement for each unique pebble. Length of arrows represents the distance of motion. Rings represent unmoved pebbles.

There was a weak positive correlation between water velocity over beds and the average distance travelled by pebbles supposedly moved by fish (r^2=0.20) (Figure 9). Though, the correlation was not significant ($F_{1,3}$= 0.73, p= 0.4555).

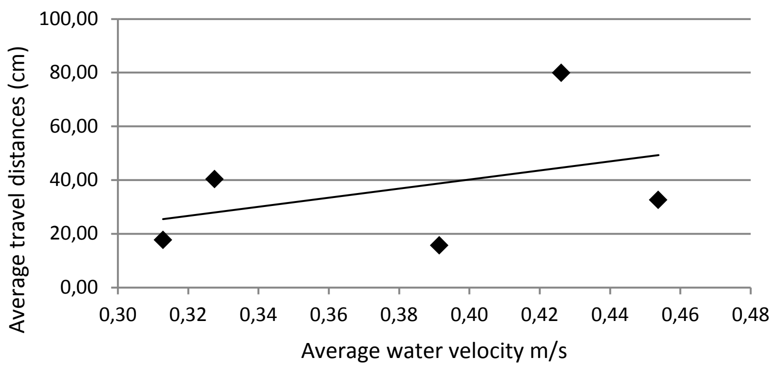

Figure 9. Relationship between water velocity of beds and the average travel distance for pebbles.

The longevity model suggest that a 410 cm long and 350 cm wide spawning bed (i.e. the average dimension of the 5 beds used in this study) with an initial gravel depth of 15 centimeters will have a longevity of 13 years provided that the erosion between bed sections is spatially heterogeneous and that trout will utilize a bed for spawning as long as the prisms in the central bed section have an average gravel depth of at least 10 cm. Under the same conditions but instead assuming that trout will utilize a bed for spawning as long as the prisms in the central section have an average gravel depth of 5 cm, the bed will have a lifespan of 23 years. By changing the initial gravel depth to 20 cm the bed has a longevity of 24 and 35 years provided that the erosion between each bed section is spatially heterogeneous and that trout will utilize a bed for spawning as long as the prisms in the central bed section have an average gravel depth of at least 10 cm and 5 cm respectively. According to the model, the middle section of a bed will be thinned out sooner than the upstream and downstream sections. A 3D rendition of the gradual erosion pattern of a bed over 30 years is illustrated in figure 10, and can be viewed at http://youtu.be/I6c8pSMtCJU. Year 0 the bed is untouched and all sections contain the same amount of gravel. As time goes the middle section is thinned out as the gravel travel downstream, the downstream section is continuously filled with gravel from the middle section, thus is not thinned out in early life stages of the spawning bed. The upstream section is thinned out, though very slowly. Year 30 almost the entire middle section is emptied on gravel except a few pebbles provided from the upstream section (too few to be illustrated in the rendition). The upstream section still contains gravel, while the downstream section is almost completely emptied.

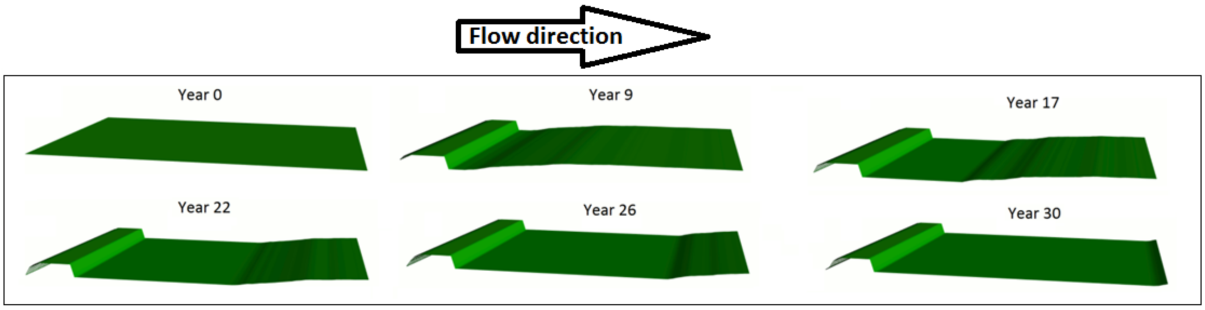

Figure 10. 3D rendition of morphology and structure of a bed over 30 years based on bed dimensions; 410 cm long, 350 cm wide and initial gravel depth 15 cm. The rendition illustrates that according to the longevity model the middle section of a bed will be thinned out sooner than the upstream and downstream sections. The downstream section will be continuously filled with gravel from the middle section, though get thinned out after the middle section is emptied. The upstream section is exposed for the least erosion due to spawning and will be thinned out last of the three sections, provided that the erosion pattern is consistent over the lifespan of the bed.

DISCUSSION

Study 1: Erosion of spawning beds caused by water flow

The analyses reveal shortcomings in methodologies to predict initiation of spawning substrate motion and highlight the complexity of near-bed shear stress and water velocity. I give suggestions for improved data collection approaches and bring forth alternative methodologies.

My conclusions regarding accuracy of the models used to predict erosion caused by water flow need to be tempered with an understanding of a strongly influencing factor. When designing this study I planned to measure water velocities and shear stresses during the snowmelt flood peak, since the mean travel distances of bed load increases exponentially with increasing discharge (e.g. Reid and Frostick 1986; Leopold and Emmett 1997; Emmett 2010). My design though had to be modified due to safety reasons. The water flows during the snowmelt flow peak was too high to allow me to carry out measurements. Consequently, I had to await the discharge to decline enough to safely perform measurements. It has been suggested that as much as 70 to 80 percent of the bedload is transported by that 10 to 20 percent of the annual water budget occurring at highest flows during only a few percent of total time (Emmett 1999). Thus, no water velocity or shear stress data for my study streams was achieved for the period under which the majority of erosion on studied spawning beds supposedly occurred. This obviously has affected the prediction accuracy of the models in a negative way and this I will discuss for each model separately.

The first method that was used to evaluate predictions of erosion of spawning beds in study 1, where shear stress was compared to critical shear stress and Shields curve was used to determine Shields parameter (τ_c^*), turned out to be unreliable (i.e. prediction accuracy was low). Measurements during peak flow would not have given higher prediction accuracy for this model. This since even during intermediate flow my analysis suggest the computed bed shear stress (τ_0) in a majority of study streams were higher than computed critical shear stress (τ_c) of particles on the spawning beds. Most beds should thus have been significantly, if not completely, eroded. This did not coincide with the actual scenario though, since only

28% of the studied streams were significantly eroded. Results from this method indicates two things; the computed τ_0 were overestimated and/or the computed τ_c of bed materials was underestimated.

Overestimation of τ_0-values is likely attributed to channel properties which are not taken into consideration in the equations, such as shape of the channels, topography of streambeds and extent of the occurrence of large woody debris and bed forms, which all contributes to hydraulic roughness (Buffington and Montgomery 1997;1999; Fischenich 2001). The hydraulic roughness complicates calculations and measurement of bed shear stress in natural streams, since it contributes to turbulence and differences in local hydraulic environments (Wohl, 2000). Turbulence can lead to substantial variability in shear stress at different points in streams during a constant discharge (Fischenich 2001) and since data used in my calculations are spatial averages they may not provide good estimates on bed shear stress at certain spawning beds. Large boulders and woody debris may this way lower τ_0 at points and shield smaller substrate from direct impact (Buffington and Montgomery 1999; Fischenich 2001). There are ways to determine effective shear stress or grain shear stress, which is the shear stress available for sediment transport after subtraction of other types of roughness opposing the flow of water (e.g. Einstein 1950; Einstein and Banks 1950; Hey 1979). To do this, additional data is needed and I encourage performing such calculations in future studies to achieve more accurate predictions. Furthermore, slope estimates are spatial averages of the studied stream reaches. The streambed topography may provide slopes at specific points that differ from the average slope estimation. My analysis indicates that more emphasis should be placed on performing measurements at specific points on streambeds instead of using spatial averages. Consequently, the actual bed shear stress may not be high enough to move bed material even though the computed τ_0 exceeds the computed τ_c of the bed material. Others have found (e.g. Kondolf et al. 1987) in similarity to this study, that gravels did not move at the predicted bed shear stresses, because of the non-uniform flow patterns that appear in streams with high abundance of boulders.

Underestimates of τ_c are likely attributed to sediment properties which are not taken into consideration in the equations, such as grain shape and friction angles of the bed material and position of particles in the matrix of surrounding bed material (USACE 1989; Buffington and Montgomery 1997; Fischenich 2001). Shields' equations are developed from uniform bed material (Shields 1936) and are not optimized for bed material comprising mixed gravel sizes like bed material on beds in this study. Within a size mixture larger particles tend to be more prone to move and smaller particles tend to move less readily than in uniform substrates due to bed attributes such as grain protrusion, packing and friction angles (Gordon et al. 1992; Buffington and Montgomery 1997; Fischenich 2001). Thus, the values of τ_c^* for particles in a mixed bed material may differ from values for the same size particle in a uniform bed material obtained by using Shields curve (USACE 1989; Buffington and Montgomery 1997; Fischenich 2001). A wide range of values for τ_c^* has been determined by a large number of experimenters using different investigation methodologies and there is no universal value for τ_c^* in gravel-bed rivers (Buffington and Montgomery 1997). Even if some values for τ_c^* would give a higher value for τ_c, accurate values for beds in this study is still unknown. Besides, if some τ_c^* -values generate a better prediction rate, it would not necessarily mean that τ_c^*-values are the crucial factor, since it is as possible that τ_0-values are underestimated. By adjusting a τ_c^* -value to give an erosion prediction which coincides with actual erosion on a specific spawning bed, one would to some extent compensate for the poor estimation of τ_0 and would not achieve the accurate τ_c^* -value to use if the τ_0 was correctly estimated. Thus one would not achieve the correct τ_c^* -value for determining a new location for constructing a spawning bed since τ_0 or D_{50} here would not be the same as for the bed of which the τ_c^* -value was adjusted for. Consequently, complexity of factors that influences τ_c^* -values makes it exceedingly difficult to compute accurate threshold values for initiation of movement of mixed sized gravels like those which are dispersed to provide suitable spawning habitats in natural streams.

The second method that was used to predict initiation of motion of sediment particles as a result of high water flows where water velocity was compared to critical water velocity, the Isbash method, did to the contrary underestimate the rate of erosion.

Lack of high flow velocity data may have influenced the prediction accuracy for this model significantly. My analysis suggested that water velocities were below threshold velocities of spawning bed gravels at all times from the point of the first measurement and throughout the study for all but two beds. Velocities during peak flow would most likely have exceeded the threshold values for sediment transport at some point on a larger number of spawning beds than suggested by my model. This presumably is the main reason for my water velocity model to underestimate the magnitude of erosion on spawning beds. Water velocity over spawning beds was measured at too few occasions (i.e. a minimum of three times for each bed) to allow me to make a function for the relationship between water velocities and discharge over each bed. Thus, I could not use calculated discharge to estimate water velocities for the period from which data was lacking.

Not solely lack of high flow data may have influenced the prediction accuracy of this model. When measuring water velocity, the flow meter recorded 10 values from which a mean was obtained. Since the water flow in a stream is intermittent, pulses occur in which the water velocity is two to three times the average (Fischenich 2001). These pulses likely contribute to more erosion than what is predicted. A more accurate method might have been to use the highest value out of ten recordings instead of the mean value. Another thing to take into consideration is the definition used for an observed eroded spawning bed. No gradual range was applied when evaluating bed erosion by observations. An eroded bed in this study have had rather extensive losses of gravel while a bed that have lost a minor amount of gravel, but where gravel still have been displaced, is not defined as an eroded bed. Thus, some predictions that were considered to have failed may have been partly correct if the bed was predicted to erode and the bed was eroded, but not significantly. In future studies, if conducted in a similar way as this, one should apply a ranged scale when retrospectively evaluating erosion by observation.

One more factor that is plausible to influence the estimations of water velocities is the direction of stream current over the beds. To achieve accurate velocity data one is required to keep the flow meter in the exact direction of the current. The margin of error increases with increased angle between the flow meter direction and the flow direction. In turbulent flow it is very difficult to assess the near-bed current direction and at times, when turbulence was high, even negative values were achieved. When the water current is perpendicular to the flow meter, the value achieved is zero, even though the velocity may be substantial in the perpendicular direction. Preferably, a velocity meter should be used that is able to measure velocity in all directions.

Since both described approaches for predicting initiation of motion require complex calculations and includes sources of uncertainty, alternative methods more applicable for fisheries managers would be to prefer. The first method I would suggest is the use of tracer gravels. This method has been used with good results by a number of researchers (Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008). With tracer gravels one can avoid safety problems associated with measuring shear stress and water velocity in high flows. Though the transport rate may not be the same for marked gravels placed on an unrestored stream bed as it would be for gravels placed on top of a constructed gravel spawning bed at the same location. Another method that has been practiced in many studies is the use of pit trap samplers (e.g. Wilcock 2001; Sterling and Church 2002; Macdonald et al. 2010). A major drawback with this method though, is that they may be filled to capacity at large transport rates, before the samples are retrieved. This limits their application to flows producing relatively small transport rates. Another drawback is that during high flows, particles may overpass the sampler (Macdonald 2010). A method that also should be considered when choosing erosion prediction tool is the FliessWasserStammtisch (FST)-hemispheres method. The FST-hemispheres method includes a set of 24 hemispheres of equal size, identical surface textures and differing densities plus a Plexiglas plate. The Plexiglas plate is placed in a horizontal position on the stream bed and the hemisphere are in succession applied on top of the plate. The heaviest hemisphere displaced by the flow indicates the magnitude of bed shear stress at that specific location (Statzner and Müller 1989). The hemispheres method is easy applicable and provide a rapid characterization of the physical conditions in a stream reach and generates shear stress information from easily obtained input variables (Statzner and Müller 1989; Lamouroux et al. 1992; Dittrich and Schmedtje 1995).

Study 2: Erosion of spawning beds caused by spawning activity

My results from study 2 suggest that trout females, while spawning, contribute significantly to erosion of spawning beds in studied stream. The finding that spawning activity of trout likely plays an integral role in spawning substrate movement dynamics is consistent with previous studies on spawning bed substrate entrainment (Montgomery et al. 1996; Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008).

My results also suggest that trout utilize the central section of a bed for spawning more than the outer perimeters, and hence that there likely is a spatial heterogeneity in erosion probabilities over a spawning bed. Erosion differed in magnitude between central-, downstream- and upstream sections, though no difference in movement between pebbles deployed along the edges of the bed compared to pebbles deployed in the middle of the stream could be proven. The low magnitude of erosion in downstream sections is supposedly the result of trout burying their eggs in patches located in the most downstream parts of the central sections, as suggested by Svensson (2012), and use gravel from the more upstream parts of the central sections to fill up the egg pockets. The upstream sections have a lower rate of erosion than both the central- and the downstream sections. This may be a result of micro-scale spawning habitat preferences (i.e. water velocity, water depth or oxygen availability in upstream sections may be unsuitable for spawning) (Shirvell and Dungey 1983; Armstrong et al. 2003; Nika et al. 2011). Upstream sections, for example, were in general deeper and with lower flow velocities than central sections. Also, as female trout often cover eggs with gravel shuffled from the bed surface immediately upstream of the egg pocket (Montgomery et al. 1996; Rennie and Millar 2000), the upper most section of a bed may be less suitable for spawning as the access to upstream gravel will be lacking.

Since no pit-tagged pebbles were deployed over any unused spawning grounds as a control group in the study, other evidence is needed to assure that the brown trout spawning activities, and not the water current itself, was responsible for the movement of gravel. I argue spawning activity is indeed the main cause of erosion in my study since gravel mobility was highest in central bed sections even though water velocity were in general higher in downstream bed sections than in central sections. If gravel was to be moved exclusively by the water current, it would presumably have been moved further where the water velocity was higher, i.e. in the downstream sections of the beds.

There is a potential risk that the deployed PIT-tagged pebbles were more prone to move compare to “native” top layer pebbles. This since the “native” pebbles in a gravel mixture covered each other and may be partly buried by other top layer pebbles. Even though the deployed PIT-tagged pebbles were gently pushed into the gravel bed they were not covered by other top layer pebbles. If PIT-tagged pebbles were more prone to move compare to “native” pebbles, it could potentially result in an overestimation of erosion probabilities of the beds in this study. However, I considered this unlikely, since only a minor amount of top layer pebbles were covering each other. Also, this presumption would concern all PIT-tagged pebbles, regardless their spatial distribution, thus would not affect the spatial heterogeneity of erosion between bed sections.

The model suggests that a spawning bed have a lifespan of 13 to 35 years, depending on initial gravel depth and minimum average depth in the central section for utilization. It is realistic to assume that the average spawning bed has initial gravel depth of 20 cm and can be utilized for spawning as long as the average gravel depth in the central section is at least 10 cm (e.g. approx. 3 layers of pebbles) (Palm, D. pers. com. 2012). On the basis of this assumption, bed longevity is 24 years. This indicates that spawning bed construction is a very cost effective measure and should have a high priority in stream restorations. If beds are regularly maintained by minor improvements, such as raking and cleaning of gravel, the longevity might be even longer and the benefits may be even more cost effective. As shown in the 3D rendition the central and downstream section are thinned out first, while the upper section remains almost untouched even after 30 years. Maintenance should hence be concentrated to the central and downstream section of a bed. The 3D rendition also reveals that the effective spawning ground will move further downstream every year. A reaction to this will supposedly be that the bed will be utilized for spawning further downstream each year. When spawning substrate eventually becomes too sparse in the central and downstream sections of the bed, it plausible will be utilized in the upstream section. The 3D rendition can be used as a practical guide to predict where on beds maintenance efforts are likely to be most needed and how to construct beds for higher persistence (e.g. disperse more gravel in the central section).

Even though the longevity model provides erosion predictions of bed lifespans related to spawning activity, it does not take into account the erosion due to the spring flood events, which play an important role in bed load transport (Gottesfeld et al. 2004; Hassan et al. 2008), thus have a significant impact on bed longevity. Therefore predictions by this model could be expected to overestimate bed lifespans. According to Gottesfeld et al. (2004), range and median travel distances of tagged particles mobilized by snowmelt flood and fish were comparable in areas with high density of female spawners each year between 1992 and 1996. Gottesfeld et al. (2004) conclude that during years with high magnitude flood events and relatively low spawning activity, floods are the most effective contributors to sediment mobility. Though, in years with low magnitude flood events and high spawning activity, fish spawning contributor more to sediment transport than floods (Gottesfeld et al. 2004). Hassan et al. (2008) found indications that sockeye salmon spawning activity cause direct sediment movement accounting for between a third and a half of the net bed load moved. This might not be directly transferrable to my study since the relative sediment transport done by floods and by salmons is dependent on many factors, such as scale of the channel, channel slope, density of spawning females and flood magnitude (Gottesfeld et al. 2004). Though, by using the relationship suggested by Hassan et al. (2008) as a guideline and assuming that a third of the net bedload transport would be attributable to trout spawning in my study stream, longevity of the hypothetic spawning bed would be about 4-12 years. By referring to my previous statement that it is realistic to assume the average spawning bed may have an initial gravel depth of 20 cm and can be utilized for spawning as long as the average gravel depth in the central section is at least 10 cm, the lifespan may be approximately 8 years. Merz et al. (2006) measured longevity of spawning habitat rehabilitation projects using digital elevation model (DEM) differencing and found that up to 50 % of imported gravel volume was lost over 4 years, which is about twice as much as my prediction. Though, of the mechanisms monitored in their study gravel deflation was the greatest contributor to volumetric reductions, followed by hydraulic scour and spawning. They estimate that fish spawning alone would mobilize an entire enhancement site in about 49 years (Merz et al. 2006). Their study may not be comparable to this, since it was carried out in a regulated river and gravel imported was of another magnitude than that of my study. In my study, beds were constructed with about 1-2 m^3 (Spade, E. pers. com. 2013) gravel while in the study by Merz et al. (2006) 649-1323 m^3 of gravel was dispersed for each enhancement site.

Moreover, it has been suggested that vertical mixing of the gravel bed by spawners decrease the critical shear stress of the gravels since this prevent development of well armored surfaces, thus floods following large spawning events may be expected to move gravels larger distances (Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008). On the contrary, others have suggested that spawning activities make the surface rougher and significantly increase the critical sheer stress of the gravels since removal of finer grains during spawning activities produce deeper intergranular pockets which imply higher friction angles (friction angles depend on the size of the particle of interest related to its neighbors) (Montgomery et al. 1996; Buffington and Montgomery 1999). The net effect of these two processes has not been analyzed and presumably varies on a case by case basis, something that I do not address here.

Both mean burial depth and travel distance of marked tracer gravels have been found to increase with increasing numbers of spawning fish (Gottesfeld et al. 2004; Gottesfeld et al. 2008; Hassan et al. 2008). For my study, this suggests that my longevity model is only valid for fish spawning densities similar to that of my study stream during fall of 2012. Since the relative spawner density in this channel for 2012 is not known, it is not possible to make the model account for variation in spawner densities. Consequently, transferability of the model is limited to streams with a similar number of female spawners per unit spawning area.

My results suggest there is no significant correlation between water velocity and average distance travelled by pebbles. The same conclusion is suggested by Gottesfeld et al. (2004), where field data was collected from five seasons between 1992 and 1996. Their finding though, may not be completely comparable to mine since instead of using water velocity they use the unit “specific discharge” (m^2/s) for testing correlation, a unit of which I have not all necessary data to compile. However, since neither this study or the study by Gottesfeld et al. (2004) found a significant correlation between water velocity and pebble travel distance, I have reason to assume that discharge variation during spawning periods between years and streams can be negligible. Supposedly since discharge suitable for spawning is well below the threshold discharge for initiating gravel entrainment, which also is suggested by Hassan et al. (2008). This per se is another evidence for fish being the actor for moving pebbles during spawning period. In respect to water velocities, I am confident that my model can be transferable to other streams.

Spawning activity may also alter the spatial distribution of bed material. One assumption in the longevity model is spatial homogeneity within each bed section, though this might not be consistent with the actual scenario. Due to erosion, some areas may end up having a gravel depth too thin to be utilized for spawning even though the average gravel bed depth is far more than required. Such patchiness of suitable gravel could result in a smaller effective spawning bed and might affect the production efficiency negatively. Thus although the model predicts longevity, the productivity of the bed may not be satisfying throughout the lifetime.

It is not possible to alter the substrate size in the model. This because it is designed for a median particle diameter of 31mm (i.e. the movement probabilities used were based on PIT-tagged pebbles with a diameter of 31mm) and is not compatible with other substrate sizes. Beds with particles sizes not similar to those of this study will have other erosion ratios which would limit the applicability of the model to gravel beds with similar substrate sizes. Neither is it possible to alter the bed dimensions in the model (except from the initial gravel depth). A larger bed with the same initial gravel depth and median particle diameter contains a larger amount of pebbles, which would suggest a longer lifespan for the bed. Though, a larger bed may likely be utilized by a greater number of spawning trout. Longevity for a larger bed than the one in the model, with respect to the gravel bed area, may therefore not differ.

The model used for testing if there was a difference in movement between pebbles deployed along the edges of the bed compared to pebbles deployed in the middle of the bed did not take into account edge effects contributed by the frame of rocks and boulders put in place to support the gravel bed. Edge effects on erosion may occur not solely along the edges but also adjacent to rocks in the middle of the stream. If pebbles location in relation to rocks in the middle of the stream had been taken into consideration in the model, the result may have suggested that there indeed was an edge effect.

In conclusion, mapping of PIT-tag equipped pebble motion was proven to be a promising method to generate estimates of stream bed substrate movement attributed to trout spawning activities. By knowing where on a bed the probability of erosion is most significant, fisheries managers can more effectively counteract erosion process through more specific construction measure, as well as maintenance procedures focusing on the most susceptible areas. Next step using this method is to extend it to also evaluate the erosion attributed to flood events.

Even though prediction tools presented here needs to be refined and alternative methods needs to be developed, careful use and application of my prediction methods and an understanding of their limitation can provide guidance for fisheries managers and significantly improve and facilitate restoration efforts.

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