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# Report

## Linking shelter abundance and grain size distribution

A correlation analysis between shelter abundance and particle size of river substratum

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**ABSTRACT**

## Linking shelter abundance and grain size distribution

It is assumed that hydropeaking causes elevated degrees of fine sediments in river beds which affect negatively habitat quality for juvenile salmon. Finstad et al. (2007) developed a method to measure interstitial space (shelter abundance for fish) in running waters. Shelter availability is a candidate mechanism for survival of juvenile salmon due to reduction of predation risk and influenced by the degree of fines. The goal of this study was to find a relationship between shelter abundance (measured with the method by Finstad et al.) and grain size distribution to be implemented in predictive models for the assessment of the ecological status in running waters. The developed approach to reach this aim was conducted by gathering data in representative places both for shelter abundances and grain size distributions. The results of the study indicate that particle distribution parameters generated in grain size analysis are correlated to shelter abundance to a certain degree, especially percentiles describing the fine tail of the distribution are highly correlated to shelter abundance. Also distribution parameters show relatively high correlation quality, however under certain restrictions. The findings are used to develop assessment and management tools for hydropeaked rivers.

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# 1 Introduction

## 1.1 Problem description

When hydro power is operated with frequent changes in production (denoted as hydropeaking), downstream flow variations will vary along a wave front leading to wetting and drying of river sections. The understanding and modeling of these dynamic processes are crucial to evaluate environmental impacts. Direct and indirect impacts on the substrate composition, erosion, siltation processes, pore space changes, interactions with ground water flow and the hyporheic zone, water temperature and ice conditions and changes in embeddedness are important to identify.

It is hypothesized that hydropeaking and alternative regulation will change the pattern of erosion and sedimentation processes, in many cases leading to more disturbance in the substrate composition. However, increased variation within some limits may also lead to increased armoring and embeddedness. As the substrate is important for all aquatic organisms, it is crucial to study and predict changes in substrate conditions as well as to develop sustainable mitigation.

Embeddedness is regarded as one of the influencing parameters on habitat quality for fish regarding the substrate (Sylte and Fischenich, 2002) and therefore different approaches and methods were developed to measure it. Although it was initially chosen as a parameter to measure habitat space for juvenile stages of fish in running waters, the results of the methods do not give direct output to the requirements of fish and are not easily capable to be implemented in predictive models. The development of other methods with direct output considering ecological relevant parameters was needed. In this context Finstad et al (2007) developed a method to measure shelter for fish in running waters as a parameter of substrate quality and embeddedness.
The objective of this study was to find a correlation between shelter abundance and grain size distribution which could be used as a basis to assess the long-term development of substrate quality for juvenile salmon of hydropeaked rivers, as well as regulated rivers in general by use of predictive sediment transport models.

## 1.2 Literature review on shelter availability as habitat factor for Atlantic Salmon

Salmons show a seasonal shift in behaviour and habitat selection. While their dominant behaviour in summer is feeding during the day, they change to a diurnal pattern in winter with sheltering in interstitial spaces during the day and holding position close to the substrate in shallower areas with lower flow velocities during the night (Heggenes & Dock, 2001; Heggenes & Saltveit, 2007).

Studies showed that when temperatures fall below 10°C salmonids change to the “winter-pattern”, potentially a shift form perpetual activity in summer to restricted night time activity in winter. Other studies showed this shift in behavior at water temperatures between 3ºC and 6ºC (Armstrong et al., 2002). Additionally reasons like increasing discharge or changes in day length are presented to play a role for the induction of the shift in behavior (Huusko et al., 2007).

Two hypothesis for explaining the winter behavior were established; hiding against predators and sheltering from the current to reduce energy expenditure. Other explanations like avoidance of displacements by flood and ice, trapping by anchor ice or avoidance of light at cold temperatures were introduced. Testing the two main hypothesis Valdimarsson & Metcalfe (1998) observed that the use of interstices is more likely based on predator avoidance than on protection from the current, shelter opportunities with a relatively high through-flow of water are even preferred. A high percentage of salmonids´ mortality is caused by birds and the main bird predators are diurnal. Therefore a shift to nocturnal activity is likely to be effective in terms of reducing risk of predation (Valdimarsson & Metcalfe, 1998).

Availability of shelter provided by the substrate increases therefore survival probability of fish. It was shown that a higher availability of shelter significantly improves juvenile salmon performance due to reduced metabolic costs. Consequently substrate structure is likely to be a key factor of predator avoidance behavior. It offers places to flee and reduces thereby the probability for being detected by predators. Anti-predator behavior leads to reduced energy intake due to decreased foraging efficiency and a low level of shelter opportunities probably increases the maintenance metabolism of salmons because of increased levels of escape preparedness and elevated mental alertness (Finstad et al., 2007).

Heggenes and Dock (2001) stated that cover supplied by coarse substrate is an important habitat factor during the day and slow-flowing areas are important during the night in winter.

It was also shown that salmons are attracted by shadow and fish in culture perform worse due to chronic stress experienced by lack of overhead cover. Millidine et al. (2006) showed that the maintenance metabolism of juvenile salmon without shelter possibility is increased compared to a situation where visual cover without protection against the flow is available. It is assumed that the pure possibility to hide against predators reduces the stress level of the fish rather than the active act of sheltering. Finstad et al. (2007, 2009) showed that shelter opportunities are one limiting habitat variable for juvenile Atlantic salmon and possibly affecting the population demographics and long-term evolutionary processes. Therefore it is a key habitat factor that needs to be taken in account in stream evaluation and habitat assessment procedures for salmons.

What is in common throughout literature is the importance of visual cover and shelter opportunities as an important habitat variable. It is possibly the most important single habitat factor determining salmonid abundance which can be provided by different structures, e.g. deep or turbulent water, overhanging or submerged vegetation, beaver ponds and unembedded coarse substrate (Armstrong et al., 2002).

# 2 Methodology

## 2.1 Shelter measurement

Finstad et al (2007) developed an easy and fast conductible method to evaluate substrate quality and embeddedness in terms of valuable interstitial space for fish. With the help of rubber tubes interstitial voids are detected and quantified.

In an initial experiment 20 semi natural channels were prepared to provide a differing number of interstitial voids used as shelter by the fish. The experiment showed that shelter availability is negatively correlated with observed number of fish not finding shelters and growth performance is worsening with decreasing number of shelter. Moreover, negative effects of shelter reduction were observed on increasing fish body size and may therefore influence the size selection gradients. Shelters were measured using five different tube diameters (outside diameter 5, 10, 13, 16, 22 mm). For each tube diameter only voids deeper than 3 cm were counted. In the end a number of shelters with a mean depth was obtained for each tube diameter and channel. Shelters are defined by every single entrance to an interstitial void. A Y-shaped void under a larger particle for example is counted as three shelters. And thereby the exposition of the entrance relative to the direction of flow is of no interest because the shelters are rather used as visual cover than as protection against the flow.

The shelter abundances measured with the tube diameter of 13 mm explained best the variation in fish sheltering between channels. Additionally the performance (growth) of fish was strongest correlated to the shelter values determined with the tube diameter of 13 mm.

Considering these results and facilitating the study only one rubber tube with 13 mm outside diameter was in use. The tube (a flexible PVC tube for aquarium) is shown in the following figure, attached to it three rings indicating three categories of shelter depth (3 cm, 7 cm, 12 cm).

Figure 2.1: flexible rubber tube with attached rings indicating shelter depth

Shelter availability is measured within an iron square of 0.25m² which is placed on the river bed with the help of random tosses in visually homogeneous appearing areas.

Figure 2.2 shows how the iron frame is lying on the dry river bed and shelter abundance is measured with the rubber tube. Thereby the whole area within the square is schematically scanned and the tube tried to be plunged into the voids in between the sediment particles without moving the particles.

Figure 2.2: measurement square and tube in use during shelter measurement session

The following figures illustrate examples of shelter of different depth. As mentioned before three rings are attached to the PVC tube indicating three categories of shelter depth.

Figure 2.3: example of shelter (category I )

Figure 2.3 shows a shelter of category I (3 cm deep) where the first ring of the tube is completely plunged into the interstitial space and not visible anymore. The picture was taken on a dry river bed for better visibility, but the method is also applicable in wadable rivers with clear water when the tube is extended e.g. with a wooden pole.

Figure 2.4 shows a shelter of category II (7 cm) where the first two rings are completely plunged into the void and not visible anymore.

Figure 2.4: example of shelter (category II)

Figure 2.5 shows a shelter of category III (12 cm deep) where all three rings on the tube are plunged into the void and not visible anymore.

Figure 2.5: example of shelter (category III )

The three categories were introduced to facilitate the measurement procedure. It is not necessary to know the exact depth of the shelter. However, it is interesting to get an idea about the depth of the shelter e.g. to estimate the total shelter space of the area. Therefore the rings are attached to the PVC tube in order to get fast visual information about the depth which can be noted and later analyzed.

## 2.2 Grain size analysis

### 2.2.1 Sampling procedure

The first step of grain size analysis is the sampling of representative substrate probes of the specific layer of interest. The basic classification of four stratigraphic units commonly used in literature (Bunte & Abt, 2001) is presented in Figure 2.6.

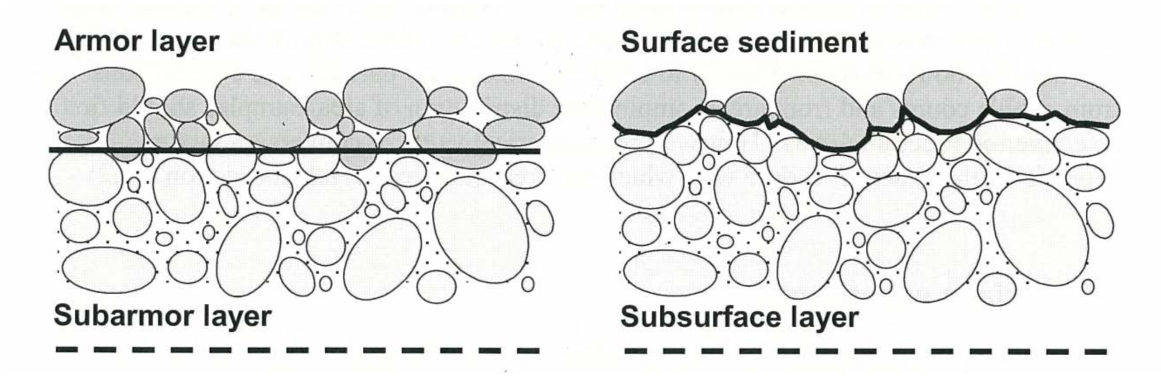



Figure 2.6: Stratigraphic units of the river bed (Bunte & Abt, 2001)

The surface sediment layer is restricted to only these particles visible from top whereas the armor layer comprises all particles down to the depth of the largest visible particle from top. The material has to be excavated and thereby it is distinguished between sampling on dry bed conditions and in submerged conditions. In the study the armor layer on predominantly dry bed conditions simply using small scoops was excavated (precisely explained later in chapter 2.3).

### 2.2.2 Particle analysis

The three dimensional shape of a particle is described by three mutually perpendicular axes: the longest (a-axis), the intermediate (b-axis) and the shortest (c-axis) axis. For most applications, however, it is more convenient as well as sufficiently accurate to describe the particle by just one variable such as the intermediate axis or the sieve size on which the particle was retained. Especially for large sediment samples it is needed to analyze the grain sizes in a practical way and mechanical sieving (Krumbein and Pettijohn, 1938) is a commonly employed procedure.

The Wentworth scale in mm was applied during the particle distribution analysis and the part used in this study is shown in the following table.

Table 2.1: Wentworth scale of size classes

| Description of particle size | | | Size class [mm] | Size class [Ψ] |
|---|---|---|---|---|
| boulder | | | >256 | 8 |
| cobble | Large | | 128 – 256 | 7 |
| | Small | | 64 – 128 | 6 |
| gravel | Very coarse | pebble | 32 – 64 | 5 |
| | coarse | | 16 – 32 | 4 |
| | Medium | | 8 – 16 | 3 |
| | Fine | | 4 – 8 | 2 |
| | Very fine | granule | 2 – 4 | 1 |
| sand | Very coarse | | 1 – 2 | 0 |
| | | | <1 | |

Particles smaller than 0.063 mm are summarized to the term of silt and particles smaller than 0.0039 mm are called clay. Both are lacking in table 3.1 due to irrelevance of distinction in this study. One size class smaller than 1 mm comprises all particle sizes of different groups. Sieving was realized with a square hole sieve set after completely drying the samples.

### 2.2.3 Calculation of parameters

After sieving the particles are sorted according to the given size classes and weighed for their statistical analysis. As first and second step the masses of the particle size class fractions and percentage frequency distributions were determined and out of that as third step a cumulative distribution curve is derived.

### 2.2.4 Percentiles

Based on the distribution of grain sizes per size class, percentile values are calculated. Bunte & Abt (2001) define a percentile to be “the sediment size indicated by the cumulative distribution curve for a particular percent finer value”. For example the $D_{50}$ percentile indicates that 50% of the sediment sample mass is finer than this specific value where D stands for the particle size in mm. The percentiles are used both to characterize the sample by themselves and to calculate distribution parameters which characterize the sample.
The values were calculated using a mathematical linear interpolation between two known data points on the sieve line. The particle size is computed in Ψ-units from:

where
$y_x$ is the desired cumulative frequency
$y_1, y_2$ are the two values of the cumulative frequency distribution just below and above the desired value
$x_1, x_2$ are the particle sizes associated to $y_1$ and $y_2$

and afterwards calculated in mm units using a simple transformation:

$$D_x = 2^{\Psi}$$

The percentile values computed for this study are listed in the following table and their relevance is shortly explained.

Table 2.2: percentiles and their relevance

| Percentile value | Significance |
|---|---|
| $D_5$ | Characteristic percentile of the fine tail of the distribution, used as itself |
| $D_{10}$ | Characteristic percentile of the fine tail of the distribution, used as itself |
| $D_{16}$ | Statistically characteristic value, used to calculate parameters |
| $D_{25}$ | Quartile, used to calculate distribution parameters |
| $D_{50}$ | Median point, divides distribution in two equal halves |
| $D_{75}$ | Quartile, used to calculate distribution parameters |
| $D_{84}$ | Statistically characteristic value, used to calculate parameters |
| $D_{90}$ | Characteristic percentile of the fine tail of the distribution, used as itself |
| $D_{95}$ | Characteristic percentile of the fine tail of the distribution, used as itself |

### 2.2.5 Particle distribution parameters

Distribution parameters were introduced in the middle of the last century as a means to classify the sediment in general as well as to offer a possibility to distinguish between sediments of different origins and transport modes (Bunte & Abt, 2001).
Fundamentally two different approaches to compute distribution parameters were developed: graphical (percentile method) and frequency distribution (moment method) approach.
For this study the parameters were computed using the graphic geometric approach which is applicable to particle sizes in mm units.

In the following the four basic parameters are listed and their relevance is shortly explained:

**mean**, used to characterize the central part of the distribution
**sorting**, gives an idea about the range of particles which are contained within a preset percentage of the data set
**skewness**, describes the deviation from symmetry of the distribution
**kurtosis**, is the peakedness or flatness of the distribution

According to Bunte & Abt (2001) an approach for the calculation of the parameters is used, the $n^{th}$ root computation. The geometric mean and Fredle index is given in mm units whereas the indexes sorting and kurtosis are dimensionless. The formulas to compute are shown in Table 2.3.

Table 2.3 particle distribution parameter calculation

| Distribution parameter | $n^{th}$ root computation |
|---|---|
| Geometric mean [mm] | |
| Sorting [ - ] | |
| Skewness (Fredle index) [mm] | |
| Kurtosis [ - ] | |

### 2.2.6 Granulometric index

Another calculated variable is the granulometric index which was introduced by biologists to avoid two parameters (dominant and sub-dominant grain size) to describe substrate. Instead one value for an overall description of the substrate is achieved to facilitate habitat investigations. The calculation in this study is adapted to the procedure explained in Hedger et al. (2005) and explained in the following.

First, the employed particle size classes are numbered (shown in Table 2.4) and with these values the granulometric index is calculated.

Table 2.4: granulometric classes

| Grain size class [mm] | ‹1 | 1 - 2 | 2 - 4 | 4 - 8 | 8 - 16 | 16 – 32 | 32 - 64 | 64 - 128 | 128 - 256 |
|---|---|---|---|---|---|---|---|---|---|
| Granulometric class number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

The index is calculated by

$$G_i =$$

where

$G_i$ is the granulometric index

$G_c$ is the granulometric class

$G_u$ is the proportion of the mass of the class in %

### 2.2.7 Substrate sample size

Large particles influence the distribution curve by their relatively large mass. The absence or presence of one particle can shift the distribution parameters considerably and therefore it is important to take samples sufficiently large to include large particles representatively.

A common way to determine sample mass is to compute it as a function of $D_{max}^3$ including different criteria, e.g. effect of including or excluding the largest particle on the total sample mass, acceptable error for large size fraction particles or number of particles included in the largest size class (Bunte & Abt, 2001).

Figure 2.7 shows several functions between sample mass and $D_{max}$ particle size. One criteria used to establish the functions is the percentage of one $D_{max}$ particle of the whole sample. In small samples of poorly sorted material, the absence or presence of one of the largest particles affects the mass of the total sample mass and consequently affects the sieve line. Neumann-Mahlkau (1967) specifies the function between sample mass and $D_{max}$ particle size to be:

$$m_s = 13800\ D_{n,max}^{\ 3}$$

where
$D_{n,max}$ is the nominal diameter (~ sieve size) of the $D_{max}$ particle in meter
$m_s$ is the sample mass in kg

The function is valid for a potential error up to 10% for the largest particle in the sample and plotted in Figure 2.7. Beside of it, curves for 1%, 0.1% and 0.01% and curves using different approaches to generate dependencies between sample mass and $D_{max}$ are shown. The line on the very right side shows the absolute minimum values for sample sizes given by the 10% sample mass criteria of the largest particle size.

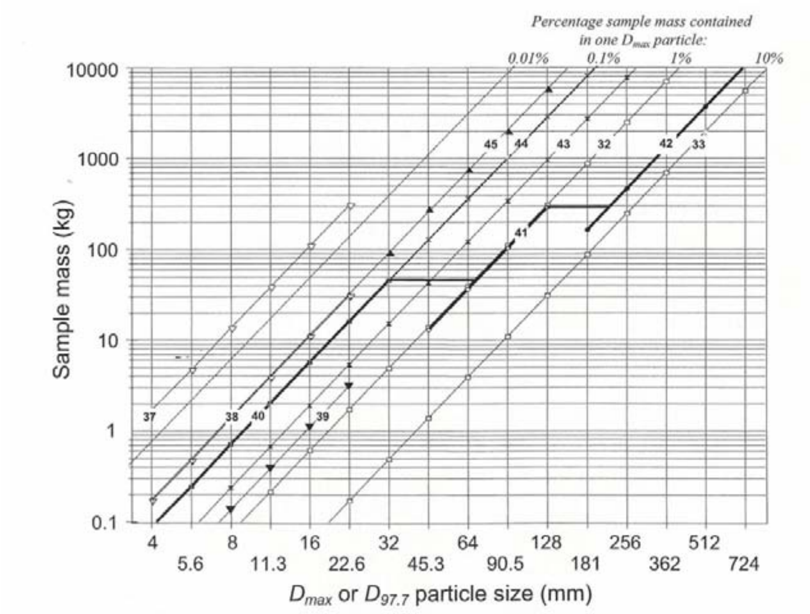



Figure 2.7: sample mass recommendations (adapted from Bunte & Abt, 2001)

For example the sample mass with a $D_{max}$ particle size of 100mm is to be at least 13.8 kg for a potential error of 10% inherent in the largest particle.

## 2.3 Approach to combine shelter measurement and grain size analysis

### 2.3.1 Motivation

The idea of the study is to establish a correlation between the biological measure of shelter abundance for juvenile fish and the physical measure of grain size distribution parameters to be used for improved interpretation of substrate quality regarding juvenile Atlantic salmon needs in modeling applications. Currently there is no approach to implement shelter abundance in dynamic habitat modeling for juvenile fish stages. The method developed by Finstad et al. (2007) gives valuable information about substrate quality regarding fish needs but cannot be modeled. However, it is possible to model substrate composition changes over time by use of computer aided sediment transport models. A correlation between shelter abundance and substrate composition would open the possibility to predictive modeling of substrate quality for fish based on sediment transport model output. Together with other basic habitat parameters water velocity and depth a dynamic habitat modeling approach could be developed which takes into account the altering morphology and composition of the river bed in a biological relevant aspect.

### 2.3.2 Boundary conditions

Two methods are tried to be combined where restrictions on both sides need to be considered in the development of an approach.

First, it is needed to ensure that data are taken from the same layer in the river bed and the same area. The method by Finstad et al. (2007) measures shelter in the top layer of the river bed, more or less coinciding with the armor layer. The 0.25 m² square to measure shelter abundance defines the area to be sampled. The locations of the frame are determined by random tosses in areas of optical homogenous sediment compositions. A rubber tube with 13 mm outside diameter and markings for three categories of depth (3 cm, 7 cm and 12 cm) is in use (see
Figure 2.1).

As the sample size regarding the area is predetermined by the square size of 50cm x 50cm the largest particle size to be included into a sample within this square is limited by the mass of the samples to be taken. The sampling depth is determined to be down to the level of the largest particle visible from the surface, the armor layer to guarantee the adequate description of the amount of fines surrounding the large grains in the probes.

These restrictions led to two different approaches of sampling strategies which are explained in the following.

### 2.3.3 Single square approach

For this approach one square of 0.5 m x 0.5 m is used to conduct shelter measurement as well as sediment sampling. The largest particles in a probe are determined to a maximum value of $D_{max}$ = 122 mm for 25 kg samples with a potential error of 10% for the largest particle. This accuracy is sufficiently high for the objective of the study and allows the feasibility of substrate sampling considering the sample weight. Adapting this boundary condition to the employed Wentworth scale of particle size classes the maximum grain size was determined to be 128 mm for that approach.

In the figure below pictures of a sample location are shown.

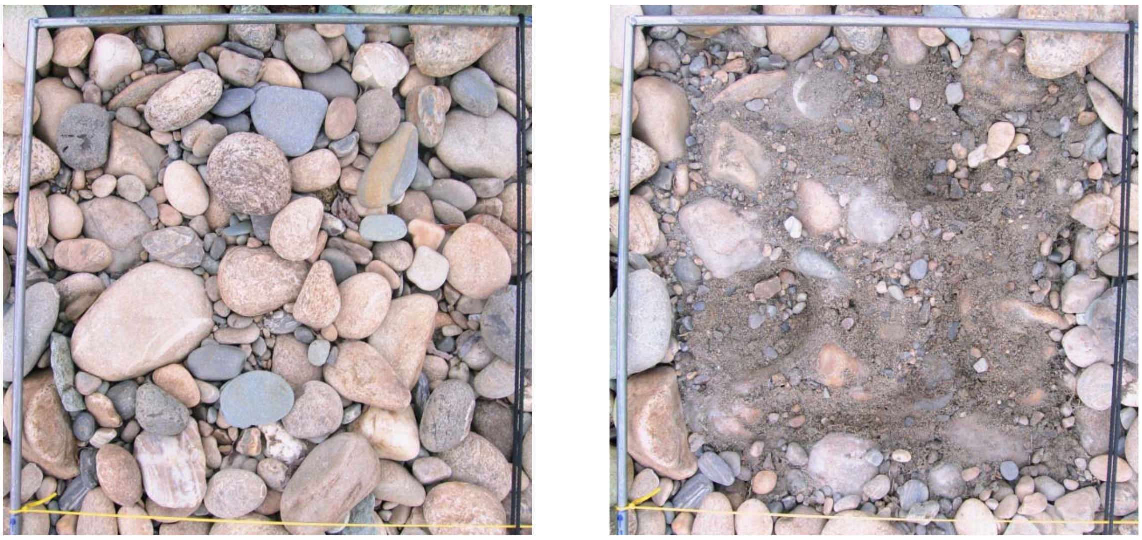


Figure 2.8: excavation sampling location, untouched (left) and excavated (right)

The approach is structured in 9 steps:

**selection** of an area with optical homogeneous substrate composition on the river bank
**random** toss of the 50cm x 50cm frame within the area
**taking** of a picture of the untouched substrate with the frame
**measurement** of shelter number with the 13mm rubber tube
**excavation** of the substrate material down to the depth of the largest visible particle and filling it into a labeled bucket
**taking** of a picture of the location with the frame where the material was excavated
**drying** and sieving of substrate samples in the laboratory
**statistical** analysis of the substrate samples including the calculation of percentile values and particle distribution parameters
**establishment** of correlations between shelter abundance and grain size distribution parameters of all samples

### 2.3.4 Multi square approach

For that approach a larger area is investigated. This includes 10 squares of 50cm x 50cm to conduct shelter measurement and 2 to 3 substrate samples (depending on visual estimation of coarseness of the substrate; coarser material needs more substrate material to be sampled) in order to describe the substrate composition representatively including large particles (>128 mm). It was shown during the first field working days that sample masses containing particles of about 120 mm on 10% potential error (~25 kg) are suitable to realize field workings. Larger particles increase the sample mass too much and therefore samples containing particles of size class 128 – 256 mm do not comply with before mentioned requirements of sample mass but seem to be of sufficient accuracy for the study (Jocham, 2010).
Hence, a strap of 10 m length is placed on the ground in an area of visually homogeneous substrate composition to mark the area to be sampled.
Figure 2.9 shows an example where the strap is lying on the dry river bed.

Figure 2.9: multi square approach location (example)

All steps to conduct field work and data analysis of this approach are listed here:

**selection** of an area with optical homogeneous substrate composition on the river bed
**placing** of a 10 meter strap within the area
**shelter** measurement 10 times along the strap with the help of the measurement frame and the 13mm rubber tube
**random** tosses of the frame along the line to specify locations for excavation sampling (2 -3 times depending on coarseness of the substrate, visual estimation)
**excavation** of substrate material down to the depth of the largest particle visible from top and filling it into a labeled bucket
**drying** and sieving of substrate samples in the laboratory
**statistical** analysis of the substrate samples including the calculation of percentile values and particle distribution parameters
**establishment** of correlations between shelter abundance (average values of 10 measurements per strap) and grain size distribution parameters of all samples

# 3 Study sites

Four study sites were chosen to conduct data recording in the field, locations in the rivers Lundesokna and Gaula south of Trondheim in Norway as well as in the river Surna southwest of Trondheim.

The river Lundesokna is part of a complex system of reservoirs and hydro power plants. The study site was chosen in the most downstream part which is influenced by hydropeaking before the river confluences with the river Gaula.

The study site in the river Gaula is located about 8km downstream the confluence with Lundesokna.

In the figure below the locations of the study sites as well as satellite pictures of them are shown.

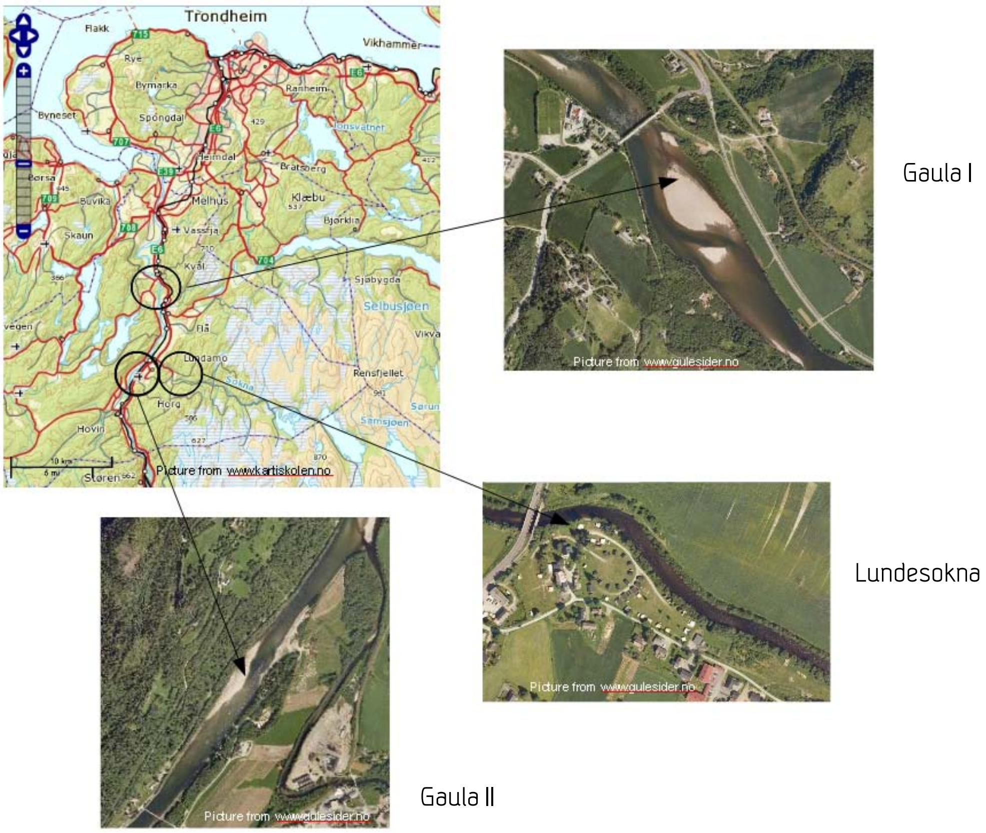



Figure 3.1: field work locations rivers Lundesokna and Gaula

On the pictures of Figure 3.1 a map of the region south of Trondheim is shown. The locations of the study sites are indicated with black circles. Satellite pictures give an impression of the constitution of the rivers. While the river Lundesokna is captured in a quite narrow and straightened river bed the river Gaula is flowing in a broad river bed with meandering flow of water.

The differences in flow in river Lundesokna induced by varying hydro power plant operation are between ~1 $m^3$/s and 20 $m^3$/s. River Gaula has a catchment area of 3661$km^2$ and is not regulated beside the inflow of river Lundesokna. The flow varies between ~25 $m^3$/s in winter and more than 700$m^3$/s in the usual annual spring flood.

In the river Surna south-west of Trondheim few more samples were taken in an unregulated part of the river. The conditions in the river are comparable to the ones in river Gaula, although the standard runoff is lower. The study location is shown in

Figure 3.2.

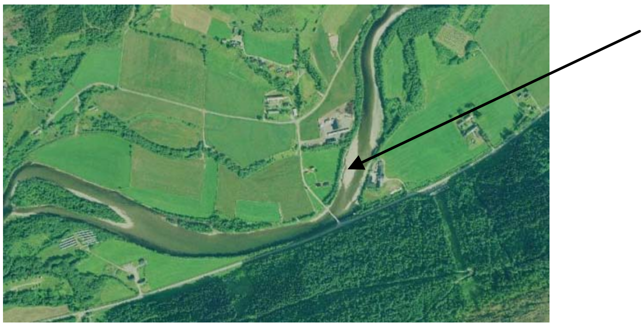


Figure 3.2: Study site river Surna

The four study sites were chosen because of the differences regarding the sizes of the rivers and flow variability. Thereby a high degree of variability between the substrate compositions was expected. In the rivers Gaula and Surna regular major flood events occur where the armor layer is opened and the fine sediments are flushed away. This leads to a good mixture of the sediments and generally to a lower level of embeddedness. In the river Lundesokna the range of flow is not big enough to induce a regularly appearing opening of the armor layer. Therefore the river bed is characterized by a very stable armor layer which is strongly packed. A high amount of fines clogging the voids is the consequence and thereby a high level of embeddedness.

# 4 Data analysis

Two field work approaches were conducted in three rivers Gaula, Lundesokna and Surna. All samples are united to one data set and all beforehand mentioned percentiles and distribution parameters were calculated and analyzed. However, the presentation of results is restricted to these ones which are meaningful and valuable for the aim of the study. Hence, the presented parameters are $D_5$ , geometric mean, sorting, skewness, kurtosis and granulometric index.

During data analysis it was shown that particles of size class 64 – 128 mm are at least needed to provide measurable shelter opportunities. Samples consisting of only particles smaller than 64 mm do not provide shelter opportunities and are therefore excluded from the presentation of data. In chapters 4.1 and 4.3 the samples are divided into these ones containing maximum particle sizes of 128 mm and these ones containing maximum particle sizes of 256 mm, respectively.

The idea in these chapters is to separate the samples regarding their $D_{max}$ values which influence on the calculated distribution parameters. In chapter 4.4 all samples are pooled to one data set to check for remarkable differences in correlation quality when mixing samples in a broad range of included grain sizes. Finally, all results are summarized and compared and the best found parameter is examined more in detail.

## 4.1 Samples containing maximum grain size particles ≤128 mm

In this chapter all samples with a maximum grain size $D_{max}$ of 128 mm (maximum particles in size class 64 – 128 mm) are examined. The majority of samples was gathered by the single square approach and only two samples with the help of the multi square approach (for two samples gathered with the multi square approach it was realized during the analysis that they consist only of particles <128 mm and therefore they are included herein). Shelter abundance was measured in three categories (3, 7, 12 cm depth), but regarded as total quantity of shelters and not distinguished in the categories because the absolute majority of measured shelter was of category I and only a very small part of category II and III.

The calculated parameters are plotted against shelter abundance and presented in the following figures.

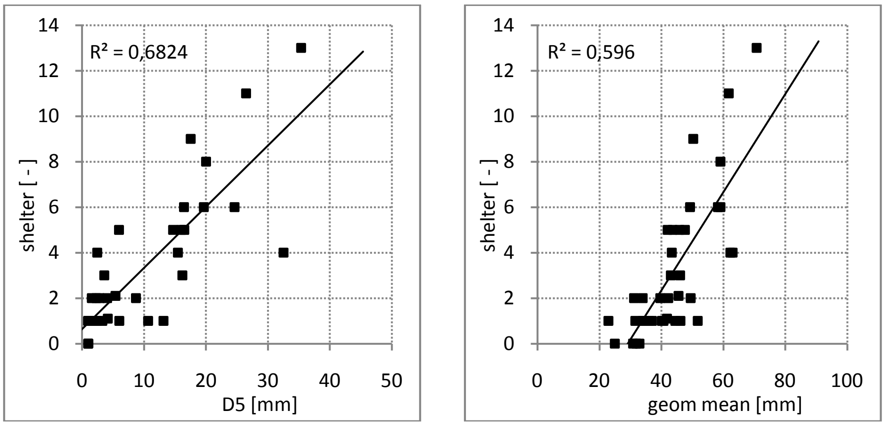



Figure 4.1: $D_5$ (left) and geometric mean (right) plotted against shelter abundance (all samples <128 mm, n= 38)

Shelter abundances plotted against $D_5$ values deliver a coefficient of determination of $R^2 = 0.68$. The theory is that the amount of shelter possibilities is strongly influenced by the amount of fines in the probes. The $D_5$ percentile indicates that 5% of the mass of the probe is finer than the indicated grain size and is therefore a good indicator of fines in the probe. The graph shows that the amount of fines is strongly varying among the probes and the number of measured shelter depends on the amount of fines. Only few outliers on the right side below the regression line affect negatively on the determination coefficient. For $D_5$ percentiles the range reaches from 1 mm leading to no measured shelter and up to ~35 mm leading to 13 measured shelter possibilities within the square of 0.5 x 0.5 m.

Geometric mean delivers a lower determination coefficient of $R^2 = 0.6$. The slope of the regression line is steeper and geometric mean values of about 50 mm deliver shelter abundances between 1 and 9 which is a relatively high range of values. Generally a tendency of increasing number of measured shelter with in the same time increasing values of geometric mean is recognizable but correlation quality is not as high as shown for $D_5$.

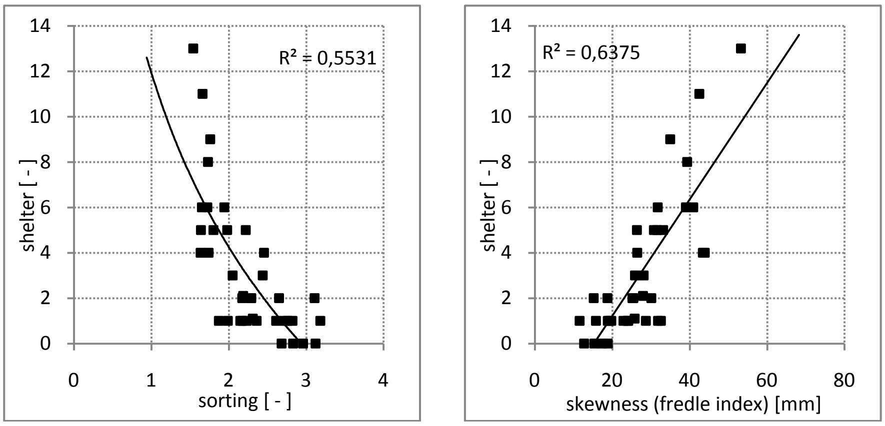



Figure 4.2: Sorting index (left) and skewness (right) plotted against shelter abundance (all samples <128 mm, n= 38)

The pattern to characterize the relationship between shelter abundance and sorting index is better matched by a logarithmic regression than by a linear one. The high percentiles in the equation are relatively constant among the probes, so the difference in sorting index is based on the lower percentile. The logarithmic regression shows that there is a certain threshold value (around 2) from where the sorting index decreases only slowly by increasing number of shelter. Above sorting index 2 the values increase faster by little change of shelter number. Equal sorting index values can be generated by two completely differing distributions. This leads to the assumption that the number of measured shelter varies by relatively constant sorting index values due to increasing $D_{max}$ values which imply more interstitial space on well sorted material.

The skewness results have a clear tendency towards higher skewness (fredle index) values with in the same time increasing shelter abundance. The equation shows that fredle index is generated by geometric mean divided by sorting index. Geometric mean is increasing with increasing shelter abundance and sorting is relatively constant with increasing shelter abundance; only in the lower part sorting increases with decreasing shelter abundance leading to a stretching in the skewness-shelter relationship, especially in the lower part and subsequently to a little increased determination coefficient compared to geometric mean.

In Figure 4.3 the correlations for kurtosis and granulometric index are shown.

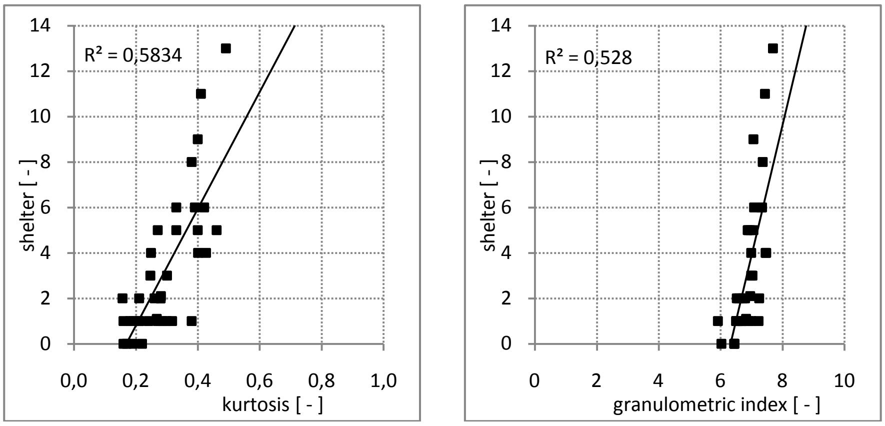



Figure 4.3: Kurtosis (left) and granulometric index (right) plotted against shelter abundance (all samples <128 mm, n=38)

Kurtosis is theoretically a ratio between sorting and sorting, however on basis of different percentiles and in the denominator the inverse value. Practically means this that well sorted material (low sorting index) produces high kurtosis values. In the graph to the left the relationship of well sorted material (high kurtosis) and high shelter abundance is confirmed, though not on this high level as e.g. shown for fredle index.

The relationship for granulometric index is characterized by a linear dependency. The granulometric index values itself can be interpreted as an average grain size value because all fractions are put together considering their proportion of the whole sample and consequently averaged. Like geometric mean the index values increase with in the same time increasing shelter abundances but the finer fractions are not remarkably stressed like for the calculation of geometric mean (see equations) and therefore the correlation quality is not as high. Nevertheless this is a very simple description of the general sediment composition leading to relatively good results regarding the correlation to shelter abundance.

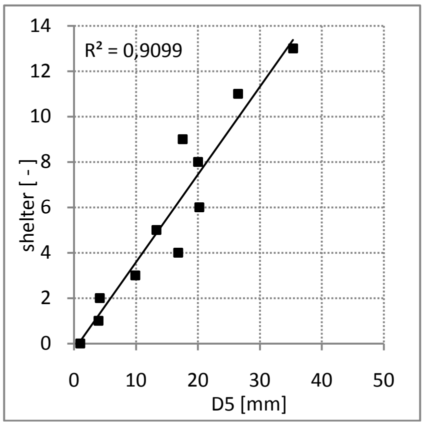
## 4.2 Summary

Highest determination coefficient is achieved by $D_5$ percentiles plotted against shelter abundance with $R^2 = 0.68$. All of the four distribution parameters geometric mean, sorting, skewness and kurtosis deliver determination coefficients between $R^2 = 0.55$ and 0.65. The lowest one is achieved by plotting granulometric index values against shelter abundance with $R^2 = 0.53$.

In Figure 4.1 (left) few outlier points on the right side of the regression line are conspicuous and affect negatively correlation quality. Excluding this outlier point increases the determination coefficient from $R^2 = 0.68$ to 0.84. This outlier is not so conspicuous considering the other parameters and consequently doesn`t help to increase correlation quality by excluding.

Other percentiles ($D_{50}$, $D_{90}$, $D_{95}$) are calculated for all samples but are lacking in this presentation of results because correlation quality was shown to be too low (maximum determination coefficient of $R^2 = 0.25$). $D_{10}$ percentile showed relatively high correlation quality ($R^2 = 0.67$) but nevertheless lower than $D_5$ and is therefore not considered either.

The graphs are characterized that the numbers of shelter are often associated with more than one grain size parameter. This is a consequence of the method by Finstad which implies only integer results, e.g. 1, 2, 3, and so on. Especially in the low part several samples were taken with the same quantity of measured shelter. In the higher part only few samples were taken with the same shelter quantity or even only a single one.
In the next graphs the grain size parameter values with equal associated number of shelter are averaged. This means that the corresponding grain size parameters of the samples with equal shelter abundances are averaged and plotted against shelter abundance for all observed shelter abundances. The same parameters as seen before are included and presented.



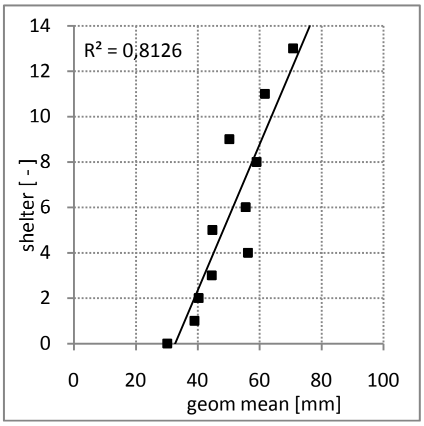




Figure 4.4: Per shelter number averaged $D_5$ (left) and averaged geometric mean (right) plotted against shelter abundance (all samples <128 mm, N= 38)

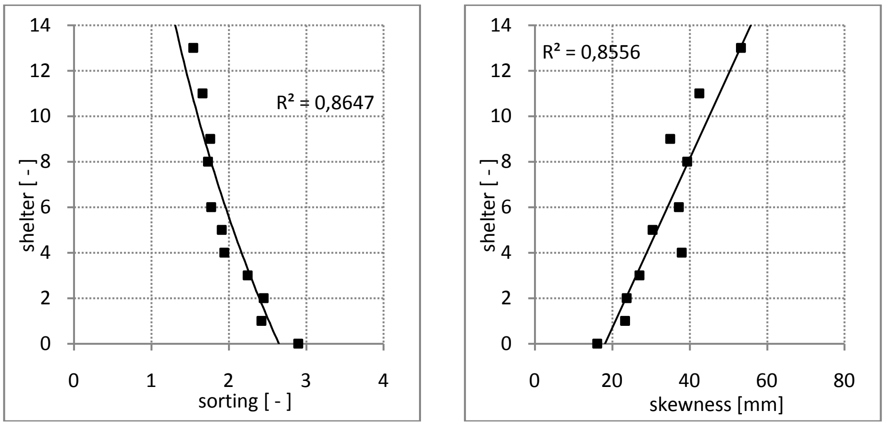



Figure 4.5: Per shelter number averaged sorting index (left) and skewness (right) plotted against shelter abundance (all samples <128 mm, N= 38)

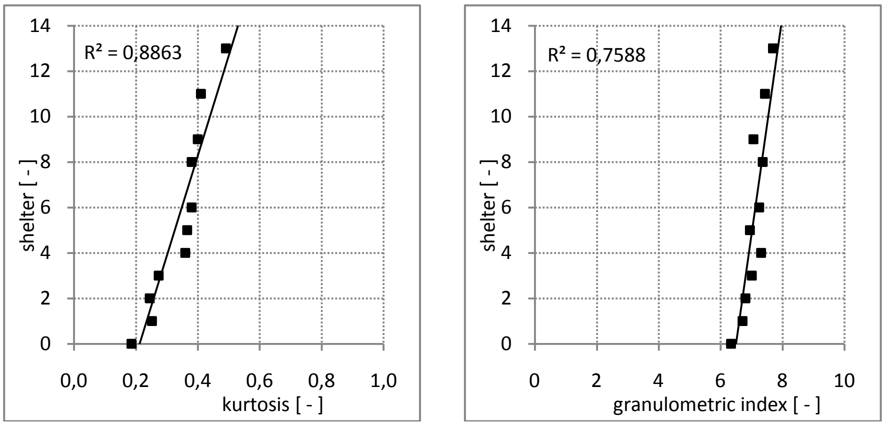



Figure 4.6: Per shelter number averaged kurtosis (left) and granulometric index (right) plotted against shelter abundance (all samples <128 mm, N=38)

Highest observed coefficient is delivered by $D_5$ plotted against shelter abundance (according to raw data; not averaged $R^2 = 0.68$) with $R^2 = 0.91$ and lowest one is delivered by granulometric index with $R^2 = 0.76$ (not averaged raw data, $R^2 = 0.53$). Sorting index coefficient increases very strongly to $R^2 = 0.86$ for the averaged data set.

Finally, there is hardly any effect remarkable for excluding before mentioned outlier points when averaging grain size parameters. The so gained grain size parameters should again be examined regarding their standard deviation around the mean values for later investigations.

## 4.3 Samples containing maximum grain size particles ≤ 256 mm

In this chapter all samples with a maximum grain size $D_{max}$ >128 mm (maximum particles in size class 128 – 256 mm) are examined. The majority of the samples was gathered by the multi square approach and only few samples with the help of the single square approach (similar to the chapter before samples containing particles >128 mm are gathered with the multi square approach but some of the single square approach samples were realized during the analysis process to contain grains >128 mm and are consequently presented herein). Shelter abundance was measured in three categories (3, 7, 12 cm depth), but regarded as total quantity of shelters and not distinguished in the categories to facilitate the analysis.

The examined parameters are plotted against shelter abundance and presented in the following figures.

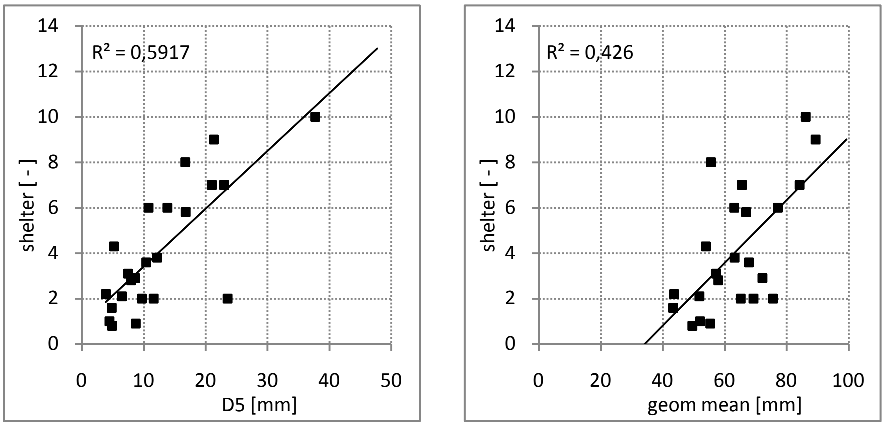



Figure 4.7: D5 percentiles (left) and geometric mean (right) plotted against shelter abundance (all samples >128 mm, n= 23)

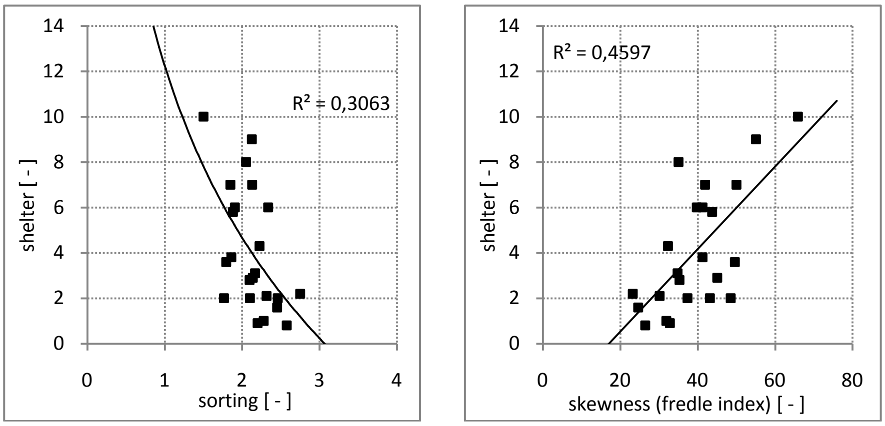



Figure 4.8: Sorting index left) and skewness (right) plotted against shelter abundance (all samples >128 mm, n= 23)

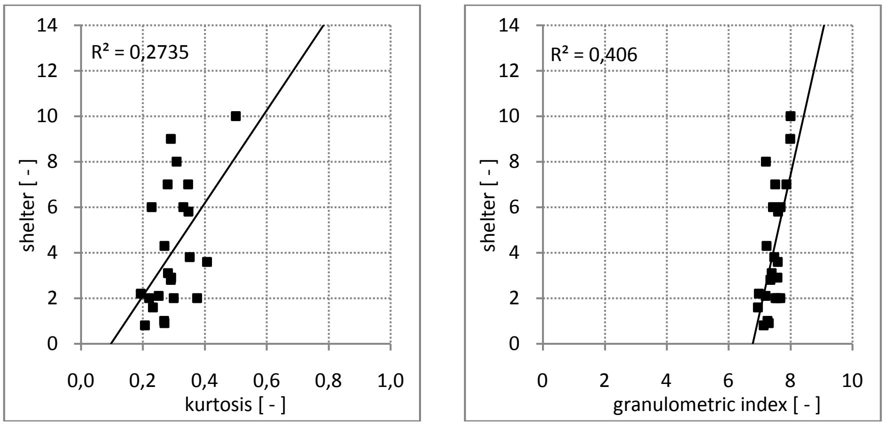



Figure 4.9: kurtosis (left) and granulometric index (right) plotted against shelter abundance ( all samples >128 mm, n= 23)

Correlation quality is generally lower than in the previous chapter. Highest determination coefficient is again delivered by $D_5$ percentile plotted against shelter abundance with $R^2 = 0.59$. The four distribution parameters geometric mean, sorting, skewness and kurtosis deliver determination coefficients between $R^2 = 0.25$ and 0.45. The lowest one is achieved by plotting kurtosis values against shelter abundance with $R^2 = 0.27$. Granulometric index delivers a determination coefficient of $R^2 = 0.4$.

Lower correlation quality in general compared to the previous chapter can be explained by more varying $D_{max}$ values which affect strongly on the grain size parameters, in particular on geometric mean and skewness. In chapter 4.1 $D_{max}$ values are more constant due to a more homogeneous distribution of large particles in the sediment samples and differences in grain size parameter values are more based on the amount of fines (consequently higher correlated to number of measured shelter). In this chapter $D_{max}$ values are more differing due to a broad range of particle size in the coarsest size class (128 – 256 mm). So, the parameters are influenced by both the amount of fines and coarse particles and cannot explain shelter abundance to such a high degree as seen before.

D5 percentile is least affected by varying $D_{max}$ and delivers highest determination coefficient among all parameters. Moreover, in the graph (Figure 4.7, left) one outlier point is clearly visible on right side of the regression line. Determination coefficient increases from 0.59 to 0.75 when excluding it.

Again for all shelter abundances the corresponding grain size parameters are averaged and plotted against shelter abundances. The graphs are shown in the following.

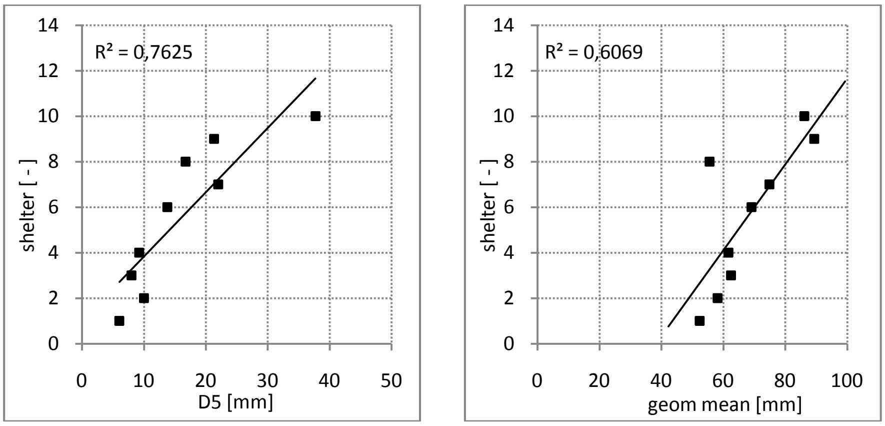



Figure 4.10: Per shelter number averaged $D_5$ (left) and averaged geometric mean (right) plotted against shelter abundance (all samples >128 mm, N= 23)

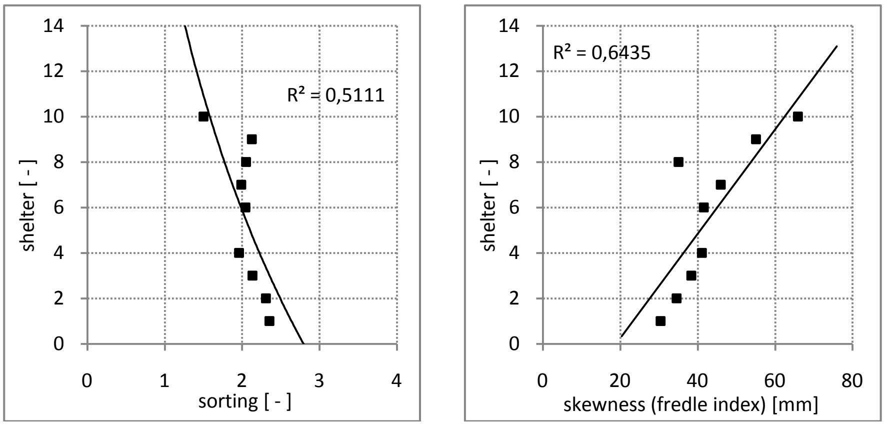



Figure 4.11: Per shelter number averaged sorting index (left) and skewness (right) plotted against shelter abundance (all samples >128 mm, N= 23)

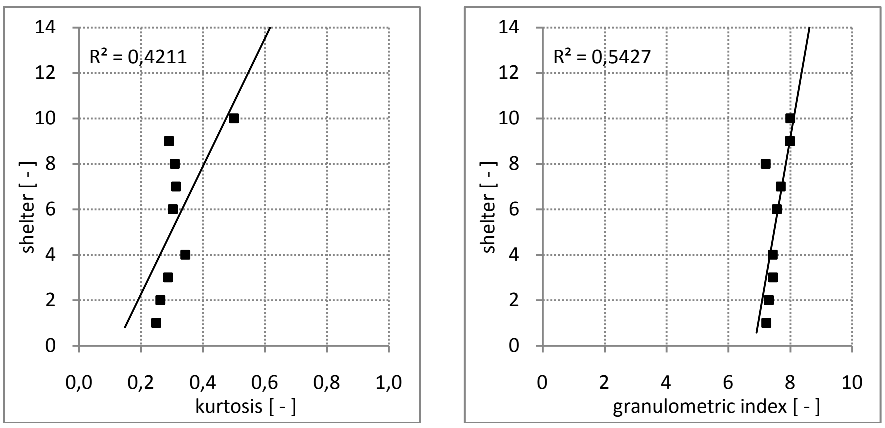



Figure 4.12: Per shelter number averaged kurtosis (left) and granulometric index (right) plotted against shelter abundance (all samples >128 mm, N=23)

Highest observed determination coefficient is delivered by $D_5$ plotted against shelter abundance (according to raw data, not averaged $R^2 = 0.59$) with 0.76 and lowest one is delivered by kurtosis with 0.42 (raw data, not averaged $R^2 = 0.27$). However, correlation quality is generally lower than the one achieved in the previous chapter for before mentioned reasons.

## 4.4 Pooling of all samples

In the previous chapters the samples were distinguished regarding their maximum particle size. In this chapter all samples are pooled into one data set and the parameters are plotted against shelter abundance. The following figures show the graphs.

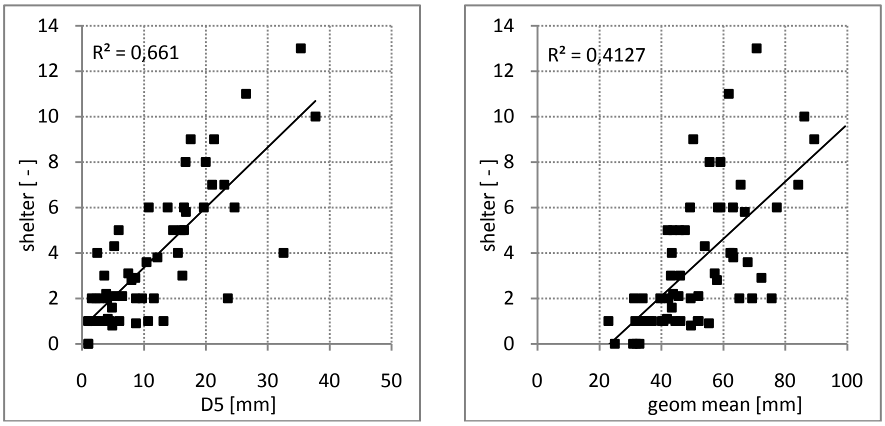



Figure 4.13: D5 percentiles (left) and geometric mean (right) plotted against shelter abundance (all samples, n= 61)

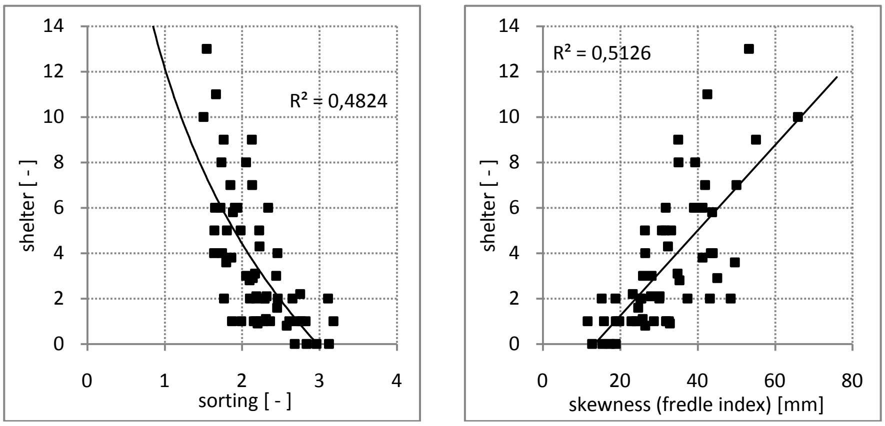



Figure 4.14: Sorting index (left) and skewness (right) plotted against shelter abundance (all samples, n= 61)

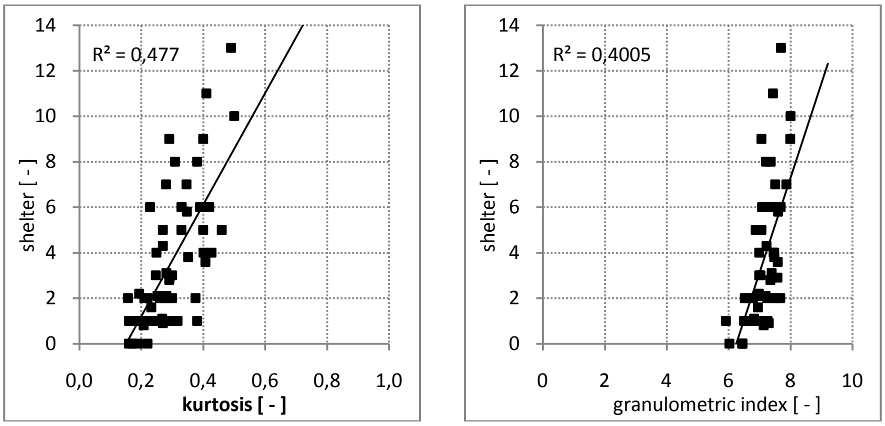



Figure 4.15: kurtosis (left) and granulometric index (right) plotted against shelter abundance (all samples, n= 61)

Highest determination coefficient is delivered by $D_5$ percentile plotted against shelter abundance with $R^2 = 0.66$, lowest one is delivered by granulometric index with $R^2 = 0.4$. Compared to the so far seen results it is only $D_5$ percentile which delivers a stable determination coefficient. For all other parameters correlation quality decreases, partly strongly.

Again for all shelter abundance numbers the corresponding grain size parameters are averaged and plotted against shelter abundances. The graphs are shown in the following.

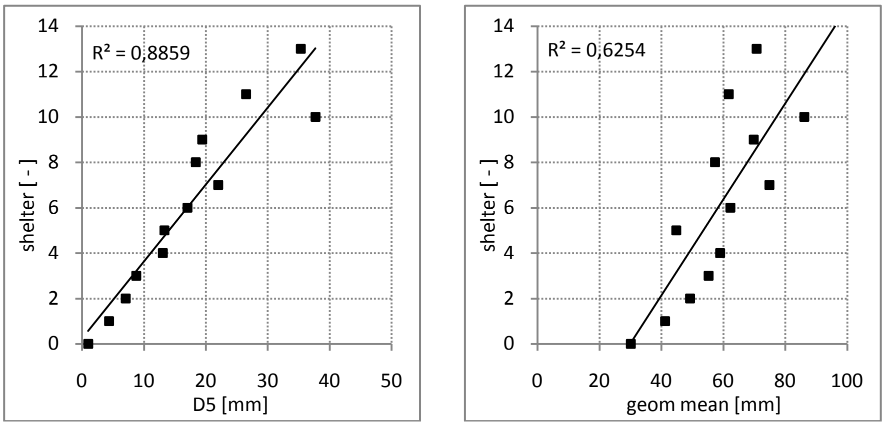



Figure 4.16: Per shelter number averaged $D_5$ (left) and averaged geometric mean (right) plotted against shelter abundance (all samples, N= 61)

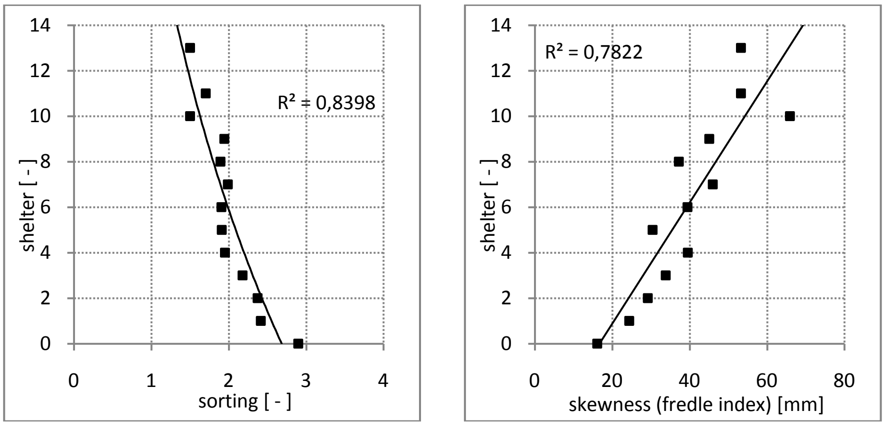



Figure 4.17: Per shelter number averaged sorting index (left) and skewness (right) plotted against shelter abundance (all samples, N= 61)

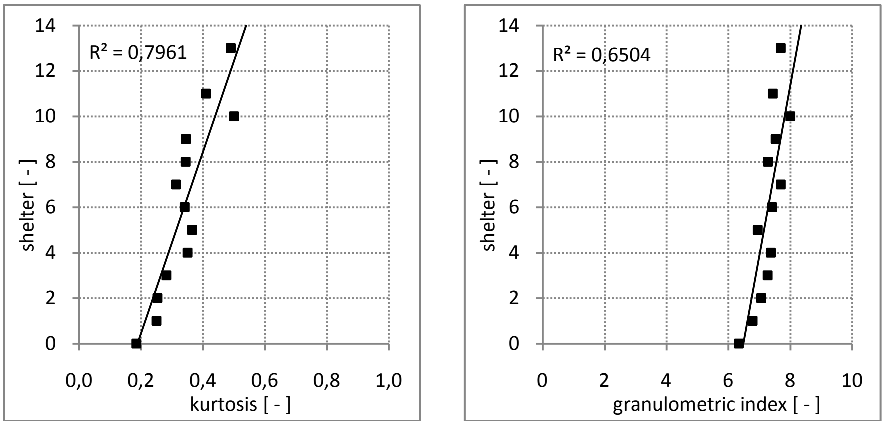



Figure 4.18: Per shelter number averaged kurtosis (left) and granulometric index (right) plotted against shelter abundance (all samples, N=61)

Highest observed determination coefficient is delivered by $D_5$ plotted against shelter abundance with $R^2$ = 0.89 and lowest one is delivered by geometric mean with 0.63 (raw data, not averaged $R^2$ = 0.41). Sorting index coefficient increases very strongly to $R^2$ = 0.84 for the averaged data set.

In the next chapter all gathered determination coefficients are summarized and discussed in detail.

## 4.5 Summary of results and detailed examination of $D_5$

In the previous chapters all parameters were plotted against shelter abundance. All gathered determination coefficients are summarized in the following table for an overview of so far shown results.

Table 4.1: comparison of determination coefficients

| Parameter | Determination coefficients $R^2$ Samples ($D_{max} \leq 128$ mm) | | Determination coefficients $R^2$ Samples ($D_{max} \leq 256$ mm) | | Determination coefficients $R^2$ All samples | |
|---|---|---|---|---|---|---|
| | Raw data | Averaged grain size parameters | Raw data | Averaged grain size parameters | Raw data | Averaged grain size parameters |
| $D_5$ percentile | 0.68 | 0.91 | 0.59 | 0.76 | 0.66 | 0.89 |
| Geometric mean | 0.60 | 0.81 | 0.43 | 0.61 | 0.41 | 0.63 |
| Sorting | 0.55 | 0.86 | 0.31 | 0.51 | 0.48 | 0.84 |
| Skewness (Fredle index) | 0.64 | 0.86 | 0.46 | 0.64 | 0.51 | 0.78 |
| Kurtosis | 0.58 | 0.89 | 0.27 | 0.42 | 0.48 | 0.80 |
| Granulometric index | 0.53 | 0.76 | 0.41 | 0.54 | 0.40 | 0.65 |

The best parameter found to explain shelter abundance is $D_5$, both for the samples including maximum particles ≤ 128 mm and ≤ 256 mm and also in the combination of these data sets. Also, when averaging the grain size parameters and plotting against shelter abundance the correlation quality is highest for $D_5$ percentile.

It is assumed that the amount of fines influence on shelter availability for fish. $D_5$ percentile is an indicator of the amount of fines and explains best measurable shelter abundance. The other parameters describe the sediment composition more comprehensively and are possibly therefore lower correlated to shelter abundance than $D_5$.

Remarkably is, that sorting index delivers a relatively high determination coefficient when pooling all samples and averaging the grain size parameters compared to the raw data. This implies a tendency of grain size parameters however on a broad range especially for low shelter quantities (see Figure 4.14).

Geometric mean is relatively high correlated to shelter abundance for the samples ≤ 128 mm but loses correlation quality considering the samples ≤ 256 mm and also when pooling all samples. It seems that this parameter is able to explain shelter abundance in stable $D_{max}$ environments but not in strongly fluctuating $D_{max}$ environments. In this respect kurtosis and skewness are more stable, at least for the averaged parameter consideration.

Granulometric index behaves relatively similar to geometric mean, which is also a parameter describing the whole sediment composition with an average value.

$D_5$ percentile is examined more in detail in the following and graphs are shown in Figure 4.19 and Figure 4.20.

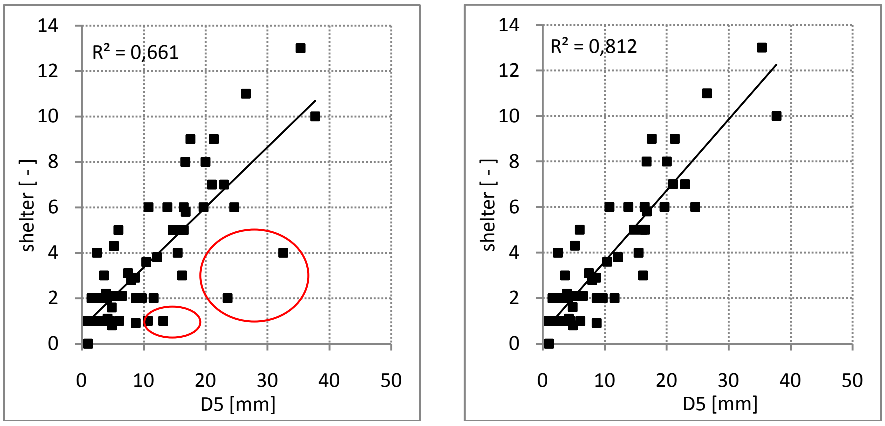



Figure 4.19: $D_5$ percentiles plotted against shelter abundance, all samples (left, n =61), outlier points excluded (right, n= 57)

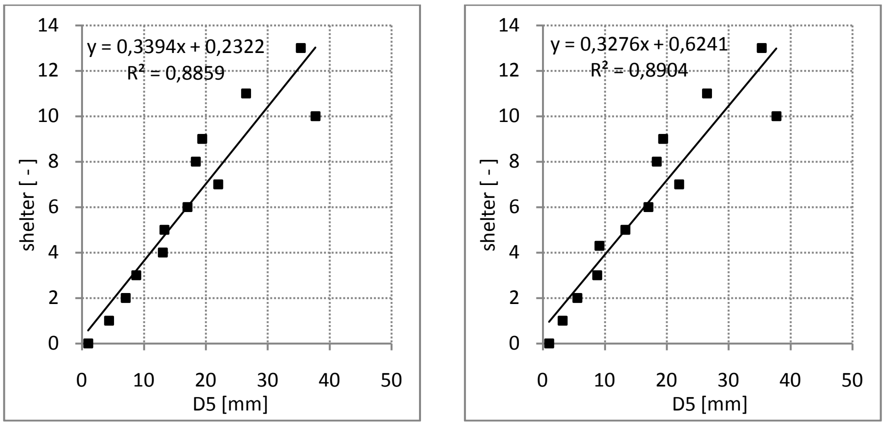



Figure 4.20: averaged $D_5$ percentiles per shelter number plotted against shelter abundance, all samples (left, N= 61), outlier points excluded (right, N= 57)

On the left side of Figure 4.19 the graph for D5 percentiles plotted against shelter abundance consisting of all samples is shown. Supposed outlier points are emphasized in red circles and excluded on the right side graph of Figure 4.19.

Correlation quality increases strongly. The excluded outlier points are all below the regression line, meaning that for observed $D_5$ values the measured shelter abundance is too low, maybe an effect induced by shelter measurement with the relatively large outside diameter of the PVC tube.

In Figure 4.20 the averaged $D_5$ percentiles are plotted against shelter abundance, the left graph using the whole data set as basis and the right one excluding the outlier points analogue to Figure 4.19. The determination coefficient increases only marginally when excluding outliers. Another problem are values gathered for high shelter abundances. Firstly, they are scarcely and secondly, following from that, they deviate from the generated regression line quite strongly. Probably, more values in these shelter classes would have an averaging effect and increase correlation quality.

# 5 Discussion

## 5.1 Methods

The method by Finstad et al. (2007) was developed in the context of embeddedness methods, which have been established to describe habitat quality for juvenile fish. The method offers the possibility to measure and quantify places for fish to shelter and thereby valuable habitat space in contrast to traditional embeddedness methods. It is easily conductible, objective and neither expensive equipment nor experienced operators are needed. Additionally it is applicable in dry as well as in inundated areas when the water is not too turbid. The results of the method are a quantity of voids which can be used by fish as shelter possibility, both against the current and predators. However, the method is not able to be modeled neither in currently existing sediment transport nor habitat models. The fish used in the initial experiment were one summer old generation salmon (0+) with a mean length of 105 mm (± 9 SD). Based on this study the rubber tube in use has 13 mm outside diameter which implies shelter space for relatively large juvenile fish. Shelter were measured in three categories but considered in the analysis as a total quantity because of a small data pool which didn`t allow to distinguish regarding the shelter depth.

Traditional grain size analysis using small scoops and sieving technique was executed. Problems in this study arose thinking about the size of the sediment samples. Restrictions were given for the area to be sampled by the square of 0.5 m x 0.5 m and the depth to be excavated by the largest particle visible from top, the mass of the samples regarding the portability (conductibility of field work) and the adequate size of samples to representatively reflect the grain size distribution. Theoretically, particles <128 mm can be sampled adequately within the area and resulting sample mass. Larger particles, however rather need larger sample masses.

Field work was restricted to dry areas because it was preferred not to lose fine sediments in the current. More advanced techniques to sample sediments in running waters are presented in literature. Two different kinds of freeze approaches using liquid nitrogen are proposed, freeze core and freeze panel sampling. The freeze core technique enables the user to sample undisturbed stratified subsurface / subarmor probes but loses the armor layer due to cooling losses induced by the current in the top layer. The freeze panel technique enables the user to sample surface sediment as well, explained in Blaschke et al. (2003). Another technique proposed is the McNeil Sampler (explained in Bunte & Abt, 2001) to capture fine sediments. Above mentioned devices were not available for this study but are subject to think about for future investigations. This would open the possibility to take representative samples in inundated areas as well.

## 5.2 Results

The aim of this study was to find a usable correlation between the physical measures of grain size distribution parameters and the biological measure of shelter abundance serving as a basis to be implemented in sediment transport modeling. The results show that relationships between grain size distribution parameters and shelter abundance can be described. The results show as well that certain grain size distribution parameters are capable to explain shelter abundance to a relatively high degree whereas others are not suitable for this purpose.

The analysis is divided in three parts. The first part examines all samples gathered with a maximum grain size $D_{max} \leq 128$ mm, the second one all samples with a maximum grain size $D_{max} \leq 256$ mm and in the third part data all samples are examined together. Finally, best found grain size parameter to explain shelter abundance is examined more in detail.

Probes with $D_{max}$ values below 64 mm (no particles in size classes >64 mm) lead consequently to zero measurable shelter possibilities. These samples were excluded from the analysis but herein mentioned as investigated and used as information for a lower boundary of grain size leading to shelter activity.

## 5.3 Samples containing maximum grain size particles ≤ 128 mm

Percentile values of the center ($D_{50}$) and coarse tail of the distribution ($D_{90}$ and $D_{95}$) are not able to explain shelter abundance. They are weakly influenced by fines and consequently weakly correlated to shelter abundance. Observed correlation quality was so low that these parameters are completely excluded from the data presentation. In contrast, the percentiles of the fine tail of the distribution ($D_5$ and $D_{10}$) as an indicator for the amount of fines explain shelter abundance to a relatively high degree. $D_{95}$ values are relatively constant indicating that the frame of coarse particles is similar among the probes. The amount of fine sediments is differing between the probes indicated by fluctuating low percentiles. This reflects and confirms the assumption that shelter abundance is influenced by the amount of fines in the sediment composition. Moreover it shows that percentiles characterizing the fine tail of the distribution are able to act as indicators for interstitial voids under the restriction of nearly constant $D_{max}$ values (around 120 mm) which is valid for all included samples in this part of the analysis.

## 5.4 Samples containing maximum grain size particles ≤ 256 mm

The excavated samples of the approach do not comply with the requirement of sample size regarding correct representation of coarse particles. Despite of that they were analyzed and the computed parameters plotted against shelter abundance. The results imply that possible incorrectness of calculated grain size parameters is superimposed by other effects related to the correlation precision, e.g. the fuzziness inherent in the biological method of measuring shelter abundance. This part of the analysis shows similar tendencies like the ones observed in the previous chapter, but generally on lower correlation quality. One main difference to part one is that $D_{95}$ values are not very stable around one value and fluctuating in between the borders of the coarsest grain size class (128 – 256 mm). However, they are not strongly correlated to shelter abundance. This means that high $D_{max}$ values do not lead consequently to high shelter quantities. $D_5$ percentile values are relatively robust against this influence but distribution parameters which consider the whole range of the grain size distribution are more impacted and show lower correlation quality.

## 5.5 Pooling of all samples

The range of included coarse particles is very large and consequently the $D_{95}$ values are strongly differing but not correlated to shelter abundance, however. On the other hand $D_5$ percentiles deliver high coefficients of determination in changing $D_{max}$ environments. The combination of data shows that the distribution parameters geometric mean and skewness (fredle index) which delivered high determination coefficients in the first part (constant $D_{95}$ environment) are not robust enough to deliver high determination coefficients during the combination. Sorting index, however provides high determination coefficients under changing $D_{95}$ environment which makes it to the most robust distribution parameter beside of $D_5$.

## 5.6 Averaging grain size parameters

With averaging the grain size parameters for samples with equal number of measured shelter the correlation quality reaches values around $R^2 = 0.8$ to 0.9 which implies a high dependency between grain size parameters and shelter abundance (excluded geometric mean and granulometric index). What needs to be checked for further investigations and developments are the standard deviations around the mean values of grain size parameters per shelter number. These are very differing because of differing numbers of samples with equal shelter abundances and consequently resulting differences in the range of deviations around the mean value.

# 6 References


Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M. and Milner, N.J. (2002) Habitat requirements of Atlantic salmon and brown trout in rivers and streams. *Fisheries Research*, 62, (2), 143-170

Blaschke A. P., Steiner K.H., Schmalfuss R., Gutknecht D., Sengschmitt D. (2003) Clogging Processes in Hyporheic Interstices of an Impounded River, the Danube at Vienna, Austria, International Review of Hydrobiology, Volume 88, Issue 3-4, pages 397–413

Bunte, K., and Abt, S. R. (2001) Sampling surface and subsurface particle-size distributions in wadeable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring," General Technical Report RMRS-GTR-74, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO

Finstad, A. G., Einum, S., Forseth, T. & Ugedal, O. (2007) Shelter availability affects size-dependent and mean growth of juvenile Atlantic salmon. Freshwater Biology, 52: 1710-1718

Finstad, A. G., Einum, S., Ugedal, O., Forseth, T. (2009). Spatial distribution of limited resources and local density regulation in juvenile Atlantic salmon. Journal of Animal Ecology, 78, 226-235

Hedger, R.D., Dodson, J.J., Bergeron, N.E., Caron, F. (2005) Habitat selection by juvenile Atlantic salmon: the interaction between physical habitat and abundance. Journal of Fish Biology, Volume 67, Issue 4, pages 1054–1071, October 2005

Heggenes, J., Saltveit, S.J. (2007) Summer stream habitat partitioning by sympatric Arctic charr, Atlantic salmon and brown trout in two sub-arctic rivers. Journal of Fish Biology, Volume 71, Issue 4, pages 1069–1081

Heggenes, J., Dokk, J.G. (2001) Contrasting temperatures, waterflows, and light: seasonal habitat selection by young Atlantic salmon and brown trout in a boreonemoral river. Regulated Rivers: Research & Management, Volume 17, Issue 6, pages 623–635

Huusko, A., Greenberg, L., Stickler, M., Linnansaari, T., Nykänen, M., Vehanen, T., Koljonen, S., Louhi, P., Alfredsen, K. (2007) Life in the ice lane: the winter ecology of stream salmonids. River Research and Applications, Volume 23, Issue 5, pages 469-491

Jocham, S. (2010) An approach to link shelter abundance and grain size distribution for the assessment of substrate quality for juvenile Atlantic salmon, Diploma Thesis, University of Stuttgart

Krumbein, W.C., Pettijohn, F.J. (1938) Manual of Sediment Petrography: New York, Appleton-Trask, P.D., 1932. *Origin and Environment of Source Sediments in Petroleum*. Gulf Publishing Company, Houston, Texas, 324 pp. Century Crofts, Inc., 549 p

Millidine K.J., Armstrong J.D. & Metcalfe N.B. (2006) Presence of shelter reduces maintenance metabolism of juvenile salmon. Functional Ecology, 20, 839–845

Neumann-Mahlkau, P., (1967) Korngrößenanalyse grobklastischer Sedimente mit Hilfe von Aufschluß-Photographien. [Granulometric analysis of rudites on outcropphotographs.] Sedimentology 9: 245-261

Valdimarsson, S.K., Metcalfe, N.B. (1998) Shelter selection in juvenile Atlantic salmon, or why do salmon seek shelter in winter? Journal of Fish Biology 52: 42–49

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