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Shelter for juvenile Atlantic salmon: availability and prediction in rivers with and without hydropower regulation.

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Master's Thesis
Submission date: June 2015
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Abstract

It is assumed that river regulation in general and hydropeaking in particular, cause 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 spaces (shelter abundance for fish) in running waters. Shelter availability is a candidate mechanism for the survival of juvenile salmon due to the reduction of predation risk and is influenced by the degree of fines.

The first goal of this study is to find better relationship between shelter abundance measured with the method by Finstad et al. (2007), and grain size distribution. This relationship will be based on a dataset by (Jocham, 2010) and own data gathered from the river Gaula in Norway.

The second goal of the study is to implement the new relationship into the one-dimensional hydraulic model HEC-RAS, in order to predict the development of shelter over time. Here, two main flow scenarios will be investigated at two river sites, Lundesokna and Nidelva streams from Middle-Norway. As a forerunner before the main simulations, sensibility tests will be run to estimate differences between several empirical sediment transport equations, sorting methods, computational time steps and an extreme flood event's effect on river bed. In the case of main flow scenarios, the first hydrograph consists of an average yearly runoff without the hydropower regulation. The second hydrograph will be in correlation with the yearly energy production of the regulation power company.

The comparison at the end of the study contains the main differences between the two type of hydrograph related to chosen and calculated parameters. These variables proved their worth to play key factors in the differentiation between operated and natural type of hydrographs with their effects on river bed morphology. Nevertheless, major differences cannot be observed among the cases, some anomalies are occurred in details, which are going to be explained at the evaluation of the results.

Tartalmi kivonat

Feltételezhető, hogy a folyószabályozás általánosságban, a vízerőművek pedig különösen veszélyeztetik a fiatalkori lazacok természetes élővilágát a megnövekedett finomszemcséjű hordaléknak köszönhetően. A menedékkeresés kényszerűség a fiatal lazacok számára, hiszen megbújva bennük nő a túlélés esélye. E búvóhelyek elérhetősége azonban nagyban függ a mederben található finomabb szemcsék részarányától. Finstad és munkatársainak (2007) köszönhetően egy egészen egyszerű módszert sikerült kifejleszteni az említett búvóhelyek felmérésére a folyómederben.

A tanulmány egyik célja, hogy a Finstad módszer (2007) által feltárt búvóhelyek és a befoglaló közeg, azaz görgetett hordalék szemeloszlása közötti kapcsolatot egyértelműsítse. Egy korábbi tanulmány (Jocham, 2010) saját mintákkal kiegészített adatbázisa szolgál alapul a fizikai kapcsolat megerősítésére.

A diplomamunka második fele a korábban definiált kapcsolatot használja fel egy-dimenziós hidraulikai modellben (HEC-RAS), hogy vizsgálja a búvóhelyek idő alatt bekövetkező változását. Kétféle vízjárási állapot kerül tanulmányozásra közép Norvégia két modellezett vízfolyásán, a Lundesokna és Nidelva folyón. A ténylegese futtatásokat megelőzően érzékenységvizsgálat készül a modell kezdeti beállításaira, mely során eltérő hordalékszámítási összefüggések, hordalékvastagság osztályozás, számítási időlépés, valamint két, eltérő maximális vízhozamú árhullám hatása kerül röviden értékelésre. Ezt követően a kiválasztott folyószakaszokra egy természetes és egy az energiatermelést tükröző szabályozott vízjárási állapotra történnek a főbb vizsgálatok.

A tanulmány végén a két vízjárási állapot összevetése található modellezett és azokból számított változókon keresztül. E változók kulcsfontosságúak lehetnek a későbbiekben is a szabályozott és szabályozatlan vízjárások folyómederre gyakorolt hatásainak elemzésében. Mindazonáltal a nagyobb különbségek helyett számos kisebb eltérés figyelhető meg a két eset között, melyek az adatok értékelésénél kerülnek tárgyalásra.

Preface

The effect of an engineering facility cannot be assessed from one perspective only, and for this reason we, engineers have to be open minded to understand what others represent in their views. Although an engineering student meets with scientific disciplines predominantly during his/her semesters, personal meeting with stakeholders is of similar importance. This meeting could be a personal talk, participation at local forum, measurement in a laboratory or just observation on the field. The investigations should be made in collaboration with other sciences related to natural habitat where shelter abundance belongs to as well. This prologue ought to clarify my engagement in the eco-hydraulic researches.

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1 Introduction

The world's energy demand along with its supply, is permanently growing. The generally accepted and applied energy sources, like fossil oil and gas as non-renewable or wind, solar or hydropower as renewable and their technologies have to compete with each other. In the 21^{st} century the winner of this race shall be those types of applications, which will produce more energy in a sustainable way, both in environmental and economic terms. In a nutshell, humanity has to find the balance between the energy production and its impact on the environment. The hydropower is a promising solution, where it can be applied.

Norway has a good hydro-potential, and the country already utilizes that for produce enough energy to cover almost fully its needs. In 2012, Norway generated 143 TWh energy by hydropower plants (IEA, 2013), which was the highest among the European countries. The hydropower plants have low carbon emission into the nature, however, it have a great impact on the environment locally. Many studies had been born to provide better insight into the effect of these constructions on a river and the ecosystems, but this problem calls for further inquiry.

One of the most honoured treasures of the Norwegian rivers is the *Salmo Salar*, aka the Atlantic salmon. It prefers to spawn at upstream river sites, and it grows there in its first years. Earlier studies have already showed that juvenile fish prefers river beds which have a good shelter potential. Based on those studies, the next investigation of this research is to examine the coarse sediments changing in a long-term period on regulated and unregulated scenarios, by one-dimensional hydraulic modelling associated with the habitat of the salmon.

2 Objective/Task

Design and plan an engineering facility is more complicated nowadays, than it was before. An engineer, mainly an infrastructural engineer, not only serves the economic and social interests, but the nature must be taken into account as well. Extensive research has already been conducted and is under process to estimate how the facilities effects on the environment. Before regulating a river, it has its own range of hydrograph, which has an impact on its river bed. The natural flows carry fine sediments, and flood events can form the bed easily with moving fine and course particles away. When the river is being regulated, for example by constructing a dam, or by bed protection, it is known that it has a huge impact on a river and its ecosystem. In the upstream of the dam fine sediment can stagnate, while the downstream can lack it. Still, the regime of hydropower plant tends to change rapidly and frequently (the process called: hydropeaking), which reduces the aforementioned problem. One has to look up bed embeddedness, which is one of the relevant parameter to estimate the natural habitat of the juvenile fish (Sylte & Fischenich, 2002). A number of methods were developed to measure its level in different ways. In this study the method of Finstad was chosen, based on the main finding of earlier projects (Jocham, 2010). This method tries to find shelters on an area of a predetermined size, where young salmons can hide. After counting shelters with different depths samples of the river-bed must be taken from the same area, and further investigated in laboratory. Earlier studies proved that there is correlation between a few geometric parameters, such as distribution frequencies and shelter abundance (Jocham, 2010; Honsberg, 2011). In the first part of this thesis I try to confirm their results with my own gathered samples, then to clarify correlation by moderate changes in the process.

In the lower section of river Lundesokna and Nidelva I will analyse the coarse sediment changing over 20 years, with quasy-unsteady flow conditions by using 1D hydraulic engineering software (HEC-RAS). Lundesokna and Nidelva are regulated rivers in Middle-Norway, their powerplant were built in the 20th century and the proper hydrograph activity is same old. With long term simulations I will compare the effects of the flows among the cases. The time-series are ready to use for each case. Sediment samples are taken at same river part to set up the models based on the reality. After the simulations the received outcomes must be taken under post-processing to evaluate them. Furthermore, this post-processing contains the aforementioned aspects which considering the status of natural habitat of young Atlantic salmon. In connection with this, I'll try to overview entire database of the results to understand more the affected environmental conditions for the natural wildlife.

3 Biological bases

3.1 Natural habitat

The physical and chemical factors that affect an animal not just in the immediate vicinity, but also on a broader scale of spatial and temporal impacts are commonly summarized in the phrase: 'habitat' according to Armstrong et al. (2002).

The freshwater fish requires a few physical parameters that can be simply measured related to water flows such as water depths, flow velocity, suspended sediment, bed material's grain size, temperature and brightness. Biological parameters and factors, such as availability of food, hiding from predators, competition amongst others or mitigation are slightly harder to examine. The proper habitat plays a key role for the fish as it grants good conditions for reproduction and growth in safe. Thereby the habitat is a limiting factor, and it determines the water-carrying capacity and population density for running water fish, according to Armstrong, et. al. (2002) and Heggenes et. al. (1999). There are two main types of habitat variables which affect carrying capacity and are shown on the next figure.

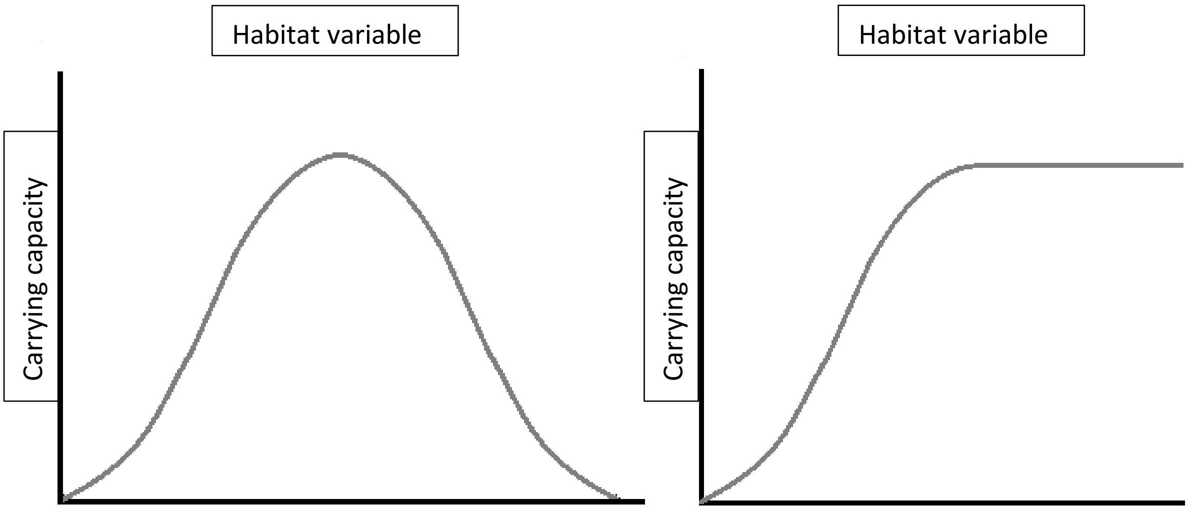


Figure 3-1 Two main types how habitat variables effect on carrying capacity

The first curve on the left side of Figure 3-1 shows a habitat pattern where there is an optimum value of carrying capacity but below and above of it the capacity decreases. On the right side of the Figure 3-1 the pattern shows that after reaching the maximum value of carrying capacity it is no longer a limiting factor for an animal. Carrying capacity like the shelter availability belongs to the second type (Jocham, 2010), tough it is difficult to classify the habitat itself by selecting one limiting factor according to Armstrong et al. (2002). Physico-chemical parameters like pH, dissolved oxygen, water depth, flow velocity change frequently, the substrate with shelters might change during flood events, therefore it seems as an alternative way to get information about types of habitat which are already successfully used by fish (Jocham, 2010; Honsberg, 2011).

3.2 Atlantic salmon

The Atlantic salmon (aka. *Salmo Salar*) is a good indicator species for grading the river ecosystems (Noack, 2005). As the Atlantic Salmon Federation writes:

„Flashing silver as it jumps a 3 meter waterfall, the Atlantic salmon has become a symbol of wildness that is to be cherished into the future. It is a symbol of healthy river systems and of the importance of looking at a species in a truly international way."

This kind of fish is anadromous, means it grows in its first years in sweet water after hatching, then moves into the sea to spend the major part of its life there and later on migrates back to spawn in the river where it was born. Therefore its life cycle can be divided into the aforementioned three major parts. In regard of my thesis the relevant part of its life cycle is the first stage.

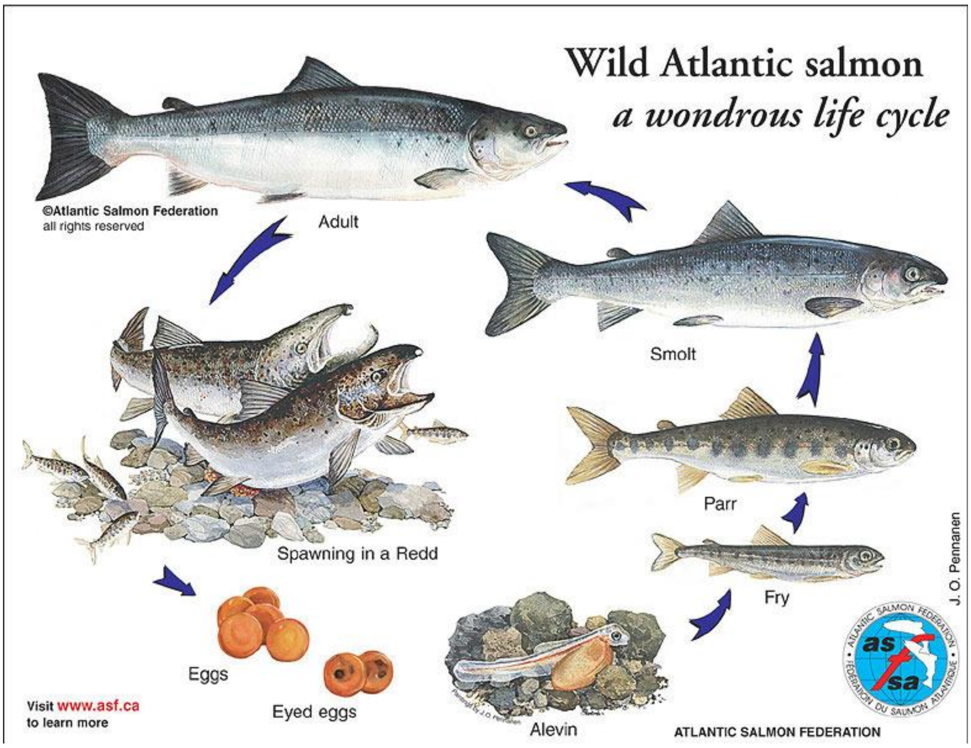


Figure 3-2 Life cycle of the Atlantic salmon (source: www.asf.ca/life-cycle.html)

Atlantic salmon is shown in its different life stages in Figure 3-2 . When mature fish spawn in rivers during autumn the salmon eggs hatch at the next spring. The 2 cm long alevins initially stay in the river-bed and subsist of their yolk sac in the next 45-140 days. Within this time they avoid the predators and waits for suitable temperature. When the egg yolk is already absorbed they make their way up through the gravel, and swim as a fry. They are called fry until they reach the 5-8 cm length until the end of their first summer, and then become parr. Generally they spend their first 2-4 years in sweet water to earn 12-24 cm length, depending on environmental conditions, until they physiologically can adapt the salt water and start migrate into the sea.

Shelter abundance is a significant parameter of the river-bed when we examine the habitat of the Atlantic salmon in rivers. The interstitial space for juvenile fish is more relevant to avoid predators than for example protection from the current. Their predators, like birds and mammals, hunt during daytime from the shore, therefore remaining invisible can increase the chance of survival in these times. Earlier studies had proved that young fish prefer those river stretches where corresponding abundance of shelters can be found (Valdimarsson & Metcalfe, 1998). Shelter availability means that the river-bed contains low amount of fine sediments in the same time, namely the embeddedness is low.

3.3 Preferences for juvenile Atlantic salmon

The response by the Atlantic salmon to the environmental condition varies seasonally. In summer times their dominant behaviour is mainly nutrition during the daytime, and it changes as the weather becomes colder. Their diurnal pattern to sheltering in interstitial gaps during the whole day, where they can be closer to the substrate and the current flow is slower (Heggenes & Dokk, 2001; Heggenes & Saltveit, 2007).

The optimal water level for salmonids is changing during their life-cycle. The newly emerged fries prefer maximum 10 cm water depth according to Heggenes et al. (1999), which is increasing during their growing. As to the few weeks old fries their preference is changing from 20 to 40 cm as stated by Morantz et al. (1987) and as a parr they preferentially chose river sites with 65 cm maximum water depth according to Hedger et al. (2005). Their preference to water velocity is changing as well. As a new-born fry the maximum water speed has to be around 5-15 cm/s as stated by Morantz et al. (1987) but few weeks later they already strong enough to live areas with 4-43 cm/s water velocity according to Hedger et al. (2005), and as a parr it increases 100 cm/s based on the study of Heggenes et al. (1999). The substrate preference is different from the named physical parameters. Generally the Atlantic salmon parr avoids those sites where the substrate size 16 mm or less. According to Heggenes et al., (1999), young salmonids can be found easily at river parts with coarser elements (16-256/512 mm). In addition, they migrate to lower parts as they become from parr to smolt, but to look for deeper areas and pools becomes more important than substrate for habitat choice as stated by Morantz et al. (1987).

Aforementioned two hypotheses also had been supported by real tests by Valdimarsson and Metcalfe (1998), and they observed that to avoid predators is more significant than the protection from the current. A section of the river-bed, where flow is relatively strong but shelter abundance is high is even preferred by salmonids. Their main predators are birds who hunt in daytime. Therefore shelter availability increases the chance of survival for juvenile fish. The essential parameter could be the fragment size, or an index related to that (Jocham, 2010). Thus the substrate structure can be a key factor to describe generally their hiding possibilities, while it can grant places where they can flee, hide or reduce their visibility from the air, and determines their long-term population. Another study had revealed that the aforesaid behaviour leads to decreased maintenance of metabolism due to the reduced levels of mental alertness, thanks to Finstad et al. (2007), and it is assumed to say that the pure chance to hide against predators, which means being covered from above, decreases salmonids' stress level rather than the active act of sheltering based on the work of Millidine et al. (2006). Consequently it is a limiting habitat variable and thereby it has to be a key habitat factor which should be investigated in environmental assessment procedures of the Atlantic salmon (Jocham, 2010).

4 Basis concepts

4.1 Embeddedness

When the degree of larger substrate particles buried in fine materials is determined, it is called embeddedness. This feature can be separated to inner and outer embeddedness. The deposition of the fine particles in the pore space of the river bed is called inner, when the deposition is on the river bed it is called outer embeddedness (Schaelchli, 2002). Inner embeddedness causes degradation of pore spaces and uploading of river bed. The permeability is reduced whereas oxygen flux is habited. Outer embeddedness leads to unstable bed substrate while reduces permeability and oxygen flux of river bed. Based on the geometrical embeddedness criterion which defines the particle size that can pass through interstitial spaces or wedged there (Noack, 2005). According to Schaelchli (2002), a few negative effects on natural habitats appear as fine sediments accumulation appears.

Fine particles are unstable and altering discharge leads to changing living environment. Accumulation of fine sediment leads to reduce infiltration to deeper zones, which provides less oxygen there. Sufficient oxygen is a critical condition for gravel spawning fish species and benthos to ensure survival. The valuable natural habitat for macrozoobenthos is the interstitial spaces which can be uploaded by fine particles easily. Different levels of embeddedness can be seen in the following Figure 4-1.

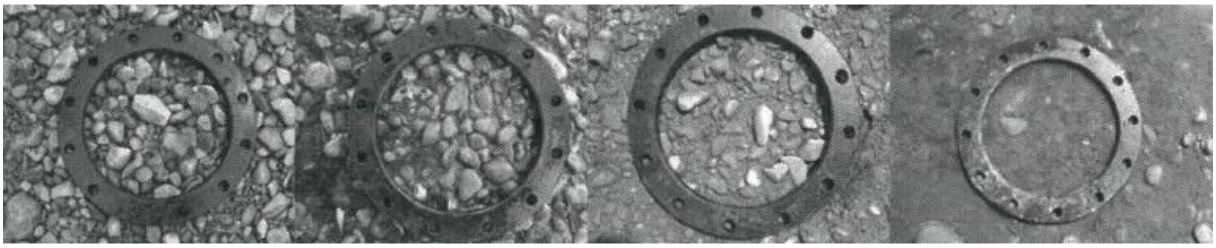


Figure 4-1 Different levels of embeddedness (Eastman, 2004)

As a conclusion the juvenile fish like salmonids prefer interstitial spaces because of different approaches, thereby this study only deals with inner embeddedness, where the increased degree of accumulation affects negatively their natural habitat according to Finstad et al. (2007).

4.2 Shelters and their measurements: the Finstad method

Measuring shelters can be difficult at first sight. The description and quantifying of embeddedness and substrate quality for juvenile fish is strongly connected with fine sediments accumulation or lack thereof, which has effect on shelter abundance. Keeping this in mind Finstad et al. (2007) developed an easy and fast method to evaluate substrate and embeddedness in regards to measure available interstitial places for young salmonids.

By using a rubber tube shelters can be detected and classified easily. Experiments were carried out in semi-natural channels where hiding places were searched with different tubes with various diameters (5 – 10 – 13 – 16 – 22 mm) by Finstad et al. in the year of 2007. Using a selected tube they tried to place them into interstitial voids, and if the penetration was deeper than 3.0 cm the shelter has been registered. Each shelter with a single entry is counted, for example a Y shaped void with three enters was counted three times. Substrate must be let undisturbed during the process. Each rubber has different marks to classify shelters. Three classes were determined to sort shelters into different types based on their depth: 3.0 – 7.0 – 12.0 cm. Unseen marker determines the class of a shelter during process.

The tube with 13 mm outside diameter served the best variation in fish sheltering and was strongly correlated with juvenile fish of different life stage (newly-emerged fry, fry, parr). Therefore this study uses the results which were provided by a tube diameter of 13 mm.

The rubber tube (normal PVC tube) is shown in the next figure (Figure 4-2), and attached three markers to identify the category of shelters (3.0 – 7.0 – 12.0 cm category I., II. and III.):

Figure 4-2 Rubber tube with the markers and a wooden frame on the background

Shelter abundance was measured inside a square wooden frame with 50 cm edge length, which was placed on the river-bed. Within this 0.25 m^2 area the shelter measurement was proceeded, for instance from one corner to diagonal one. The placed wooden frame with the plastic tube are shown in the following figures, during measuring

Figure 4-3 Placed wooden frame in right place to measure

Furthermore some shelter examples are appeared in the next figures (Figure 4-4 and Figure 4-5) as an illustration about detecting shelters with different depths.

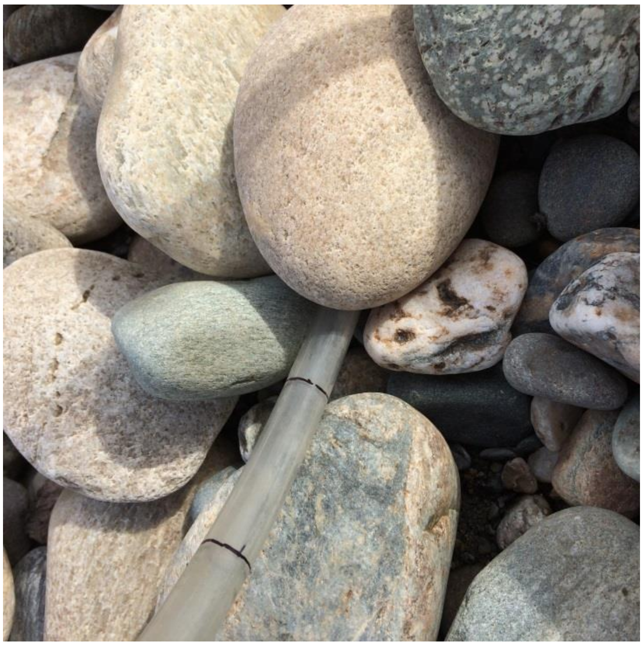
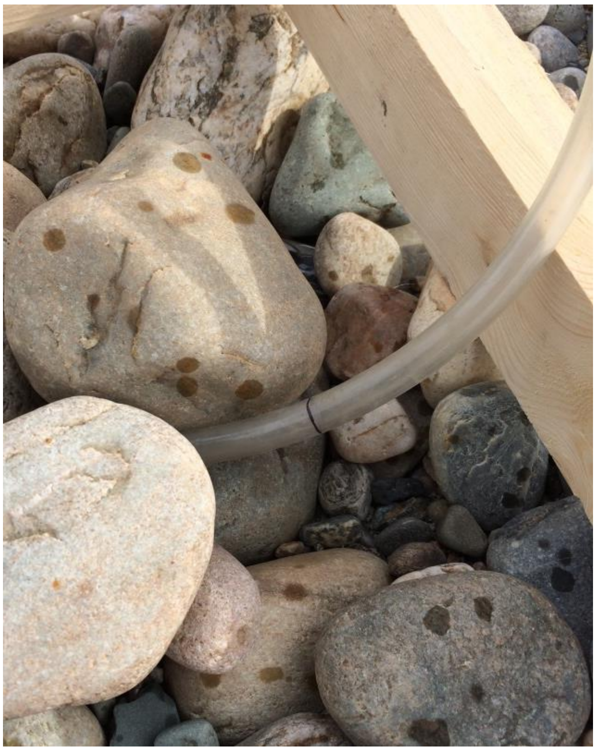
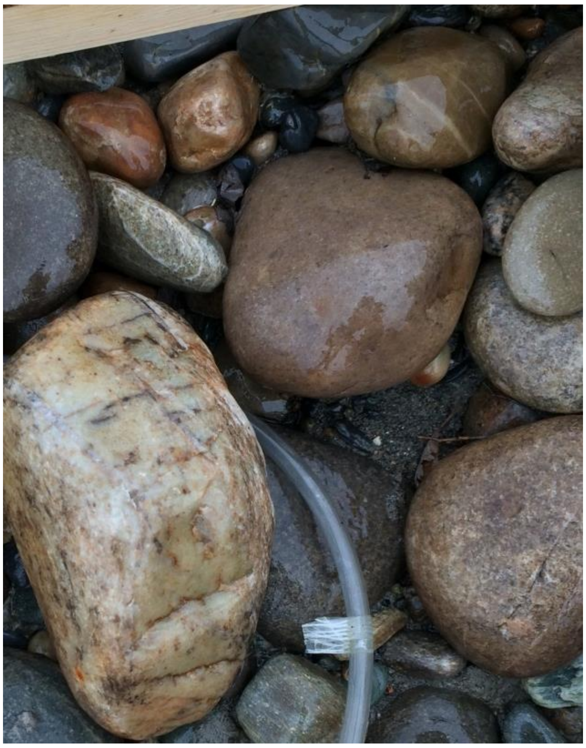


Figure 4-4 Measured shelter, category I.

During the application of Finstad's method it is not necessary to know the depth of a shelter. However it gives little more information about the habitat. The markers help the analyser to get quick visual information about the approximate depth of an interstitial space, which can be registered. An example of recorded shelters is shown in the following table.

Sample no.	Collector	River	Category I.	Category II.	Category III.
1	Marcell	Gaula	6	4	0

Table 4-1 Example of shelter recording

After each shelter measuring samples were taken into laboratory of Department of Hydraulic and Environmental Engineering (IVM), NTNU for further analysis, which is described in chapter 6.1.

5 Introduction of the study sites

The shelter measurements and sediment samples were gathered from two different sites, at Gaula, where shelter measuring and sediment sampling happened, and at Nidelva, where only sediment samples were taken. Although the 1D model was built on Lundesokna and Nidelva, in this chapter the three mentioned rivers will be presented.

5.1 River Gaula – where most of the samples were taken

The river Gaula is located in Sør–Trøndelag region, Central Norway. The source of the river is located around 950 m height from the sea, near the Swedish border, and flows through the region until it reaches Trondheimsfjorden. With its 145 km length and 3661 km^2 catchment area it is one of the largest rivers of the county besides the river Nidelva. The river is not regulated which causes its discharges vary between 1–20 m^3/s in winter time and 6-700 m^3/s during late-spring, early-summer flood. At mean discharge most of the gravel banks are usually dry, and with the shallow water depth it is easy to measure shelters and get samples from the gravel. The next figure shows the site where most of the samples were taken in 2010 and in 2015.

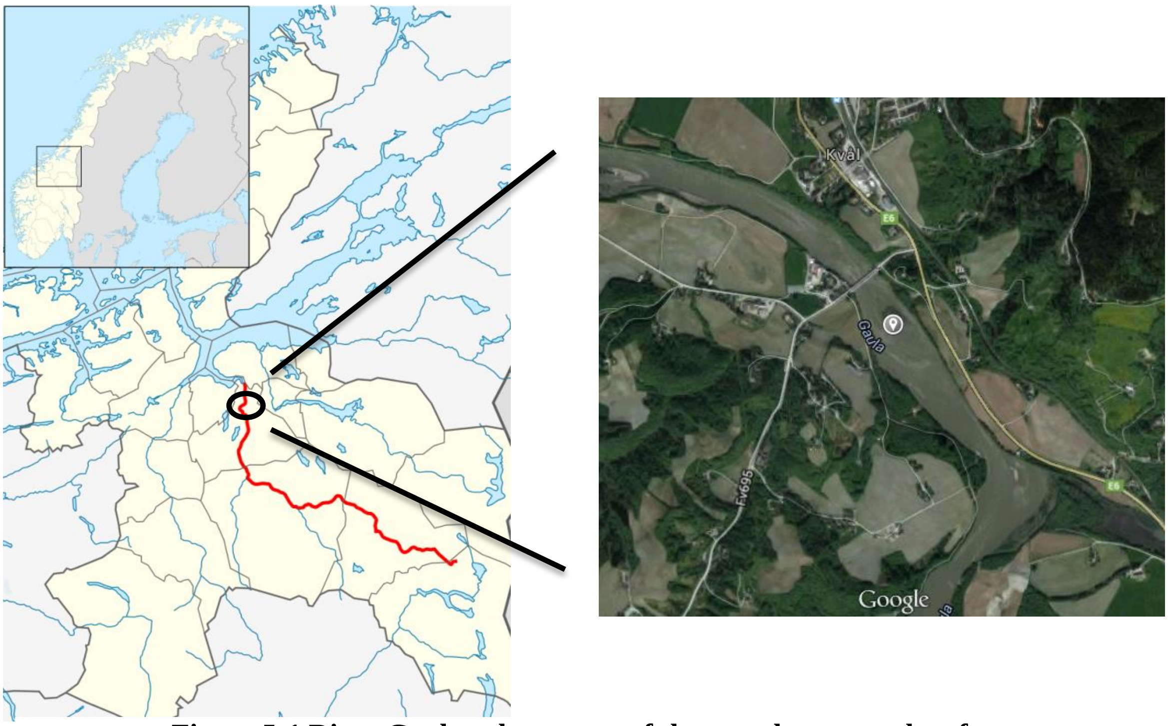


Figure 5-1 River Gaula, where most of the samples were taken from (source: Wikipedia and Google maps)

The sampling site at Gaula is located 8 km downstream of the point where Lundesokna enters river Gaula.

5.2 River Lundesokna

The second river where additional shelters were measured and samples were taken, and which is modelled is called Lundesokna. This stream is a tributary of the Gaula on its right side and this stream is highly regulated, not its banks but its range of hydrograph, by hydropeaking. The hydropower system of Lundesokna contains three powerplants with their artificial reservoirs and three interbasin transfers with a total average production of 278 GWh per year according to Casas-Mulet et al. (2013.). The area of the river basin is 243 km^2. The study site is situated on the furthermost downstream of Lundesokna before it reaches Gaula. This reach is 2.1 km long and due to regular hydropeaking operation its average discharge varies between 0.45 m^3/s and 20,0 m^3/s.

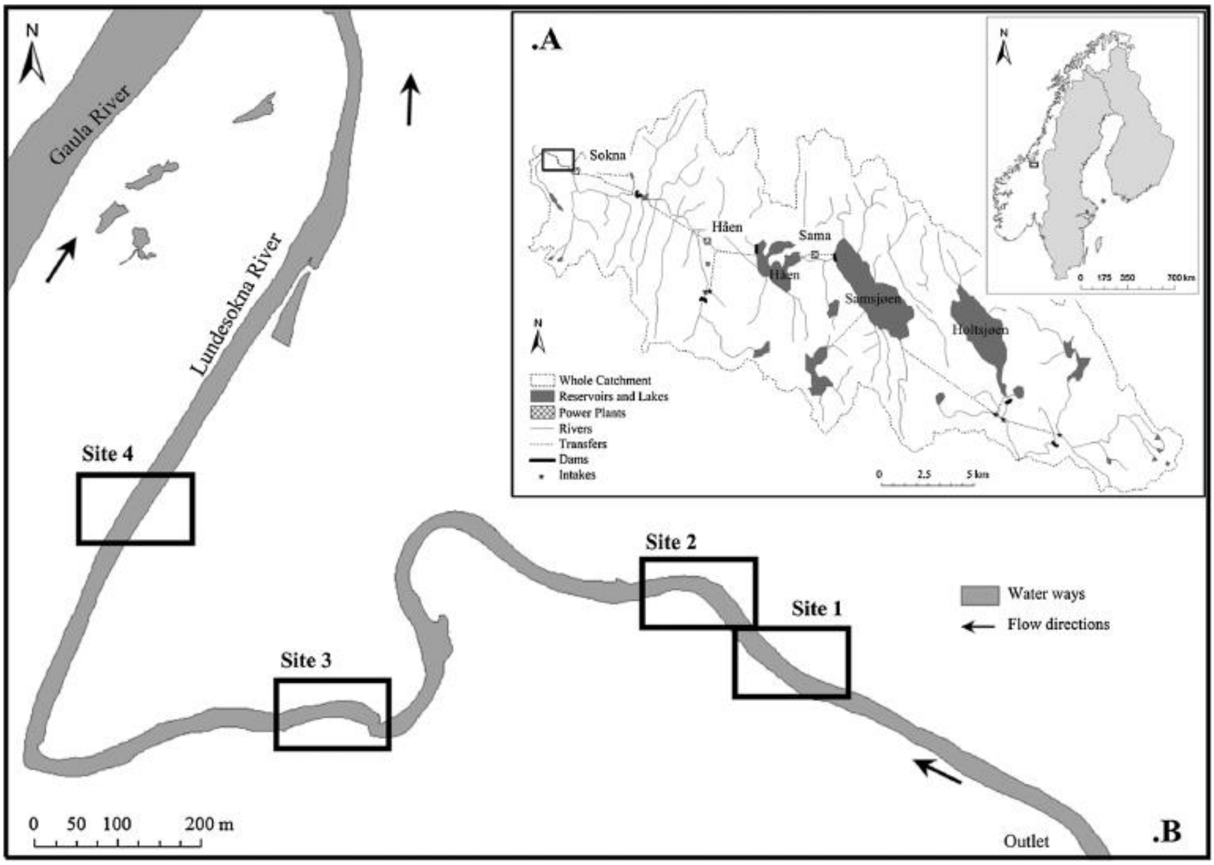


Figure 5-2 Catchment area and hydropower-plant system (A.) of river Lundesokna, with detailed study of the sub-sites (B.) by Casas-Mulet et al. (2013.)

As it is shown in the Figure 5-2 Lundesokna is a part of a complex of reservoirs and hydro-powerplant system. This study site contains more detailed sub-sites, where the finished model (chapter 7.1) has more cross-sections. The described river site used to have a very good potential of salmon spawning long time ago, but during the last decades the population of young salmonids decreased here. This is the reason why it is chosen to simulate the long term sediment changing under regulated and natural flow conditions.

5.3 River Nidelva and Nea-Nidelva river basin

Trondheim's river, called Nidelva is the second largest river in Middle-Norway, and the main river of the Nea-Nidelva river basin. This 3118 km^2 catchment area contains a whole hydro-powerplant system with reservoirs, bypasses and other production facilities, similar to Lundesokna, but with higher capacity. The annual average of the energy production on the basin is around 2550 GWh (King, 2012). The largest reservoir in the basin is the Selbusjøen with its 58 km^2 water surface is the last artificial lake of the hydropower system. This lake is the largest in the Sør-Trøndelag county and the 17th largest in Norway. The catchment area within Norway is shown in the following figure Figure 5-3.

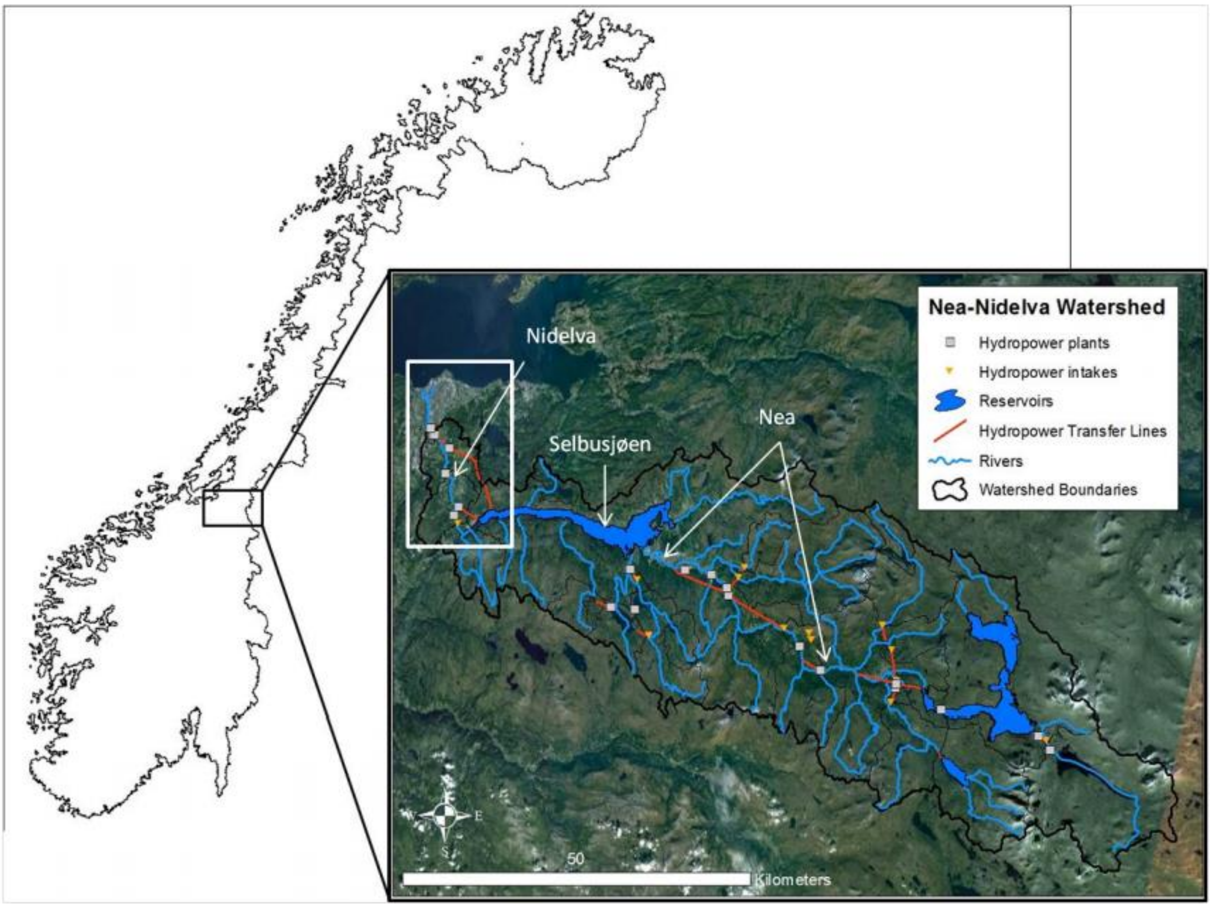


Figure 5-3 Nea-Nidelva cathcment area with its rivers, reservoirs and transfer lines (King, 2012)

The chosen river section from Nidelva is located between a hydropower plant, called Nedre Leirfoss, and the Trondheimsfjord (Fjord of Trondheim). The powerplant provides 30 m^3/s as the lowest, 90 m^3/s as a moderate and 120-250 m^3/s discharges during high water as an output.

This river part is 10.5 km long, and has a very good potential for salmon spawning, therefore an interesting river site with higher spawning potential besides the river Lundesokna.

6 Approach to combine shelter measurement and grain size analysis

The following chapters contain the description of shelters and their measuring method. Additionally the current chapter will make clear the correlation between measured shelters and their analysed samplings. First it is necessary to present the process of grain size analysis.

6.1 Grain size analysis: distributions and frequencies

For the assessment of the sediment status at rivers, it is indispensable to excavate samples and investigate them in laboratory. The composition of the substrate depends on location, gradient, morphology of the river, as well as its range of hydrograph. Grain size analysis is a way to investigate distribution of different sized particles from one or more represented site at the river. In addition, the distribution of particles is a necessary input parameter for sediment transport modelling.

6.1.1 Sampling method

The basic classification of coarse sediment layers in river bed is presented on the following the Figure 6-1 (Bunte & Abt, 2001):

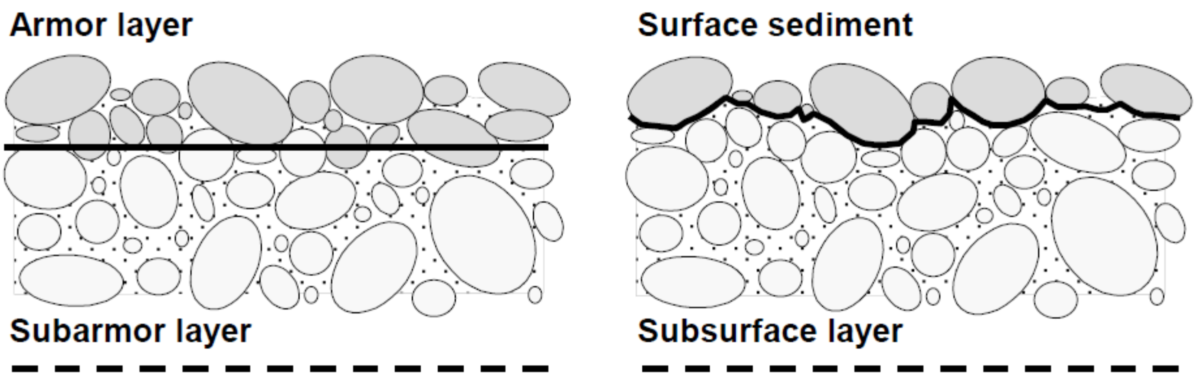


Figure 6-1 Stratigraphy of a riverbed with coarser sediment particles (Bunte & Abt, 2001)

The first of all steps is to collect representative samples from the river field. Basically, there are two ways to gather samples correctly, (i) *volumetric sampling* or (ii) *surface sampling* procedures.

The *volumetric sampling* method is determined by a specific layer of interest where the substrate has to be excavated (Figure 6-1, left side). It can be used both in dry and submerged conditions. On the other hand the surface samplings are based on counting the particles along a line, on even spaced grid points or in an exact area (Figure 6-1, right side). The result of the *surface sampling* is a particle size distribution, calculated by pebble counting, compared to volumetric sampling, where distribution of the particle sizes is calculated by the excavated mass. Following the suggestions of earlier studies (Jocham, 2010), volumetric sampling was applied under dry conditions for this study.

The samples gathered from Gaula and Nidelva were taken into the laboratory of the Department of Hydraulic and Environmental Engineering for further investigations. The whole process is described step by step below:

- selection of an area where the probability of shelters is significant in the river bank, as close to the current water level of the river as possible
- random toss of the wooden frame within the selected area
- taking a photo of the undisturbed substrate composition
- discovering the shelters from one corner to the diagonal one with the 13 mm OD rubber tube
- recording the shelters by their class
- excavating the top layer of the substrate from the same containment area, down to the depth of the largest visible particle, and putting the reclaimed material into one of the marked buckets
- taking a photo about the excavated area with the frame
- bringing back the filled buckets to the laboratory
- drying and sieving individually the samples in the laboratory, and recording the results

In case of Nidelva, last four points were followed, since only sediment samples were taken here. After gathering samples from the field (repeat the steps described above), the filled buckets were taken back to the laboratory for further studies. The processing of the obtained results was made by statistical analysis.

6.1.2 Particle analysis

Although a particle as a three dimensional shape can be described by three mutually perpendicular axes (longest as an a–axis, intermediate as a b–axis and shortest as a c–axis), it is sufficiently accurate to describe the grains with only one variable, for instance with the sieve size where the gravel piece was remained, i.e. b-axis. The common procedure for the assessment of larger sediment samples (with larger particles) is generally the mechanical sieving, which is sufficient for further investigations (Krumbein & Pettijohn, 1938).

Although the categorisation of size classes (hence the size of the sieve hole as well) can be different based on the literature, part of the Wentworth scale was adapted for the study. It is shown in the following Table 4-1.

Description of particle size			Size class [mm]
Boulder			> 256
Cobble	large		128 – 256
	small		64 – 128
Gravel	very coarse	pebble	32 – 64
	coarse		16 – 32
	medium		8 – 16
	fine		4 – 8
	very fine	granule	2 – 4
Sand	very coarse		1 – 2
			< 1

Table 6-1 Wentworth scale – extracted (Bunte & Abt, 2001)

Particles below 1 mm were grouped together, marked as fine sediments. It is a possible way to categorize the grains (Table 6-1) since the shelters can form from substrate with decent particles.

In the laboratory the further investigations starts with measuring the samples, then they are heated in a special oven to get their dry weight (Figure 6-2, left). This oven is heating its interior space up to 55 °C and keeps the temperature for hours to let the moisture on particles to evaporate. The average drying time was around 2-4 hours per sample.

Figure 6-2 Heating oven to dry the gathered samples (left) and the siever machine (right)

The final step in the laboratory to get the required data is to sieve samples individually. The sieve was operated automatically (Figure 6-2, right). A square hole sieve is shown on the following picture. The sizes of the sieve holes were 64–32–16–8–4–2–1 mm and an extra compartment at the bottom to catch fine sediment. Every retained mass was measured on a scale (Figure 6-3, left) after the sieving, to get the exact mass in stated range.

Figure 6-3 Scale with a few sieving particles (left) and a handmade Wenthworth template (right)

Particles larger than 64 mm were measured with a Wenthworth template, which was made in the laboratory in 2010 (Figure 6-3, right). It helped to determine heavier pieces in the sediment samples, and sort of classes between 64 – 128 mm and 128 – 256 mm.

6.1.3 Particle size distributions

During the examination in the laboratory, the particles were sorted into the determined classes and weighted for statistical analysis. When masses were determined per class fractions frequencies could be calculated as well. The next table shows one sample's recorded masses in grams and percentages per classes, just as the cumulated masses.

Size class [mm]	Mass [g]	Mass [%]	Cumulative mass [g]	Cumulative mass [%]
< 1	1920	9.7	1920	9.7
1 - 2	240	1.2	2160	10.9
2 - 4	380	1.9	2540	12.8
4 - 8	510	2.6	3050	15.3
8 - 16	2540	12.8	5590	28.1
16 - 32	3900	19.6	9490	47.7
32 - 64	7380	37.1	16870	84.9
64 - 128	3010	15.1	19880	100.0
128 - 256	0	0.0	19880	100.0
Summary	19880	100		

Table 6-2 Example for distribution frequency

The next Figure 6-4) shows the grain size distribution with the cumulative curve for the chosen sample from above.

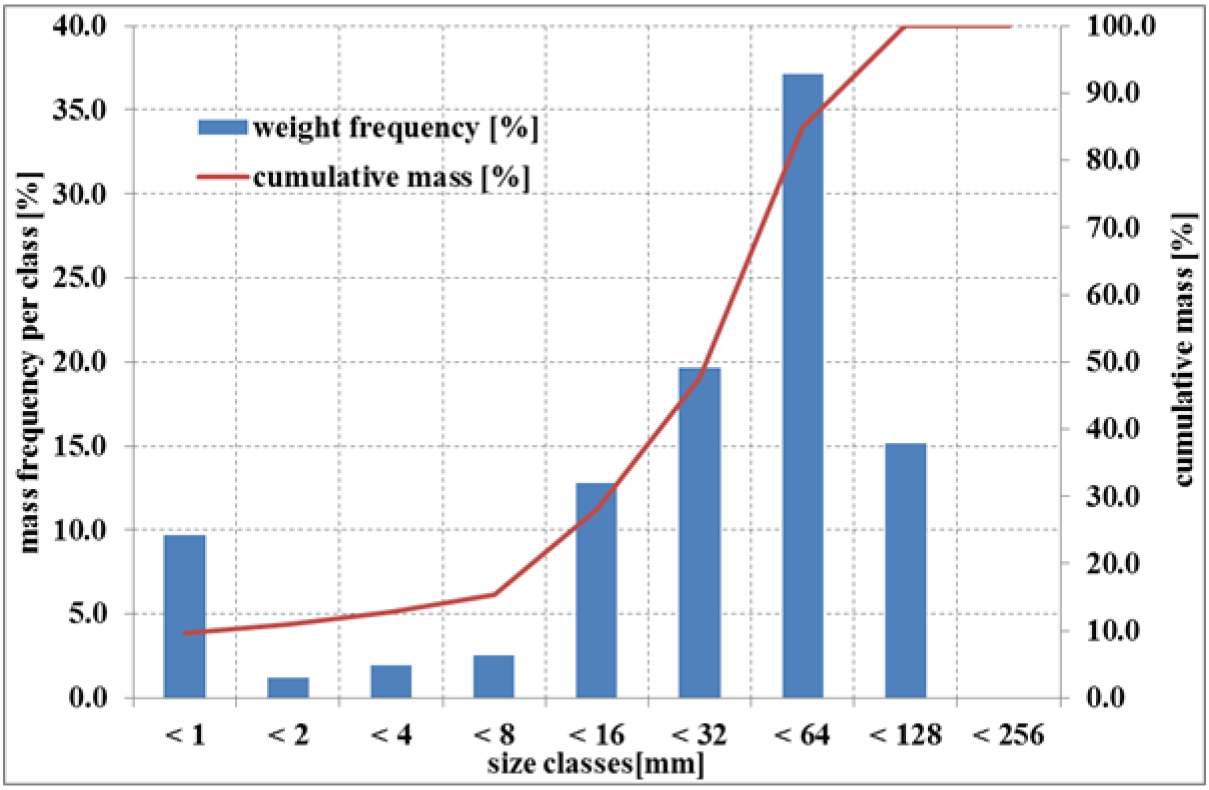


Figure 6-4 Example of a grain size distribution with its cumulative curve

6.1.4 Calculation of percentiles

Bunte and Abt (2001) defined a new parameter as a "sediment size indicated by the cumulative distribution curve for a particular percent finer value". For example the notation of D_{10} means the sediment size for which 10% of the sediment sample is finer than 10 percentile. The percentiles were calculated followed the next equation:

$$D_x = 10^{(\log(x_2)-\log(x_1))*\frac{y_x-y_1}{y_2-y_1}+\log(x_1)} \qquad \text{(eq. 1)}$$

Where: D_x – desired percentile, cumulative frequency [mm]

x_1 and x_2 – the particle sizes in mm units associated with the cumulative frequencies y_1 and y_2

y_1 and y_2 – the two values of the cumulative percent frequency just below and above the desired cumulative frequency

In the literature many frequencies can be found defined, but the percentile values computed for this study is D_5 and D_{10}. Considering earlier studies, these parameters characterize the fine tail of the distribution which is the most relevant frequencies for finding correlations between shelter abundance and grain size parameters (Jocham, 2010).

6.2 Brief description of previous studies

A few previous researches addressed the issue of finding a link between shelter numbers and grain size distributions. One of these studies was written by Martin Honsberg in 2011, who measured the shelters on the field of the river Gaula, and collected sediment samples using different techniques, but especially the freezing core method. Furthermore Martin investigated his results based on an earlier study from the previous year. The most significant research was carried out by Stefan Jocham in 2010 in cooperation with the SINTEF research organisation.

Jocham started with gathering data from the field, Lundesokna and Gaula, and he used different sampling methods. He investigated the river bed at approximately 60 different spots, where he measured the available shelters, then collected the cover sediment layer in each case. These samples were collected using a single square method, which was followed by measuring and collecting samples for this paper as well (the same method, which is described on the chapter 6.1.1).

Jocham assumed that the shelter availability has a connection with some physical parameters related to the enclosing substrate. His study tried to find that link with some general percentiles (Ps) of the grain size distribution. The tested distribution frequencies are sorted in the following Table 6-3):

Ps	Description	Used for
D_5	Characteristic percentile of the fine tail	used as itself
D_{10}	Characteristic percentile of the fine tail	used as itself
D_{16}	Statistically characteristic value	to calculate parameters
D_{25}	Quartile	to calculate distribution parameters
D_{50}	Median point	divides distribution in two equal halves
D_{75}	Third quartile	to calculate distribution parameters
D_{84}	Statistically characteristic value	to calculate parameters
D_{90}	Characteristic percentile of the coarse tale	used as itself
D_{95}	Characteristic percentile of the coarse tale	used as itself

Table 6-3 Percentiles used by Jocham, 2010

The parameters sorted above are calculated by the outlined equation from chapter 6.1.4.

In additional to the percentiles, some other distribution parameters were calculated for each of the samples, based on the work of Bunte and Abt (2001). The discussed parameters are presented below:

- **Geometric mean** [mm]: characterizes the central part of the distribution
- **Sorting** or width of the distribution [-]: the range of particle sizes within which a preset percentage of all data are contained
- **Skewness** [mm]: measure of deviation from symmetry of a distribution
- **Kurtosis** [-]: flatness or peakedness of the distribution

The calculations of the sorted parameters are described below.

Distribution parameters	n^{th} root calculation
Geometric mean	$\sqrt{D_{16} * D_{84}}$
Sorting	$\sqrt{D_{84}/D_{16}}$
Skewness	$\sqrt{\frac{D_{16} * D_{84}}{D_{75}/D_{25}}}$
Kurtosis	$\sqrt{\frac{D_{16}/D_{84}}{D_{75}/D_{25}}}$

Table 6-4 Calculation of distribution parameters (Bunte & Abt, 2001)

Different suggestions can be found in the literature how to calculate parameters from Table 6-4 and Jocham used the n^{th} root computation in his paper.

His research aimed at finding a clear correlation between the number of shelters and physical parameters related to the river bed material. The study was successful. The main goal was the clarification whether that some comparison with different parameters has a stronger connectivity (correlation coefficient is higher) than other ones. Based on his own samples and the further investigations, Jocham could reveal that distribution parameters (presented in Table 6-4) show relatively high correlation with shelter abundance, but under certain restrictions. However stronger link appears between the hiding place of the juvenile salmonids and the grain size distribution from the substrate, especially with percentiles which represent even more the fine tail of the distribution (Figure 6-5).

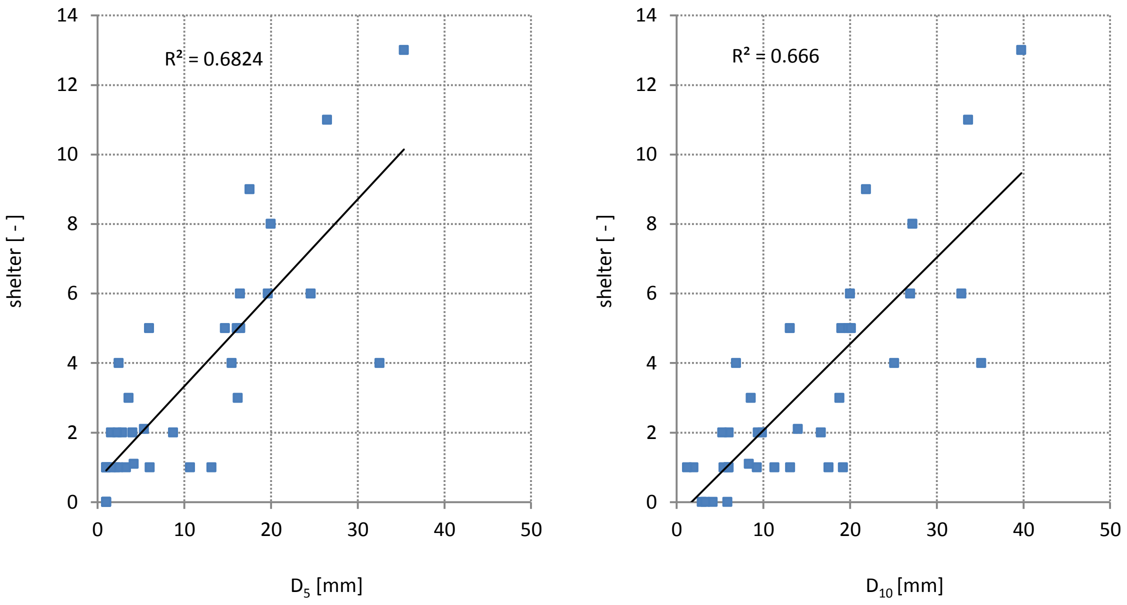


Figure 6-5 Correlation between D_5 (left) and D_{10} (right) parameters and number of shelters with the R^2 coefficients (Jocham, 2010)

The presented relationship is more significant when Jocham averaged the different values of grain size distribution but with the same amount of recorded shelters. It is shown in Figure 6-6.

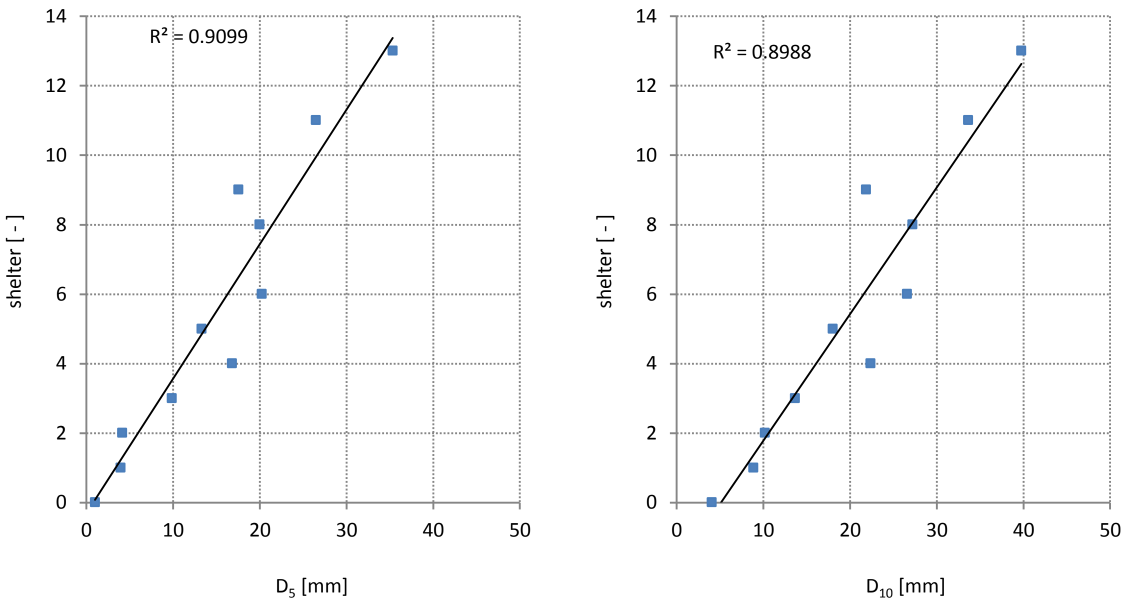


Figure 6-6 Correlation between averaged D_5 (left) and D_{10} (right) parameters and number of shelters with the R^2 coefficients (Jocham, 2010)

Based on the briefly presented results the D_5 and D_{10} were adapted as a physical indicator of shelter abundance from Jocham's study to this paper.Although this study contains samples from Jocham, both of the above mentioned studies (Jocham's and Honbersg's) gave dependable base and idea for further investigations. To figure out the next step in this statistical analysis, thanks to their well recorded and stored database, I had the chance to recalculate most of their results.

6.3 Collected samples

As it was written above, Martin and Jocham measured shelters and collected many samples from the river site of Lundesokna and Gaula as well. Due to the different sampling techniques, 47 samples were able to adopt in total. These samples with their measured properties were available through my supervisor, Nils Rüther at IVM. The calculated D_5 and D_{10} parameters with the corresponding values of shelter numbers for each sample can be found in Appendix A.1 and A.2.

Besides the received data it seemed worthy to collect more samples by myself to extend the database. During the semester taking samples from the river Lundesokna was impeded, because of the heavy rains and/or the contentious energy production indicated by the market. However with the warmer temperature I had the opportunity to measure shelters and collect sediments on the riverside of Gaula at the village of Kvål (Figure 5-1), close to the estuary of Lundesokna, downstream. 11 samples were taken into the laboratory from dry gravel banks during low water, but close to the water line. The calculated D_5 and D_{10} parameters with the corresponding values of shelter numbers for each sample can be found in Appendix A.3.

Additional 5 samples were collected from the Nidelva, close to the Nidelv sport centre, in Trondheim which is approximately 7 km away from the fjord. Sediment samples were collected only from the cover layer. The method was the same what was presented in chapter 6.1.1, but with no shelter measurements. The purpose of the sample collection was to parameterize the sediment transport model of the one-dimensional hydraulic model of this river reach, based on the field data.

The averaged cumulated grain size distributions of collected and analysed samples from Lundesokna and Nidelva are shown in the next table (Table 6-5).

Rivers	Bed gradation classes [mm]								
	0.5-1	1-2	2-4	4-8	8-16	16-32	32-64	64-128	128-256
Lundesokna	1.67	3.40	5.01	7.92	12.91	24.43	53.84	92.34	100.00
Nidelva	0.15	0.20	0.31	0.61	1.75	7.86	35.67	100.00	100.00

Table 6-5 Cumulated grain size distribution of modelled rivers (values are in percentage [%])

6.4 Correlations

After determining the required parameters from the samples, I could extend the database with them and calculate the correlation coefficients between D_5 or D_{10} and the number of shelters. The extended database includes the next appendices: A.1, A.2 and A.3. The results are shown in the following figures.

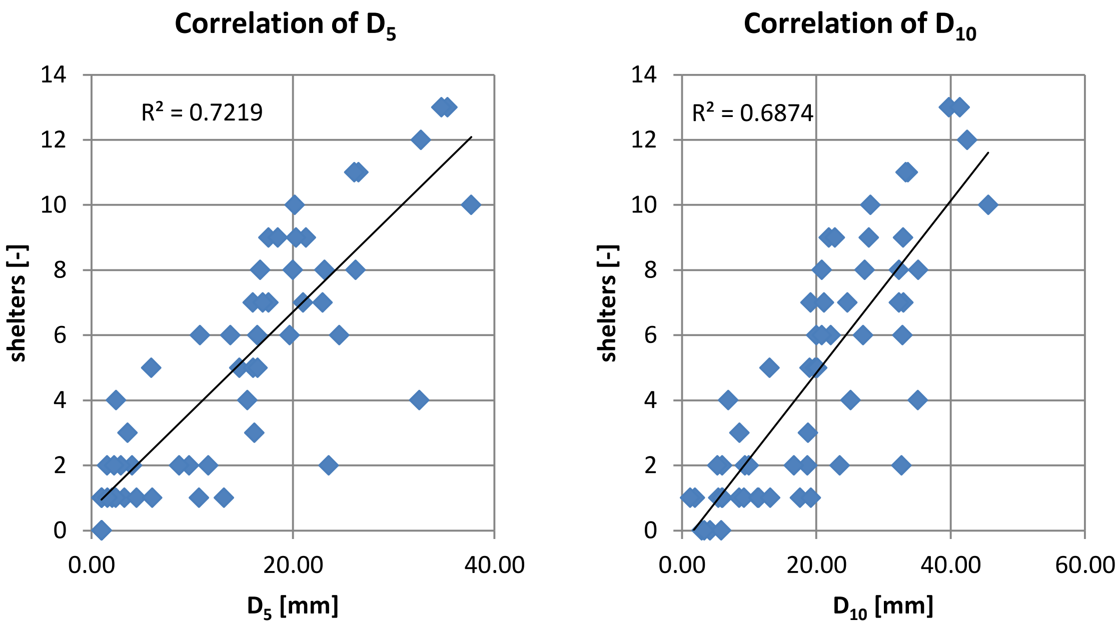


Figure 6-7 Correlation of the extended database between D_5 (left) and D_{10} (right) parameters and number of shelters with the R^2 coefficients

Up to this point every recorded shelter from each category was counted as one. For example a sample with five recorded shelter from category I, four recorded shelter from category II, and one from category III. Summing this up, the sample has ten registered shelter, without any differentiation between the categories of hiding place. The shelter abundance is highly related to the amount of fine materials, hence the size of the shelter, ergo the shelter category could matter. Forseth and Harby (2014) suggest a method to handle this question. The formula they proposed is the following:

$$Sum = S_I + 2 * S_{II} + 3 * S_{III} \qquad \text{(eq. 2)}$$

Where: Sum – the summed number of shelters of a sample [-]

S_I – the number of shelters which were uncovered as category I.

S_{II} – the number of shelters which were uncovered as category II.

S_{III} – the number of shelters which were uncovered as category III.

Based on this equation, each investigated river section can be classified from the point of shelter abundance, according to the following:

Classes	low shelter	moderate shelter	high shelter
Number of shelters	< 5	5 – 10	10 <

Table 6-6 Classification by summed shelter numbers (Forseth & Harby, 2014)

The registered shelters should be observed within 0.25 m^2 area to classify the river segment by using the values of Table 6-6.

The weighted method was followed, and the results are shown below.

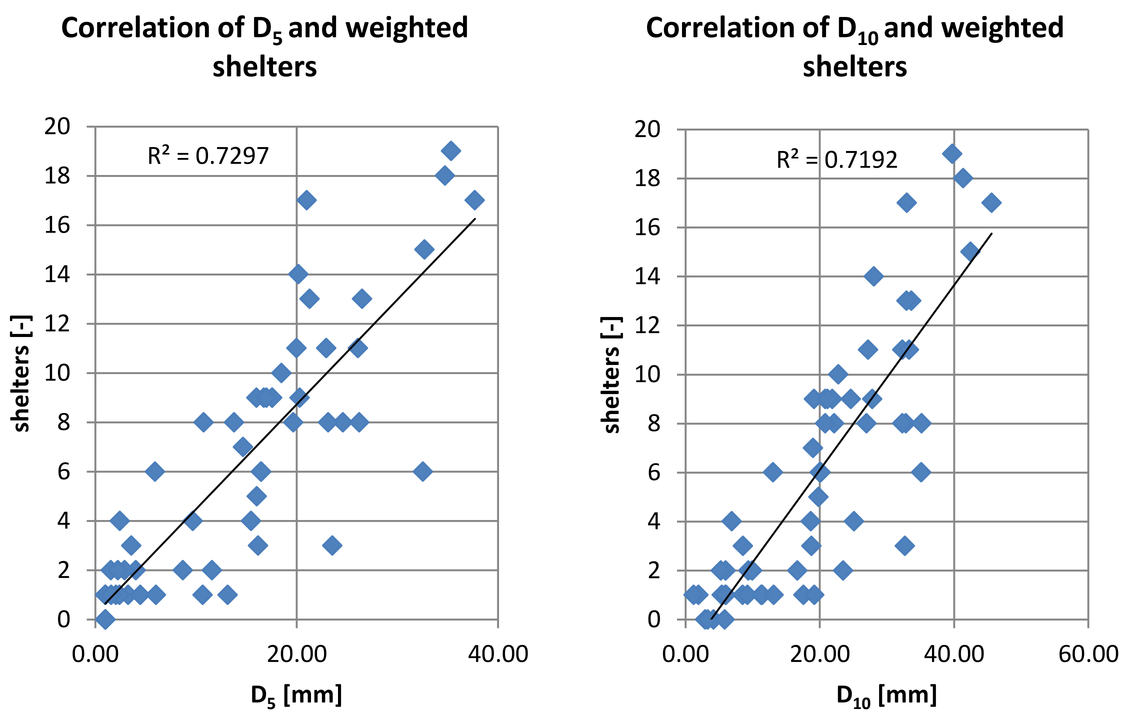


Figure 6-8 Correlation of the extended database between D_5 (left) and D_{10} (right) parameters and number of weighted shelters with the R^2 coefficients

In Figure 6-7 and Figure 6-8 it is shown that the values are scattered close to the origin point, but they are shrinking with the increased number of shelters. To moderate this case the next step is the averaging. Most of the shelter numbers that are registered have several distribution values, therefore their arithmetic mean can be calculated. Thus one physical parameter belongs to one shelter number and vice versa. It helps to get more information about a random gravel site along a river. Without any shelter measuring the potential shelter abundance could be estimated based on some sediment samples from the cover layer. The next Figure 6-9 shows the averaged result from weightless and weighted values too.

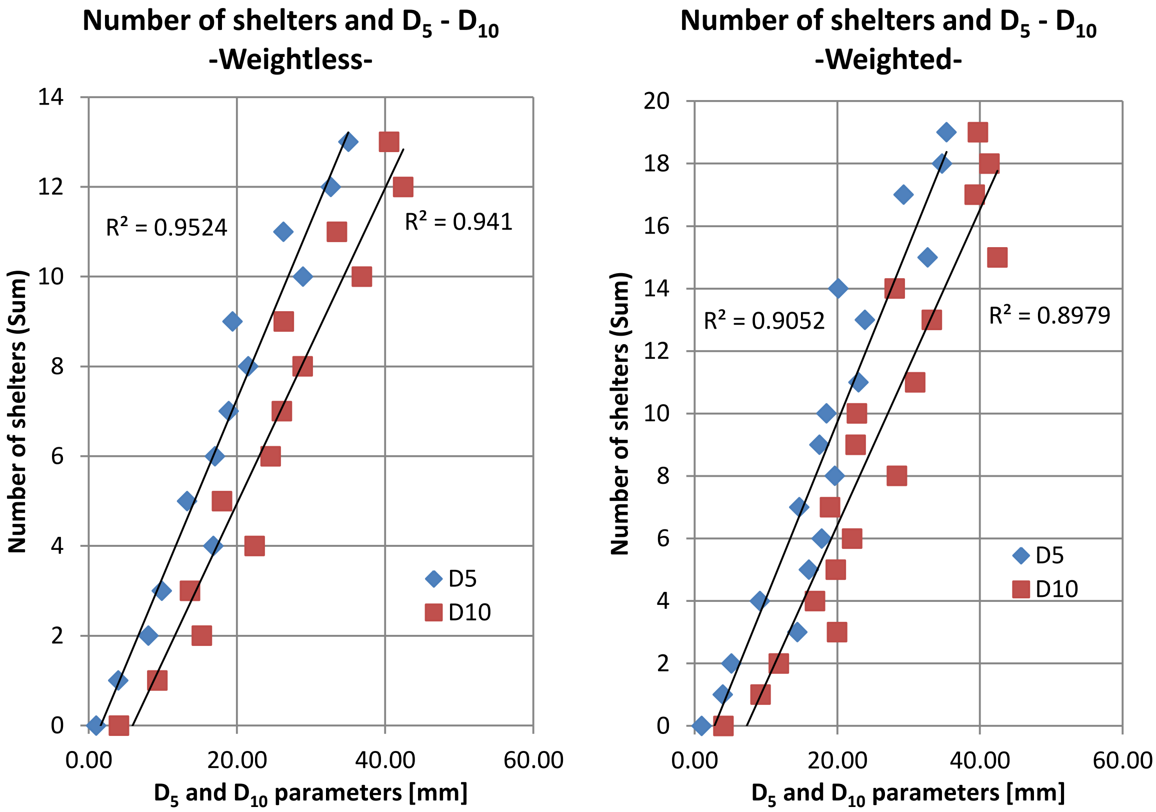


Figure 6-9 Correlation of the extended database between D_5 and D_{10} averaged parameters and number of weightless (left) and weighted (right) shelters with the R^2 coefficients

The presented methods and coefficients show a clear relationship between distribution parameters and the number of shelters, where all of the shelter categories were included. Thinking one step further the physical parameters could be correlated separately to the different category of shelters. More information could be received about the estimated shelter types and amount of them, if a strong link is revealed in these cases too. The next Figure 6-10 shows the averaged D_5 and D_{10} parameters with the shelter numbers only from one category. During the application of this method the weighting is useless, since every shelter within one category would be multiplied with the same constant, depending on the investigated category. It has to be noted, that this investigation is not useable for shelter category III since there were not enough sample recorded with that type of hiding place.

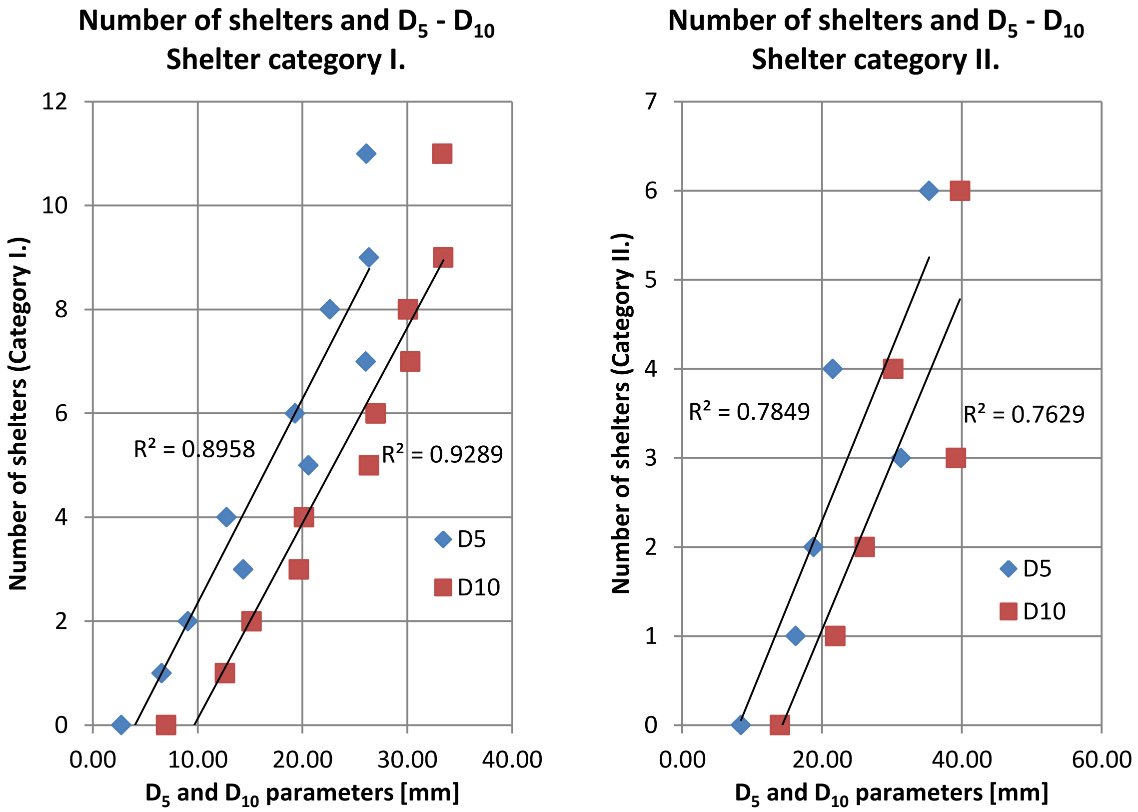


Figure 6-10 Correlation of the extended database between D_5 and D_{10} averaged parameters and number of weightless shelters of category I. (left) and category II. (right) with the R^2 coefficients

The next table summarizes the correlation coefficients which were presented above using different methods.

Different cases	Coefficients	
	D_5	D_{10}
Jocham's dataset	0.68	0.67
Jocham's dataset – averaged	0.91	0.90
Extended dataset – weightless	0.72	0.69
Extended dataset – weighted	0.73	0.72
Averaged – weightless	0.95	0.94
Averaged – weighted	0.91	0.90
Averaged – shelter category I.	0.90	0.93
Averaged – shelter category II.	0.78	0.76

Table 6-7 Correlation coefficients for all of the presented cases

Table 6-7 shows that the previously identified connection is exists between the number of shelters and distribution percentiles, moreover with some improved calculating method the correlation is even stronger. The weighting led to slightly higher coefficient without averaging the frequencies, however it resulted a little decrease in averaging method. Averaging separately by different shelter categories shows a strong connection too, to predict one type of shelter according to the D_5 or D_{10}. However this connection can be strengthened with further shelter measures on the field, where deeper interstitial spaces rather occur repeatedly. Although every method has an acceptable coefficient, the averaged method with weighting was chosen for further analysis. Thus a river site can be classified based on the number of predicted shelters, when the grain size distribution is already known.

7 Investigations with HEC-RAS

Both of the examined river sites, Lundesokna and Nidelva were investigated by the one-dimensional hydraulic software, HEC-RAS, version 4.1. This program is able to simulate steady, quasi-steady and unsteady water flows during long term with water quality, temperature or sediment modelling. For the task of the thesis the sediment transport model was important, which is described in details in chapter 7.3.

From previous studies and publications the hydraulic models for lower part of Lundesokna and Nidelva were already constructed and available through the database of the department at NTNU. The mentioned models will be briefly introduced in the following chapters.

7.1 Model of Lundesokna

The original model of Lundesokna lower part was constructed by Thibault Boissy and Roser Casas–Mulet in 2013. They compared the simulated stranding areas under hydropeaked conditions with measured values from the field. Within their research they provide a specific guideline to accurately predict potential stranding areas in a cost-effective way. That means that an optional geometry can be defined for a 1D model for smaller-scale issues.

That is why the geometry of the used HEC-RAS model varies in profile. The density of the cross-sections is slightly fragmented. The model contains 179 cross-sections in total.

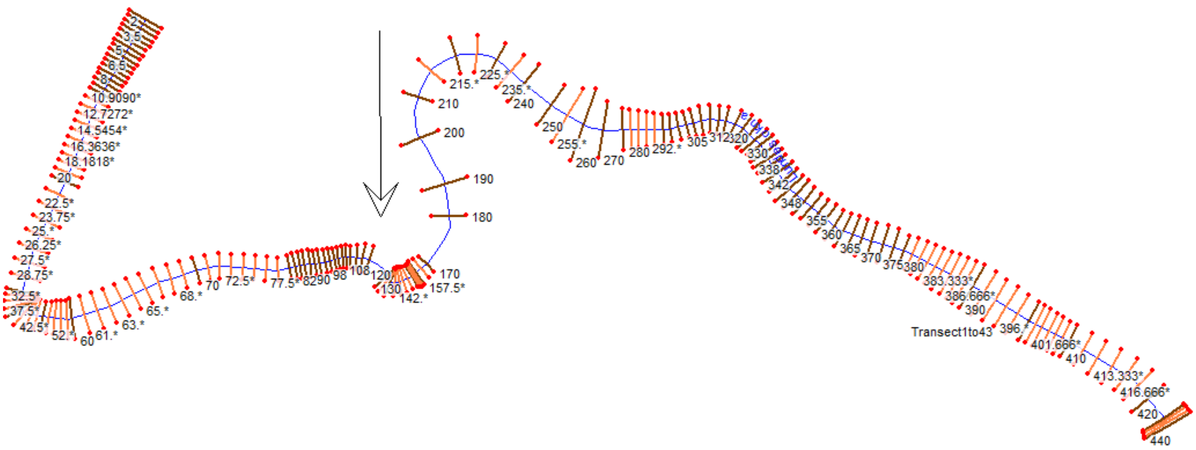


Figure 7-1 HEC-RAS geometry of Lundesokna (arrow shows the direction of South)

This formation (Figure 7-1) was accurate enough to simulate the stranding areas with adequate number of cross-sections. The interpolated cross-sections at lower and upper part could improve the stability of the model running. The width of a cross-section varies between 20 and 40 m. A few cross-sections are presented below (from Figure 7-2 to Figure 7-4).

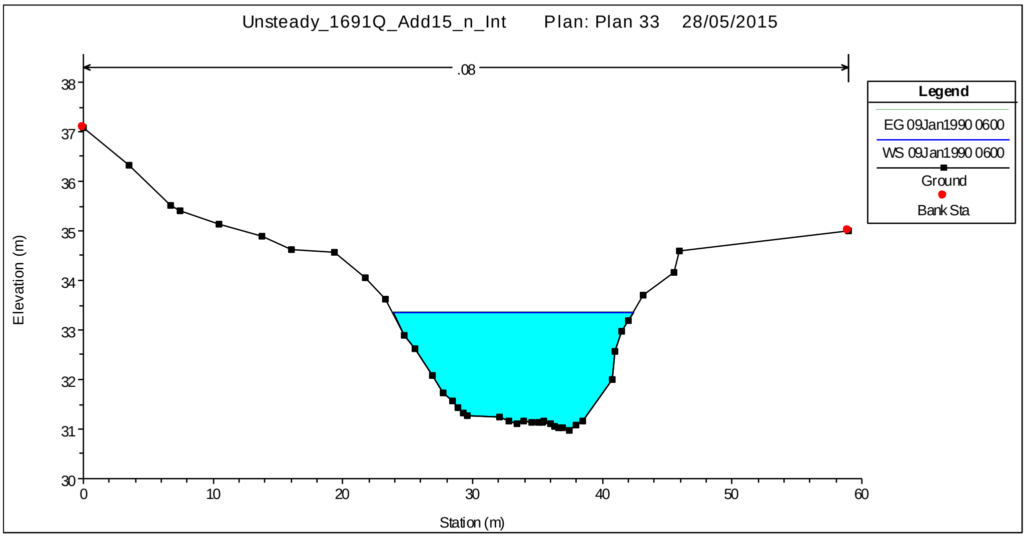


Figure 7-2 Lundesokna cross-section from upper section (Transect 440)

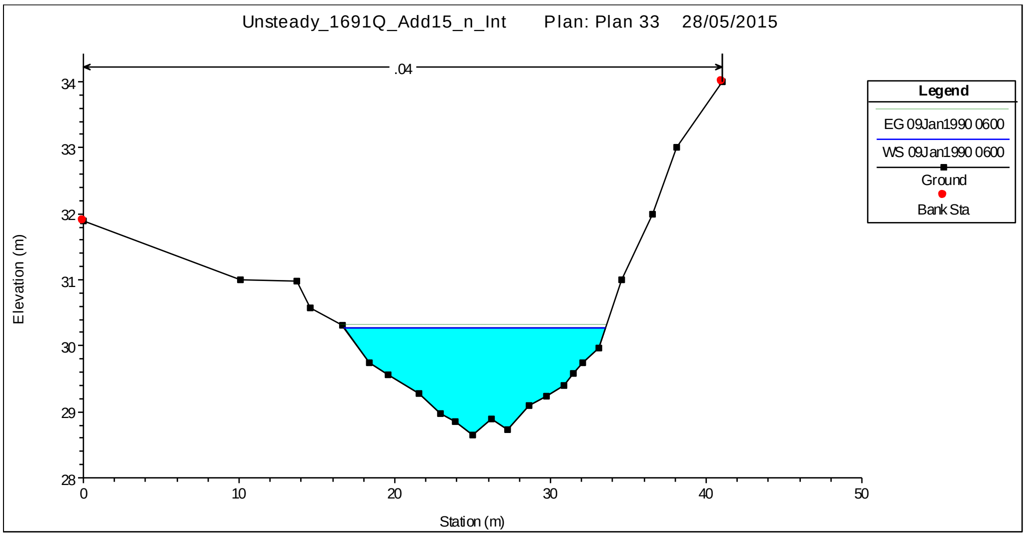


Figure 7-3 Lundesokna cross-section from middle section (Transect 220)

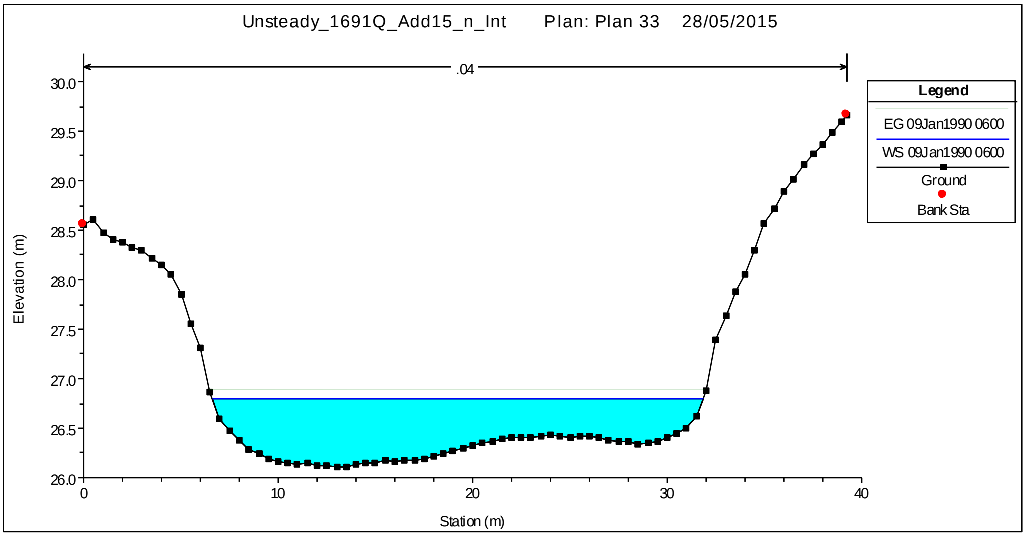


Figure 7-4 Lundesokna cross-section from lower section (Transect 0.5)

7.1.1 Calibration of the model Lundesokna

The received model was already calibrated which was achieved by adjusting the Manning numbers (one/cross-section) from one cross-section to another one until the simulated and observed water levels (with the simulated and observed stranded areas) fit well at detailed sub-sites (for sub-sites see Figure 5-2. B.). Therefore a re-calibration with slight changes was necessary to get the adequate fit with maximum water levels for the whole profile of the model Lundesokna.

Observed water levels were available for some flood events named water levels at cross-sections were registered with the current discharge. The calibration aimed at getting the necessary fit between simulated and observed maximum water surface elevation during high flow (**Q_c=19.79 m^3/s**) under unsteady conditions.

The boundary conditions were unchanged during the calibration, except for adjustment of the Manning numbers. The type of the upstream boundary condition is *Flow Hydrograph* where the computation time was set to **one hour**, and at downstream boundary *Normal depth* was set up, with **0.0092** slope value based on the study by Casas-Mulet et al. (2013.).

The final Manning numbers are presented in the following Figure 7-5):

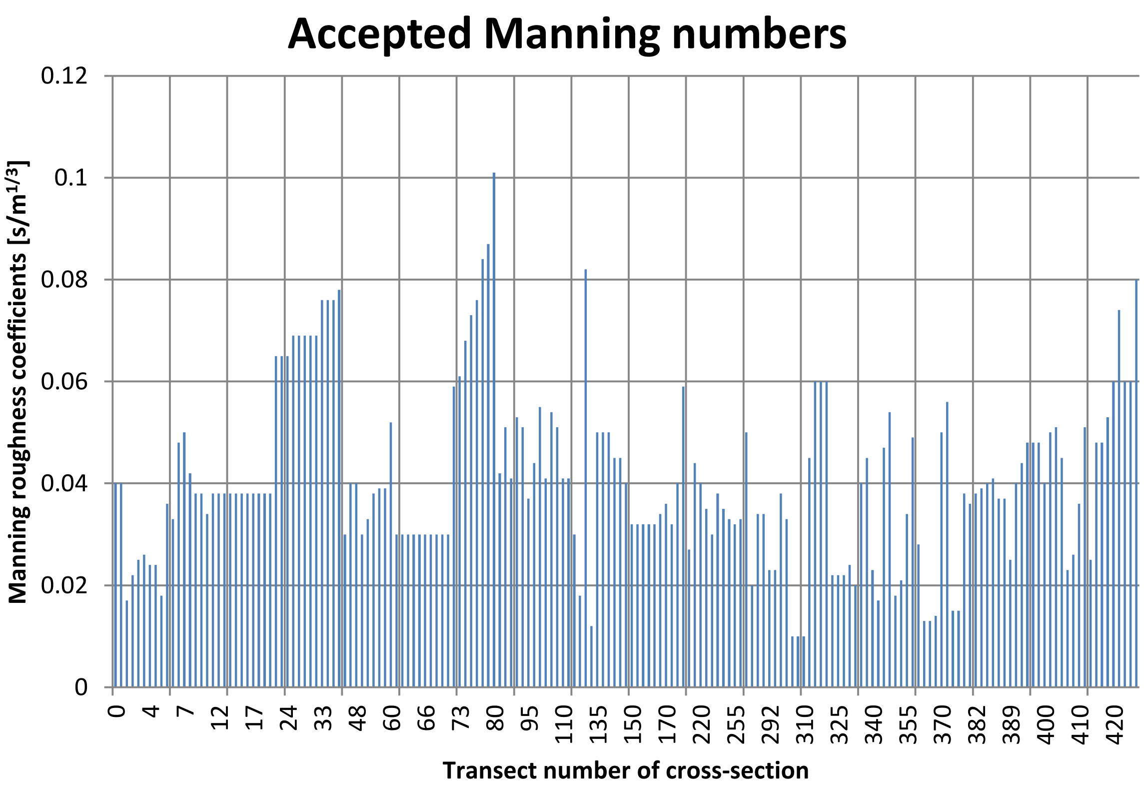


Figure 7-5 Final Manning roughness coefficients of the model Lundesokna

The differences between the simulated and observed max water levels are plotted in the next figure Figure 7-6):

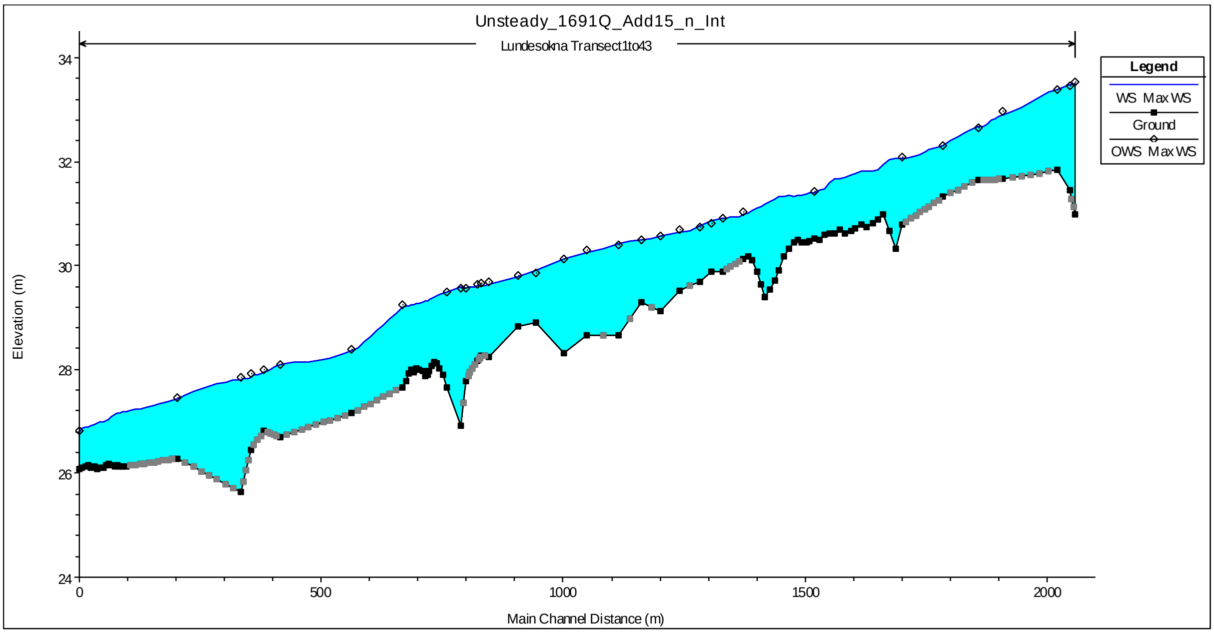


Figure 7-6 Observed and simulated water surface elevations during calibrating

The maximum difference during calibration between the registered and modelled values was not higher than 6.0 cm.

7.1.2 Validation of the model Lundesokna

The process of the validation was under the same hydraulic conditions, except for the modelled hydrograph. In this case the mean flow was set up as a water flow with a maximum discharge of $\mathbf{Q_v=15.25\ m^3/s}$.

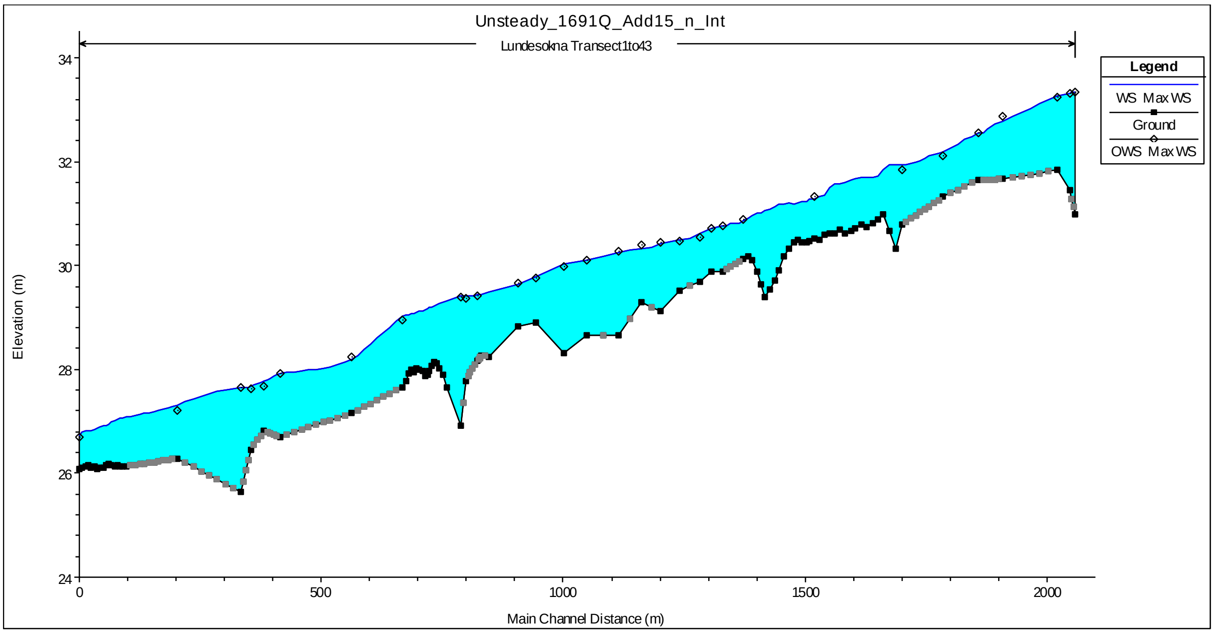


Figure 7-7 Observed and simulated water surface elevations during validating

Figure 7-7 shows the simulated and observed water levels, similar to the calibration plot. The highest difference between the registered and modelled water levels in this case was not more than 10.0 cm, which is a bit higher than at the calibration. Although a better exactness could be reached, this accuracy was enough and acceptable because this study does not focus on pure hydrodynamic modelling, but (instead of flood events and their maximum water levels) it is focusing on the sediment transport on a long timescale.

7.2 Model of Nidelva

At this river site as well a constructed model was available at the Department of Hydraulic and Environmental Engineering. The original HEC-RAS model of Nidelva was built by Tyler King in 2012, who investigated the temperature changing at regulated arctic rivers, by hydropeaking, in connection with the biological activity.

The schematic geometry of the 10.5 km long river site is shown on the following figure:

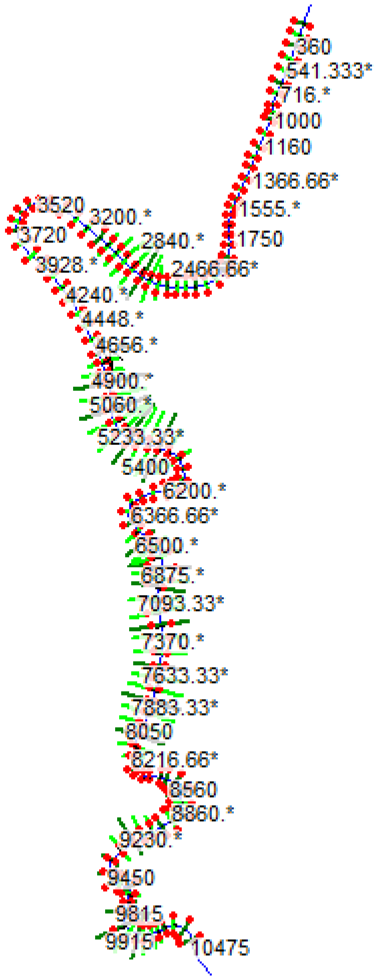


Figure 7-8 HEC-RAS geometry of the river Nidelva

The model contains 135 cross-sections. The average distance between them is approximately 80 m. The river flow close to Nedre Leirfoss is registered daily since the year 1881, which means the natural river flow was recorded before the powerplant was built in the beginning of the 20th century. Due to a strict operating regulation the powerplant has to let out at least 30 m^3/s as minimum flow. The moderate discharge is around 90 m^3/s and the high flows starts from 120 m^3/s up to 200-250 m^3/s, depending on the weather conditions and the energy production. The average width of the cross-section is around 90 m, but varies between 60 and 140 m. Some of them are shown in the following figures (from Figure 7-9 to Figure 7-11). Obstacles like bridges are not included in the model, their effect was corrugated by the Manning numbers.

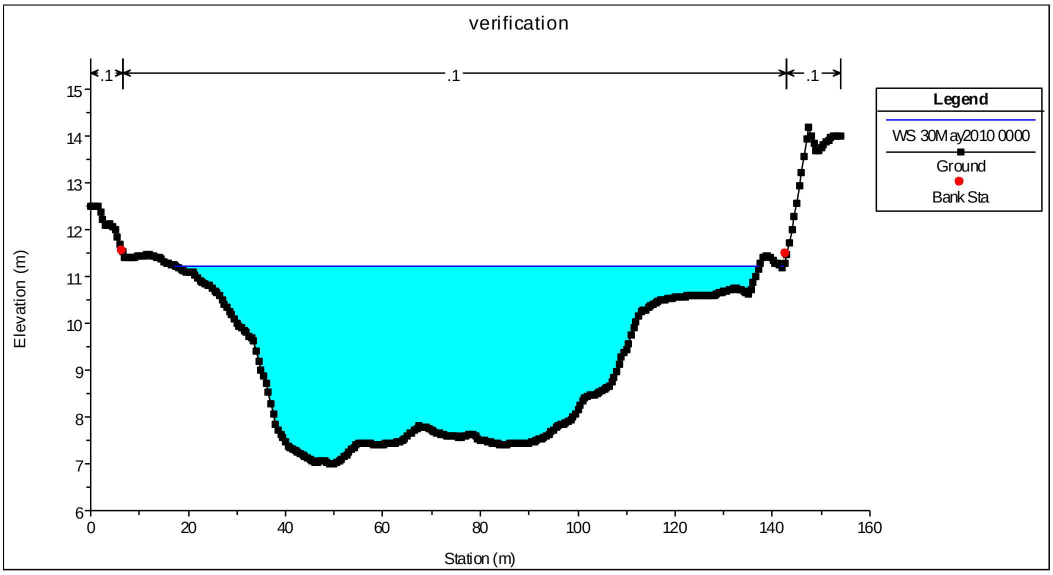


Figure 7-9 Nidelva cross-section from upper section (tagged: 10475)

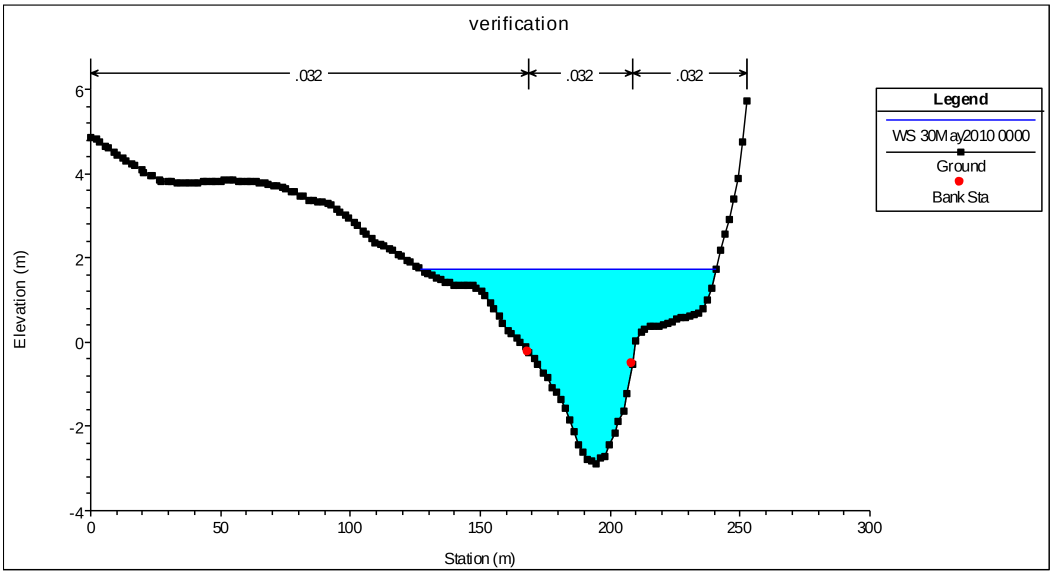


Figure 7-10 Nidelva cross-section from middle section (tagged: 6600)

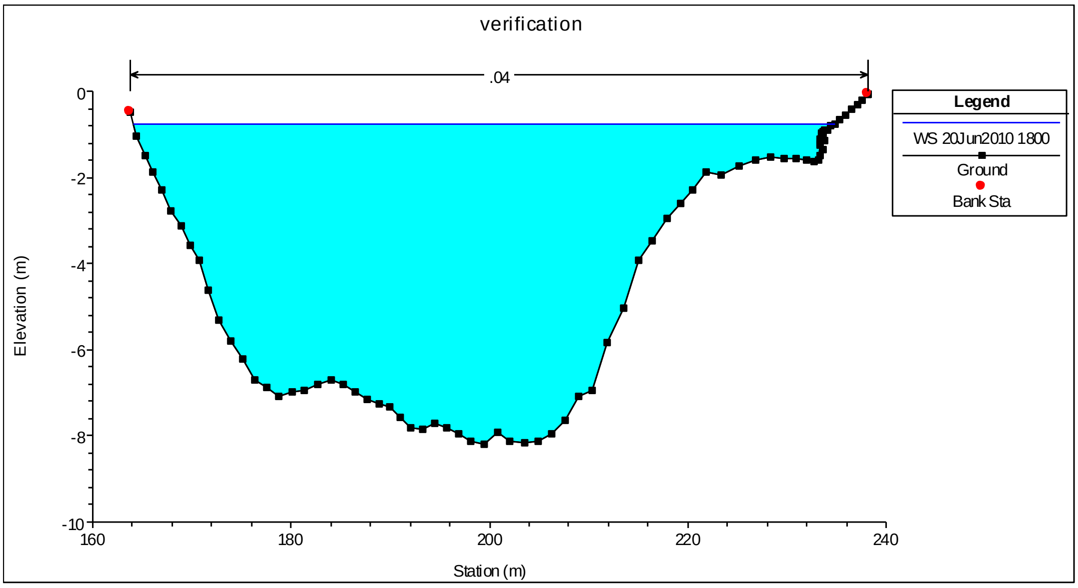


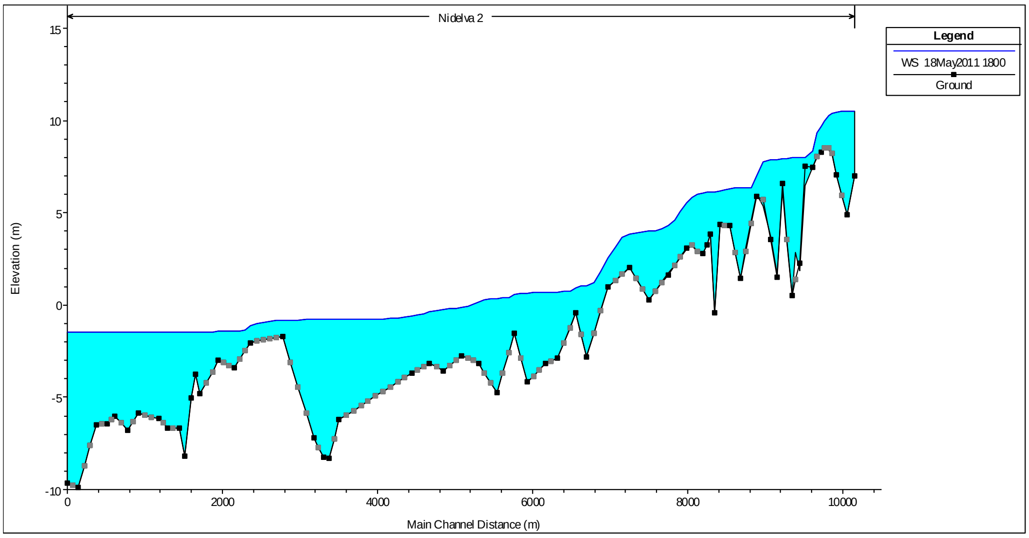
Figure 7-11 Nidelva cross-section from lower section (tagged: 1830)

The cross-sections are tagged by the distance from the fjord. The last 2000 meter is highly channelized before the river reaches the fjord.

7.2.1 The tide effect

The river Nidelva runs into the fjord of Trondheim, which is connected to the high seas. Hence the tide occurs periodically at the fjord as well, which is connected to the discussed river site. Therefore, it has an affects the lower parts of Nidelva. The range of the water level occurred by the tide varies between -1.86 and +1.83 m referred to the sea level. This has a strong effect on the flow of the rivers' lower part. The following two figures (

Figure 7-12 and Figure 7-13) show the modelled water level at low water during both extreme



values of the tide.

Figure 7-12 Water levels at downstream of the Nidelva, during ebb-tide (Q=32.6 m^3/s)

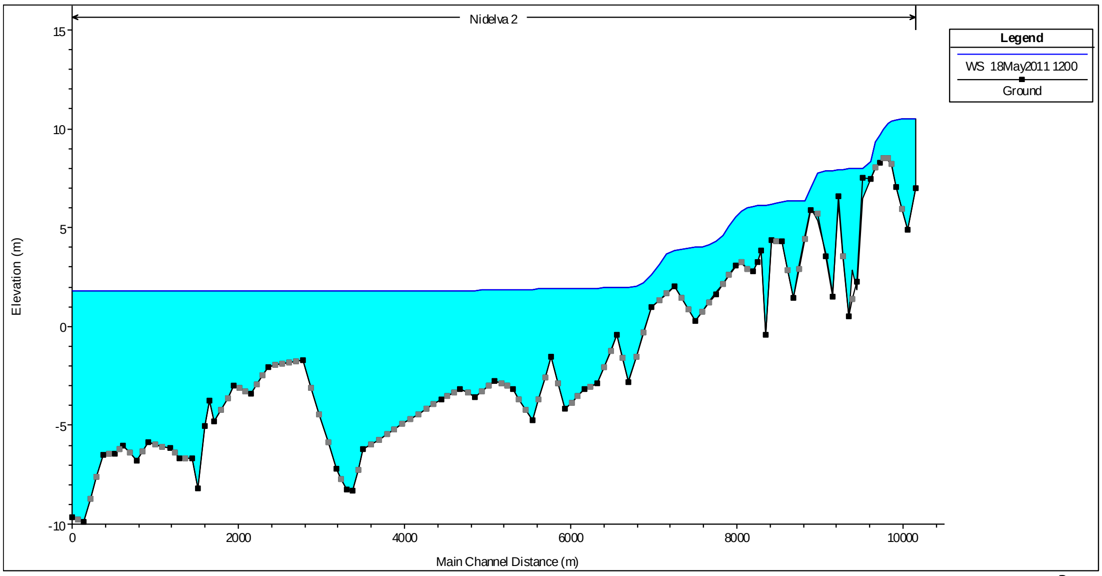


Figure 7-13 Water levels at downstream of the Nidelva, during flood-tide (Q=32.6 m^3/s)

It can be seen, that the tide has a strong effect on the water levels at downstream, and when flood tide occurs it appears 6-6500 meter further from the fjord in the river Nidelva profile. Therefore the river segment in interest from the aspect of natural habitat of juvenile fish is the section starting from 6100 m to the powerplant, which is located 10475 meter away from the estuary.

7.2.2 Calibration and validation of the model Nidelva

The received model was already calibrated and validated, by King (2012). In the following the calibration and validation methods will be presented through his work, since the used model and hydraulic parameterization in this study is exactly the same with which King worked.

The investigated river section is located between a hydropower plant, called Nedre Leirfoss and the Trondheimsfjorden which is connected to the Norwegian Sea. This situation sets up the boundary conditions easily. From upstream the powerplant serves the inflow boundary condition, since the outlet section of the powerplant is registered and so the *flow series* are known. At the downstream boundary the sea level determines the water levels with its tide effect, thereby it can be set up as *stage serie* with 10 minutes duration time (the sediment models were set up with 6 hours delta time).

The calibration was aimed at finding a setting of Manning's roughness coefficients, where the observed water levels can be simulated precisely. Though the simulations were run under steady conditions, the goal was to achieve the desired accuracy for different flow series with the same Manning values.

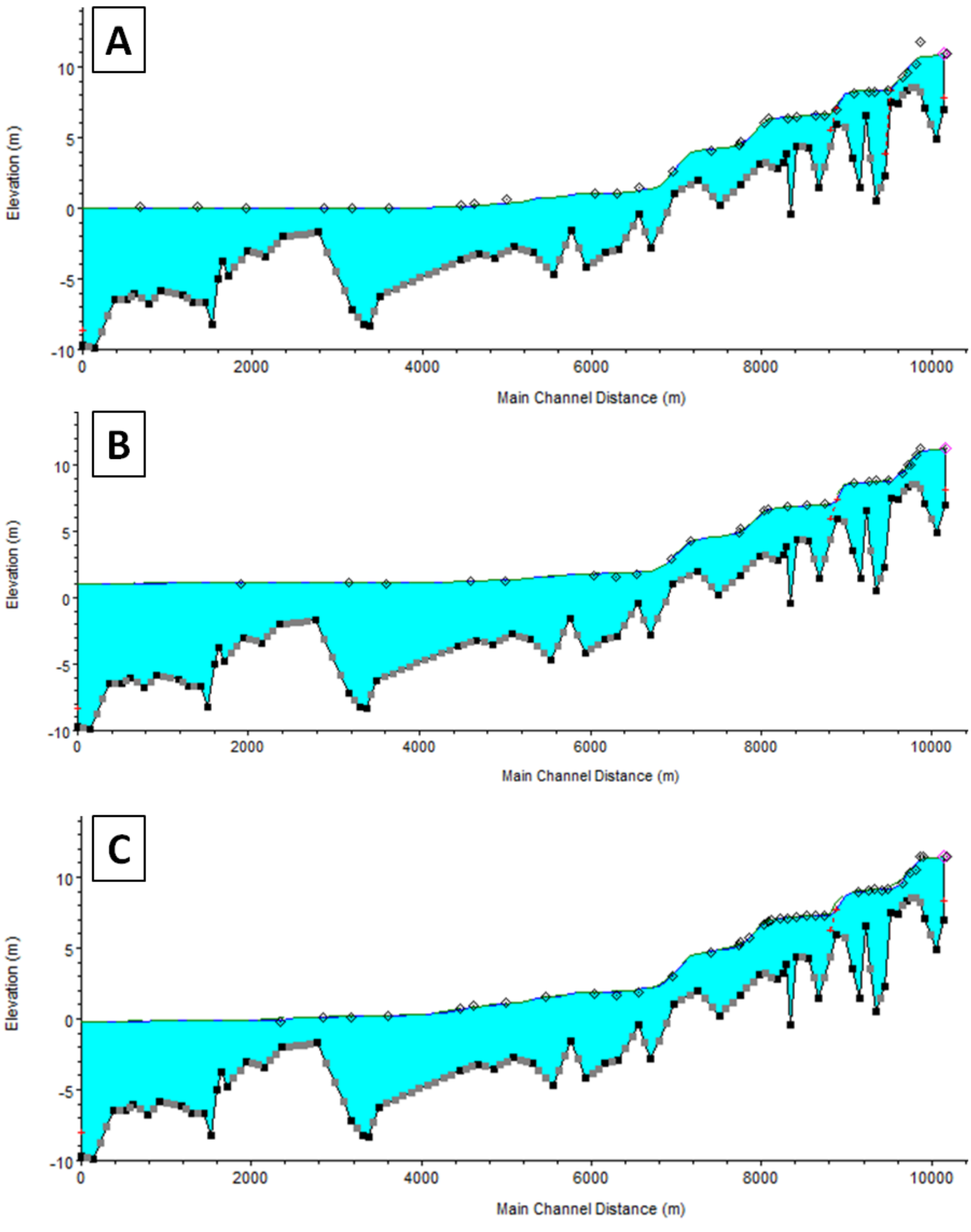


Figure 7-14 Observed (o) and modelled (-) water levels in meters over sea-level [m o.h] for discharges of 43 m^3/s (A), 90 m^3/s (B) and 140 m^3/s (C). Reprinted with the permission from King (2012)

From now on the calibration and the validation methods are almost the same, since the Manning numbers were tested with three different flow stage, low with 43 m^3/s, moderate with 90 m^3/s and high flow with discharge of 140 m^3/s (Figure 7-14). First it had to be decided either to take a set of roughness coefficients which fit the best on average, or to let the coefficients to scale with the flow. The latter was chosen.

There is an option within HEC-RAS to set the roughness coefficients, which should be multiplied by a determined constant if the current discharge reaches the set value, while the simulation is going on. The next table contains the multipliers with the discharges where they activate.

Discharge	Roughness multiplier
150 m^3/s	1
90 m^3/s	1.3
40 m^3/s	2

Figure 7-15 Discharge based scaling parameters applied to roughness coefficients (King, 2012)

The final setting of roughness coefficients is shown on the following figure. Note that rapids and bridges required higher coefficients, since the energy losses around locations are higher, while pools have lower roughness values.

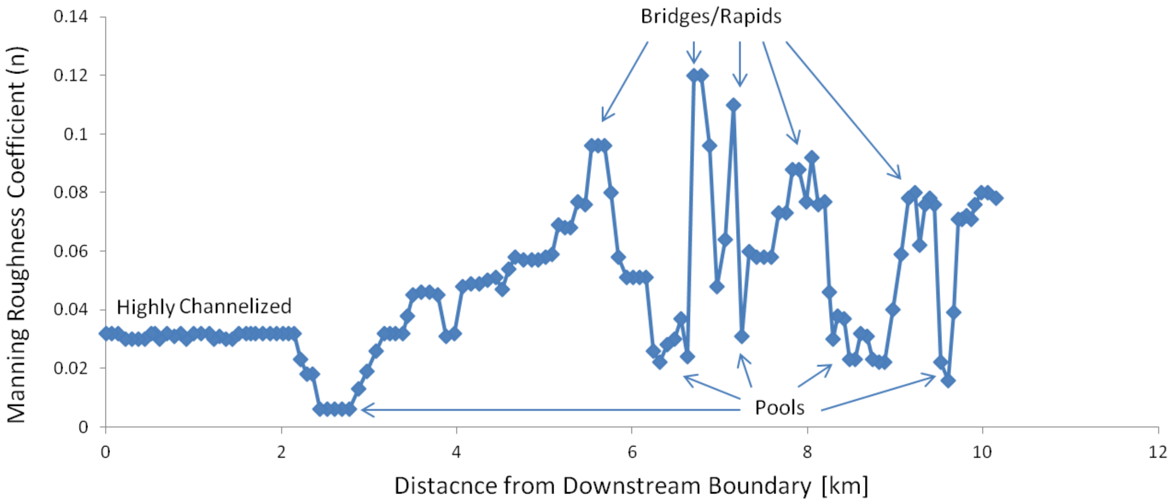


Figure 7-16 Accepted set of Manning numbers along the study reach. Reprinted with the permission from King (2012)

The next figure shows the correlation between the observed and modelled water levels for three different discharges.

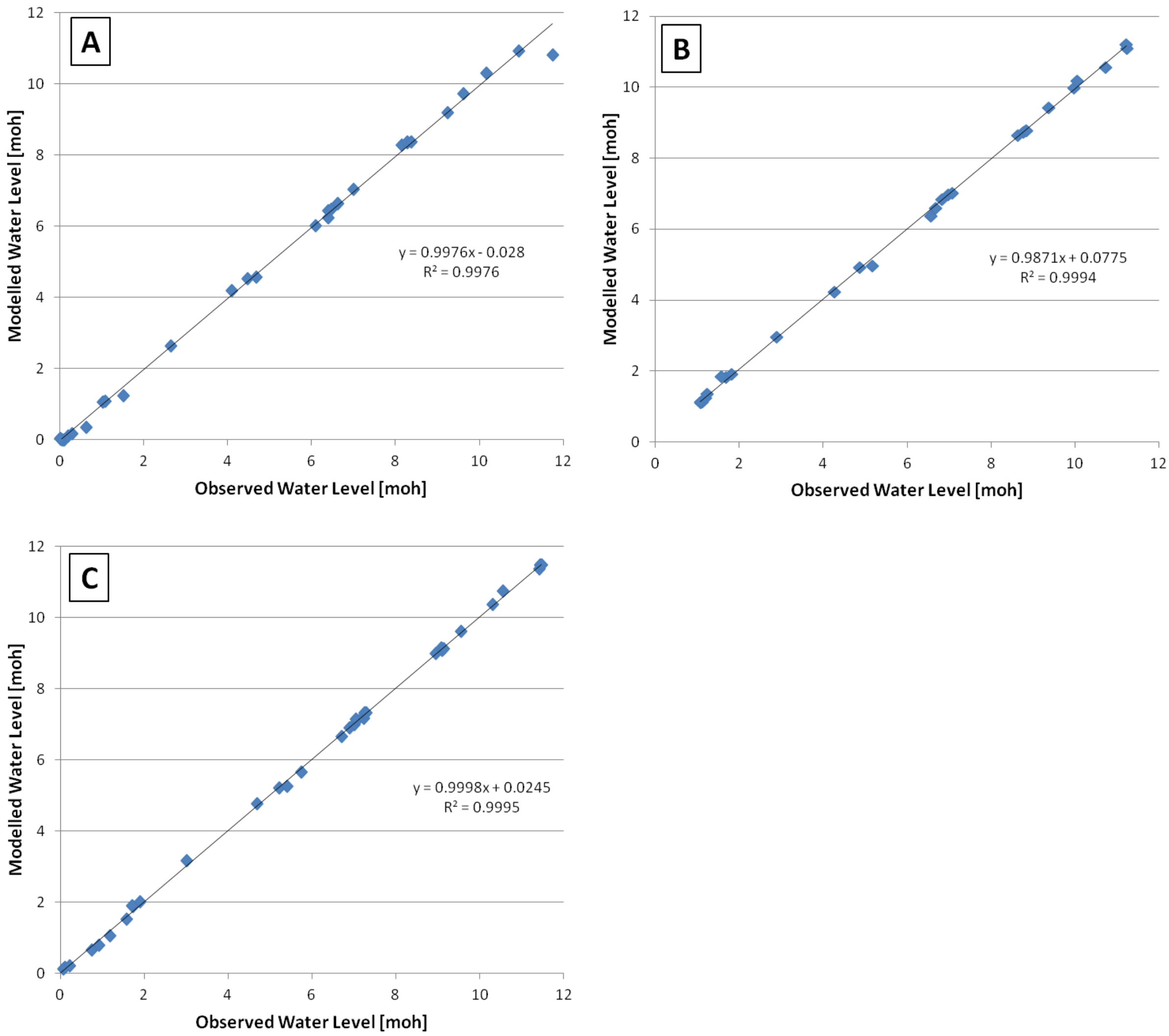


Figure 7-17 Observed and simulated water levels in meters over sea-level [m o.h] for discharges of 43.0 m^3/s (A), 90 m^3/s (B) and 140 m^3/s (C). Reprinted with the permission from King (2012)

Based on the brief description above the model set up was accepted and used to run sediment simulations.

7.3 Parameterization of the sediment transport model

The main focus of this study is on the spatial and temporal changes of the river bed composition, therefore, this chapter enhances the sediment transport related options within the HEC-RAS software. The boundary conditions and input data with sediment transport parameters have to be chosen and given as basic information to the model. At first the input data with some sediment transport parameters are going to be presented.

Sediment transport function

A few methods are available to set up, followed by different empirical equations by *Ackers-White*, *Engelund-Hansen*, *Laursen-Copeland*, *Meyer-Peter-Müller*, *Toffaleti*, *Yang* or

Wilcock. The choice of the right method is based on grain size distribution of the sampled sediments. In the case of the river Lundesokna and Nidelva Table 6-5 shows that sediment particle size ranging from 0.5-1 mm up to 128-256 mm, therefore consist mostly of sand and gravel particles. The suspended sediment is not significant in these rivers due to the hydrogeological conditions and the regulations.

Not every empirical equation was developed for this bed material type. According to the literature (Brunner G. W., 2010) three of the sorted methods are relevant, which are described shortly below.

Meyer-Peter-Müller

One of the earliest equations developed and still one of the widely used. It is a strictly bed-load equation developed from flume and river experiments with sand and gravel under plain bed conditions. Recently the HEC can use the equation which was reconstructed by Wong and Parker (2006), based on MPM original database, who, in order to improve the function, recast the base to excess the shear stress:

$$q_b^* = 3.97 * (\tau^* - \tau_c^*)^{3/2} \quad \text{(eq. 3)}$$

Where: q_b^* – is the Einstein bedload number (correlated with bedload)

τ^* – is the Shield's stress which is compared to

τ_c^* – is the critical Shield's stress, equal to 0.0495

Laursen-Copeland

The Laursen equation was developed to calculate total bed load, and was initially based on flume equations, then extended with a basic function of excess shear and a ratio of the shear velocity to the fall velocity. Later Copeland (1989) generalized the equation for coarse material transport, thus it could be used for gravel beds.

$$(\tau_o' - \tau_{ci}) - 1 \quad \text{(eq. 4)}$$

Where: τ_{ci}– is the critical shear stress for the ith grain size; and

$$\tau_o' = \frac{\rho * V^2}{58} * \left(\frac{d_{50}}{R_b'}\right)^{\frac{1}{3}} \quad \text{(eq. 5)}$$

Where: τ_{ci}– is the grain shear stress

ρ – water density

V – water velocity

R'_b – hydraulic radius of the bed attributed to grain roughness

d_{50} – centre of the grain size distribution

Wilcock

One of the most significant equations to calculate bedload for graded bed which contains sand and gravel. It is a surface transport method, based on the theory that transport is dependent on the surface gradation of rivers, therefore the gradation should reflect the bed surface properties (Wilcock & Crowe, 2003).

$$W_i^* = f(\tau/\tau_{rm}) \qquad \text{(eq. 6)}$$

Where: W_i^* – dimensionless transport rate of size fraction *i*

τ – is the bed shear stress

τ_{rm} – is the reference shear stress

$$\tau_{ri} = 0.21 + 0.015 * e^{-20*FS} \qquad \text{(eq. 7)}$$

Where: FS – is the sand content in percent

And

$$W_i^* = \frac{(s-1)*g*q_{bi}}{F_i*u_*^3} \qquad \text{(eq. 8)}$$

Where: s – is the ratio of sediment to water density,

g – gravity,

q_{bi} – volumetric transport rate per unit width of size *i*

F_i – proportion of size *i* on the bed surface

u_* – shear velocity

Sorting method

Currently two methods are available in the HEC-RAS to compute the active layer thickness and vertical bed layer tracking assumptions (Brunner G. W., 2010).

Active layer

This simple method separates the definition of sediment layer into active and inactive layer. The thickness of the active layer is set up to be equal with d_{90} particle size of the layer. This method is preferably used when the bed material is coarser.

Exner 5

Similarly to the Active layer method the adjusted sediment layer is separated into two different layers, but the active layer is also divided into two parts, cover and subsurface layer. This method is actually a three layer approach. This setting takes into account to the capability of forming the coarser surface layer, therefore the erosion at subsurface stratum could decrease in a manner. That means that armouring occurs during the simulations.

The next figure Figure 7-18) schematically represents the aforementioned methods.

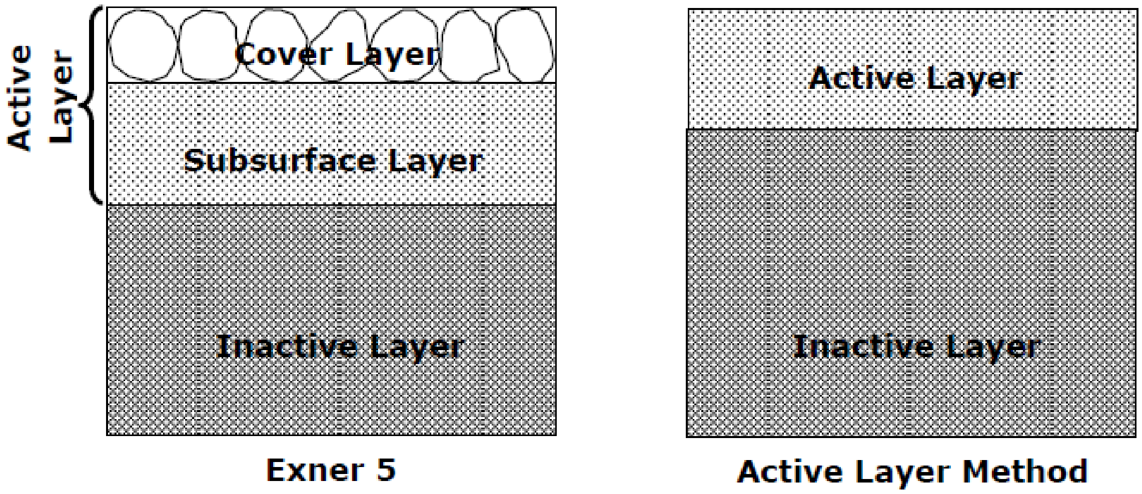


Figure 7-18 Mixing of layers with two different settings in HEC-RAS (Brunner G. W., 2010)

Fall velocity method

Subsidence can happen when very fine bed material moves together with the water flow in the whole water column as suspended sediment. Due to the variant density of water and bed material the latter can settle during the flows. This phenomenon can be simulated by empirical, half-empirical equations within HEC-RAS. The used software contains the following methods, named after *Van Rijn*, *Ruby*, *Toffaleti* and one more, called *Report 12*. The fall velocity of a fine bed particle depends on different factors, such as flow velocity, density of the material and water, viscosity, particle size and shape.

As in the present case the amount of suspended material is almost negligible (<1-2%), the thesis does not include more detailed description about mentioned fall velocity methods. Default setting was accepted and used for the simulations (*Ruby*).

Transport parameters

Some properties related to the sediment can be set up in the hydraulic model. For instance, gravity, shape factor, unit weights of different types of bed materials, or predetermine different variables of the chosen transport method are available to change. Default values were accepted in every case for the simulations without any modification.

Initial conditions

Bed gradation and maximum depth or minimum elevation of the examined sediment layer has to be given as an input to the model from cross-section to cross-section. As the aim of the thesis is to detect the qualitative changes between regulated and natural flow cases, the initial conditions were therefore exactly the same for all of the cross-sections within the model of a river reach. The bed gradations for Lundesokna and Nidelva were set up according to Table 6-5.

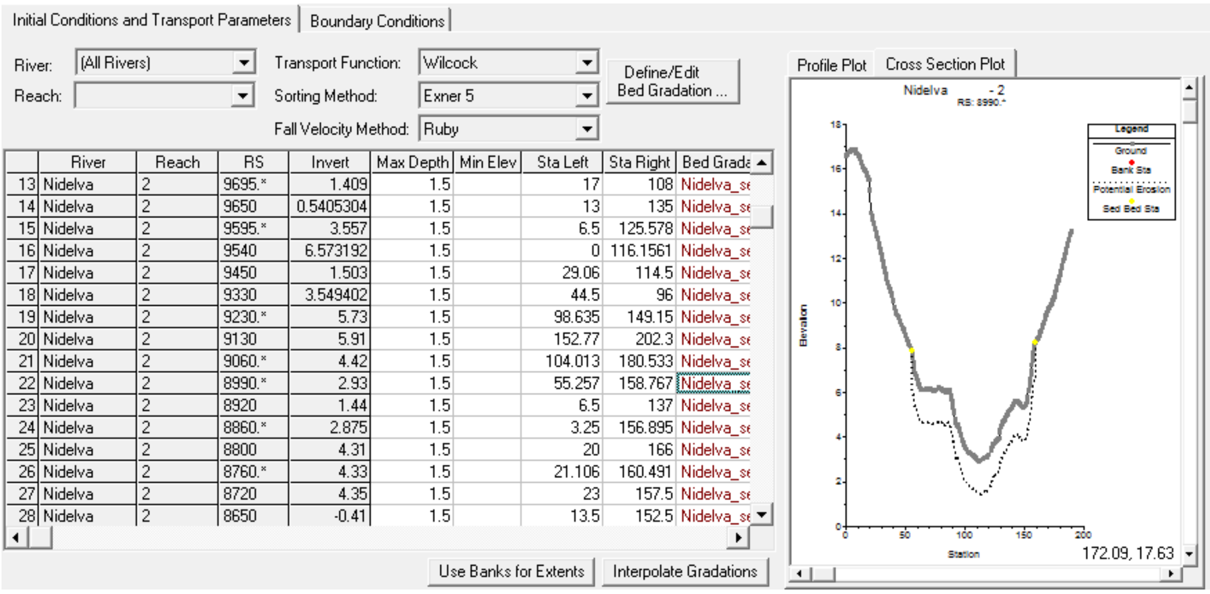


Figure 7-19 Initial conditions at a part of river Nidelva and used settings of the sediment model

Maximum depth was determined as 1.50 meter in a cross-section within the defined river banks, to both river sites (Figure 7-19).

Boundary Conditions

In additional to the initial settings, boundary conditions have to be given for the sediment model as well. Three different types of conditions can be chosen, *rating curve* or *sediment load series*, which are quite analogous in the hydraulic boundary types, and *equilibrium load* which is only available for upstream external cross-sections. Lacking of accurate measurement of sediment transport in Nidelva and Lundesokna, only the equilibrium load was optional as an upper boundary condition. This condition 'refills' the model with the exact amount of eroded material from upstream external boundary. Therefore this cross-section is the only one without any elevation and bed material change during the simulated time. Lack of relevant measured sediment load data for downstream boundary condition the *downstream pass-through boundary* was set up, which means that the material is transported out of the downstream.

8 Hydrographs

The long-term morphological changing, under different types of hydrographs is going to be presented in the thesis. The sediment transport model as an input for the main simulations was already described above, and now the used hydrographs is going to be presented in this chapter. Each of the river sites will be investigated under two different scenarios, natural and regulated (aka. hydropeaked) waterflows. For every case, 1 year of recorded or calculated flows were chosen with continuously data and without any unusual extreme values, and was repeated 19 times in a row to simulate exactly 20 years. This method was necessary to grant the same conditions of the streamflow choice for every case of simulations.

8.1 Lundesokna

The land of Norway has a lot of lakes and rivers for ages, nevertheless the recording of water levels or discharges is not completely extensive in the country. The hydroflow of Lundesokna with its smaller river basin (compare to the average in Norway) was ignored by this issue until the hydropower plant started to build in the 1970's. The recording at the lower part of the catchment area (where the chosen river site has the upstream boundary) only contains data from hydropeaked times. However, some hydrological methods were established to estimate the natural flow hydrograph, too.

8.1.1 Regulated flow time series of river Lundesokna

As the upstream boundary condition is actually a hydropower plant, the daily recorded data were available from 1975 to the present by the Norwegian Water Resources and Energy Directorate (NVE). This river site has not significant floods as it was mentioned before, discharge varies between 0.45 m^3/s at low flow and 20.0 m^3/s at high flow.

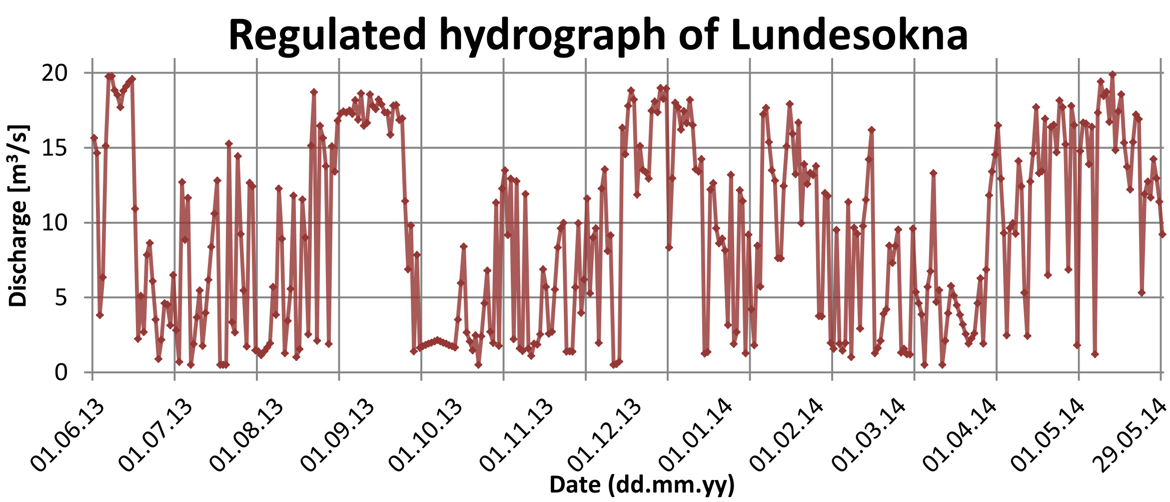


Figure 8-1 Chosen flow series of Lundesokna for regulated scenario

The chosen one year of recorded data from 30.05.2013 to 29.05.2014 are shown in Figure 8-1. Due to the ever-changing energy demands, the hydropower can be operated rapidly, which appears on the diagram above.

8.1.2 Natural flow time series of river Lundesokna

Although the natural flow series were not recorded in the river basin, some hydrological methods were tested to calculate the unregulated range of hydrograph at Lundesokna. Thanks to these investigations 1 year of estimated river flow was obtainable from the IVM to define as an input to the model. The used method, which is going to be represented briefly below, was developed by Teklu Tesfaye Hailegeorgis at NTNU in 2015.

Estimated time series of streamflow on Lundesokna by Hailegeorgis (2015)

The identification of independent variables and choice of the dependent variables are important for the used statistical (regression) model. The focus of the presented method is to derive the flow duration curves and time series of the streamflow. A simple linear regression model was used with normal and homoscedastic precipitation assumptions. The set of parameters were estimated for minimizing the standard error of estimates.

$$\underline{Y} = \underline{X} * \underline{\beta}^* + \varepsilon \qquad \text{(eq. 9)}$$

$$\varepsilon \approx N(\underline{0}, \underline{I}\sigma^2) \text{ and } \underline{Y} \approx N(\underline{X\beta}^*, \underline{I}\sigma^2) \qquad \text{(eq. 10)}$$

Where: $\underline{Y}$ – is nx*1* column vector of response (dependent) variable,

$\underline{X}$ – is nxp matrix of independent variable,

$\underline{\beta}^*$ – is nx*1* column of regression parameters,

ε – is *nx1* column vector of the error term that indicates the deviation of the estimate from the true value,

N – represents the assumed Normal distribution,

$\underline{I}$ – is a nxn identity matrix

σ^2 – is the variance,

$*$ represents the 'true' values, underline represents the vector or matrix notation,

n – is the number of observations (data points).

To produce the time series of the streamflow a simple method was proposed to derive the required data for ungauged catchments from flow percentiles of gauged and ungauged river basins (which comes from regional regression). The main premise of the method that for river basins which are homogenous in terms of their range of hydrographs and streamflow percentiles at a similar time *t* exhibit the same percentile for the homogenous donor (gauged catchment) and the recipient (ungauged catchment). A simple *lookup* function was used in Microsoft Excel:

$$Q_t^{ungauged} = lookup(Per_t^{Qgauged}, Per^{0:1:100}, Q_{Per}^{reg:ungauged}) \qquad \text{(eq. 11)}$$

Where: Q_t – is ungauged time series of the streamflow,

Per_t – are percentiles from 0 % to 100 % at 1 % intervals,

Q_t – is streamflow corresponding of percentile per (derived by eq. 9).

The predicted time series, which start from 09.01.2009 and last till 08.01.2010 with daily values, show two major flood events during the year with nearly 60 m^3/s flood peak in both cases. The complete hydrograph is represented on the following figure.

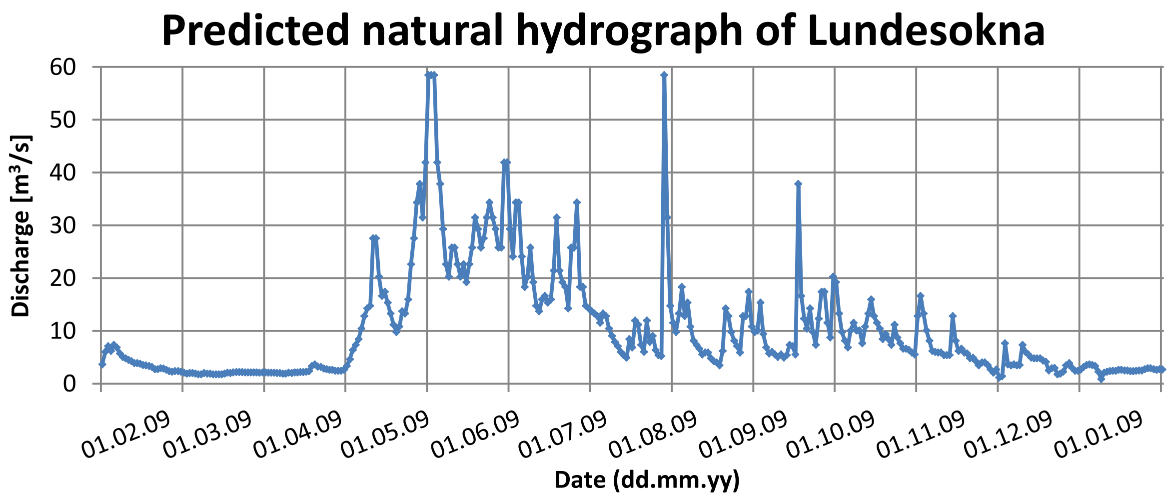


Figure 8-2 Predicted natural hydrograph of river Lundesokna (Hailegeorgis, 2015)

The availability of represented data was the limiting factor for designation time series for each simulation in the followings.

8.2 Nidelva

In the case of the river Nidelva the water level recording, approximately 2 km upstream away from the powerplant Nedre Leirfoss, contains more than 130 years registered data. The hydropower plant was built in the 1910's which means years of unregulated flow data are available too. The following figure shows the entire measured data.

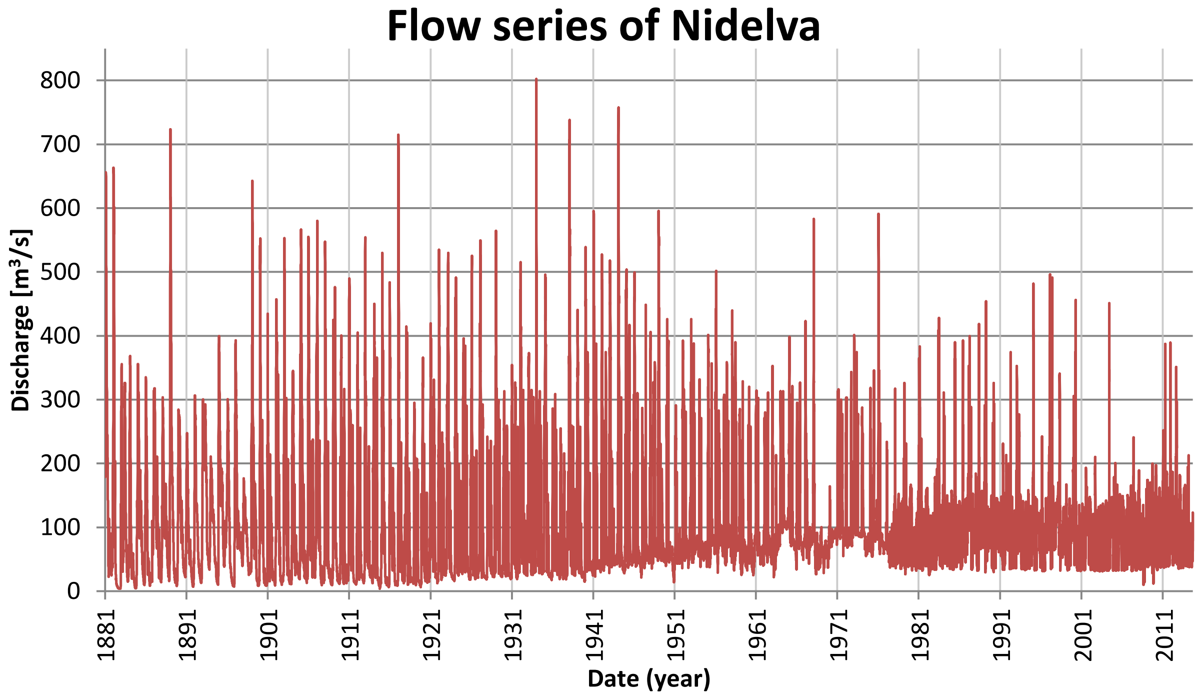


Figure 8-3 Flow serie of the river Nidelva from 1881 to 2014

8.2.1 Regulated flow time series of river Nidelva

The effect of the increasingly developed operation method can be seen in Figure 8-3. Thanks to some strict regulations in the last decades, the minimum flow was predetermined and must be provided in almost any case. Therefore 30 m^3/s flow is ensured at this river part. The choice was made through a short overview of the flood events from the year of 2000 to the present. The herein used flow series (Figure 8-4) starts from 30.05.2010 to 29.05.2011 with a maximum flood peak 252 m^3/s.

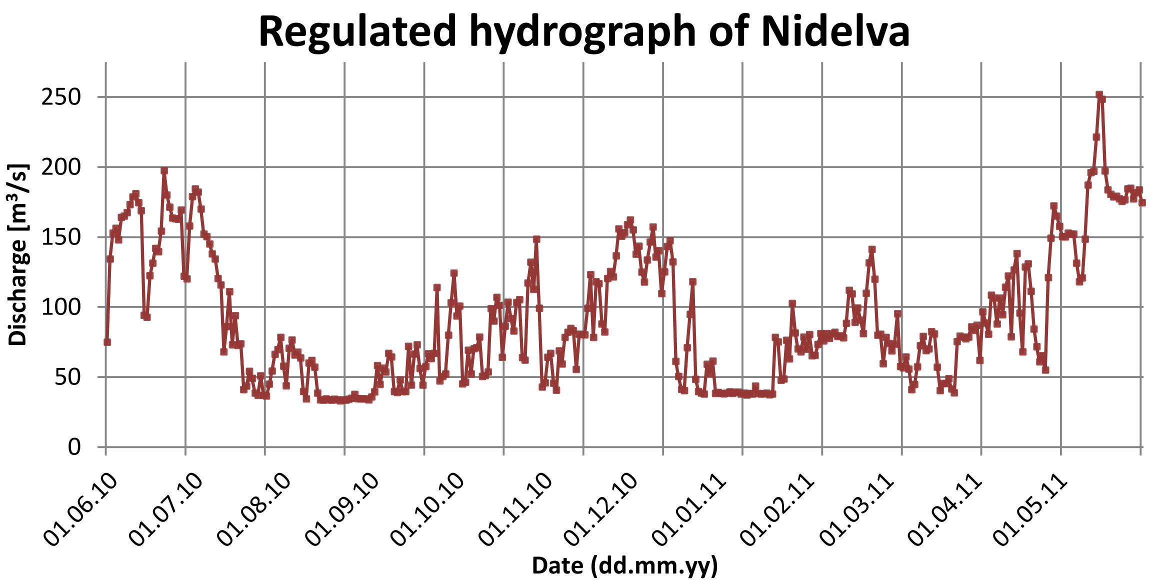


Figure 8-4 Chosen flow series of Nidelva for regulated scenario

8.2.2 Natural flow time series of river Nidelva

The hydropower plant at lower part of Nidelva, called Nedre Leirfoss was started to produce electricity from the year of 1910, while the recording of flow series had started in 1881. It means that less than 30 years of natural hydrograph was available to designate one year of it for the numerical simulations. The chosen period for the main simulations starts from 24.04.1896 and finishes at 23.04.1897. The maximum flood water level during the year was 300 m^3/s.

An additional half-year of hydrograph was chosen from the year of 1899 with peak discharges 650 m^3/s extreme value. Although a few years of unregulated hydrograph were available, it was not possible to find two years with quite similar range of hydrograph, but excursive flood peaks. For the main simulations the natural flow with 300 m^3/s peak discharge was used from Figure 8-5, but the reason to choose another 5-months flood event was to make a comparative study between two different peak discharges within nearly half simulated year. The hydrograph with different flood events can be seen on the Figure 8-5.

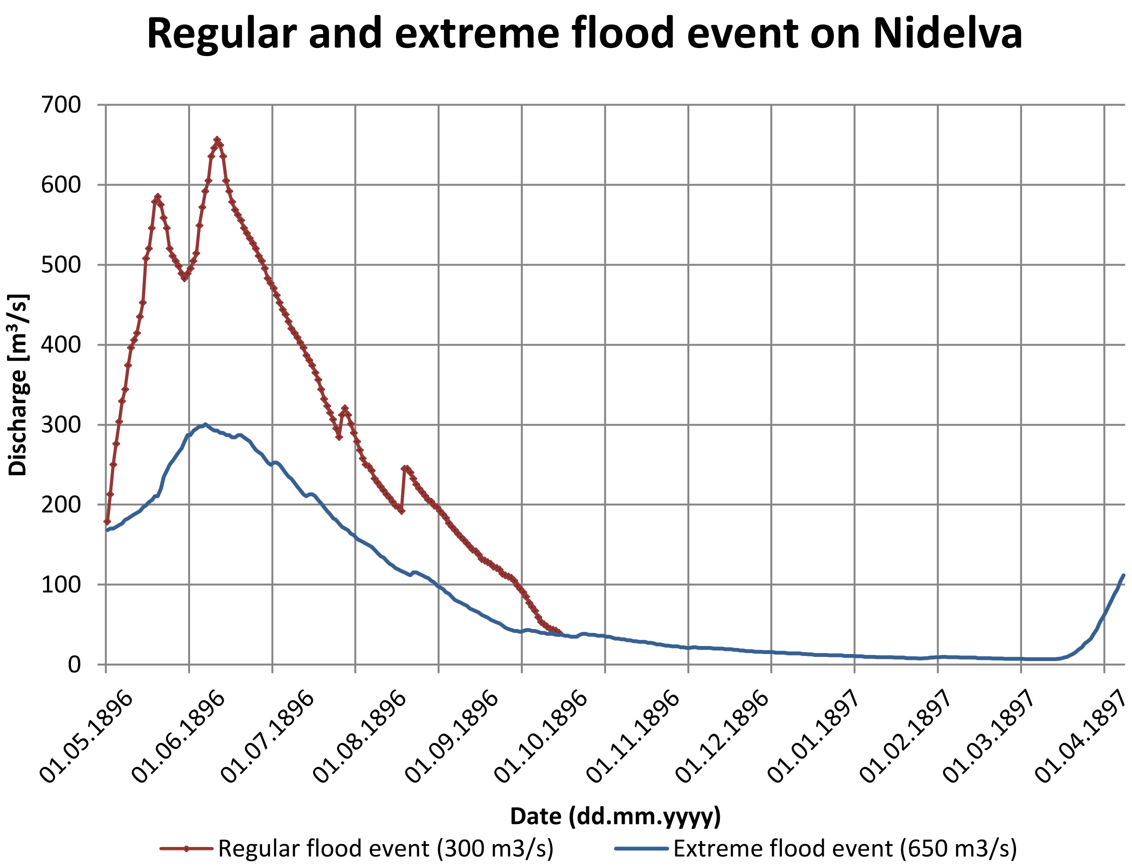


Figure 8-5 Regular (lasts for 1 year) and extreme flood event (lasts for 5 month) at Nidelva

9 Simulations

The main runs are simulating 20 years under regulated and natural hydrographs both for Lundesokna and Nidelva rivers. With the aforementioned time series and sediment settings the model parameterization was carried out and the models were ready for further simulations. Present chapter briefly summarizes the initial settings, and presents the results of a sensitivity analysis.

9.1 Input data and settings of simulations

Before the sediment transport analysis within HEC-RAS can be started some hydrodynamic functions must be determined. The quasi-unsteady flow assumption is a continuous hydrograph approach with a series of discrete steady flow profiles, which means that for every record in the flow series the computed water level stays constant over a specified time while transportation occurs (Brunner G. W., 2010).

To set up quasi-unsteady options the following settings must be carried out:

- Selecting the cross-sections for boundary conditions: same as the previous ones from chapter 7: one upstream and one downstream boundary for Lundesokna, and one upstream and one downstream boundary for Nidelva as well.
- Selecting types of boundary conditions: similar to the presented ones from chapter 7
    - In the model of Lundesokna: upstream boundary type *Flow hydrograph* with the chosen streamflows (based on Figure 8-1 and Figure 8-2 and repeated up to 20 years in both cases) with daily values (duration: 24 hours) and 1 hour time step; downstream boundary type *Normal depth* (value: 0.0092)
    - In the model of Nidelva: upstream boundary type *Flow hydrograph* with the chosen streamflows (based on Figure 8-4 and natural flow from Figure 8-5 flood event with 300 m^3/s, and repeated up to 20 years in both cases) with daily values (duration: 24 hours) and 1 hour time step; downstream boundary type *Stage series* with measured Tide series (Figure 9-1, duration of one value: 6 hours)
- Setting Temperature: temperature time series were added with the same date as flow series in order to be sufficient. However, the simulations tend not depends on the temperature changing, because of the lack of suspended sediments (Brunner G. W.,

2010). The values vary between 0.5 °C and 14 °C depending on the season and the hydropeaking operations.

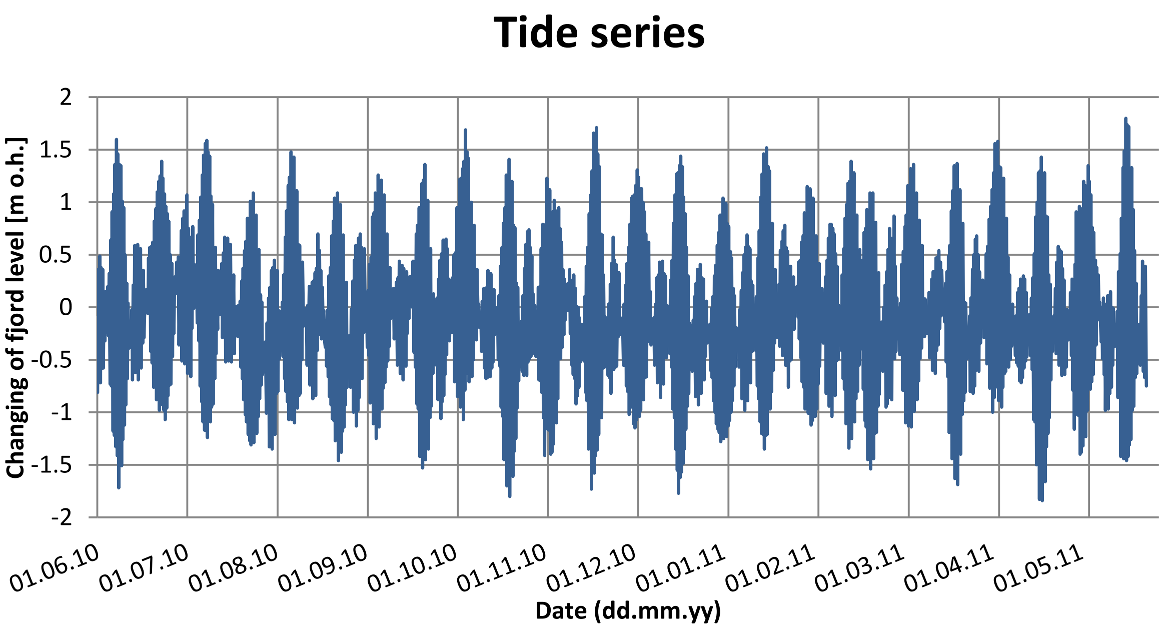


Figure 9-1 One-year tide series

One-year tide serial, was extended up to 20 years by repetitions for long term simulations.

Start simulations

The geometry file, quasy-unsteady flow and sediment data are prepared, but in the HEC-RAS within the Sediment analysis window a few other options can also be set up, such as computational options, tolerances or output options. The latter one is very important to get all the requested variables at the end of the simulations. The next table helps to decide which output level should be chosen for different variables before the simulation starts.

Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Bed Elevation	Bed Elevation WSE Observed Invert Change	Bed Elevation WSE Observed Invert Change Velocity Flow Shear XS Mass Out Tot	Bed Elevation WSE Observed Data Invert Change Flow Velocity Shear Energy Grade Slope Mass Out Tot Mass Out Cumulative Mass Bed Change Tot Mass Bed Change Cum Tot Mass Capacity tot Mean Effective Channel Invert Mean Effective Channel Invert Δ Longitudinal Cum Mass Change	All From Level 4 and… d50 Cover d50 Surface d50 Inactive Cover/Active Layer Thickness Subsurface Layer Thickness Mass Cover (All) Mass Surface (All) Mass Inactive (All) Sediment Concentration	All From Level 5 and… Sediment Discharge (Tot) Channel Manning's n Channel Froude # Shear Velocity (u*) d90 Cover d90 Surface d90 Inactive Effective Depth Effective Width Dredged Volume

(All) = This variable is output as a total for all materials and separately for each of the 20 grain classes
Tot = Only total for all grain sizes combined Cum/Cumulative =Cumulative mass from the beginning of the simulation to the current time
WSE = Water Surface Elevation
Delta Bed = Change of bed elevation

Table 9-1 Variables at different output levels (Brunner & CEIWR-HEC, 2010)

The default level is 4, but in the case of this study the requested data can be obtained with the choice of level 6. Finally with the filling of the simulation time window (e.g. 30MAY1990 – 23MAY2010), the model running can be executed.

9.2 Sensitivity analysis

Sensitivity analysis was made with different sediment settings and flood events to reveal the reaction of the model to different computation methods and inputs. The attention was focused on several sediment transport equations, sorting methods, time steps and flood events, which were run on model of Lundesokna with regulated river flow and at the model of Nidelva with regard to flood events. The default settings for the sensitivity analysis are presented below:

- Transport equation: Wilcock
- Computation time step: 60 minutes
- Sorting method: Exner 5

In most cases only one option was changed from the list above, the other ones were kept on the defaults. During modelling flood events default settings were used. The comparison is going to be made through the following variables: *river bed elevation* [m o.h.], *river bed elevation relative changing* [m], and *cumulative mass bed change* [tons].

Empirical methods – transport equations

Three different empirical methods were changed to test their conformity with the main simulations. Each case was tested for 1 modelled year. The assessment is made by Table 9-2 and the figures which can be found in Appendix B.

In the figures from Appendix B.2 it clearly appears that the Laursen–Copeland equation is not stable enough, the result of the transport equation is oscillating on this level. Even the highest extreme values evolve greatly compared to the others. The Meyer–Peter–Müller equation seems more calculable than the previous one, but the growth of the extreme values is intensive, similar to the Laursen-Copeland ones. The Wilcock method shows moderate changes during the simulated 1 year, and the equation method seems stable enough for longer runs too.

The next table summarizes the cumulative mass of bed changing along the full section in tons.

Mass bed changing (cumulative)		
Meyer - Peter - Müller	-27461	tons
Laursen-Copeland	-159482	tons
Wilcock	-874	tons

Table 9-2 Cumulative mass changing during 1 simulated year on total river site by different transport equations

Similar to the bed elevation changes, the three variant methods lead to three different scales values. The Laursen-Copeland is irrationally high, while with Meyer-Peter-Müller and even with Wilcock settings the results are much less, the latter result stays relatively close to the reality.

Computation time step

Considering the previous results two different calculation intervals were tested out of the several empirical methods, to make them more stable. Each case modelled 1 year. The assessment was made by the Table 9-4 plots from Appendix B (B.3).

The result of the Wilcock method was rational, but the Laursen–Copeland with its oscillated outcomes and the extreme high values which occurred with the Meyer–Peter–Müller equations can be tested for more reasonable results by defining smaller time step. Therefore, after the last simulations with 60 minutes computation time step it was reduced to 6 minutes. According to Appendix B.3 the Laursen–Copeland equation gives the same results for smaller time step as for the default settings. The Meyer–Peter–Müller equation leads to realistic outcomes with the smaller computation interval.

Mass bed changing (cumulative)		
Meyer - Peter - Müller 6 min	-4404	tons
Meyer - Peter - Müller 60 min	-27461	tons
Laursen-Copeland 6 min	-159282	tons
Laursen-Copeland 60 min	-159482	tons

Table 9-3 Cumulative mass changing during 1 simulated year in total river site by different time steps at different transport equations

The table above show the insentience of the Laursen – Copeland equation on this level with regard to the total mass changes, the Meyer – Peter – Müller method resulted about the same in scales as Wilcock (Table 9-2). Although the Meyer – Peter – Müller equation seems a good choice with smaller time step for the main simulations, the actual execution time of one simulated year was nearly as high as the execution time of 20 simulated years with the default time step.

Sorting method

There are two options available to set up the model how to interpret the active sediment layer during the simulations, the *Active layer* and *Exner 5* adjustment. Recent simulations modelled 20 years. The assessment was made by the Table 9-4 and the figures from Appendix B (B.4, B.5).

Two different approaches are represented by the two sorting options (Figure 7-18). The figure B.4 from the Appendix B. shows the main differences between the elevations computed by two different methods. The deposit at upstream section leads to extremely high changes in bed level for Active layer method, which is not reasonable. The reason for the great deposit is the equilibrium state as an upstream boundary condition. A possible explanation is that while the sediment layer at the upstream cross-section is easily washed away in time, the model refills the same amount as the washed out sediment, which is not transported much further away, therefore the deposition occurs. The Exner 5 method leads to more realistic sorting.

Mass bed changing (cumulative)		
Active layer	1379296	tons
Exner 5	-34525	tons

Table 9-4 Cumulative mass changing during 20 simulated years in total river site by different sorting methods

For an evaluation of the total mass change in the river bed during twenty simulated year the table above summarizes main values. As it was expected after the elevation results the Active layer method resulted in very high value positively, while the Exner 5 method gives a realistic alteration. Without any significant sediment input on the river site, the extremely high deposit is unacceptable, but with a realistic sediment rating curve or sediment time series (as an upper boundary condition) the Active layer method could be used as well.

Flood events at Nidelva

Similar flood events but with quite different flood peak were tested to estimate the effect of one extreme flood event. The simulated time was 5 month in both cases. Although, the accepted hydrographs for the main simulations are based on 1 regular year in each case, the study wants to take a quick overview for a short comparison between similar flood events, but with variant flood discharge. The assessment was made by Table 9-5 and by the plot from Appendix B (B.6).

According to the extreme values the highest deposition occurred during the flood event with peak discharge 300 m^3/s near river station 9680m. The deepest erosion occurred right after the mentioned cross-section, around 9550m with -0.16 m minimum value during the flood event with 650 m^3/s peak discharge. Although the smaller flood event produced the highest relative changing, the extreme flood event with twice higher discharge eventuated more significant changing in the river bed along the profile downwards, in regards of the following table the stronger effect of a major flood event is clear. The transported bed mass over 5 simulated months is greater with an order of magnitude.

Mass bed changing (cumulative)		
Flood peak 300 m^3/s	-796	tons
Flood peak 650 m^3/s	-4259	tons

Table 9-5 Cumulative mass changing during 5 simulated month in total river site of Nidelva after different flood events

Summary of the sensibility investigations

All of the results presented above prove the fact that sediment analysis within HEC-RAS is quite sensitive for the chosen empirical method and its computational time step as well as for the sorting methods with regard to the input sediment boundary conditions. However there was some opportunity to choose from different suitable settings in regards to estimated execution time and the basic equations Wilcock method with 60 minutes time step and Exner 5 sorting method is an optimal set up for main simulations. Thereby the default settings for the sensibility simulations were accepted to the main modelling as well.

As it has clearly been established, recent study aims only to investigate the qualitative differences of long term sediment changing in two various state hydrograph. Nevertheless, it is important remark, that this analysis and method could strongly be supported from the reality, by proper sediment analysis in the field (long term elevation changing, measuring bed load and coarse materials transport, etc.). That would lead to execute not only qualitative but quantitative investigations as well.

Regarding the effects of different flood events it has been showed that a higher flood event does not automatically rebounds greater extreme values in the river bed. But its effect on the transported mass bed is obviously high.

10 Model results

Table 10-1 shows the executed simulations with general informations:

River site	Type of hydrograph	Simulated time
Lundesokna	Regulated	20 years
Lundesokna	Natural	20 years
Nidelva	Regulated	20 years
Nidelva	Natural	20 years

Table 10-1 Brief summary of the main simulations

10.1 Introduction of the results

After each simulation the HEC-RAS software gives an ample result file as an output with different variables depending on the set up output level. These data can be extracted into a text format or displayed within the program along animated, plotted or tabular format. To investigate the variables of velocity or shear stress the animated display is more spectacular, but it is better to save other variables and process them in spreadsheet. The next variables were sorted out from HEC-RAS and processed in Microsoft Excel:

Variables	Unit	Description
Ch Invert El	m	Minimum elevation of the main channel at each output time.
Invert Change	m	Delta change in the minimum elevation of the main channel.
Mass Bed Change Cum	tons	Cumulative mass of the change in the bed elevation over time.
Mass Cover: All	tons	Total tons of material in the cover layer at the end of each computational time step.
Mass Cover: Class 9-17	tons	Tons of material in the cover layer at the end of each computational time step, by individual grain size fractions. (0.5-1 mm; 1-2; 2-4; 4-8; 8-16; 16-32; 32-64; 64-128; 128-256)
d50 Cover	mm	d_{50} of the cover layer at the end of the computational increment.
d90 Cover	mm	d_{90} of the cover layer at the end of the computational increment.

Table 10-2 Description of sorted variables from HEC-RAS (Brunner & CEIWR-HEC, 2010)

Variables calculated at the end of each computational step or over time were processed at the last simulated time, at the end of the 20-years period. There is only one exception, the river bed elevation in initial state (i.e. unchanged bed level) was extracted, to plot together with actual changing over time.

The invert elevation values of the channel (hereafter referred to as river bed elevation) were simply plotted per river site together with the other type of hydrograph in the same way as the invert elevation (hereinafter relative changing of the river bed), but in different figures. One example for each result variable is shown in the current chapter, but the complete list of the figures with proper matches can be found in Appendix C.

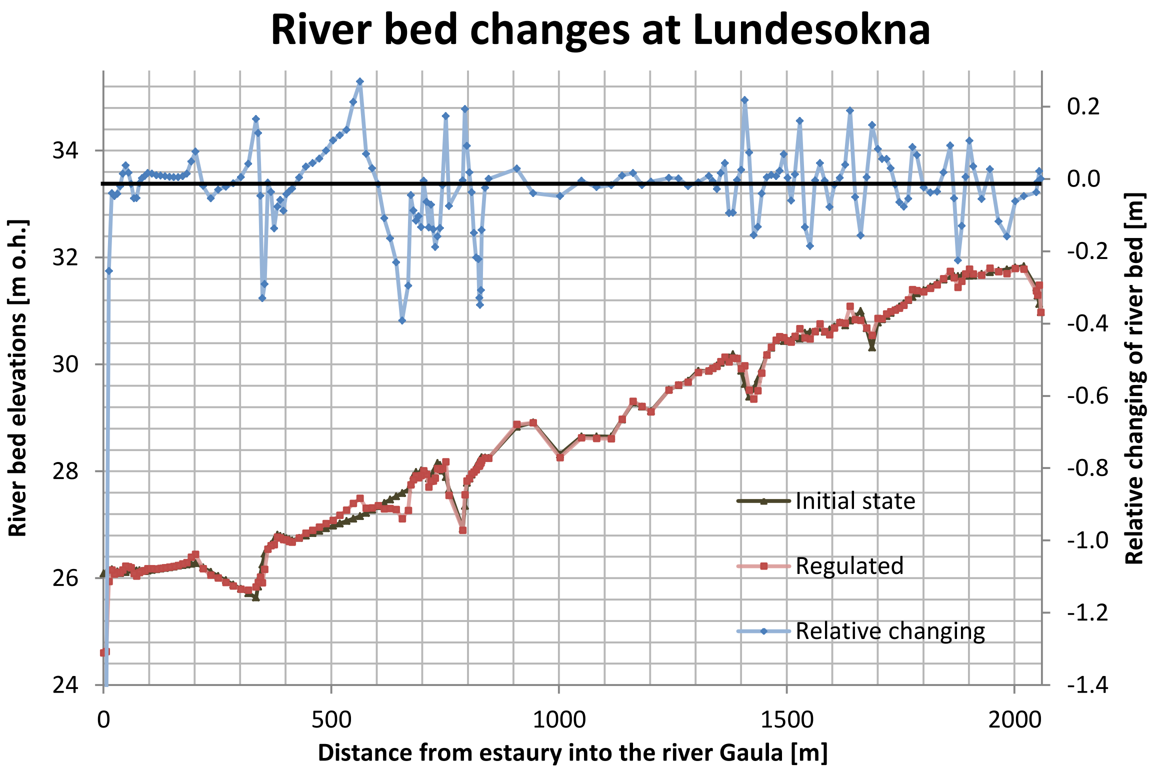


Figure 10-1 Relative and absolute river bed elevation changing at Lundesokna under regulated conditions

The relative river bed changing can be averaged too, and the values of cumulated mass bed change over time can be summarized to see how the river bed changing developed over two ranges of hydrograph scenario during the simulated years.

	Cumulative mass bed change [tons]	Averaged relative river bed change [m]
Natural	-30717	-0.024
Regulated	-34525	-0.044

Table 10-3 Cumulative mass bed change and averaged river bed changing over 20 years under regulated and natural conditions at Lundesokna

Special value of grain size distribution in the cover layer is the d_{50} and d_{90} which represent the centre and the coarse tail of the distribution. The study investigates the relative changing of these parameters individually and also matched with the relative changing of river bed.

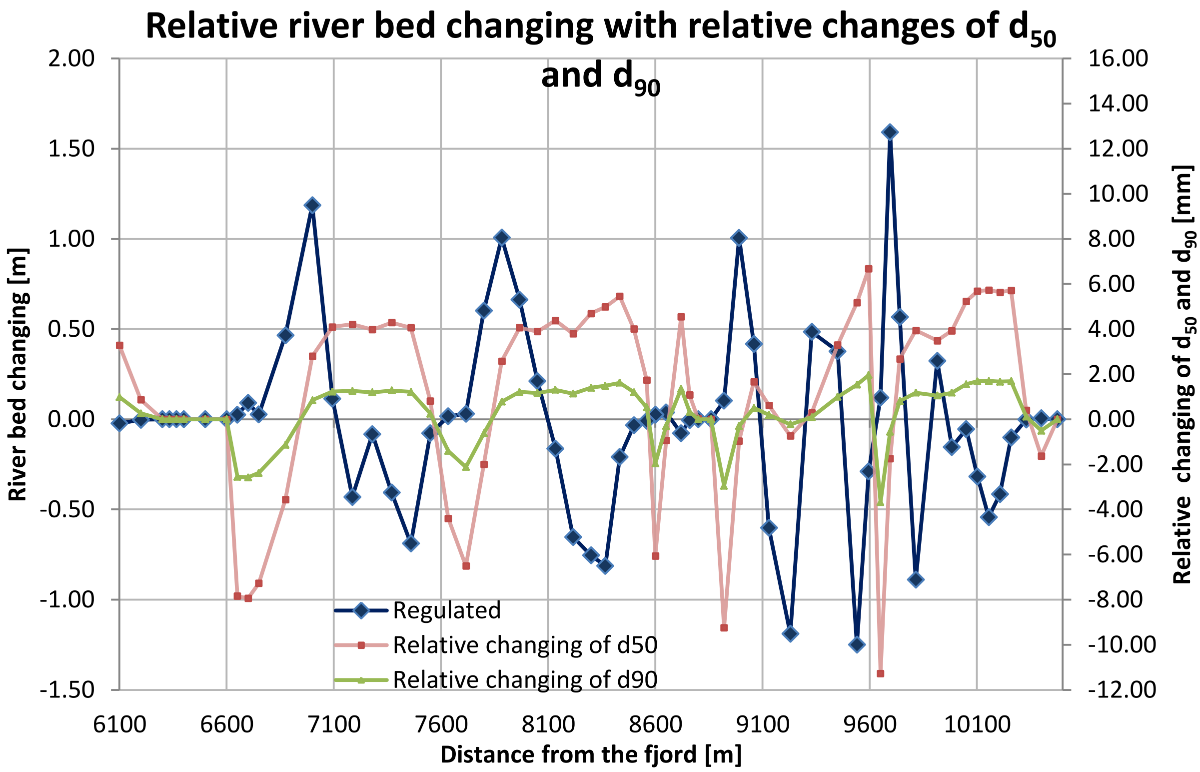


Figure 10-2 Relative river bed changing matched with relative changes of d_{50} and d_{90} at Nidelva under regulated scenario

The initial value of the mentioned percentiles is given at the upstream boundary due to the equilibrium load boundary condition in each case.

It has to be noted, that these parameters are slightly different from the values what we could get from (eq.1). For this reason the distribution parameters which come directly from HEC-RAS as an output are denoted with lowercase *d* as d_{50} and d_{90}, and the calculated parameters from grain size distribution are denoted with capital *D* as D_5 and D_{10} to be sure.

10.2 Grain size distribution and predicted shelter abundance

The shelters were measured on the surface, and sediment samples were taken from the cover layer of the river bed. Therefore, the granulometry of this stratum were queried from the HEC-RAS (Mass Cover: All and Mass Cover Class 9–17). Hence, the grain size distribution can be calculated at every cross-section, since the mass of each fraction in the cover layer is calculated by the software.

If values of gradation are calculated, D_5 and D_{10} could have been defined as well by (eq.1). In chapter 6.4 the correlation between shelters and distribution parameters is significant, the linear connection can be used to calculate shelters, if the fine tail of the distribution is known. Following this theory and the model results the shelter abundance can be predicted based on D_5 and D_{10} parameters for every cross-section with the next equations.

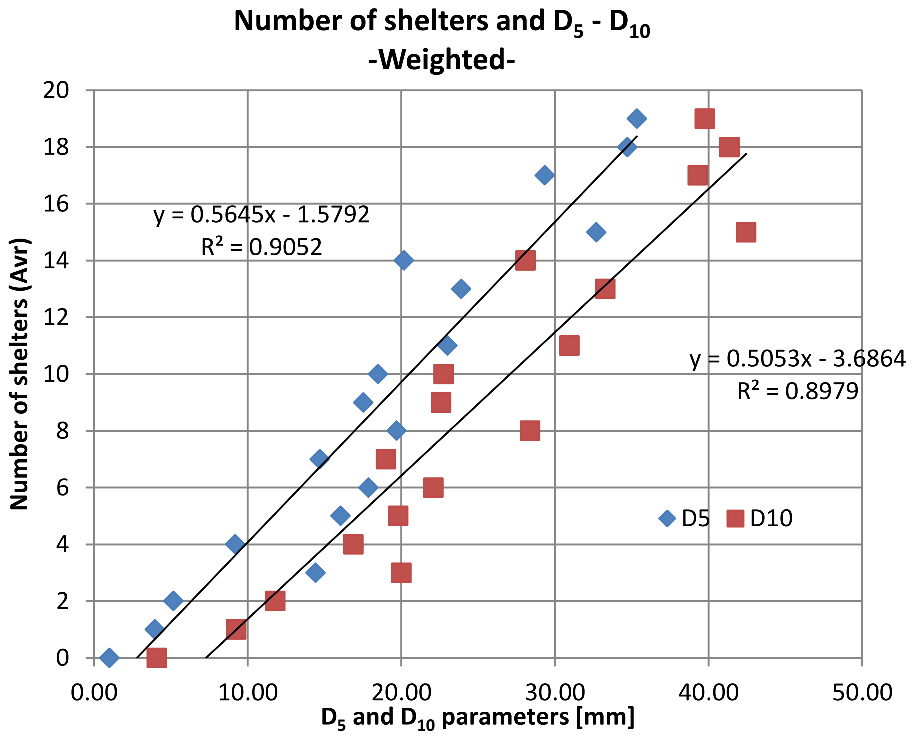


Figure 10-3 Linear trend line with number of shelters and D_5 and D_{10} parameters with its equation displayed (See Figure 6-9 right side)

$$S_{D_5} = 0.5645 * D_5 - 1.5792 \qquad \text{(eq. 11)}$$

$$S_{D_{10}} = 0.5053 * D_{10} - 3.6864 \qquad \text{(eq. 12)}$$

Where: S_{D_5} – is the predicted shelter number, based on D_5 parameter,

S_{10} – is the predicted shelter number, based on D_{10} parameter,

D_5 and D_{10} – are distribution parameters, calculated by (eq. 1).

The equations determine the presented linear correlation on the weighted shelters method (see chapter 6.4, Figure 6-9 right side). According to this linear relationship every cross-section has its own predicted shelter abundance, and they can be rated according to the following table:

Classes	low shelter	moderate shelter	high shelter
Number of shelters	< 5	5 – 10	10 <

Table 10-4 Classification by summed shelter numbers (Forseth & Harby, 2014)

It must be noted, that these values are specific values, a predicted number of shelter refers to a 0.25 m^2 area. Values were rounded downwards to the first even number. The next figure shows an example for the predicted values.

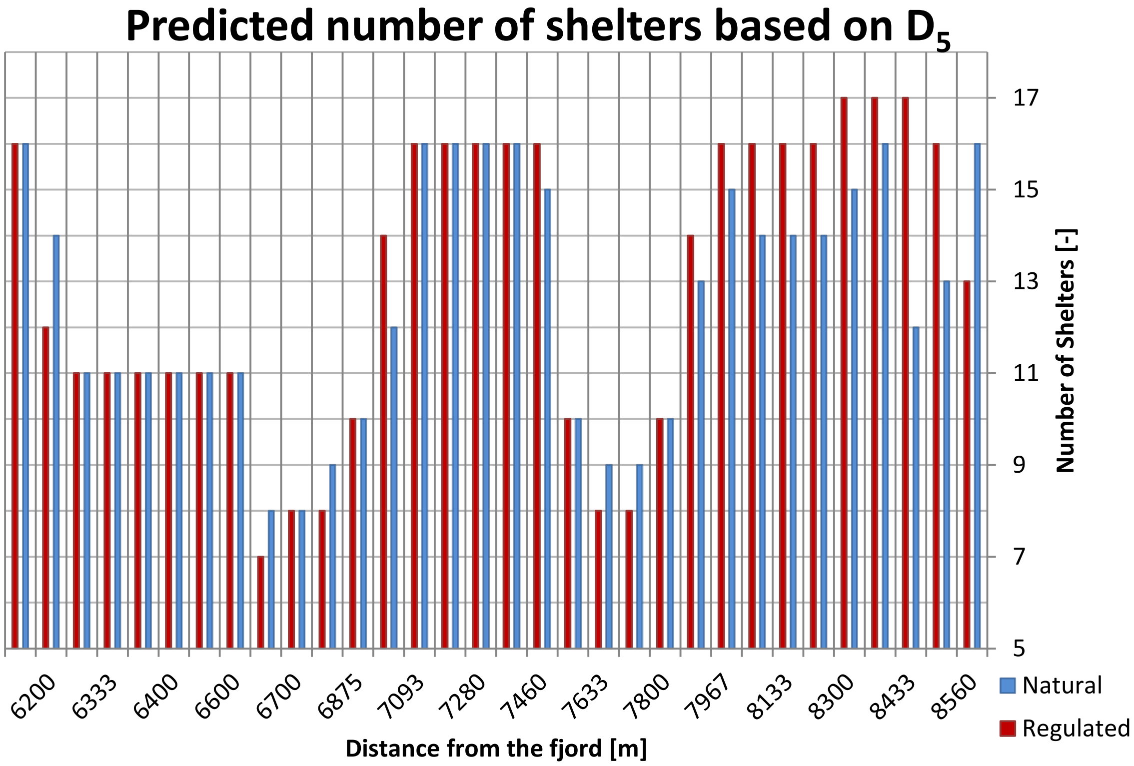


Figure 10-4 Calculated shelters based on D_5 at one river site of Nidelva

The cross-sections with the specific values can be summed up over the river length by the associated section length, and at the end sections can be summed up according to Table 10-4. This kind of assessment gives another starting point to compare the simulations.

Sections in running meter (D_{10})

Shelter Abundance	Natural	Regulated
High	4219	3877
Moderate	149	490
Low	0	0

Table 10-5 Summarized river sections related to different shelter abundance (based on D_{10}) between natural and regulated scenarios at the river Nidelva

11 Evaluation of results

The current chapter contains the assessment of the results from the models. The first half of the chapter discusses several cases at river sites; in the second part all "natural" cases will be compared with all "regulated" cases.

The assessment which will be presented through the paragraphs refers to figures which can be found in Appendix C, however, some key figures are going to be presented in a small size in the current chapter as well.

River Lundesokna, simulated 20 years with regulated and unregulated hydrograph

The river bed changing can be divided into three phases in both cases. The upper section starts from upstream boundary (2058 m from the estuary into the river Gaula) till the river station 1350 m. The bed elevation at this part changed frequently, deposition and erosion occurred sequentially. The middle phase starts from 1350 m and lasts approximately till 850 m river station. Here the elevation of the main channel did not changed significantly, the bed can be considered stable during the simulated years in every case. The last section from 850 m to river station 0 m has more alteration. Here the frequency of the changes is lower than at the upper phase, but the extreme values are higher, and an erosion section can occur through 100 m over the river profile, while the most significant deposition lays 175 m right after the largest deepening along the river.

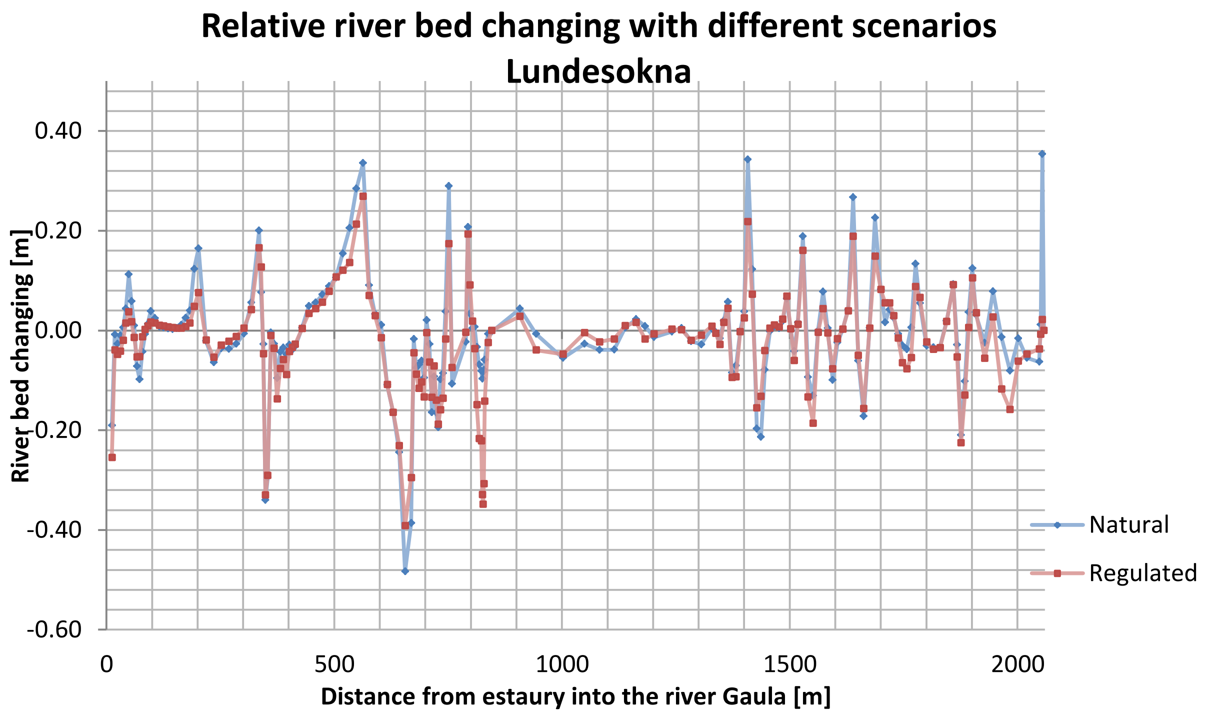


Figure 11-1 Relative changing of the river bed at Lundesokna under altered hydrographs

The interval of extreme values over whole river length starts from -0.39 m up to +0.27 m in regulated and +0.34 m and -0.48 m in unregulated scenarios. The Figure 11-1 presents the greater changes in general at natural hydroflow.

It has to be noted, that the absolute lowest erosion occurred at the downstream boundary (0) with -1.48 m bed change, and the absolute highest deposition occurred at upstream boundary (2058) with +0.35 m value, but due to the uncertainty of boundaries (the chosen hydraulic and sediment load conditions) these values are going to be ignored from most of the figures and the evaluation in the followings.

The averaged elevation change over the whole river section and the cumulated mass bed changes are presented in the following table.

	Average elevation changing [m]	Cumulative mass of bed changing [tons]
Regulated	-0.007	-34525
Natural	-0.027	-30717

Table 11-1 Average river bed and cumulative mass bed change over 20 years in different cases at river Lundesokna

Regarding the results summarized above, the river bed can be determined as a stable on average, but on Figure 11-1 it can be concluded that non-negligible aggradations or degradations could occur during a few decades.

It is a general hypothesis in the study that where erosion occurs (elevation level goes down), there the gradation parameters are increased generally and vice versa. It is obvious when finer fractions (more movable particles in river flows) are washed away, their amount in the gradation is decreased which leads to higher distribution parameters. This hypothesis is right in most of the cases, and it is supported by the results of the simulations as well. However, some exceptions of this assumption were found. The possible reasons are going to be described where anomalies happen.

In the next figure predicted shelter numbers (based on D_{10}) are presented in regulated and natural simulations along with the relative changing of river bed. Two things should be noted in the followings. First, that the predicted number of hiding places has positive linear correlation with D_5 or D_{10} grain size distribution parameters (see chapter 6.4 or Figure 10-3). Therefore, when the evaluation refers to distribution values in connection with figures which present calculated shelters, the referring is correct. Second, the scale of relative changes of river bed is reversed in its values (in current chapter and in Appendix C. where relative changes of river bed is shown), to observe more that when erosion occurs the gradation becomes coarser, and at degradation distribution shifts to finer direction generally (based on mentioned hypothesis).

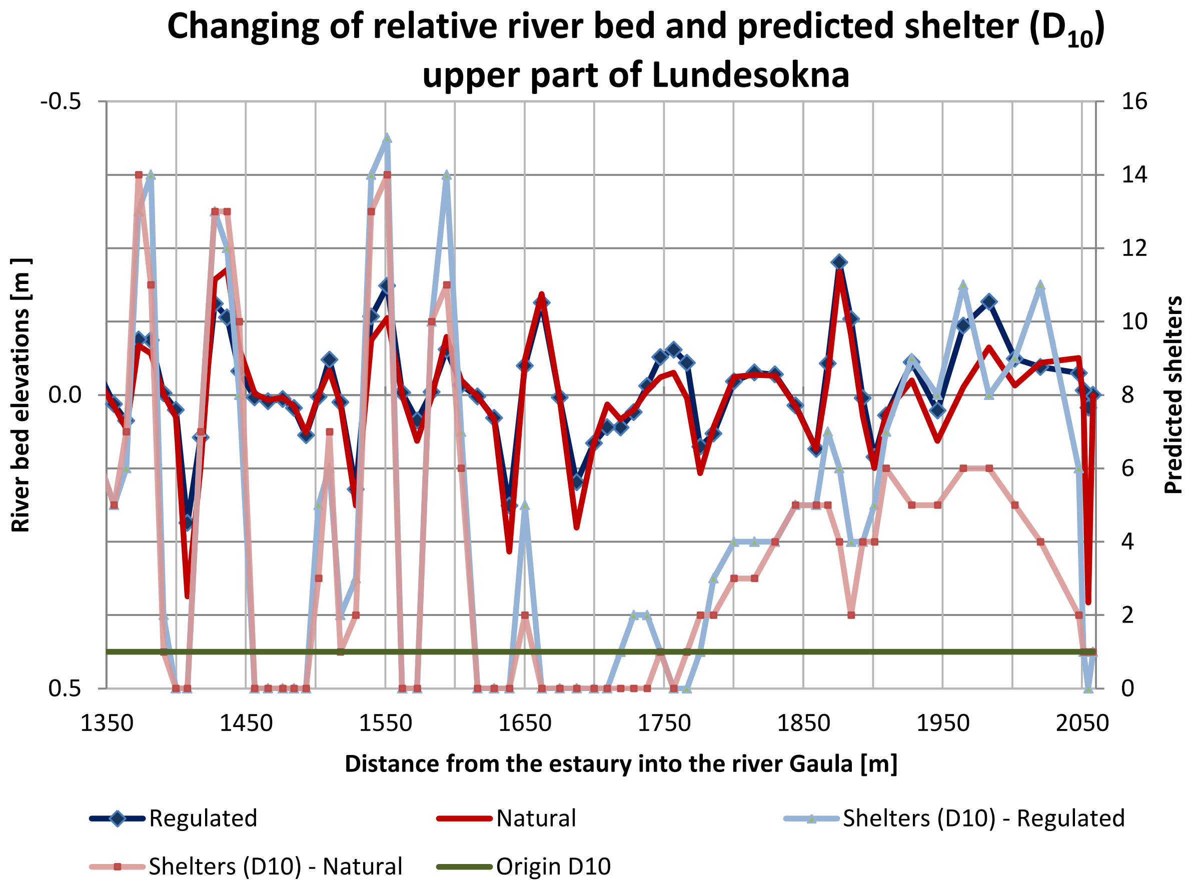


Figure 11-2 Relative river bed and shelters changing at upper part of Lundesokna based on two scenarios

The changing of distributional parameters strengthens the assumption, however, exceptions to the theory can be found in both simulations as well.

In case of the regulated simulation the main reason of exceptions was the strong selective transport (e.g. between river site 1950 m and 1850m). For instance, the fractions between 0.5-64 mm are clogged, therefore their amount is increased, at the same time the amount of coarser particles between 64-256 mm are decreased. Namely *embeddedness* occurs. In other cases the gradation of the cover layer was kept similar to the initial state, which means the distribution parameters are relatively low at the river Lundesokna.

	D_5	D_{10}	d_{50}	d_{90}
Initial state	4.0	10.7	41.3	86.8

Table 11-2 Initial values of several distribution parameters at Lundesokna. The dimension of the values is [mm]

At the frequented bed changes (upper and lower part), it sometimes happened that the structure of the coarser fractions (32-64mm, 64-128mm and 128-256mm) is transformed, while the finer particles (<32 mm) stayed in their original state. This transformation disrupted the initial balance, meaning that the amount of one mentioned fraction class from the coarser ones was extremely increased while the other two coarser classes greatly reduced. A few times the reason of some anomaly (at middle part and lower section) was the sheet flow, thus the fine materials raised, thereby values of the gradation parameters were reduced.

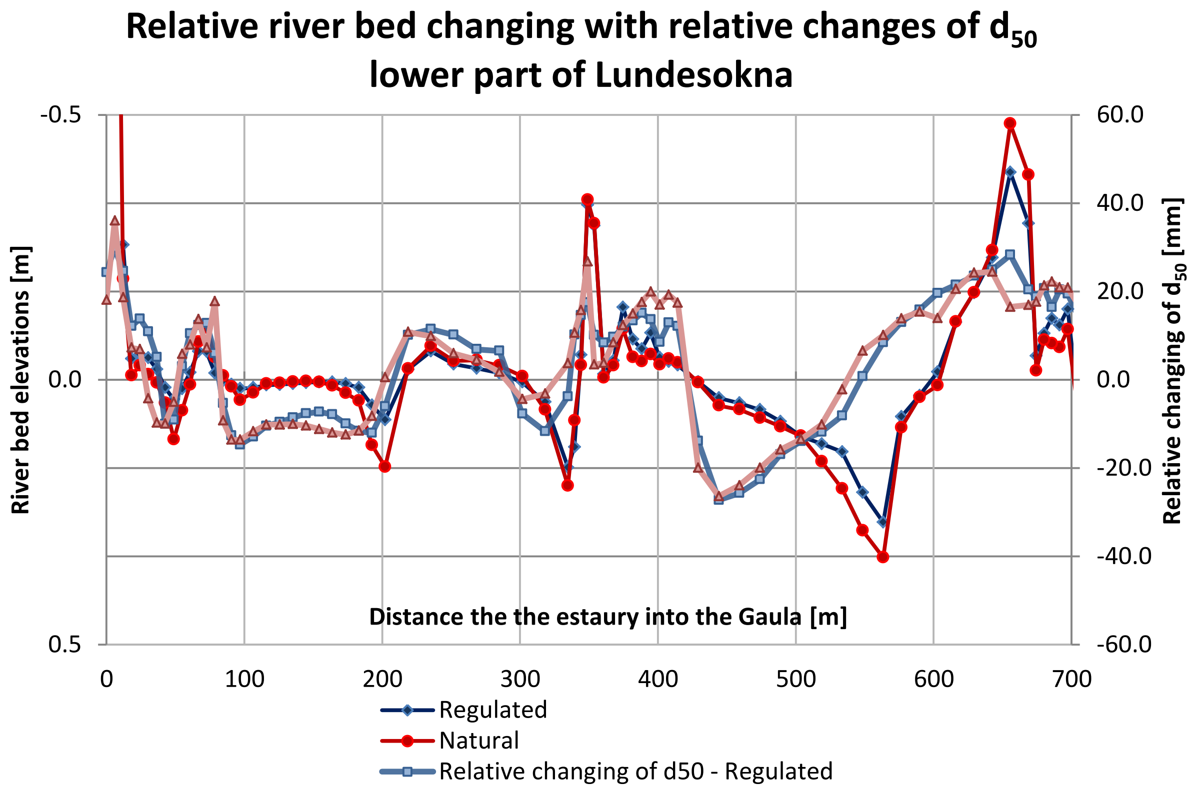
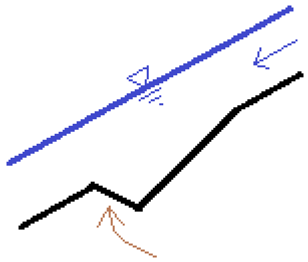
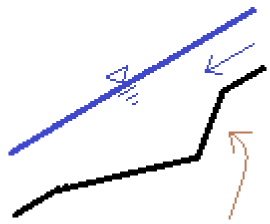


Figure 11-3 Relative changing of river bed and d_{50} at the lower part of Lundesokna with two scenarios

Nonetheless, some anomalies might have other explanation. At middle and lower parts of the river the coarse fraction is to disrupt its initial balance in both cases as well. Mainly the 32-64 mm fraction decreases strongly which leads to reduced d_{50} value. Another interesting anomaly can be found in the unregulated cases. A slightly delayed reaction of the d_{50} and d_{90} values to degradation or aggradation should be observed at the lower part, from approximately river station 650 m to downwards (Figure 11-3). Similar shift was recognised in the regulated scenario as well, but in unregulated cases it is more obvious. A possible explanation is that the raising side of the deposition has reduced the amount of finer material (hence D_5 and D_{10} are increased), while the failing side of aggradation is the opposite, with smaller particles the parameters of the gradation fine tail were decreased.



In the case of unregulated simulation a few differences were noted, among triangle shaped pools, similar to the one sketched at the left hand side. It was noticed that in this case the distribution stays close to the original, but the coarse fraction (>32mm) stacks up at the angle of the pool, thereby at the signalled part a slight shelter development was recognised. This kind of pools can be found at the upper and middle part. From the middle part and at the lower section the direction of the pool is changed (next sketch, on the right hand side). In this case the first segment of the pool is the place where finer particles are clogged, thus this section has less shelter abundance (smaller D_5 and D_{10}).



After 20 simulated years the average distribution parameters besides to the predicted shelter numbers are summarized in the following table for both investigated hydrograph events, with their initial values.

	Distribution parameters [mm]				Predicted shelters	
	D_5	D_{10}	d_{50}	d_{90}	based on D_5	based on D_{10}
Initial state	4.0	10.7	41.3	86.8	0	1
Regulated	6.9	14.4	45.5	97.2	2	3
Natural	6.0	13.3	45.2	99.9	1	3

Table 11-3 Distribution parameters and predicted number of shelters initially and after the simulated years at both cases on river Lundesokna

An obvious increase means that the average gradation of the river bed shifted to coarser fractions in both cases. Although the regulated case produced higher values the difference is not significant. The average hiding places per quarter square meter, based on the values from Table 11-3, are not high, therefore shelter abundance is low. Fortunately during the simulations many river sections abound in increased number of shelters and as it was shown above, it can be classified. The next table shows the result summarized the channel distances where low – moderate and high shelter abundance separately occurred.

	Regulated		Natural	
Shelter Abundance	Based on D_5	Based on D_{10}	Based on D_5	Based on D_{10}
High	120m	234m	19m	157m
Moderate	308m	473m	233m	532m
Low	1626m	1347m	1802m	1365m

Table 11-4 Summarized river sections related to different shelter abundance based on D_5 and D_{10} at the river Lundesokna under regulated and unregulated conditions

The numbers of hiding places at several river sections at natural hydrograph are lower, almost in every aspect, except the moderate sections based on D_{10}. Although moderate and high abundance can be found close to the erosion or deposition extreme values, the total river site with low shelter abundance is significant in both cases.

River Nidelva, simulated 20 years with regulated and unregulated hydrograph

The river bed elevation changing at Nidelva is also frequented over the examined length (Figure 11-4). Nearly the same aggradation and degradation can be observed between river stations 9300 m and 6600 m. At the beginning of the section, upwards, significant deposition occurs. On the profile of the river a narrow elevation decrease is located in the same place, where bed incision happened. Fine sediments are stacked at the regulated case, and it happens at natural simulation too, but in this case the eroded material is full with coarse fractions (64-128mm) from upstream which are deposited right on the bottom of the deepening. It is interesting to see the development of the river bed at this section, because the newly emerged deposition, under natural flows, in its shape and direction is similar to the next, already changed river bed formation in the profile.

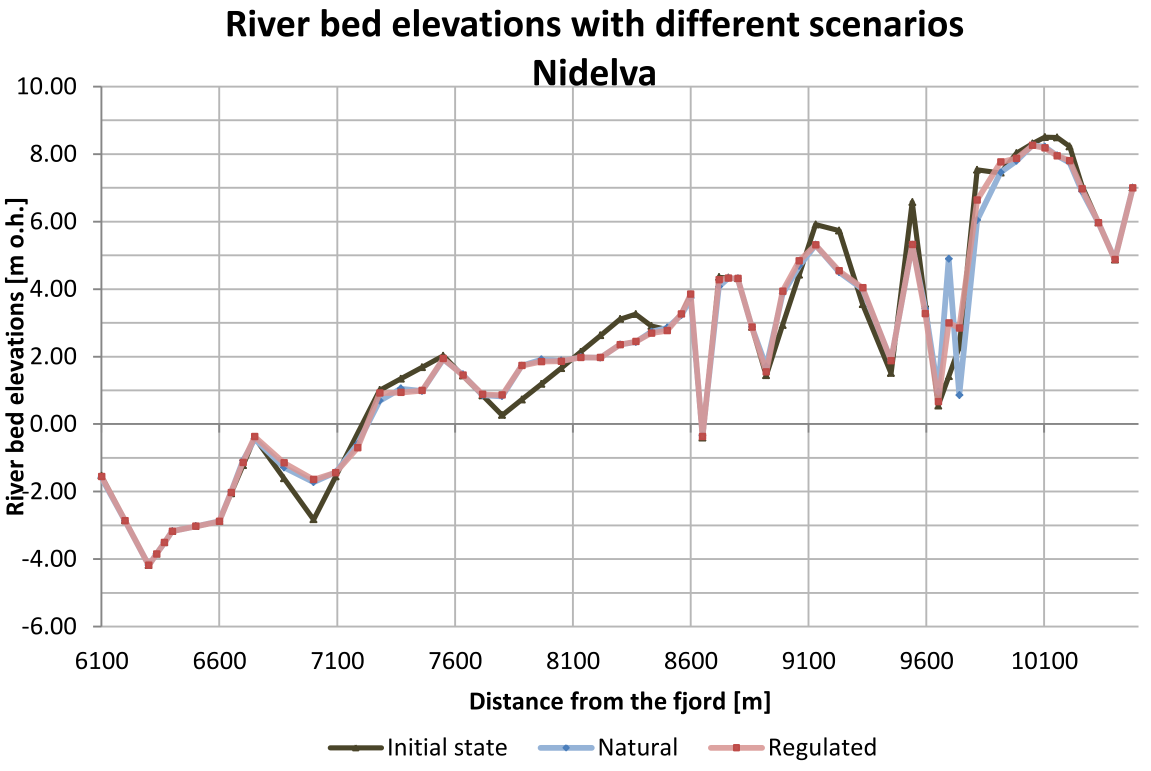


Figure 11-4 River bed elevation changing at river Nidelva under alterred hydrographs

Extreme values appear on the same part in every case of Nidelva. The maximum value of the relative bed elevation changing is +1.60 m while the minimum is -1.25 m under regulated, and +3.50 m and -1.49 m under natural conditions. The averaged elevation change over the whole river section and the cumulated mass bed change are presented in the following table.

	Average elevation changing [m]	Cumulative mass of bed changing [tons]
Regulated	-0.012	-18665
Natural	-0.034	-21680

Table 11-5 Average river bed and cumulative mass bed change over 20 years in different cases at river Nidelva

The natural range of hydrograph has more ability to form the river bed, however, its hydrograph contains less frequency than the regulated one.

The distribution parameters initially are presented in the table below.

	D_5	D_{10}	d_{50}	d_{90}
Initial state	23.13	33.75	52.7	81.2

Table 11-6 Initial values of several distribution parameters at Nidelva. The dimension of the values is [mm]

It is obvious that this river section of Nidelva has much coarser gradation. After the simulation there is less variation of the distribution parameters than at Lundesokna, while the flood events and the modelled river length are even higher. The based hypothesis is proved in this case as well, but some anomalies occurred too.

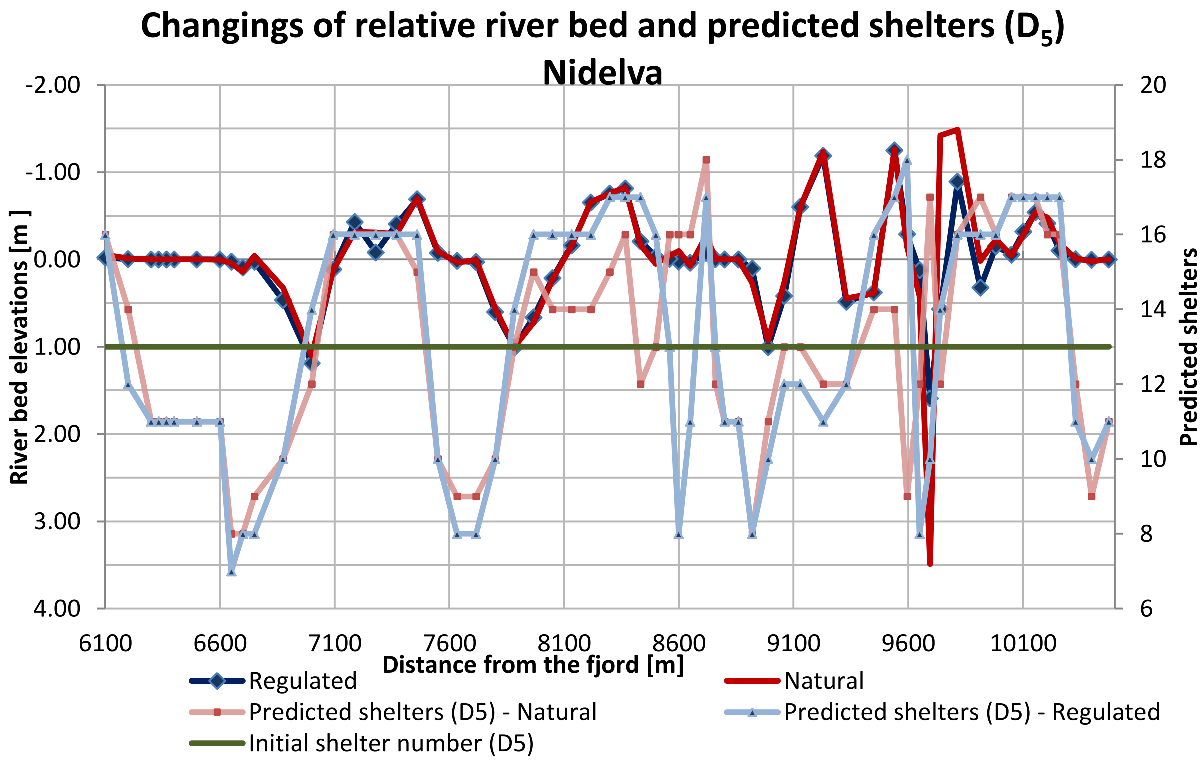
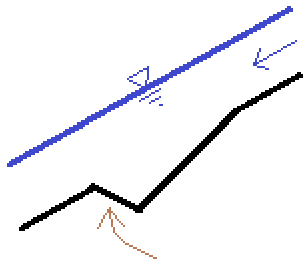


Figure 11-5 Relative river bed and shelter (based on D_5) change at Nidelva based on two scenarios

At the upper part of the section where erosion occurs (around to river state 9200 m) the D_{10} stagnates and the D_5 stagnates or has a slight decrease depending on the simulation case. It had to be noticed, that here the cross-sections are quite wide and the flow is sheet-like, which can led to settled bed gradation similar to the initial status. Then pool structures similar to



cases at Lundesokna appeared on the profile of Nidelva too, like the sketch on the left hand side shows, but in this regulated case the indicated segment has less ability to maintain shelter, moreover it is dropped, because the finer particles are clogged within this section. This shape at regulated simulation acts like a trap for finer sediments (D_5 and D_{10} decreased). However, the river profile contains a narrow deepening (from river station 9600m to 8600m) where the bed changing is significant. During the elevation alteration they remain almost completely in their shape similar to their initial form. There is one section, where after a sharp change (down to river state 8600m) a little pool disappeared (Figure 11-4) during the simulated years in both scenarios, and the river formed a new bed level with lower slope over the next 600-meter section. Here, all the investigated distribution parameters are high, and they nearly stagnated on their level (Figure 11-5). When the bed elevation has a section with moderate or mild slope at the middle part and lower part of the focused section, the distribution parameters have less sensitivity to change, moreover they stagnates. A shift between the morphology changes and distribution parameters was observed in both events. The explanation of this 'behaviour' is already discussed at Lundesokna.

After the model runs at Nidelva the average distribution parameters next to the predicted shelter numbers are summarized in the following (Table 11-7) table from both of the investigated hydrograph events, with their initial values.

	Distribution parameters [mm]				Predicted shelters	
	D_5	D_{10}	d_{50}	d_{90}	based on D_5	based on D_{10}
Initial state	23.1	33.8	52.7	81.2	11	13
Regulated	27.0	35.2	53.7	81.5	13	14
Natural	26.8	35.2	54.0	81.6	13	14

Table 11-7 Distribution parameters and predicted number of shelters initially and after the simulated years at both cases on river Nidelva

Similarly to Lundesokna, the average distribution of the gravel bed become coarser, and the results of different hydrograph conditions are similar to the previous data. Though it has a high class of shelter abundance in its initial status, the average hiding places are increased in a moderate level to clarify this river section where the abundance of shelters is high. The next table summarizes the channel distances where low, moderate and high shelter abundance separately occurred, to view possible differences between the two cases.

	Regulated		Natural	
Shelter Abundance	Based on D_5	Based on D_{10}	Based on D_5	Based on D_{10}
High	3795m	3877m	3764m	4219m
Moderate	572m	490m	603m	149m
Low	0m	0m	0m	0m

Table 11-8 Summarized river sections related to different shelter abundance based on D_5 and D_{10} at the river Nidelva under regulated and unregulated conditions

The current cases are similar to each other, but the natural hydrograph could hold more river sections on high level when prediction of shelter was made with the help of the D_{10} parameter. Otherwise it is a good sign that none of the cases could rebound strong decreases of shelter numbers, none of the modelled river sections classified with low abundance of hiding places.

Regulated vs. unregulated cases

The chosen and calculated parameters proved their worth to become key factors in the differentiation between regulated, i.e. operated and unregulated, i.e. natural type of hydrographs with their effects on river bed morphology. The final comparison is to be written using these variables.

The change of river bed elevation and the relative river bed differences as parameters served a conspicuous comparison between the two cases. Though the alterations were quite similar in both scenes, the interval of their extreme values showed some diversity. It was general, that the natural hydrograph supplies higher deposition values at Lundesokna and Nidelva likewise. Although, regarding of the minimum values unregulated river flow caused lower values the conjunction is not clear enough.

The average bed elevation changes after twenty simulated years confirmed the assumption that natural flows have major effect on stable river beds compare to regulated one, numerically three or four times lower the summarized variation.

The total mass bed change over time gives a simple comparison between the hydrograph types. The cumulative values were negative in every case, averaged values of river elevation were about the same at all times.

The distribution parameters in the regulated case are similar to unregulated ones in general. It should be noted that large differences occurred in details between the simulations. The basic theory is where erosion occurs reaction of gradation becomes coarser generally, and opposite in deposition case. This theory was proved over the flows, mainly at upper side of the rivers. Nevertheless, a slight shifting reaction was observed along the river site downwards. Approaching to the downstream boundary the shift increases. Another deduction was that sometimes fractions of the river bed were sorted out to transport in different methods over the various flows. The strong selective transport and its effects (varying distribution parameters) were observed more times during operated flows. This made the gradation of a river section slightly unpredictable. Therefore, anomalies occurred more times than at natural flows, where the alterations in the morphology and in the gradation were more reasonable and understandable. The differences do not play an important role among several scenarios in separated distribution parameters like D_5, D_{10}, or d_{50} and d_{90} in general. Still some exceptions were noticed at several river sections. While a distribution parameter changed frequently in a short range according to the aggradation/degradation changes over natural flows, this 'behaviour' was not typical at regulated model runs. This might be the explanation of the following anomaly related to river bed formations. At some river reaches despite the similarity of the bed morphology distinct behaviour of the sediment transport was observed. For example, at the last part of a smaller pool in the river bed finer particles trapped at operated runs, embeddedness occurred, but in the same section coarser gradation was recorded over the natural simulations.

Although, the D_5 and D_{10} variables reflect the number of shelters, the calculated hiding places served with some extra information about several model runs. In addition, they even moderately represent the natural habitat. Coarser gradation produced better shelter availability in every case, development was not significant enough to find a relevant difference between the regulated and unregulated investigations concerning of the natural habitat. Thanks to the classification river sections could be summarized separately by their class. In the case of Lundesokna regulated runs resulted more river sections with better shelter abundance, and these segments were more separated, than at natural simulations. At river Nidelva the natural scenario clearly provided better conditions for juvenile fish over the whole river section. The initial status was not decreased to an extent as it was under hydropeaked operations. Therefore, it should not only examined whether how much the development of the shelters, but the degree of embeddedness must be included as well.

12 Summary and conclusion

The influences of hydropeaking operations on habitat of salmonids are not clear enough in details. Although humanity builds dams and regulates the rivers for ancient ages, we are not aware of their extended effect yet. Fortunately, we have gained experiences from ancestors of science and technology, and have better tools to make further investigations.

The first half of the thesis contained more interdisciplinary approach, since the hydropeaking could have a strong effect on the surrounding wildlife. Discussing natural habitat related to the Atlantic salmon some physical parameters were found to grade the potential abundance of shelters. Hence the present study is strongly connected to ecology, besides hydraulics and sediment modelling. This kind of research is tagged as eco-hydraulic.

The link between shelter abundance and a few physical parameters, named D_5 and D_{10} is obvious to characterize a river section by its gradation in regards of juvenile fish habitat. This connection was supported by samples gathered during the present study as well as by previously collected data. The relationship includes all shelter types in the same way as separated shelter category I. For shelter category II the link seemed to be significant, but for category III the correlation is only hypothetic, since the database has not enough samples with registered shelter from this category.

Physical parameters can found to be relevant can be investigated from several aspects, for instance under variant effects of operated or natural hydrograph. The thesis examined the long term morphological changing of two rivers in Middle-Norway: river Lundesokna and river Nidelva. Both of the river sites are hydropeaked and regulated by hydropower plants. Various tests were executed on these river sites by a 1D flow and sediment transport model (HEC-RAS), where sensitivity analysis and multifarious scenarios were tested over 5 months, 1 or 20 years, with different flood events, or variant set ups for sediment analysis under regulated and unregulated conditions. The main findings of this analysis were that for coarser gradation Wilcock and Meyer-Peter-Müller empirical equations can be used, but the latter with smaller computational step option. As to the active sediment layer, the Exner 5 method is the one that provides results regarding the cover layer in riverbed where hiding places occur. In this way, the predicted shelter numbers could be calculated based on gradations by cross-sections. The main simulations were set up with 1-1 year regulated and natural type of hydrograph. The selected one-year periods were repeated 19 times in a row to simulate 20 years in each model variant. Since the correct validation of the sediment transport model was not feasible due to the lack of field data, the evaluation of the model results were considered to be only qualitative. Despite that the simulations showed that the investigated river sites have considerably stable river bed due to the sanded, gravelled sediment layers and moderate discharges, some conclusions could be made for differentiation between the two types of hydrographs. The main statement is that there is no conspicuous difference between regulated and unregulated hydrograph on this level, but some can be found in details. Due to the sudden changes in the hydrograph, significant selective transport occurred more times in the regulated case, thus more anomalies in the bed changing were noted. The distribution parameters seems less sensitive to aggradation/degradation, which can lead to less shelter availability at several river sections, where more should originally have appeared. However, due to the abrupt changes of the hydrograph some river sections at Lundesokna have better potential of shelters, but in other case the degree of embeddedness, i.e. the amount of fine particles was significantly higher than in the natural scenario. Therefore, the studied river sections (see e.g. Table 10-5) with higher shelter potential were slightly better in Nidelva.

Outlook

This kind of investigation is not a completely new idea, but the methodology itself is novel. Thanks to Finstad and his colleges (2007) and other researchers (Jocham, 2010; Honsberg, 2011), who had made examinations in the same area and collected samples prior to this study, this research area shows clear and practical results for further studies. It is promising that we can determine the fine fractions (<8-16mm, related to habitat of salmons) for better shelter potential. However, this also means that based on actual D_5 and D_{10} parameters there is a method to predict potential shelters, which has virtual benefits too. For example, it can be a relevant information for maintaining river beds at those river sites, where juvenile fish growth. In addition, correlation between distribution parameters and the number of shelters from separated categories shows a way that is worth following in the future. The averaged number of shelters by one shelter category (mainly category II. or category III.) may have a significant relationship with some distribution parameters. This relationship should be strengthened by further field measurements from relevant river sites. The numerical modelling of river morphodynamics also calls for continuation since the one-dimensional model with its modest results shows the relevance of the area (eco-based examinations of long term changes in sediment transport and river morphology). Furthermore, the modelling could be improved using two-dimensional models, and at the most remarkable spots, like pool structures where anomaly occurred, even three-dimensional numerical modelling could be applied. Prior to such investigations, however, proper sediment information from the field is essential to support the numerical model parameterization and validation.

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Appendix

Appendix A. Measured shelters by categories and computed D_5 and D_{10} data

A.1 Collected data from Jocham (2010) to present D_5, D_{10} and number of shelters by categories, first set

Sample	Collector	River	D_5	D_{10}	Shelters			
			[mm]	[mm]	Cat. I.	Cat. II.	Cat. III.	Sum
2	Jocham	Gaula	35.34	39.76	7	6	0	13
3	Jocham	Gaula	24.61	32.86	4	2	0	6
4	Jocham	Gaula	1.00	6.03	1	0	0	1
5	Jocham	Gaula	20.00	27.21	5	3	0	8
6	Jocham	Gaula	1.00	5.42	1	0	0	1
8	Jocham	Gaula	4.04	9.40	2	0	0	2
9	Jocham	Gaula	1.00	1.96	1	0	0	1
11	Jocham	Gaula	19.67	26.96	5	0	1	6
12	Jocham	Gaula	14.69	19.01	3	2	0	5
13	Jocham	Gaula	16.06	19.81	5	0	0	5
14	Jocham	Gaula	16.45	20.01	6	0	0	6
15	Jocham	Gaula	16.73	20.84	7	1	0	8
16	Jocham	Gaula	1.00	4.18	0	0	0	0
19	Jocham	Gaula	1.00	2.93	0	0	0	0
20	Jocham	Gaula	1.00	1.22	1	0	0	1
21	Jocham	Gaula	17.56	21.88	9	0	0	9
22	Jocham	Gaula	10.69	17.56	1	0	0	1
23	Jocham	Gaula	3.28	11.30	1	0	0	1
24	Jocham	Gaula	1.00	5.88	0	0	0	0
26	Jocham	Gaula	1.00	3.35	0	0	0	0
27	Jocham	Gaula	16.48	20.14	4	1	0	5
28	Jocham	Gaula	26.50	33.66	9	2	0	11
29	Jocham	Gaula	16.18	18.79	3	0	0	3
30	Jocham	Lundesokna	2.91	9.95	2	0	0	2
31	Jocham	Lundesokna	2.07	8.54	1	0	0	1
32	Jocham	Lundesokna	2.42	9.26	1	0	0	1
33	Jocham	Lundesokna	1.58	5.96	1	0	0	1
34	Jocham	Lundesokna	5.94	13.08	4	1	0	5
35	Jocham	Lundesokna	1.56	6.02	2	0	0	2
36	Jocham	Lundesokna	9.68	18.69	0	2	0	2
37	Jocham	Lundesokna	21.00	33.00	1	2	4	7
38	Jocham	Lundesokna	11.60	23.51	2	0	0	2

A.2 Collected data from Jocham (2010) to present D_5, D_{10} and number of shelters by categories, second set

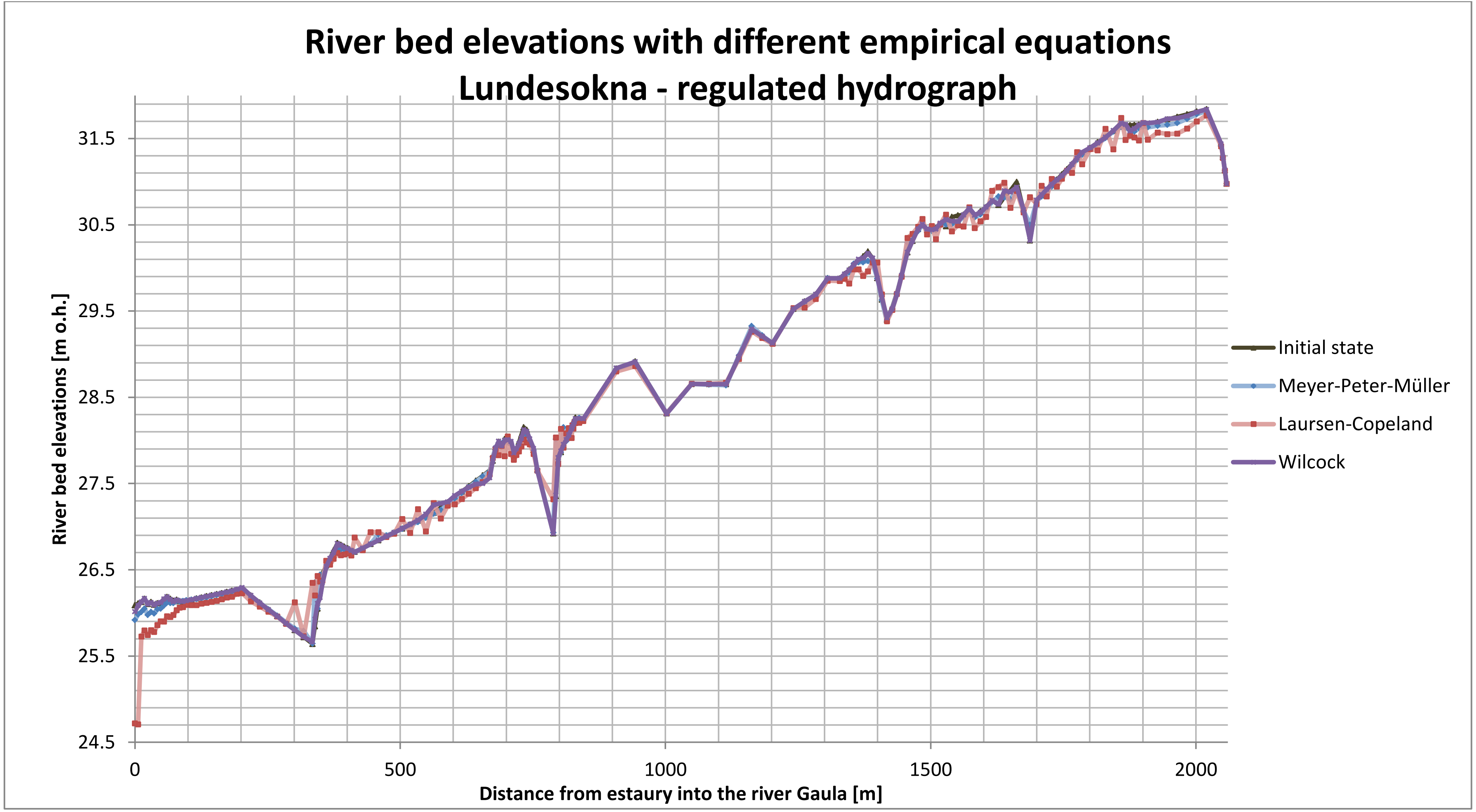
Sample	Collector	River	D_5 [mm]	D_{10} [mm]	Shelters Cat. I.	Cat. II.	Cat. III.	Sum
51	Jocham	Lundesokna	2.27	5.28	2	0	0	2
52	Jocham	Lundesokna	3.58	8.56	3	0	0	3
53	Jocham	Lundesokna	4.48	11.45	1	0	0	1
54	Jocham	Gaula	22.96	32.31	3	4	0	7
55	Jocham	Gaula	13.80	22.15	4	2	0	6
56	Jocham	Gaula	13.17	19.20	1	0	0	1
57	Jocham	Gaula	37.69	45.61	5	3	2	10
58	Jocham	Gaula	32.55	35.14	2	2	0	4
59	Jocham	Gaula	23.54	32.67	1	1	0	2
61	Jocham	Gaula	2.44	6.89	4	0	0	4
62	Jocham	Gaula	10.76	20.82	4	2	0	6
63	Jocham	Gaula	6.04	13.13	1	0	0	1
64	Jocham	Gaula	8.71	16.67	2	0	0	2
65	Jocham	Gaula	21.30	32.92	6	2	1	9
66	Jocham	Gaula	15.47	25.10	4	0	0	4

A.3 Own collected data to present D_5, D_{10} and number of shelters by categories

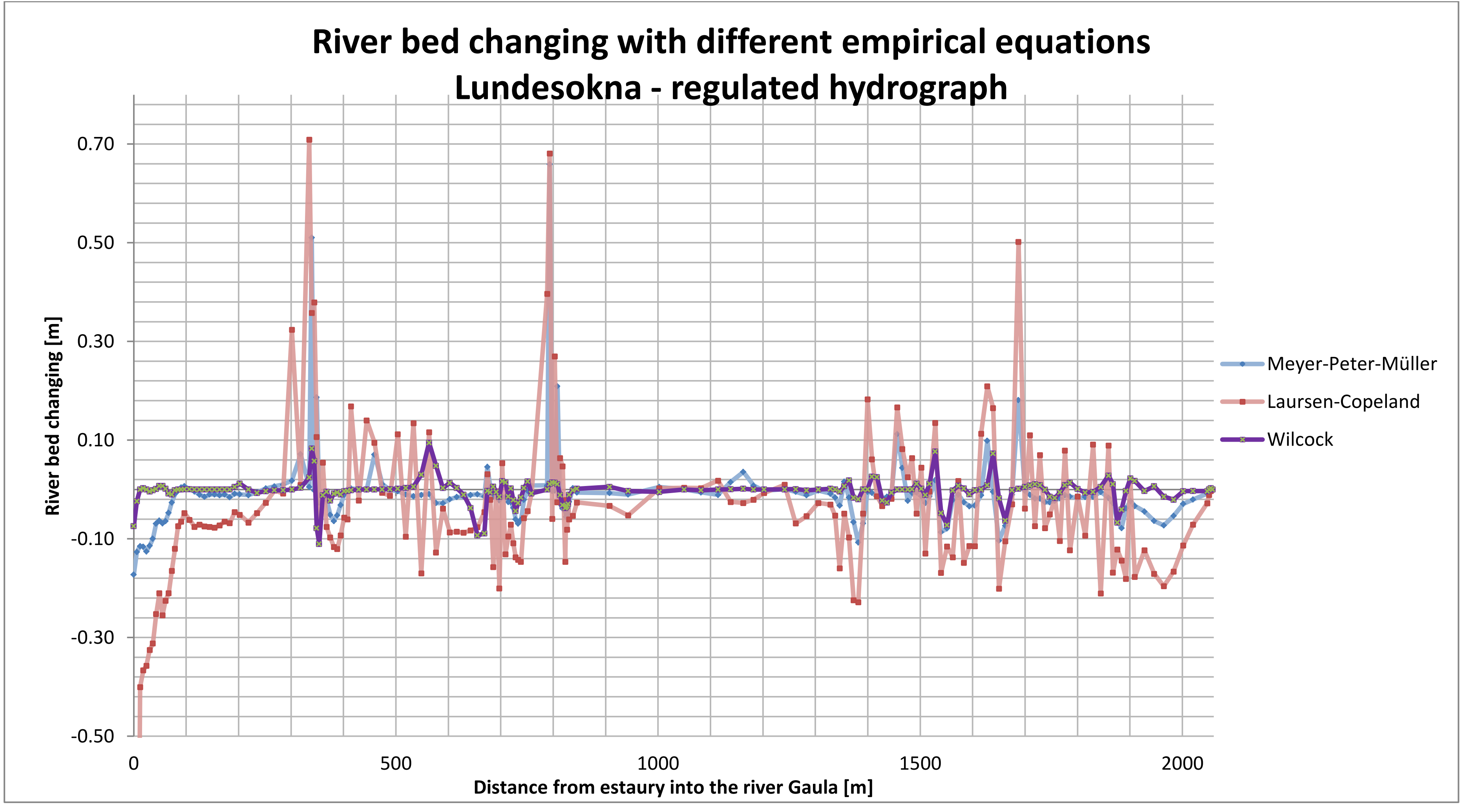
Sample	Collector	River	D_5 [mm]	D_{10} [mm]	Shelters Cat. I.	Cat. II.	Cat. III.	Sum
1	Marcell	Gaula	20.17	28.09	6	4	0	10
2	Marcell	Gaula	18.49	22.76	8	1	0	9
3	Marcell	Gaula	20.30	27.82	9	0	0	9
4	Marcell	Gaula	16.02	19.14	5	2	0	7
5	Marcell	Gaula	17.57	21.18	5	2	0	7
6	Marcell	Gaula	34.73	41.36	9	3	1	13
7	Marcell	Gaula	17.01	24.66	5	2	0	7
8	Marcell	Gaula	26.10	33.34	11	0	0	11
9	Marcell	Gaula	23.15	32.32	8	0	0	8
10	Marcell	Gaula	26.22	35.18	8	0	0	8
11	Marcell	Gaula	32.69	42.46	9	3	0	12

Appendix B. Plots of sensibility simulations

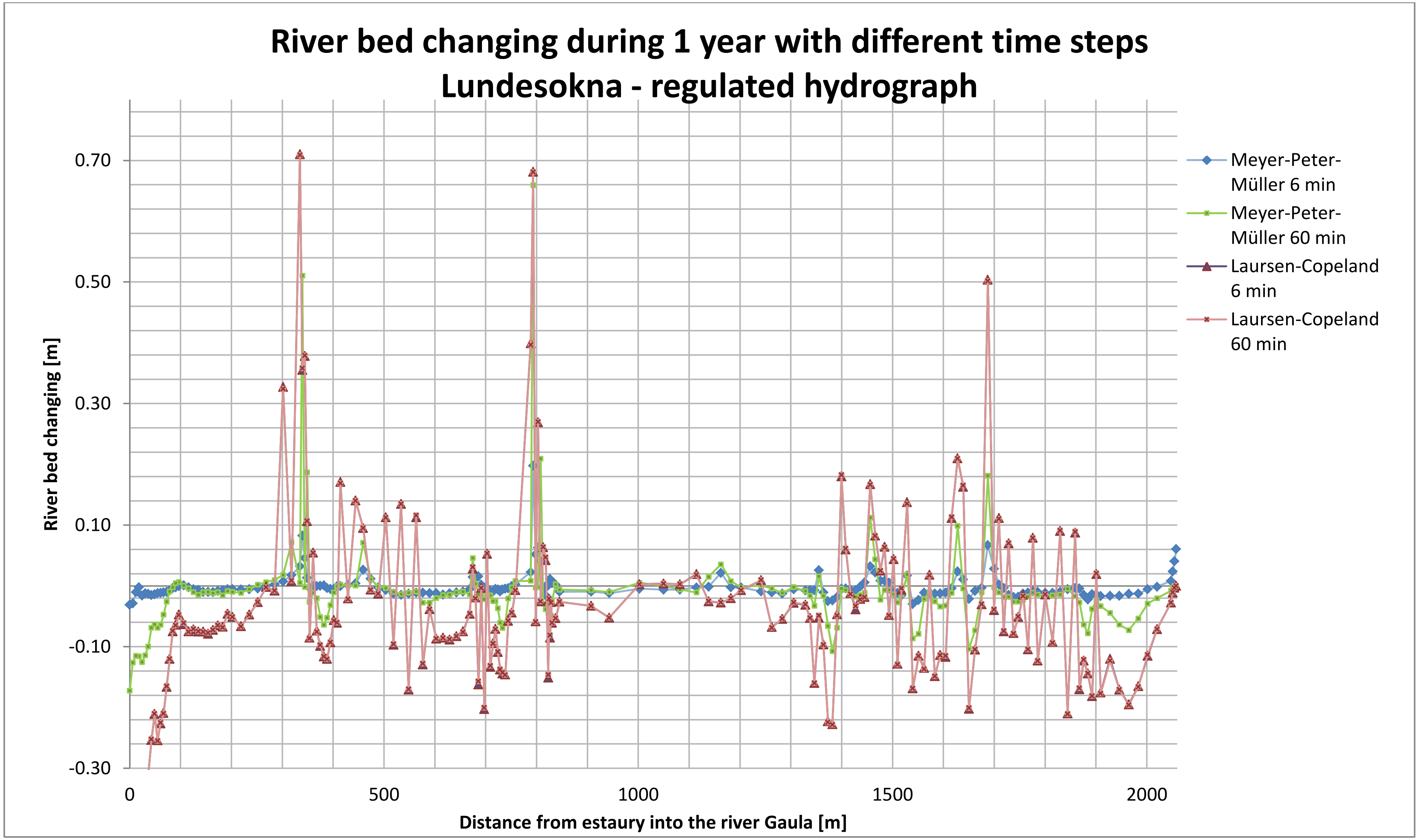
B.1 Calculated river bed elevations using different sediment transport equations in the 1D model (initial state is also indicated)



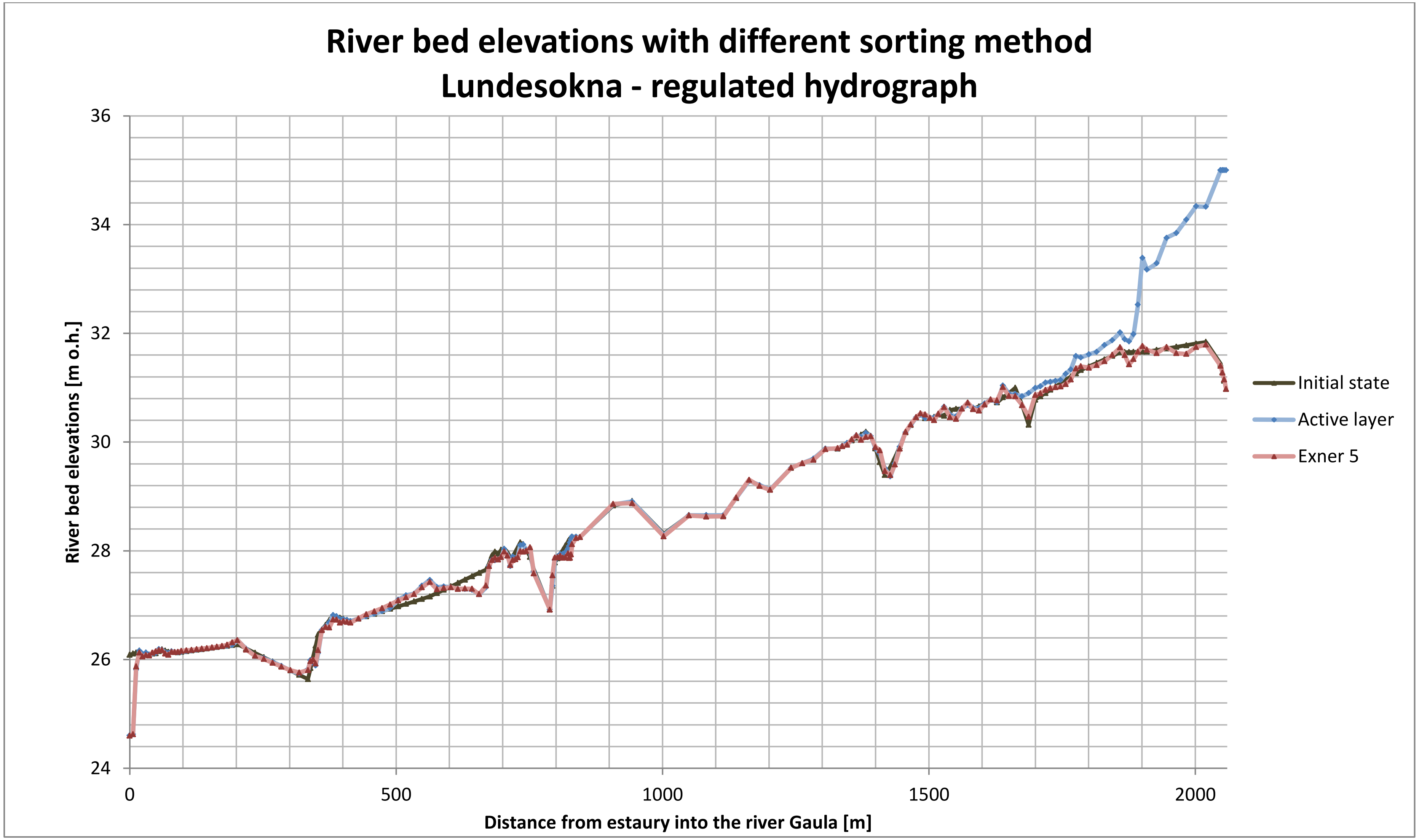
B.2 Relative changes of river bed with different sediment transport equations compared to initial state (the lowest value of Laursen-C. series at the downstream boundary (-1.48 m) was cut off from the graph, to see enhance the other results)



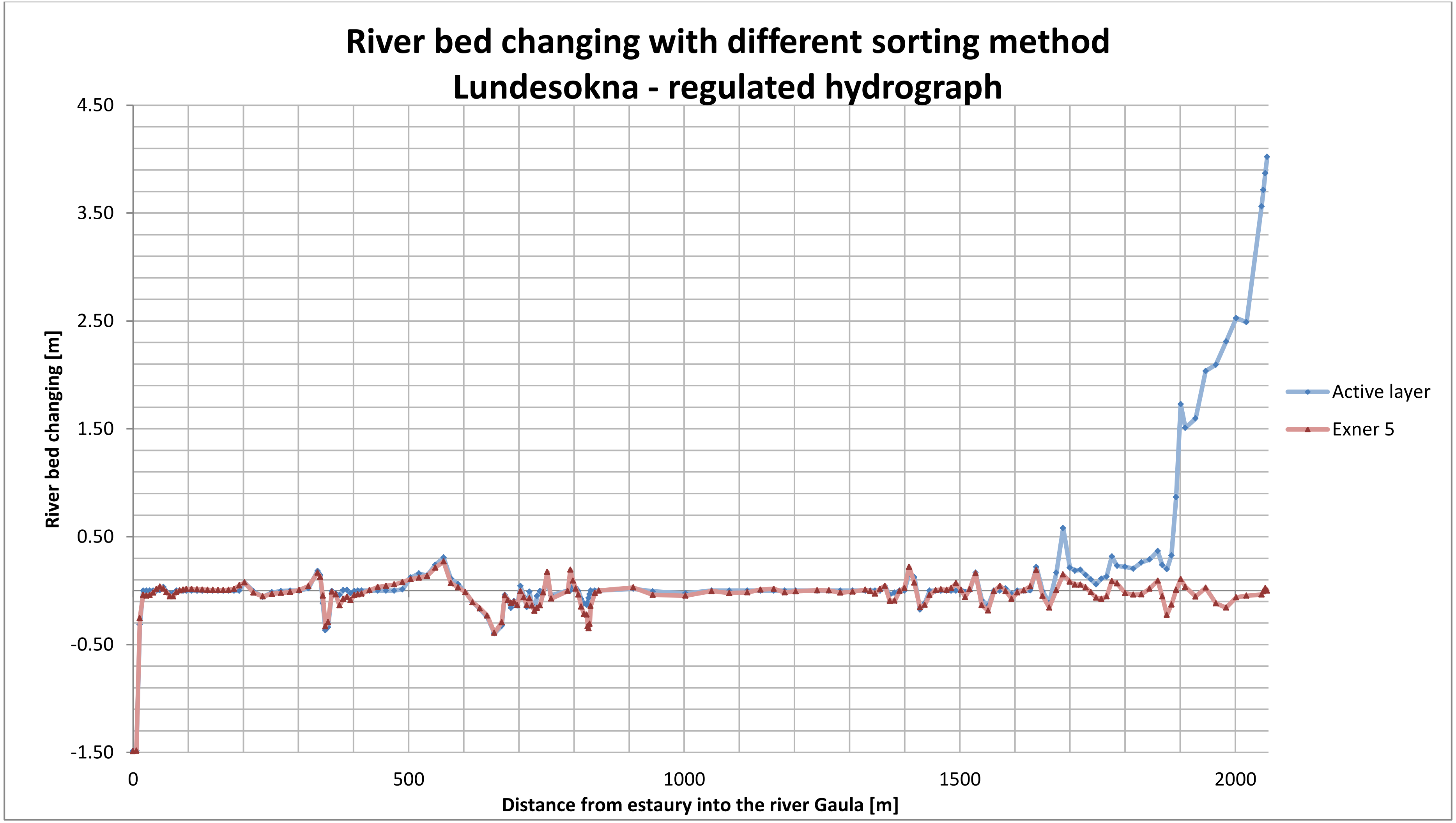
B.3 River bed changes during a one year long period with different time steps using Laursen-Copeland and Meyer-Peter-Müller equations



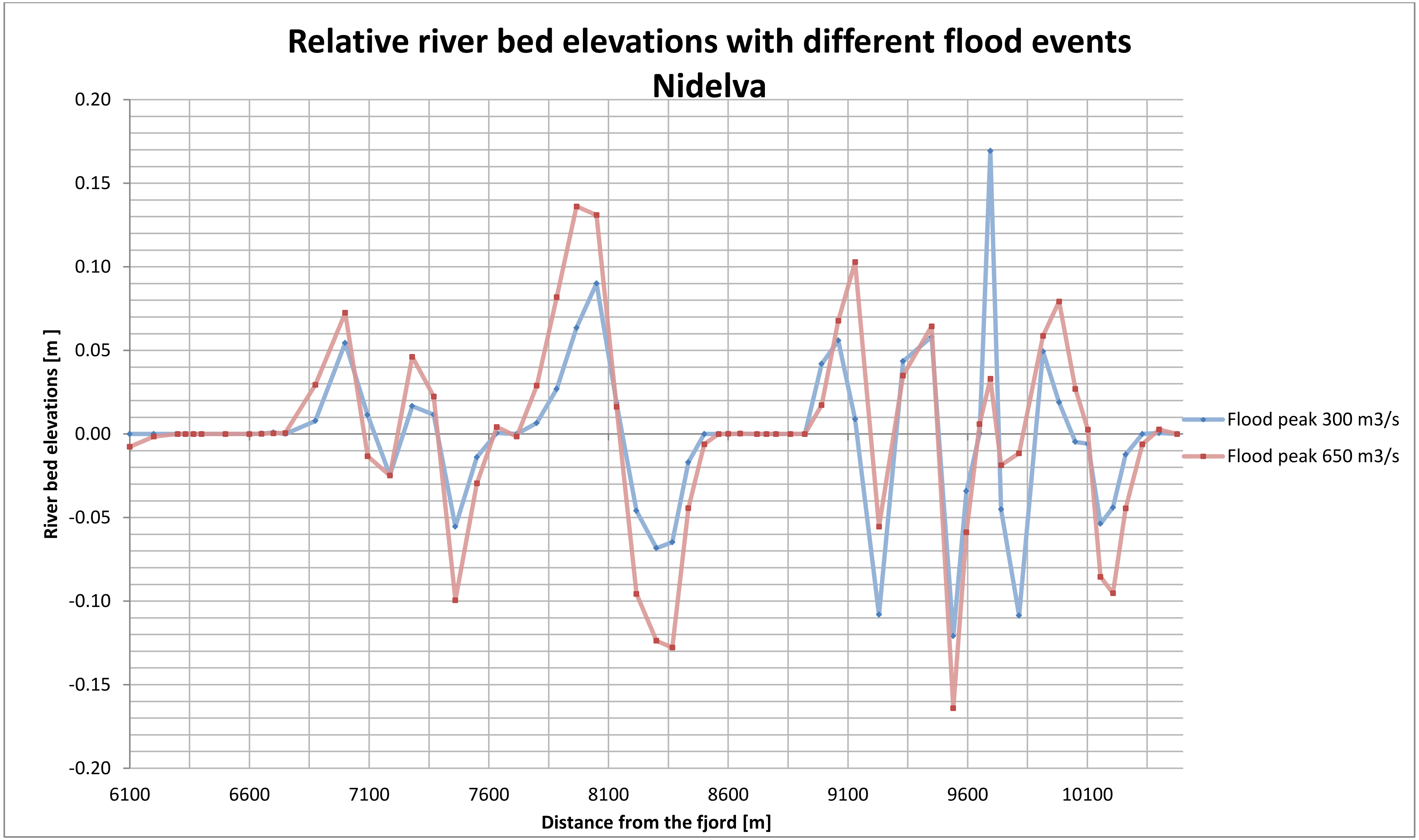
B.4 Calculated river bed elevations using different sorting methods compared to the initial state



B.5 Relative changes of river bed with different sorting methods compared to initial state

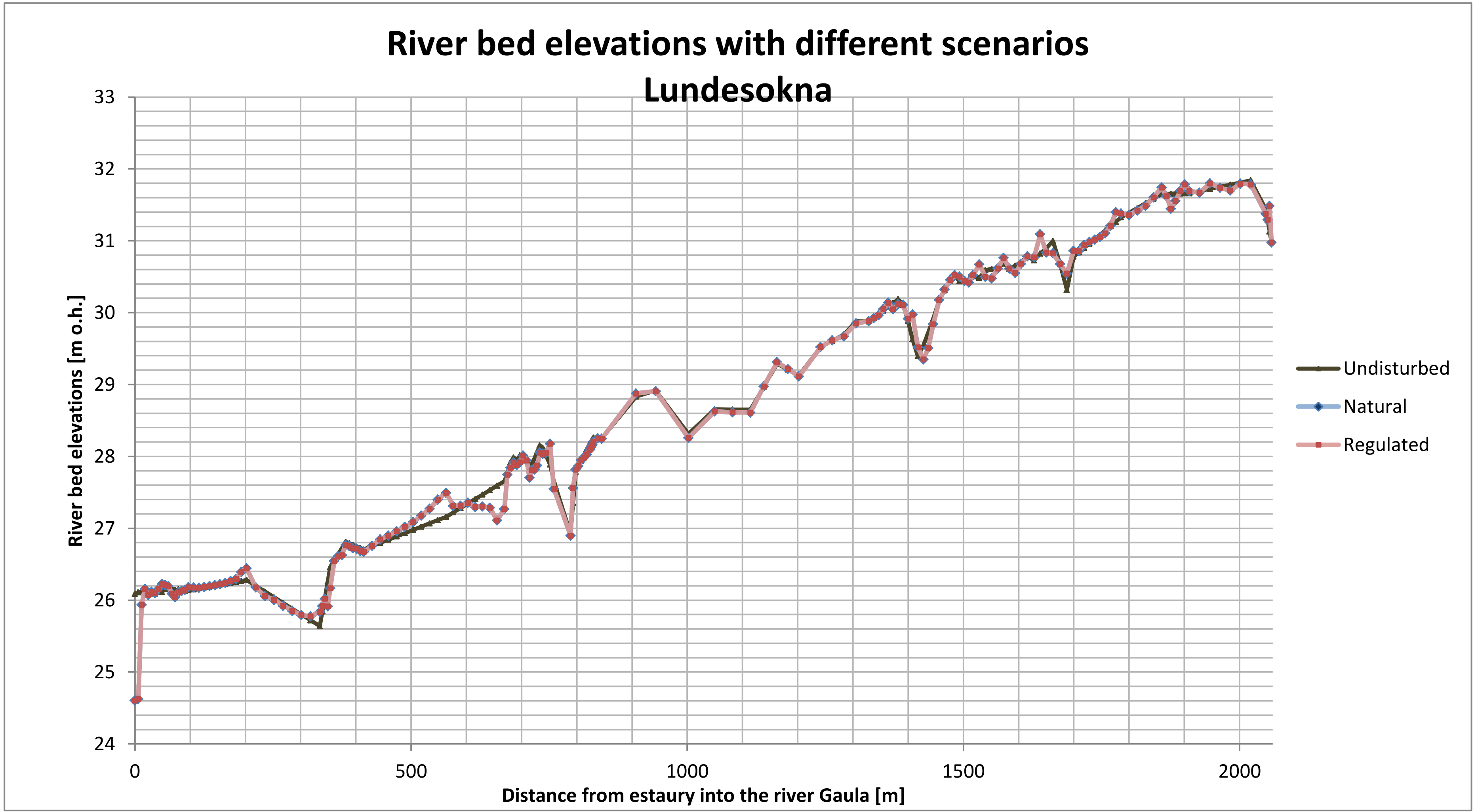


B.6 Relative changes of river bed at Nidelva after different flood events

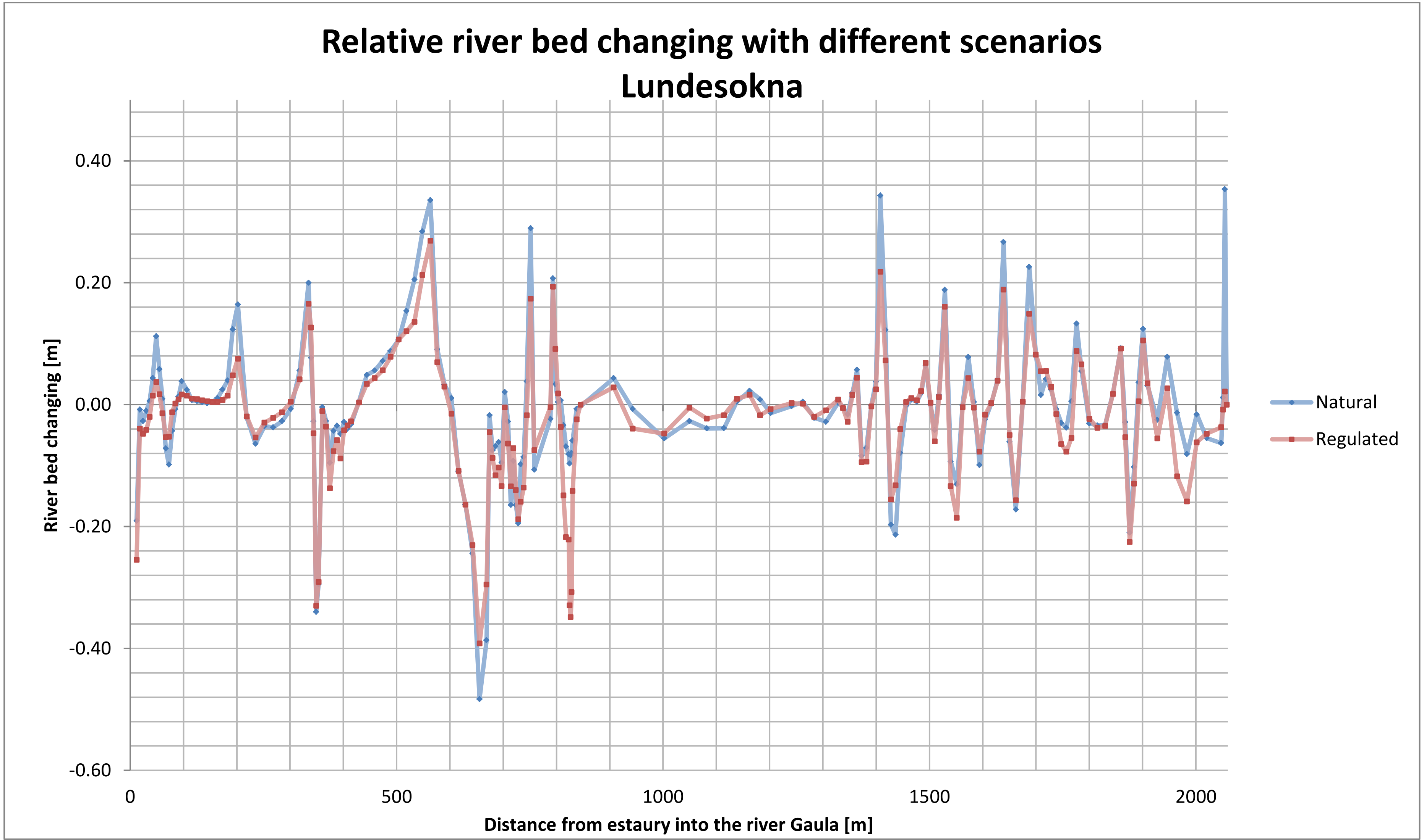


Appendix C. Results of the main simulations

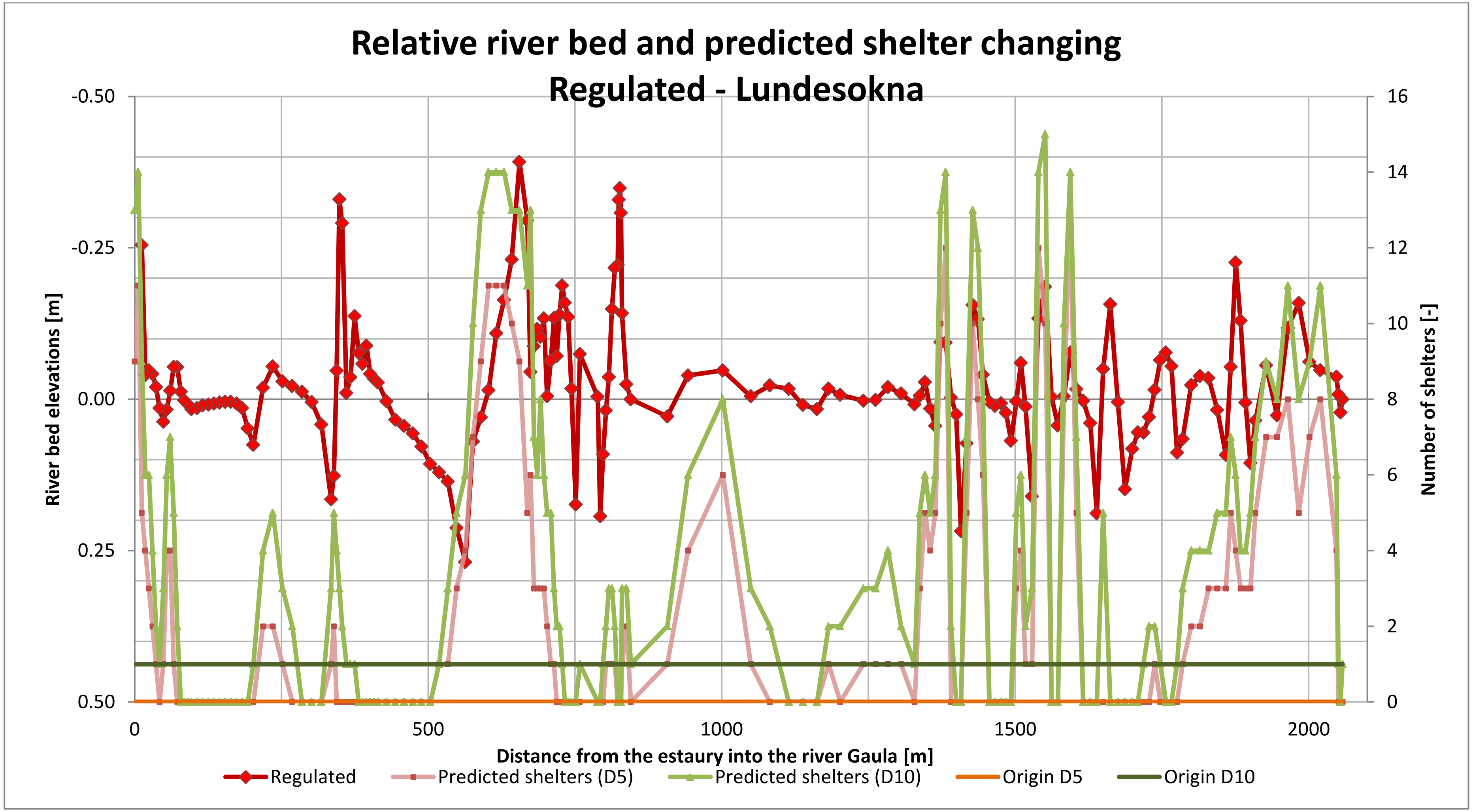
C.1 River bed elevation changes over 20 years at Lundesokna, with different types of hydrographs



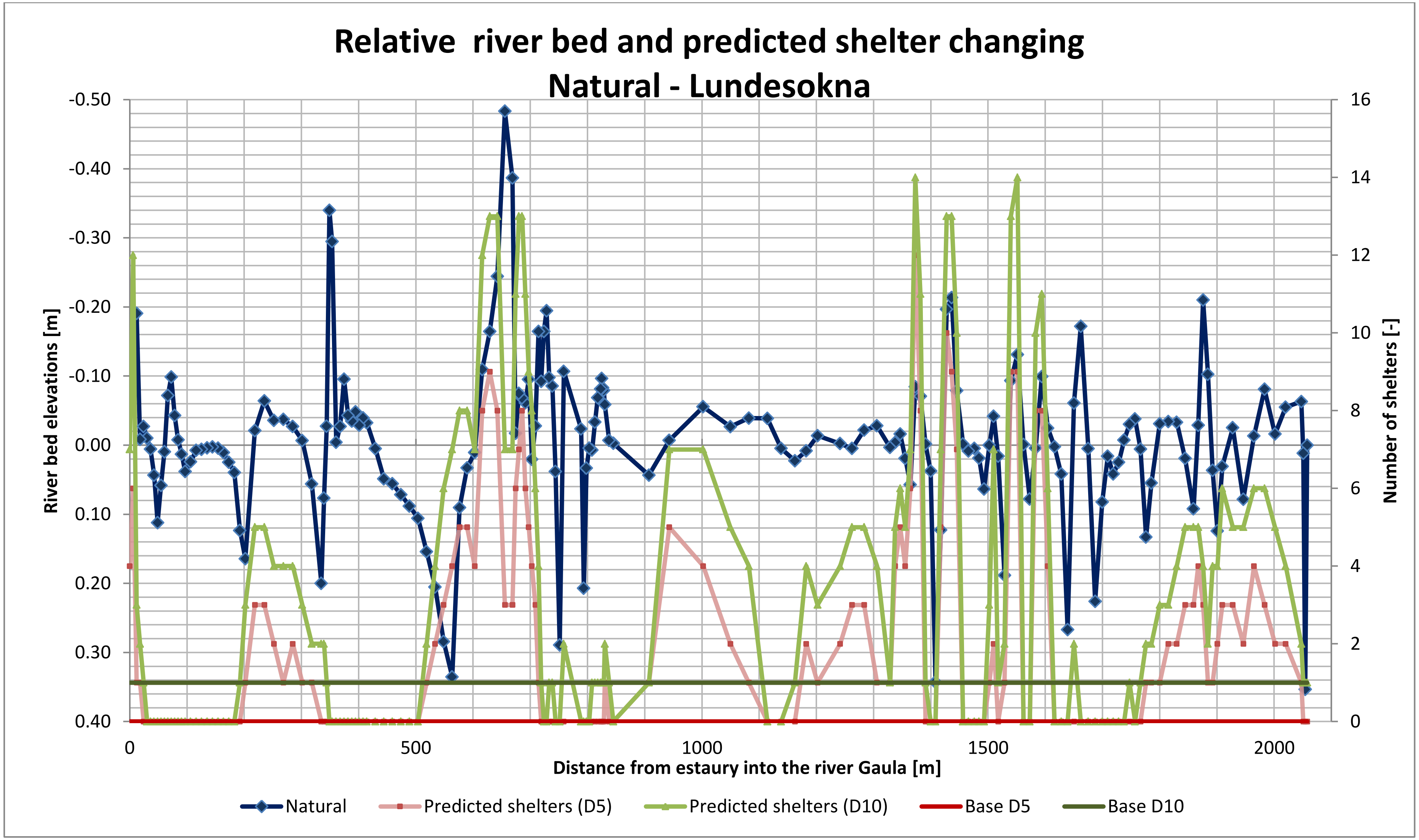
C. 2 Relative river bed changes over 20 years at Lundesokna, with different type of hydrographs



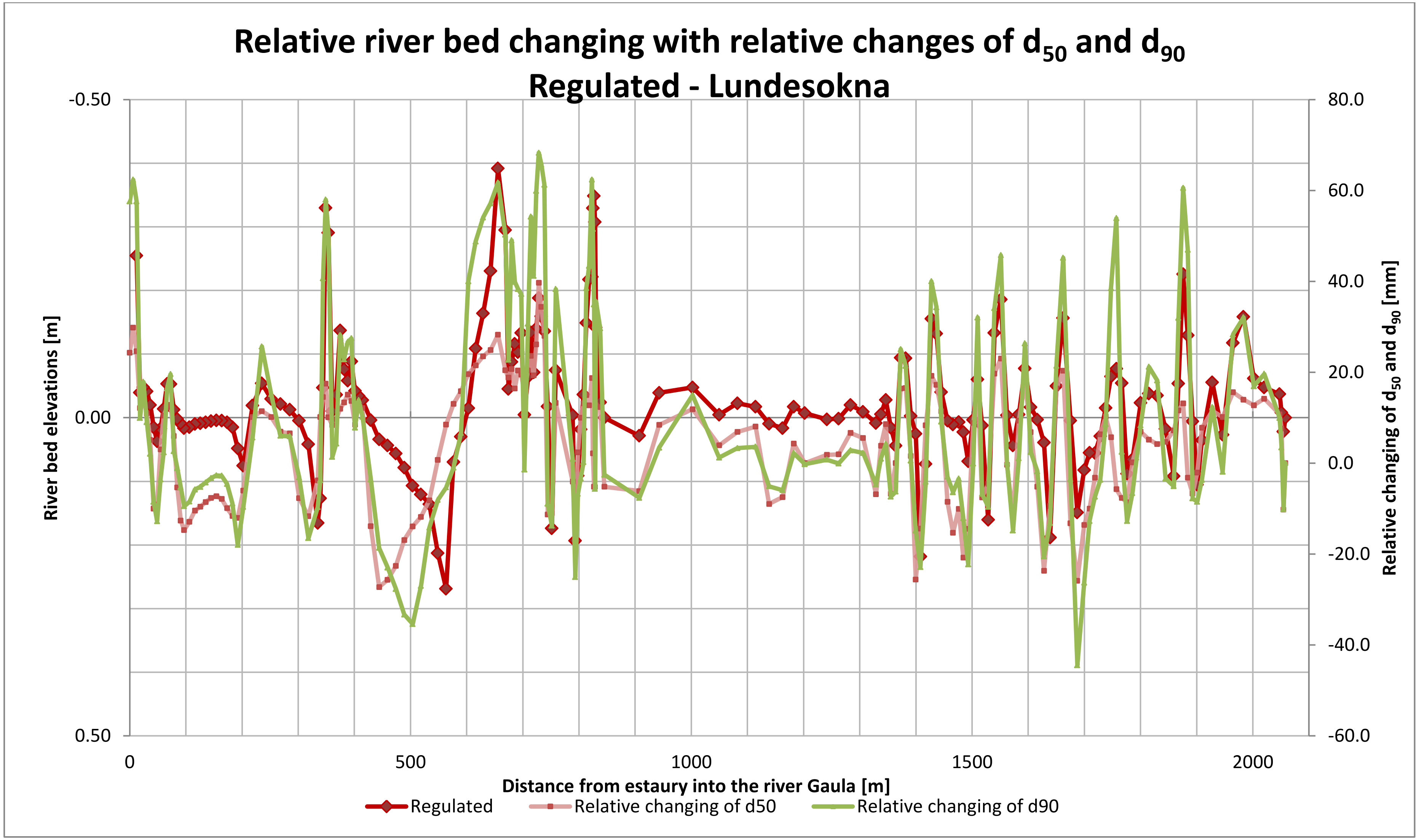
C. 3 Relative river bed and predicted shelter changes at Lundesokna under regulated conditions (Reversed elevation scale)



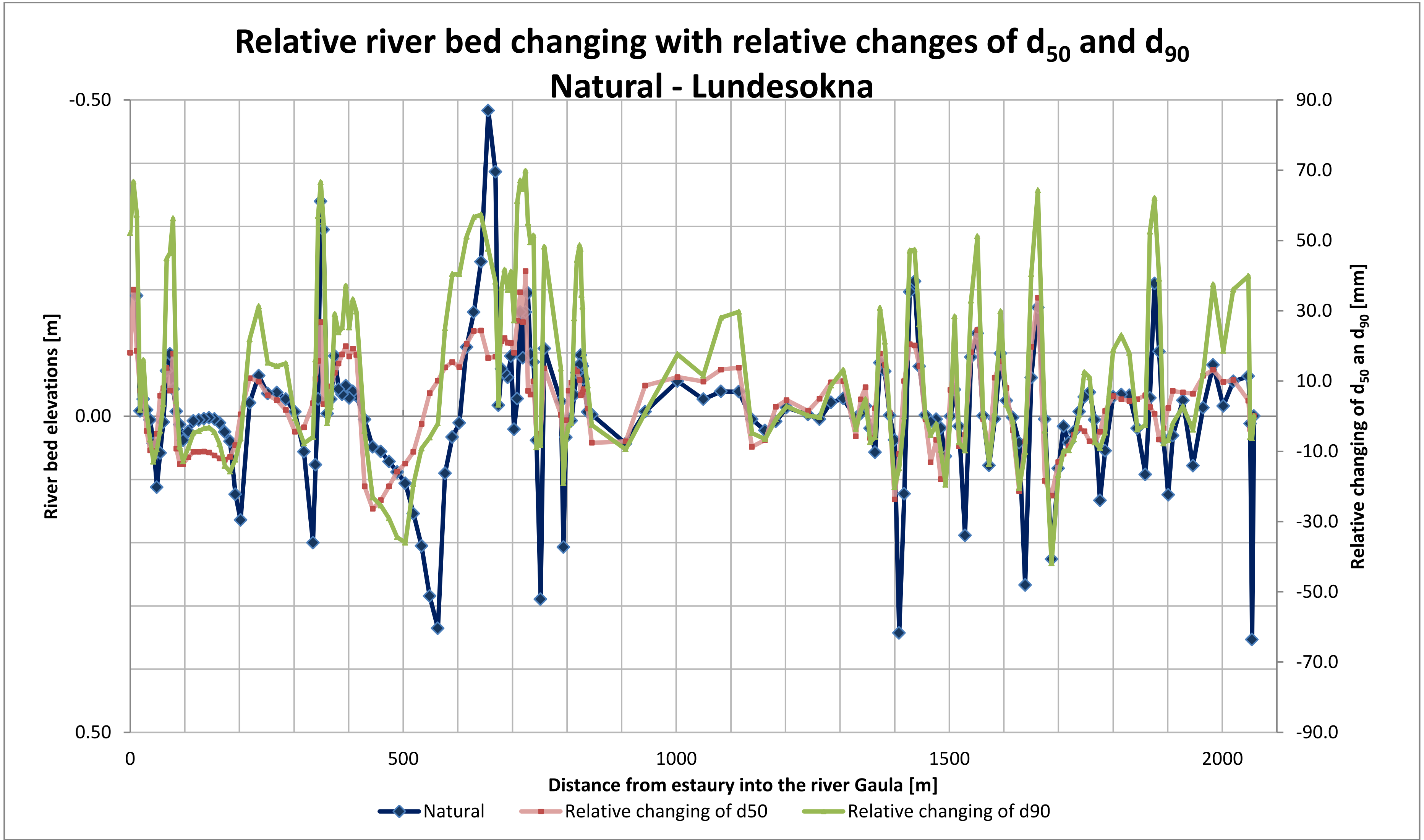
C.4 Relative river bed and predicted shelter changes at Lundesokna under natural conditions (Reversed elevation scale)



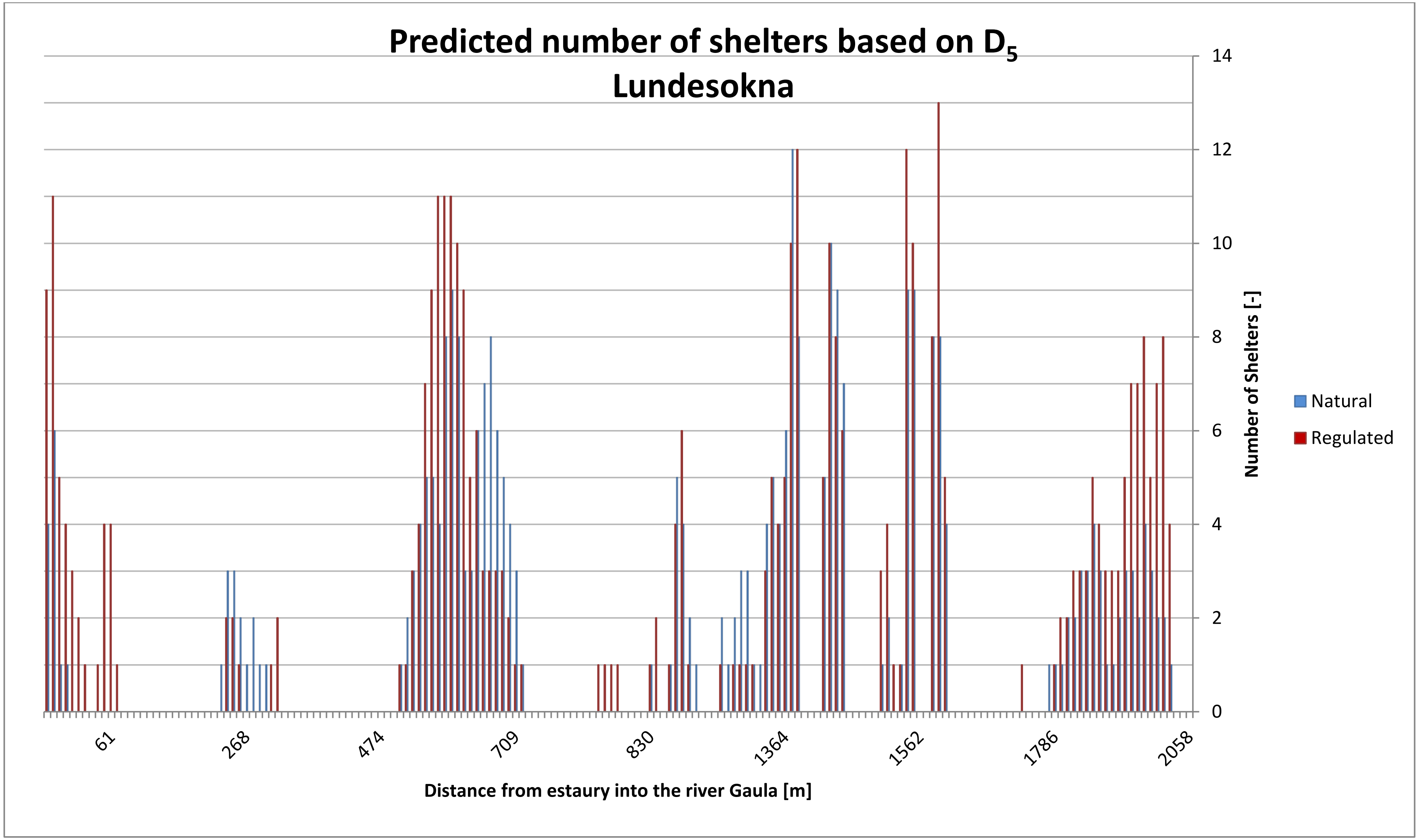
C.5 Relative river bed and d_{50} and d_{90} changes at Lundesokna under regulated conditions (Reversed elevation scale)



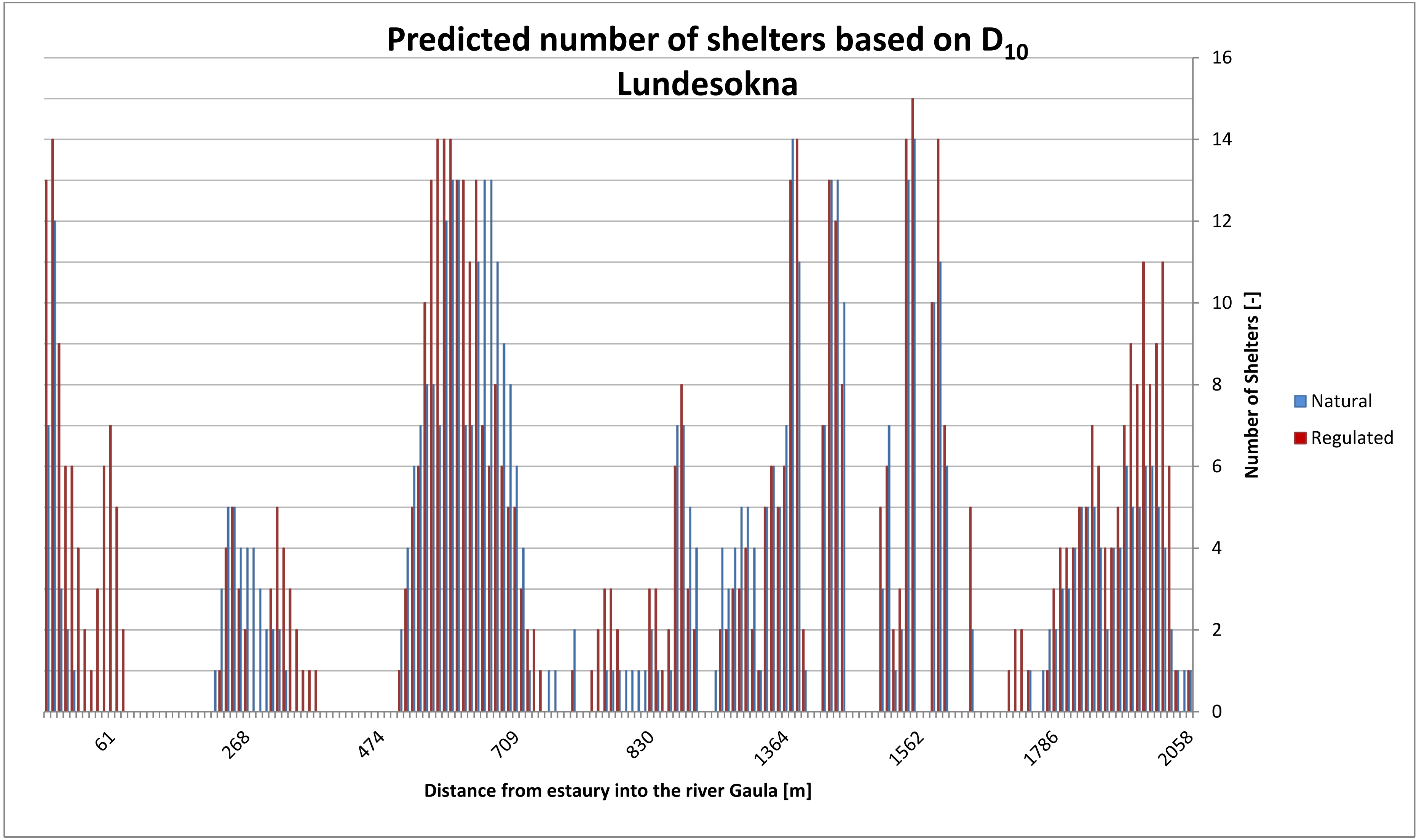
C. 6 Relative river bed and d_{50} and d_{90} changes at Lundesokna under natural conditions (Reversed elevation scale)



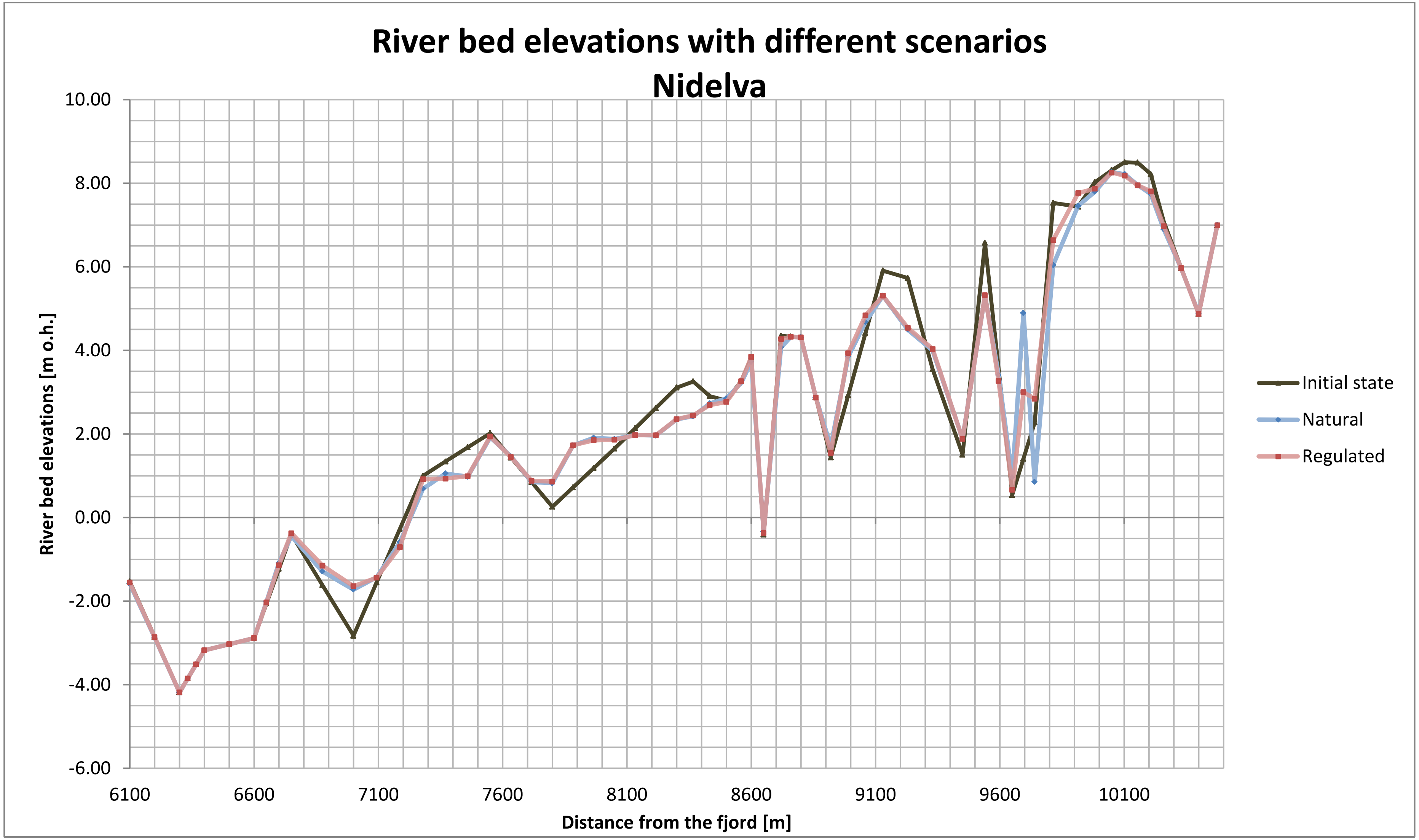
C. 7 Predicted shelter numbers (based on D_5) at the two studied cases in Lundesokna (Initial value of shelters: 0)



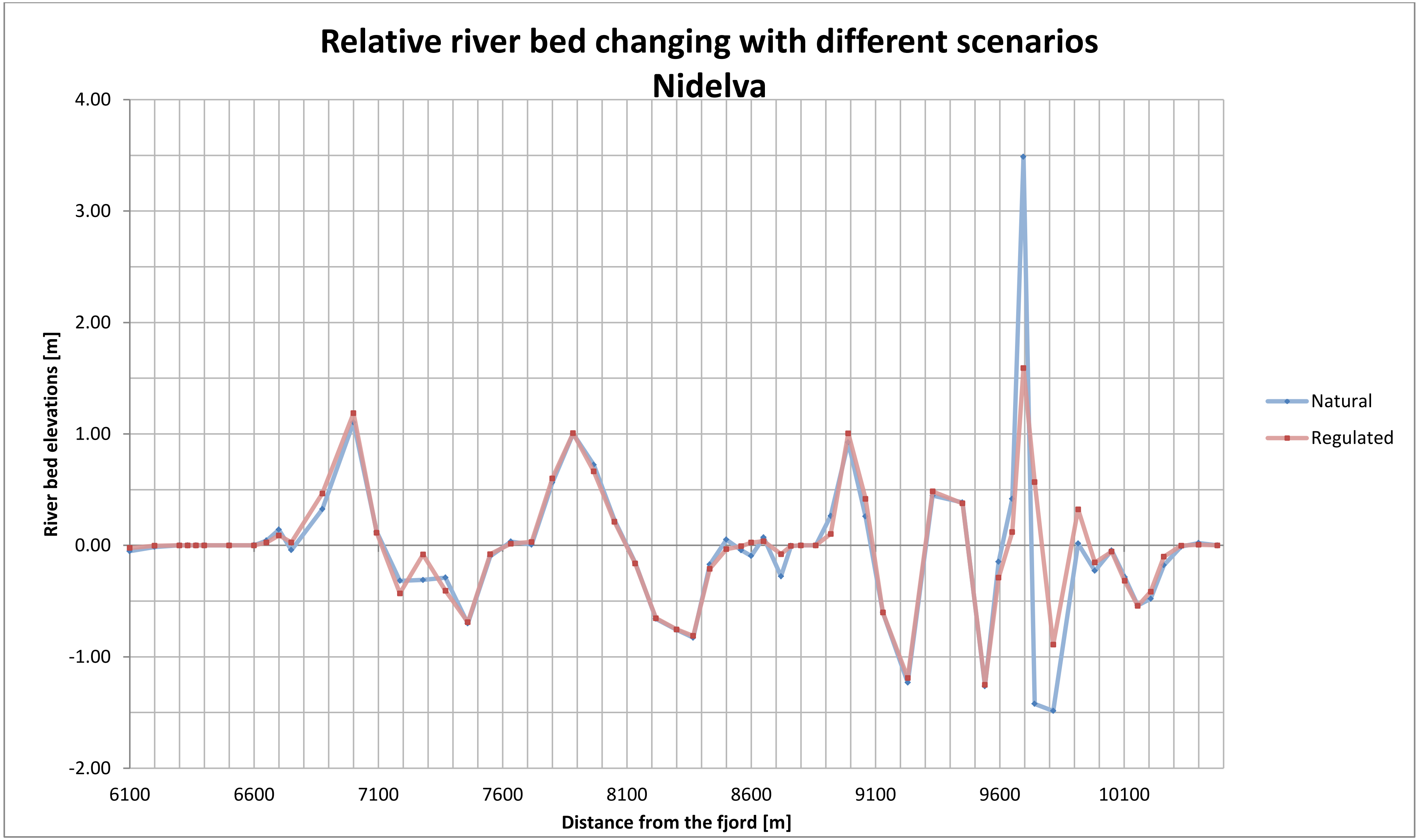
C.8 Predicted shelter numbers (based on D_{10}) at the two studied cases on Lundesokna (Initial value of shelters: 1)



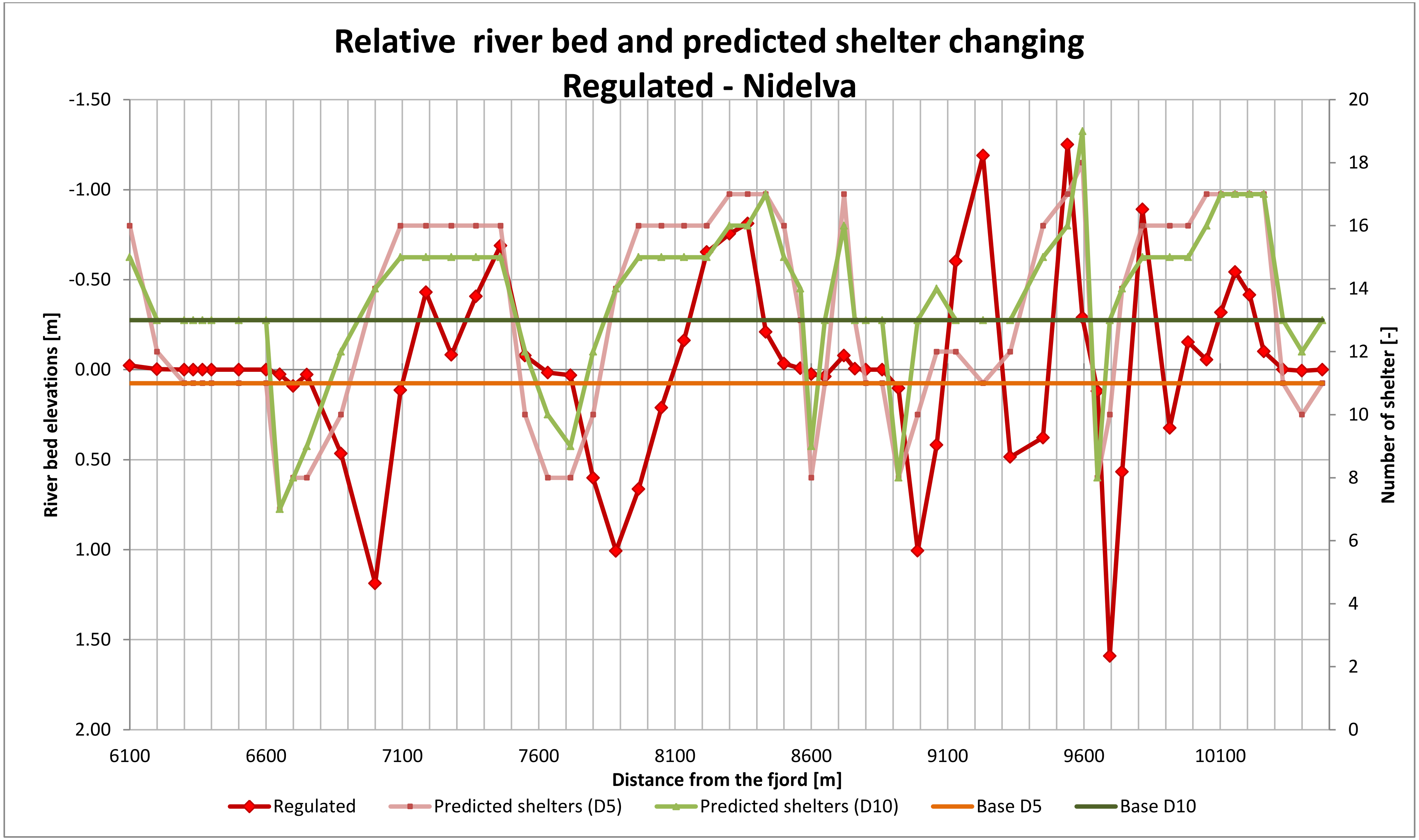
C.9 River bed elevation changes over 20 years at Nidelva, with different types of hydrographs



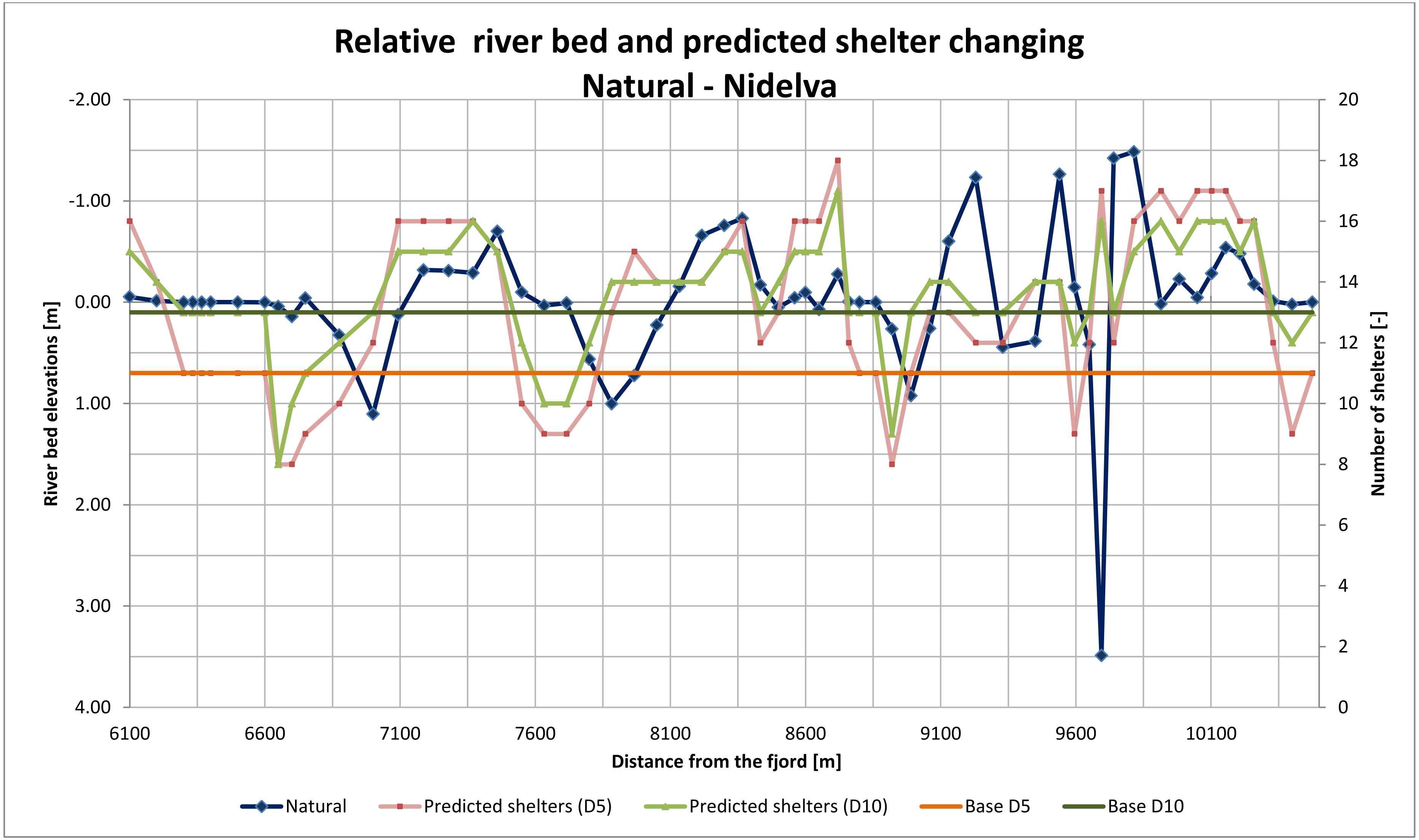
C.10 Relative river bed changes over 20 years at Nidelva, with different type of hydrographs



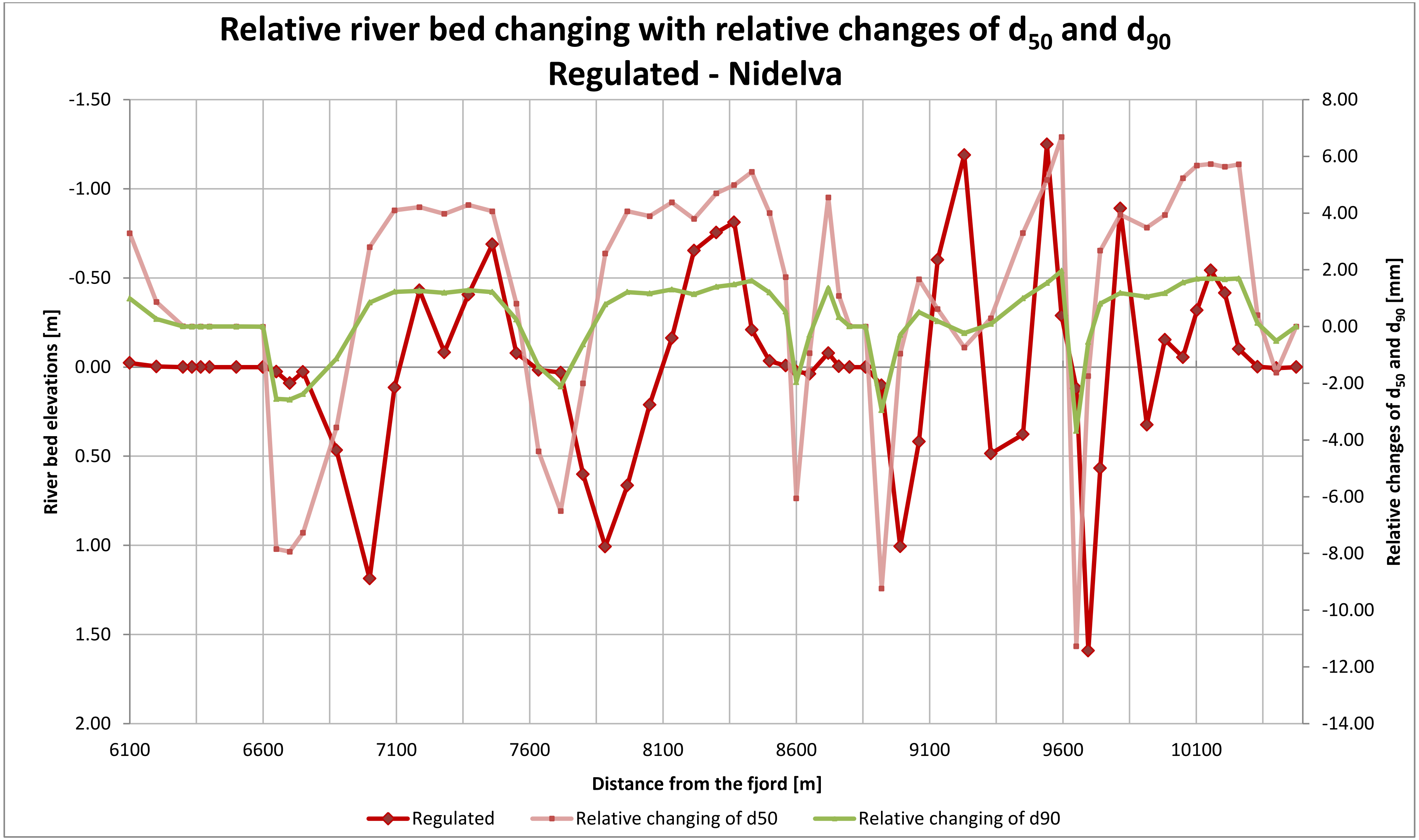
C.11 Relative river bed and predicted shelter changes at Nidelva under regulated conditions (Reversed elevation scale)



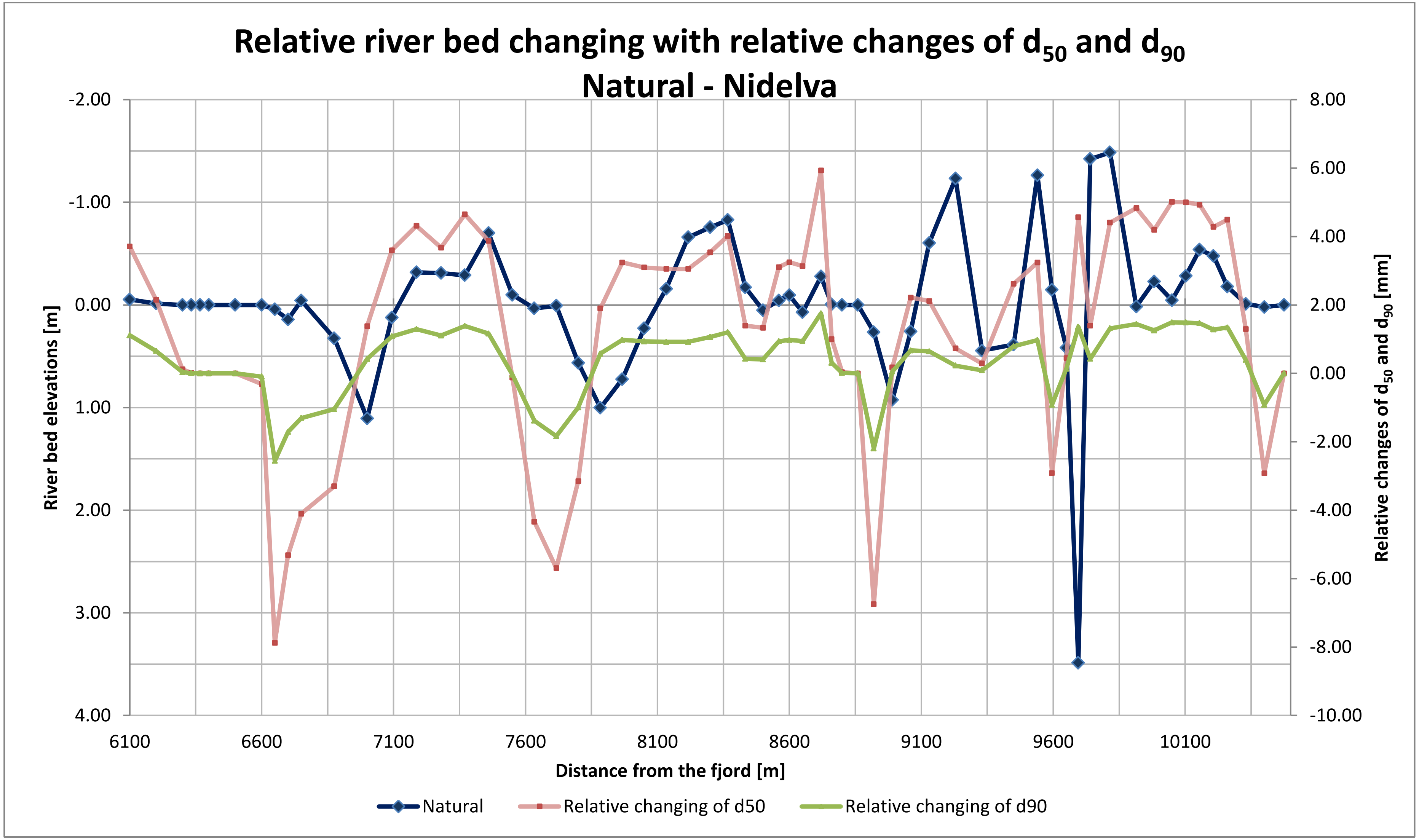
C.12 Relative river bed and predicted shelter changes at Nidelva under natural conditions (Reversed elevation scale)



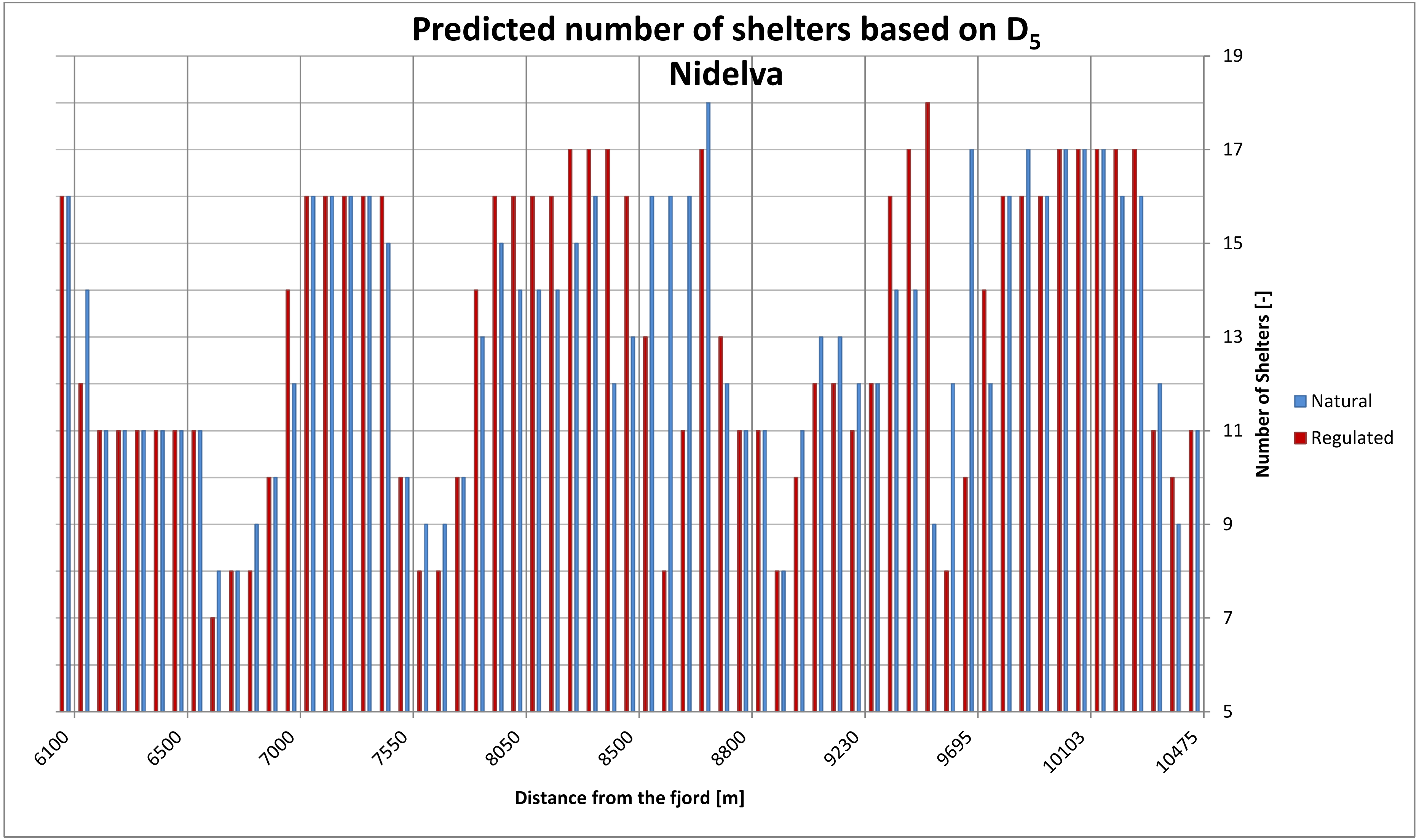
C.13 Relative river bed and d_{50} and d_{90} changes at Nidelva under regulated conditions (Reversed elevation scale)



C.14 Relative river bed and d_{50} and d_{90} changes at Nidelva under natural conditions (Reversed elevation scale)



C.15 Predicted shelter numbers (based on D_5) at the two studied cases in Nidelva (Initial value of shelters: 11)



C.16 Predicted shelter numbers (based on D_{10}) at the two studied cases in Nidelva (Initial value of shelters: 13)