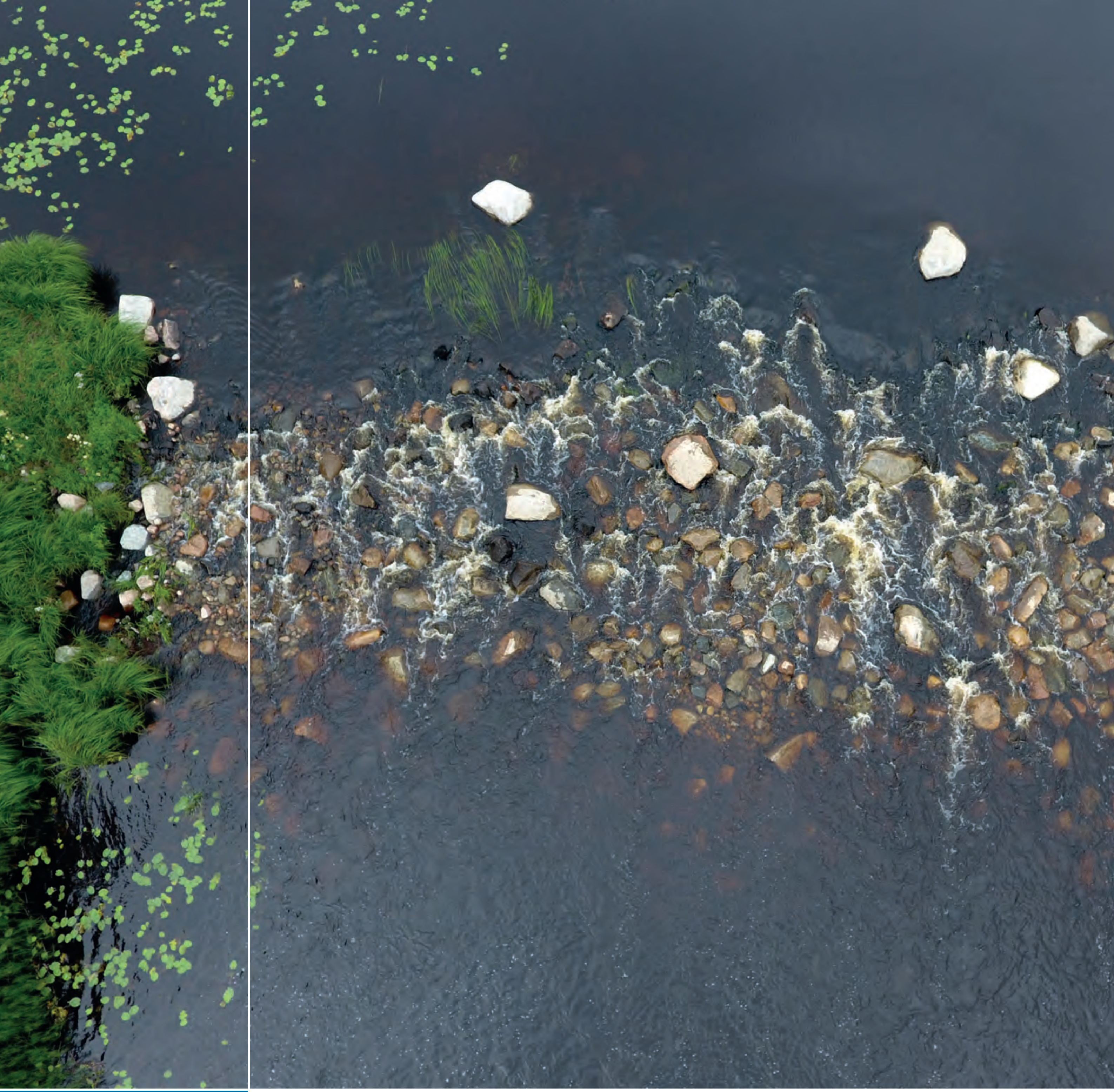

Coastal watercourses

Methodological Development and Restoration

Interreg Nord
Europeiska regionala utvecklingsfonden

EUROPEISKA UNIONEN

Kustmynnande Metodutveckling Restaurering Vattendrag

Länsstyrelsen Norrbotten

Title:	Coastal watercourses - Methodological Development and Restoration
Publication No:	6/2019
Cover photo/photos:	Länsstyrelsen i Norrbottens län
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LAPIN LIITTO

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Preface

Coastal waters, method development and restoration are an EU interregional project in the Nord program, which was carried out in collaboration between ELY-Center in Lapland, LUKE and GTK in Finland and the County Administrative Board in Norrbotten County and SGU in Sweden.

The project has included six major sub-projects for three years:

- Mapping of acidic sulphate soils
- Pilot study of a regulated drainage on arable land
- Restoration of watercourses
- Fish biological studies
- Modeling of fish biotopes before and after restoration
- Development of various new innovative methods, among others, developed a fish ladder in composite

The project has contributed to new knowledge in each area and received great attention locally, regionally and nationally but also internationally. Several of the results and methods in the project have since been able to be used further in the daily work and in new, ongoing projects in the region and Europe. As a project manager for this project, it has been a fun and interesting journey where we worked together for common goals and bridged the border regional differences between our countries. I would like to thank everyone who contributed to this project - none of this would have been possible without each one of you.

Project Manager
Magnus Johansson

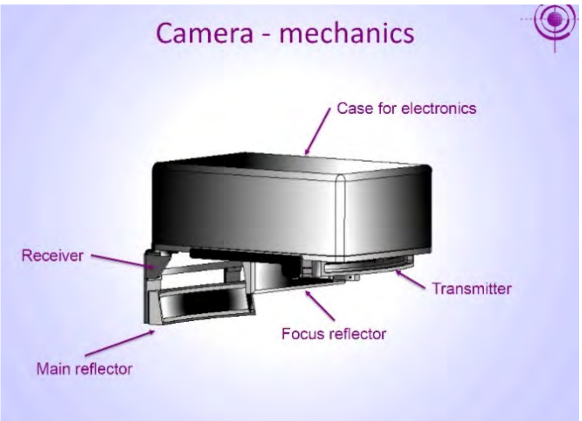
Index

Final report
Coastal watercourses - Methodological Development and Restoration (Interreg Nord)

1. Fish migration studies

Materials and methods

To study the total number of migrating whitefish (Coregonus lavaretus) and burbot (*Lota lota*) in the Alterälven and Råneälven rivers, an ultrasound camera (Simsonar) was installed by the Finnish company Simsonar Oy. The ultrasound camera consists of three components; the audio transmitter, receiver and reflectors are installed in the camera housing (Figure 1.1). The echo signals received (vertical 12° degrees and horizontal 44° degrees) are processed and transmitted by cable from the underwater camera to a land based PC where they are stored on files created for each hour recorded. These files are analysed using Simsonar's software (UVC). When recording data, fish migration is automatically logged according to set auto-detection variables so as to obtain a preliminary estimate of the number of fish that have passed upstream and downstream. The equipment was remotely monitored by software via a router, ZTE MF910, for mobile connection.



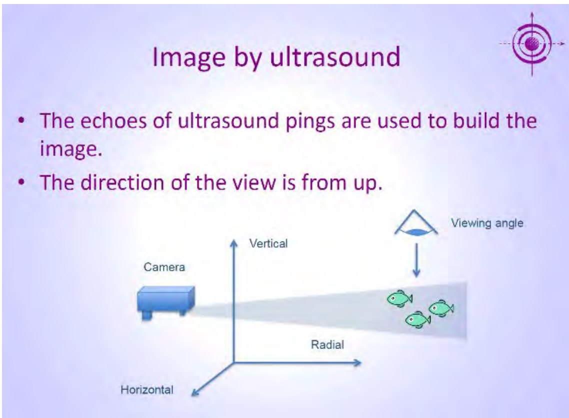


Figure 1.1. Description of simsonar ultra ecosound camera and the technical principal, illustration from Simsonar Oy.

When logging fish using the ultrasound camera, data is obtained on their direction of travel (movement upstream, downstream and even laterally), the date and time fish are logged, their size (cm) and their distance (metres) from the camera. Species-specific information is not obtained. The study of migrating whitefish was made possible thanks to few other species migrating in the Alterälven and Råneälven rivers in late autumn. The upstream migration of whitefish is generally in small shoals (5-20 individuals, observations from the analysis of data). Few other species have the same migration pattern at this time of year, so most of the fish logged in the 35-50 cm size range are whitefish.

Logging the migration to their spawning grounds of burbot using an ultrasound camera in the Alterälven river in the winter of 2017/2018 was made possible thanks to few species in the size range 65-120 cm migrating upstream during this part of the season. This means that the greatest proportion of fish logged were migrating burbot.

Results and discussion

Whitefish occur as two different varieties throughout the Baltic, one that spawns in the sea and one that spawns in rivers and freshwater (anadromous). Tagging has shown that the saltwater whitefish is fairly stationary, migrating up to 20 kilometres, while anadromous whitefish can migrate over 500 kilometres. Genetic studies show no difference between these types of whitefish. However, a study of predominantly sea spawning whitefish along the Swedish coast suggests that the fish stocks are local, but with a stronger genetic differentiation between the spawning grounds in the Gulf of Bothnia than in the actual Baltic (Havs- och vattenmyndigheten 2018 [The Swedish Agency for Marine and Water Management]).

The population of whitefish in the Alterälven and Råneälven rivers migrates up these rivers to spawn in the autumn. Spawning takes place in flowing areas over gravel and sandy river beds in late autumn. Whitefish fry hatch early in the spring and migrate almost immediately to the sea to grow. The size of the whitefish fry when they migrate is about 25-30 mm (Figure 1.2)

Figure 1.2. Electric pulse fishing for whitefish fry in the Alterälven river early spring 2016.

The migration of the whitefish was monitored in the lower reaches of the Alterälven river in 2015 and 2017, and in the lower reaches of the Råneälven river (reference) in 2016 (Figure 1.3). Behind the choice of location was finding the optimal ultrasound camera site and getting close enough to the mouth of the river to obtain information about the total upstream migration of whitefish.

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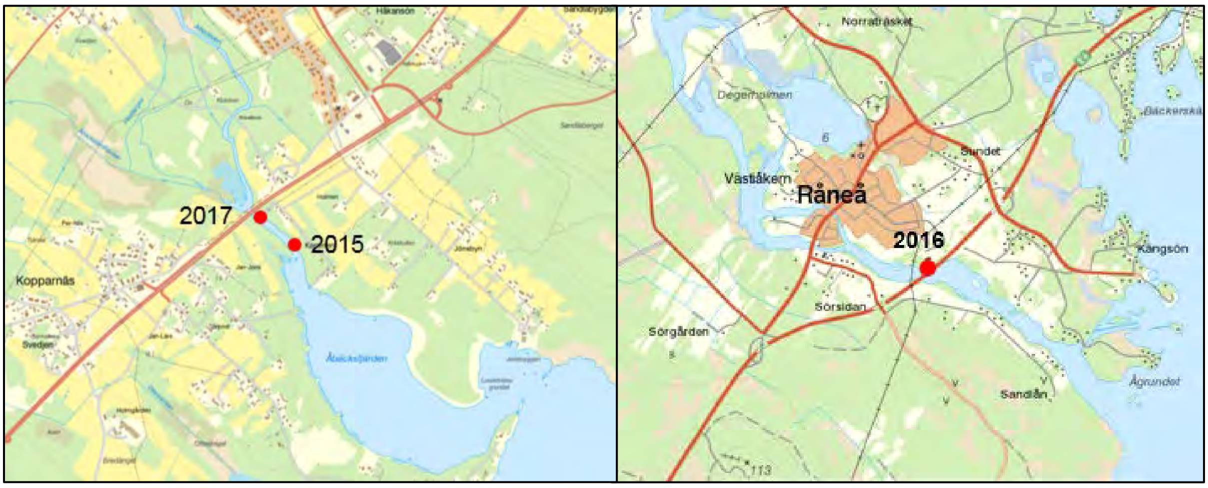

Figure 1.3. Map of the lower reaches of the Alterälven and Råneälven rivers upstream of where they run into the sea, with the red dots indicating the installation site and year of fish migration monitoring using ultrasound cameras in 2015, 2016 and 2017.

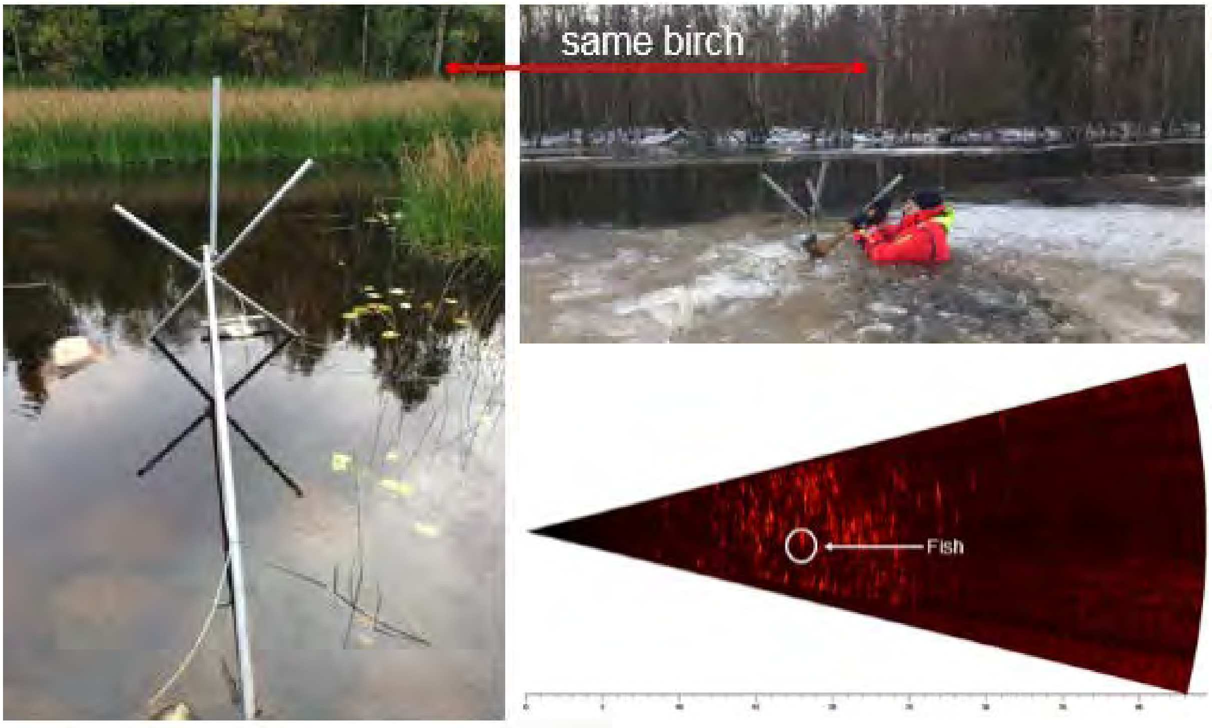

Figure 1.4. Ultrasound camera (Simsonar) installation site in the Alterälven river, showing the different water levels during the monitoring of the migration of whitefish to their spawning grounds in 2015. On the right is the echosounder area with logged fish ringed.

The Råneälven river was selected as a reference watercourse in which the upstream migration of whitefish to their spawning grounds was studied in 2016. The ultrasound camera was positioned under the E4 bridge, which is approximately 2 kilometres from the mouth of the river.

The upstream migration of whitefish to their spawning grounds in 2015 shows the start of migration in early October and concentrated migration activity from 19–28 October (Figure 1.5). A total of

2,465 whitefish migrating upstream were logged. Due to the difficult ice conditions, the camera was uninstalled on 31 October.

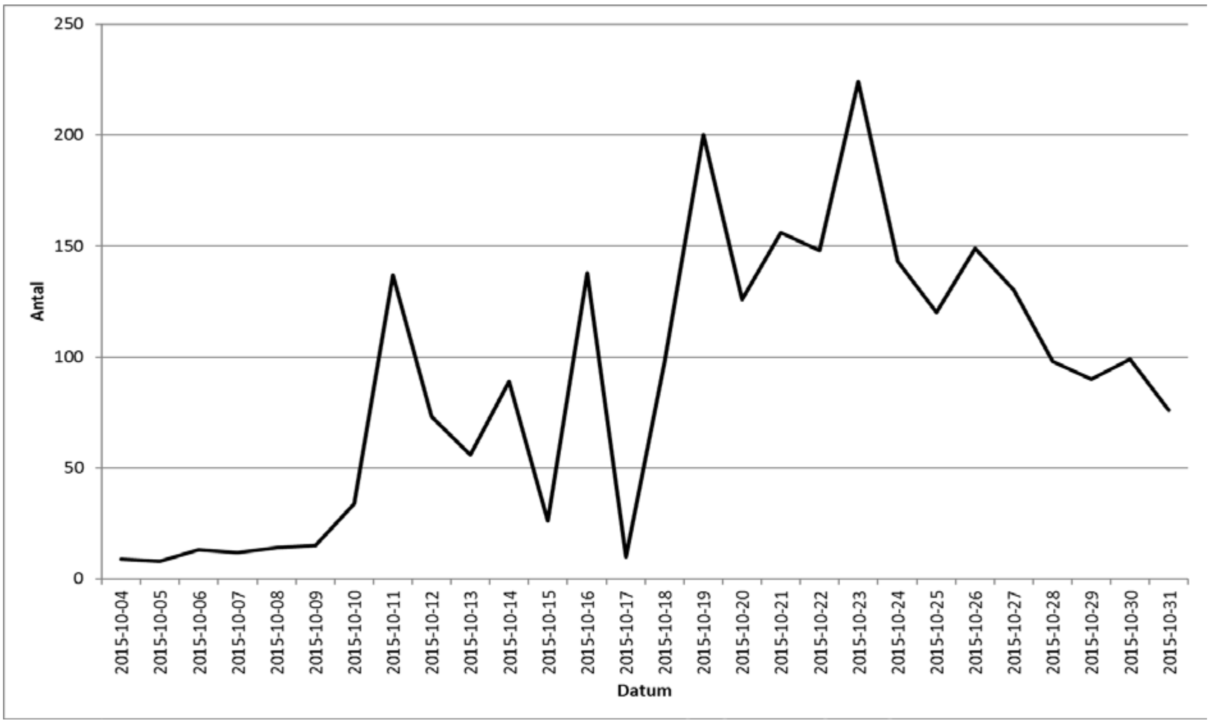

Figure 1.5. The number shows the total number of fish logged by the ultrasound camera in the size range 35 - 50 cm in the Alterälven river in 2015. A high level of upstream migration activity was recorded over a 10 day period 18/10 – 28/10. From 10/10 to 17/10 there was a high level of activity in front of the camera with large numbers fish migrating downstream. The total number of fish logged upstream was 2,465.

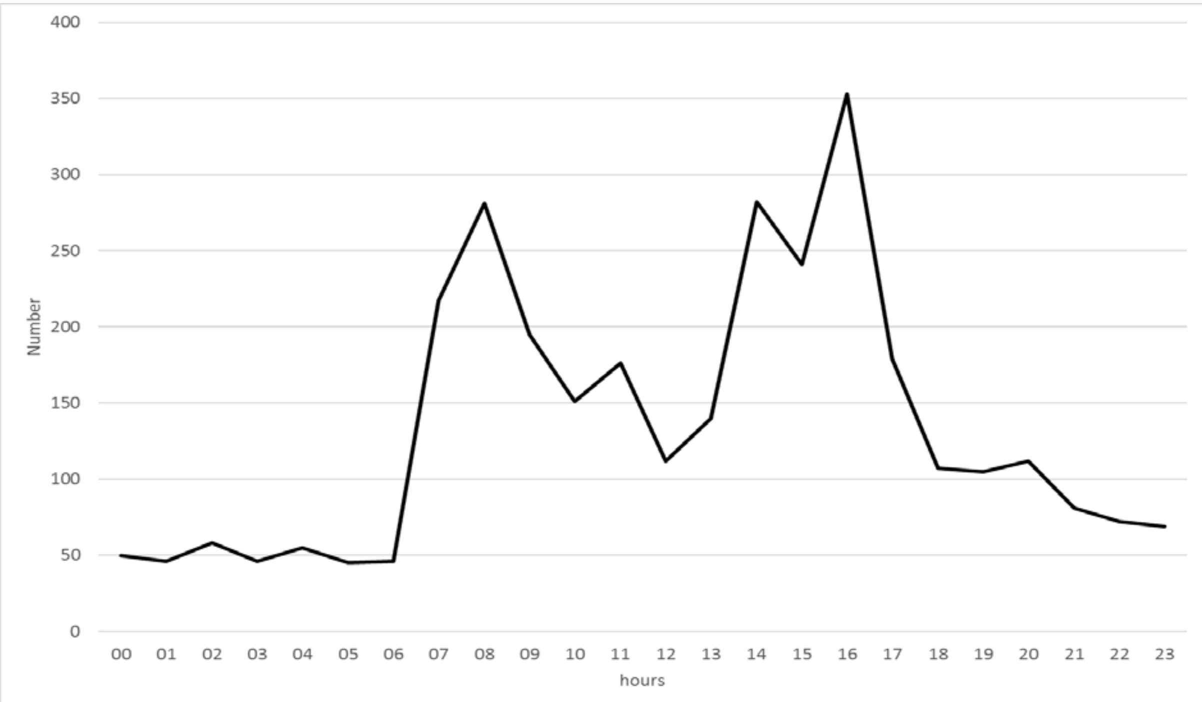

Figure 1.6. Total number of fish in the 30-50 cm range migrating upstream and downstream in October 2015.

Increased upstream migration activity in 2015 was logged in the middle of the day from about 07:00 - 18:00 of 30-50 cm fish. These were for the most part whitefish (Figure 1.6).

In 2017 the installation in the Alterälven river was moved about 200 meters upstream to the area just downstream of the E4 bridge. This was because there was a power supply for the equipment available from the Pite municipality pumping station at the bridge, and the area is somewhat deeper allowing for better study of burbot migrating to their spawning grounds as monitoring migration takes place under the ice. The area immediately downstream of the bridge is a spawning ground for whitefish and probably burbot as well; this resulted in a higher number of logged upstream and downstream fish movements than for 2015 site about 200 meters downstream in an area with a faster current, where it is unlikely that spawning takes place due to the high water speed.

Figure 1.7. The 2017/2018 installation site for the monitoring of upstream migration of whitefish and burbot in the Alterälven river.

The upstream migration of whitefish to their spawning grounds in 2017 shows the start of migration in late September and concentrated migration activity from 17–28 October (Figure 1.8). A total of 2,622 whitefish migrating upstream were logged. Figure 1.8 shows that the fish stayed in the area in front of the camera for about seven days when high upstream activity and, in particular, downstream activity was occurring. This is probably some form of spawning activity in the area in front of the camera. This area has also been identified as a spawning ground in a study of radio tagged whitefish 2015 and 2017 (see the section entitled "Identification and documentation of the spawning grounds of whitefish"). The number of whitefish logged migrating upstream has probably been slightly underestimated for total migration in the Alterälven river in 2017 because the spawning ground was identified as being approximately 300 metres downstream of the ultrasound camera in the 2016 telemetry study.

Increased upstream and downstream activity during the day, from late September to mid November, was logged in the middle of the day from about 08:00 – 15:00 of fish in the size range 35 – 50 cm (Figure 1.9. These were for the most part whitefish.

In 2016, migration was monitored in the Råneälven river to log the migration of whitefish to their spawning grounds so as to obtain a reference basis for studies in the Alterälven river. The upstream migration of fish in the size range 30 – 50 cm started at the end of September and had a marked increase in mid-October (Figure 1.10). The most intense migration to their spawning grounds lasted about 10 days, which corresponds to logging undertaken in the Alterälven river in 2015 and 2017. The dates of the of the upstream migration in the Råneälven river also coincide with the dates in the Alterälven river.

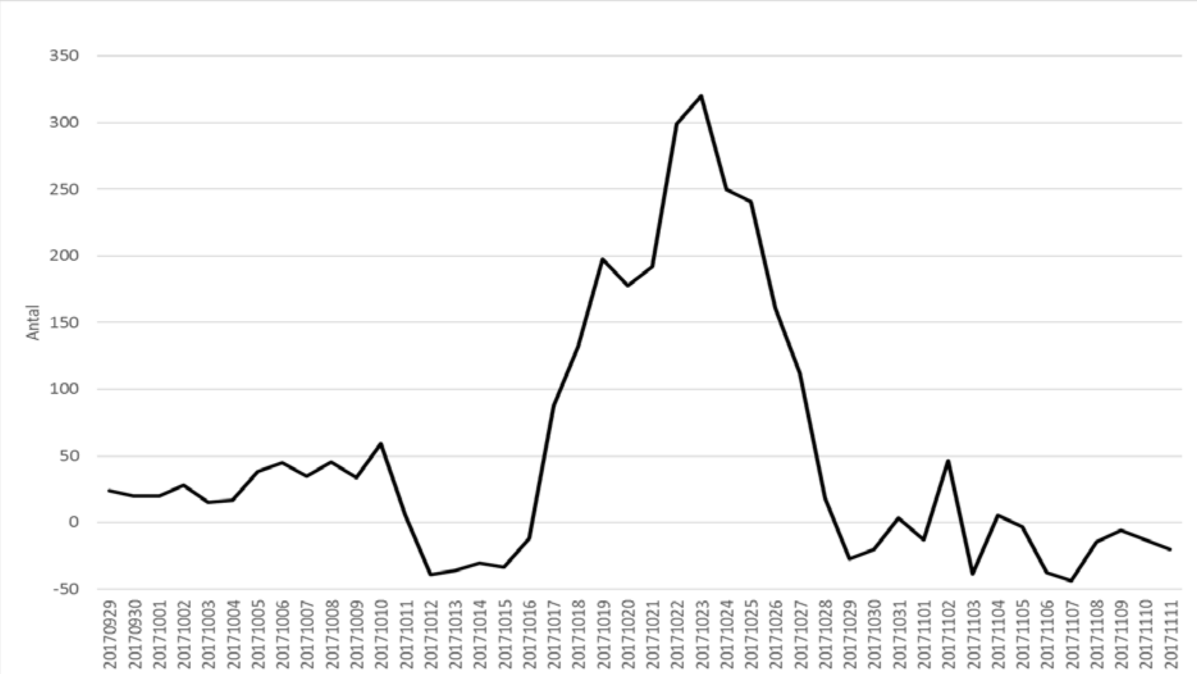

Figure 1.8. The number shows the total number of fish logged migrating upstream minus the number of fish migrating downstream by the ultrasound camera in the size range 35 – 50 cm in the Alterälven river in 2017. A high level of upstream migration activity was recorded over a 10 day period 17/10 – 28/10. Negative values indicate higher downstream than upstream migration. The total number of fish logged upstream was 2622.

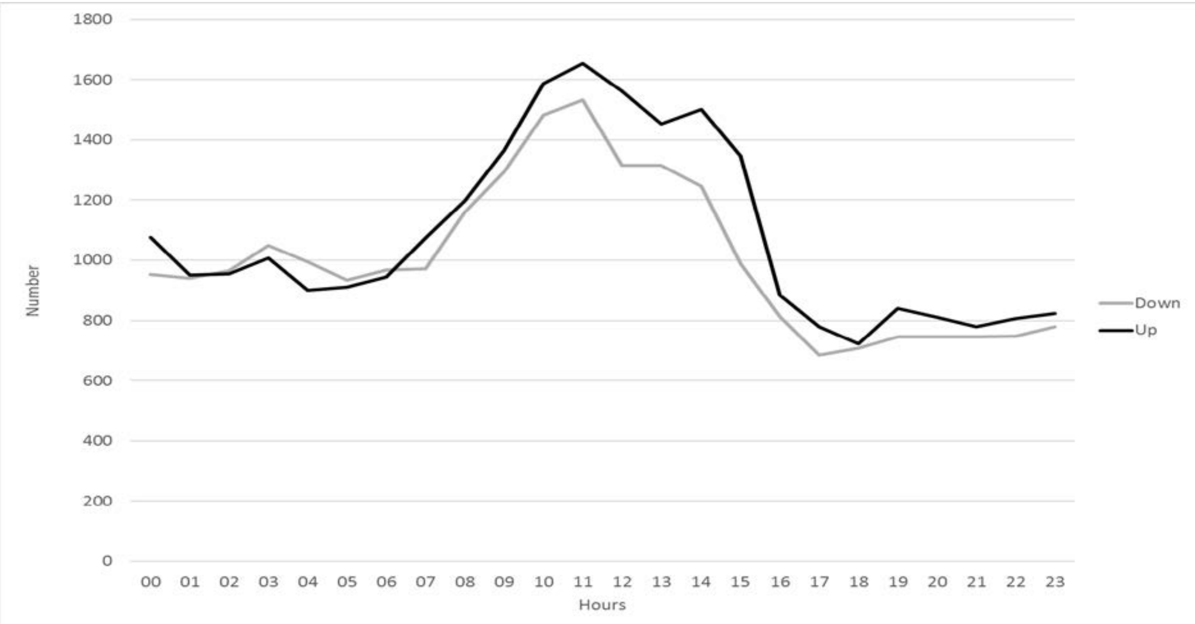

Figure 1.9. The combined upstream and downstream migration of fish in the size range 35–50 cm was logged during the day from 29/09/2017 to 11/11/2017 in the Alterälven river.

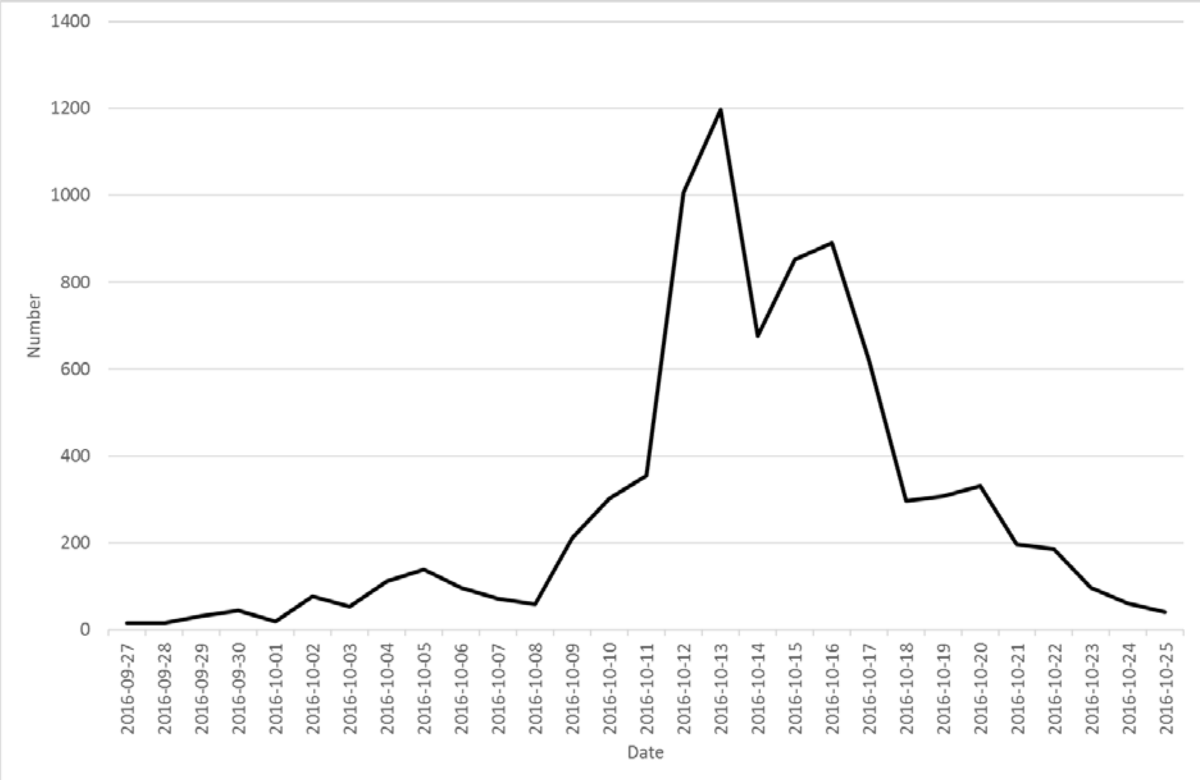

Figure 1.10. The number of fish logged migrating upstream in the Råneälven river in the size range 30 – 50 cm in 2016 from 27/9 - 25/10. The total number of fish logged migrating upstream was 8,370.

In the winter of 2017/2018, a study was undertaken of burbot migrating to their spawning grounds in the Alterälven river from the sea to the river. Burbot start their migration to their spawning grounds in November/December and spawn at the end of January/February. Spawning takes place in the period December to March in shallow water (0.5–3 m) at a water temperature between 0.5–4 °C. Spawning takes place at a depth of one to three metres in locations with a strong current with a gravel or sandy bed. As with cod the female produces a large quantity of eggs, up to several million. The total length of the burbot can be up to 120 cm, and is usually around 65 cm. Electric pulse fishing data from watercourses show a decrease of 13% in the number of localities with burbot. The seawater population is also decreasing. Locally in the Gulf of Bothnia this reduction can be up to >50%. A decline in population is underway or is anticipated. This decline relates to range, area of occupancy, quality of species habitat and number of reproductive individuals. Based on the most probable estimates, the species is in the near threatened category (SLU Species Database 2018).

Logging using the ultrasound camera in the Alterälven river in the late autumn/winter of 2017-2018 of fish in the 65-120 cm size range resulted in high upstream activity from mid-October, decreasing in mid-November. Since no other species in this size range migrate during the late autumn/winter, most of the fish logged are likely to be burbot migrating to their spawning grounds. The fish migration logged from mid-October to mid-November is for spawning, but it could also be combined with foraging, i.e. predation on whitefish roe, as this period coincides with whitefish spawning. The low levels of activity in the winter/spring show that downstream migration to the sea after spawning seems to occur later, this is because there is no increase in activity logged from the end of December.

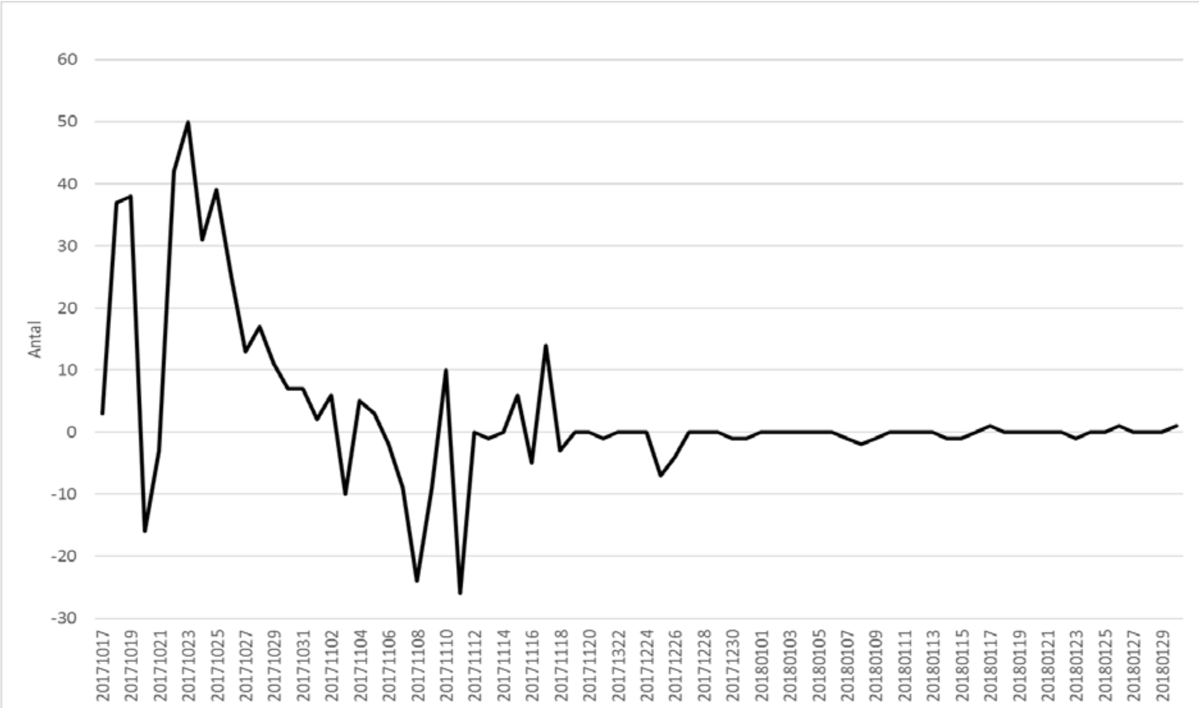

Figure 1.11. The ultrasound camera logged the number of fish in the size range 65 – 120 cm in the Alterälven river 17/10/2017 to 31/01/2018. Negative values indicate higher downstream than upstream migration. The net total (up minus down) of the number logged was 240.

Logging with the ultrasound camera shows movement throughout the day. However, there is increased activity, both upstream and downstream, in the middle of the day from about 08:00 to 15:00, of fish in the size range 65 – 120 cm. These were for the most part burbot.

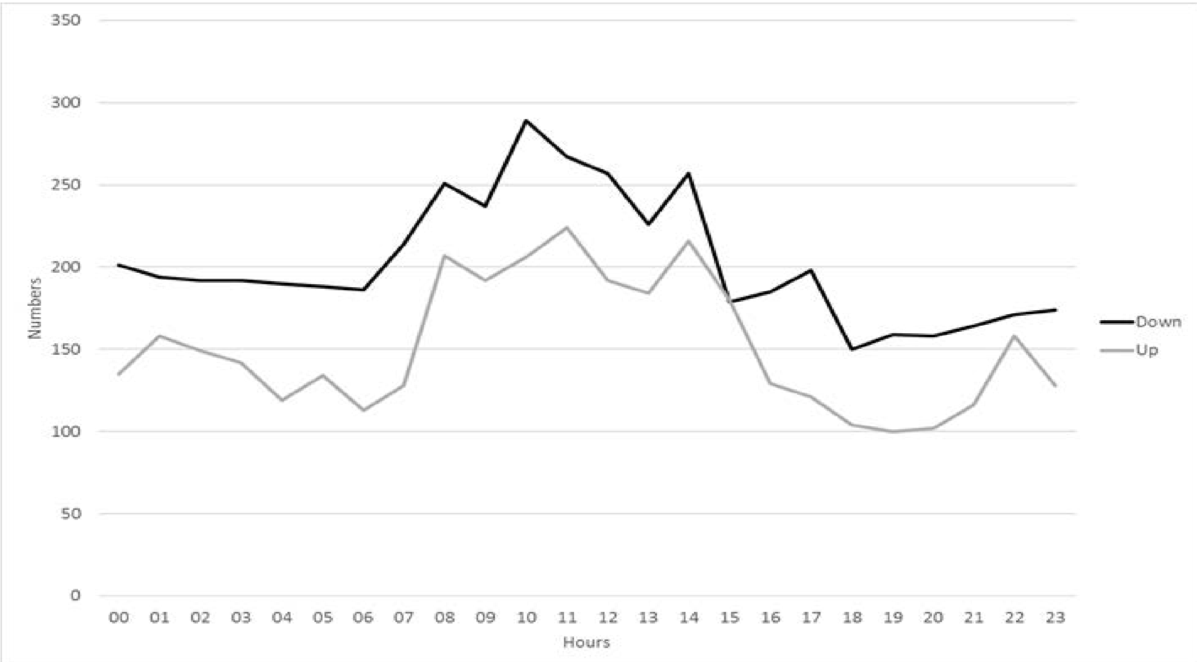

Figure 1.12. The combined upstream and downstream migration of fish in the size range 65–120 cm was logged during the day from 17/10/2017 to 31/01/2018 in the Alterälven river.

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Conclusions

The results of fish logging using an ultrasound camera in the Alterälven river in the autumn of 2015 and 2017, indicate that the river has a population of river spawning whitefish and burbot that migrate from the sea. The number of whitefish logged passing the fish counter in the Alterälven river seems to be realistic when compared with the number of whitefish logged in the Råneälven river, which was about three times higher. The upstream migration period in the Alterälven and Råneälven rivers is very consistent for the three different years that the study was undertaken. The most intense upstream migration period for whitefish in both watercourses lasted for about two weeks. The circadian rhythm also exhibited the same pattern in both watercourses, with upstream migration concentrated to daytime. When netting whitefish in 2015 and collecting them for radio tagging with an electric pulse fishing boat in 2017, most were caught during the day, indicating higher daytime activity. The fishing pressure in the archipelago off the mouth of the Alterälven river can acutely impact the population of river spawning whitefish. There is some angling in the Alterälven river in the autumn but catches are low so this probably does not significantly affect the population.

The County Administrative Board had no knowledge of the upstream migration of burbot in the Alterälven river. Information from the local population confirms that burbot have been fished in certain locations during the winter (January-February) downstream of the outlet of the Porsnäsfjärden lake and at the stone dump downstream of the Tullnäsbron bridge. Logging, using an ultrasound camera, of fish in the size range 65–120 cm in the lower reaches of the Alterälven river in the late autumn/winter of 2017 showed a high level of activity in late autumn, declining during the winter. In total, 240 fish in this size class passed upstream, and these are judged to be burbot migrating upstream to spawn. The high level of activity during the late autumn could be burbot foraging for whitefish roe in the area by the ultrasound camera. A spawning migration study using radio tagged whitefish identified the area as a spawning ground for whitefish.

2. Identification and documentation of whitefish spawning grounds

Materials and methods

In order to study the migratory behaviour of whitefish; identify their spawning grounds; and see whether the migration barrier at the outlet of the Porsnäsfjärd lake into the Alterälven river was passable or not; radio telemetry studies were undertaken in the in Alterälven river during migration to their spawning grounds in 2015 and 2017. In 2016, a supplementary radio telemetry study was carried out in the Råneälven river to see how far whitefish migrate in a watercourse where there is no migration barrier.

Prior to tagging in the Alterälven river in 2015 and Råneälven rivers in 2016, whitefish were caught using nets (40–60 mm mesh). In the 2017 Alterälven river study, an electric pulse fishing boat was used instead for catching whitefish.

Whitefish for tagging were caught at the mouth of the Alterälven river. After tagging the whitefish were released just upstream of the catch area. See Figure 2.1.

In the Råneälven river, the whitefish for tagging were caught in the calm water downstream of the lowermost rapids. After tagging the whitefish were released just upstream of the catch area. See Figure 2.2.

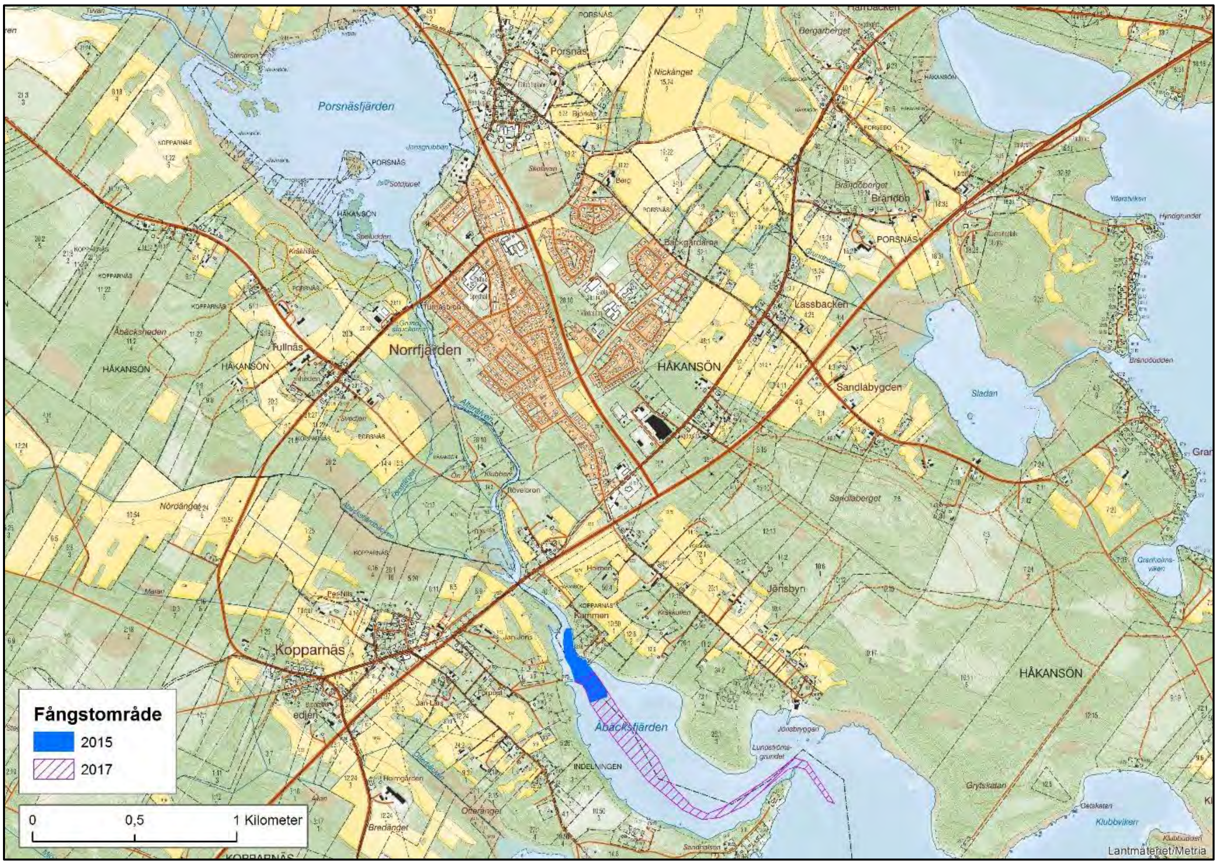
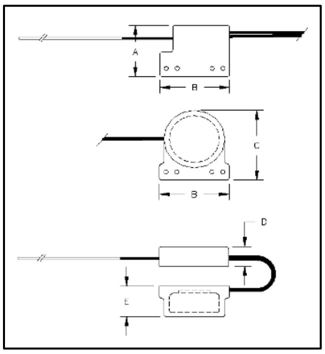


Figure 2.1. Map of the catch areas in the Alterälven river in 2015 and 2017.

Figure 2.2. Map of catch areas in the Råneälven river 2016.

Whitefish were tagged with an ATS F2210 Fish Ext. radio transmitter. Saddle Mount (Figure 2.3).



Model	Battery	Weight (g)
F2210	357HC (3,5 V)	4.5

Dimensioner (mm)				
A	B	C	D	E
12,5	16	17	5	7,5

Figure 2.3. Specifikation av de radiosändare som användes vid telemetristudierna.

The radio transmitters were attached over the dorsal fins of the whitefish with the transmitter battery side to the right of the fish and the transmitter electronic side and antenna to the left of the fish (Figure 2.4).

After tagging the whitefish were kept in reserve (in 2015) and in a large oxygenated tub (during 2016 in the Råneälven river and in 2017 in the Alterälven river) to ensure that they recovered before release.

In the Alterälven river two stationary receivers were used to log tagged whitefish. One at the mouth of the river and one at the outlet of the Porsnäsfjärden lake. During the 2017 study a switch box was used by the receiver at the Porsnäsfjärden lake so that an additional antenna could be used. We did this to increase resolution and detect whether tagged whitefish passed the migration barrier on which remedial work had been carried out. See Figure 2.5 for the set up and positioning of antennae.

Figure 2.4. Photograph of a whitefish with a radio transmitter mounted over the dorsal fin.

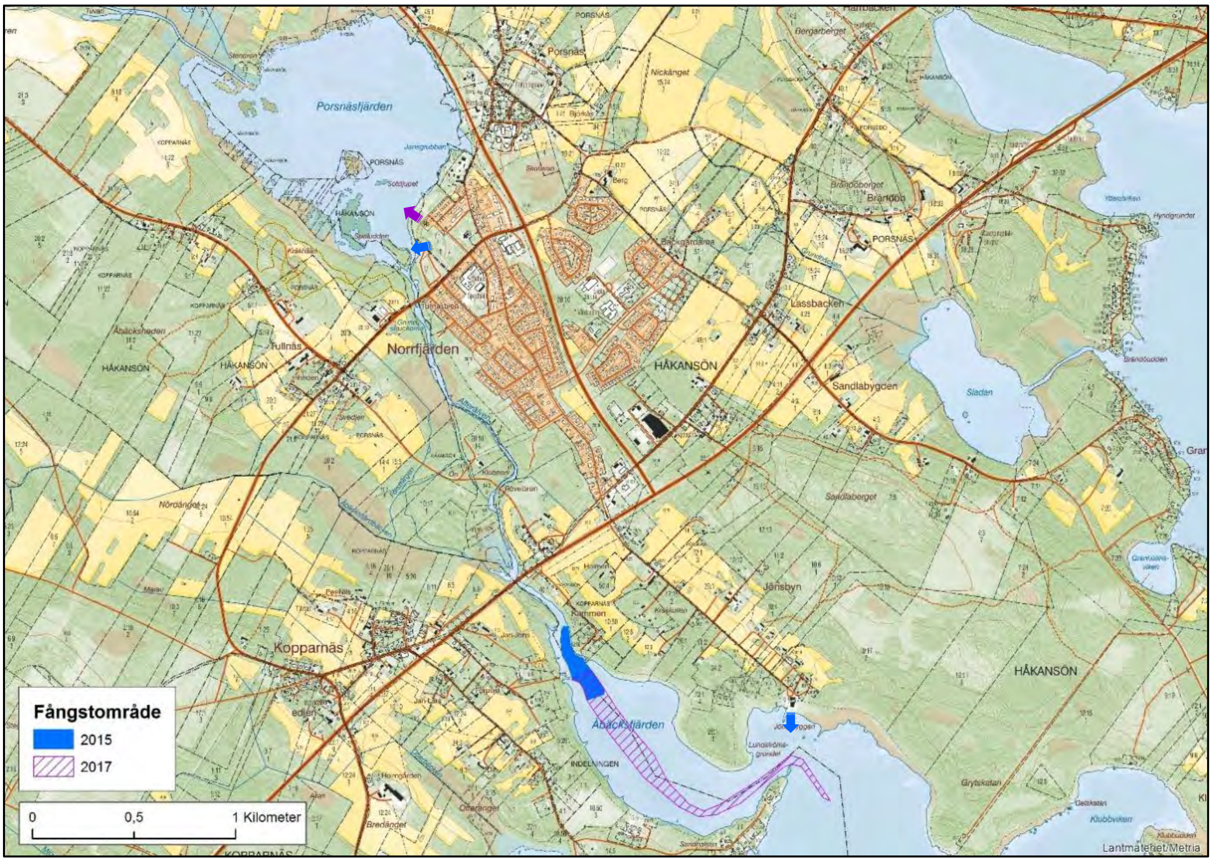


Figure 2.5. Map of the Alterälven river and the positioning of the telemetry study in 2015 and 2017. Blue arrows show the positions of fixed receivers and the direction of antennae in 2015 and 2017. The purple arrow shows the position and direction of the extra antenna used during the 2017 study to increase resolution at the modified migration barrier.

In addition to the stationary receivers, a hand held receiver was used to track the tagged whitefish more accurately. Hand held tracking was carried out regularly after tagging until spawning was definitely over (until 2 December 2015 and 23 November 2017)

Under samtliga tre telemetristudier mättes temperaturen i vattendragen kontinuerligt varje timme med temperaturlogger.

During all three telemetry studies, the temperature in the water was measured continuously every hour using a temperature logger.

Whether spawning behaviour was observed or not was also documented in conjunction with hand held tracking in the Alterälven river (fish chasing each other and splashing on the surface).

In the Råneälven river study in 2016 two stationary receivers were used to log tagged whitefish. One at the E4 bridge and one upstream of the Norrgren rapids. A switch box and two antennae were used at the receiver in Norrgren to increase resolution and detect whether tagged whitefish continued upstream in the river. See Figure 2.6 for the set up and positioning of antennae.

In addition to the stationary receivers, a hand held receiver was used in the Råneälven river to track the tagged whitefish more accurately. Hand held tracking was carried out regularly after tagging until spawning was definitely over (at the start of December).

Figure 2.6. Map of the Råneälven river and the positioning of the telemetry study in 2016. Blue arrows show the positions of fixed receivers and the direction of antennae.

In order to identify the most important spawning grounds in the Alterälven river it was divided into 10 metre long zones. Based on these zones and tracking data, GIS analyses were undertaken to identify the zones in which many whitefish could be found during spawning. Each whitefish found in the zone added a point to that zone. So zones in which many whitefish could be found received many points. This type of analysis was only undertaken in the Alterälven river because the Råneälven river was too large to identify where the fish could be found at a level of detail required for analysis. This type of zoning could be carried out in the Råneälven river because the tagged whitefish could not be located with the same accuracy as in the Alterälven river (due to the Råneälven river being so much larger).

To verify where the whitefish eggs lay after spawning and to be able to describe the spawning grounds in detail, a new method (for Sweden) was tested using a water pump to suck eggs from the river bed (see Figure 2.7).This method was used in 11 locations in two of the spawning grounds identified (upstream and downstream, see Figure 2.7). The pump we used had a capacity of 233 l/min and a four stroke 3 hp/2.2 kW petrol engine. The suction nozzle was 12 cm in diameter and had 1x1 cm stainless steel mesh that would let the eggs through undamaged, but prevent stones and gravel from being sucked in with them. The collection screen was provided with 1x1 mm mesh so that eggs were collected while sand and sediment was flushed out.

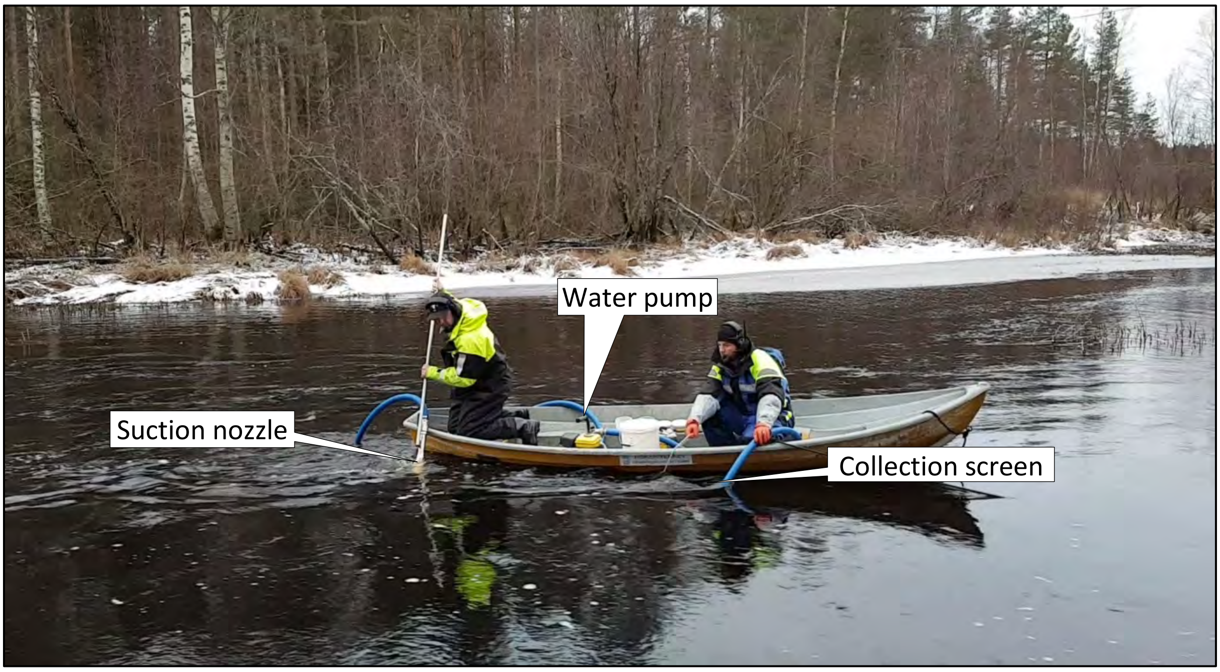


Figure 2.7. Photo showing egg pumping in the Alterälven river on 13 November 2017.

Results and discussion

Experience of the studies undertaken as part of this project shows that the whitefish is a very sensitive species. Much more sensitive than salmon and trout which have been the subject of many similar studies. Despite the water temperature being about 8 degrees and lower during tagging, the whitefish were exhausted after capture, measurement, weighing and tagging. During tagging before the studies in 2016 in the Råneälven river and 2017 in the Alterälven river, tagged fish were put into an oxygenated tank. We could observe the whitefish in the tank and check that they behaved normally before they were released.

Catching the fish using an electric pulse fishing boat was considered kinder than netting. However, whitefish that had been touched by either the anode or cathode took a long time to recover. We chose not to tag fish that were touched by the anode or cathode, not including them in the 2017 study.

The type of transmitter used in the studies that were part of this project did not require any surgical intervention in the muscle tissue of the fish. This means that they are kinder than many other transmitters. Based on our experience in this project, we believe that it is very important to use gentle tags when working with whitefish. Partly because the handling time (the time it takes to measure, weigh and tag) is short, and partly because the intervention itself is gentle.

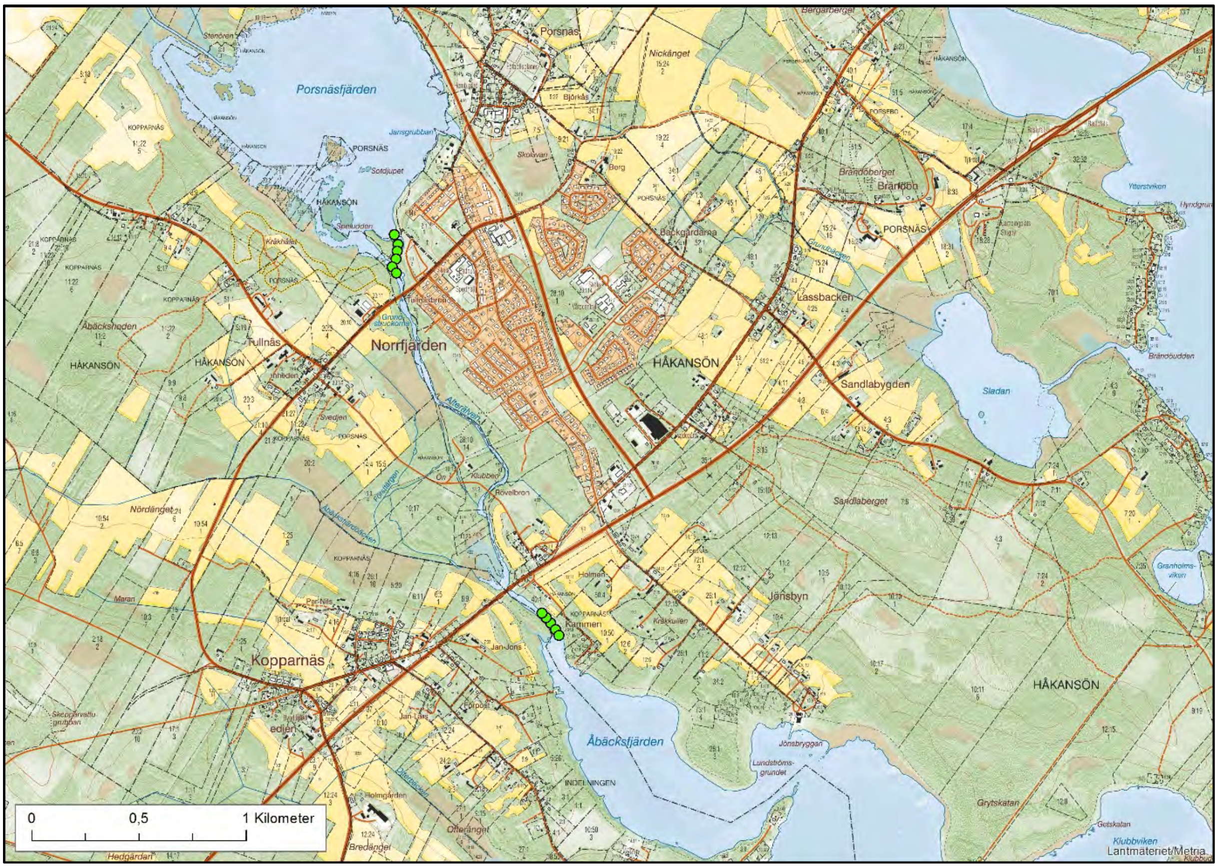


Figure 2.8. Map of locations for egg pumping on 13 November 2017. Sampling points one to five in the downstream area and six to eleven in the upstream area.

Alterälven river

During the study in the Alterälven 2015 none of the tagged whitefish passed the migration barrier in the outlet of the Porsnäsfjärd lake. All of the tagged whitefish stayed around the currents and rapids downstream of the Porsnäsfjärd lake, but most were found in the currents farthest downstream in the system.

Even during the study in 2017 (after work had been carried out on the barrier) most of the tagged whitefish were found in the currents farthest downstream in the watercourse. However, two of the tagged whitefish passed the location of the migration barrier in the outlet of the Porsnäsfjärd, on which work had been carried out in the autumn of 2016. Neither of these two whitefish swam farther into the watercourse than a few hundred metres upstream of the remedied migration barrier. Since whitefish have probably not been able to pass the migration barrier in the Porsnäsfjärd lake for a very long time, all the whitefish in the river will have been born downstream of the Porsnäsfjärd lake. It is possible that they do not have the spawning instinct to migrate farther upstream than where they were born? In order to find out if whitefish will venture farther up the system over time, follow-up studies will be needed in about 10-15 years.

The migratory behaviour of females and males did not differ significantly from each other during the 2015 study (see Figure 2.9). It is possible that males moved upstream and downstream between different locations in the river slightly more.

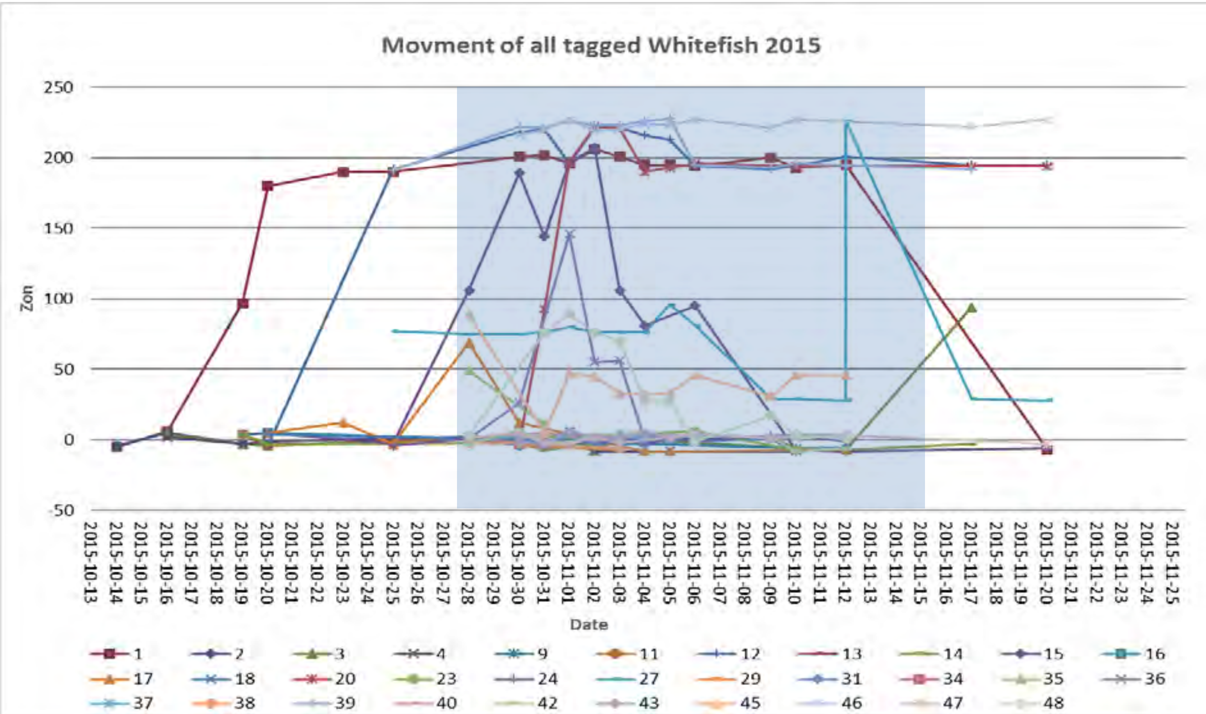


Figure 2.9. Diagram of the migratory patterns of tagged whitefish in the Alterälven river in 2015. The time period when spawning behaviour was observed has been highlighted with a blue background. 18, 27, 29, 34, 36, 38, 39, 42, 45, 47 and 48 show the movement of the females.

The 2017 study confirms the picture of males moving somewhat more (see Figure 2.10).

During the 2017 study, when we had better control of when tagged fish migrated out of the river, more than half of the males chose to stay in the river after spawning, while half of the females had swum out after spawning behaviour had ended.

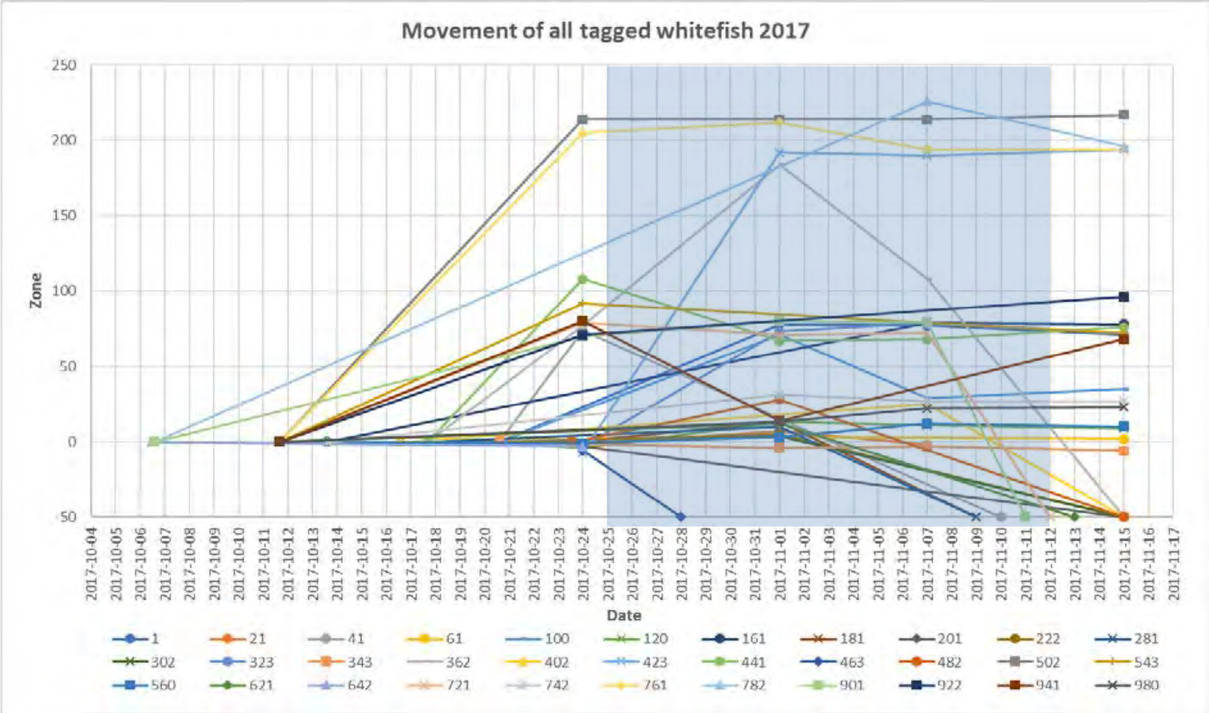


Figure 2.10. Diagram of the migratory patterns of tagged whitefish in the Alterälven river in 2017. The time period when spawning behaviour was observed has been highlighted with a blue background. 1, 41, 281, 343, 482 and 782 show the movement of the females.

Based on where spawning behaviour was observed (fish chasing each other and splashing on the surface), four main spawning grounds were identified (Figure 2.11). The same areas were also included in the results of GIS analyses of the zones in which the tagged whitefish were found during the period in which spawning behaviour was observed (Figure 2.12). Certain spawning behaviour was also observed outside the identified zones, but always in close proximity to them.

Based on the results of tracking and where spawning behaviour was observed, spawning seems to occur mainly upstream and downstream of rapids at a water depth of approximately 1-0.5 metres. The river flow at the spawning grounds was relatively laminar with a water velocity of about 0.2-0.5 metres per second, and the river bed consisted of gravel, stone and individual boulders.

During both studies, most of the tagged whitefish were found in the lower reaches of the Alterälven river, becoming fewer the farther upstream one looked. In view of the life cycle of the whitefish, hatching close to the coastal nurseries may be an advantage for fry. If fry hatched close to coastal nurseries have a higher survival rate, this would mean that most fish returning to spawn are born farther downstream than upstream. If the whitefish has a strong homing behaviour, this could explain why most of whitefish spawn in the lower reaches of the system.

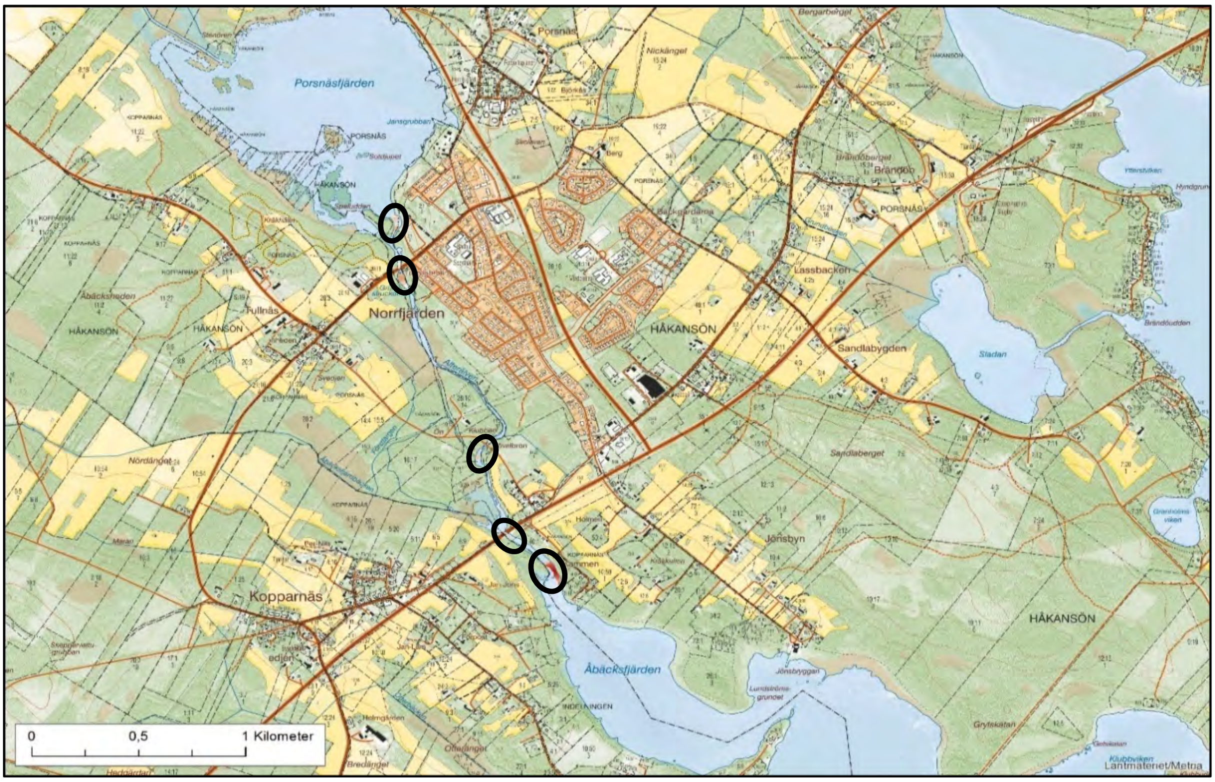


Figure 2.11. Map of the zones used and their scores in the Alterälven river during the 2015 study (the darker the red colour the higher the score). Blue ovals show the spawning grounds identified.

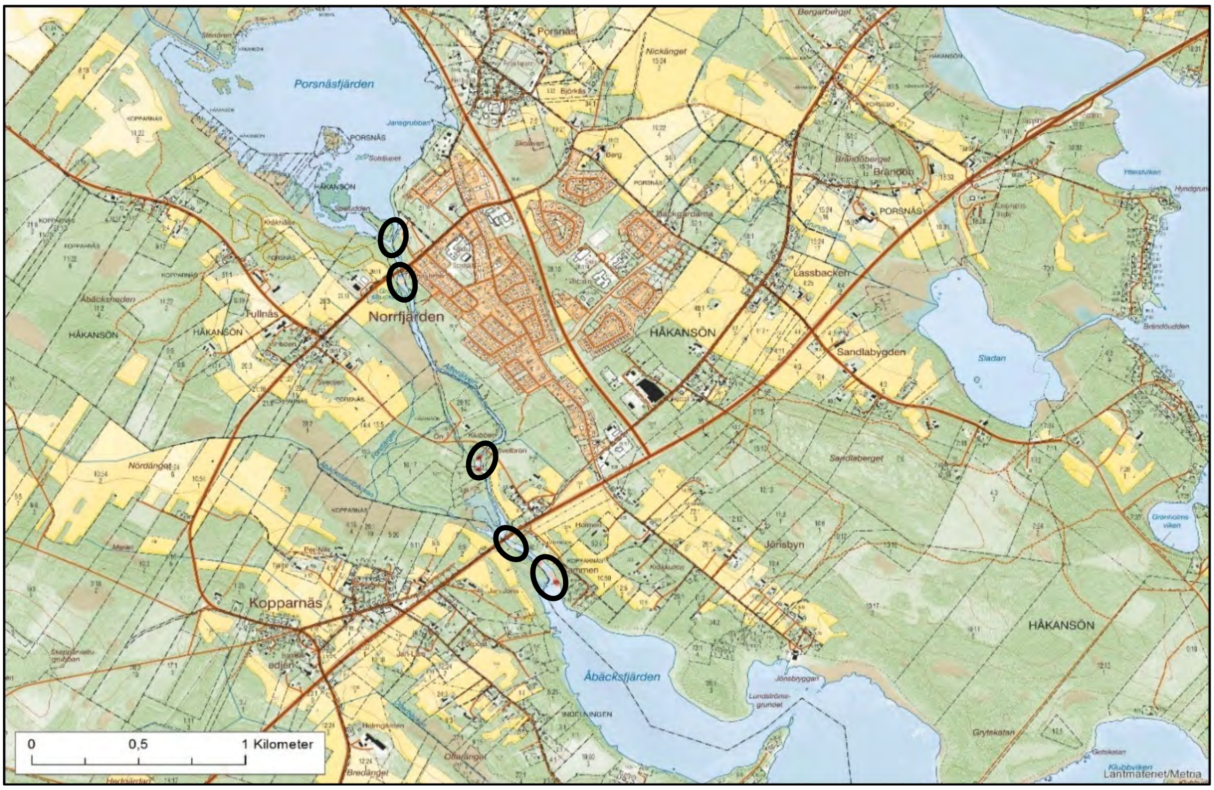


Figure 2.12. Map of the zones used and their scores in the Alterälven river during the 2017 study (the darker the red colour the higher the score).

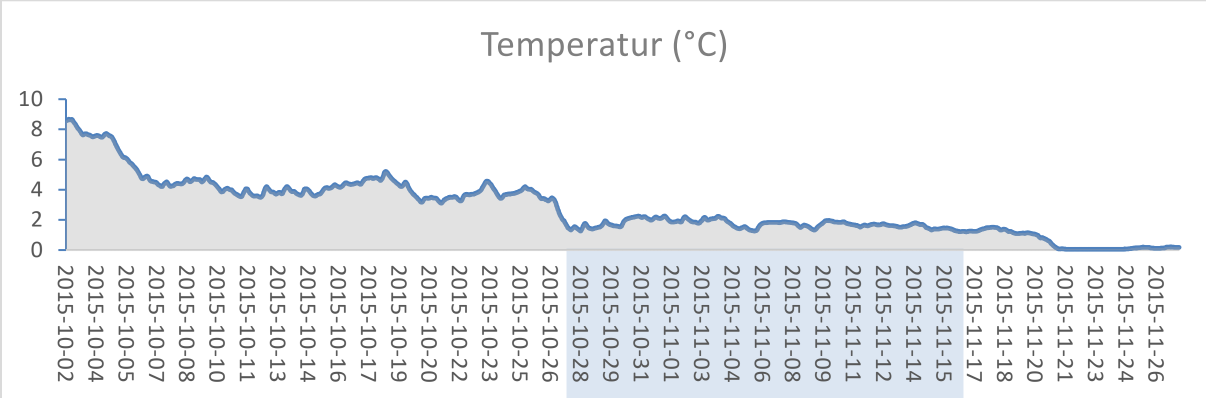


Figure 2.13. Diagram of how the water temperature varied during the study in the Alterälven river 2015. The time period when spawning behaviour was observed has been highlighted with a blue background.

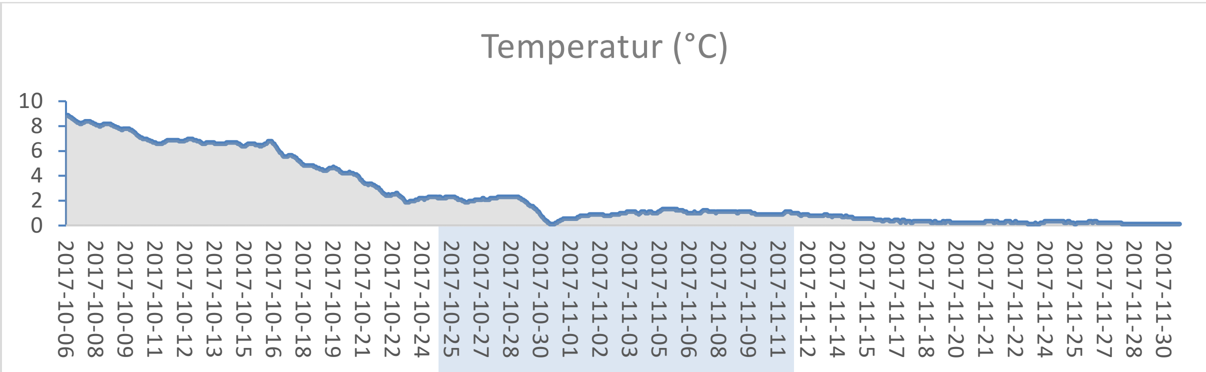


Figure 2.14. Diagram över hur vattentemperaturen varierade under studien i Alterälven 2017. Tidsperiod när lekbeteende observerades har markerats med blå bakgrund.

The dates that the spawning behaviour of whitefish was observed, coincided in both 2015 and 2017 when the water temperature fell below two degrees Celsius. This suggests that the water temperature can be crucial to when whitefish spawning occurs. The dates when water temperature fell below two degrees only differed by three days between the two study years. Daylight can therefore be of equal importance as water temperature.

The results of egg pumping show that eggs were present in all locations, and that there were more eggs at the spawning ground farthest downstream than upstream (see table). Eggs were also found upstream of the remedied migration barrier in the outlet of the Porsnäsfjärd lake, proving that the whitefish had been able to pass it following the work undertaken.

Tabell 2.1. Number of eggs present in each location.

Lokal	WGS84 (lat, lon)	Plats	Anta ägg
1	65.404892, 21.497629	Nedersta lekområdet	106
2	65.404774, 21.497707	Nedersta lekområdet	72
3	65.404671, 21.497814	Nedersta lekområdet	61
4	65.404577, 21.497878	Nedersta lekområdet	33
5	65.404441, 21.497865	Nedersta lekområdet	13
6	65.422087, 21.485385	Ovanför åtgärdat vandringshinder	1
7	65.421725, 21.485605	Översta lekområdet	2
8	65.421411, 21.485567	Översta lekområdet	1
9	65.421243, 21.485374	Översta lekområdet	18
10	65.421031, 21.485154	Översta lekområdet	65
11	65.420777, 21.48495	Översta lekområdet	9

Råneälven river

Tagged whitefish in the Råneälven river in 2016 exhibited similar behaviour to the whitefish in the Alterälven river; most whitefish were found in the lower reaches, becoming fewer the higher in the system one looked. The two tagged whitefish that migrated farthest up the Råneälven river migrated 12 kilometres upstream of the tagging site to the rapids at Södra Prästholm.

Based on tracking, four main spawning grounds were identified in the Råneälven river (see Figure 2.15).

As the Råneälven river is significantly larger than the Alterälven river, and spawning takes place under the cover of darkness, it was difficult to accurately identify where spawning was taking place. However, spawning in the Råneälven river seems to happen at the same time as in the Alterälven river, and the main spawning activity could be observed immediately upstream and downstream of the rapids from Prästholm and down to the mouth of the river on the coast.

The depth of water in locations where spawning could be observed in the Råneälven river was deeper than in the Alterälven river, varying between 1-1.5 metres. However, water velocity, the laminar flow and the river bed substrate were similar. This indicates that water velocity and flow are more important than depth when whitefish choose a spawning ground.

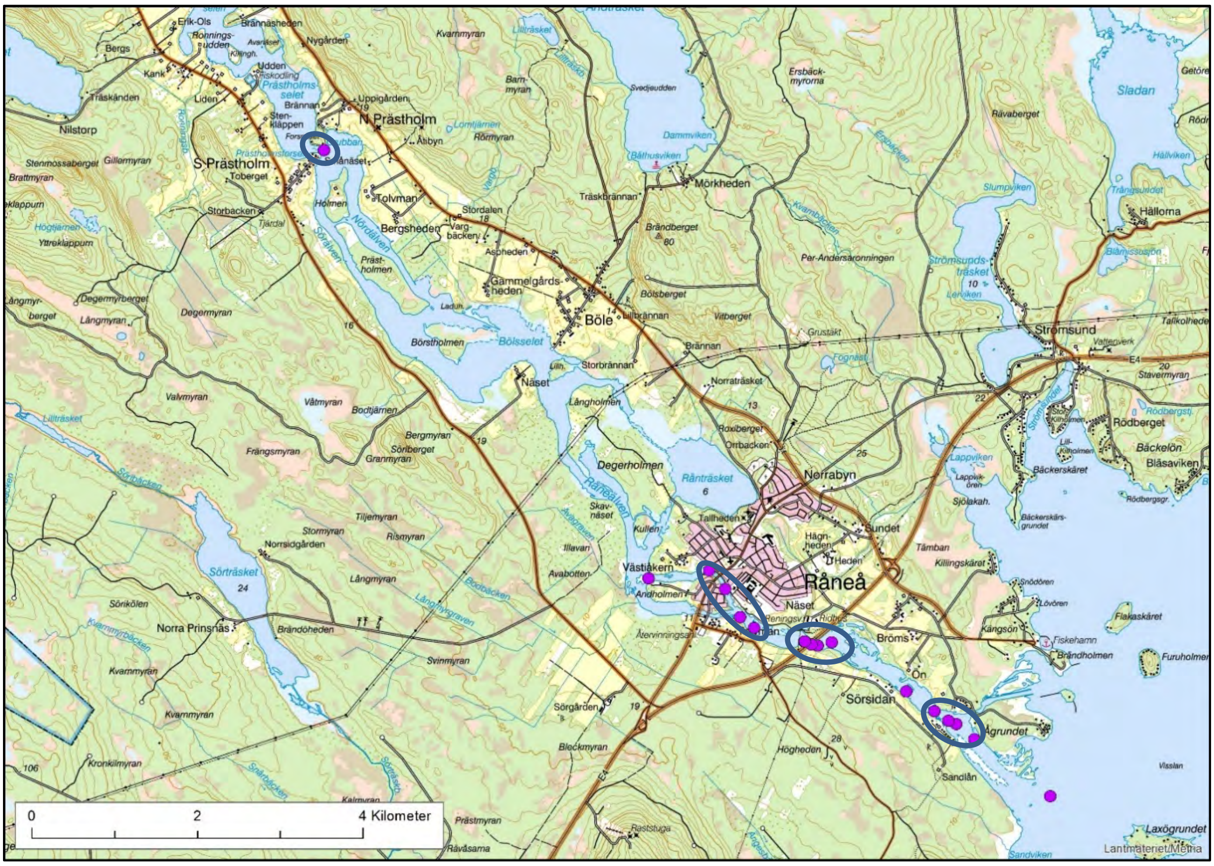


Figure 2.15. Map of the positions of tagged whitefish in the Råneälven river based on tracking using a hand held receiver. Blue ovals indicate areas in which whitefish were found during the spawning period.

Conclusions

The whitefish is a very sensitive species that needs to be handled with extra care when tagging. An oxygenated recovery tank is a must when working with the species.

In the Alterälven river the whitefish use the currents in the two kilometres of lowest reaches of the watercourse for spawning. Spawning takes place from the last week of October until mid-November. The study in the Råneälven river shows that the whitefish migrate twelve kilometres in the system.

The whitefish seem mainly to spawn just upstream and downstream of rapids, where the current is slower and not as turbulent as in the rapids.

The currents downstream in the systems appear to be the most important spawning grounds where most fish choose to spawn.

Whitefish seem to select a spawning ground based on distance from the sea and current conditions.

The studies indicate that the water temperature governs when the whitefish spawn. Day length may also be significant.

3. Exploratory fishing for crayfish

Materials and methods

In order to map the distribution of noble crayfish in the Alterälven river and the Rosån river system, qualitative exploratory fishing was carried out in 15 localities in the period 30 August to 7 September 2017 (10 localities in the Alterälven river and five in the Rosån river, see Figure 3.1).

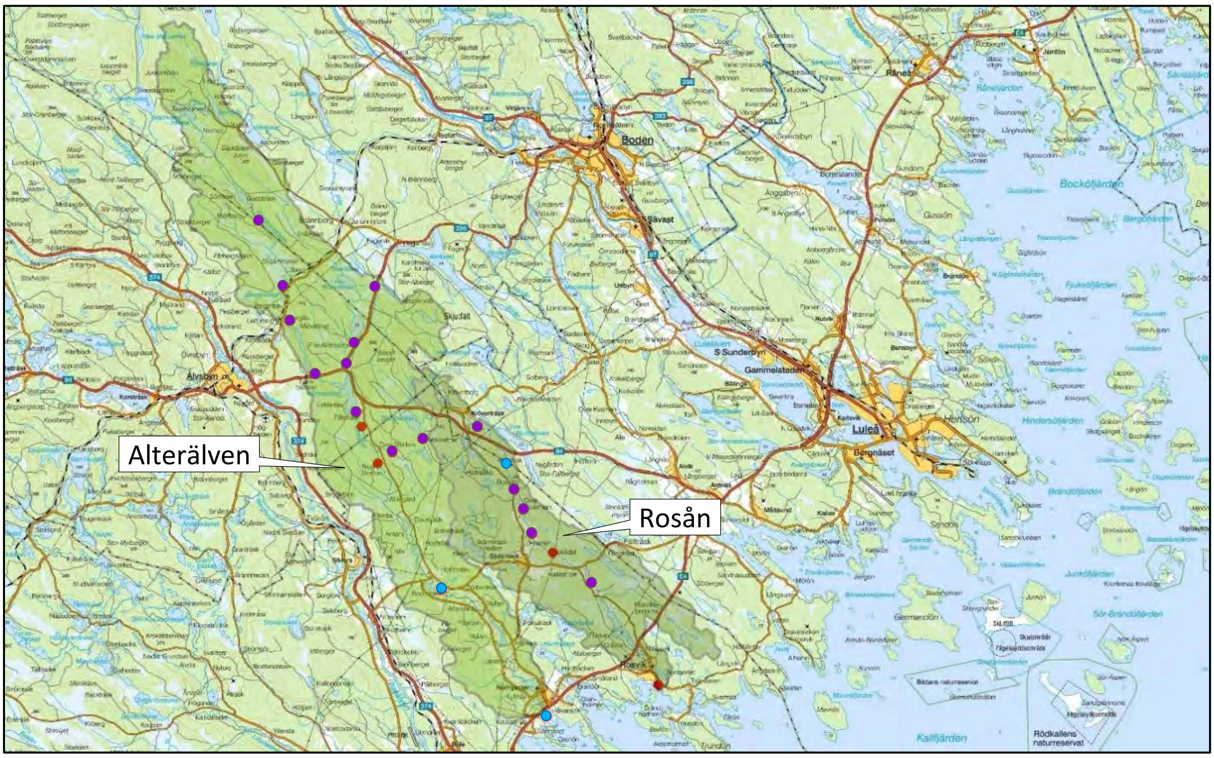


Figure 3.1. Map of the localities where exploratory fishing took place in the Alterälven and Rosån river systems. Purple dots show localities where exploratory fishing was carried out. Red dots show localities where exploratory fishing was not carried out. Blue dots show locations where the incidence of noble crayfish has been confirmed using other methods (electric pulse fishing, remedial mapping, netting).

The traps used were a model with two horizontal entrances and two escape openings for small crayfish (Figure 3.2). Exploratory fishing was carried out in each locality using eight crayfish traps baited with pieces of roach and bream. The crayfish traps were set out in the evening between 20:00 and 22:00 and were checked in the morning of the following day between 06:00 and 08:00.

Results and discussion

The natural distribution of the noble crayfish in Sweden extends from Scania in the south to northern Gävleborg county. It has then been spread through human intervention and introduced to many waters in the north (The national action programme for the noble crayfish).

The crayfish was introduced into Norrbotten county during the 1950s and 1960s. Although the species is not naturally occurring in the Norrbotten, the population in the county is considered to have a high biological value because it is severely threatened by crayfish plague and acidification in Europe and southern Sweden.

Figure 3.2. Photograph of a crayfish trap being checked in the Alterälven river.

In several locations in the county where the noble crayfish has been introduced, it has subsequently disappeared, but in some waters it has gained a proper foothold. Including in the Alterälven river and a small section of the Rosån river.

The results of the exploratory fishing in this project show that the distribution of noble crayfish in the Alterälven river system extends from the mouth of the river up to the Pite-Alterwater lake and the Nedre Mjöträsket lake in the Gäddträskälven tributary (Figure 3.3). No noble crayfish were caught in the two localities fished in the Mattesbäcken tributary, so it does not seem to occur there.

In the Rosån river system, noble crayfish were only caught in the locality just downstream of Rosfors. The species has also been caught by electric pulse fishing a short distance upstream of Rosfors, indicating that the species is also present there. However, farther upstream towards the Klöverträsk lake there were no catches resulting from the inventory fishing that was part of this project. The assessment based on this project is that the distribution in the Rosån river system only extends a few kilometres around Rosfors. One explanation of the very limited distribution in the

Rosån river may be the sensitivity to acidity of the species; this is because the Rosån river occasionally has a very low pH due to agriculture on acid sulphate soils.

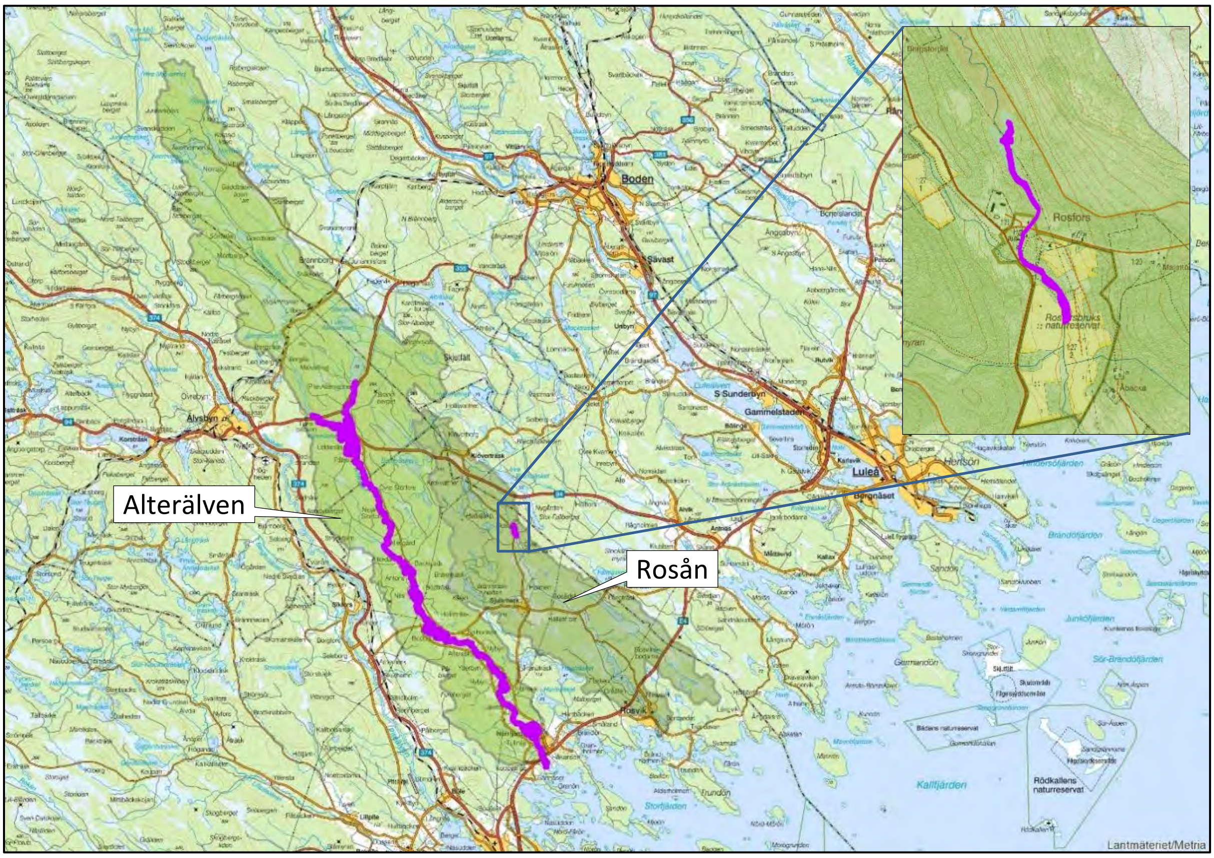


Figure 3.3. Karta över identifierad utbredning i Alterälvens och Rosåns vattensystem.

Conclusions

The noble crayfish occurs in virtually the entire Alterälven river system, except the smaller tributaries.

In the Rosån river the distribution is very limited and occurs only around Rosfors. The limited incidence in the Rosån river may be due to acidification linked to agriculture in combination with acid sulphate soils.

4. Physical initiatives

Rock weirs, dams and culverts have been constructed in the Alterälven, Rosån and Alån rivers for various reasons (mills, log floating, road crossings and sawmills). These structures have created migration barriers for fish, especially when the water discharge is low.

These barriers to migration have been identified and action, to allow the free passage of fish and other fauna, has been planned and taken as part of this project. These remedial measures are part of the "Kustmynnande Vattendrag i Bottenviken - Metodutveckling och ekologisk restaurering. Ett gränsöverskridande Svenskt-Finskt samarbetsprojekt” [Watercourses discharging into the Bay of Bothnia - Methodological development and ecological restoration. A cross-border Swedish-Finnish joint project]. This project is a collaboration between the County Administrative Board in Norrbotten, the ELY Centre in Finnish Lapland, the Geological Survey of Finland (GTK), the Natural Resource Institute Finland (LUKE) and the Geological Survey of Sweden (SGU).

Alterälven river, outlet of the Porsnäsfjärd lake

During the log floating period in the Alterälven river, the Porsnäsfjärden lake was lowered by excavating the outlet (Figure 4.1). At the same time a channel was excavated through the lake, closing off the shallower sections at its northern end. As a result, the lake began to choke with weeds. In connection with restoration work in the 1970's, Piteå municipality constructed the rock weir at the Porsnäsfjärd outlet in order to raise the water level in the lake and restore the earlier water mirror. Unfortunately, the rock weir became a migration barrier to h during the low water discharge that usually occurs during the summer and late autumn. The aim of the planned measure is to allow the free passage of fish and other aquatic fauna through the weir at the outlet of the Porsnäsfjärd lake.

Figure 4.1. Map of the east Porsnäsdammen dam (green dot) and a contemporary aerial photograph.

In conjunction with the raising of the late an outlet was excavated to the west of the original outlet. A weir was also constructed in the western outflow, the purpose of which was to release water from the lake when the water flow was great so that the lake would not overflow at high tide more than it did before.

Results and discussion

To create a free migration route at the Porsnäsdammen dam, rocks of mixed sizes were placed out in the area, extending the short weir about fivefold. This measure created a weir with less of a slope and a longer stretch of rapids. The material placed out in the dam was transported by truck from a natural gravel quarry in Kallaxheden. The material consisted of large and medium rocks and smaller stones. The rock was tipped out at the dam and an excavator arranged the material following instructions from the county administrative board (Figure 4.2).

Figure 4.2. Transport and arranging the rock using an excavator.

In total approximately 400 m3 of rock was arranged in the weir. In migration studies carried out as part of this project on radio tagged whitefish in 2015 and 2017 in the Alterälven river, no fish passed the weir at the outlet of Porsnäsfjärden lake in 2015, while two tagged whitefish passed the site of the migration barrier in the outlet of the Porsnäsfjärden lake which had been remedied in 2016. These results show that whitefish, and probably other species, can pass the remedied weir when water discharge is low. At high outflows the weir does not constitute a migration barrier for any species.

Figure 4.3. Porsnäsdammen befor (upper photo) och after (lower photo) remedial work in 2016.

Alterälven river, fishway at Altersbruk

After the Alterälven river stopped being used as a log floating route in 1965, Piteå municipality undertook a series of measures to promote fishing and protect the landscape in the Alterälven river. A fishway was constructed in the early 1970's at the mill dam in Altersbruk as part of this work. Piteå municipality owns the license to the fishway and has an agreement with the owner of the power plant which is responsible for its maintenance.

The fishway, which is now in poor condition, is a pool and weir fish ladder with openings in the bottom of the transverse walls alternating on the right and left-hand sides. The height of fall in the fishway is relatively steep, about 11%. This design is primarily intended for fish species with a good migratory capacity, such as sea trout and salmon, making it difficult for other species in the Alterälven river to pass.

The fishway opens about 30 m downstream of the mill dam, between the dam and turbine outflows.

The Alterälven river has a population of anadromous whitefish, ide, bream, pike, perch, bleak, roach, common dace and burbot that spawn in the river. In addition, there are common species of freshwater fish in the river, such as brown trout, grayling and bullhead, which probably do not migrate to their spawning grounds from the sea. There is a population of noble crayfish in the river that was originally introduced. There is also a documented incidence of the red listed otter in the catchment area of the Alterälven river. The entire catchment area is designated as valuable for fishing. The old fishway at Altersbruk constitutes a migration barrier to fish and other aquatic fauna (Figure 4.4). As part of the project Piteå municipality has planned and started the construction of a new fishway.

Figure 4.4. The old fishway to the left and the new fishway to the right, manufactured in composite with slot openings 2018.

Results and discussion

The remedial work planned is to replace the existing dilapidated fishway with a vertical slot fishway. A design suitable for fish species that are poor swimmers (Figure 4.4). The fishway is of a modular construction in composite material from Composite Service Europe AB in Öjebyn. Slots in the channel control water flow and reduce the energy in the water current. The new fishway has a lower incline than the old one, allowing the passage of fish species that are poor swimmers. The measure did not require any new intervention in the dam structure as the new fishway is in the same place as the old one.

The fishway is manufactured in sections at the factory and assembled on site on poured concrete foundations. The fishway incline is approximately 6% and will follow the route of the old fish ladder with an extra u-bend below the mill to reduce the gradient. The inlet section can be adjusted to accommodate variations in flow with varying amplitude.

Rosån river, Baronselsdammen dam

The Rosån river has been used for log floating since 1919. In 1927 the Rosån river was established as a public floating channel. The Baronselsdammen dam lies about 400 metres downstream of the Baronsselet lake in the Rosån river. The dam was constructed in connection with the establishment of the public floating channel in the late 1920s but was demolished in 1940 and rebuilt in 1943. The Rosån river log floating association was made liable for the upkeep of the dam after its rebuilding. Log floating in the Rosån river stopped in 1948 and the public floating channel ceased to be in 1956. After this the dam was not maintained and after years of neglect It has fallen into disrepair.

The dam is a stop log weir with a spillway and floor in poured concrete. During the early 1970s, Piteå municipality conducted a series of measures to promote fishing in the Rosån river and to counteract the adverse effect that log floating had had on the watercourse. In connection with this work a 2 m wide trench was opened in the cast concrete floor in the Baronselsdammen dam and a cross beam on the downstream side of the sluice floor of the dam was lifted out. Today the remains of the dam are very dilapidated, and despite past action, the dam constitutes a migration barrier for fish and other aquatic fauna. As part of the InterReg North project it was decided to remedy the migration barrier by removing the decayed concrete structures and creating a free migration route for fish and other aquatic fauna (Figure 4.5).

Figure 4.5. Map of the Rosån river with the Baronselsdam dam ringed and a picture of the concrete and metal debris which constitute a migration barrier for fish.

Results and discussion

The concrete debris that has fallen into the Rosån river and created a migration barrier for fish and aquatic fauna were lifted out. The side structures on either side of the watercourse were also demolished as they leaned in towards the watercourse and risked falling into the Rosån river, posing a risk to the general public. Structures made of metal that had fallen into the Rosån river were also removed (Figure 4.6).

Figure 4.6. Baronselsdammen dam in the Rosån river prior to work being undertaken. Concrete and metal structures were removed from the watercourse and from both banks.

When the concrete and metal structures that formed a migration barrier for fish had been removed, work was carried out on the stretch of river by the dam to create a free migration route. All concrete and metal structures were transported away from the dam. The contractor was responsible for the recovery and transport of material to landfill (Figure 4.7).

Figure 4.7. Baronselsdammen dam, Rosån river after work to create a modified channel for migrating fish. The concrete material on the right was transported to landfill. There was an extremely low water discharge (about 3 litres per second) when the work was carried out.

Rosån river, Sjulsmarksdammen dam

According to information, the dam was demolished some time ago and what remains is an approximately 40 metre long weir of large rocks across the Rosån river. The difference in level between the upper and lower water mirrors is about 1.5 metres. The weir is not considered a definitive migration barrier at high water levels when fish can get past it. However, at low and very low flows, the water runs between the rocks, making it impossible for fish to get past the weir (Figure 4.8).

Figure 4.8. Map and photography (very low water level) with the Sjulsmarksdammen dam (green dot inside the red ring).

Results and discussion

To allow fish and other aquatic fauna to pass, a passage was constructed through the existing rock weir. Boulders were moved using an excavator so that a concentrated channel could be constructed through the rock weir. This channel acts as a passage for fish when water levels are low in the Rosån river (Figure 4.9 and 4.10). When the water discharge is higher the water passes across the entire with of the weir and so does not prevent fish migration.

Figure 4.9. The picture on the left shows the weir before work was carried out, and the picture on the right shows the concentrated channel at the bottom of the rock weir. On the day that work was carried out the water flow was about 5 litres/s.

Figure 4.10. The picture on the left shows the middle section of the weir following the work and the picture on the right shows the upper section of the work. On the day that work was carried out the water flow was extremely low, about 5 litres/s.

Rosån river, Rosfors

Rosfors has a long history of industry. The ironworks was granted a franchise in 1832 and operated until 1875. In the early 1900s agriculture and forestry in the area were prosperous and the dam was used to power a sawmill. In 1940 the dam and sawmill were demolished, marking the end of industry in the area. The area has been designated as valuable for its cultural heritage. In 1984 the county administrative board was granted permission to rebuild the dam where the old sawmill dam stood. Rebuilding the dam was a measure to raise the cultural heritage value of the industrial environment in the Rosforsbruk nature reserve. However, rebuilding the dam created a migration barrier for fish and other aquatic species. About 50 metres upstream of the works dam is a road culvert which is also a migration barrier for fish (Figure 4.11). The aim of the planned work is to allow the free passage of fish and other aquatic fauna past the rebuilt dam and road culvert.

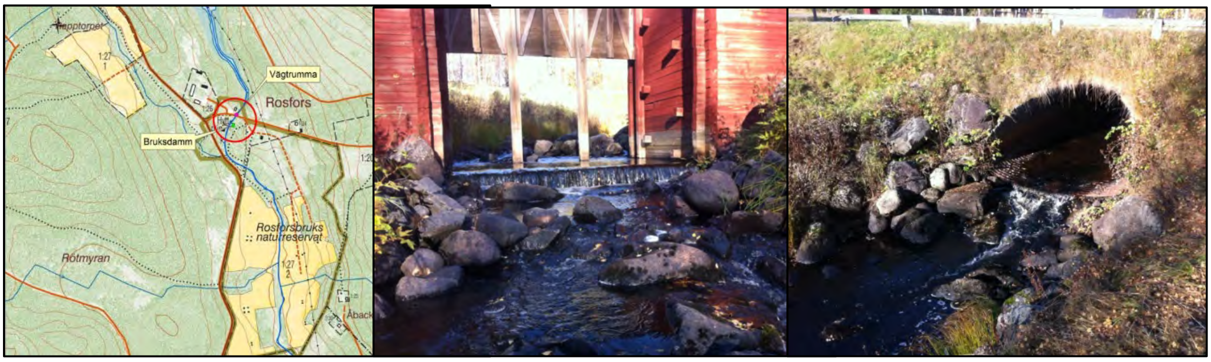


Figure 4.11. Map of Rosfors Bruk with the works dam and road culvert that constitute a migration barrier for fish when the water discharge is low in the Rosån river.

Results and discussion

The planned remedial work at the dam was to add varying sizes of rock to the downstream side of the dam's central spillway. In total, 5 m3 of rock was added downstream of the dam. Due to the area's cultural protection, the work was carried out by hand. To concentrate the flow at very low water discharges, wooden beams were mounted in the floor of the dam, raising the water level and concentrating the outflow. As a result of this the unnatural fall was removed and height of fall was levelled out, allowing the free passage of fish and other aquatic species even at very low water discharges. When the work was carried out the water discharge was very low, about 4 litres/s (Figure 4.12 and 4.13).

About 50 metres upstream of the dam a road passes over the Rosån river. A sheet metal drum has been laid in the watercourse to allow the road to pass. The road culvert is too level which means that fish cannot pass the fall on the downstream side when the water discharge is low in the Rosån river. By adding rocks of varying sizes, the fall height was evened out and the unnatural fall was reduced (Figure 4.14). When the work was carried out inflow was extremely low which meant that the Rosån river had an extremely low water discharge. When the water discharge is extremely low there are several locations in the Rosån river at Rosforsbruk, besides the dam and the road culvert, which become migration barriers to fish. In total, 30 m3 rock was deposited downstream of the road culvert using an excavator, the work took a day to carry out.

Figure 4.12. Dammen i Rosfors, Rosån innan åtgärd. Extremt låg vattenföring i Rosån.

Figure 4.13. Dammen i Rosfors, Rosån efter åtgärd. Extremt låg vattenföring i Rosån.

Figure 4.14. Rosfors, road culvert in the Rosån river. The two pictures on the left are before the work was carried out and the picture on the right is after the work was undertaken.

Alån river, Ale Kvarn mill

In the Alån river at Ale Nedre Kvarn there is a dam with gates and three spillways in poured concrete. The dam and neighbouring cultural environment are considered worth conserving from a cultural heritage standpoint. Ale Kvarn has a long history and it is included on a map from 1645. The mill was in operation until 1957 when it was closed. The area contains the miller's house, a working mill, smithy, fulling mill, splitting mill, framesaw mill and planing mill (Figure 4.15).

Figure 4.15. Map of Alån river with Ale Nedre Kvarn and a satellite image of the area.

The Alån river was previously used as a floating channel. It has also been impacted by agriculture in the lower reaches of its catchment area. The Alån river has a population of anadromous whitefish, ide, bream, pike, perch, bleak, roach, and burbot that spawn in the river. Locals say that adult brown trout (probably anadromous) and grayling have been caught in the Ale Kvarn area. There is also a documented incidence of the red listed otter, which lives mainly on fish, in the catchment area of the Alån river.

Today, the area is a popular tourist destination. It has a café and information displays describing the cultural environment. The mill dam is owned by the Ale village association, which was licenced to rebuild it on the site of a previous dam structure in 1990. A condition for the permit was that a fishway would also be constructed, but no such structure has ever been built.

Results and discussion

Most of the water flows through the middle spillway in the dam structure; this is where the flow of water is concentrated and where the flow rate increases over the gently sloping dam floor. On the downstream side of the spillway a fall forms towards the bottom of the watercourse. This means that fish and aquatic species cannot pass upstream, particularly when the water discharge is low, the site was therefore considered a migration barrier (Figure 4.16).

Figure 4.16. The Alån river with Ale Kvarn at an extremely low water discharge. Before work was carried out on the left and after work was carried out on the right.

Because the dam and its associated buildings are considered to have a conservation value from a cultural heritage standpoint, the work was planned taking this into consideration. In total approximately 120 m3 boulders and rocks were transported and arranged in the area below the body of the dam (Figure 4.17).

Figure 4.17. Arranging boulders and rocks at Ale Kvarn in the Alån river.

The arrangement of boulders downstream of the dam meant that the water level there was raised; creating free passage for fish (Figure 4.18). Immediately work arranging the rock was finished five perch were observed moving upstream past the dam. Later fish were observed passing the floor of the sluice upstream.

Figure 4.18. The weir at Ale Kvarn in the Alån river before work was carried on the left, and after work was carried out on the right. The water level was very low when the work was carried out.

Alån river, Selets bruk

At the village of Selet, the Alån river flows through the Selets Bruk nature reserve. The area has Natura 2000 status. In addition to a high conservation value the area has a long history of industry, and there are several archaeological remains on the site (Figure 4.19). To increase the value of the area from a cultural and scientific conservation standpoint, in the late 1970s the county administrative board reconstructed the dam structures associated with historical industry.

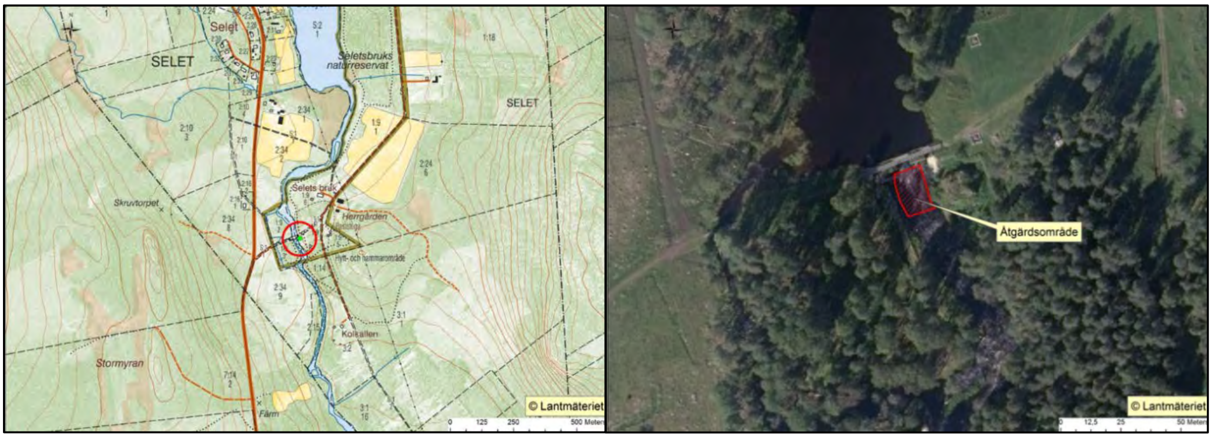


Figure 4.19. Map with Selets Bruk ringed and on the right a satellite image with the works area ringed.

The dam constructed created a migration barrier for fish and other aquatic species. To enable fish migration and recreate the natural ecological conditions in the river, the migration barrier at Selets Bruk was inventoried, planned and remedied.


Figure 4.20. The dam construction at Selets Bruk, Alån river. The picture on the left shows the gates open and the picture on the right shows them closed.

Results and discussion

The migration barrier at the dam was remedied by raising the water level downstream of the middle spillway by adding rock. This evened out the height of fall and allowed fish and other aquatic fauna to pass the middle spillway. Rock for the construction of the weir structure was transported from Kallax gravel quarry to the site by lorry. Once there, boulders and rocks were transported by dumper truck and then the material was arranged in the water by an excavator.

The work at Selets Bruk was carried out at the end of April 2018 by building a winter road in March to reduce soil damage and so as to be able to drive an excavator and dumper truck outside the nature reserve and also in the side channel to the left of the main channel of the Alån river. The choice of dates for work also meant that no cultural artefacts were affected.

Figure 4.21. Map of Selets Bruk in the Alån river with the winter road (for the excavator and dumper truck) marked (dashed red line) and pictures of the winter road.

A total of 170 m3 boulders and rock was transported to the site on public roads. From there the material was reloaded onto a dumper truck that transported the material on the winter road down to the main channel of the Alån river, about 20 meters upstream of the outflow of the side channel (on the right bank viewed from above) to the main channel (Figure 4.22).

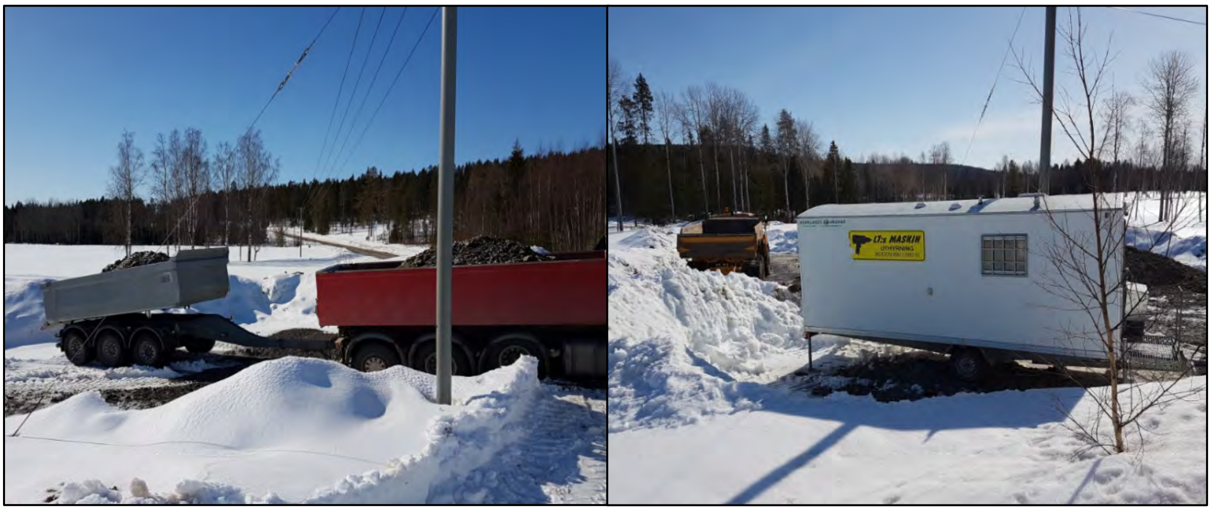


Figure 4.22. Transporting material for reloading onto a dumper truck (picture on the right).

From the dumper track's unloading site in the main channel of the Alån river, the material is lifted up by the excavator to the works area (Figure 4.23).

Figure 4.23. The picture on the left shows the transport of material by an excavator into the main channel of the Alån river, and the picture on the right shows the arrangement of rock in the works area.

The rock raised the water level closest to the dam by about 30 cm, creating a free migration route for fish through the opening of the middle gate, even when the water flow was low in late winter when the work was undertaken (Figure 4.24).

Figure 4.24. The picture on the left is before work was carried out and on the right after work was carried out at Selets Bruk, Alån river. After the work was carried out the water level below the dam was raised, creating a free migration route for fish (picture on the right).

Because the work was carried out in April on snow covered and frozen ground, rutting was barely visible where the excavator and dumper truck had driven (Figure 4.25 and 4.26). No trees needed felling for the work. The tree stumps visible in the pictures were felled for conservation in the past. No cultural heritage objects (such as shaped rock) were disturbed because the transport of material was carried out outside the nature reserve and on the frozen side channel on the right (viewed from downstream) and in the main channel of the Alån river.

Figure 4.25. Transport route for the excavator and dumper truck at Selets Bruk showing little rutting after the work carried out in April 2018.

Figure 4.26. Transport route of the excavator and dumper truck at Selets Bruk with barely visible rutting on the slope between the two nearest tree trunks. The side channel is on the right of the picture and the main channel at the top of the picture.

Conclusions

Biotope measures carried out at dam structures in the Alterälven, Rosån and Alån rivers and the road culvert in the Rosån river have made passage possible for fish and other aquatic fauna. At the mill dam in the Alån river, fish could be observed passing on various occasions after the work had been completed. After the work carried out in the Alterälven river at the outlet of the Porsnäsfjärd lake, radio tagged whitefish were logged above the dam. By sucking up roe upstream of the newly constructed weir, spawning could also be observed. This shows that the work was successful in late autumn when water levels are low. The work in all of the watercourses mean that they can be reclassified to a higher status in the VISS [Water Information System Sweden]. The work in Selets Bruk, carried out on snow-covered frozen ground did not rut the ground too much and allowed other access routes to be used. This can be contrasted with the period when the ground is not covered with snow. There has been a positive reaction to the work carried out from the public, mainly from the remedial work at the outlet of the Porsnäsfjärd lake and at Ale Kvarn in the Alån river.

PROJECT REPORT

Habitat modelling as a tool for evaluating fishery restoration – the case of Simojoki

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Introduction

Restoration and maintenance of habitats is of key importance in the management of fish stocks. Restoration aims to improve the ecological status of a river system and fishes' ability to reproduce and survive. Restoration of flowing waters is particularly needed in order to restore rivers' fish spawning- and reproduction areas that have disappeared due to dredging and other practices. Evaluation of the results of restorative efforts has generally been based on the changes (which have been verified by test fishing and/or population modelling) that have occurred in the population density levels/production of a given fish species as a result of restoration. Changes in the riverbed/rapids that have occurred in the restoration process, affecting the riverbed's structure and flow conditions, have been evaluated mainly by eye-test, on the basis of an experience-based conception of what the rapids look like in their natural state. To evaluate the results of structural restoration of a riverbed, tools are needed that provide, in addition to traditional eye-test assessment of the riverbed, information on how the structural and hydraulic properties of the restoration site changed in the restoration process, and how these changes affect the quality and amount of the spawning- and reproduction areas of (for example) salmon under different discharge conditions of the river. This project report presents the level of results achieved in rapids restoration projects carried out on the Simojoki River, based on salmon fry population density as estimated via electrical test fishing, and habitat modelling is applied to the estimation of structural and hydraulic changes to the habitat quality of the salmon fry that have occurred in the process of rapids restoration.

Simojoki

The Simojoki River drains out of lake Simojärvi and descends to the corner of the Gulf of Bothnia (65°38'N, 25°00'E). The river is 175 km long, it has a drop of 175 m, and its average discharge rate at the Simo flow-measuring station is 38 m^3/s. The quality of the water is good for salmon reproduction, although the river is burdened by forest draining, agriculture and peat production. A particularly high humus and iron concentration, due to the swampy drainage basin, and a low level of conductance are characteristic of the quality of the water (Perkkiö et al. 1995). Variation in the discharge rate of the Simojoki is also high due to the intensive draining of the drainage basin, and this may be a factor restricting the success of salmon in the river. Extreme values for discharge rates have varied between 730 and 3 m^3s^{-1}, and the lowest rate generally occurs in March. The low point in the flow is of interest in the matter of salmon reproduction, because the larger part of the surface area of the rapids is dry at that time, and this may affect the survival rate of spawned roe.

Most of the loading of phosphorus and nitrogen nutrients into the waters of the Simojoki takes place through natural leaching. The main source of the load caused by human activity, in regards to these nutrients, is agriculture, which has its strongest effect on the middle and lower course of the river in particular (Nenonen 2007). The load from forestry activities is the strongest in the upper course of the river and the drainage basins of the river's tributaries. By contrast, the overall load of peat production is low, even though it can be quite considerable in certain drainage basins of tributaries.

Salmon stock of the Simojoki River

The established area where salmon come upriver to spawn is a 110 km stretch from the mouth of the river to Portimojärvi lake, even though a small number of salmon also reproduce between Portimojärvi and Simojärvi (Jokikokko & Jutila 1998). Before human activity began to have a larger-scale effect, in the 1950s, it is estimated that about 75,000 smolt salmon migrated down Simojoki each year (Jutila & Pruuki 1988). However, salmon stocks in the Baltic region took a downward turn after World War II, first due to the damming of major rivers, and then as a result of accelerated sea fishing (Eriksson & Eriksson 1993, Anon. 2000). Additionally, modifications made to river drainage basins, and drainage of these areas, had a negative effect on the quality of the water and river bottom in terms of the ability of salmon to spawn and their further success. A particular disruption in salmon reproduction occurred in the 1990s with the so-called M74 phenomenon, which killed salmon fry when they were still at the yolk sac stage, and is thought to have had a harmful effect on the natural reproduction of salmon stocks (Keinänen et al. 2000).

In the early 1980s, obligatory introductions of migratory salmon fry were started in the large, built-up rivers of the Bothnian Bay, the Iijoki and Kemijoki rivers, for the purpose of maintaining salmon stocks, and to compensate for the harm caused by river damming. These extensive introductions were aimed at protecting and maintaining fishing activity in the sea- and estuary areas, and not at affecting natural reproduction volumes. In addition to the aforementioned obligatory introductions of salmon, efforts began in the 1980s to introduce salmon fry of varying ages into the rivers of the Gulf of Bothnia in order to secure and preserve the rivers' salmon stock and natural processes of reproduction. In 1997, an international programme of action for salmon, the Salmon Action Plan (SAP), was initiated. Its aim was to maintain the salmon stock in rivers where salmon naturally reproduced, and to restore it to rivers where natural reproduction was possible. Simojoki was one of the most important introduction sites, because the river has a naturally reproducing salmon stock, but this stock was in a weakened condition in the 1980s, particularly as the 1990s approached, due to heavy sea fishing. Levels of reproduction and the success of salmon fry had already been negatively affected by the dredging of rivers in the 1950s for the purpose of log driving. However, the reintroduction programme was ended a few years later, after it was discovered that the water quality and other physical properties of some of the selected sites was preventing the natural circulation process from properly taking hold there. However, in the Simojoki and Tornio Rivers, natural reproduction was restored from the effects of sea fishing through regulation, and the introductions of salmon were therefore no longer needed (Romakkaniemi et al. 2003).

The introductions in the Simojoki River were started in 1984, and the greater part of the salmon introduced were young-of-the-year and yearling fry, along with a certain amount of migration-ready smolts. The yield from the introductions was poor due to heavy sea fishing (Jokikokko & Jutila 1998). However, the introductions did serve to maintain the existing salmon stock in the Simojoki: during the leanest years, in the mid-1990s, the majority of spawning female fish in the river originated from earlier introductions (Jokikokko 2006).

The salmon stock in the Simojoki has been researched since the 1970s, first by the Finnish Game and Fisheries Research Institute, and now by Natural Resources Institute Finland. Fry population density has been researched for decades at 36 standard test zones between Simojärvi lake and the sea. Properly speaking, fry population density has been measured in an area stretching from the river mouth to Portimojärvi lake, because salmon fry are only sporadically found between Portimojärvi and Simojärvi. Population density is measured separately for young-of-the-year fry and older fry. Ages of young-of-the-year fry have been assessed based on size, while ages of older fry have been assessed based on the scales. Wild-born fry and externally introduced fry have been differentiated on the basis of different cuts on the fins: the latter were given cuts on the adipose fin and/or pelvic fin based on their age when they were introduced.

When the salmon stock of the Simojoki began to recover as a result of stricter regulation of sea fishing after 1996, introductions of fish into the river were reduced, and they were stopped entirely in the early 2000s. By the turn of the millennium, fry population density levels had reached a point where they have largely remained since. Though there have been large year-to-year variations, the trend has remained at largely the same level for both young-of-the-year and older fry. Despite the variation, a slight increase in population density levels can be discerned, and these levels have been particularly high in the past few years, the current record year being 2017 (Figure 1). This is largely due to increased numbers of fish swimming upriver to spawn, which, in turn, results from further tightening of restrictions on sea fishing. Increased fry population density is reflected in the smolt numbers, with a delay of a year or two, even though these numbers do not directly track fry population levels. It has been assumed that wintertime conditions have limited the success of fry, and that this is why smolt production has not rebounded in the same proportion as the fry population.

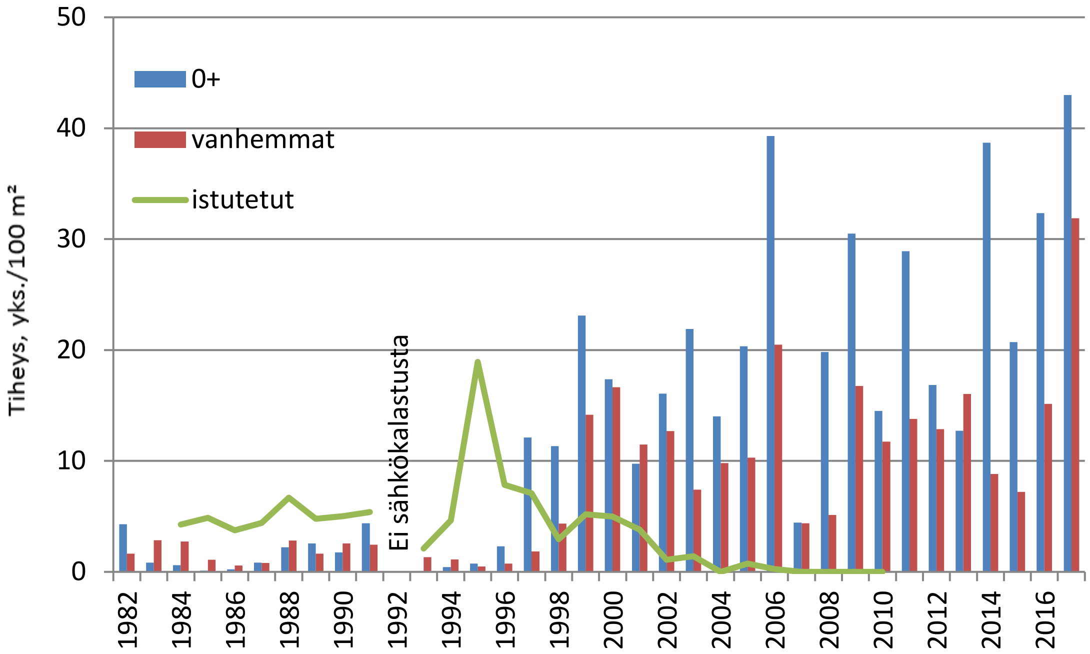


Figure 1. Average salmon fry population density (number of individuals per 100 sq. m.) in the rapids of the Simojoki, 1983-2017.

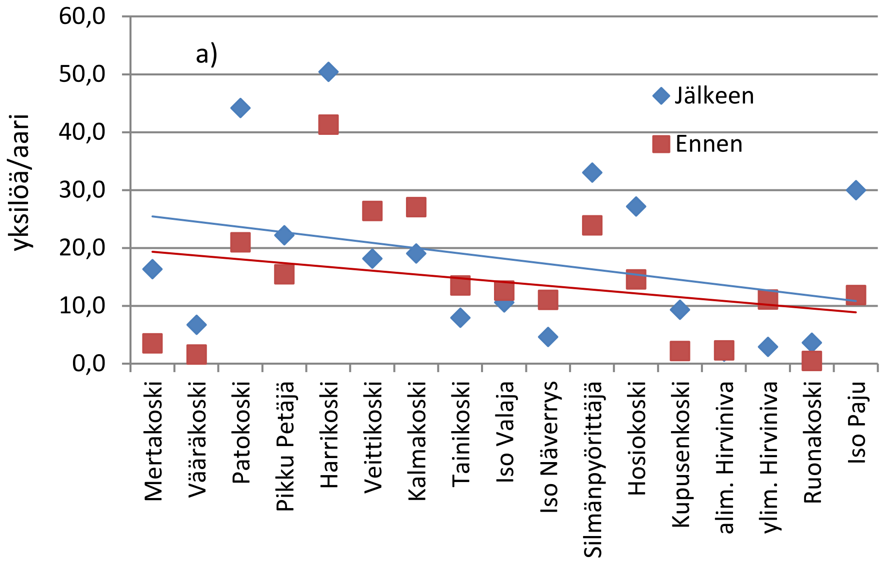
Fishery restoration and salmon fry population density in the Simojoki River

Although the Simojoki is a free-flowing river, human activity has had a significant effect on its properties, as well as its salmon stock. The actions that caused the greatest change in the river's natural state was the dredging of the river in the 1950s for the purpose of log driving. The upper part of the river was dredged mainly by hand, so the changes in that section were not so significant. By contrast, the lower 50 km of the river were dredged by machine, quickly turning the stony rapids that had been hospitable to salmon into fast-flowing riverbeds, largely lacking any concentrations of spawn or fry (Jutila 1990). A further problem was that wide areas of rapids were left dry when the water flowed down the dredged central riverbed. Toivonen (1966) estimated that 1/5 of the rapids areas were lost due to the dredging, leading to the loss of 7,500-9,000 smolts. Populations of fry also decreased in connection with the dredging. According to Toivonen and Jutila (1982), the salmon fry population density in the dredged rapids averaged 2.2 fry per 100 square metres between 1972-1976, in contrast to 7.7 in rapids that remained in their natural state. Jutila (1987) estimated that there had been annual losses of 45,000 smolts due to the dredging.

Log driving on the Simojoki ended in the 1960s, and the first restorations of rapids were done in 1976-1977. These efforts were extended in the 1980s, and in the early 2000s immediately after the turn of the millennium. The impact of the restoration was researched on the basis of the results from 1972-1980 (Toivonen & Jutila 1982), and later on the basis of the 1982-1985 results (Jutila 1987). In these assessments, it was observed that fry population density had increased from 2.2 fry / 100 sq. m. in the newly-dredged rapids to 5.5 fry / 100 sq. m. in the restored rapids. Increased levels of sea fishing at the time reduced the numbers of fish swimming up the river to spawn, and thus reduced the amount of spawn itself. Even so, it is estimated that the restoration efforts increased smolt numbers by 22,500 annually. A third wave of restoration occurred in 2002-2006 with the Simojoki LIFE project. The purpose of this ecological restoration venture was to ensure good levels of conservation on the Simojoki, which is a river included in the Natura 2000 network (Nenonen 2007). During the Simojoki Life project, 17 rapids were restored, and their net yield was estimated at 5,000-7,000 smolts per year (Hiltunen 2007).

If one looks at the population density levels of restored rapids before and after restoration, over a nearly 20-year period from the end of the 1990s to 2015, one sees that there was a slight increase in the average density of young-of-the-year fry after the restorations, but no change appears to have occurred in the case of older fry (Figure 2). Restorations of the monitored set of rapids were done during the period of 2003-2006. For each of the rapids involved in this comparison, the average densities were calculated as an average of at least 5 years before the restorations, and an average of about 10 years afterwards. This examination yields a very rough picture of the effects of restoration, as not all test areas were in the restored chain of rapids (the restoration did not necessarily affect the entirety of a given rapids). However, it can be assumed that the positive affects of restoration would manifest themselves in the probability of spawn appearing. Given the dispersal tendencies of river fry, increased numbers of fry would probably appear throughout the area of a given rapids (Jokikokko 1999, for example).

In the 2017 round of electrical fishing carried out in the standard test zones, the observed density of young-of-the-year fry at the Saukkokoski rapids (64.2 individuals per 100 sq. m.) was average, and the density of older fry (37.9) had nearly doubled (cf. Table 1). At the standard test zone located at the upstream start of the lowest section of the Mötyskoski rapids, the density of both young-of-the-year fry and older fry had tripled to 87.4 and 52.4 fry per 100 sq. m. Even though this is only one year's worth of results, and the fry population density was exceptionally good that year throughout the length of the river, it seems that the restorations carried out in summer 2016 in the lowest section of the Mötyskoski rapids were very successful.



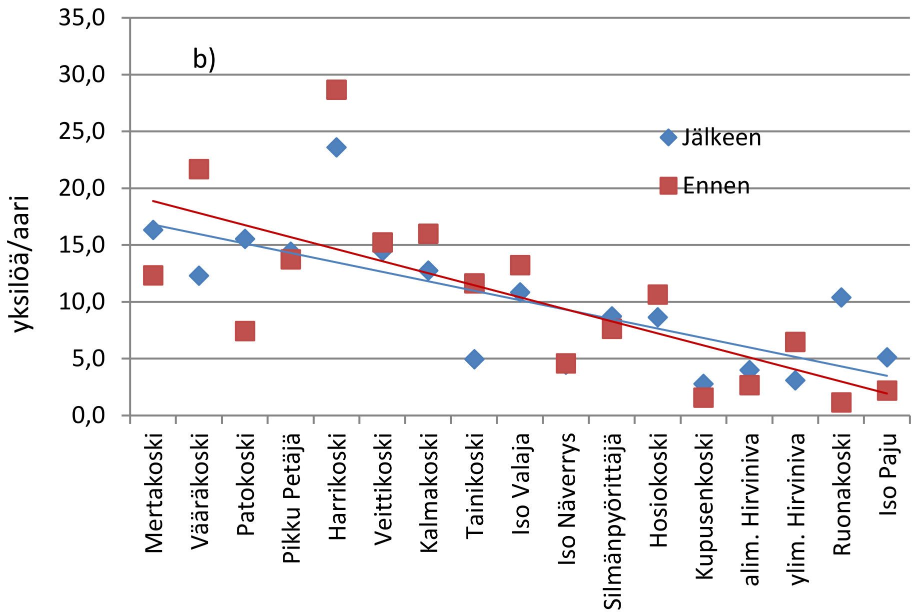


Figure 2. Average density of young-of-the-year (a) and older (b) salmon fry before and after the restorations. The test fishing sites are ordered in an upstream direction from the river mouth, with the uppermost rapids being approx. 80 km from the river mouth.

Modelling of habitats at the Simojoki rapids sites

Evaluation of the restorations along the Simojoki have previously been based on salmon fry densities estimated through electrical test fishing and the changes observed in these tests. Changes brought about by the restorations in the structure and properties of rapids have been evaluated by eye-test, relative to the habitat requirements of salmon fry -- i.e., in relation to a general conception of what rapids with good fry production look like (e.g. Hiltunen 2007). After comparing the area of the rapids habitat as measured before and after restoration, it was determined how much the fry production area has expanded, and accordingly, estimates were made of the changes in the potential for smolt production. Precise measurements of the properties of the rapids (the quality of the bottom of the riverbed, the depth of the water, the speed of the current, and how these features vary locally depending on discharge rate) have not been made.

The habitat modelling process involved an integration of data on the riverbed structure and the environmental needs of the fish (Bovee 1982, Scruton et al. 1998, Gard 2009, Boavida et al. 2012). On top of a relief map of the riverbed, consisting of topographical measurements and measurements of the quality of the river bottom in the area of focus, a refined water flow model is built whereby properties of the water depth, current speed, and river bottom quality can be studied under different discharge conditions. The status of a particular species of fish with respect to the properties of the focus area can be obtained by modifying the local values for depth, current speed and quality of the river bottom with the preferences of a given species in regards to these factors. The final result of the modelling are habitat maps of the focus area, indicating the most favourable areas of habitation for a given fish species' stages of life, and the number of such areas under different flow conditions (Figure 3).

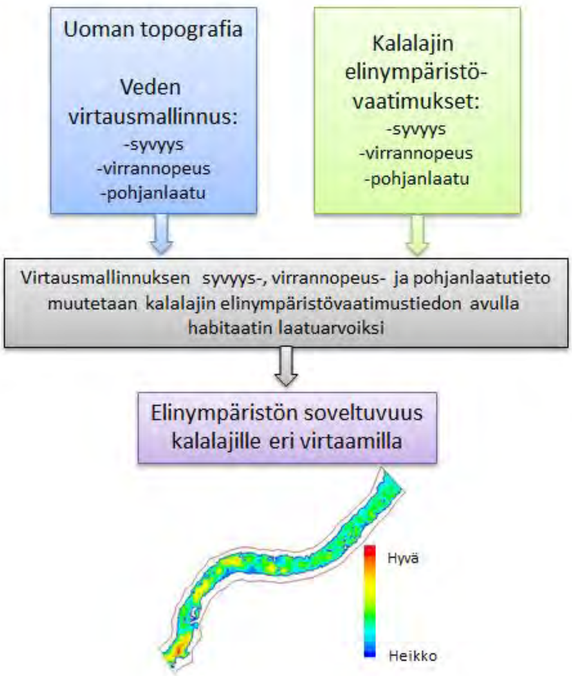


Figure 3. Principle of habitat modelling.

In this project, two rapids sites on the Simojoki River were selected for habitat modelling. One of them (Saukkokoski) is a good site for salmon fry, and the other (Mötyskoski) is poorer but was selected for restoration. Both rapids sites were measured and modelled; for the latter site, this was done both before and after restoration. The post-restoration modelling of the restored site indicates what changes the restoration procedures were able to bring about in the rapids' properties. By comparing the restoration results to the properties of the good salmon fry site, the basis for evaluating restoration results can be expanded (Figure 4). Information obtained in the project regarding the suitability and productivity of this habitat modelling in evaluation of the restorations can be utilised in the future, in the planning and implementation of other river-/rapids restorations.

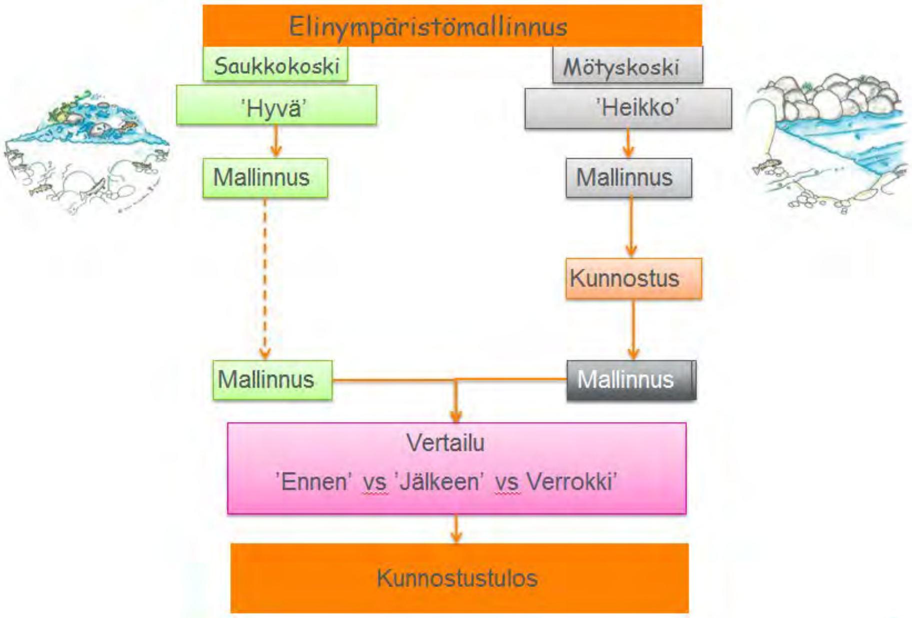


Figure 4. Evaluation process for Simojoki restoration site.

Sites and methods

Sites

Saukkokoski and Mötyskoski

The Saukkokoski rapids are one of the best rapids in the Simojoki River for salmon roe production: based on the tracking data of Natural Resources Institute Finland (LUKE), the fry population density in these rapids has been on the order of 65 young-of-the-year fry per 100 sq. m. in recent decades (Table 1). The Saukkokoski rapids are located about 20 km upstream from the mouth of the river, by the village of Mikkolanmäki. The continuous rapids area of Saukkokoski is about 1 km long, and its total area is about 7 hectares when the river is at its average discharge rate. An approximately 400 m stretch of the lower section of the rapids, the average width of which is 65 m, was chosen as the modelling area (Figure 5). There is a zone in this area where LUKE carries out fishing for the purposes of monitoring salmon fry population densities.

The Mötyskoski rapids are located about 50 km upstream from the mouth of the river, by the village of Saarikoski. The rapids area is composed of three stretches of rapids, of which the uppermost stretch is about 50 m long, the middle stretch about 350 m, and the lowest stretch about 200 m. The aggregate length of these chains of rapids is thus about 600 m, and the aggregate area about 3 hectares. There is a roughly 300 m stretch of still water between the uppermost and middle chain, and a roughly 100 m river section between the middle and lowest chain that, in places, has features of a small set of rapids. Therefore, the total length of the fluvial areas of the Mötyskoski rapids is about 1,000 m, and the surface area is about 6.8 hectares. The lowest section of the Mötyskoski rapids contains LUKE's tracking area for salmon fry population density, where fry population density during the past decade has been on the order of 30 young-of-the-year fry per 100 sq. m. -- i.e., an average of half the density levels found at the Saukkokoski rapids (Table 1).

The middle rapids section of Mötyskoski, the average width of which is 40 m in the upper section of the rapids and nearly 100m in the lower section, was selected as the modelling area for Mötyskoski. The lower section contains a cove of the river that widens the surface area of the water (Figure 5).

Table 1. Population densities of young-of-the-year salmon fry (0+) and older fry in the Saukkokoski and Mötyskoski rapids, 2002-2016. The area of the Mötyskoski rapids was not fished in 2004 or 2016. The standard test fishing zone in the Mötyskoski rapids is not situated in the habitat modelling area.

Vuosi	Saukkokoski		Mötyskoski	
	0+	Vanhemmat	0+	Vanhemmat
2002	53,3	22,3	42	29,9
2003	65,9	17,3	48,4	8,1
2004	64,7	20,8		
2005	36,2	28,2	35	22
2006	125,9	27,2	65,8	30,3
2007	13	14,7	0	8,1
2008	59,9	13,6	58,3	4,5
2009	70,1	19,2	13,4	6
2010	45,6	20,3	23,1	17,7
2011	89,1	18,9	24	20
2012	49,1	12,2	10,7	15,1
2013	42,3	34,8	12	9,9
2014	147,9	28,7	51	3,7
2015	79,8	8,3	13,6	2,5
2016	43,3	13,2		
Keskiarvo	65,7	20	30,6	13

Figure 5. Habitat-modelled rapids of the Simojoki River.

Implementation of the restoration of Mötyskoski

Restorations of the Mötyskoski rapids were carried out in 2016-2017. In summer 2016, restorations were hampered by the heavy flow of the river. The rapid current and great depth of the water made it difficult for machinery to move on the riverbed, and some of the summer 2016 restorations were left incomplete as a result. Additional restoration was done in summer 2017, when conditions were more favourable for river restoration work. Restorations of the Mötyskoski rapids took place mainly in the middle and lowest sections of the rapids. 690 tonnes of sifted spawning gravel (grain size of Ø 20–100 mm), 370 tonnes of stones for fry (grain size Ø 100- 200 mm) and 200 tonnes of bed stones intended for the river bottom in the fry area (grain size Ø 200- 500 mm) were brought to the aforementioned restoration sites. Of these amounts, about 300 tonnes of spawning gravel and 150 tonnes of fry stones were placed in the area of the rapids' middle section.

In the middle section of the rapids, the spawning areas were constructed near the edges of the riverbed. As an extension of the spawning areas, so-called small-fry areas, intended to be easy for salmon hatchlings to reach, were constructed. In the middle section of the Mötyskoski rapids, a total of 7 spawning areas were constructed, 4 of them located on the right edge of the riverbed (total area approx. 250 m^2) and 3 of them on the left edge (total area approx. 90 m^2), beside the thresholds constructed at the rapids. The depth of the riverbed in the spawning area varied between 40 -150 cm, and the thresholds were constructed so that water depth would increase towards the centre of the riverbed. The speed of the current in the spawning areas varied between 0.5 - 0.8 ms^{-1}.

The plan for reshaping the riverbed was made in the autumn of 2016 during a time when the flow was greater than average; this plan ended up being changed in summer 2017 so that the current and its speed in the restored areas would be as adequate as possible even during the time of the lowest discharge. A total of 5 threshold structures were either constructed or partly reinforced in the middle section of the Mötyskoski rapids. The threshold structures made for the riverbed were aimed at keeping the riverbed wet across the whole breadth thereof, and to create variation and twists in the flow of water through the riverbed. Stone material that was needed to supplement the gravel and stones brought in during summer 2016 was obtained from the small jetty that had previously been established at the right edge of the riverbed. About 250 m downstream from the start of the middle section of the rapids, the riverbed broadens to a width of nearly 100 m. At around this point, older small jetties were demolished, and fry areas with a total area of about 1,500 m² were constructed using the stone material obtained from the demolished jetties. Jetties that had trees or extensive shrub growth on them were not demolished.

Topographic measurements for habitat modelling

Topographical riverbed measurements were made by wading into the water or from a rubber boat in cases where wading was impossible due to depth and/or the speed of the current. The coordinates of each measuring point (ETRS-TM35FIN system), and the elevation of the riverbed bottom (N2000, m above sea level) was measured with GNSS equipment (Javad Triumph 2; http://www.javad.com/jgnss/products/receivers/triumph-2.html) that included RTK adjustment from Geotrim Oy's VRS service (https://www.geotrim.fi/palvelut/trimnet-vrs). With RTK adjustment, the device can achieve an accuracy of ± 2 cm.

The base set of points at the rapids sites was measured by making cross-sections (with respect to the direction of the river current) at 4-metre intervals, using rope. The points were measured at 4 m intervals from the cross-section lines. From these base points, the quality of the river bottom (stone size, and the degree of sedimentation (to the river bottom) of stones) was visually assessed using water binoculars and an effective searchlight (Ferei W163) from an area of about 1 m^2 around the measurement point. Stone size was assessed using a modified Wentworth scale (Table 2), and the degree of sedimentation of the stones was assessed with a 3-level scale (fully sedimented = index 3, partially sedimented = 2, and completely loose = 1). In cases where river bottom quality changed significantly before the next base point, an additional base point was chosen in between and data on river bottom quality was gathered on it.

Table 2. Rating used in assessments of the stone size of the riverbed bottom.

Koodi	Raekoko (cm)
0	< 0,1
1	0,1 – 0,4
2	0,4 - 1
3	1 - 2
4	2 - 3
5	3 - 6
6	6 - 12
7	12 - 25
8	25 - 50
9	50 - 100
10	> 100

In addition to the base points, elevation points were selected in the riverbed bottom and were measured**,** without river bottom quality data, on the basis of how much variation there was in the topography of the riverbed. In flat areas, no additional points were measured, but in all uneven areas (groups of stones, individual large stones, pits, etc.), points were measured at approx. half-metre intervals as needed. The total number of points measured at the Saukkokoski rapids was 2,702. At the Mötyskoski rapids, the total number of points measured prior to restoration was 4,000, and the total after restoration was 7,197. The increase in total points measured was due to the fact that numerous large stones and groups of stones were added to the riverbed in the process of restoration, and the consequently increased variation in the structure of the river bottom required a greater number of points in order to measure the prevailing conditions with sufficient accuracy. In addition to these manually measured points, the modelling process used echolocation data collected via boat in the upper and lower parts of the modelling area by the Mitta Oy company. There was no Mitta Oy data from the main modelling area. Additionally, laser measuring data from the National Land Survey of Finland was used for points along the riverbank. This was important in the modelling of discharge during flooding.

For modelling of water flow, information is needed not only on the topography of the riverbed, but also on the level of the water surface and the distribution of discharge in cross-sections of the riverbed in order to calibrate and validate the flow model. The elevation of the water surface was measured at intervals of 10-30 metres (depending on the thresholds that were in place) along the length of the modelling area of both rapids under study. Measurements were made under three different flow conditions: maximally low discharge (there were readings of 11.5 m^3/s at Mötyskoski, and of 18.5 m^3s^{-1} at Saukkokoski), moderate discharge (36.1 m^3s^{-1} at Mötyskoski, 69.1 m^3s^{-1} at Saukkokoski), and relatively high discharge (68.6 m^3s^{-1} at Mötyskoski and 101.0 m^3s^{-1} at Saukkokoski).

During the time of the lowest discharge rate, water surface measurements were made with a Javad Triumph 2 device, flow lines were established by wading in, and the speed of the current was determined with a Schiltknecht Mini Air device from three depths, at 1-2 metre point intervals, depending on how level the river bottom was. When other discharge rates obtained, Mitta Oy measured the flow with an ADCP device (Sontek M9 flow measurement device in a radio-controlled boat (Inertia compensated + DIFF GPS/RTK GPS location)), and measured the elevation of the water surface with a Stonex device (VRS RTK GPS).

Flow modelling

For both modelled sites, water discharge curve adjustments were made at the elevation of the water surface in the upper- and lower half of the modelling area, on the basis of paired measurements of water surface elevation and discharge (Figure 6). During the years when the study was taking place, discharge rates during open water season (ice-free season) on the Simojoki were relatively high, and it was only possible to make paired measurements of water surface elevation and discharge during situations of over 10 m^3s^{-1} discharge (lowest discharges: Mötyskoski 11.5 m^3s^{-1} and Saukkokoski 18.5 m^3s^{-1}). Thus, water-surface elevation values that were sufficiently accurate for flow modelling could only be obtained for discharges over 10 m^3s^{-1}. When discharge rates are lower than this, the elevation of the water surface changes considerably (Figure 6), and the use of water surface curve adjustments in the modelling without real topographic observations of the terrain could lead to

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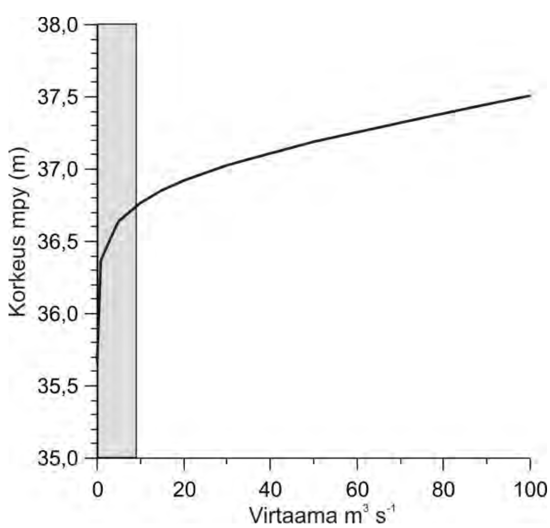
major errors in the calculations of water depths and current speeds in the modelled area. Flow modelling was thus possible to carry out in the Mötyskoski rapids area during discharge rates of 10, 15, 20, 25, 30, 43, 50, 65 and 90 m^3s^{-1}, and at the Saukkokoski rapids during discharge rates of 10, 15, 22, 30, 37, 45, 55, 70, 90 and 135 m^3s^{-1}.

The topography of the riverbed (topographical model) was interpolated on the basis of the river bottom-elevation measurement points that were established in the terrain. Flow modelling was done with a Mike3D FM (DHI) calculation model. The model was calibrated separately for each discharge rate calculated. In this calibration, surface-elevation values calculated from discharge curves, along with one riverbed roughness coefficient, were used as the surface elevation of the upper and lower waters. Calibration was carried out until the deviation at the reference point between the curve-adjustment-based surface elevation and the surface elevation produced by the model was less than 1 cm. The model used calculation zones of which the maximum length was 2 metres, and the maximum width (in the direction perpendicular to the river) was 1 metre. In practice, these values only showed up if the distribution of length was fairly equal in both the lengthwise and width-wise directions of the modelling area, and at the widest points of the riverbed. The area of the zones was generally 1-2 m^2 in the rapids area. There were 22,064 zones in the model for Mötyskoski. The water column of these elements could only be divided into two water levels due to a high degree of roughness at the riverbed bottom (the size of the stones). At the Saukkokoski rapids, there were 8,348 zones, and the water column was divided into four water levels.

At the moment, no flow model is available that is suitable for habitat modelling and is able to simulate the freezing of the river and river ice conditions (Heggenes et al. 2018). The frazil ice and anchor ice that forms in the autumn during the river freezing stage can significantly alter the prevailing flow conditions. The duration of the freezing stage depends on late fall/early winter weather conditions. Once a durable ice cover has formed, the flow conditions of the water stabilise. The ice cover causes friction with the water current, so the speed of the water current below the ice cover is immediately lower than the surface water currents that occur in ice-free conditions.



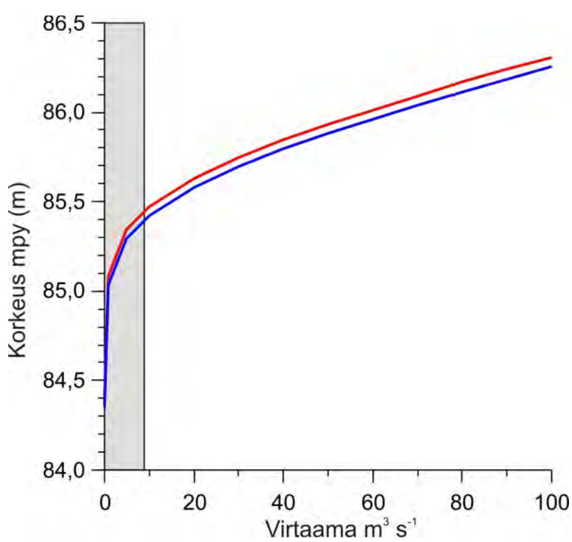


Figure 6. On the left is the water discharge curve (the elevation of the water surface in the upper section of the area) relative to discharge rates for the Saukkokoski rapids, and on the right is the corresponding curve for the Mötyskoski rapids. The red curve pertains to the time before restoration, and the blue curve pertains to the time after. No topographic measurements were available for discharges below 10 m^3s^{-1} (grey zone), so for this range of discharges, the curve is based on a curve-fit equation. The threshold elevation when there is a zero discharge rate is 84.41 m above sea level at Mötyskoski, and 34.82 m above sea level at Saukkokoski.

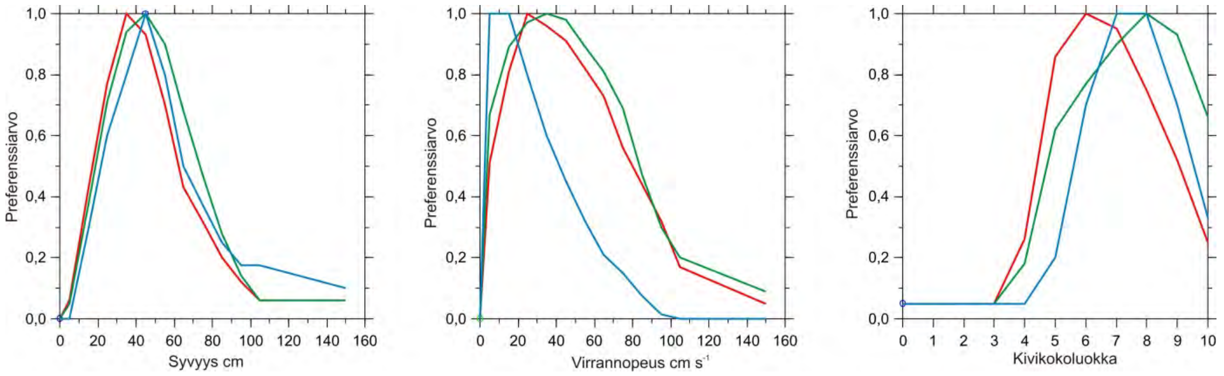
Habitat preferences

In the modelling process, preference curves of differently-aged salmon fry (young-of-the-year and older fry) relative to depth, speed of current, river bottom quality (stone size), and degree of sedimentation were applied (Figure 7). These curves were produced by Natural Resources Institute Finland (Mäki-Petäys et al. 2002). Summer- and winter conditions were restricted using a temperature of 6 °C as the threshold value (Huusko et al. 2007, Huusko et al. 2010, Heggenes et al. 2018). In regards to salmon spawning area preferences, data based on Louhe et al.’s (2008) broad survey of the literature were applied (Figure 7).

Habitat modelling

Using preference information from the different salmon life stages, local hydraulic habitat variable values (depth, speed of current, and river bottom quality of the flow modelling zones) were transformed into suitability values for these different life stages, indicating how suitable the local habitats inside the rapids were for the salmon (preference value 0 = completely unsuitable habitat; preference value 1 = excellent habitat).

In the basic modelling process, the depth and average current speed in the water column (at the level of 0.4 x [water depth]) of each modelling zone were converted to suitability values based on the preference curves, and the quality of the hydraulic habitat was calculated as the arithmetic average of these variables. Correspondingly, the quality of the river bottom habitat was assessed separately for each calculation zone, on the basis of the predominant stone sizes (most predominant stone size = D1, second-most predominant size = D2, with the most predominant size being weighted slightly more: 0.6 x D1 + 0.4 x D2) and the degree of sedimentation of the stones. The total habitat was calculated as the arithmetic average of the suitability values of the hydraulic habitat and river bottom habitat.



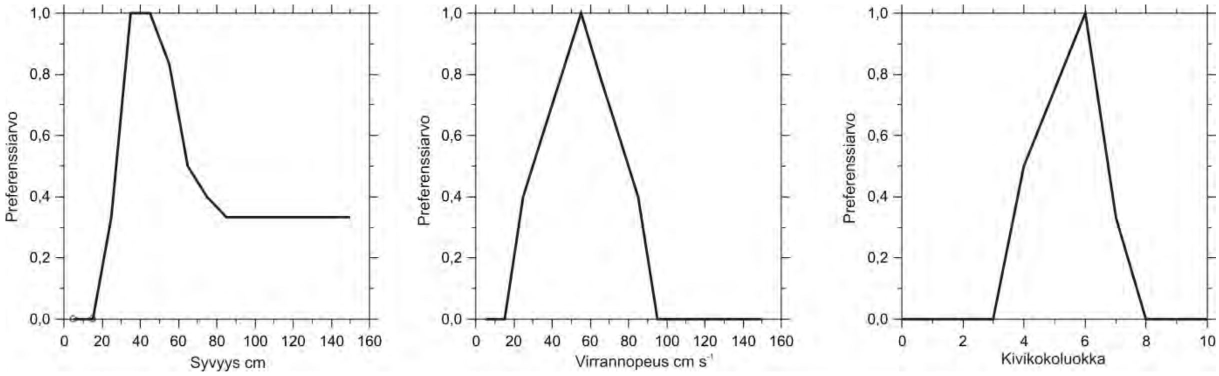


Figure 7. Above are the preference curves of the salmon fry relative to water depth, current speed and river bottom quality (red = 0+ fry, green = > 1 year-old fry, blue = winter conditions (water temperature < +6 °C). Below are preference curves representing properties of a habitat that is suitable for salmon spawn. Rating of stone size (0-10) is presented in Table 2.

On the basis of habitat modelling results, and using the statistics for the prevailing discharge rates and river water temperature between 2002-2014, the amount of suitable habitat in both rapids during the whole river stage of the salmon fry's life was calculated. Over the period of 2002-2011, calculations started at the beginning of July and ended in the third spring counting from each start year (at the end of April). After this, it was assumed that the salmon fry would develop into smolt and migrate to the sea. The period of study was divided into smaller, 10-day periods, for which the average discharge and water temperature was calculated (Figure 8). The habitat suitability value pertaining to the average discharge for each period was taken from the modelling results. A water temperature of +6 °C was used as the threshold value between summer and winter -- in other words, when water temperatures were any colder than this, a habitat quality based on the winter preference curves was applied (Figure 8).

As part of defining where the spawning areas were, zones in which the quality of the river bottom habitat received a suitability value of at least 0.6 were accepted as potential spawning areas. For these zones, the quality of the spawning area was calculated as the arithmetic average of the suitability values of the river bottom habitat and the hydraulic habitat. Finally, high-quality spawning areas were restricted to zones in which the quality of the spawning habitat exceeded a suitability value of 0.5.

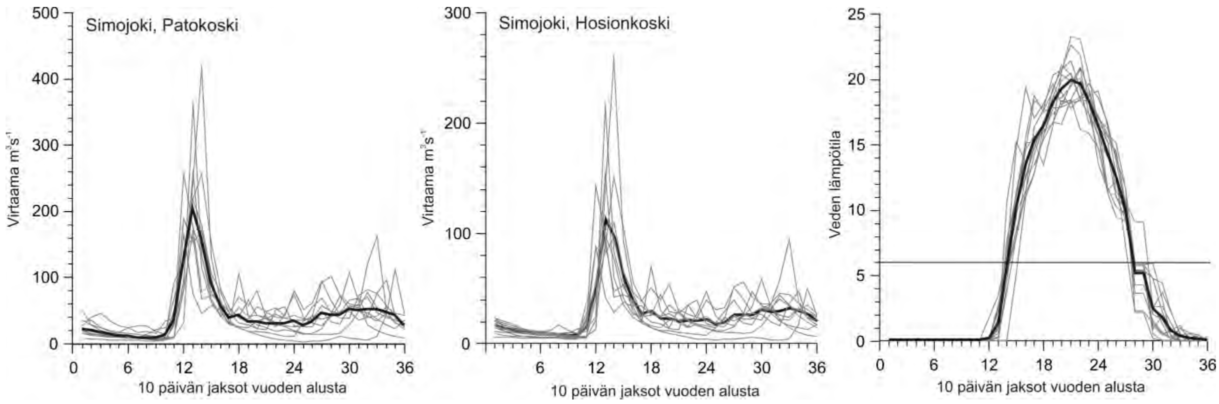


Figure 8. Discharge rate and water temperature of the Simojoki River between 2002-2014, expressed as averages of daily values from 10-day periods. The thick line represents the average of all the data, and the thin lines represent annual data. The discharge rates of the Patokoski rapids were used in the habitat modelling for the Saukkokoski rapids, and data from Hosionkoski was used in the habitat modelling for Mötyskoski. In the graph depicting temperature, the thin horizontal line represents a temperature of + 6^{o}C, which was used as a threshold value between the use of the salmon fry's summer and winter habitat preferences. Basic source material for the data on discharge rates and temperature: Finnish Environment Institute.

Electrical test fishing at the Saukkokoski rapids

Discharge rates during both years of field work remained high in the late summer, making it difficult to carry out electrical test fishing. In autumn 2016, location-detecting electrical fishing of salmon fry was carried out at Saukkokoski rapids, on 65 patches with an area of 9 sq. m each. The types of fish caught in each patch, and the number of individuals in each patch, were counted; the salmon fry were grouped into young-of-the-year and older fry. The location of each patch in the rapids was set, using a GPS device, at the same set of coordinates as those of the habitat modelling measurements.

Restoration work was carried out in the Mötyskoski modelling area during late summer 2016 and in 2017. Due to problems arising from the restoration work (periodic muddying of the water, alteration of river bottom elements), no location-detecting electric fishing was done.

Results

Properties of modelling sites

Saukkokoski

In the Saukkokoski rapids modelling area, the area covered by the water decreases somewhat linearly as one goes from high discharge rates down to a discharge rate of 10 m^3s^{-1} (Figure 9). During the years of the study, volumes below 10 m^3s^{-1} were not observed during the time period that would have allowed water surface elevation to be measured (only in winter). On the basis of discharge curve modelling of Saukkokoski, it should be assumed that the surface area covered by the water will become considerably smaller at discharge rates of less than 5 m^3s^{-1}.

The most predominant stone sizes at Saukkokoski are 10-30 cm; larger stones are sporadically found in the rapids area. A considerable portion of the riverbed bottom is very loose: i.e., stones have not become sedimented to the river bottom (Figure 10). Dense, fine soil is found in both the base riverbed and the flood zone, which is covered by vegetation.

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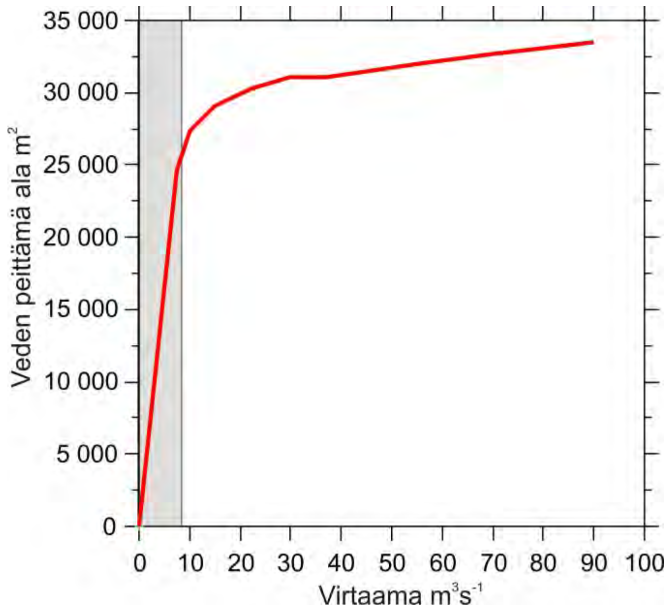

Figure 9. Area covered by water in the Saukkokoski modelling area, as affected by different discharge rates. No topographic measurements were available for discharges below 10 m^3s^{-1} (grey zone), so for this range of discharges, the curve is based on a water discharge-curve fit equation.

The water depth and speed of current in the Saukkokoski rapids remain at moderate levels until one reaches a discharge rate of 30-40 m^3s^{-1}. When the base riverbed is filled up, the speed of the current and the depth increase, and become even throughout the modelling area (Figure 11).

Mötyskoski

Before restoration at the Mötyskoski rapids, the riverbed going through the rapids can be seen to be over half a metre deeper than the areas at the edge of the rapids. In the restoration process, the turning of river bottom material into threshold structures, together with stone material brought from other locations, increased the elevation of the river bottom, particularly in the middle section of the riverbed, and a corresponding decrease in the elevation of the bottom in the areas at the edge of the riverbed (Figure 12). Large local changes of elevation, exceeding 50 cm, are due to large stones and groups of stones that were transferred to the threshold structures. Demolition of the small islands (old jetty structures) in front of the cove in the lower section of the rapids, and the dispersal of the material that was in these islands through the area, is also reflected in the elevation of the bottom.

In the Mötyskoski rapids modelling area, similarly to Saukkokoski, the area covered by the water decreases somewhat linearly as one goes from high discharge rates down to a discharge rate of 10 m^3s^{-1} (Figure 13). During the years of the study, volumes below 10 m^3s^{-1} were not observed during the time period that would have allowed water surface elevation to be measured (only in winter). On the basis of discharge curve modelling of Mötyskoski, it should be assumed that the surface area covered by the water will become considerably smaller at discharge rates of less than 5 m^3s^{-1}. As a result of restoration, the area covered by the water grew by 6-7 hundred square metres with normal summertime discharge rates (10-30 m^3s^{-1}). With large discharge rates, the water fills the whole of the base riverbed, so that the added-area advantage of the restoration carried out in the base riverbed ends up being small (Figure 13).

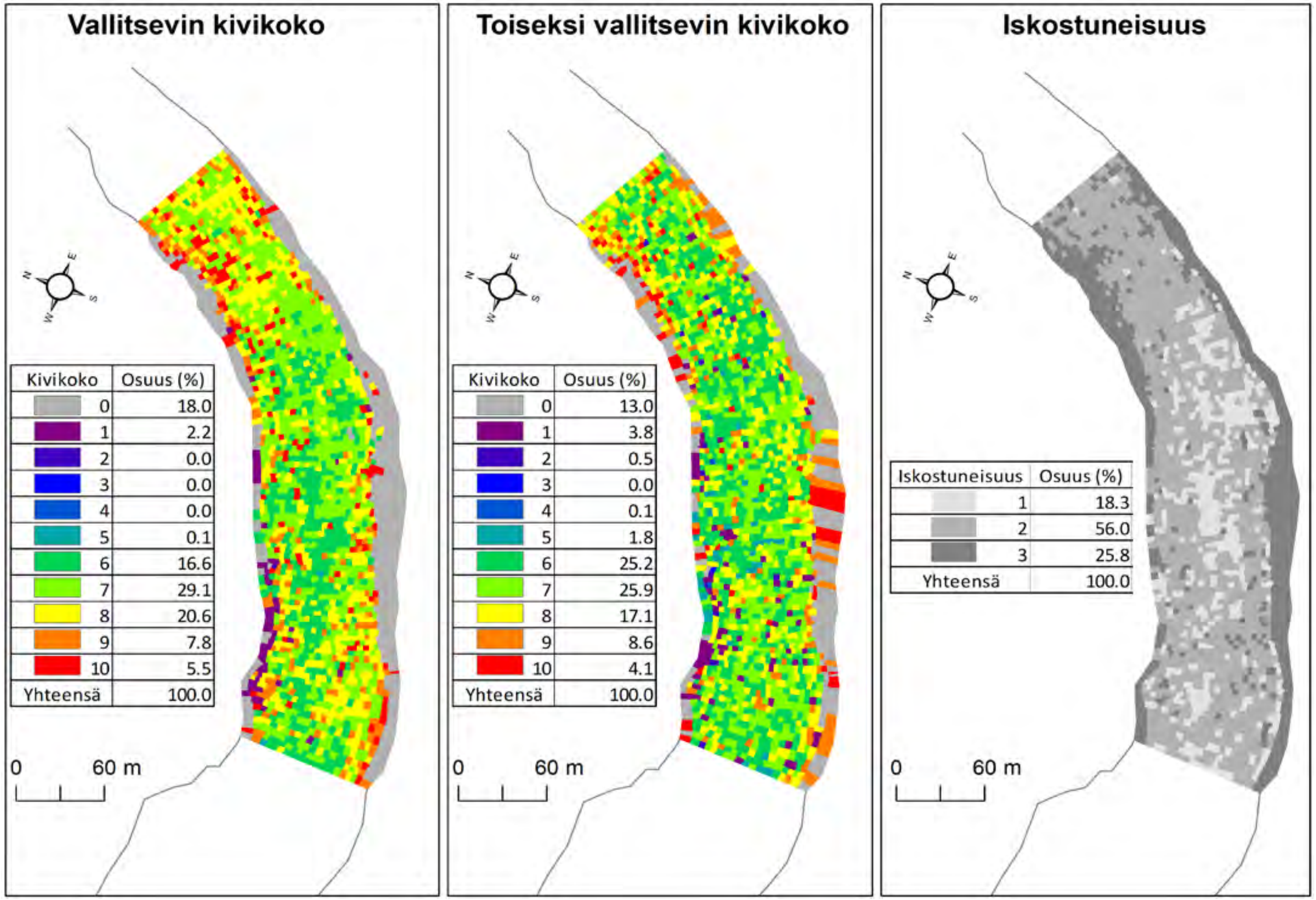

Figure 10. Map detailing the stone sizes on the riverbed bottom at Saukkokoski rapids, as well as the percentage distribution of stone sizes, with respect to the two most predominant sizes. Rating of stone size (0-10) is presented in Table 2. On the right is a ranking of the degree of sedimentation of the river bottom stones at Saukkokoski (1 = stones are loose; 3 = stones are tightly sedimented to the river bottom).

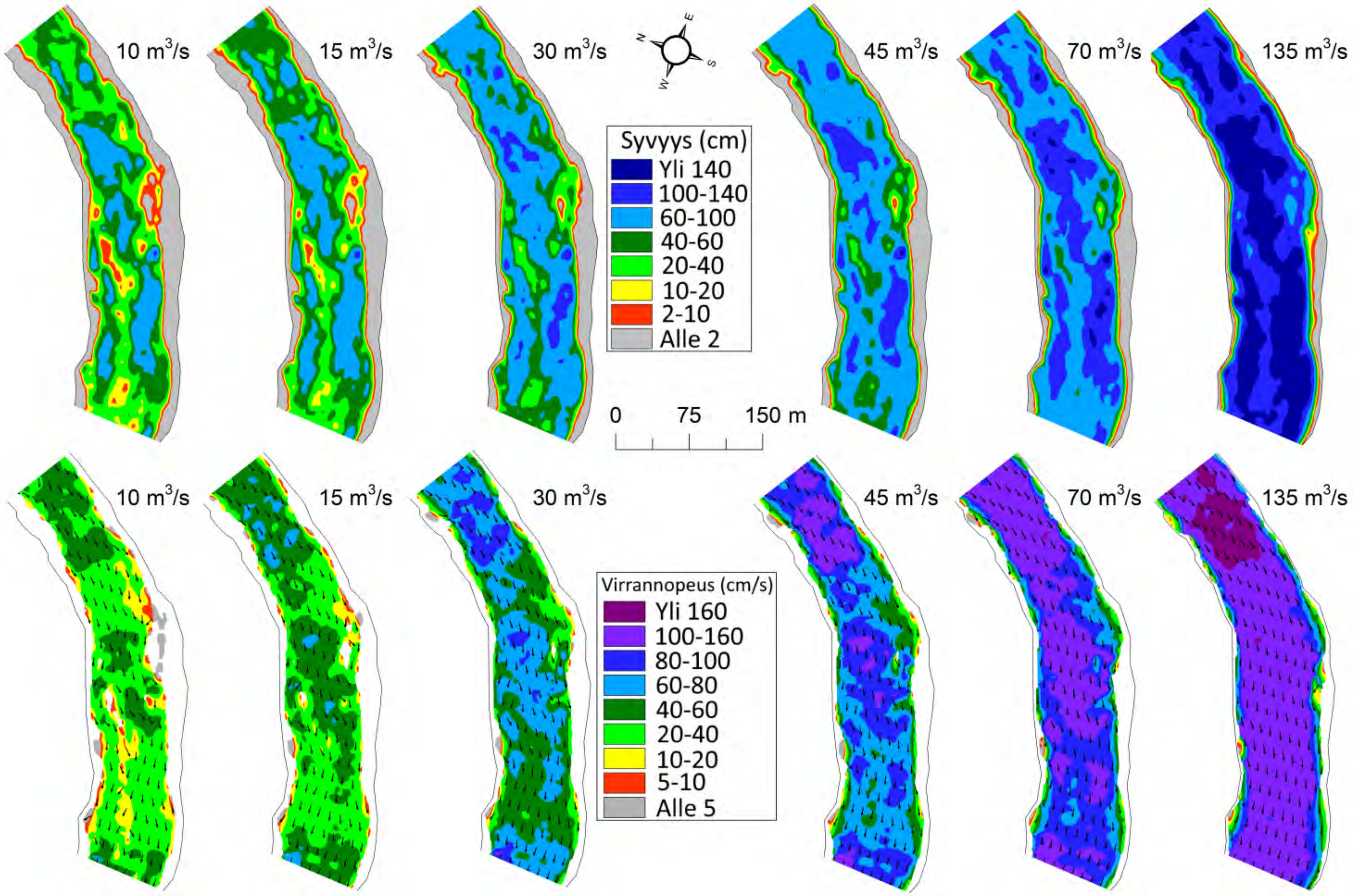

Figure 11. Water depth (above) and water current speed (below), plus the primary local direction of the current (arrows) at Saukkokoski, as affected by different discharge rates.

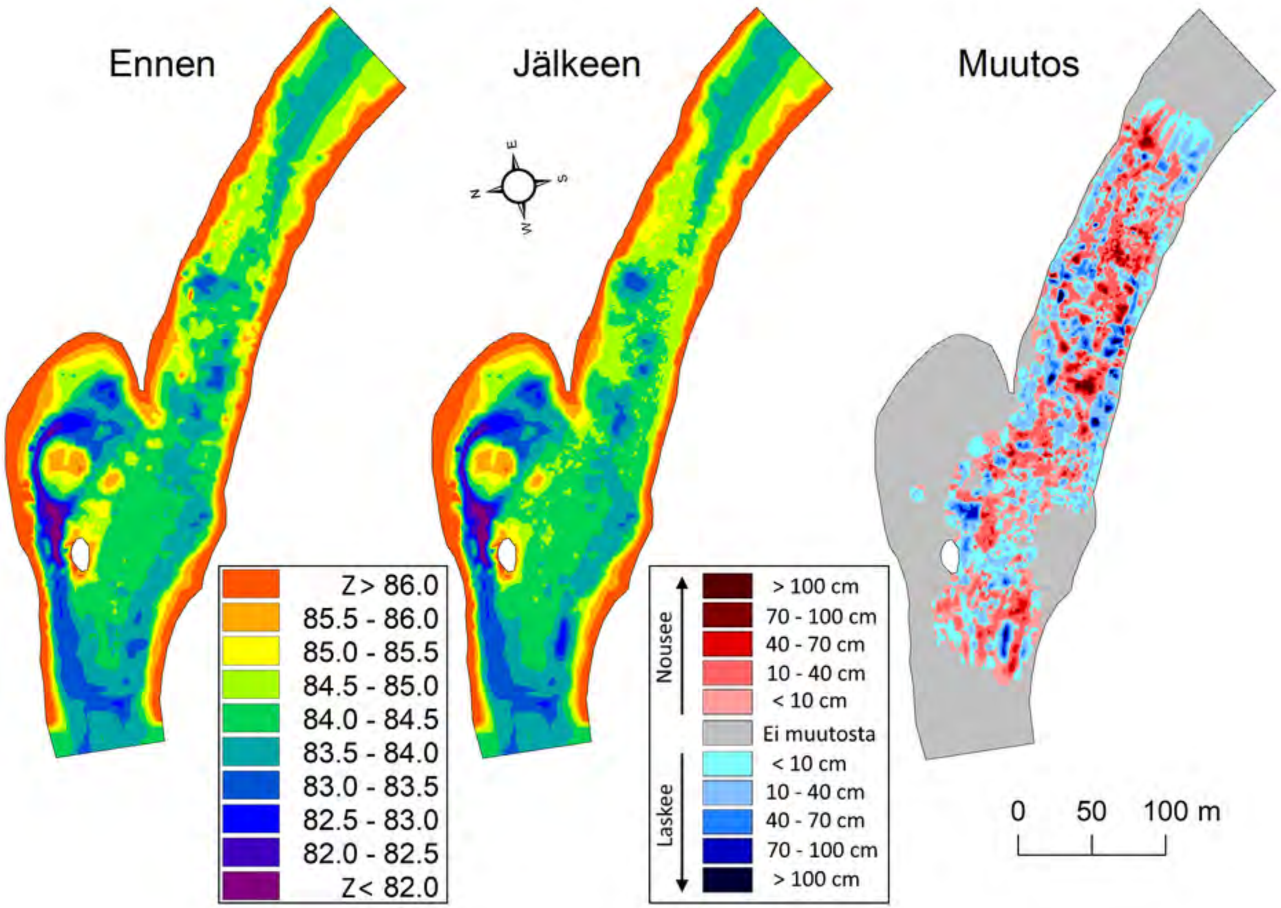

Figure 12. Topography of the riverbed of the Mötyskoski rapids (Z = elevation of the river bottom in m above sea level) before and after restoration, and local topographic changes that occurred in the restoration.

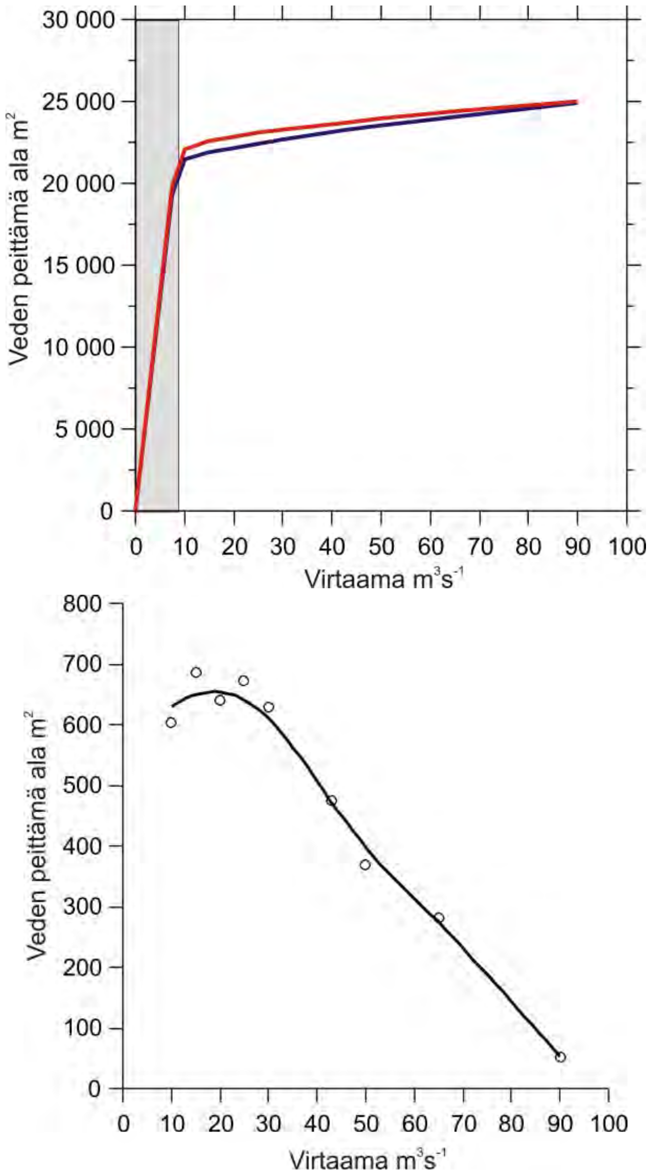

Figure 13. Above: area covered by water in the Mötyskoski modelling area before (blue) and after (red) restoration, as affected by different discharge rates. No topographic measurements were available for discharges below 10 m^3s^{-1} (grey zone), so for this range of discharges, the curve is based on a water discharge-curve fit equation. Below is the addition to the water-covered area that occurred in restoration, relative to the situation that prevailed prior to restoration.

Compared to Saukkokoski, the predominant stone size at Mötyskoski is larger in terms of grain size, both before and after restoration, but on the other hand, more fine-grained gravel and sand are also present on average, particularly in the lower section of the rapids (Figure 14). The large rocks situated in the threshold structures of the middle section of the riverbed appear to be of a larger stone size compared to the situation that prevailed before restoration. The stones have a poor deegree of sedimentation, particularly in the spawning- and small-fry areas constructed of new material brought to the site from elsewhere. The river-bottom material present in the cove in the lower section of the rapids consists of fine sand and mud. Riverbank areas outside the base riverbed are made of dense, fine material, and are covered with vegetation.

The Mötyskoski rapids are deeper in their basic structure than Saukkokoski. The main channel of the current stands out as the deeper riverbed that runs alongside the rapids. This was particularly the case in the situation that prevailed before restoration. As a consequence of restoration, the river bottom elevation at the rapids has grown, and the water depth has decreased (Figure 15). The thresholds that have been constructed serve to accelerate the water current speed, even when low discharge rates obtain (Figure 16). When the base riverbed is filled up, the speed of the current increases, and becomes evenly strong throughout the modelling area. As a result of the removal of the small islands (old jetty structures) in the lower section of Mötyskoski, the water current is no longer directed powerfully towards the cove in the lower section, even when discharge rates are at their highest. Apparently, the uppermost of the removed islands had the effect of damming the water current and directing more water in the direction of the cove under the situation that prevailed before restoration.

The modelling sites as a habitat for salmon fry

At both modelling sites, the amount of suitable habitat varies in the same way according relative to the river's discharge rate (Figure 17). The amount of suitable habitat is at its most extensive when there is a discharge rate of 10-20 m^3s^{-1}, and when the discharge rate grows to 90 m^3s^{-1}, the amount of habitat reduces by 1/3 at Mötyskoski and by about 40 % at Saukkokoski. With discharge rates of under 10 m^3s^{-1}, the amount of habitat declines steeply, but the modelling sites have some uncertainty in this respect (see the discussion of methods). It is difficult to precisely determine, on the basis of the results, the discharge rate threshold value at which (for example) the amount of suitable habitat becomes half the value seen with a 10 m^3s^{-1} discharge. It should be assumed that, with a discharge of 5-6 m^3s^{-1}, the amount of suitable habitat will be a factor limiting the success of salmon fry in both of the rapids, since, on the basis of the calculated discharge curve, the area covered by water at both rapids will halve, and at the same time, the local water depth and water current speed values will most likely become too low in the larger part of the rapids area to meet the habitat requirements of the salmon fry.

At Saukkokoski, with small discharge rates of 10-30 m^3s^{-1}, the amount of suitable habitat is about 20% greater than at the restored Mötyskoski; with a large discharge rate (90 m^3s^{-1}), it is about 10% greater (Figure 17). The prevailing conditions at Saukkokoski are nearly optimal for salmon fry, as the amount of suitable habitat available is, depending on the salmon fry age group and the season, 70-80% of the water-covered area of the rapids when the discharge rate is 10-30 m^3s^{-1}. Habitat patches of excellent quality are found throughout the area of these rapids (Figures 18-20).

The restoration of Mötyskoski increased the amount of suitable habitat during summertime by an average of 1-3%, depending on the age group of the salmon fry and the discharge rate. The greatest increase occurred in the amount of habitat present when 10-30 m^3s^{-1} discharge rates obtained (1.5% for young-of-the-year fry, and 2.8% for > 1 yr.-old fry). It is notable that there was particularly significant growth in the amount of excellent habitat patches (suitability value > 0.7) (Figure 21; depending on age group, and with normal summertime discharge rates, 5-9%). The best fry habitats are located in zones at the edge of the rapids (Figures 18-20). By contrast, the restoration generally brought about only small changes in the amount of suitable winter habitat for salmon fry under different discharge rates (Figures 17-20), even if the number of habitat patches of excellent quality decreased by about 4% in connection with the smallest modelled discharge rate (Figure 21). On the basis of the results, river bottom quality (stone size and degree of sedimentation of stones) is a limiting factor in the quality of the Mötyskoski winter habitat, more so than the hydraulic habitat (local combinations of water depth and speed of current).

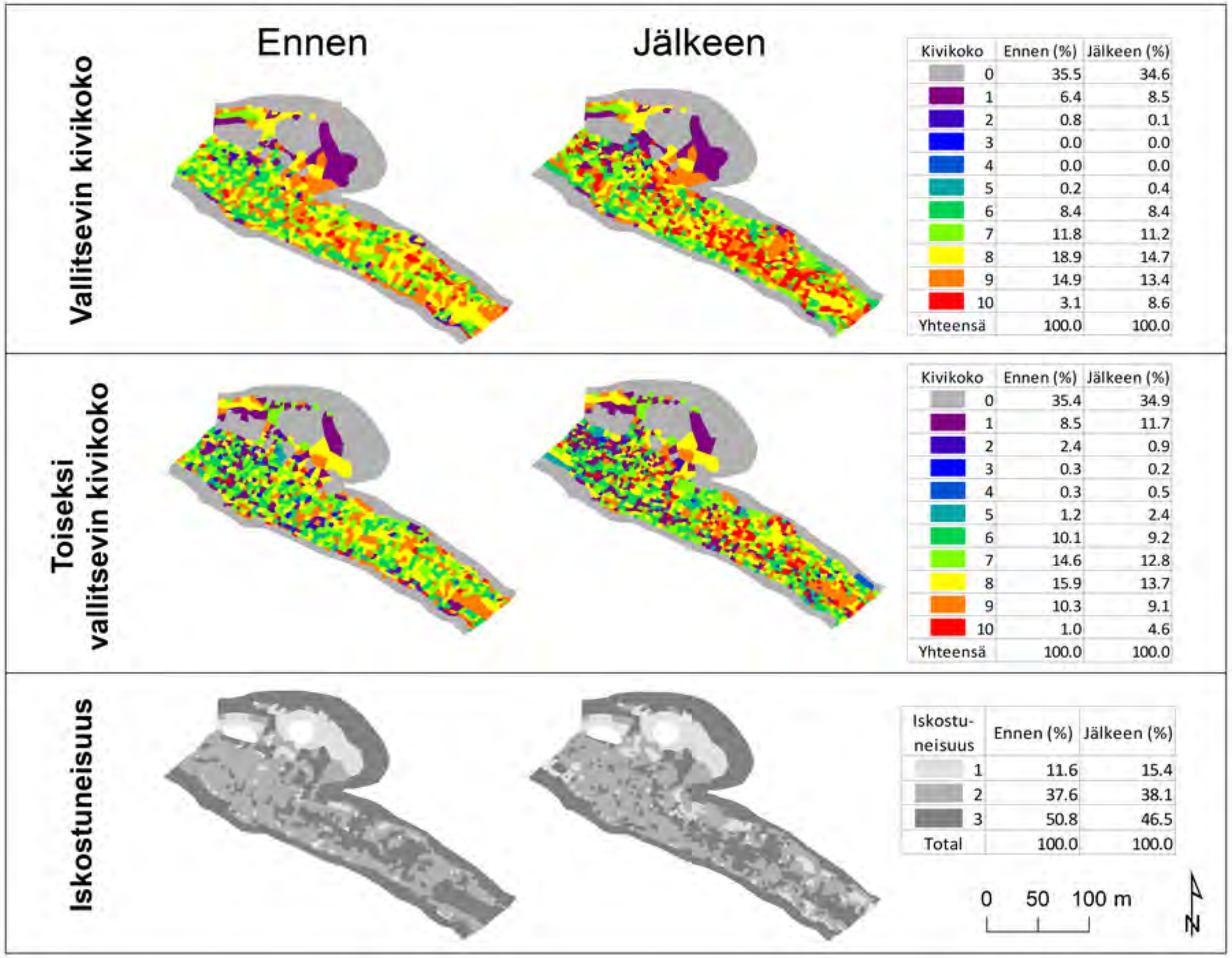

Figure 14. Map detailing the stone sizes on the riverbed bottom at Mötyskoski rapids before and after restoration, as well as the percentage distribution of stone sizes, with respect to the two most predominant sizes. Rating of stone size (0-10) is presented in Table 2. At the bottom is a ranking of the degree of sedimentation of the river bottom stones at Mötyskoski (1 = stones are loose; 3 = stones are tightly sedimented to the river bottom).

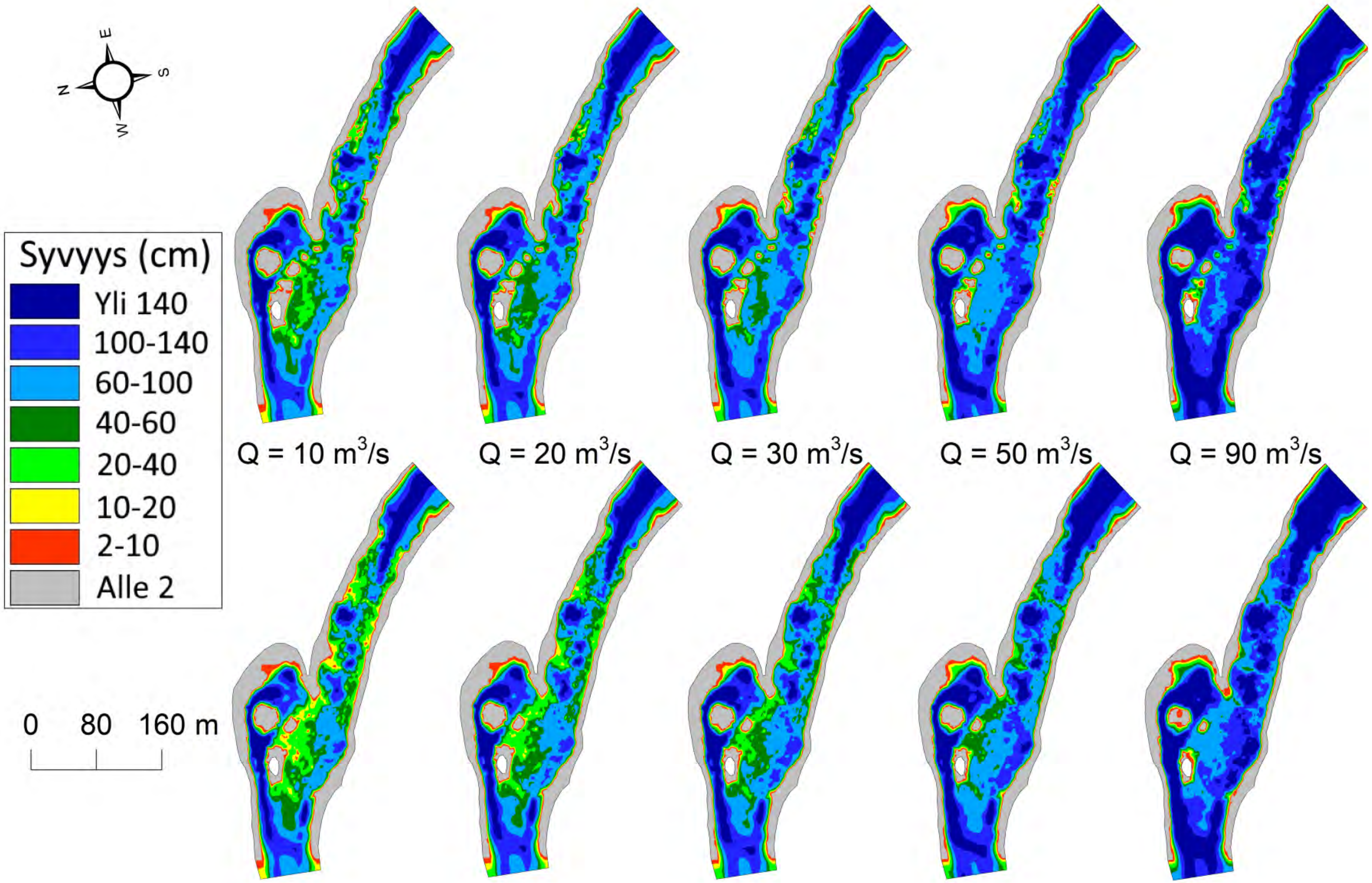

Figure 15. Depth of water at Mötyskoski before (above) and after (below) restoration, as affected by different discharge rates.

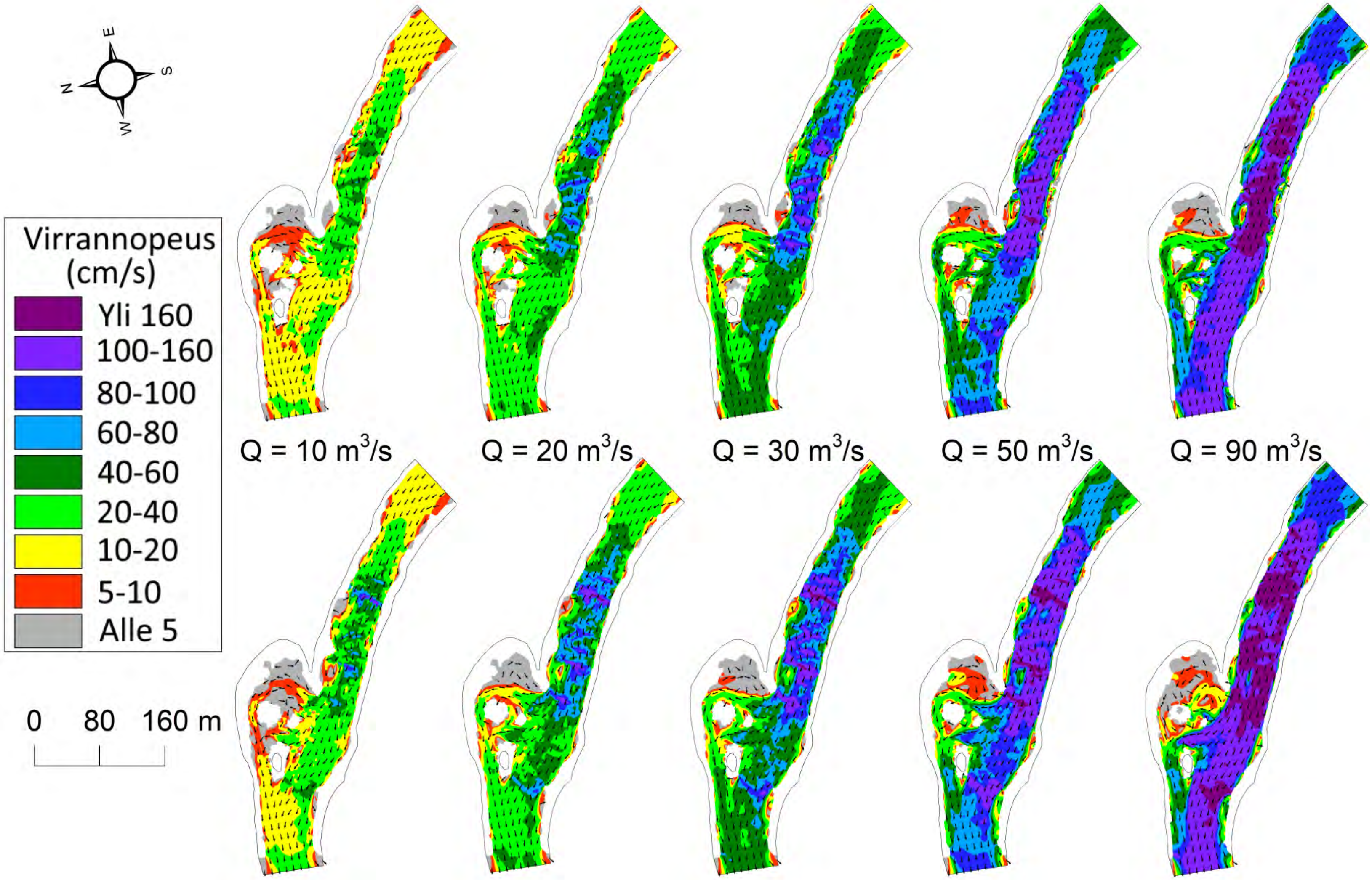

Figure 16. Speed and main local direction of the water current (arrows) at Mötyskoski before (above) and after (below) restoration, as affected by different discharge rates.

Variation in suitable habitat during the river life stage of salmon fry

Habitat modelling carried out throughout the river life stage (0-3 yrs.) of the salmon fry, modelling the habitat relative to the prevailing environmental conditions during this river stage, showed that the amount of suitable habitat is at its lowest in early winter, at both the Saukkokoski and Mötyskoski rapids (Figure 22). The high discharge rates that occur in late autumn and early winter, when the water temperature is clearly below 6 ^{o}C (Figure 8), create the least favourable (seasonally speaking) of all conditions for salmon fry that have already settled into "wintering mode". Although the calculated amount of suitable habitat during spring flooding season is smaller than the amount seen during early winter, the simulation carried out during spring flooding season in this project did not yield reliable results. Additionally, the smallest modelled discharge rate, 10 m^3s^{-1}, is larger than the low-point of the river's discharge during late winter, so the effect of low flow rates on the quality and amount of late-winter habitat could not be thoroughly analysed in this project (see the discussion of methods).

At Mötyskoski, the benefits derived from the restoration are focused on the amount of summertime habitat (Figure 23). Wintertime habitat in early winter has remained somewhat at the same level, and has even slightly decreased in late winter.

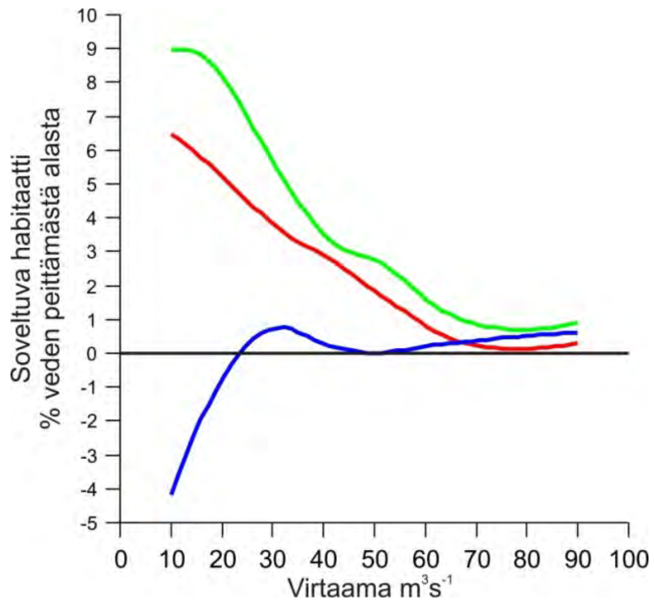

Figure 21. Percentage change in the area of excellent-quality salmon fry habitats (preference higher than 0.7) brought about by the restoration at Mötyskoski (red = habitat of the 0+ age group; blue = winter habitat; green = habitat of > 1 yr.-old fry).

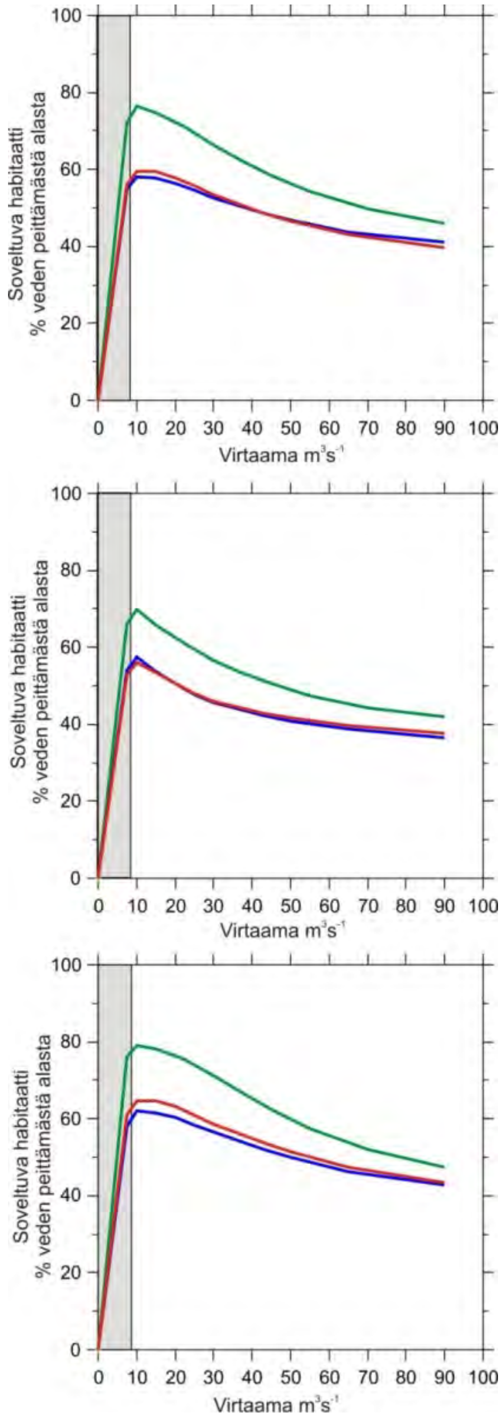

Figure 17. Percentage of the area covered by the water that is a suitable habitat for salmon fry, as affected by different discharge rates, at Saukkokoski (green), Mötyskoski before restoration (blue), and Mötyskoski after restoration (red). At the top is the amount of habitat for fry in the 0+ age group during summer; in the middle, the corresponding figure for all age groups during winter; and at the bottom, the figure for > 1 yr.-old fry during summer. It was not possible to carry out habitat modelling for discharge rates below 10 m^3s^{-1} (grey zone), so for this range of discharges, the data is based on an estimate made for each of the rapids based on the water discharge curve.

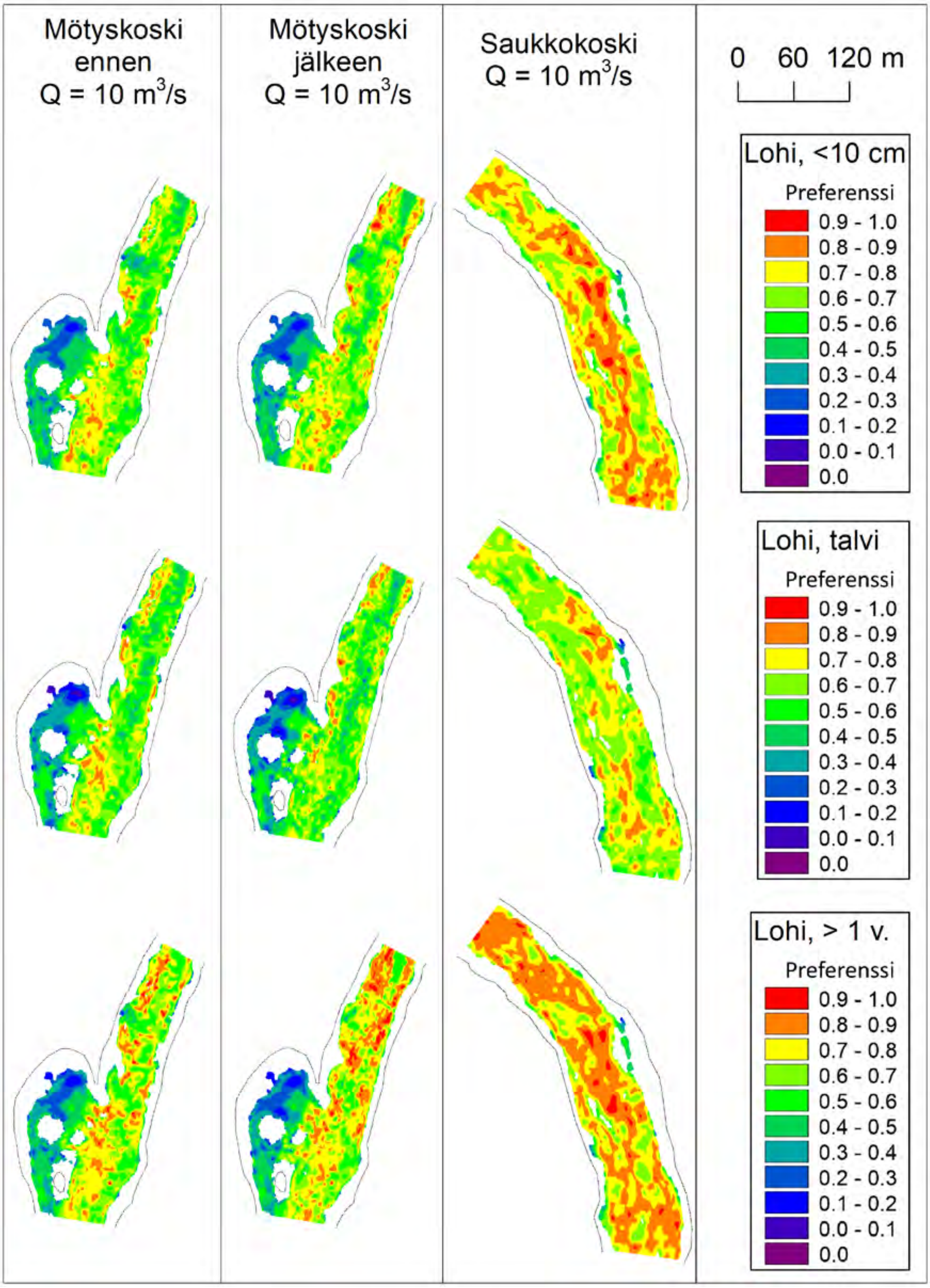

Figure 18. Maps detailing the quality of salmon-fry-suitable habitat, in a situation of 10 m^3s^{-1} discharge, at Saukkokoski (right) and Mötyskoski before (left) and after (middle) restoration. At the top is the quality of habitat for fry in the 0+ age group during summer; in the middle, the corresponding figure for all age groups during winter; and at the bottom, the figure for > 1 yr.-old fry during summer.

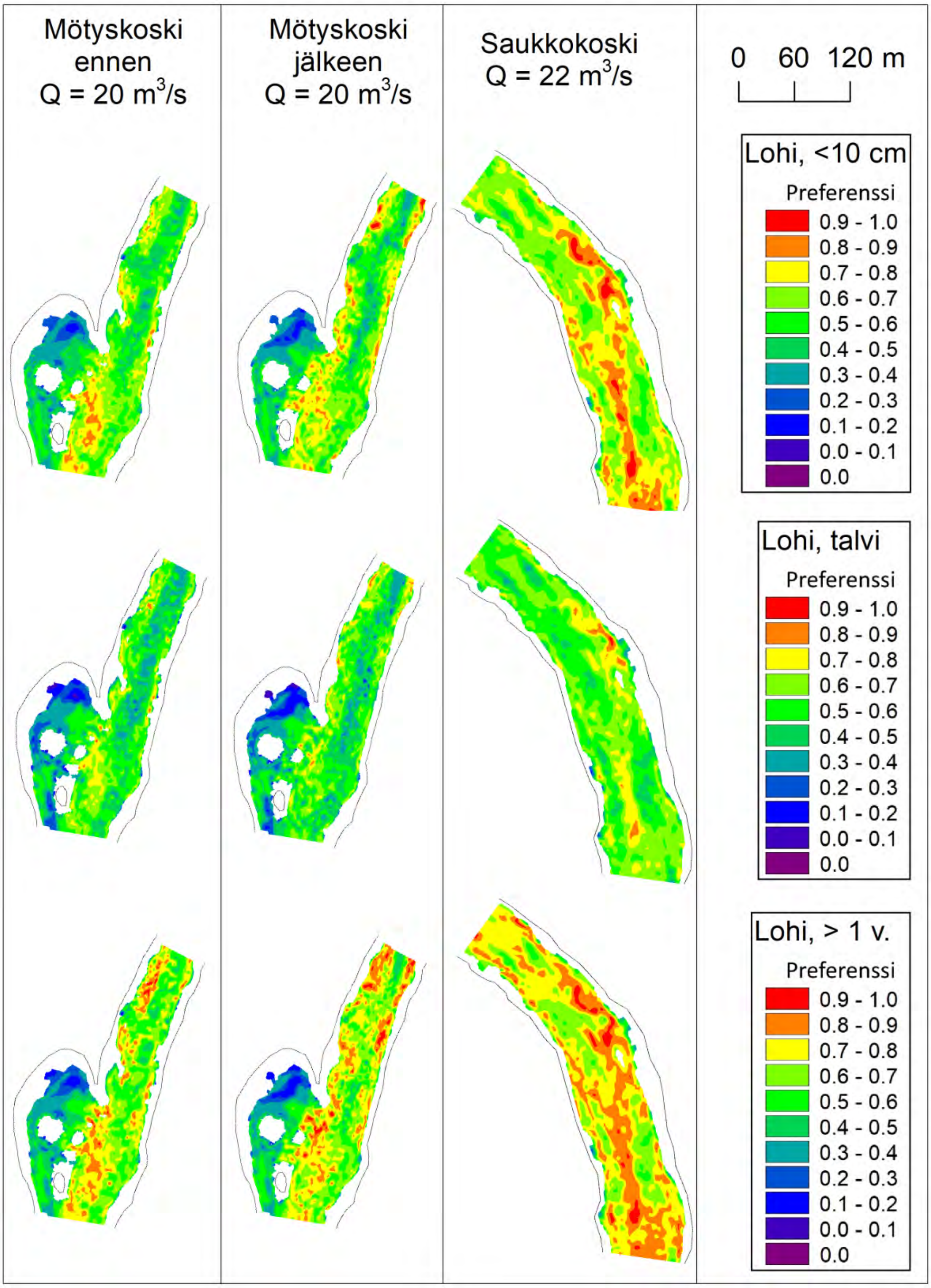

Figure 19. Maps detailing the quality of salmon-fry-suitable habitat, in a situation of approx. 20 m^3s^{-1} discharge, at Saukkokoski (right) and Mötyskoski before (left) and after (middle) restoration. At the top is the quality of habitat for fry in the 0+ age group during summer; in the middle, the corresponding figure for all age groups during winter; and at the bottom, the figure for > 1 yr.-old fry during summer.

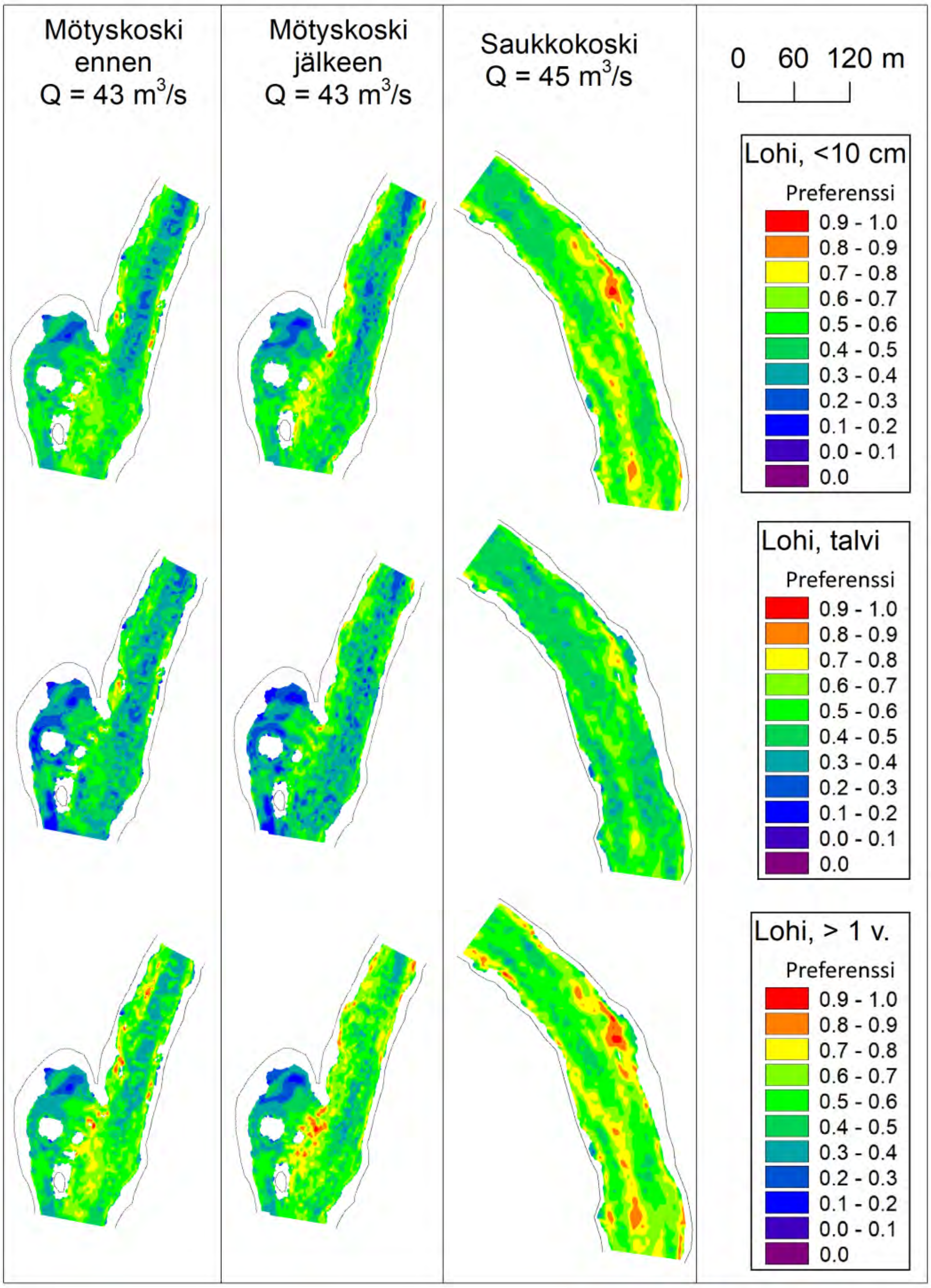

Figure 20. Maps detailing the quality of salmon-fry-suitable habitat, in a situation of approx. 40 m^3s^{-1} discharge, at Saukkokoski (right) and Mötyskoski before (left) and after (middle) restoration. At the top is the quality of habitat for fry in the 0+ age group during summer; in the middle, the corresponding figure for all age groups during winter; and at the bottom, the figure for > 1 yr.-old fry during summer.

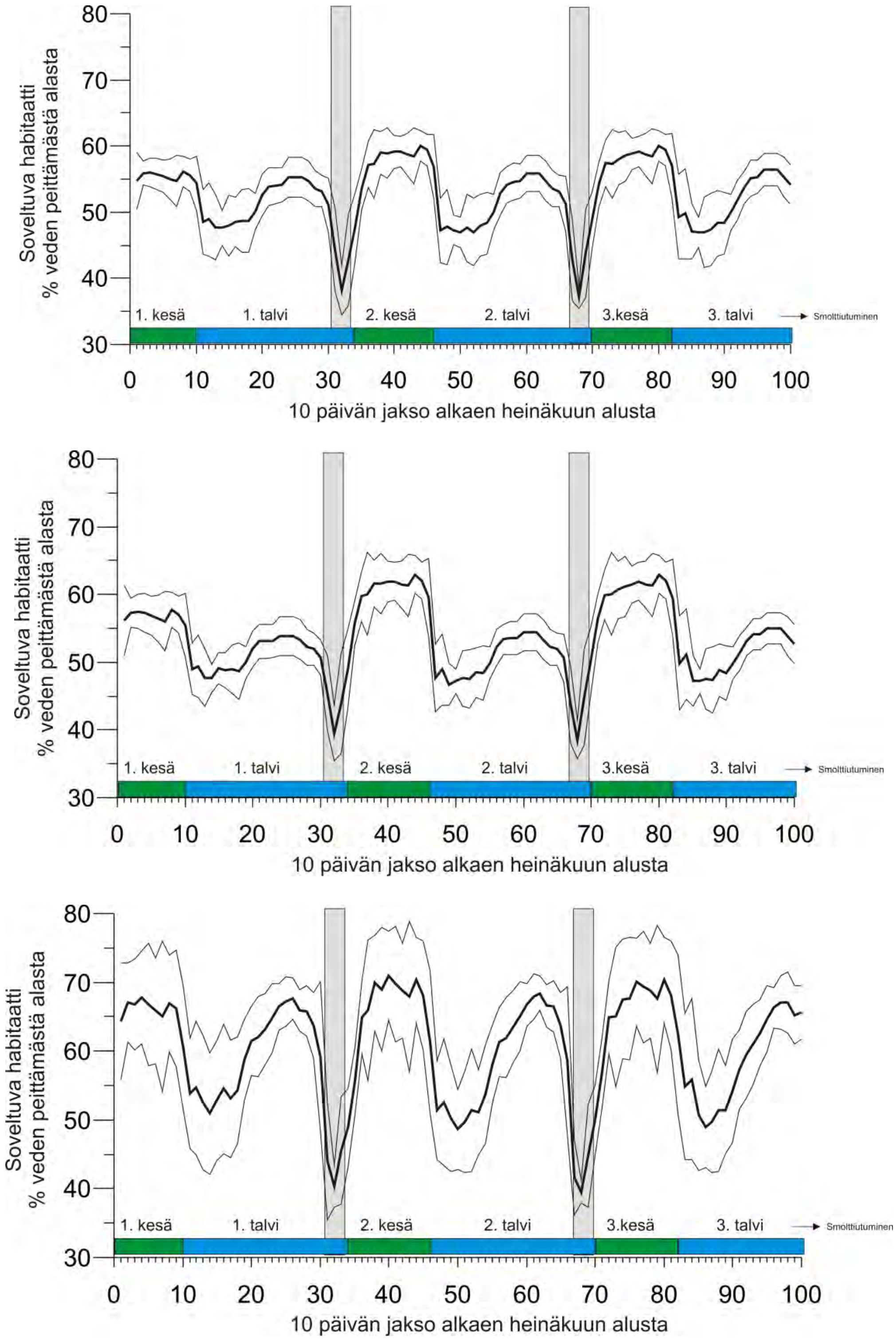

Figure 22. Percentage of the area covered by the water that constitutes suitable habitat and that was present during the river life stage of the salmon fry, as affected by different discharge rates, at Mötyskoski before restoration (top), Mötyskoski after restoration (middle), and Saukkokoski (bottom). The thick line indicates the average amount of suitable habitat, as based on the prevailing environmental conditions between 2002-2014, and the thin line indicates the 95% confidence interval of this average. The grey zones denote the spring flooding period for which habitat modelling is unreliable, because no salmon fry habitat preferences are available with respect to high discharge rates.

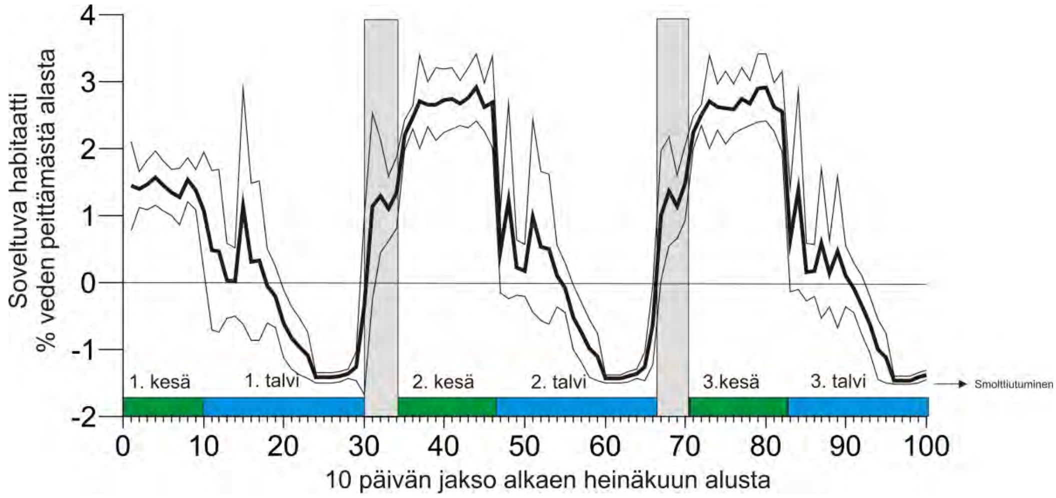

Figure 23. Change in the suitable-habitat proportion of the area covered by water at Mötyskoski that took place during the river life stage of the salmon fry as a result of restoration (%; before – after restoration). The thick line indicates the average change, as based on the prevailing environmental conditions between 2002-2014, in the amount of suitable habitat, and the thin line indicates the 95% confidence interval of this average. The grey zones denote the spring flooding period for which habitat modelling is unreliable, because no salmon fry habitat preferences are available with respect to high discharge rates.

Spawning habitats

Prior to restoration, spawning areas of excellent quality, with a suitability value exceeding 0.7, and occurring during discharge rates of 20-30 m^3s^{-1}, made up about 1.4% of the area covered by water at Mötyskoski. Following restoration, the corresponding figure was 2%. The proportional increase in area is 160 m^2. In addition to this, 8.1% of the water surface's area consisted of fairly suitable spawning areas, but the amount of such spawning areas decreased by about 1000 m^2 caused mainly by a reduction in suitable spawning areas in the lower section of the rapids, due to the fry areas constructed in this area from material from the demolition of the jetty islands. The Mötyskoski rapids area clearly has fewer excellent-quality spawning areas than that of Saukkokoski, where the quantity of such spawning areas constitutes 7% of the area covered by water. Saukkokoski and Mötyskoski both have about the same proportion (9.5%) of areas that are fairly suitable for spawning (Figure 24).

Through habitat modelling, prevailing conditions of water current speed in the spawning areas, during the season when discharge rates are at their low point, were also studied. Due to limitations of the modelling process, studies could only be done at a discharge rate of 10 m^3s^{-1} (see the discussion of methods). Prior to restoration, a notable percentage of Mötyskoski's spawning areas had a comparatively low water current speed (5-10 cm s^{-1}) close to the river bottom (10 cm above the bottom), and some of the spawning areas were nearly dry (Figure 25). Following restoration, water current speed near the river bottom remains good (10-40 cm s^{-1}) in almost all of the defined spawning areas, and current-speed conditions resemble the corresponding conditions at Saukkokoski. If the water current speed is sufficient in spawning areas, even during the season when discharge rates are at their low point, this decreases the sedimentation of spawning gravel and improves roe eggs' survival rate.

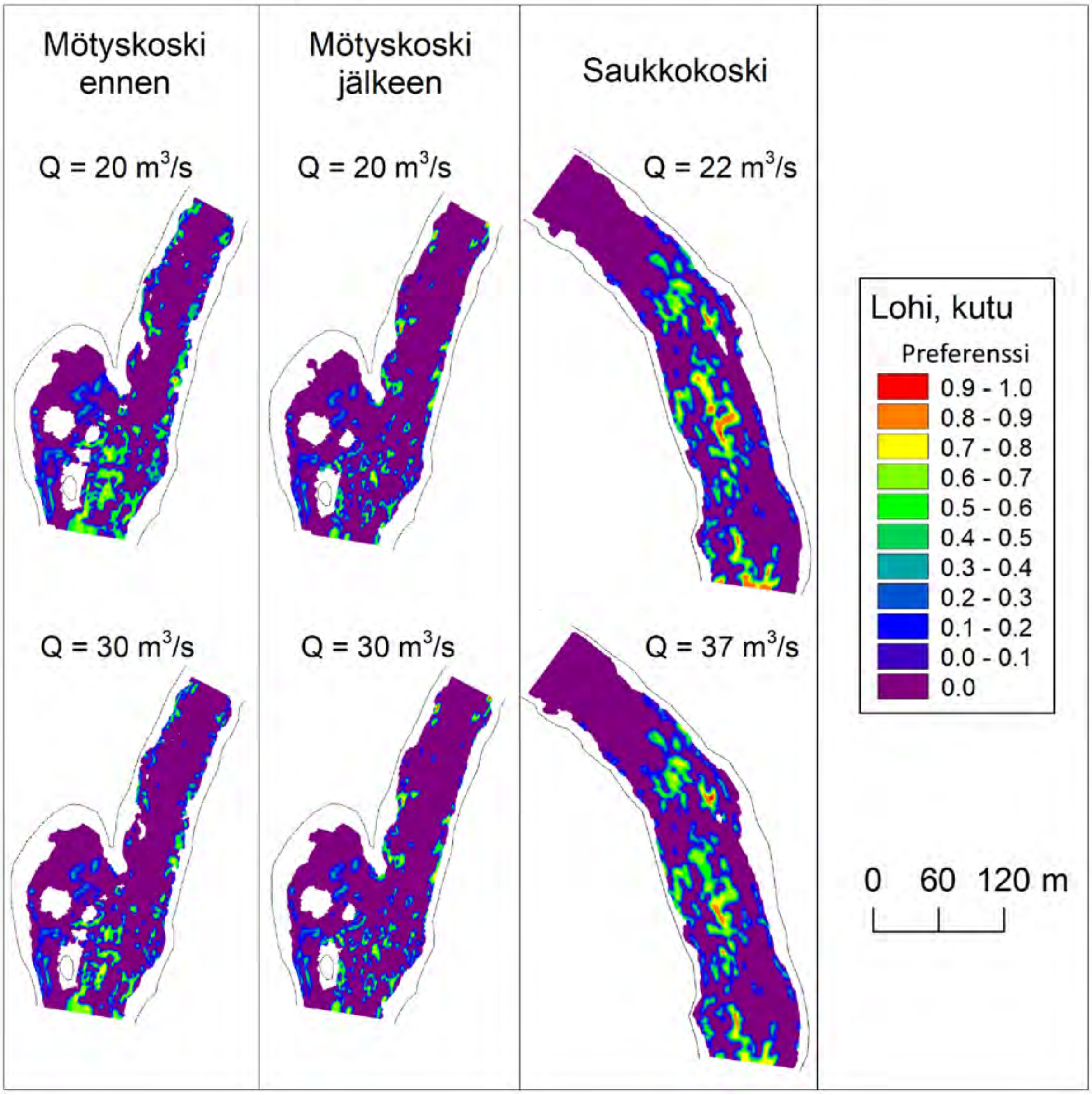

Figure 24. Suitable salmon spawning areas under conditions of typical spawning-period discharge rates (20 – 40 m^3s^{-1}), at Mötyskoski and Saukkokoski.

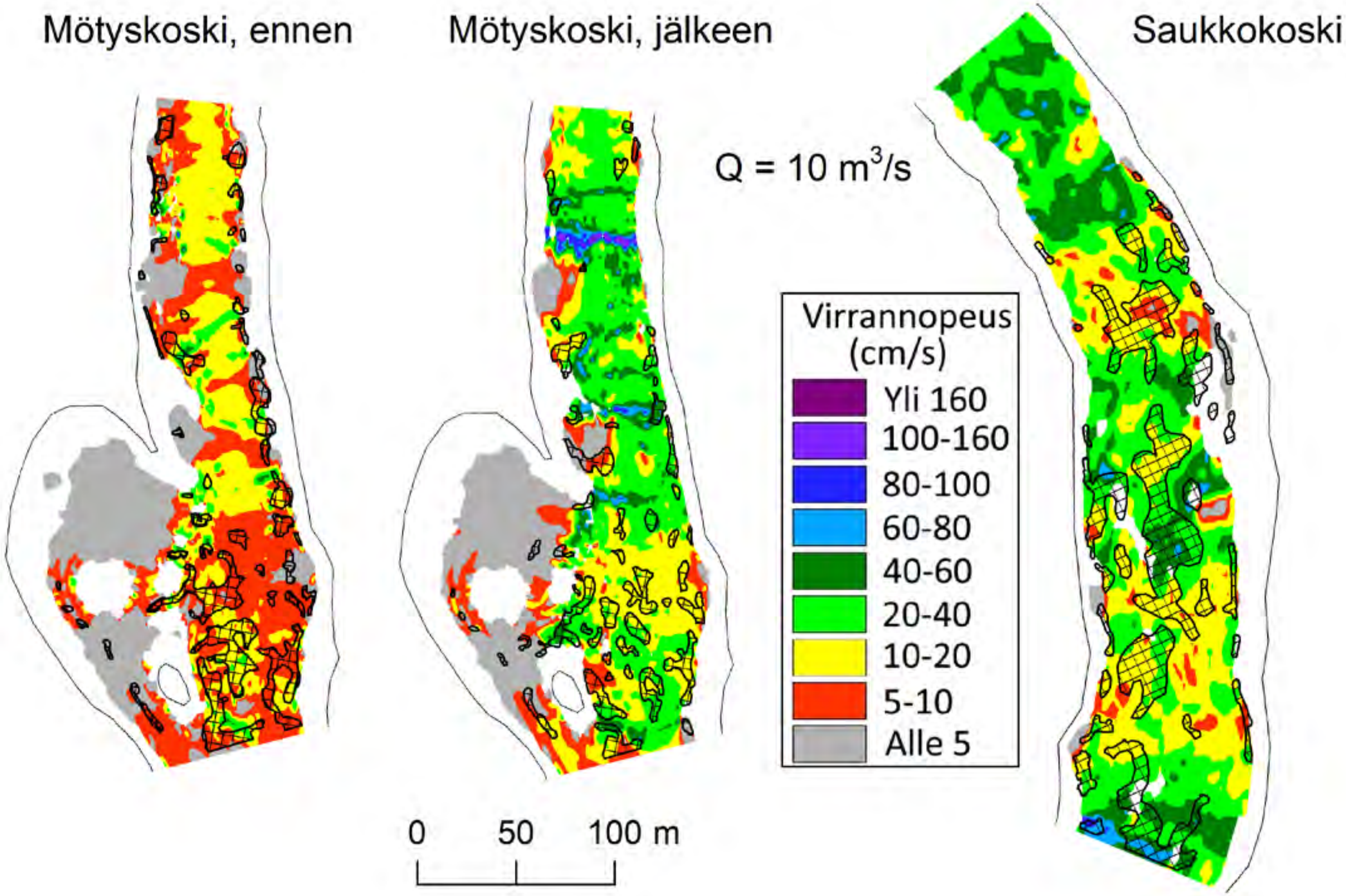

Figure 25. Water current speed near the river bottom (10 cm above the bottom) during the time of winter when discharge is at its low point (10 m^3s^{-1}), in spawning areas defined during the salmon spawning period (discharge rate: 20-40 m^3s^{-1}). Suitable spawning areas are indicated with an overlaid grid pattern.

Effect of calculation method

The amount of habitat estimated through this habitat modelling process is crucially influenced by the way in which the preference values of the different habitat variables of the fish species in question (water depth, speed of current, river bottom quality) are combined. A fundamental question is: does the fish select its location relative to each variable separately? Or does the fish optimise the different habitat variables so that the prevailing conditions at the location it chooses are the best possible in regards to (e.g.) energy efficiency? If the latter is the case, then some of the simultaneously operating habitat variables may be more important than others. A habitat that is excellent with respect to one habitat component may compensate for a habitat that is poorer with respect to some other habitat variable, and as a whole, the first habitat may end up being more favourable from the fish's standpoint. In practice, when the quality of the whole habitat with respect to different habitat variables is calculated as an average, the habitat variables compensate one another in the previously described manner. Correspondingly, if habitat variables are multiplied with one another, then there is no compensation between variables, and the variable of the smallest preference value has a powerful effect on determining habitat quality (Figure 26). In this project, the quality of the whole habitat was calculated as the arithmetic average of habitat variables, resulting in the strongest degree of compensation between variables. If it had been calculated as the product of the habitat variables instead, then the quality value of a suitable habitat would have been 53% smaller (with a 0 - 90% range of variation depending on the preference values of the habitat variables). Correspondingly, if it were calculated as a geometric average, it would have been 10 % smaller (with a 0 – 43 % range of variation depending on the preference values of the habitat variables).

Validation of the modelling –Saukkokoski

The reliability of the habitat modelling results can be checked by comparing, on the one hand, the habit quality value that the modelling produced for a given discharge rate and, on the other, the locations where the fish are observed to be situated when there is an equivalent discharge rate. During the years when the field work in this project was conducted, the discharge rates of the Simojoki were relatively high in late summer and early autumn, and this made it difficult to carry out wide-reaching location-detecting procedures on the river's fish. It was only possible to do location detection in autumn 2016, at Saukkokoski (Figure 27), and even then, discharge rates (35 – 45 m^3s^{-1}) were higher than what is typical for summertime. Quantitative electrical fishing becomes less reliable when the water depth is greater than "wading depth", and therefore, location-detection procedures were only carried out on the river's fish in regions of the water that were shallower than 70 cm (Figure 27).

At Saukkokoski, discharge rates of 35 – 45 m^3s^{-1} obtained at the time of observation, and under these conditions, the salmon fry stayed in areas where the habitat suitability value was higher than 0.7, or in the immediate vicinity of such areas. This speaks for the correctness of the modelling process (Figure 27). On the other hand, these areas were also shallower than 70 cm, and no data was collected on salmon fry numbers in deeper areas due to restrictions of the test fishing method (Figure 27).

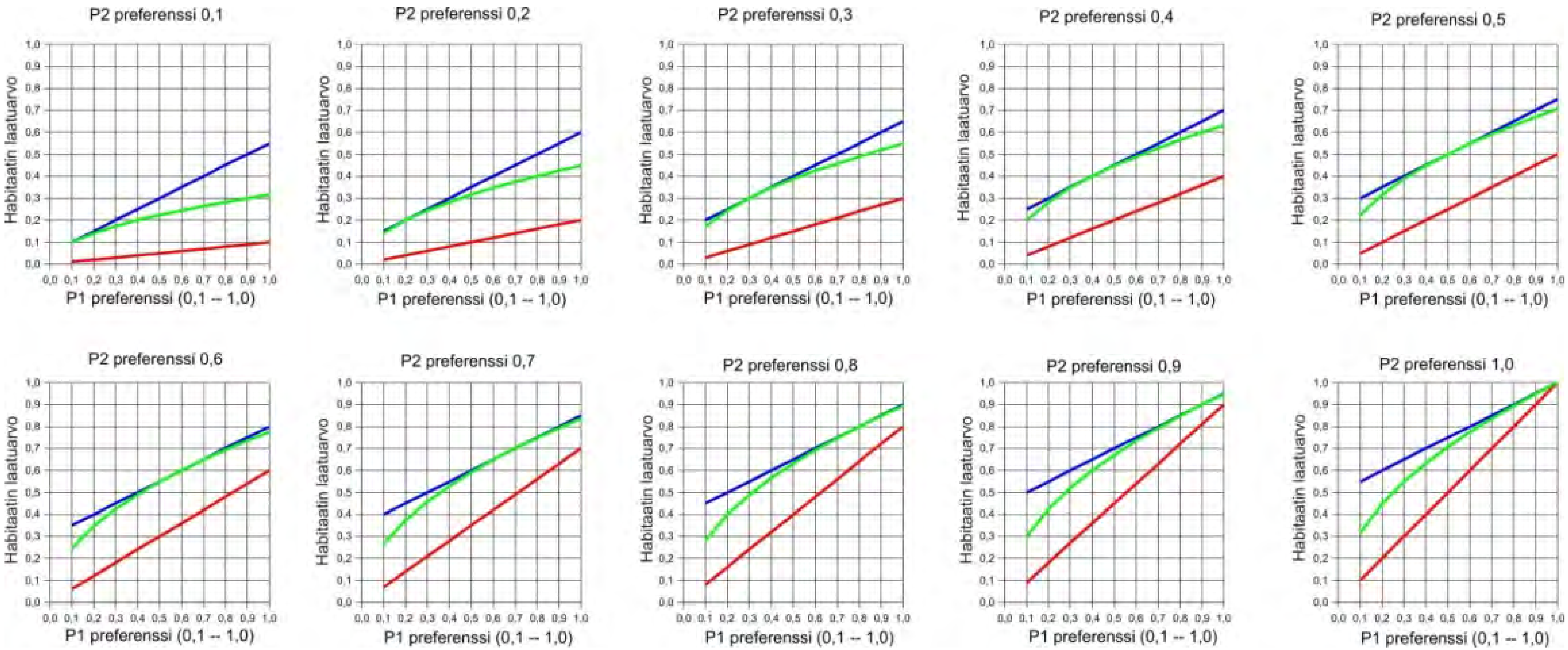

Figure 26. Effect of different calculation methods on habitat quality value. In the example, two habitat variables (P1 and P2) are used. Blue curve = arithmetic average of habitat variables; green curve = geometric average of habitat variables; red curve = product of habitat variables.

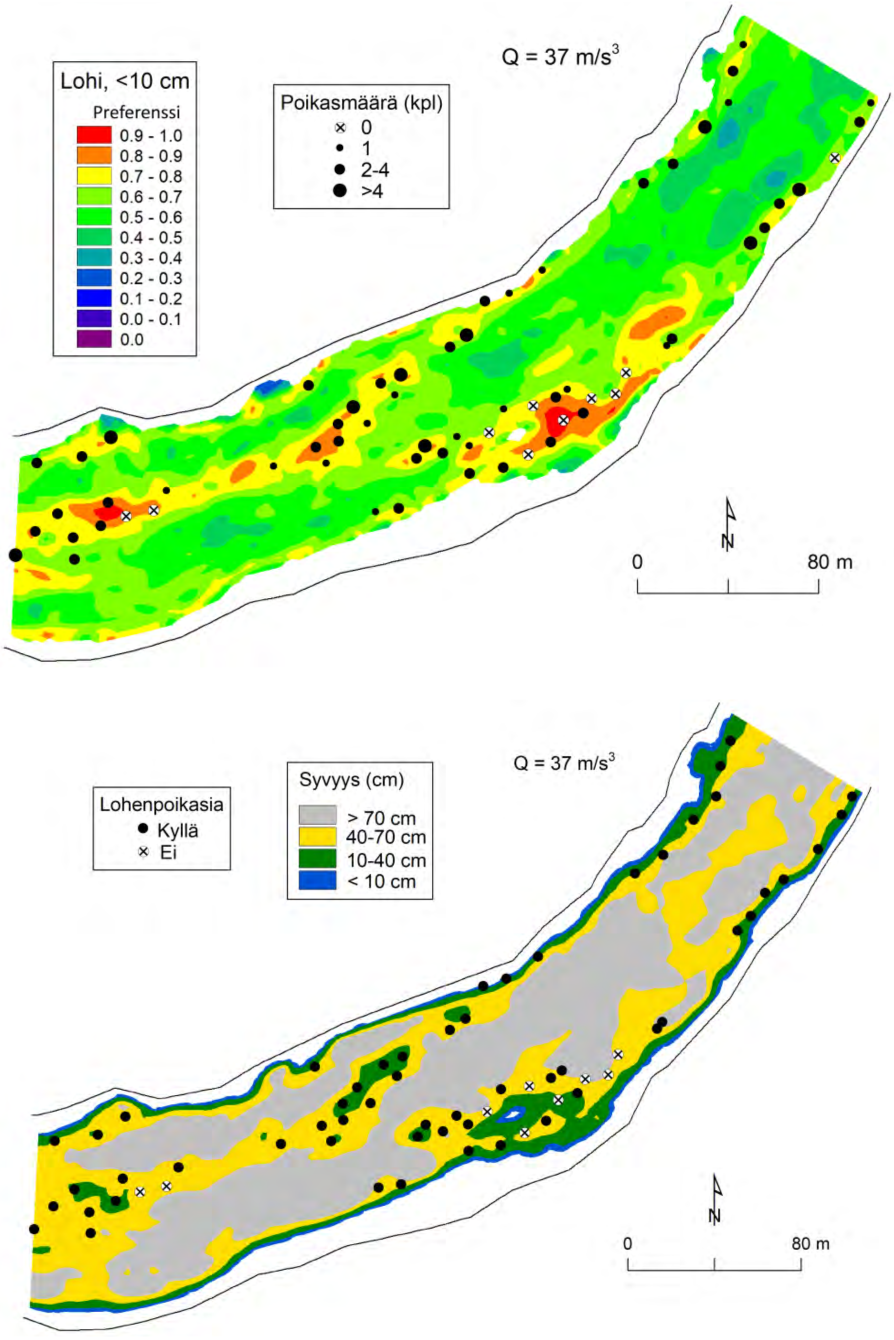

Figure 27. Location of salmon fry as detected through electrical fishing in <70 cm deep areas of the Saukkokoski rapids. Above is the location and quantity of the detected fish on the habitat quality map, and below is the occurrence (Yes/No) of fish on the depth map. When electrical fishing is done, by wading, in areas of > 70 cm depth, the reliability of the method worsens considerably. Maps of depth and current speed for Saukkokoski are presented in Figure 11, and Saukkokoski's habitat quality is presented in Figures 18-20.

Review of results + conclusions

The aim of the restoration efforts at the Mötyskoski rapids was to increase the amount of areas suitable for spawning, and to improve the areas that were highly suitable for salmon fry. The restoration was carried out by modifying the river bottom material of the rapids and bringing spawning gravel and stone material from other locations. The restoration work carried out clearly changed the river bottom topography at Mötyskoski, which was reflected as local changes in the area's water depth and water current speed. On the basis of the habitat modelling, improvements did take place in the summertime quality of the salmon fry habitat, even if the final result clearly fell short of the amount of suitable habitat available for salmon fry at the Saukkokoski rapids (which are among the best rapids for salmon fry in the whole of the Simojoki River). However, it is notable that Mötyskoski saw a significant increase (5-9 %) in the amount of high-quality summertime fry habitats. By contrast, no practically significant changes occurred in the amount of suitable habitat present during winter. Regrettably, during the years when the project took place, the predominant discharge rates of the Simojoki were high, and this did not allow for the collection of topographic measurement data for conditions prevailing during low discharge rates of less than 10 m^3s^{-1}. Reliable flow modelling had to be restricted to a discharge rate of 10 m^3s^{-1}, and it was not possible to carry out modelling of habitats with the sub-10 m^3s^{-1} discharge rates that occur commonly in the winter, and from time to time in summer. It has been thought that success of salmon fry in the Simojoki is decisively impaired by the low discharge rates that occur during winter. The habitat modelling that has been conducted up to this point has not contributed any further information, due to the aforementioned reasons. On the basis of the modelling results, when the discharge rate was 10 m^3s^{-1}, the quality of the river bottom (stone size, degree of sedimentation of stones) at Mötyskoski, under both summer- and winter conditions, was a greater limiting factor in habitat quality than the hydraulic habitat (depth- and current-speed conditions). The reshaping of the river bottom of the rapids most likely improved the hydraulic habitat, but the rearrangement of largely pre-existing stone material at the rapids, and the restricted (relative to the total area occupied by the rapids) amount of new stone material suitable to the fry, produced only a slight improvement in observed conditions of the rapids as a whole.

On the basis of the habitat modelling, conditions during late autumn/early winter, in cases where the discharge rate is under 10 m^3s^{-1}, turned out to be minimal with respect to the quality of suitable salmon fry habitat. As the water cools in the autumn, the behaviour of salmon fry shifts to "winter mode", and they begin to search for shelter (Huusko et al. 2007, Heggenes et al. 2018). When discharge rates are high, the hydraulic habitat (depth- and current-speed conditions) becomes unfavourable, and the quality of the river bottom habitat (the optimal stone size and the number of shelter locations) becomes more significant. Ice formation increases the importance of the quality of the river bottom habitat (Huusko et al. 2007, Heggenes et al. 2018).

On the basis of test fishing carried out by Natural Resources Institute Finland for monitoring purposes, earlier ecological restorations of rapids in the Simojoki have increased the average population density of young-of-the-year salmon fry to some extent, but no change could be detected with respect to older fry. Marttila's (2017) meta-analytic analysis of the productiveness of rapids restorations carried out in Finland, with respect to young-of-the-year salmon fry, produced the same result: on average, restoration had a positive effect on population densities of young-of-the-year fry, but the result was not statistically significant. There was significant variation between rivers, and between rapids in individual rivers. The results of the habitat modelling of Mötyskoski further support this conclusion. The quality and amount of suitable summertime habitat at Mötyskoski increased, but the amount of wintertime habitat remained more or less unchanged. If the results obtained at Mötyskoski can be generalised, the observations of changes in habitat quality and quantity can more broadly serve to explain the variability (between different rapids sites) in how fry population densities respond to restoration (Koljonen et al. 2012, Marttila 2017).

The habitat modelling showed some degree of increase in the amount of excellent-quality spawning areas at Mötyskoski: about 160 m^2 in terms of proportional area, which is close to the estimated (during restoration) approx. 250 m^2 of newly-built spawning area. Areas suitable for spawning made up 2% of the water-covered area of the rapids when the rate of discharge was 20-40 m^3s^{-1}. This is clearly a lower amount than the corresponding figure at Saukkokoski (7 %). On the basis of the modelling done, the prevailing conditions in the spawning areas during the season when discharge is at its low point improved with the restoration of Mötyskoski. The now-shallower rapids and the threshold structures most likely accelerated water current speeds, even during low-discharge season, compared to the situation prevailing before restoration. The spawning area needs to be high-quality during the spawning period, and water current speed and water depth in the spawning area must also remain adequate throughout roe incubation season. In this respect, the restoration of Mötyskoski seems to have been a success.

Habitat modelling is a good addition to the toolkit for evaluation of the restorations, even though the method is relatively expensive to carry out, particularly in regards to topographic measurements. In the gathering of basic data from the modelling of Saukkokoski and Mötyskoski, efforts were made to measure the topography of the riverbed with high accuracy, and the measurements were therefore done manually. It is possible to use more automated measurement methods, such as laser scanning, aerial photography and echolocation, but the functionality of (for example) echolocation in rapids is often limited, and measurement data would thus have to be filled in manually regardless. New measuring methods suited to the mapping of river environments, such as geospatial information, remote sensing, and photogrammetric methods, are undergoing rapid development, as is these methods' accuracy (Alho et al. 2011), and they are enabling cost-effective mapping of both the above-water area of river environments, and the underwater geometry of riverbeds. This increases the possible applications of habitat modelling for the assessment of how a river environment, and restoration work done therein, can affect the living conditions of different fish species.

Habitat modelling is also suitable as an aid to the planning of a restoration project, if it is possible to model the site to be restored as early as the project planning stage. The topography and river bottom quality of the site to be restored can be altered based on the restoration plan, and the site can be modelled virtually, making the effect of planned restoration structures visible before terrain work is done. After completion of restoration work, by measuring the topography and refining the habitat model to better fit the actual situation, it can be assessed how well the plan was realised, and what sorts of changes occurred, in practice, relative to the situation that prevailed before restoration.

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Restoration of salmon spawning- and fry areas in the Simojoki

The Finnish section of the project was coordinated by the Lapland Centre for Economic Development, Transport and the Environment (ELY). Besides the aforementioned, the role of the Lapland ELY Centre in the project was to take responsibility for the habitat restoration work to be done in the Simojoki River, to prepare national matching-funds applications, and to publicise the project in Finland.

General

In the past, Finland's rivers were dredged to make log driving easier. These actions caused massive changes in the hydrology of these waterways, and damaged, among other things, the habitats of the organisms living there.

After log driving stopped being done on rivers, starting in the 1970s, restorations of fish habitats and waterway areas began in what were previously log-driving channels on rivers. The main purpose of the fish habitat and waterway restorations has been habitat improvement for e.g. salmon and other aquatic organisms whose lives are connected to these waterways, and to restore dredged waterways to a condition that is closer to their natural state.

Almost all rapids areas of the Simojoki River have been dredged, and so have almost all the river's tributaries. The most intensive dredgings occurred in the lower section of the river, approx. 50 km upstream from the mouth of the river. The regulation concerning log driving on the Simojoki was repealed in 1976, and the government agency in place at the time, the National Board of Waters, was tasked with carrying out the necessary restorations. The restorations were carried out mainly between 1976 – 1977. In the 1970s restorations, the possibility of log driving in crisis situations had to be accounted for, and partly as a result of this, the restorations could not be carried out along the whole breadth of the riverbed. For example, the small jetties built to aid the log-driving process were not demolished -- instead, holes a few metres wide were made in the jetties to help direct water to dried-out areas behind them. Thus, the aforementioned restoration work ended up incomplete in many locations (Huhtala 1999).

A fish habitat restoration plan, started at the initiative of the municipalities of Ranua and Simo, targeting the main riverbed of the Simojoki and certain rivers draining into the Simojoki and Simojärvi lake, was approved in 1999 by the Water Court of North Finland. Mapping work for the aforementioned plan was carried out between 1994–1996. During that time, the Lapland Regional Environment Centre mapped out the restoration needs of the main riverbed of the Simojoki. The mapping covered all rapids areas of the main riverbed in which it was thought that the potential habitat of valuable types of fish could be increased, and the river landscape could be restored to a point closer to its natural state. The aforementioned fish habitat restoration was carried out between 2002 – 2007 as part of the LIFE-Nature project, Restoration and Protection of the River Simojoki. The rapids areas that were restored in this project are among *those that were left out of the LIFE-Nature restorations.*

Länsstyrelsen
Norrbotten

Project work, 2015-2018

Restoration of salmon spawning- and fry areas in the Simojoki

The work was initiated by carrying out an investigation of the ownership of the project area, and obtaining necessary consents. On 26/6/2015, 247 consent forms were sent out by post to the owners of the land parcels covering the project area, requesting their signatures. 57 persons did not return these consent documents. The consent forms were re-sent to these 57 persons for signatures, and also to 34 persons who had joint-ownership properties (shared water and lands), on 18/11/2015, and to some of them on 26/11/2015. 19 persons did not reply to the second consent letter, and thus, the return rate of the consent letters was 93.24% in total.

After this, it was necessary to update the Simojoki fish habitat restoration plan that had been produced at the Lapland Regional Environment Centre in 1999. The aforementioned project was commissioned by *Osuuskunta Virtatiimi*, and *planning engineer Eero Hiltunen* was responsible for carrying out the work. Eero Hiltunen served as director of the restorations in the Simojoki LIFE project, and he had the information necessary for updating the plan. The update of the 1999 plan started with the mapping of the rapids areas that had been left out of the Simojoki LIFE project restorations. The aforementioned mapping work was carried out in July-August 2015. Approx. 12 km of rapids areas were mapped in all, of which about 4,800 m were surveyed by diving with surface diving equipment (dry-suit, mask and snorkel). The mapping work was carried out by Eero Hiltunen from Osuuskunta Virtatiimi, and Marko Kangas from the Lapland Centre for Economic Development, Transport and the Environment. Following the mapping, a total of 12 rapids areas with an evident need for restoration were picked out.

An investigation of these rapids areas selected for restoration, as required by the Finnish National Board of Antiquities, was carried out. This investigation, titled ”Restoration Areas of the Fluvial Zones of the Simojoki - Archaeological and Cultural History Investigation”, was performed by the archaeological services organisation Keski-Pohjanmaan Arkeologiapalvelut, and a report on the work done was completed on 27/8/2015.

A restoration plan, including appendices, was submitted to the Regional State Administrative Agency of North Finland on 3/11/2015, and a decision to award a permit for the planned restorations was obtained on 25/5/2016.

The following people participated in producing the *restoration plan for the salmon reproduction- and fry areas in the lower section of the main riverbed of the Simojoki*: Project Coordinator *Marko Kangas*, M.Sc. Fisheries Science (Lapland ELY Centre), who finalised the restoration plan, prepared restoration guidelines for the individual rapids, carried out photography of restoration sites, and obtained consent for the proposed restoration work from the owners of the land- and water areas involved; and Planning Engineer *Eero Hiltunen* (Osuuskunta Virtatiimi), who prepared planning maps and otherwise updated the restoration plan. Biologist *Jukka Ylikörkkö* (Lapland ELY Centre) prepared the water quality section of the plan. Geospatial engineer *Riku Elo* (Lapland ELY Centre) prepared the map data for the plan. Clerical secretary *Merja Tähtisaari* (Lapland ELY Centre) investigated the ownership information for the lands and waters involved, and Ylitarkastaja *Jarmo Huhtala* Lapland ELY Centre) directed the updating process for the restoration plan.

An announcement of the request for tenders for the restoration work to be done on the Simojoki, and for the delivery of spawning gravel, was submitted in the HILMA system on 15/6/2016 (HILMA is a free digital notification service maintained by Finland's Ministry of Economic Affairs and Employment that is used by procuring parties to announce their public procurements).

At the opening session on 30/6/2016, it was established that 6 contractors had asked for a tender request, and that 4 contractors had submitted a tender for the Simojoki restoration work by the deadline. All contractors who submitted bids were acceptable, but only two of them had the required work experience *(as mentioned in the request for tenders: The excavator operator must have sufficient experience in similar work. For fish habitat restoration work, the minimum required work experience is 6 months / two sites where work was carried out).*

At the opening session, a tender-comparison table was prepared, in which the tenders submitted by the two contractors with sufficient competence were compared. The most economical bid, which was submitted by the company Situra Group Oy, was chosen for the restoration work and delivery of spawning gravel. A contract for the restoration work and spawning-gravel delivery was signed with Situra Group Oy on 25/7/2016.

Saarikoski

The project's restoration work started at the Saarikoski rapids on 8/8/2016. The rapids are located about 50 km upstream from the mouth of the river, by the village of Saarikoski. The rapids area consists of two individual rapids separated by an approx. 200 m stretch of still water. In keeping with the rapids' name (saari = "island"), there is an island in both of these rapids. The total length of the rapids is approx. 300 m, and the area is approx. 1.6 ha. The total elevation drop at the rapids is 1.6 m (National Board of Waters 1980), and the gradient is 0.53 %. The larger part of the elevation drop occurs at the lower rapids, which were found to be in need of restoration. The upper rapids, which are also called Lapionniva, were not in need of restoration.

The high discharge rates of the river in summer 2016 hampered the restoration efforts at Saarikoski, and prevented e.g. vehicles from moving in the middle of the riverbed. Because of this, restoration work focused on the salmon spawning area near the tip of the island, rather than the planned location in the middle of the riverbed. The stone material that was needed as support for the spawning area, and for creating water-current guiders, was found in the tip of the island, and also at the right edge thereof, where it had been moved when the riverbed was dredged. An area for small fry, which deepened in the direction of the centre of the riverbed, was constructed in the riverbed on the right side of the island, at the banks on the island side.

In all, about 480 m^2 of salmon spawning- and small-fry areas were restored at Saarikoski. About 43 tonnes of sifted natural gravel were brought to Saarikoski.

Mötyskoski

The next restoration site was Mötyskoski, located about 500 m downstream from Saarikoski. The rapids area is composed of three stretches of rapids, of which the uppermost stretch is about 50 m long, the middle stretch about 350 m, and the lowest stretch about 200 m. The aggregate length of these chains of rapids is thus about 600 m, and the aggregate area about 3 hectares. The elevation drop of the rapids is 2.5 m (National Board of Waters 1980), and the gradient is approx. 0.38 %. There is a roughly 300 m stretch of still water between the uppermost and middle chain, and a roughly 100 m river section between the middle and lowest chain that, in places, has features of a small set of rapids. Therefore, the total length of the fluvial areas of the Mötyskoski rapids is about 1,000 m, and the surface area is about 6.8 hectares. Restoration work at Mötyskoski was hampered by the high discharge rate of the river during the summer of 2016. The rapid current and great depth of the water made it difficult for machinery to move on the riverbed, and some of the summer 2016 restorations were left incomplete as a result. Additional restorations on the middle and lower sections of Mötyskoski were performed in summer 2017, when conditions for river restoration work were favourable. Restorations of the Mötyskoski rapids took place mainly in the middle and lowest sections of the rapids. The restoration plan produced at the Lapland ELY Centre in 2015 did not find any need for restoration in the uppermost rapids. When the restoration work began in August 2016, the owners of the local lands and waters proposed a restoration of the uppermost rapids area at Mötyskoski in conjunction with the other restoration work. They submitted old photographs showing the dredging of the upstream starting area of the rapids, and they showed where the stones removed from the riverbed had been placed. In a departure from the original restoration plan, the upstream starting area of Mötyskoski was also restored at the wishes of the local land- and waters owners. The work done in this area was small-scale, and the aim of the restoration work was to bring the area closer to its former natural state. No spawning gravel or other stone material was brought to the upstream starting area of the rapids, and the restoration work consisted mainly of restoring stone material that had been removed from the riverbed. Prior to restoration, the area of the uppermost rapids at

Mötyskoski was approx. 4,500 m^2. Over the course of restoration, this area increased by just over 10% to 5000 m^2. The most labour-intensive restoration work in the project occurred in the middle and lower rapids sections of Mötyskoski. About 690 tonnes of sifted spawning gravel (grain size of Ø 20–100 mm), 370 tonnes of stones for fry (grain size Ø 100- 200 mm), and 200 tonnes of bed stones intended for the river bottom in the fry area (grain size Ø 200-500 mm) were brought to the aforementioned restoration sites. In the middle section of the rapids, the spawning areas were constructed near the edges of the riverbed. The decision to do this was compelled by the conditions that prevailed during the summer of 2016. As an extension of the spawning areas, so-called small-fry areas, intended to be easy for salmon hatchlings to reach, were constructed. In the middle section of the Mötyskoski rapids, a total of 7 spawning areas were constructed, 4 of them located on the right edge of the riverbed, and 3 of them on the left edge, beside the thresholds constructed at the rapids. The depth of the riverbed in the spawning area varied between 40 -150 cm, and the thresholds were constructed so that water depth would increase towards the central riverbed. The speed of the current in the spawning areas varied between 0.5 - 0.8 m/s. A large difference between the discharge rates in summer 2016 and 2017 was caused by the fact that the plan for reshaping the riverbed, and the consequent discharge rates, ended up being changed in summer 2017 in such a way as to ensure that the current and its speed in the restored spawning areas would be adequate even during the time of the lowest discharge. A total of 5 threshold structures were either constructed or partly reinforced in the middle section of the Mötyskoski rapids. The threshold structures made for the riverbed were aimed at keeping the riverbed wet across the whole breadth thereof, and to create variation and twists in the flow of water through the riverbed. The needed stone material was obtained from the small jetty that had previously been established at the right edge of the riverbed. About 250 m downstream from the upstream start of the middle section of the rapids, the riverbed broadens to a width of almost 100 m. At around this point, older small jetties were demolished, and fry areas with an area totalling about 1,500 m^2 were constructed using the stone material obtained from the demolished jetties. Jetties that had trees or extensive shrub growth on them were not demolished. The threshold crossing the riverbed in the lower rapids section was reinforced, and a salmon spawning area was constructed upstream from this threshold. The upstream starting area of the lowest rapids section of this fluvial area was reinforced, and the spawning area running across the riverbed in this area was restored. Immediately downstream from the spawning area, small-fry areas, which deepened in the direction of the central riverbed, were constructed at both edges of the riverbed. In all, about 5,300 m² of salmon spawning- and small-fry areas were restored at Mötyskoski.

Figure 1. Water current speed and riverbed depth are measured in connection with the restoration work.

Figure 2. Stone material ready to be used for making a rocky salmon-fry area at Mötyskoski.

Kalliokoski

The third restoration site of the summer was the Kalliokoski rapids, located about 25 km upstream from the river mouth. The length of the rapids is 1,500 m, and its area is about 11.4 hectares. The elevation drop of the rapids is 8.1 m (National Board of Waters 1980), and the gradient is 0.54 %. There is an island about 350 m downstream from the upstream start of the Kalliokoski rapids. The larger part of the river's discharge goes along the riverbed on the left side of the island. Previously, there was a sawmill operating in the narrow riverbed on the right side of the island, and this riverbed was later dredged for the purposes of log driving as well. The discharge going through the riverbed was previously directed to the side-riverbed on the right of the island, by means of a small jetty that was partially demolished and dispersed into the main riverbed as part of the 1975-76 restorations. The riverbed on the left side of the island has been preserved in a nearly natural state.

The restoration work at Kalliokoski was hampered by heavy discharge rates on the river in summer 2016, which to some extent prevented the movement of workers/apparatus in the riverbed. A salmon reproduction area was constructed in the upstream starting area of the Kalliokoski rapids, at the left edge of the riverbed, and small-fry areas were constructed near the banks of the left edge of the riverbed. Upstream from the tip of the island, the planned spawning areas were left uncompleted when it was noticed that the river bottom at this site was nearly pure rock.

About 250 m downstream from the upstream starting point of the rapids, remnants of the partially-demolished jetty could be seen. This structure is about 80 m long and 5 m wide. The remnants of the jetty were dispersed so that water would flow through the area even during the season when discharge rates are at their lowest, and so that a suitable area for salmon fry could be formed in these remnants. There was a desire to avoid major changes in the flow of the rapids, and therefore the jetty was not demolished / flattened entirely. In all, about 2,500 m² of salmon spawning- and small-fry areas were restored at Kalliokoski. In all, about 130 tonnes of sifted natural gravel were brought to Kalliokoski for the purposes of spawning area restoration.

Kalmakoski

The final restoration site in the summer of 2016 was the Kalmakoski rapids, located about 37 km upstream from the river mouth, in the vicinity of the village of Alaniemi. The length of this fluvial area is about 600 m, and the surface area is about 3.3 hectares. The fluvial area consists of two rapids sections, in which the total elevation drop is 1.2 m (National Board of Waters 1980) and the gradient is 0.20 %. Most of the elevation drop occurs in the lower rapids section. The upper rapid of this fluvial area was restored at the start of the 2000s, as part of the Simojoki LIFE project. In between the chains of rapids, there is a deep stretch with features of a small set of rapids, where bedrock can be seen in places on the riverbanks and riverbed bottom. In the lower section of the lower rapids, on the left side of the riverbed, a roughly 150 m long jetty could be seen that had not been fully demolished. In the lower chain of rapids at Kalmakoski, the main current proceeds down the right side of the riverbed.
Restoration work at Kalmakoski was hampered by the high discharge rate of the river during the summer of 2016. Salmon reproduction areas were created at the left edge of the upstream starting area of the lower rapids section. The small jetty that had been on the left side of the riverbed was demolished, and in its place, an area suitable for small fry was constructed. The restored fry area was shaped in such a way that it deepened in the direction of the right side of the riverbed.
In all, about 720 m² of salmon spawning- and small-fry areas were restored at Kalmakoski. About 90 tonnes of sifted natural gravel were brought to Kalmakoski for the purposes of spawning area restoration. Restoration work on the Simojoki for 2016 ended at Kalmakoski on 14/9/2016.

Figure 3. Restoration of spawning area at Kalmakoski - 2016

In October 2016, it was announced that Situra Group Oy, the contractor that had been taking responsibility for the restoration work, had been declared bankrupt. The Lapland ELY Centre therefore dissolved its contract with Situra Group Oy. A new contract review session was held on 24/11/2016 with Konepalvelu Ramlin Oy, the contractor that had come in second in the tender competition. It was agreed that Konepalvelu Ramlin Oy would review its own earlier bid estimates, and submit a tender for completion of the restoration work in the Simojoki. The new tender was submitted on 20/3/2017. This tender contained the same prices for personnel and machinery as those the company had submitted in the tender competition that ended on 30/6/2016. The unit price of spawning gravel (per 1,000 kg brought to the site) rose slightly. This was due to the available supply of gravel in the supply area during January-February 2017, and the fact that the amount of gravel had decreased by half compared to the amount that appeared in the request for tenders. The higher price of gravel (an added expense) made up < 1% of the total restoration costs.

2017 restoration work

Preparations were made for the summer 2017 work by bringing the needed spawning gravel to the vicinity of the restoration areas in late March - early April 2017. At that time of year, the hard, frozen ground / roadbeds are better able to bear the weight of heavy vehicles, thereby reducing potential damage to roads from vehicle movement. Spawning gravel was driven to two different riverbank locations from which it could be easily transported to the restoration sites. The spawning gravel was transported along the riverbed to the restoration sites with a Ponsse Vincent forest machine containing a built-in gravel-transport bed with a tipper.

Länsstyrelsen Norrbotten

Figure 4. Spawning gravel transported to the riverbank, near the restoration areas, in March-April 2017

Tammakoski

The summer 2017 work started on 28 June at the Tammakoski rapids, located about 23 km upstream from the river mouth. The rapids are about 400 m long, and about 2.4 hectares in area. The elevation drop of the rapids is 1.0 m (Lavy 1970), so the gradient of the rapids is 0.25 %. The elevation drop of Tammakoski is concentrated at the upstream starting point of the rapids, and in the lower rapids section. 100 m downstream from the upstream start of the rapids, on the right side of the riverbed, is a small jetty, about 50 m long and 5 m wide, that has not yet been fully demolished. On the riverbanks of the rapids, a substantial amount of stone material that had been removed from the riverbed could be seen. Under summertime water conditions, the surface area of the rapids was almost 50% "standing" water.

Salmon reproduction areas were restored in the upstream starting area of the Tammakoski rapids. The gravel in this part of the rapids was initially mixed with sand, but it was then sifted clean of the sand using the sieve bucket of an excavator. Sifted gravel was also brought to this area. The small jetty at the right edge of the rapids was widened into an area for small fry, so that it now deepens in the direction of the centre of the riverbed. A small-fry area, which deepened in the direction of the centre of the riverbed, was restored at the inner curve of the rapids, at the left edge of the riverbed.

In all, about 6,800 m² of salmon spawning- and small-fry areas were restored at Tammakoski. About 40 tonnes of sifted natural gravel were brought to the restoration site. About 350 tonnes of stone material from the demolished jetty were sifted and utilised in the restoration work.

Soikonkari, Lappalaisenkoski, Maitokallionvirta, Mikkolankari.

In the restoration plan prepared for the project, the rapids chain of Soikonkari - Lappalaisenkoski - Maitokallionvirta - Mikkolankari - Saukkokoski was regarded as constituting a unified fluvial area. In a departure from the original restoration plan, the lowest rapids area of the fluvial area -- i.e., Saukkokoski -- was left unrestored. The rapids in question served as the control for the habitat modelling project, and thus those working on the project did not want to alter it. The total length of the fluvial area is approx. 4 km, and its area is approx. 30 hectares. The elevation drop of the rapids chain is 11.3 m (National Board of Waters 1980), so the gradient of the rapids chain is 0.25 %. Restoration work was done on a stretch of approx 3 km where the surface area of the fluvial area was approx 22 hectares.

The **Soikonkari** rapids are located about 500 m downstream from Tammakoski. In the upstream starting area of the rapids, a broad salmon spawning area was restored over the whole breadth of the riverbed. The aforementioned starting area had suitable gravel for the purposes of restoring the spawning areas. This gravel was partly mixed with sand. The gravel was sifted clean using the sieve bucket of the excavator. In addition to the above, sifted natural gravel was brought to the upstream starting area of Soikonkari. Immediately downstream from the spawning area, areas for small salmon fry were restored at the edges of the riverbed and in the central riverbed. Stone material that had been removed from the riverbed could be seen on the right edge of the riverbed; this material was utilised in the restoration of the site, in making e.g. the thresholds and water-current guiders.

At Soikonkari, a total of1.6 hectares of spawning- and fry areas were restored. A total of 90 tonnes of sifted natural gravel were brought to the restoration site.

The **Lappalaisenkoski** rapids are located about 450 m downstream from Soikonkari. In the upstream starting area of the rapids, spawning areas were restored for salmon by sifting in gravel and “beating” the sedimented material at the river bottom. In addition to the above, sifted natural gravel was brought to the Lappalaisenkoski rapids as well. Small-fry areas were restored near the centre of the riverbed, in the immediate downstream vicinity of the restored spawning area. In the upper section of the rapids, on the right side of the riverbed, there was a 180 m long, partly demolished jetty, and on the left side of the riverbed, there were island-like structures made of dredging debris. Stone material obtained from this dredging debris was used in e.g. spawning area restorations, and to form water-current guiders.

About 1.5 hectares of salmon spawning- and fry areas were restored at Lappalaisenkoski. 120 tonnes of sifted natural gravel were brought to the restoration site.

The **Maitokallionvirta** rapids are located about 220 m downstream from Lappalaisenkoski. Upstream from the upstream start of the rapids, at the centre of the riverbed, a small jetty could be seen, approx. 200 m long and 10 m wide, which had not been fully demolished. The threshold in the upstream starting area of the rapids was reinforced using stone material obtained from the jetty. Immediately upstream from this threshold, a spawning area running across the riverbed in this area was restored, so that this area’s spawning locations were at a range of different depths and water current-speed zones. A water-current guider was added at the left edge of the riverbed. All stone material needed for the restoration work at Maitokalliovirta was obtained from the small jetty at the restoration site.

About 8,000 m² of spawning- and fry areas were restored at Maitokalliovirta. About 700 tonnes of stone material from the demolished jetty structure were sifted and utilised in the restoration work.

Figure 5. Sifting of stone material in connection with the demolition of the small jetty at Maitokalliovirta.

The **Mikkolankari** rapids are located about 120 m downstream from Maitokallio. Numerous large stones and other stone material that had been removed from the riverbed could be seen on the banks and at the edges of the riverbed. The threshold structures at Mikkolankari were reinforced using large stones moved to the edges of the riverbed. Spawning areas were restored immediately upstream from the thresholds, using sifted gravel from the riverbed bottom. Salmon small-fry areas were restored at a location adjacent to the thresholds downstream from the spawning areas. The shape of the spawning- and small-fry areas was planned out so as to ensure that there would be a suitable amount of spawning- and small-fry area available under a range of different discharge conditions.

In all, about 3.8 hectares of salmon spawning- and fry areas were restored at Mikkolankari. A total of 400 tonnes of spawning gravel and fry-suited stones from Mikkolankari were sifted and utilised in the restoration work.

Kattilakoski, Harskukoski, Kuolemankoski, Hamarinkoski

These rapids form a unified fluvial area. The uppermost rapids of the fluvial area, **Kattilakoski**, are located about 15 km upstream from the mouth of the river, at the point where the Martimojoki River merges with the Simojoki. The rapids are about 350 m long, and about 1.8 hectares in area. The elevation drop of the rapids is 1.4 m (Lavy 1970), so the gradient of the rapids is 0.40 %. The elevation drop of the Kattilakoski rapids is concentrated largely in the 270 m long middle section of the rapids, the gradient of which is over 0.50 %. The rapids area consists of three separate chains, of which the two uppermost ones are short and threshold-like. The river bottom of the Kattilakoski rapids is rocky and jagged throughout. The upper part of the rapids has three small islands.

At the upstream starting point of the Kattilakoski rapids, a salmon spawning area was restored, as well as a small-fry area immediately adjacent to the spawning area and downstream from the islands in the rapids. Large stones that had been removed from the riverbed could be seen on the right-side riverbank next to the middle and lower sections of the Kalliokoski rapids. These stones were restored to the riverbed. At Kalliokoski, the river's discharge was concentrated toward the left edge of the riverbed, and large rocks that had been restored to the riverbed, and that were functioning as water-current guiders, were used to bring more variation and twists to the flow of water through the riverbed.

In all, about 3,000 m² of salmon spawning- and fry areas were restored at Kattilakoski. 5 tonnes of sifted natural gravel were brought to the restoration site.

The **Harskukoski** rapids are located about 200 m downstream from the Kalliokoski rapids. The rapids are about 900 m long, and about 6.3 hectares in area. The elevation drop in the rapids is about 6.0 m (Lavy 1970), so the gradient of the rapids is 0.67 %. The Harskukoski rapids were partly dredged using explosives.

The small jetty at the upstream starting point of the rapids had been partly demolished, and its remnants appeared as island-like formations. Remnants of the jetty could also be seen in the middle and lower sections of the rapids; downriver, these remnants had collected into "islands". Along nearly the whole length of the rapids, stone material that had been removed from the riverbed could be seen at the edges of the riverbed. Gravel taken from the jetties was sifted for the purpose of spawning area restoration, and stone material that had been removed from the riverbed was used e.g. to reinforce the thresholds, as water-current guiders, and as supports for the spawning areas.

A total of seven (7) separate spawning areas were restored at the Harskukoski rapids. The spawning areas were situated near the threshold structures in the rapids, on the upstream side. Small-fry areas were restored immediately downstream from the spawning areas. The threshold structures made for the riverbed were aimed at keeping the riverbed wet across the whole breadth thereof, and to create variation and twists in the flow of water through the riverbed.

Figure 6. Transport of spawning gravel to the restoration site at Harskukoski rapids, 2017.

In all, about 1.5 hectares of salmon spawning- and fry areas were restored at Harskukoski. 340 tonnes of sifted natural gravel were brought to Harskukoski. About 800 tonnes of gravel and other stone material taken from the jetties were sifted and utilised in the restoration work.

Figure 7. Inspection of the restored spawning area at Harskukoski, 2017.

The **Kuolemankoski and Hamarinkoski** rapids form a nearly unified rapids area. The length of the rapids chain is 1,600 m, and its area is about 10.5 hectares. The elevation drop of the rapids chain is about 7 m (Lavy 1970), so the gradient of the rapids is 0.44 %.

In a departure from the original restoration plan, Hamarinkoski was left entirely out of the restoration work, and at Kuolemankoski, only the salmon spawning- and fry areas at the upstream starting point of the rapids were restored. The decision to do this was made when one of the local property owners expressed opposition to the restoration work planned for the riverbed falling within this owner's property.

Nearly the entire length of Kuolemankoski and Hamarinkoski has been dredged in the past. Small jetties and stone material removed from the riverbed can be seen throughout the area of the rapids.

The small jetty islands in the upstream starting area of the Kuolemankoski rapids were demolished, and the stone material obtained thereby was utilised in reinforcing the threshold at the aforementioned starting area; it was also used to construct water-current guiders, and was used in restoring the spawning- and small-fry areas. At Kuolemankoski, spawning areas were restored in this starting area, at a range of different depths and water current-speed zones. Small-fry areas were restored immediately downstream from the spawning area. The shape of the spawning- and small-fry areas was planned out so as to ensure that there would be suitable river flow available during all seasons of the year, and under all discharge conditions of the river.

A total of 5,500 m of spawning- and small-fry areas was restored in the upstream starting area of Kuolemankoski. About 1,200 tonnes of gravel and other stone material taken from the jetties located at the upstream starting point of the rapids underwent sifting. The aforementioned gravel and stone material was utilised in e.g. restoration of spawning- and small-fry areas. 160 tonnes of sifted natural gravel were brought to the upstream starting area of Kuolemankoski.

Figure 8. Stone material ready to be used for spawning-area restoration at Kuolemankoski.

Restoration work was concluded at Mötyskoski on 8/8/2017. At Mötyskoski, unfinished restoration work from the summer of 2016, when the work had been hampered by the river's heavy discharge rates, ended up being carried out. This compensatory restoration work was done over 2 days, in the middle and lower sections of the rapids.

Summary of the restoration work

In 2016-2017, a total of 11.6 hectares of salmon spawning- and fry areas were restored on the Simojoki River. A total of 1,721 tonnes of sifted natural gravel (grain size of Ø 20–100 mm) was brought in for the purpose of spawning area restoration, and a total of 570 tonnes of stone material (grain size Ø 100- 500 mm) was brought in for the purpose of small-fry area restoration. A total of 3,450 tonnes of gravel and other stone material taken from the riverbed was sifted and utilised in the restoration work. Repairs were done on a total of 2,100 m of local cottage roads (due to damage caused by work vehicles). 550 tonnes of paving material was used, along with 195 tonnes of other ground material.

Equipment used in the restoration work:

2016: Doosan DX 256 LC excavator with rollers, equipped with claw bucket, tilt bucket, bucket rotator (roto); and a New Holland T7 200 agricultural tractor equipped with a front bucket and a 16 tonne trailer.
2017: Samsung SE 240 LC-3 excavator with rollers, equipped with a claw bucket with a screen (screen bucket); and a Ponsse Wisent 8 W forwarder (forest tractor), equipped with a separate gravel-transport bed.

Notes on the functionality of the equipment used in the restoration work: A problem encountered with the excavator used in the 2016 restorations was that the rollers would lock up (about 1x a week). It is difficult to assess whether this is due to the quality of the rollers or their age. Of the attachments, the combination of the tilt bucket and bucket rotator (roto) worked excellently in the restoration of the spawning- and fry areas, where the gravel was spread and installed at the restoration site. Arranging stones in the riverbed with a simple claw bucket was rather difficult compared to the same work done with a screened claw bucket (screen bucket). With the screen bucket, stones could be installed very precisely, in the desired position and location. The screen bucket had clear advantages in the demolition of the jetties, as well. This bucket allowed stone material of different sizes to be sifted apart, allowing the separated material to be better utilised for different purposes at the restoration sties. The agricultural tractor was used to transport the gravel when the riverbed bottom was flat. When water depth exceeds 0.8 m, and the shape of the river bottom becomes uneven / stony, then it becomes considerably more difficult for this tractor to move on the riverbed. The forwarder (forest tractor), equipped with a gravel bed, works excellently for transporting spawning gravel on the riverbed. Movement is not prevented by an uneven river bottom, and the vehicle moves moderately well even in 1 metre deep water.

COORDINATION OF THE PROJECT

The role of the Lapland Centre for Economic Development, Transport and the Environment (ELY) in the project was to direct and coordinate the progress of the project in accordance with the time table and budget, and to prepare national matching-funds applications in Finland. Contact with other Finnish project organisations and funders (INTERREG and the Regional Council of Lapland) occurred mainly by e-mail, but contact was also made by phone as needed. The project partners in Finland had a shared FLC project inspector (KPMG / Leif-Erik Forsberg), commissioned by the ELY Centre through a tendering process, who inspected each organisation's "project accounting". The Lapland ELY Centre prepared national matching-funds applications addressed to the Regional Council of Lapland, in accordance with approved expenses (FLC certificates). A total of six (6) matching-funds applications were made to the Regional Council of Lapland.

The Lapland ELY Centre was also in charge of organising the project- and steering group meeting held in Finland. This meeting was held on 30/11 - 1/12/2016, at the Simojoen Lohiranta centre in Simo.

Coordination of the project in Finland proceeded smoothly and without difficulty. This task was made much easier by the extensive project- and project reporting experience of the organisations' project personnel, and also that of the finance- and administration personnel supporting them. The Regional Council of Lapland, as well as the County Administrative Board of Norrbotten (the INTERREG funders) provided quick and straightforward advice and guidance regarding reporting and more.

PUBLICITY

Publicity is an important aspect of this project. Each project organisation took its respective responsibility for ensuring that reports and other publicity activities were done in accordance with the funders' instructions (in regards to e.g. logos). Reports produced by the Lapland ELY Centre have included the logos of the funders and the project organisations, and have also disclosed how the project financing/budget is structured. The Lapland ELY Centre has given presentations on the project at (among other places): the Simojoki Salmon Seminar in 2015, 2016 and 2017; town meetings about the restoration work in 2016 and 2017; the 2015 Tornio River Water Parliament; at the Waterway Restoration Seminar in Lappeenranta in 2016, and in Oulu in 2018; at a visit to Simo by Risto Artjoki, State Secretary, in 2017; and in Italy in 2018, during an informational and networking trip for the project. The restoration work of the project has been publicised in the following media outlets, among others: Lapin Kansa, Pohjolan Sanomat, and YLE's Lapin Radio, Radio Perämeri, and Pohjois- Suomen Uutiset. The project's home page can be found at: https://www.ely-keskus.fi/web/ely/peramereen_laskevat_joet_kunnostus;jsessionid=11C8383ADCDA6EC99AE7008E2ACA070E?p_p_id=122_INSTANCE_aluevalinta&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_r_p_564233524_resetCur=true&p_r_p_564233524_categoryId=14253. Google search: Perämereen laskevia vesistöjä menetelmien kehittäminen [water systems draining into the Bothnian Bay development of methods]

Acid sulphate soils around coastal watercourses

August 2018

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CONTENTS

INTRODUCTION

The Interreg project "*Kustmynnande Vattendrag i Bottenviken - Metodutveckling och ekologisk restaurering. Ett gränsöverskridande Svenskt-Finskt samarbetsprojekt" [Watercourses discharging into the Bay of Bothnia - Methodological development and ecological restoration. A cross-border Swedish-Finnish joint project]* is a joint project in which work has been carried out in Norrbotten in Sweden and in Northern Ostrobothnia and parts of Lapland (in the Simo Älv river catchment area; *Simojoki* in Finnish) in Finland. The overall aim has been to improve awareness of the value of coastal ponds and watercourses and the threats that they face. In Norrbotten, Northern Ostrobothnia and Lapland there are coastal watercourses in which the quality of the water has been adversely impacted by acid sulphate soils. These waters are characterised by periodically low pH and high concentrations of aluminium and other metals. Much of the work on the project has focused on investigating where acid sulphate soils occur, how they affect the quality of the water and remedial measures that can be taken to reduce the negative impact of these soils. The results presented here include those parts of the *Coastal watercourses* project that relate to acid sulphate soils. These results include results gained from the mapping and modelling of areas with acid sulphate soils, studies of sediments deposited adjacent to watercourses affected by these soils, and remedial measures tested to reduce the environmental impact of acid sulphate soils.

The work of the Swedish Geological Survey (SGU) on the project has focused on documenting the incidence of acid sulphate soils in the catchment areas of the Rosån, Alterälven and Alån rivers, which are coastal catchment areas between Piteå and Luleå in Norrbotten. Previous studies have shown that the waters in these catchment areas are to some extent adversely affected by acid sulphate soils (Filppa 2012). In Finland acid sulphate soils have been documented in general terms in the coastal area of Northern Ostrobothnia and detailed for the catchment area of the Simo Älv river by the Geological Survey of Finland (GTK). Because the GTK has documented the incidence of acid sulphate soils in Finland for many years, an important aim of the project has also been to ensure that the soils of both countries are documented in the same way, so that the results are comparable. Because environmentally harmful substances are leached from active acid sulphate soils, SGU has studied which substances have been mobilised from these soils. In conjunction with the field work samples were taken and analysed for a large number of chemical parameters. In partnership with Uppsala University, SGU has also investigated whether sediments deposited adjacent to the catchment area of the Rosån river have been affected by these soils.

Another important aim of this work has been to prepare maps showing where in the catchment areas studied, and in the coastal area of the Bay of Bothnia as a whole, that acid sulphate soils occur. Great importance has been placed on testing, if possible using data from observations of acid sulphate soils, in order to use modelling to prepare maps showing where acid sulphate soils are likely to occur in the catchment area. In the past, the incidence of acid sulphate soils in parts of Finland's coastal areas have been modelled (e.g. Beucher et al. 2014). The idea has been to use modelling to obtain a general understanding of the landscape parameters that are crucial to the incidence of acid sulphate soils. This understanding can then be used to model the distribution of acid sulphate soils in other areas. The overview map showing the likely incidence of acid sulphate soils in the coastal area of the northern Gulf of Bothnia, has been prepared in collaboration with an Interreg Botnia-Atlantica project (VIMLA – Water and man in the landscape).

The maps and data generated by the project can be used as planning materials for other authorities. The intention is to use the information to avoid land use that leads to the formation of active acid sulphate soils, but also to identify areas where it could be appropriate to implement measures aimed at reducing the environmental impact of active acid sulphate soils.

Acid sulphate soils

After the inland ice retreated from the Bay of Bothnia about 10,000 years ago, low-lying parts of what are now coastal areas were covered by the water of the Baltic. Sediments containing a relatively large amount of organic matter were sporadically deposited on the sea bed. As this organic material oxidised, the oxygen contained in the sediments was consumed. This resulted in the reduction of iron and sulphur, after which these substances reacted with each other forming ferrous sulphides. The sulphide soils, often with a high clay and silt content deposited on the sea bed are commonly referred to as sulphidic sediments. Land uplift resulted in areas with sulphidic sediments being raised above sea level. If these sulphide soils are exposed to oxygen in the atmosphere and consequently oxidise, sulphuric acid is formed, which leads to a sharp reduction in pH and the formation of active acid sulphate soils. Large quantities of metal can leach out of these soils which, when mobilised, can adversely affect the environment in adjacent watercourses. Because these sulphidic sediments can give rise to active acid sulphate soils, in this report they are also referred to as potentially acid sulphate soils, and acid sulphate soils is used as the collective name for active acid and potentially acid sulphate soils (see Appendix 1).

The negative environmental impact arising from the acidification of potentially acid sulphate soils is often triggered by the artificial lowering of the groundwater level by ditching to allow agriculture or forestry (Boman et al. 2010). The soil then dries out and oxygen penetrates the ground. Then the iron sulphides in the soil oxidise, which often causes the pH value to drop from values above 7 to about 3.5-4. At the same time the acidic conditions lead to increased chemical weathering which means that certain substances can be released from the acid soils. This has been demonstrated in several earlier studies from Finland and Sweden (e.g. Sohlenius et al. 2015, Sohlenius & Öborn 2004, Österholm & Åström 2002). This subsequently leads to watercourses in the area with a high proportion of active acid sulphate soils being characterised with a low pH and high concentrations of metals, aluminium for example (Åström & Björklund 1995, Åström 2001a). Calculations show that active acid sulphate soil in Finland releases some metals into the Baltic in greater quantities than Finnish industry as a whole (Sundström et al. 2002). In Sweden, the negative impact of acid sulphate soils on the aquatic environment has been observed in the coastal areas of Västerbotten and Norrbotten in particular (Åberg 2017); in that case in catchment areas with a high proportion of active acid sulphate soils (Filppa 2012). However, it has been recognised that acid sulphate soils occur in many areas further south in Sweden, for example around lake Mälaren (Sohlenius & Öborn 2004).

Low pH and high metal concentrations negatively affect many organisms, and in some cases can lead to fish death. Sea trout and roach for example, are very sensitive to too low a pH in bodies of water. High concentrations of metals create added stress for aquatic organisms. There are examples in both Sweden and Finland where active acid sulphate soils have completely destroyed fish populations in a watercourse (Wickström 1939, 1940, Byrsten and Sandberg 2005). In agricultural areas the low pH value of soils also means that they must be limed to allow cultivation. The high concentrations of certain metals in watercourses have also led to high levels of these metals in aquatic vegetation (Lax 2005). Sediment in inlets outside areas with active acid sulphate soils can also contain high concentrations of metals (Nordmyr et al. 2008). There are also studies showing that certain crops in areas with active acid sulphate soils contain high levels of multiple metals (Palko 1986, Fältmarsch et al. 2008) However, there is no evidence that this has a negative impact on human health, although this cannot be excluded.

Potentially acid sulphate soils mainly occur in the lowest sections of terrain where the groundwater level is naturally close to the surface. If such areas are not modified by ditches or other land use, they will form wetlands where potentially acid sulphidic sediments will eventually be covered by a layer of peat (Boman et al. 2010). However, because clay and silt soils are suitable for farming, in many areas with potentially acid sulphate soils have been ditched, and following this active acid sulphate soils have formed. Today, new drainage is unusual in Sweden, but subsurface drainage, ditch clearing and protective ditching can expose sulphide soils to oxygen. After ditching peat layers slowly collapse, and eventually with time oxidise away completely, this means that the ditches must be deepened exposing underlying potentially acid sulphate soils to the air. This means that new active acid sulphate soils can form in areas that have been ditched for extended periods as well. In addition, potentially acid sulphate soils can be exposed to air in conjunction with construction work and the dredging of waterways. Dredging spoil can contain relatively high levels of environmentally harmful metals, and it is therefore particularly important that this spoil is not exposed to air. In order to avoid land use that results in the exposure of potentially acid sulphate soils, it is important that there is planning data showing where in the landscape active acid and potentially acid sulphate soils occur.

Active acid and potentially acid sulphate soils can often be immediately recognised in the field (Sohlenius et al. 2015) (Appendix 1). Sulphidic potentially acid sulphate soils often have a black or dark grey colour (Figure 1, top right), and are sometimes called sulphide soils. However, there are soils that are flecked black with a low sulphur content that do not become acidic following oxidation, and thus are not classified as potentially acid. Furthermore, there are

Figure 1. Top left Sulphidic, potentially acid sulphate soils with the characteristic black colour. If this soil is exposed to air for a few hours, it will assume a grey colour. Photograph: Gustav Sohlenius, SGU. Upper right and lower left Active acid sulphate soil is often characterised by rusty cracks (rust coloured deposits) and jarosite (light yellow deposits). Photograph: Nelly Aroka and Christian Öhrling, SGU. Lower right Acid sulphate soils recently exposed in a ditch in the area where the county administrative board is testing measures to limit the environmental impact of active acid sulphate soils. Photograph: Christian Öhrling, SGU.

sulphidic potentially acid sulphate soils that do not exhibit the black or dark grey colour. In Finland some sandy soils have been found to be potentially acid sulphate soils (Mattbäck et al. 2017), and similar soils are, in all likelihood, also present in Sweden. Potentially acid sandy soils can be difficult to immediately identify in the field. Further south, around Uppsala for example, calcareous sulphidic soils in which the pH does not decrease when the soil oxidises have been observed (Lax & Sohlenius 2006). Acid sulphate soils are often characterised by abundant rust deposits and a very cracked soil (Figure 1, upper left and lower right and left). Sometimes the light yellow sulphate mineral jarosite, formed only at low pH values is present (Figure 1, lower left).

Acid sulphate soils in Norrbotten and Västerbotten are predominantly found in coastal areas which, on SGU's soil maps, comprise clay and silt, and which have been drained by land uplift over the last 5,000 years (Sohlenius et al. 2015). Often, the Littorina boundary is designated as the upper limit for the occurrence of sulphidic sediments (Öborn 1994). This boundary limit corresponds to the highest level covered by brackish or marine water after the last ice age, and was formed approximately 8,500 years ago (Andrén et al. 2011). According to Sohlenius et al. (2015) no acid sulphate soils were found in areas drained more than 6,500 years ago. However, acid sulphate soils occurring locally in these older areas cannot be ruled out. In Finland, mapping by GTK has found acid sulphate soils up to the Littorina boundary, and even above that boundary. There are relatively few observations in this study close to the boundary. In this project (and VIMLA), soils from these higher areas have been documented to determine whether active and potentially acid sulphate soils occur.

In Sweden, knowledge about acid sulphate soils is largely based on detailed field studies in four catchment areas – the Hertsångerälven river in Västerbotten and the Alån, Rosån and Alterälven rivers in Norrbotten (Figure 2). The latter three are adjacent to each other and in the study have been merged into one area which has been investigated in the *Coastal watercourses* project. In addition, acid sulphate soils in the Västerbotten and Norrbotten coastal areas have been investigated previously in 2012 and 2013 (Sohlenius et al., 2015). However, the systematic sampling campaign in the designated catchment areas was undertaken in 2016 and 2017. In Finland a considerably larger number of sites have been investigated with the aim of studying the incidence of acid sulphate soils (Figure 2). Between 2012 and 2014 GTK mapped acid sulphate soils in Finnish Lapland, and reports with an overview map was published in Hannukkala et al. (2015). In Northern Ostrobothnia GTK carried out the overview mapping of acid sulphate soils in a number of catchment areas. In this project the focus has been the areas not previously mapped, in 2015-2018 GTK undertook extensive overview mapping (and detailed mapping of the catchment area of the Simo Älv river) of acid sulphate soils in a large number of catchment areas.

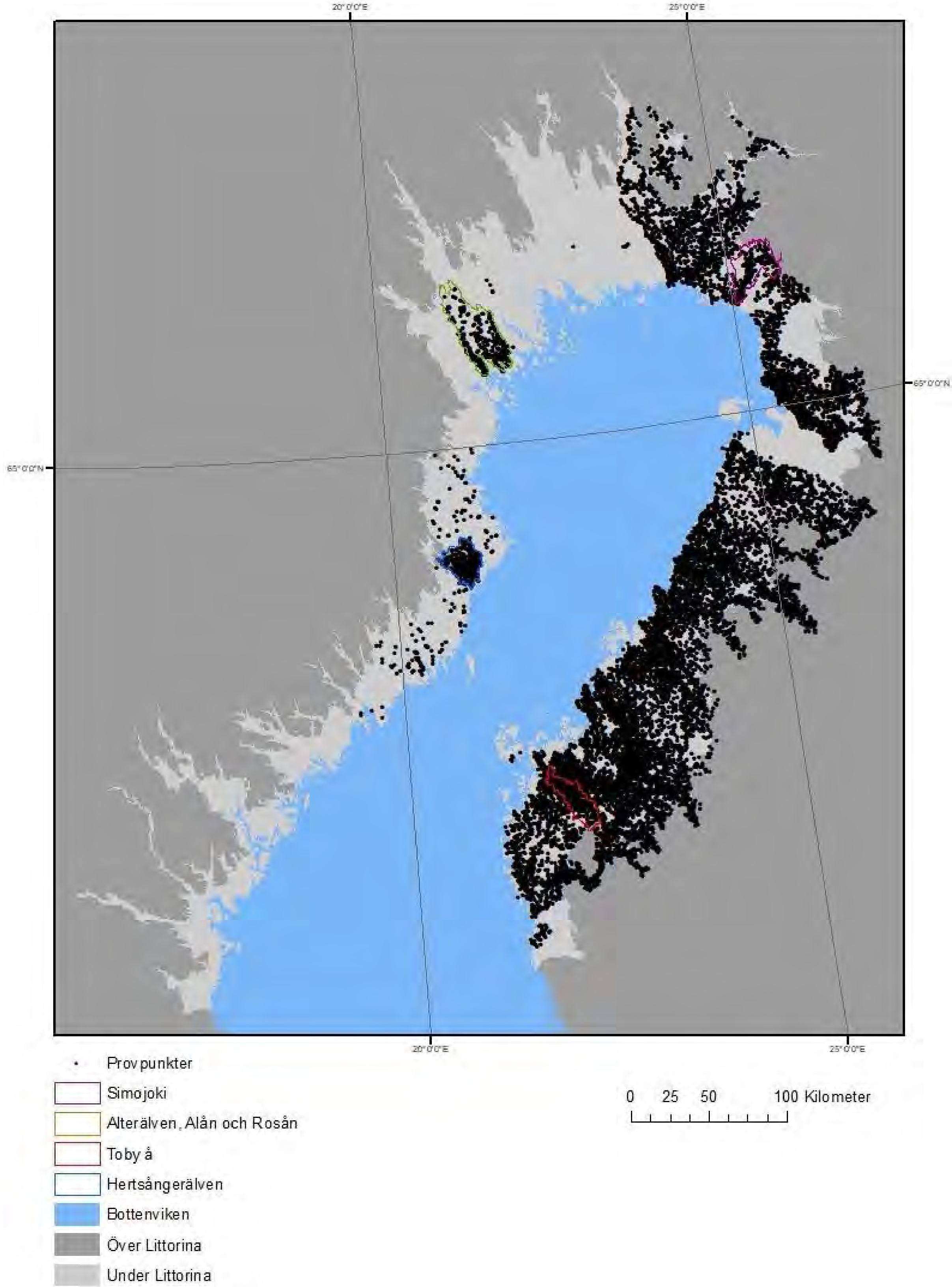

Figure 2. Map of the Gulf of Bothnia where distribution maps have been prepared of potential and active acid sulphate soils. The catchment areas of the Alån, Rosån and Alterälven rivers are highlighted in green and Simo river (Finnish *Simojoki*) in purple. The catchment areas of the Toby å and Hertsångerälven rivers are highlighted red and blue respectively have been investigated as part of an Interreg Botnia-Atlantica project. The black dots represent all sampled localities included in the model of acid sulphate soil incidence in the coastal area of the northern Gulf of Bothnia.

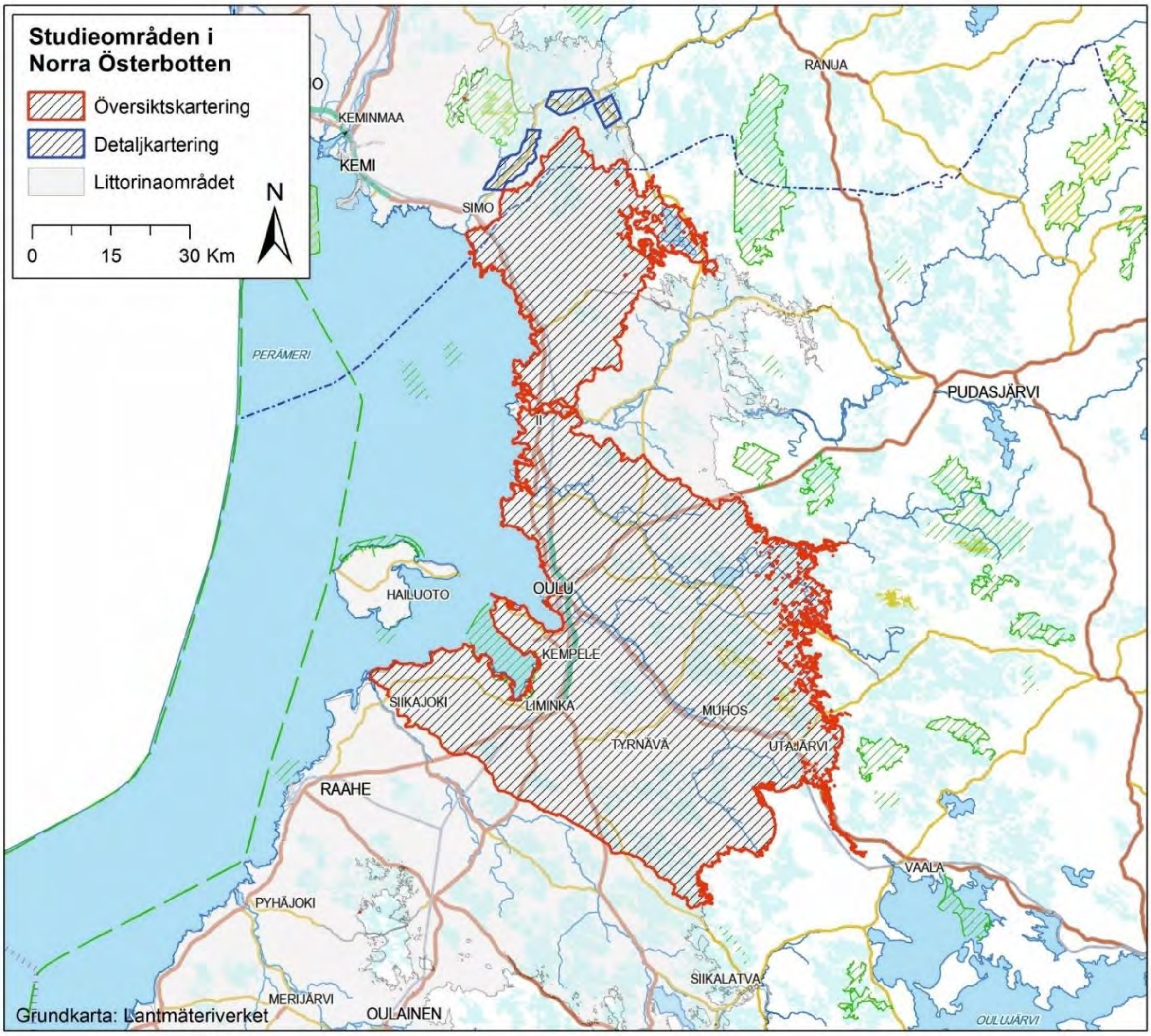

Figure 3. Study areas in Northern Ostrobothnia.

Area description

In *Coastal watercourses* the scope of mapping and the preparation of maps has been different. Field observations have been made for this project in the catchment areas of the Alterälven, Rosån och Alån rivers in Sweden (Figure 2) in 2015-2017, and in Northern Ostrobothnia in the catchment areas located between the Siikajoki catchment area, south of Uleåborg (Finnish *Oulu*), and Simo Älv catchment area (Finnish *Simojoki*) (in Lapland), south of Kemi (Figure Y). Catchment areas in which mapping was carried out in 2015-2018 include the Ule Älv river (Finnish *Oulunjoki*), Temmesjoki (Finnish name only), Kiminge Älv river (Finnish *Kiiminkijoki*), Olhavanjoki (Finnish name only), Kuivajoki (Finnish name only), and coastal areas (Finnish *Perämeren rannikkoalue*) located between these areas. In addition to overview mapping by GTK, detailed mapping of acid sulphate soils has been undertaken in three prioritised areas in the catchment area of the Simo Älv river, with particular emphasis on areas in which rapids restoration has been carried out by project partners (Figure 3).

Physiography

In general the survey area has a topographic incline towards the Bay of Bothnia, this is broken up by multiple river valleys running in the direction of the gradient. The entire survey area is located below the highest coastline, which means that after the continental ice sheet melted the entire area was under the surface of the Baltic Sea. When the ice retreated the Baltic was a freshwater lake.

Relatively quickly marine water penetrated at which time the Littorina boundary formed. Over the last 8,000 years, the coastal areas of the Bay of Bothnia have been gradually drained by land uplift. This is the elastic rebound to mantle equilibrium that has taken place since the removal of the weight of the continental ice sheet. Topographical relief varies within the survey area and generally the topography is flatter on the Finnish side.

In Sweden there are relatively large rivers with catchment areas that extend all the way up to the mountain range (i.e. not just areas below the highest coastline), while in Finland there is a larger proportion of catchment areas mostly located below the highest coastline. However, even in Sweden there are small coastal catchment areas that are wholly or mostly located below the highest coastline and thus can have a large proportion of acid sulphate soils in them.

Geology

In principle the Bothnian Basin covers the entire study area. The rock types associated with this deep-sea basin are metamorphic greywacke, schist, quartzite and arkose. Intrusions of younger granites occur throughout the area.

The soil types are dominated by till and peat (Figures 4 and 5). However, the depth of much peat land has been decimated due to cultivation and peat production, to the extent that the underlying fine sediment has been exposed. This fine sediment consists of silt, clays and gyttja clays, these can be summarised as cohesive soils because of their geotechnical properties. The till is a mixed soil type with everything from clay to block in varying proportions and it has been produced and deposited directly by glacier ice. In and along the sides of the river valleys there are ridges, terraces and the delta, consisting of another glacial soil type, glacifluvial sediment. This contains sand and gravel, sorted by glacial melt water, and was deposited below or along the edge of the retreating continental ice sheet. On and below slopes which have been exposed to wave forces, the soil types deposited by the continental ice sheet have often been rearranged, forming wave-washed sediments of gravel and sand. The glacial soils are partly covered by younger cohesive soils - glacial and postglacial - deposited in water. It is in the postglacial cohesive soils that the vast majority of acid sulphate soils are found. In the very flat landscape that characterises large parts of the Finnish area, there is a relatively high proportion of postglacial fine sediment. In the generally more hilly landscape on the Swedish side the proportion is smaller. In turn this means that the proportion of acid sulphate soils is generally greater on the Finnish side than on the Swedish.

Land use in the survey area varies, generally with distance from the Bay of Bothnia. In the coastal areas there is a greater proportion of postglacial fine sediment which is largely used as agricultural land. Further inland areas of forestry dominate with till and outcrops, as well as bogs. However, in Finland there are areas of fine sediment relatively far from the coast that are cultivated because the landscape is flat. These areas have therefore been covered with water, resulting in the sediments being deposited.

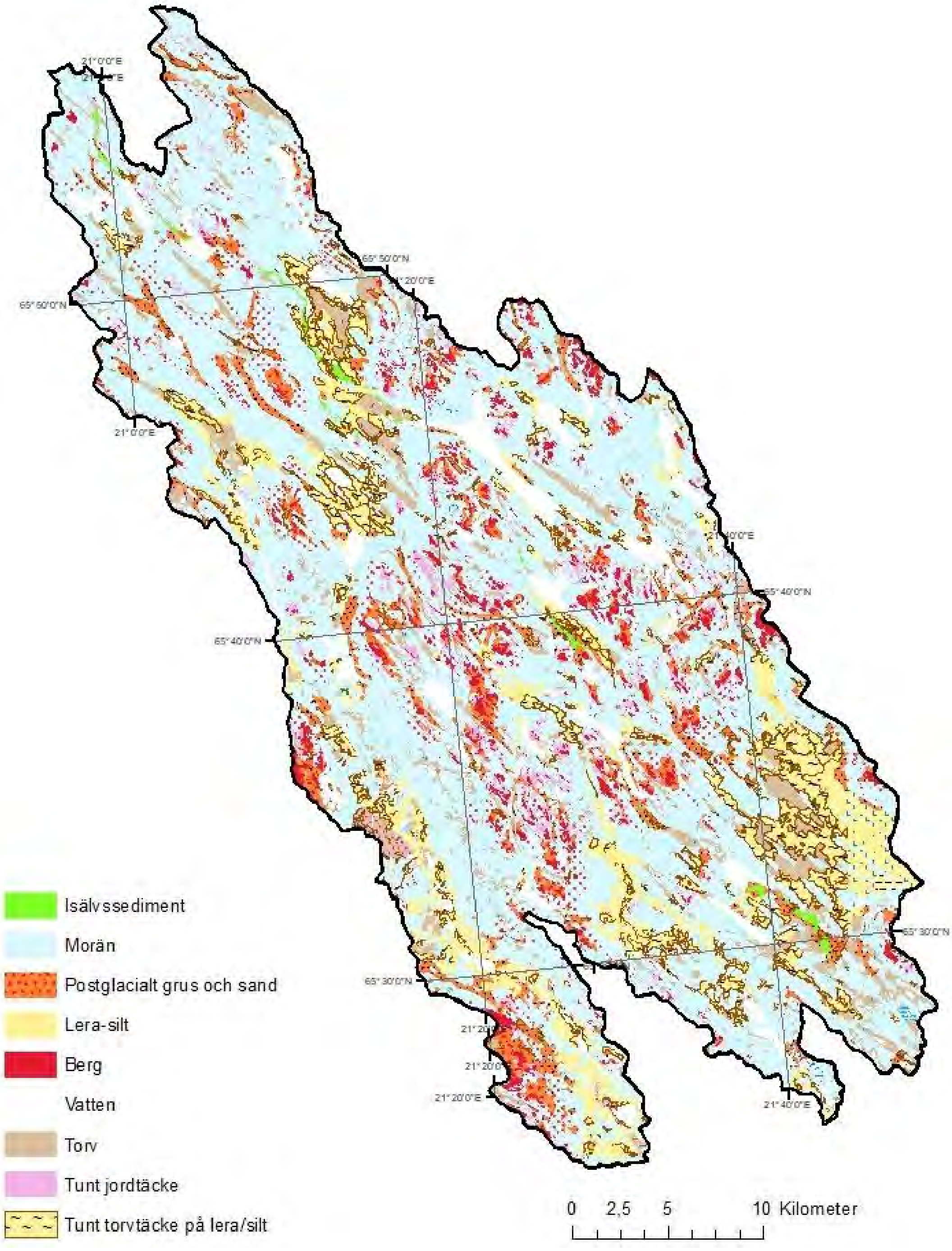

Figure 4. Soil type map according to the SGU soil type classification covering the catchment areas of the Alån, Rosån and Alterälven rivers with sampling points.

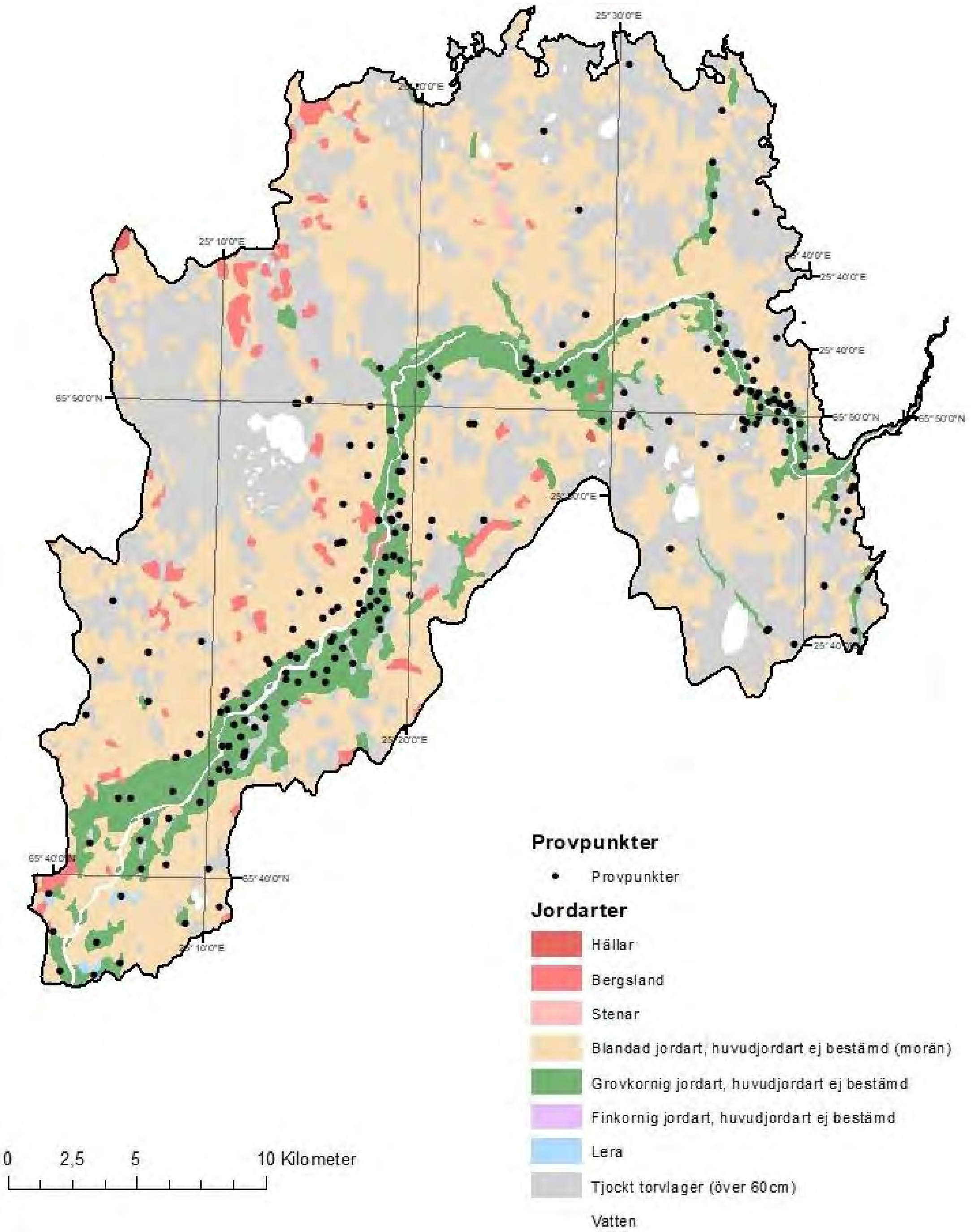

Figure 5. Soil type map according to the GTK soil type classification covering the catchment area of the Simo Älv river (Finnish *Simojoki*) below the Littorina boundary with sampling points.

Test field with controlled drainage

A possible method of reducing the leaching of acidifying substances and metals from drained agricultural land would be to install controllable wells in conjunction with subsurface drainage. Instead of allowing drainage water to drain into open ditches, the subsurface drainage pipes are connected to an outlet pipe that opens into a control well. Using this control capacity, the groundwater level below ground level can be kept as high as possible for much of the year to alleviate the effect of acid sulphate soils. The groundwater level can also be lowered temporarily when the land is being cultivated in order to improve load bearing capacity for heavy agricultural equipment. This extends the cultivation period which improves the conditions necessary for agriculture. Part of the field has been adapted for subsurface irrigation, which can further improve conditions depending on the crop being cultivated. It is also advantageous to keep the groundwater level higher than the subsurface drainage pipes because iron deposits are flushed out with the drainage water, which can otherwise be a problem as it is common for subsurface drainage pipes in agricultural land with acid sulphate soils to be completely blocked by precipitated iron oxides. However, the overall purpose of the measure is to improve water quality in nearby lakes and watercourses. To test the method a test field has been set up in the project.

The field is located about 10 km from the coast of the Bay of Bothnia, near the town Norrfjärden in Norrbotten County. The area of the test field is approximately 3 hectares of cultivated land on the property Porsnäs 44:2 called "Bäverfältet". The underlying soil horizons in the Bäverfältet consist of an approximately 0.4 m layer of topsoil, then an active acid sulphate soil follows down to between 1.5 - 2.0 m deep. The potentially acid sulphate soils, i.e. non-oxidised sulphidic sediment can be found at about 2 meters depth. The area assessed as a suitable test field because there were well-developed active acid sulphate soils and a relatively clear transition zone between the active and potentially acid sulphate soils. The intention is to make it possible to follow any changes in the transition zone and in that way determine whether the availability of the soil for oxidation decreases as a result of the measure.

METHODOLOGY

Selection of sampling points

Experience from previous studies in Finland (Beucher et al. 2014) and Sweden (Fromm 1965, Öborn, 1994; Sohlenius et al. 2015) have shown that active acid sulphate soils (and potential acid sulphate soils) is primarily a problem below the Littorina boundary. The soil types that are of interest are predominantly fine-grained postglacial sediments, but acid sulphate soils can also be formed in other soils such as sand (Figures 4 and 5). Based on these two conditions, the sampling points in Västerbotten and Norrbotten have been sited manually using the national elevation model (Lantmäteriet 2017a [*the Swedish Mapping, Cadastral and Land Registration Authority*), the soil type map (SGU database), land cover data (Naturvårdsverket 2014 [*the Swedish Environmental Protection Agency*]), orthophotos (Lantmäteriet 2017b) and the property map (Lantmäteriet 2017c). To achieve high data resolution, the points were positioned with an approximately 1 km spacing, except where topographical profiles with densely positioned points were established. The points have been distributed across different heights above sea level, inclines of different magnitudes, different soil types and different land uses. The proximity to a serviceable road was prioritised using the property map. On a few occasions a walk of up to 2 km has been necessary to achieve the desired spatial distribution. To the greatest extent possible, locations closer than 20 meters to ditches or channels have been avoided.

The sampling points in Finland were also chosen on the basis of available data (soil type maps, National Land Survey of Finland maps, LiDAR, airborne geophysics, etc.) and a sampling plan was produced in which the points were located with a density of 0.5-1 points per square kilometre. The sampling plan was purely indicative, in the field the sampling point was moved, or abandoned, if circumstances required this. Sampling density ultimately reached almost 0.4 samples per km^2. The sampling and classification of acid sulphate soils largely followed the guidelines in Appendix 1 "Classification of acid sulphate soils in Finland and Sweden". The sampling points were divided into *rapid probe points* and *type profiles*.

Soil sampling

At the rapid probe points in Finland, light sampling equipment (Figure 6) was used, while heavier equipment (Figure 7) was used for type profiles to allow the collection of larger samples. At the rapid probe points (about 95% of the points) soil samples were taken to a depth of 2-3 m, shallower if hard ground (till for example) or rock/stone was encountered. At each rapid probe point soil types, structure, texture, colour, oxidation depth and depth to reduced material were described. The pH was measured in both oxidised and reduced material. At least one sample of reduced material (or from oxidised material if reduced material was not found) from each rapid probe point was collected for further analysis (mainly pH incubation) in the laboratory. There were 2353 rapid probe points.

Figure 6. Sampling equipment used for rapid probing. The soil sampler is 18 mm in diameter and takes a core that is up to 1 m long. An extension probe is used to take samples at depth. A hammer drill is used to insert the sampler into the ground. Photograph: Moa Sunabacka, GTK.

Type profiles were also taken from larger uniform areas with similar soils (about 5% of the points) at a depth of 3 m. The type profiles were described in the same way as for the rapid probe points, but samples were taken at 20 cm intervals (taking into account soil type) and the pH was measured for each 20 cm piece of core. There were 32 type profiles. The samples collected from rapid probe points and type profiles were brought to the laboratory at the GTK for pH incubation (all collected samples).

Figure 7. Sampling equipment used for type profiles. The soil sampler is 32 mm in diameter and takes a core that is up to 1 m long. An extension probe is used to take samples at depth. The sampler is hammered into the ground using an Atlas Copco Cobra breaker. Photograph: Krister Dalhem, GTK.

Samples were sent from each type profile and from about every tenth rapid probe point to a commercial laboratory (Labtium) in Finland for an analysis of sulphur and other elements by aqua regia dissolution followed by ICP-OES. Grain size and loss on ignition were also analysed for a few samples.

Soil profiles in Sweden were taken using an extendable Edelman auger or, occasionally using a soil probe. The auger delivers a core that is approximately 5 cm in diameter divided into 20 cm long pieces, while the probe gives cores with a diameter of approximately 3 cm which are up to one meter long. The soil core was placed on the ground along a ruler and a pH measurement was usually taken every 10 cm using a WTW pH/conductivity meter (Figure 8: wtw.com). The pH value was recorded along with the soil type and colour along the soil core, and the presence of iron precipitation, mineral jarosite or sulphide precipitation was noted. Date, coordinates and a description of the site were also recorded along with relevant land use information. In addition, all locations and the sampled soil were photographed. In most cases the soils with pH below 4 were classified as active acid sulphate soils (see also the section on classification and Appendix 1). A number of samples were taken from selected locations for soil chemistry analysis, i.e. for sulphur, carbon, nitrogen and a number of other elements (see below). In addition, at least one soil sample was collected from each site for pH measurement after oxidation, see next section.

Figure 8. Measurement of pH carried out directly on the soil sample. Photograph: Gustav Sohlenius, SGU.

Oxidation of soil samples

Soil samples for oxidation were taken primarily from material at the bottom of the soil profile where reducing conditions prevail and a pH above 6 was measured. The samples were stored in a "chip tray" with space for 20 samples. After nine weeks, the pH was measured once more using the same instrument. The aim of this was to investigate whether the pH fell when the samples were oxidised, i.e. if the sample was a potentially acid sulphate soil. If the pH had fallen below 4, this indicated that the reduced sample contained sulphidic minerals which, when oxidised, gave rise to acidic conditions. If the pH had fallen below 4 after nine weeks of incubation, the analysis was considered complete. If the pH fell markedly but not sufficiently, the incubation period was extended by 10 weeks or until the pH stabilised.

Classification

After sampling in the field and pH measurement in the laboratory, all soil horizons were classified for each sampling locality in one of five classes of soil layer based on pH criteria (Table 1). Each location was then classified into one of three location classes depending on the classes of soil layer in the soil profile of the location (Table 2). See also Appendix 1.

Table 1. Classes of soil layer with description

ID	Class of soil layer	Description
0	Not assessed	
1	Not acid sulphate soil	A or B horizon pH > 4
2	Not sulphide soil	C horizon where the pH after incubation is > 4
3	Acid sulphate soil	A or B horizon where pH <4 or <4.5 where the horizon is underlain by sulphide soil
4	Transition zone	Horizon between B and C where the pH in the field is between 4.5 and 6, and after incubation <4.
5	Sulphide soil/sulphidic sediments	C horizon where the pH after incubation is <4 and the pH in the field > 6

Table 2. Location classes with the classes of soil layer included.

Location class	Modelling class	Class of soil layer
Not acid sulphate soil	Not sulphate or sulphide	not 3 or 5
Active and potentially acid sulphate soils	Sulphate on sulphide	3 and 5
Potentially acid sulphate soils	Sulphide	5

Soil chemistry

To investigate whether some elements have been mobilised from active acid sulphate soils, samples from more than 20 Swedish locations were analysed using inductively coupled plasma mass spectrometry (ICP-MS) at SGU. A total of just over 90 samples were analysed for the 52 elements: aluminium (Al), arsenic (As), barium (Ba), boron (B), beryllium (Be), lead (Pb), cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), phosphorus (P), gadolinium (Gd), germanium (Ge), holmium (Ho), iron (Fe), cadmium (Cd), calcium (Ca), potassium (K), cobalt (Co), copper (Cu), chromium (Cr), lanthanum (La), lithium (Li), lutetium (Lu), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), neodymium (Nd), nickel (Ni), niobium (Nb), praseodymium (Pr), rubidium (Rb), samarium (Sm), Selenium (Se), silver (Ag), scandium (Sc), strontium (Sr), thallium (Tl), tin (Sn), terbium (Tb), titanium (Ti), thorium (Th), thulium (Tm), tungsten (W), vanadium (V), bismuth (Bi), ytterbium (Yb), yttrium (Y), uranium (U), zinc (Zn), and zirconium (Zr). Each sample consisted of 2 g of weighed material in the <63 μm fraction, and was leached with nitric acid solution (15 ml dilute nitric acid, 7 M HNO_3 added, for 50 minutes on a hot plate). This method extracts the proportion of elements that can be dissolved into solution and is not an analysis of the total amount of the elements in the samples (i.e. no melt that releases elements bound into heavily weathered minerals).

Sulphur was also analysed at SGU using ICP, but using optical spectrometry (OES) as the detection method. The purpose of sulphur analyses was to determine whether the reduced soils contained sulphidic minerals, which would be indicated by high levels of sulphur.

Total concentrations of carbon and nitrogen were analysed at the Swedish University of Agricultural Sciences (SLU) by measuring the concentration of gases produced by the combustion of samples at 1,250 °C (Leco CN-2000 dry combustion analyser). Some of the samples were analysed for organic carbon, this was determined by measuring the concentration in the gases produced by the combustion of samples at 550 °C. The amount of carbon bound in carbonate minerals can then be calculated as the difference between the total carbon content and organic carbon. The organic carbon content was analysed to better characterise the soils, as well as to compare the content of organic material and the occurrence of sulphidic minerals.

Titan (Ti) is an immobile substance (Österholm and Åström 2002) that cannot be expected to be mobilised from active acid sulphate soil. However, the levels may vary because on extraction using nitric acid, fine-grained soil will release more titanium than coarse-grained soil. This effect of grain size applies to all of the analysed elements, i.e. coarse-grained soils will generally have lower levels of trace elements/metals than fine-grained ones. If the grain size varies in one and the same soil profile, this can lead to erroneous conclusions as to the substances that could be mobilised from an active acid sulphate soil. However, by using the ratio of an element and titanium, it is possible to get an idea of whether the element has been mobilised from a soil profile. In some cases, substances mobilised from an active acid sulphate soil can accumulate further down in the soil profile, in the transition zone. This can also be determined by dividing the concentrations by titanium.

Sediment sampling

During the winter of 2017, sediment samples were taken at the mouth of the Rosån river and in lakes located within the Rosån catchment area. This work was carried out within the framework of a degree project carried out by Carola Lindström from Uppsala University ("Sura sulfatjordar och ackumulation av metaller i sediment från Rosåns avrinningsområde, norra Sverige [*Acid sulphate soils and the accumulation of metals in sediment from the catchment area of the Rosån river, Northern Sweden*]; Lindström 2017). The work was supervised by Ian Snowball from the same university. One aim of the work was to find out if the metals and other elements leaching from acid sulphate soils accumulate in the sediments deposited in close proximity to the affected watercourses. Another aim was to investigate whether the amount of accumulated metal had increased in connection with extensive drainage resulting in the formation of acid sulphate soils. The surface samples were taken with a Willner type surface sampler (Figure 9). These surface sediments have a high water content and it is therefore not possible to transport the entire core to the laboratory undisturbed. The core was therefore sliced in-situ at two centimetre intervals. To ensure that sediment deposited before drainage was started was sampled, a Russian chamber corer was used to sample the deeper layers of sediment. The samples were taken from ice, making it possible to take relatively undisturbed samples from a stable platform. Samples were taken from two lakes where there are large proportion of acid sulphate soils upstream (Övre Träsket and Nedre Träsket lakes, Figure 10). In addition, samples were taken from a lake with a catchment area which, according to our studies, does not have acid sulphide soils (Brännträsket, Figure 10). Finally, samples were taken in the ocean off the mouth of the Rosån river (Figure 10). The concentrations of metal were determined using the same methodology used to analyse the samples taken on land (see the section above). The most exposed sediments were dated at Umeå University using lead-210. The natural radionuclide lead-210 was used to date the sampled sediment layers, that is to say determine when in the last 150 years the sediment was formed. The activity of lead-210 was determined by measuring the activity of its daughter element polonium-210 (^{210}Po). The sediment samples were completely dissolved using microwave-assisted digestion and then deposited on silver plates (Sanchez-Cabeza et al., 1998) using ^{209}Po as a trace element. The Po activity was then measured using an Ortec ULTRA-AS Ion-Implanted-Silicon Charged-Particle Detector (Model U-020-450-AS). The relationship between age and depth for the sediment profile was determined using the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1978), and dating using ^{210}Pb was validated using the occurrence of the artificial radionuclide cesium-137 (Appleby 2001).

Figure 9. On the left The surface samples were taken using a Willner type surface sampler. The core was therefore sliced in-situ at two centimetre intervals. On the right The deeper sediments were sampled using a Russian chamber corer. Photograph: Gustav Sohlenius, SGU.

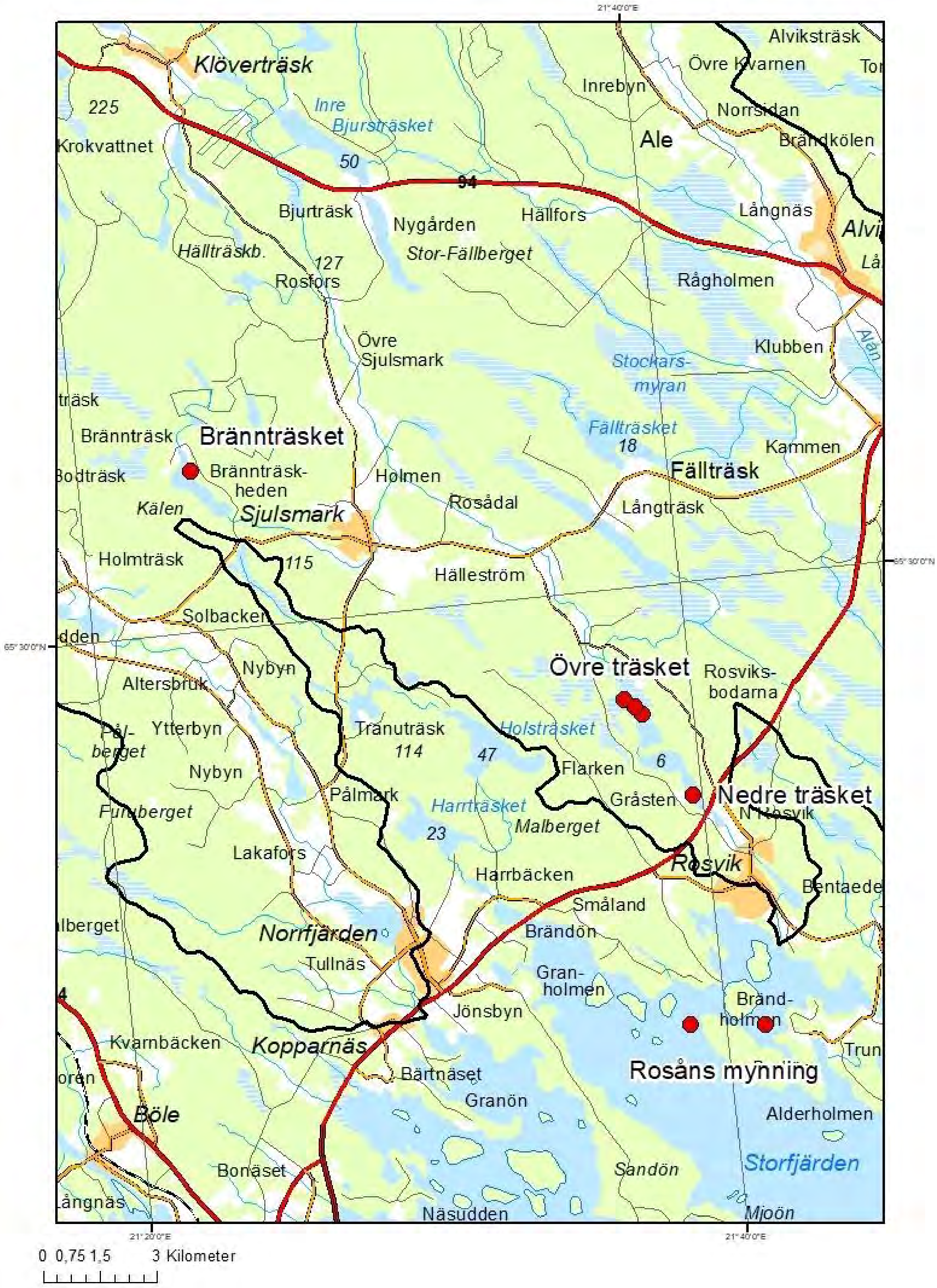

Figure 10. The locations of the sampled sites for sediment sampling. The two locations furthest to the south are in the coastal area by the mouth of the Rosån river. Upstream of the Övre Träsket and Nedre Träsket lakes, in the area around Sjulsmark, there is a high proportion of active acid sulphate soil.

Sketch maps

The area in which overview mapping was carried out in Northern Ostrobothnia is approximately 5,464 km^2 and a total of 2,324 observations have been made. All of the collected observations are used to make distribution sketch maps in a scale of 1:250,000 of the extent of acid sulphate soils in the area. Distribution sketch maps are produced by an expert with a good working knowledge of acid sulphate soils and quaternary geology. In short, the process is based on collected data (field observations and analyses) being used in conjunction with available data such as soil type maps, airborne geophysics and LiDAR (high resolution topographic maps) to prepare the overview maps. So far, an overview map, based on field data from 1,054 sampling points collected in 2015-2017, has been completed for an area of approximately 3,106 km^2 (56.8% of the entire study area; Figure 23). In the autumn of 2018 maps of the remaining area will be completed. The probability maps produced by GTK are published as part of the GTK map service (http://gtkdata.gtk.fi/hasu/index.html) and are available to the public.

Modelling

Maps that show the areas in which the incidence of active and potentially acid sulphate soils is likely, have been prepared using modelling. An overview map of the Coastal Area of the northern Gulf of Bothnia has been prepared, as have two detailed maps, one for the catchment area of the Simo Älv river (Finnish *Simojoki*) (89 km^2) and one for the catchment area of the Alterälven (458 km^2), Alån (592 km^2) and Rosån (196 km^2) rivers. The models are based in part on the observations made in the Interreg project (*Coastal watercourses*) and the Interreg project VIMLA, and in part on other available information, such as soil type maps. Not all observations made as part of the project have been included in the modelling because they were not entered into the database at the time of modelling. Furthermore, a volume calculation of active acid sulphate soils within the three catchment areas in Norrbotten has been produced.

Distribution maps

To allow the preparation of distribution maps showing the incidence of acid sulphate soils, geospatial numerical modelling has been used. The relationship between the response variable (the incidence of acid sulphate soils in a specific location) and environmental variables (such as the national elevation model and soil type map) has been used to predict the probable class of locations that have not been investigated. In this project, the Random Forest modelling method has been used with the Random Forest tool in the R statistics program (R Core Team 2014). Random Forest is a classification algorithm (Breiman, 2001) that builds a large number of classification trees that are combined into a final result. To carry out a validation of the models, the observations from the response variable were divided into two parts, where 70% of the observations were used to train the model and 30% to validate the model.

The preparation of a probability map for acid sulphate soils in the coastal area of the northern Gulf of Bothnia (Figure 2) includes observations from both the SGU and GTK. The GTK mapping of acid sulphate soils in Finland over the past nine years includes over 10,000 observations that have been classified into two classes: ‘not acid sulphate soil' and 'acid sulphate soil'. In recent years, the SGU has documented a significantly fewer number of locations (slightly over 1,000 observations) and has then used three classes: 'not acid sulphate soil or sulphide soil', 'acid sulphate soil on sulphide soil' and 'sulphide soil'. To prepare the map of the northern Gulf of Bothnia, the Swedish observations have therefore been classified into two classes. To prepare a map of the small catchment areas (Figure 2), the Finnish observations in the Simo Älv river (Finnish *Simojoki*) have been reclassified to the three classes used in Sweden.

The national elevation model with 20 m pixels (reduced from 2 m) and parameters from it (Tables 3 and 4) were used as environmental variables. The parameters from the national elevation model are calculated in SAGA GIS (Conrad et al. 2015) from two libraries, ta_morphometry (Table 3) and Ta_hydrology (Table 4). For the two small catchment areas, the soil type map was used as an additional environmental variable. To increase the accuracy of the model, 1215 points were used where, based on the soil type map, we deemed that acid sulphate soils could not be found on the soil map. These points were taken at random from areas with rock, thin overburden or till on the soil type map. On the Swedish side, soil type maps with a scale of 1:25,000 were used at best, down to 1:250,000 at worst. Polygons of the three selected classes were merged and buffered negatively 200 meters to minimise the margins of error along the map boundaries, then points were removed at random.

When presenting this modelling, 'total accuracy' and 'kappa' are used. Total accuracy is calculated as the number of correctly classed observations divided by the total number of observations. Kappa tells you how much better, or worse, the classification is than by random chance.

Table 3. Parameters from the library ta_morphometry.

Parameter	Description
Slope (slope)	Slope of the land surface
Multiresolution Index of valley bottom flatness (mrvbf)	The degree of valley and bottom flatness
Relative Heights (valdepth)	How deep the valley is
Slope position (midslope)	Where on the slope
Terrain surface convexity (TSC)	The ratio of the number of convex cells to all cells
Terrain Ruggedness Index (TRI)	Terrain heterogeneity
Topographic Position Index (TPI)	Location higher or lower than the surrounding area

Table 4. Parameters from the library ta_hydrology.

Parameter	Description
Flow accumulation (flowaccu)	Simplest flow path for each cell
Slope length factor calculation (slfactor)	Slope length
Saga wetness index (sagawi)	The relationship between the catchment area and slope to reflect flow accumulation

The model created is used in conjunction with all environmental variables to predict the incidence of acid sulphate soils throughout the area. For each location the value of each environmental variable is obtained and the probability for each class at the location is calculated. The result is a probability map for each class. A map is also prepared for visualisation showing the class that is most likely to occur for each specific location. The modelled distribution map of the catchment area of the Simo Älv river (Finnish *Simojoki*) drainage area was compared to the distribution sketch map prepared by specialists at the GTK and based on the same sampling points as the modelling.

Volume calculation

To calculate of the volume of active acid sulphate soils in the three catchment areas in Sweden that were investigated as part of this project, another classification algorithm has been used, multiple linear regression (Venales & Ripley, 2002), to prepare distribution maps and probability maps of active acid sulphate soils. The modelling method has been used with the Multinom tool in the R statistics program (R Core Team 2014). Multiple linear regression is linear regression that is used to explain the relationship between a continuous independent variable and two or more dependent variables (environmental variables). To calculate the depth of active acid sulphate soils, the Quantile Regression Forests classification algorithm is used (Meinshausen, 2006) using the quantregForest modelling method in the R statistics program (R Core Team 2014). The depth of each pixel has been calculated throughout the area based on the depth of active acid sulphate soil measured in the field and on environmental parameters. Because the depth of active acid sulphate soils was calculated throughout the area, the results from the multiple linear regression model were used to exclude those areas that do not have active acid sulphate soils. The modelled depths in each pixel are then multiplied by the probability of the incidence of active acid sulphate soils for that particular pixel, in order to calculate likely depth for each pixel. The sum the probability depth for all pixels is multiplied by the pixel resolution (20*20 m) so as to calculate the volume of active acid sulphate soil in the catchment areas of the Alterälven, Rosån och Alån rivers.

The results of the volume calculation were then used together with the results of the soil chemistry to calculate the likely amount of different metals mobilised from the area.

Test field with controlled drainage

In Finland similar test fields have been established in the past (Uusi-Kämppä et al. 2013). The County Administrative Board of Norrbotten engaged Österbottens Svenska Lantbrukssällskap (Pro Agria) to plan and lead remedial work in the field. In consultation with the County Administrative Board, a drainage plan was drawn up for the field with the aim of adapting the trials to actual field conditions (Appendix 2).

The field consists of about 3 hectares of cultivated land with a flat and a steeper section. The flatter area is located in the south west of the field and is suitable for the control of drainage outflow. The steeper section is located in the north east of the field and is more suitable for drainage without control. The ground on the flat southern area was very wet before the test field was set up and has not been possible to cultivate for many years. The lowest part of the test field consists of three controlled areas (sub-area 1 – 3) separated from each other by a 1.5 m high reinforced plastic sheet installed to an average depth of 1.9 m. The plastic film minimises the diffuse leakage of groundwater from the field and forces drainage water to pass through the well on each field. No plastic film has been installed on the uncontrolled, highest section (sub-area 4). The top layer of the entire field (about 0.4 m) will constitute a coherent and cultivable field of approximately 3 ha. The total length of installed plastic film is 822 m.

Sub-area 1 comprises 0.72 ha and is the lowest area of the test area (Appendix 2). This area is delimited with plastic film (installed as above) but has not been equipped to regulate the groundwater level. Sub-area 2 comprises 0.60 ha delimited with plastic film and has been provided with a control well. Sub-areas 1 and 2 slope downwards approximately 0.2 - 0.3 m from north east to south west. Sub-area 3 comprises 0.54 ha with plastic film, a control well and an intake chamber; making it possible to supply water to the area from nearby surface water during dry periods in order to maintain the subsurface irrigation. In sub-area 3 the slope is slightly higher compared to areas 1 and 2, about 0.5 - 0.7 m. Sub-area 4 comprises 1.25 ha, which is neither delimited with plastic film nor provided with a control well. This area is the highest in the test field and also has the highest slope, approximately 2.5 m.

A bed of gravel was laid in the bottom of the subsurface drainage gulley to reduce the transport of soil particles into the drainage water. In sub-area 4 the gravel was replaced with wood chips. The intention is for the organic material in the chips to bind iron and thereby prevent the pipes from being blocked by iron precipitation. Sub-area 4 is not controlled; this means that the groundwater level will be lower than the subsurface drainage pipes to a large extent. The surrounding open ditches were cleared in the winter of 2016. Subsurface drainage and wells were installed in the summer and autumn of 2016.

The control depth at the wells is set to 70 - 80 cm. The control system can be opened so that the drainage water flows straight through the well into the open ditch system. The control system can be opened when snow is melting to enable mechanised agriculture in the spring, and then closed to keep the surface of the groundwater as high as possible to minimise oxidation in the ground and the formation of acid sulphate soils.

Monitoring the remedial measure

Measurement of groundwater levels

Groundwater levels have been measured continuously in each sub-area so as to monitor how the drainage is working in various hydrological states (Appendix 3). Groundwater pipes have been installed within each of the four sub-areas (GR1, GR2, GR3 and GR4) in which the groundwater level is measured using a pressure logger suspended at a fixed height above ground level. Atmospheric pressure is also measured using a logger in order to calculate the difference in pressure from the groundwater level down to the installation depth of the logger.

$$p_x = p_h - p_a$$

(Where p_x = pressure difference between installation depth of the logger - atmosphere [kPa], p_h = absolute pressure at the installation depth of the logger [kPa], p_a = absolute atmospheric pressure [kPa])

The distance from the groundwater level to the installation depth of the logger has been calculated according to:

[icke kopierbar formel. Ö.a.]

(Where h = distance groundwater level - installation depth of the logger [m], p = the density of the groundwater, g = weight acceleration [m/s^2]. has been set at 9.82 m/s^2 in the calculation).

Finally, the distance from ground level to the groundwater level has been calculated by subtracting h from the distance between ground level - installation depth of the logger:

$$h_{GVY} = h_i - h$$

(Where h_{GVY} = groundwater level (m) and h_i = distance between ground level - installation depth of the logger).

The pressure has been logged every hour, and the daily mean values have then been calculated from that data to provide a more manageable dataset. The groundwater level has also been measured using a water level meter in the field on four occasions. These data have then been compared to logged data (h_{GVY}) using a scatter plot in Excel (Figure 11). Linear regression equations have been calculated from these diagrams using Excel for each of the monitored groundwater pipes. The regression equations have then been used to calibrate logged data against data measured in the field. The linear fit between the datasets compared was good as the coefficient of determination (R^2) was greater than 0.99 for all four groundwater pipes. The calibrated groundwater level was calculated by setting $x = h_{GVY}$ in the equations in Figure 1. The y calculated is the calibrated groundwater level given in meters below ground level.

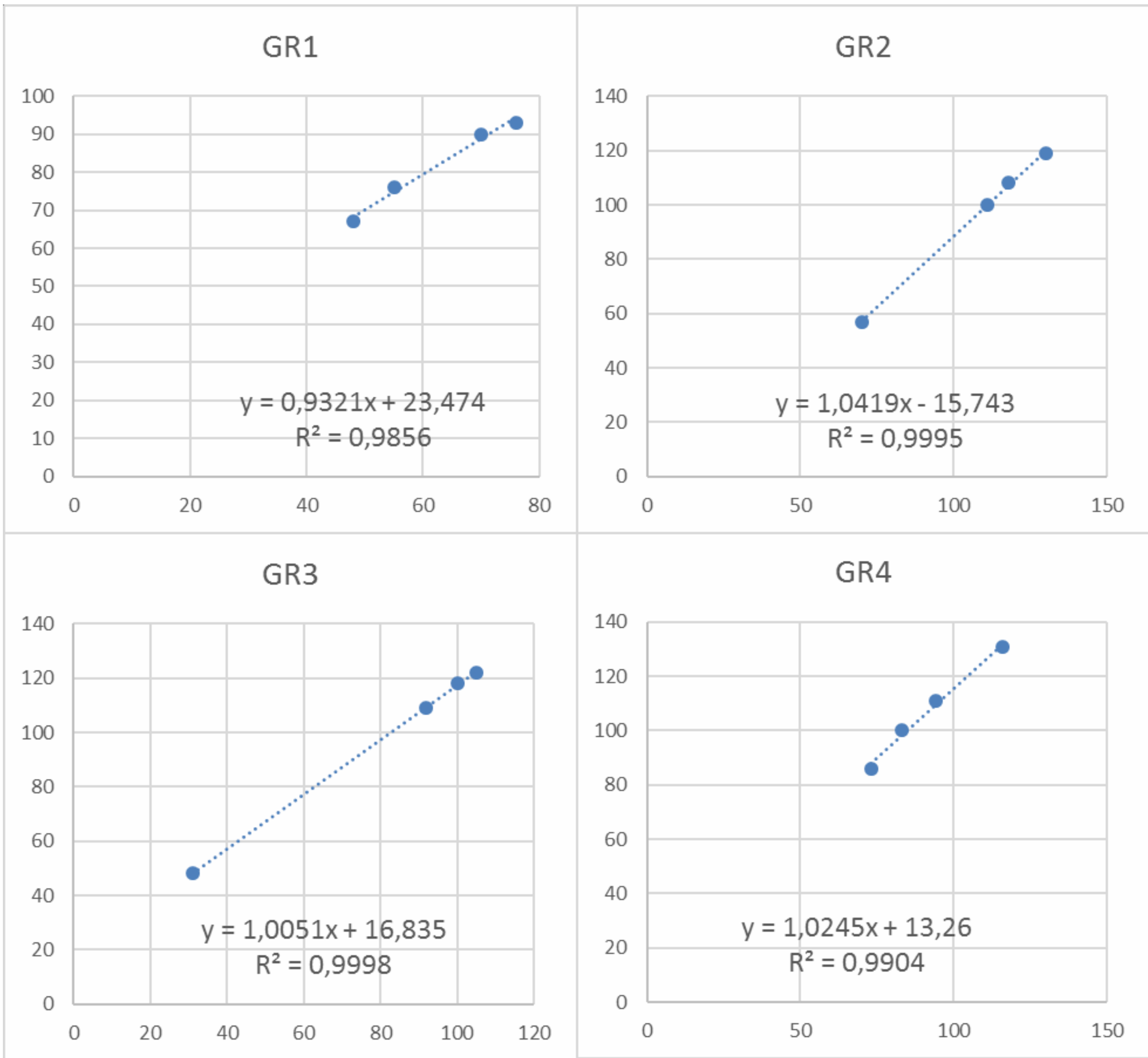

Figure 11. Simple linear regression analysis for measured (y) and logged (x) groundwater levels in four groundwater pipes. The regression equation was used to calibrate logged levels to actual measured levels.

Drainage data has been obtained from the SMHI [*Swedish Meteorological and Hydrological Institute*] water web (2018), which is modelled data for sub-area 41802 in which the test field is located.

Measurement of water chemistry parameters

Water chemistry parameters have mainly been measured through field measurements of pH and conductivity as well as the logging of conductivity. The water chemistry has been measured both before and after the construction of the controlled drainage, in both the surface and the groundwater. The conductivity of the water (electrical conductivity) has been assumed to be the most important water chemistry parameter to measure because conductivity is strongly influenced by the elevated sulphate content resulting from potentially acid sulphate soils changing into active acid sulphate soils (Myrstones, 2012). It is mainly aluminium and trace metals that are important from water sampling because as these substances can be directly fatal (aluminium precipitation on fish gills can cause fish death) or toxic. The purpose of water chemistry monitoring is to be able to measure whether the leaching of acidifying substances and metals decreases over time after the remedial work has been carried out. The time horizon for such monitoring is probably longer than the period of the project. However, it is the ambition of the County Administrative Board to continue to monitor the water chemistry after the project period has expired.

Field measurement of pH and conductivity was performed using a Hach HQ 30d measuring unit with Hach CDC40105 conductivity sensor and Hach PHC10105 pH sensor. Individual measurements were carried out using the Hanna HI991300 field instrument which measures the pH and conductivity using the same sensor. All measurements were carried out according to the manufacturer's instructions using calibration solutions with known conductivity and pH values. All pH calibrations were carried out as two point calibrations with pH 4 and pH 7 calibration solutions. To streamline the measurement procedure in the field, water was collected in sample containers from each sampling point. Conductivity and pH were then measured in the sample containers within 1.5 hours of sampling. Groundwater was taken from the groundwater pipes using plastic disposable bailers. Water samples for the analysis of chemical elements were taken directly in sample containers from surface water and using disposable bailers from groundwater pipes. Samples were sent for analysis to an accredited laboratory on the day of sampling.

Logging conductivity has been carried out at the groundwater pipes installed before controlled drainage was installed (GR0) and at all wells (BR1, BR2 and BR3). See Appendix 3 for the positions of the measurement locations in the field. The parameters logged were conductivity and temperature. The logged conductivity was temperature corrected to a specific conductance at 25 °C based on the formula (according to the manufacturer's instructions):

$$Y_e = C_S \cdot (1 - ((25 - T) * a/100))$$

(*Där* Y_e *= loggad konduktivitet [µS/cm], T = vattentemperatur [°C],* C_S *= specifik konduktans vid 25°C, a = linjär temperaturkoefficient [%/°C]*).

A value was used for *a* that was calculated from the above formula with known values for specific conductance measured in the field (C_s *[µS/cm]*, logged conductivity (Y_e *[µS/cm])* and logged water temperature (*T [°C]*). Data from 11 measurements were used for conductivity logging in GR0, giving an average of 1.90%/°C (Table 5), which is close to the value of 1.91 recommended according to US standards for water investigations (*standard methods.org*,2018). could then be calculated for the entire logged data set using values from 22 March 2016 to 16 May 2018.

Table 5. Account of the calculated values of the linear temperature coefficient a using data from 11 measurements in groundwater from GR0 and the calculated averaged a value used to calculate temperature-corrected specific conductance.

Date	***T***	Y_e	C_s	***a***
22/03/2016	1.90	505	907	1.92
20/04/2016	1.64	521	830	1.59
13/05/2016	3.52	495	653	1.12
14/06/2016	7.54	561	758	1.49
28/06/2016	9.14	580	813	1.80
10/08/2016	12.29	527	802	2.70
26/10/2016	7.81	516	804	2.08
21/11/2016	5.46	321	823	3.12
21/06/2017	5.28	939	1212	1.14
09/10/2017	8.88	636	872	1.68
25/10/2017	8.06	580	947	2.29
Average value, *a*:				**1.90**

The same calculation was made for conductivity logging in the well. Due to error when reading the logger at BR3, data before 9 October 2017 is missing for sub-area 3. Data from nine measurements were used which gave an average value of 2.50%/ºC (Table 6), which is higher than the value calculated for GR0.

Table 6. Account of the calculated values of the linear temperature coefficient a using data from 9 measurements in well water from BR1, BR2 and BR3 and the calculated averaged a value used to calculate temperature-corrected specific conductance.

Date	Well	*T*	Y_e	C_s	*a*
21/06/2017	BR1	5.26	661	1442	2.74
17/07/2017	BR1	7.34	705	1465	2.94
26/09/2017	BR1	9.08	669	1580	3.62
09/10/2017	BR1	8.59	696	1217	2.61
21/06/2017	BR2	7.33	760	1052	1.57
17/07/2017	BR2	11.01	644	1065	2.82
26/09/2017	BR2	9.32	622	927	2.10
09/10/2017	BR2	8.68	661	890	1.57
09/10/2017	BR3	8.74	645	1093	2.52
Average value, *a*:					**2.50**

Investigation of the transition zone between active and potentially acid sulphate soil

To determine whether the transition zone between active and potentially acid sulphate soils has moved in the soil horizons, soil profiles have been taken before and after the remedial measure. If the groundwater level had changed in the field as a result of the controlled drainage, then the conditions for oxygen to penetrate the soil should also have changed. Some displacement of the transition zone between the active and potentially acid sulphate soils is therefore anticipated. In each soil profile, the pH of the soil is measured every 20 cm, and in some selected profiles samples are analysed for elements from the layers of active acid sulphate soils, the transition zone and the potentially acid sulphate soils.

RESULTS

Field observations and chemical analyses

The catchment areas of the Alterälven, Alån, and Rosån rivers

In 2016 and 2017, 361 locations in the catchment areas of the Alån, Rosån and Alterälven rivers were sampled. 4,435 pH measurements were made in the field and 504 samples were taken to the laboratory to oxidise for 10-19 weeks. Of the samples in the laboratory, the pH fell to less than 4 in 250 of the samples, in the other 254 samples the pH did not fall below 4. Using the pH measurements in the field and in the laboratory, each location was classified into one of the three modelling classes: 'not sulphate soil or sulphide soil', 'sulphate soil on sulphide soil' and 'sulphide soil'. Most of the locations visited, 178, were classified as 'not sulphate or sulphide soils', 102 locations were classified as 'sulphate soil on sulphide soil' and 81 were classified as 'sulphide soil'.

According to the soil type map, the majority of the sampled 'sulphate on sulphide soils' and 'sulphide soils' were in clay/silt areas, while the sulphide locations were largely in peat, clay and silt areas (Figure 12).

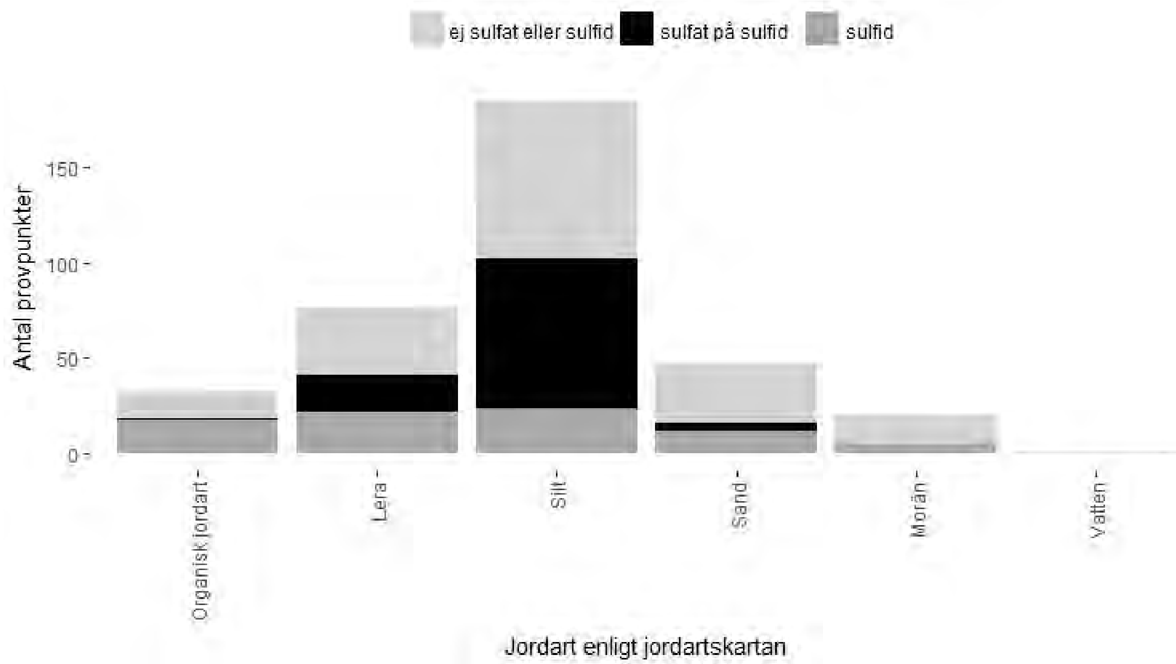

Figure 12. The distribution of classified sampling locations for the soil types detailed on the SGU soil type map.

Most of the sampling points are on arable land where the class 'sulphate soil on sulphide soil' dominates (Figure 13). None of the sampling points classified as 'sulphate soil on sulphide soil' come from higher than 90 masl (Figures 14 and 15), but a few sulphide locations were found up to 130 masl (Figure 14). The Littorina boundary in the area is approximately 160 masl.

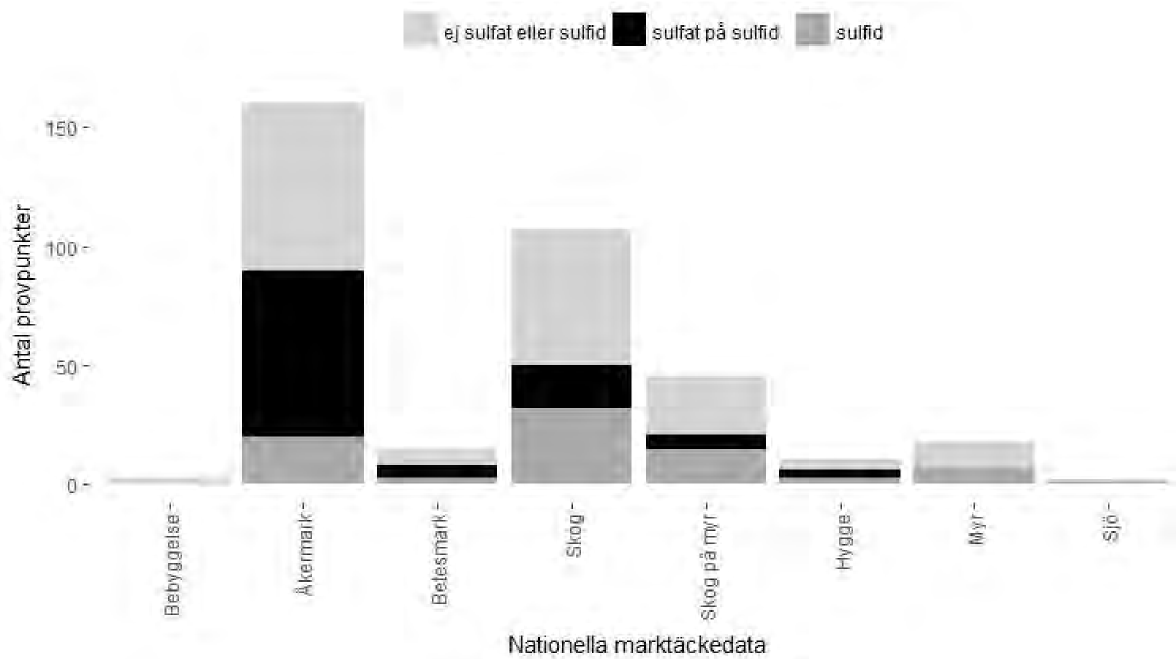

Figure 13. The distribution of classified sampling locations according to the Swedish national land cover data.

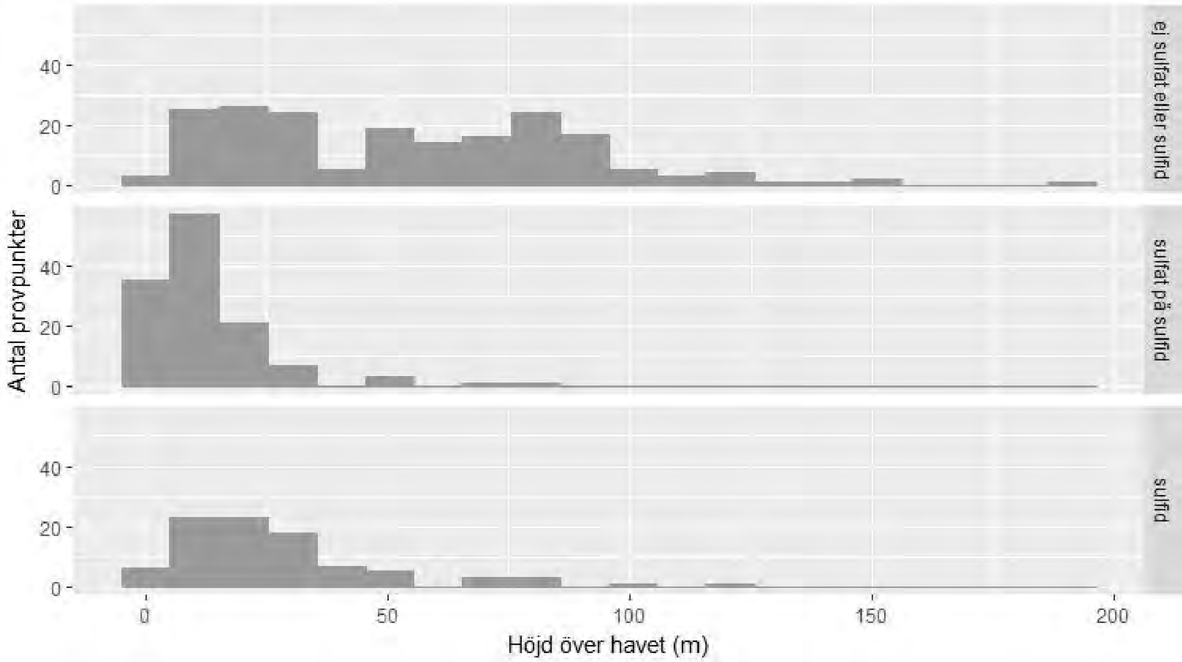

Figure 14. The distribution of classified sampling locations as a function of height above sea level.

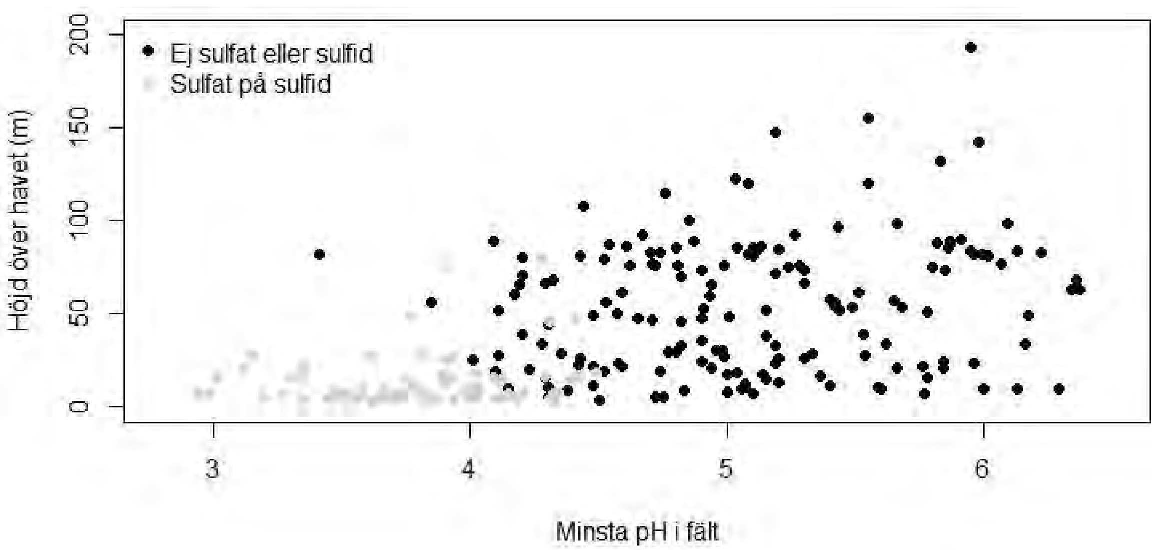

Figure 15. Minimum pH in the field vs. height above sea level for each sampling location with an oxidised layer.

Soil chemistry

A selection of results from four of the 46 locations investigated (Porsnäs 2, Figure 16, Sjulsmark 1, Figure 17, Farbrorsmyren, Figure 18, and Kvarnmyran, Figure 19) are presented below. The locations were chosen to represent both soils classified as active acid sulphate soils (Porsnäs 2 and Sjulsmark 1) and locations that had not received that classification (Farbrorsmyren and Kvarnmyran). All locations are within the three catchment areas surveyed in Sweden. Farbrorsmyren is a formerly cultivated field that had been abandoned relatively recently. The other three locations are used today as cultivated fields. Porsnäs 2 is located at the site (Bäverfältet), where the County Administrative Board started a trial to reduce the impact of acid sulphate soils through controlled drainage. All the locations are made up of clay/silt according to the soil type map. Porsnäs 2 is 4.5 masl, Sjulsmark 1 16.8 masl, Farbrorsmyren 86 masl and Kvarnmyran 26 masl.

The concentrations of the analysed metals have been divided by the titanium (Ti) content to compensate for differences in metal concentrations caused by variations in the grain size distribution of the soil profiles. The locations Porsnäs 2 (Figure 16) and Sjulsmark 1 (Figure 17) have been classified as active acid sulphate soils, where the deepest samples comprise potential acid sulphate soils (sulphidic soils). These two locations are characterized by a pH of less than 4 in the top soil horizons, while the pH is above 6 in the lower samples. However, when these deep samples had oxidised in the laboratory, the pH decreased to below 4. The Farbrorsmyren (Figure 18) and the Kvarnmyran åker (Figure 19) locations are characterized by higher pH values and have consequently not been classified as active acid sulphate soils. However, the samples from Kvarnmyran from the deepest levels have a post incubation pH below 3. This locality has consequently been classified as potentially acid sulphate soil. Even the deepest sample from Farbrorsmyren has a significantly lower pH following incubation than in the field. However, the pH is not sufficiently low for the locality to be classified as potentially acid sulphate soil. Samples of active acid sulphate soils were also taken from the Porsnäs 2 and Sjulsmark 1 localities for incubation. The results show differences after incubation. Several of the samples from active acid soil from Porsnäs 2 exhibit a significantly lower pH after oxidation. This may be because sulphide minerals have remained in active acid soils which oxidised during incubation and then gave rise to even more acidic conditions. In several cases the samples from Sjulsmark exhibit a higher pH after incubation, which indicates that the values measured in the field were too low. It should be noted that the pH values measured in the field were significantly lower than those usually measured in active acid sulphate soils present in the area.

Variations in Ti concentrations are likely to reflect variations in the grain size composition where low concentrations of Ti are an effect of relatively coarse grained material. For example, the deepest samples from Farbrorsmyren are sandier than the overlying material. A lower Ti in the surface layer is probably the effect of coarser grained material. Several localities exhibit relatively low Ti concentrations in the analysed samples that were taken closest to the surface. Previous studies have shown that clay and silt soils in Norrbotten's coastal areas are often covered by a layer containing a higher level of fine sand (Fromm 1965) which could explain the low Ti concentrations measured here.

There are differences in the profiles of all four localities with regard to the other elements. However, active acid sulphate soils from Sjulsmark 1 and Porsnäs 2 are characterised by significantly lower quotas of Co/Ti, Y/Ti, Cd/Ti and Ni/Ti in the oxidised soil, compared with the quotas measured in underlying reduced soil, indicating that these elements were probably mobilised from these active acid sulphate soils. This is particularly apparent in the Sjulsmark 1 locality (Figure 17). The two localities with active acid sulphate soils exhibit high quotas of the above elements in the transition zone between active and potentially acid sulphate soils. On the other hand, the Pb/Ti ratio only exhibits small variations in the two reported with active acid sulphate soils (Figures 16 and 17, Porsnäs 2 and Sjulsmark 1) indicating that lead has not, or only to a limited extent, been mobilised from the acid soils.

At the Kvarnmyran locality (Figure 18), the deepest soil horizon analysed consists of potentially acid sulphate soils indicating the presence of acidifying sulphidic minerals. It is therefore conceivable that the oxidised layer close to the surface previously had a lower pH which could have caused the leaching of certain elements. The Ni/Ti and Cd/Ti quotas are also lower in the oxidised soil than in the underlying soil at the Kvarnmyran locality. However, this is not as apparent as in the localities with active acid sulphate soils. At Kvarnmyran there is also no transition zone with high concentrations of metals, unlike the two localities with active acid sulphate soil. there are also differences in Cd/Ti and Y/Ti between the oxidised and reduced underlying soils at Farbrorsmyren. At this locality, however, the deepest reduced layer is coarser grained material, so it is therefore possible that the differences in quotas are due to mineralogical differences.

Several localities have been analysed for sulphur and samples from potentially acid sulphate soils often exhibit a relatively high sulphur content. For example, samples from the Porsnäs 2 locality show that the sulphur levels in the reduced potentially acid sulphate soils are close to 2%, indicating that sulphidic minerals occur in the soil. The content of organic matter is about 2% in samples from the Porsnäs 2 and Sjulsmark 1 localities, but lower from the other two localities detailed here. Because sulphidic minerals are formed in environments where the presence of organic matter leads to reducing conditions, a connection between sediment with organic matter and acid sulphate soils is to be expected. Several localities have been analysed for carbonate coal. The results show that the levels of this carbon are very low in all samples. There are, in other words, no, or only small amounts of, carbonates that can buffer the acidity that forms when sulphidic minerals oxidise.

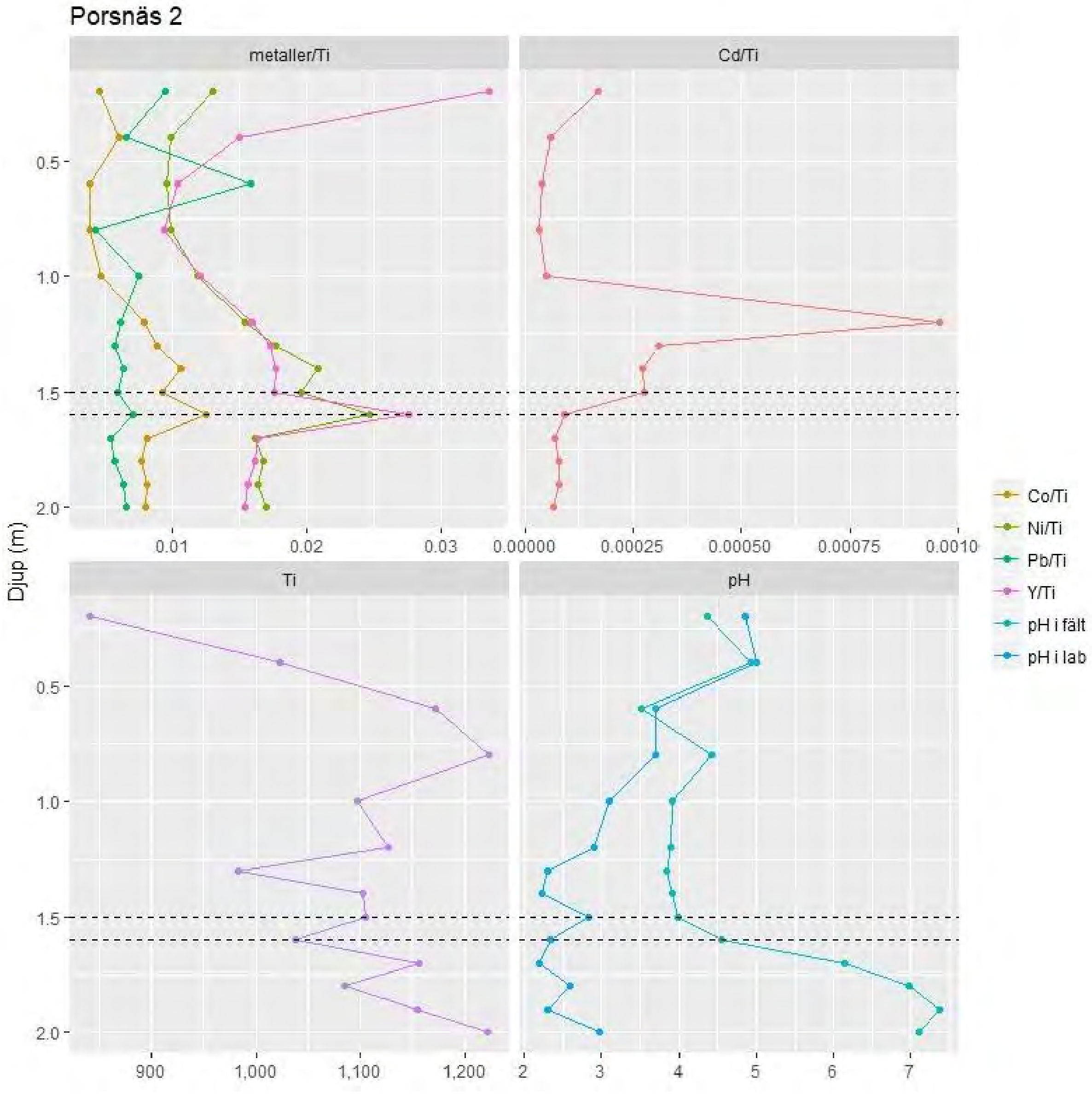

Figure 16. The distribution of some of the elements analysed and pH measured in the field in the soil profile from Porsnäs 2. The locality has been classified as active and potentially acid sulphate soil. The upper section of the soil profile is classified as active acid sulphate soil (above the upper line) and the lower section as potentially acid sulphide soil (below the line). The layer between the two lines has been classified as a transition zone. Samples from 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 2 metres below ground have been analysed.

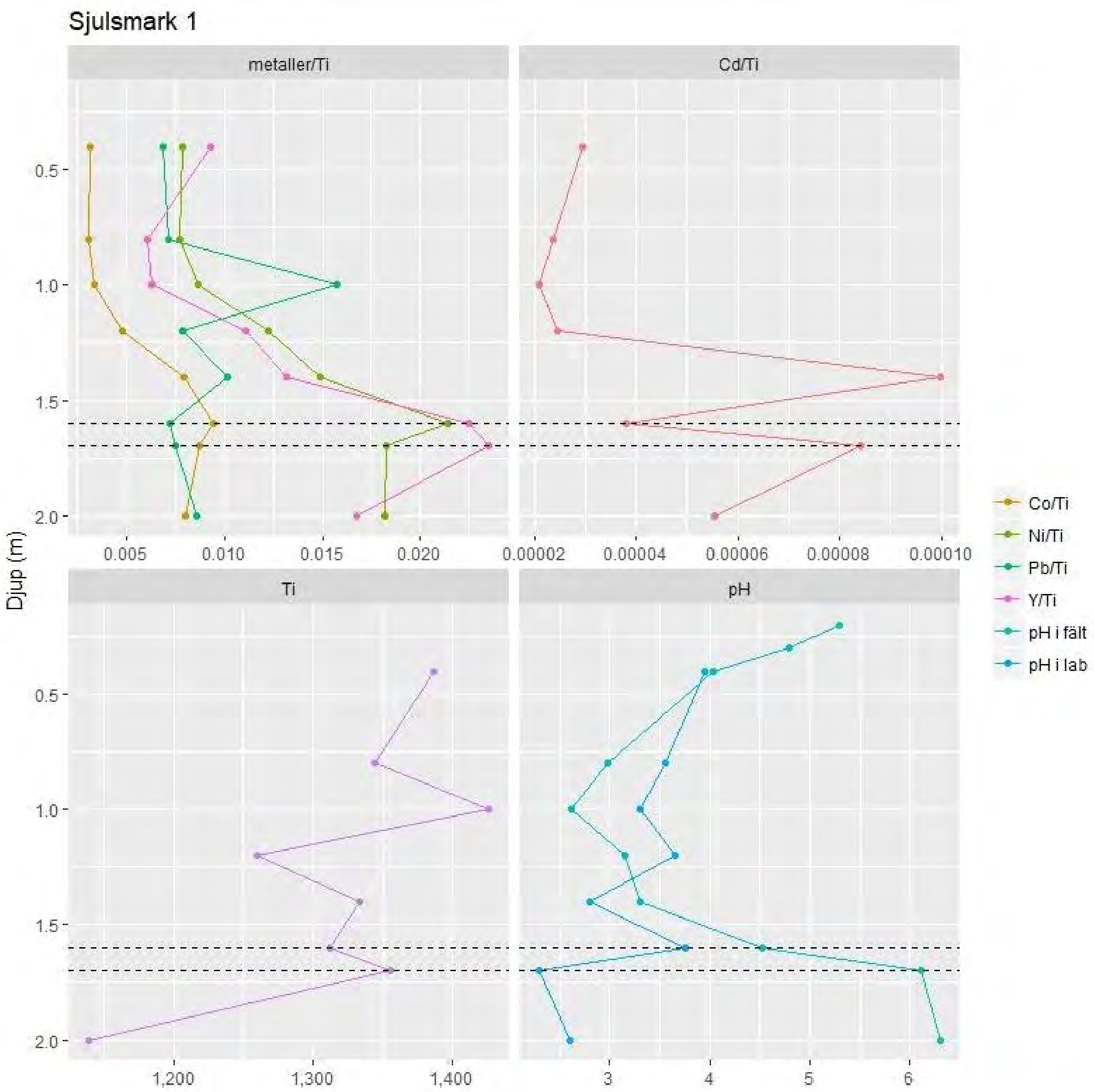

Figure 17. The distribution of some of the elements analysed and pH measured in the field in the soil profile from Sjulsmark 1. The locality has been classified as active and potentially acid sulphate soil. The upper section of the soil profile is classified as active acid sulphate soil (above the upper line) and the lower section as potentially acid sulphide soil (below the line). The layer between the two lines has been classified as a transition zone. Samples from 0.4, 0.8, 1, 1.2, 1.4, 1.6, 1.7, and 2 metres below ground have been analysed.

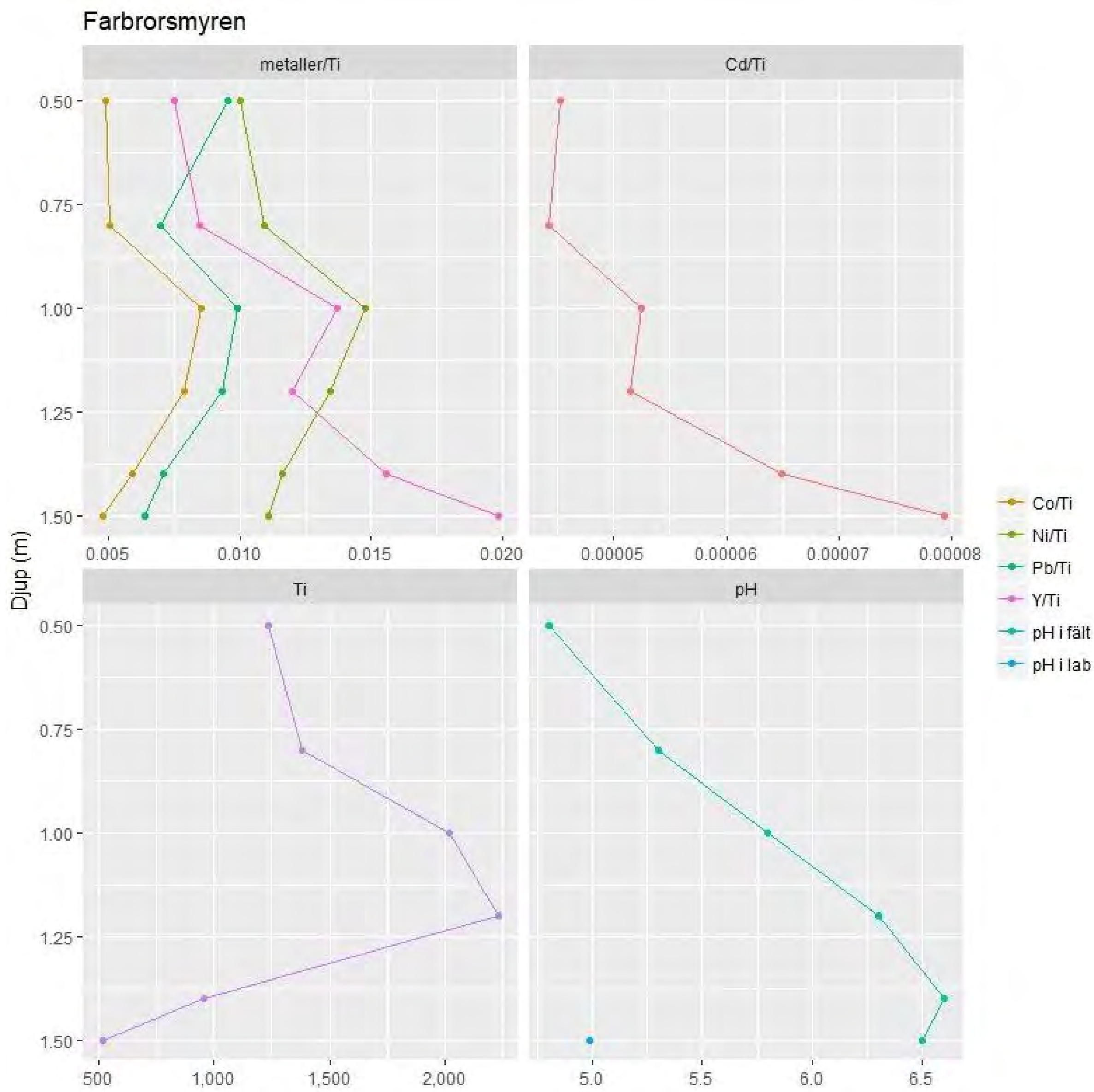

Figure 18. The distribution of some of the elements analysed and pH measured in the field in the soil profile from Farbrorsmyren. The locality has been classified as not active or potentially acid sulphate soil. Samples from 0.5, 0.8, 1, 1.2, 1.4, and 1.5 metres below ground have been analysed.

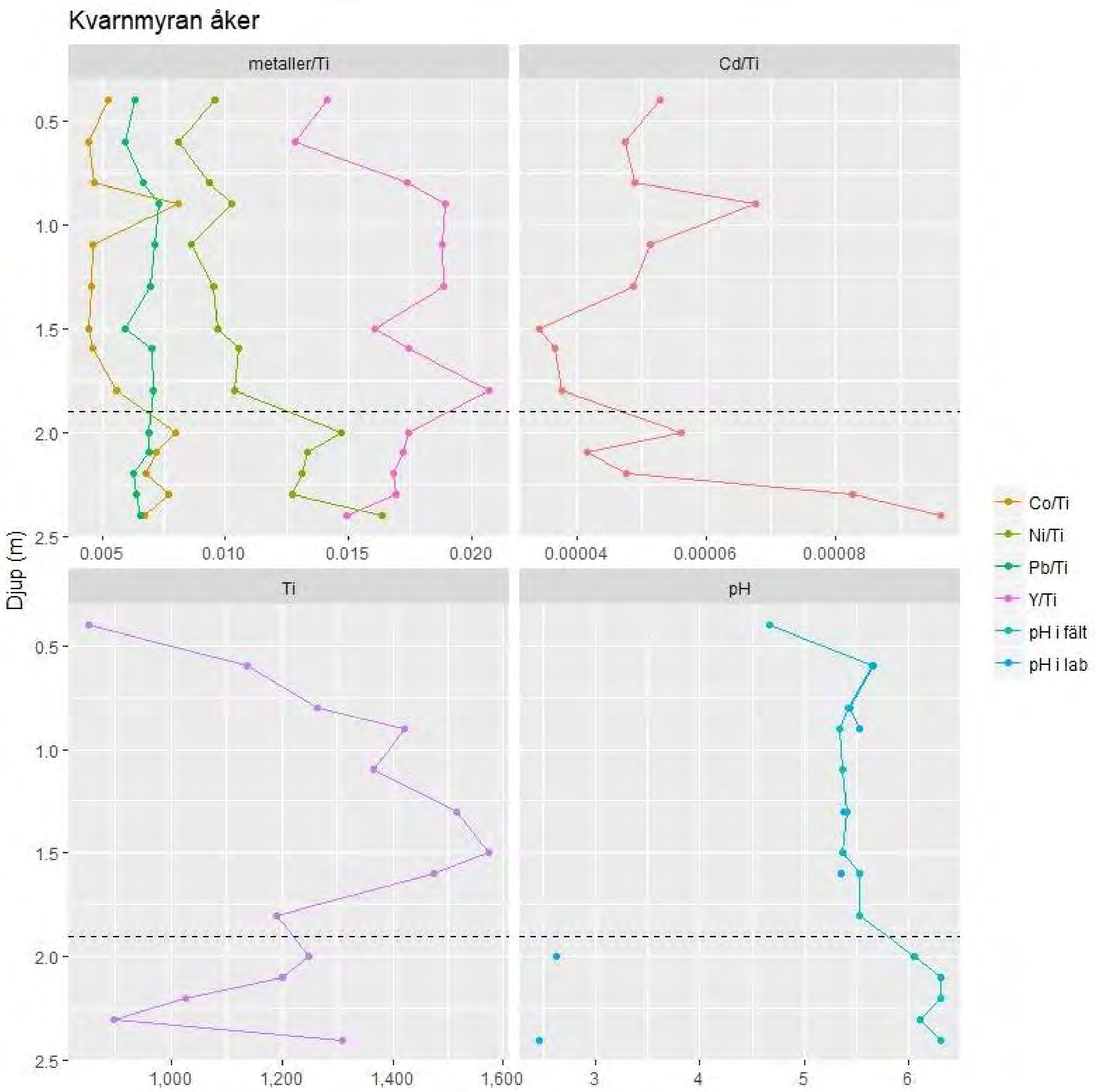

Figure 19. The distribution of some of the elements analysed and pH measured in the field in the soil profile from Kvarnmyran åker. The locality has been classified as potentially acid sulphate soil. The upper layer is classified as not acid sulphate soil (above the line) and potentially acid sulphate soil (below the line). Samples from 0.4, 0.6, 0.8, 0.9, 1.1, 1.3, 1.5, 1.6, 1.8, 2, 2.1, 2.2, 2.3 and 2.4 metres below ground have been analysed.

Sediment sampling

Dating results (Figure 20) show that the surface sediments sampled using the Willner type surface sampler were deposited in the past hundred years or so. This means that the samples come from bed accumulation where sediments have been deposited over a period in which widespread drainage took place in the area. The deeper layers sampled using a Russian chamber corer were deposited in earlier periods, before extensive drainage started in the catchment area.

As indicated above, there are a large number of elements (such as rare earth metals, Ni, Cu, Zn, Cd and Mn), mobilised from acid sulphate soils and which could accumulate in sediments deposited adjacent to watercourses affected by these soils. The results of this study show that the levels of many metals are very high in the sediments accumulated in the Övre Träsket and Nedre Träsket lakes through which the Rosån river flows (Figure 21). This has been interpreted as an effect of substances mobilised from acid sulphate soils accumulating, at least in part, in the sediments deposited in the lakes. However, correspondingly high concentrations were not encountered in the sediments deposited close to the mouth of the Rosån river in the Bay of Bothnia. However, some of the metals analysed at the coastal localities show higher levels in the sediments closest to the surface than in the deeper sediments.

In particular in Övre Träsket lake, the sediments contain high levels of certain elements mobilised from acid sulphate soils (Fe, Al, rare earth metals etc.). The highest levels were measured in individual samples, which were also characterised by high levels of organic matter. Övre Träsket lake is closest to the mouth of the Rosån river in the lake system consisting of Övre Träsket and Nedre Träsket. Upstream, around Sjulsmark (REF to map with sampling sites) there is a high proportion of active acid sulphate soils. In the downstream locality in the Nedre Träsket lake, the levels of these substances are lower, and at the localities sampled outside the mouth of the Rosån river in the Baltic, the levels are significantly lower. This indicates that these two lakes serve as a sink for certain substances. Dividing the metal content by the titanium (Ti) content, further reinforces this effect; this is because Ti is predominantly found in minerals which are not affected by leaching from acid sulphate soils. Because the samples with a high metal content contain a lot of organic material, the levels of Ti and other substances that are not mobilised from acid sulphate soils are low in these samples. According to dating one of the peaks for metal deposits was the mid-1960s, the other appears to be in the late 19th century. However, there is a relatively high degree of uncertainty associated with the oldest dated sediments (Table x). The deeper sediments, sampled using a Russian chamber corer, are characterised by significantly lower levels of these substances.

The highest levels of Co, Ni and Zn were found in the Nedre Träsket lake and at the mouth of the Rosån river; this indicates that these substances are transported farther out and deposited in coastal areas, but it is also conceivable that they are carried farther into the Bay of Bothnia. Cd also occurs in relatively high concentrations in the sediments sampled on the coast off the mouth of the Rosån river, indicating that Cd mobilised from acid sulphate soils accumulates in coastal areas.

The highest levels of Mn were found in coastal samples, which could indicate that this substance is transported along the Rosån river and accumulates a relatively long way from its mouth. However, there may be other reasons why Mn levels in the shallow coastal sediments are relatively high. Because Mn oxides are dissolved under reducing conditions, it is conceivable that this substance was mobilised from the deeper reduced sediments and has accumulated in the oxides observed in the samples taken closest to the bottom.

High levels of some elements, especially Pb, were found in the shallow sediments of the Brännträsket lake. Because lead is not a substance that is mobilised to any great extent from acid sulphate soils, and there are no known occurrences of acid sulphate soils in this lake's catchment area, it is likely that the relatively high levels in sediment from the Brännträsket lake have a different source.

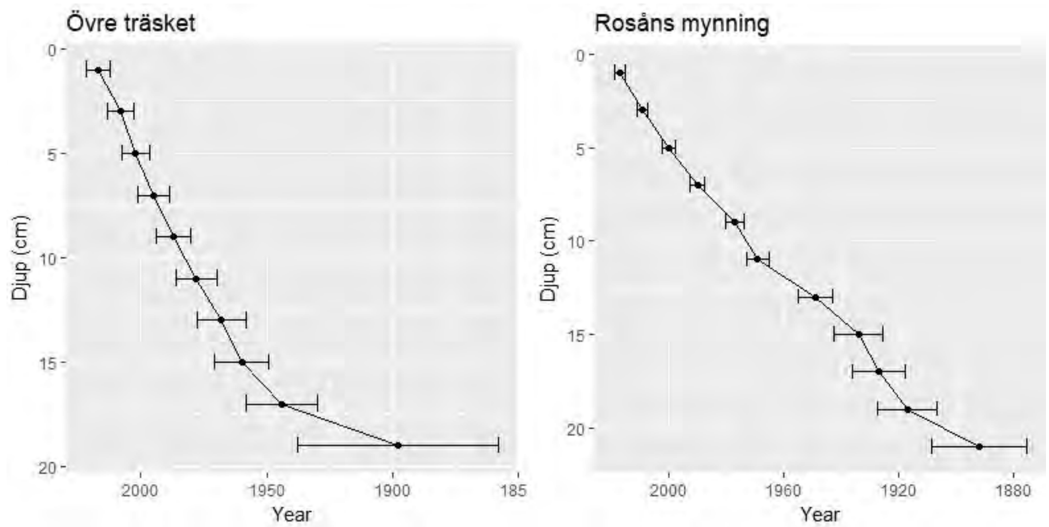

Figure 20. Results of lead-210 dating carried out on sediments deposited in the Övre Träsket lake and in the coastal area just off the mouth of the Rosån river.

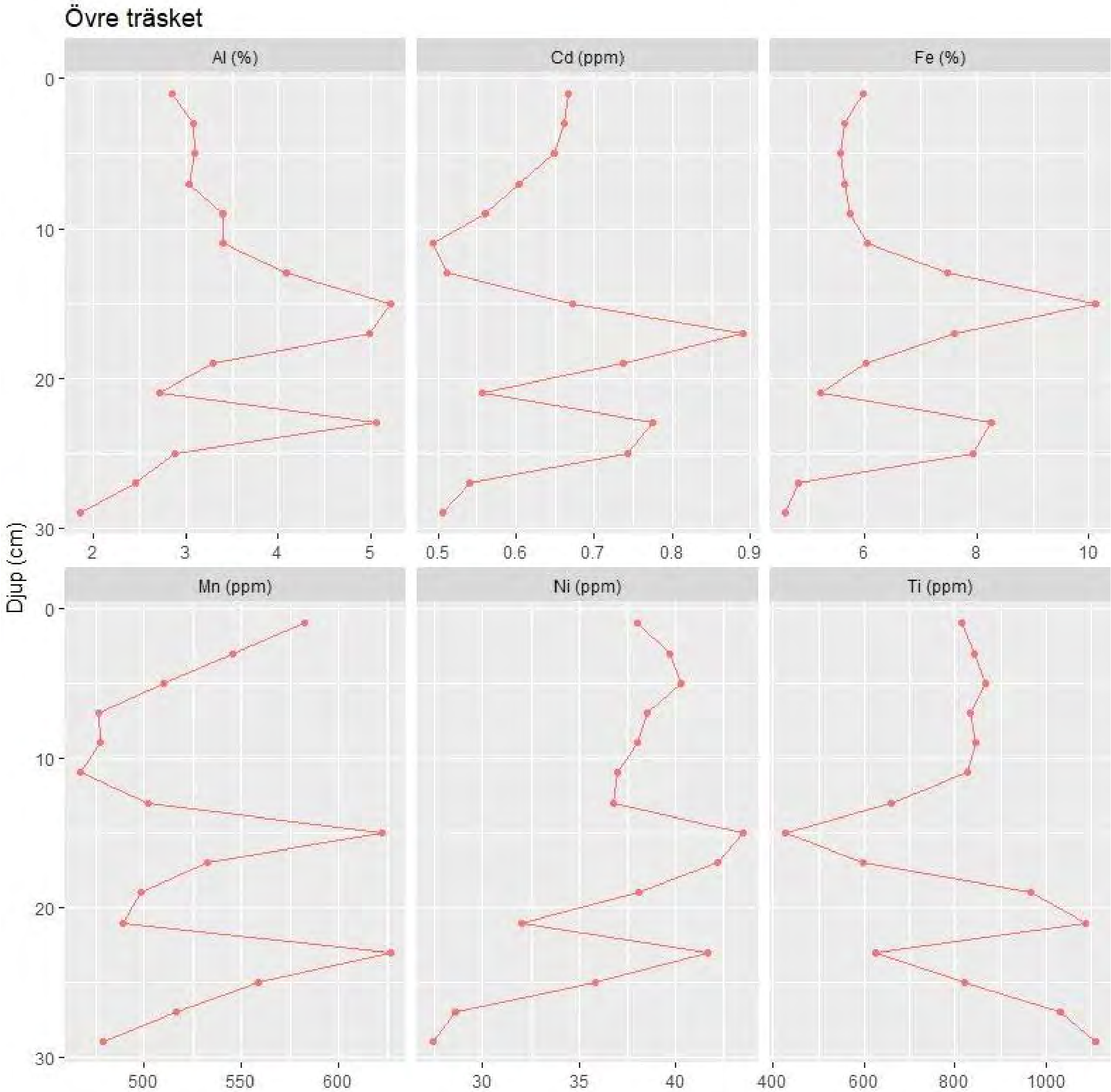

Figure 21. The distribution of some metals at various sediment depths in the Övre Träsket lake. The levels of iron (Fe) and aluminium (Al) are reported as a dry weight percentage, while other levels are reported as ppm, i.e. mg/kg.

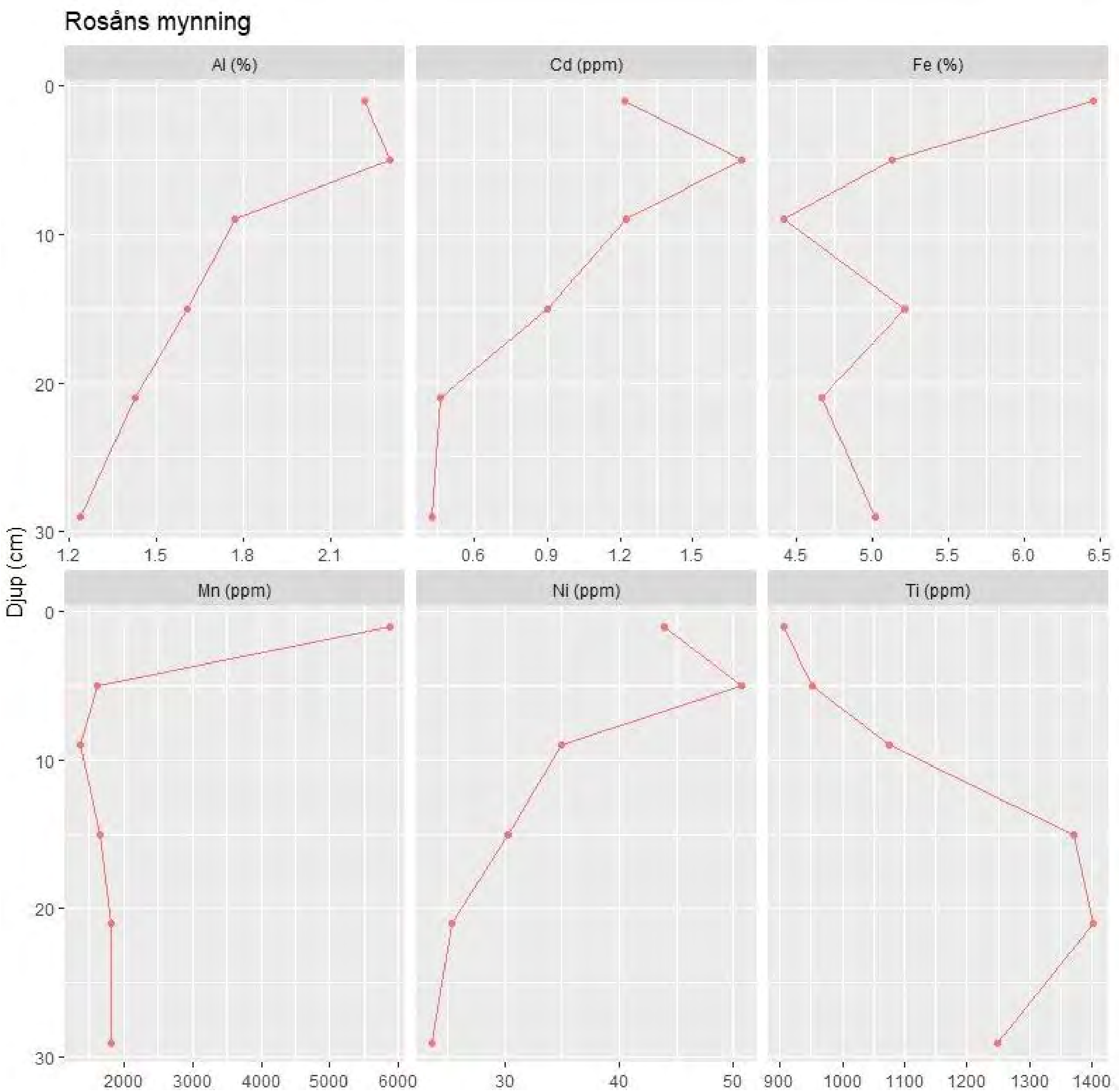

Figure 22. The distribution of some metals at various sediment depths sampled off the mouth of the Rosån river (KU_B). The levels of iron (Fe) and aluminium (Al) are reported as a dry weight percentage, while other levels are reported as ppm, i.e. mg/kg.

Sketch maps

Northern Ostrobothnia

In the distribution sketch map of Northern Ostrobothnia (Figure 23) 1054 sampling points were used, of these more than half (539, 51.1%) were classified as "acid sulphate soil", while less than half (515, 48.9%) were classified as "not acid sulphate soil". The distribution maps are divided into four different probability classes, each class indicating a "probable" chance of finding acid sulphate soils. The probability of the different classes varies slightly for each catchment area. This is because the maps are interpreted and drawn by experts and that the number of classified sampling points for an area is not exactly the same. In order to calculate the area of acid sulphate soils within a catchment area, the probability of the different classes in that area needs to be known. Table 7 presents the probability classes for each catchment area for the mapped areas in Northern Ostrobothnia.

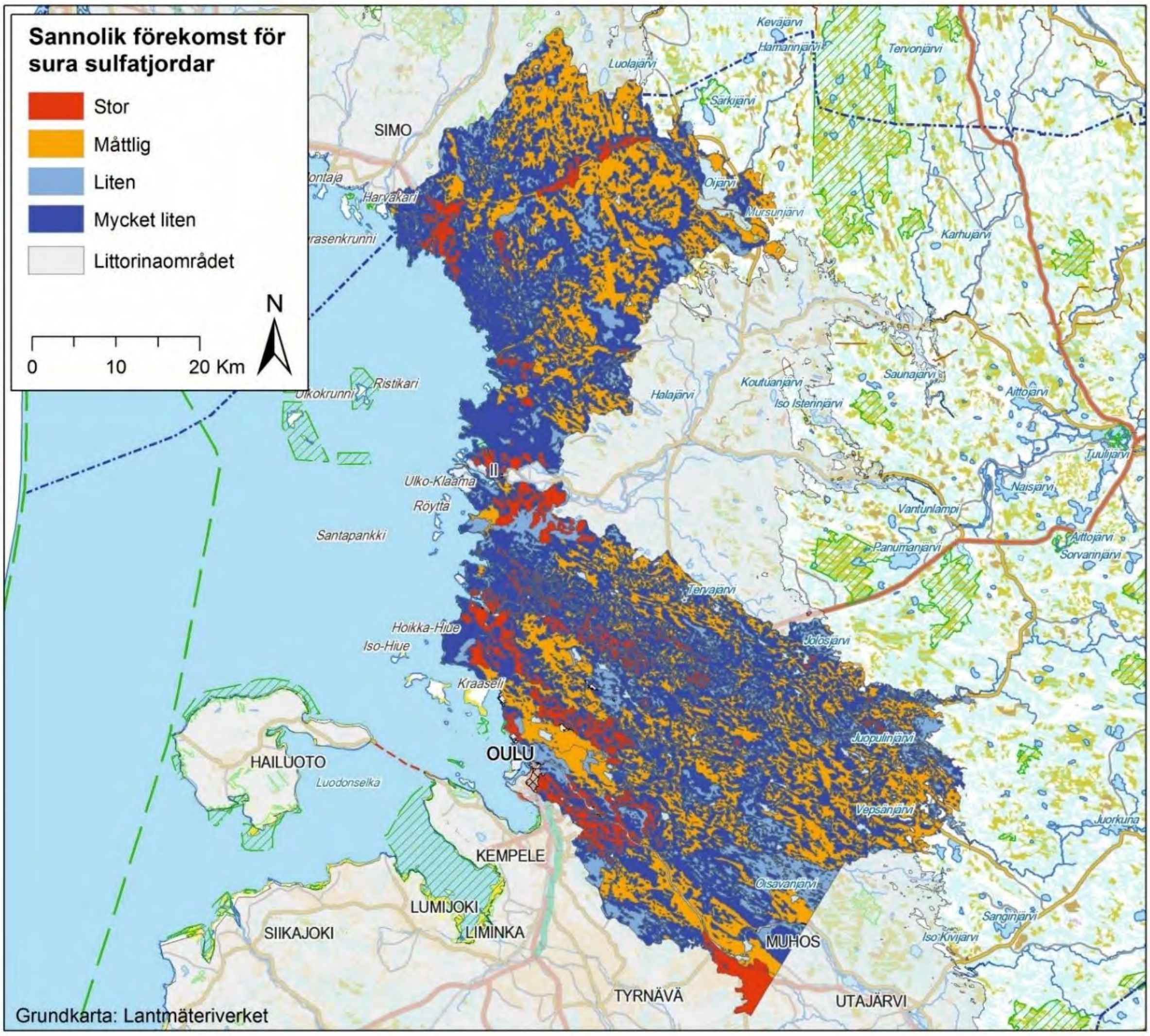

Figure 23. Probable extent of acid sulphate soils in Northern Ostrobothnia

The probability of encountering acid sulphate soils in each probability class was calculated based on the proportion of sampling points classified as "acid sulphate soil" compared to the total number of sampling points in that class. For example, if an area classified as "high probability" (red) has nine points classified as acid sulphate soil and one point classified as not acid sulphate soil, the area has a 90% probability of acid sulphate soil. The probability classes for the whole of Northern Ostrobothnia are applied on the map presented in Figure 23 as follows:

Class 1: High probability 93.4% of the sampling points (227 of 243) were classified as acid sulphate soils.

Class 2: Moderate probability: 54.9% of the sampling points (299 of 545) were classified as acid sulphate soils.

Class 3: Low probability: 6.5% of the sampling points (10 of 154) were classified as acid sulphate soils.

Class 4: Very low probability 2.7% of the sampling points (3 of 112) were classified as acid sulphate soils.

Table 7. Probability classes for acid sulphate soils for catchment areas in the area of study in Northern Ostrobothnia. The area within parentheses is the size of the area in which the overview map was finalised.

	Catchment areas					
Probability class	**Coastal area (792 km²)**	**Ule river (577 km²)**	**Kiminge river (886 km²)**	**Olhavajoki (324 km²)**	**Kuivajoki (527 km²)**	**Whole area (3106 km²)**
Class 1: High probability	95.4%	94.0 %	88.5 %	100.0 %	100.0 %	93.4 %
Class 2: Moderate probability	51.2 %	62.8 %	52.6 %	57.4 %	47.8 %	54.9 %
Class 3: Low probability	2.1 %	14.9 %	5.1 %	0.0 %	0.0 %	6.5 %
Class 4: Very low probability	6.3 %	0.0 %	0.0 %	0.0 %	0.0 %	2.7 %

Calculation of the area of acid sulphate soils in Northern Ostrobothnia

In the entire overview map (3106km^2; Figure 23) acid sulphate soils in Northern Ostrobothnia constituted class 1 (high probability) 219 km^2, class 2 (moderate probability) 960 km^2, class 3 (low probability) 305 km^2 and class 4 (very low probability) 1615 km^2. Of the whole area about 6 km^2 were lakes and other areas (urban areas for example) that could not be classified.

On the basis of the calculated probability (Chapter 1.3) of acid sulphate soils in each class, the total area of acid sulphate soils was calculated according to the formula:

[*area class 1*] **x** [*the probability of ASS in class 1*] **+** [*area class 2*] **x** [*the probability of ASS in class 2*] **+** [*area class 3*] **x** [*the probability of ASS in class 3*] **x** **+** [*area class 4*] **x** [*the probability of ASS in class 4*] **= total area of acid sulphate soils (ASS) in the area**

Where the probability of each class is based on actual observations, i.e. the number of points classified as "acid sulphate soil" divided by the total number of points in each class. The results for each probability class and catchment area are presented in Table 8.

Table 8. Calculated area (km²) acid sulphate soil for each probability class and catchment area in the study area in Northern Ostrobothnia. The total area for each catchment area and for the entire area are indicated in brackets.

Area (km^2) of acid sulphate soils per probability class	**Catchment areas**					
	Coastal area (792 km^2)	**Ule river (577 km^2)**	**Kiminge river (886 km^2)**	**Olhavajoki (324 km^2)**	**Kuivajoki (527 km^2)**	**Whole area (3106 km^2)**
Class 1: High probability	99	57	30	0.3	21	207
Class 2: Moderate probability	79	98	155	67	114	513
Class 3: Low probability	1.5	15	3.3	0	0	20
Class 4: Very low probability	29	0	0	0	0	29
Total	209	170	188	68	135	768

When each catchment area is calculated separately, the total area of acid sulphate soils in the study area in Northern Ostrobothnia (Figure 23) is 768 km^2 (76,800 ha). If the same calculations are made for the entire study area (i.e. all catchment areas together, Table 7), the result will be slightly higher, 795 km^2. The reason for the difference is the variation in the percentage of probability classes between the different catchment areas. Regardless of the result used, about a quarter of the area presented in Figure 23 are acid sulphate soils.

The catchment area of the Simo Älv river

The total catchment area of the Simo Älv river is approximately 3,157 km^2 of which approximately 655 km^2(20.7%) are located below the Littorina boundary. Overview mapping (1:250 000; Figure 24) of acid sulphate soils in the catchment area of the Simo Älv river (Finnish *Simojoki*) had been completed as part of a previous project (funded by Lapland's Centre for Economic Development, Transport and the Environment (NTM) and the ERUF 2007-2013 programme; Hannukkala et al. 2015). In this project detailed mapping (1:20 000) was carried out in three priority areas, together making up 89 km^2 (Figure 3). Particular focus was on areas where rapids restoration was being carried out by project partners. Between 2012 and 2014, 56 points were sampled in the areas where detailed mapping was carried out, and in this project 61 sampling points were added (116 in total). The sampling density for detailed mapping was approximately three times greater than for the overview mapping in Northern Ostrobothnia and amounted to 1.3 samples per km^2. The results of detailed mapping were used in conjunction with the results of the earlier overview mapping to prepare probability maps for acid sulphate soils, as described above, in a scale of 1:20 000 (Figure 25).

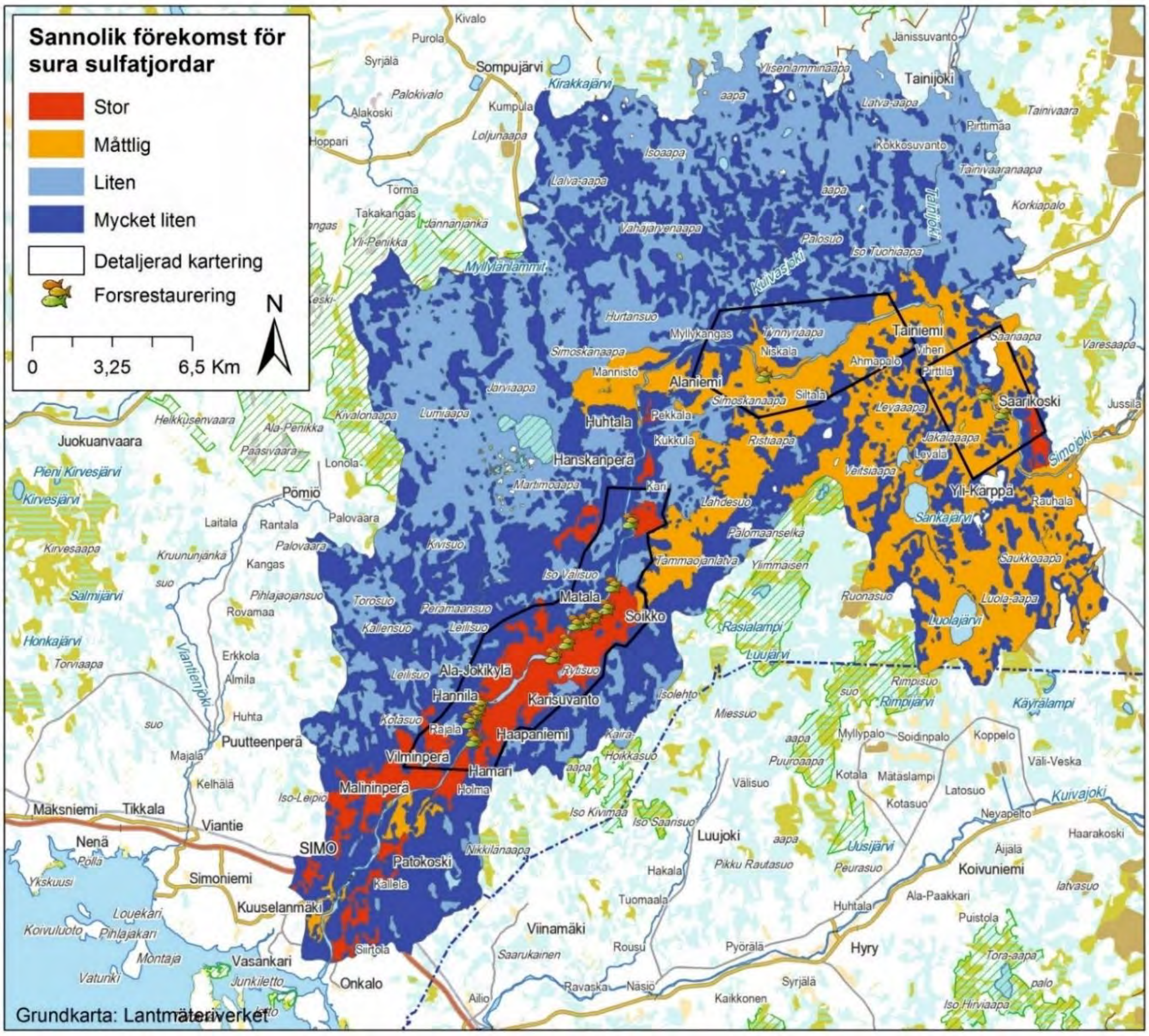

Figure 24. Areas where detailed mapping was undertaken in the catchment area of the Simo Älv river (Finnish *Simojoki*).

The overview map of acid sulphate soils in the catchment area of the Simo Älv river was completed between 2012-2014.

The probability of encountering acid sulphate soils in each probability class within the areas mapped in detail was calculated in the same way as for overview mapping and showed the following results:

Class 1: High probability 89.3% of the sampling points (50 of 56) were classified as acid sulphate soils.

Class 2: Moderate probability: 34.5% of the sampling points (10 of 29) were classified as acid sulphate soils.

Class 3: Low probability: 11.1% of the sampling points (2 of 18) were classified as acid sulphate soils.

Class 4: Very low probability 0% of the sampling points (0 of 14) were classified as acid sulphate soils.

The area of acid sulphate soils in the areas mapped in detail was then calculated in the same way as for overview mapping and amounted to approximately 37 km^2 (41.3% of the area). The probability of encountering acid sulphate soils in the two highest classes is slightly lower than for the corresponding classes on the overview map of Northern Ostrobothnia (Figure 23). What is most notable about the detailed maps is that the proportion of areas classified as "high probability" increased significantly, particularly for the two areas located in the north and east, compared with the corresponding areas on the overview map (Figure 24). This suggests that the Simo River overview map (Figure 24) probably underestimates the proportion of acid sulphate soils present in the area.

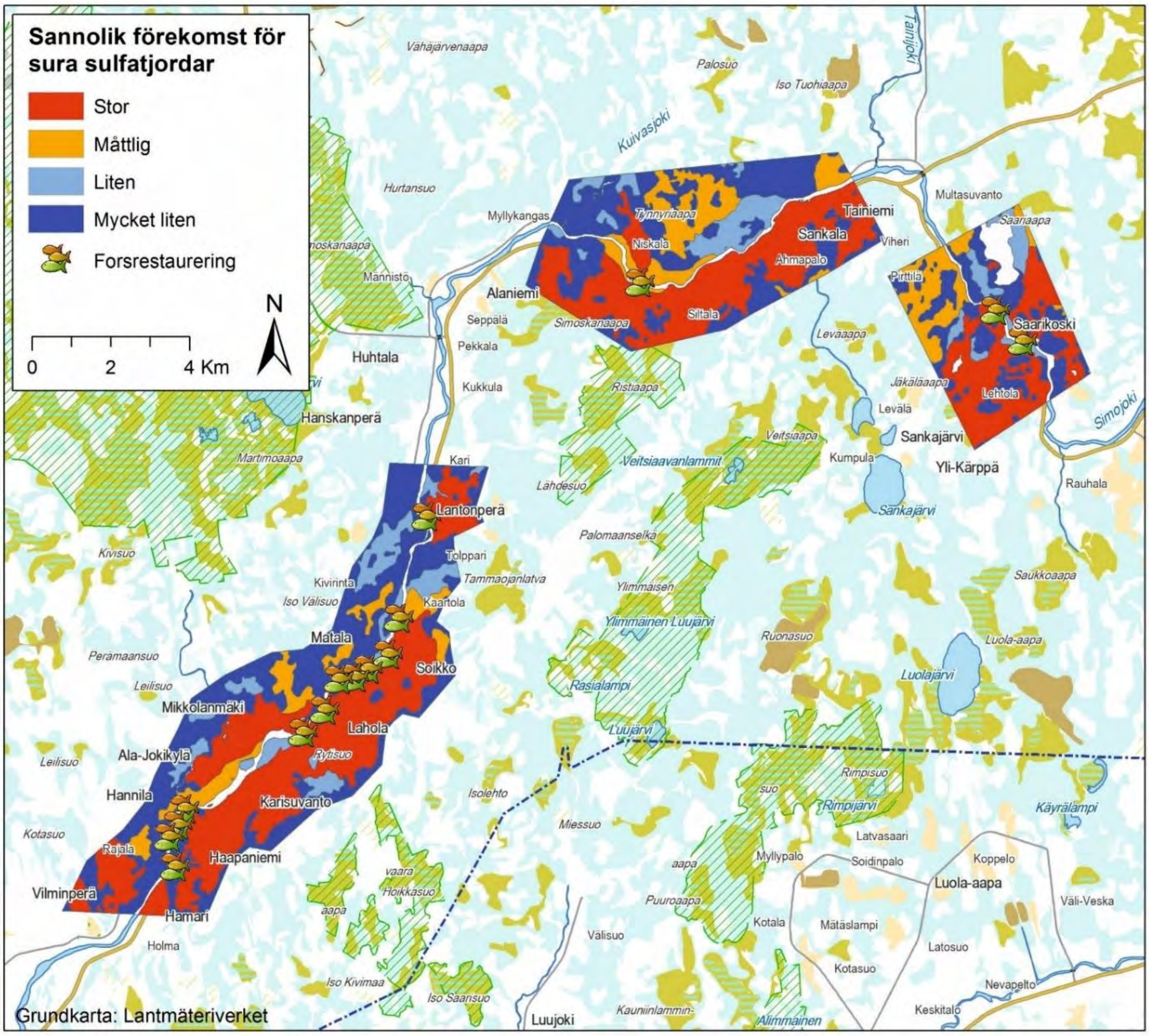

Figure 25. Probable distribution of acid sulphate soils in three areas of the Simo Älv river area (Finnish *Simojoki)* mapped in detail
Catchment areas

Modelling

Bay of Bothnia

The model of the northern Gulf of Bothnia has a total accuracy of 75% and a kappa of 0.47. The model predicts 'not sulphate or sulphide' correctly about 80% of the time, and 'sulphide' correctly about 65% of the time. Height above sea level (DEM), location higher or lower than the surrounding area (TPI) and the multiresolution index of valley bottom flatness (mrvbf) are the three environmental variables that have the greatest impact on the model (Mean Decrease Gini 1374, 690 and 615 respectively).

Around the Gulf of Bothnia, 'sulphate on sulphide' or 'sulphide' are the most likely classes in 25% of the area under the area of the Littorina Sea. They mainly occur along the coast and in low lying terrain, and in that case particularly on the Finnish side and in the northern Bay of Bothnia (Figure 26).

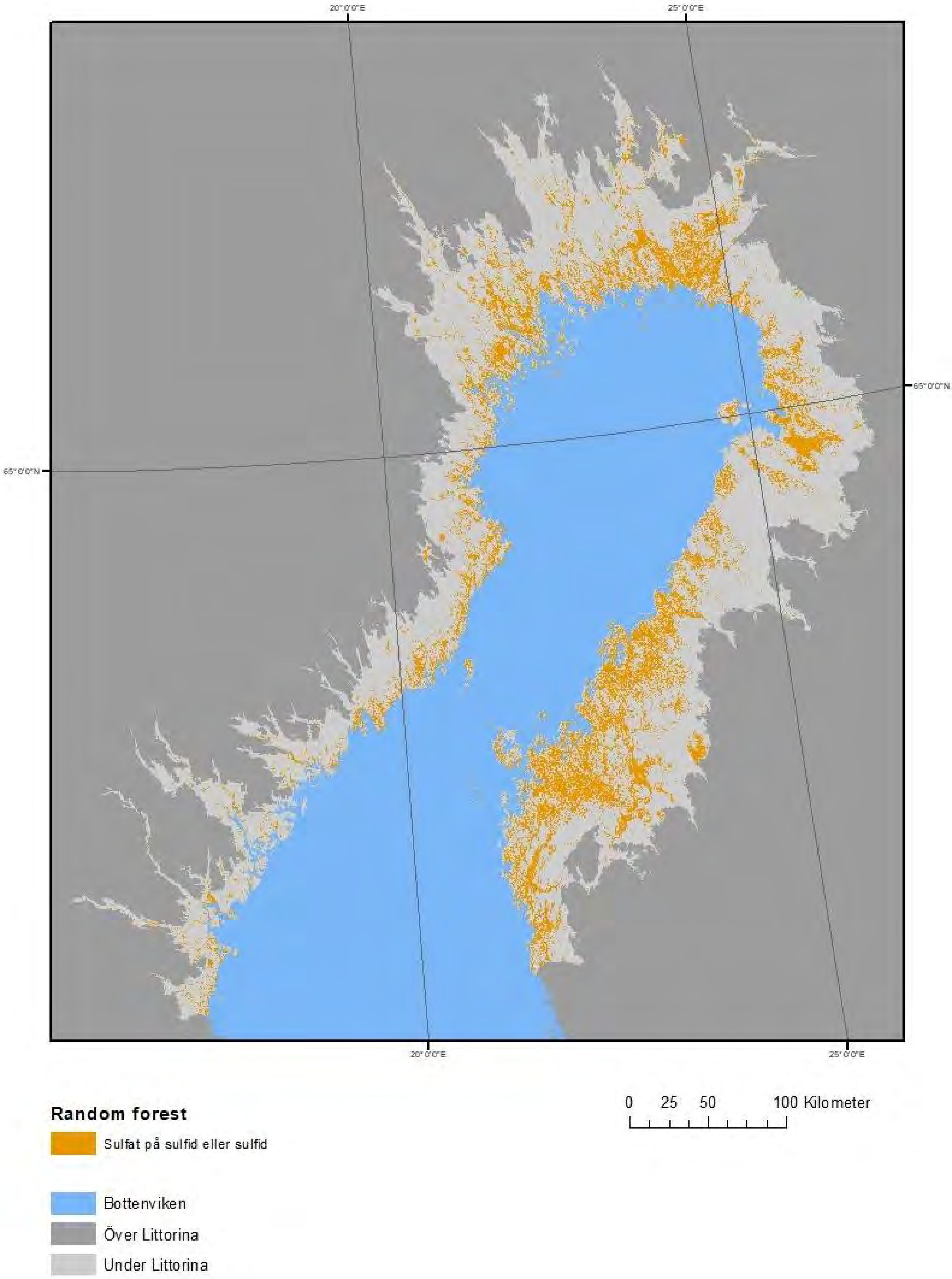

Figure 26. Map of the incidence of acid sulphate soils around the northern Gulf of Bothnia. Each pixel/location in the onshore areas below the Littorina boundary has been assigned the class which has the highest probability for the location based on the numerical modelling.

The catchment area of the Alterälven, Alån, and Rosån rivers

Distribution maps

The model used for the catchment area of the Alterälven, Alån, and Rosån rivers had a total accuracy of 60% and a kappa of 0.33. The model predicts the two classes 'not sulphate or sulphide' and 'sulphate on sulphide' correctly about 70-75% of the time, while it only predicts the 'sulphide' class of 15% of the time. Height above sea level (DEM), valley depth and the multiresolution index of valley bottom flatness (mrvbf) are the three environmental variables that have the greatest impact on the model (Mean Decrease Gini 58, 19 and 15 respectively).

According to the model the incidence of 'sulphate on sulphide' is mostly in the valleys (Figure 27) and at low elevations (Figure 28). 'Sulphate on sulphide'' does not occur at heights above approximately 40 masl, while 'sulphide' occurs up to about 50 masl (Figure 28). 'Sulphate on sulphide' are predominantly found in clay (39%), silt (26%) and till (25%) (Figure 29) while 'sulphide' occurs in till (42%), peat (17%) and clay (15%) (Figure 29).

In the catchment areas of the Alterälven, Rosån och Alån rivers there are approximately 38 km^2 of arable land according to the Swedish Board of Agriculture map of agricultural areas 2011, there are approximately 9.5 km^2 'sulphate on sulphide' and 2 km^2 'sulphide' (Figure 30).

Volume calculation

The model used for the catchment area of the Alterälven, Alån, and Rosån rivers to calculate the volume of active acid sulphate soils had a total accuracy of 90% and a kappa of 0.63. The average of modelled probability depth was 0.7 m with a maximum depth of 1.79 m. In the catchment areas of the Alterälven, Rosån och Alån rivers there are approximately 0.065 km^3 active acid sulphate soils (Figure 31).

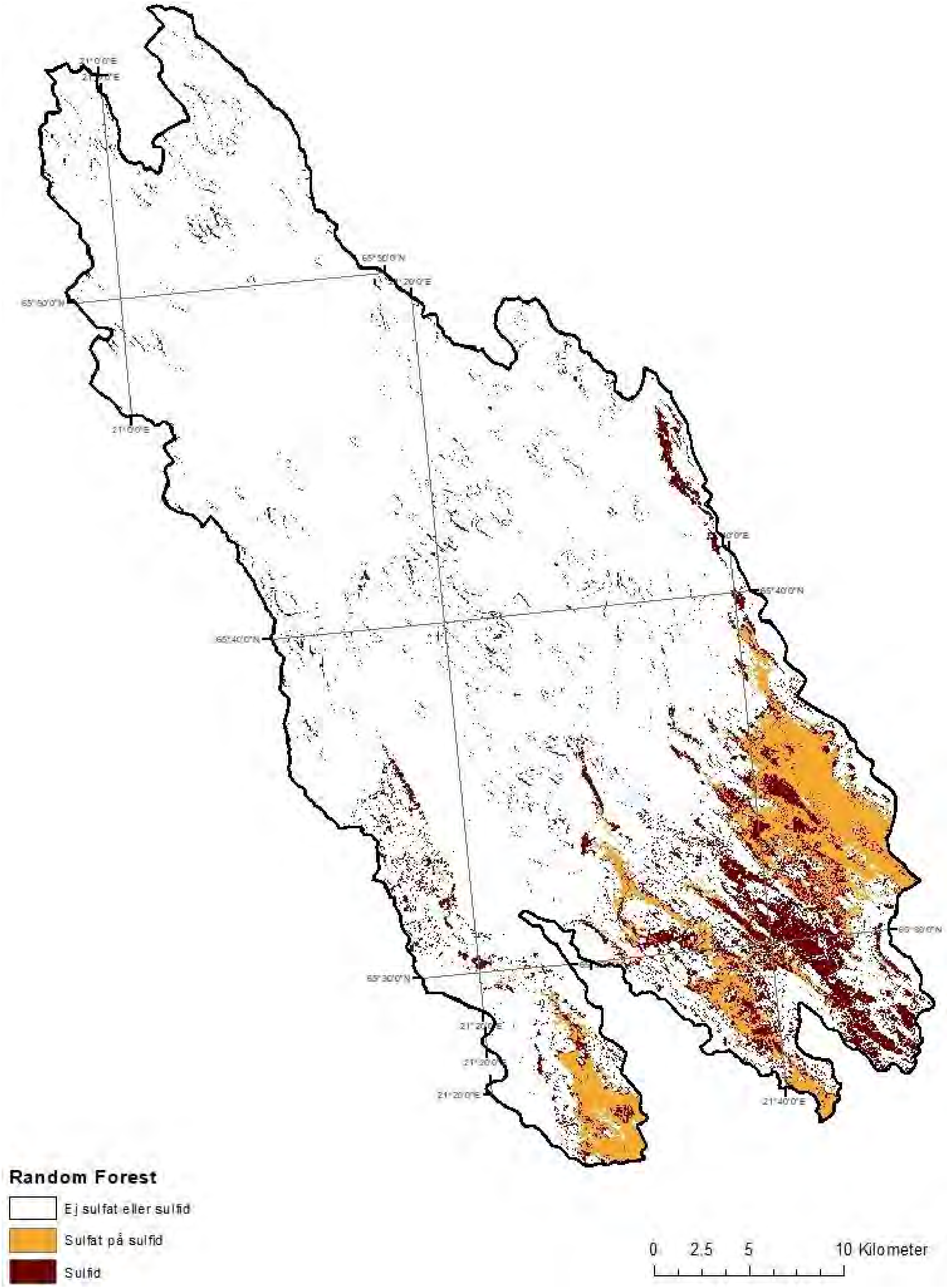

Figure 27. Map of the incidence of acid sulphate soils in the catchment area of the Alterälven, Alån, and Rosån rivers. Each pixel/location is 20 m and has been assigned the class which has the highest probability for the location based on the numerical modelling.

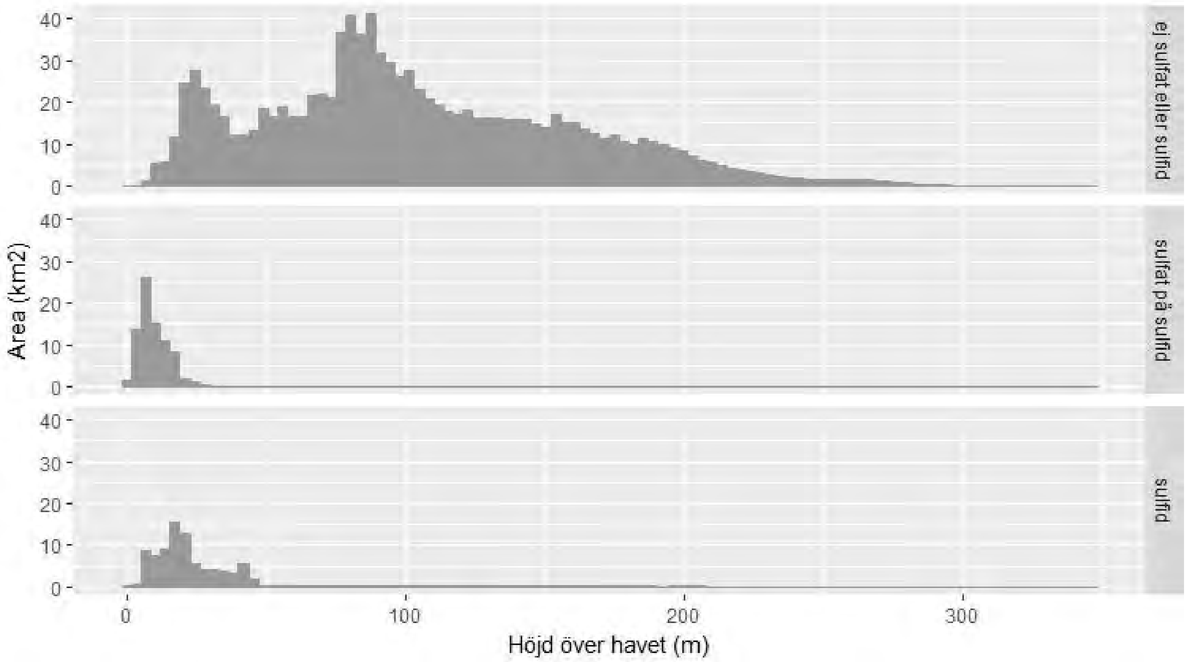

Figure 28. The distribution of the number of pixels in the three classes against height above sea level, in the catchment area of the Alterälven, Alån and Rosån rivers.

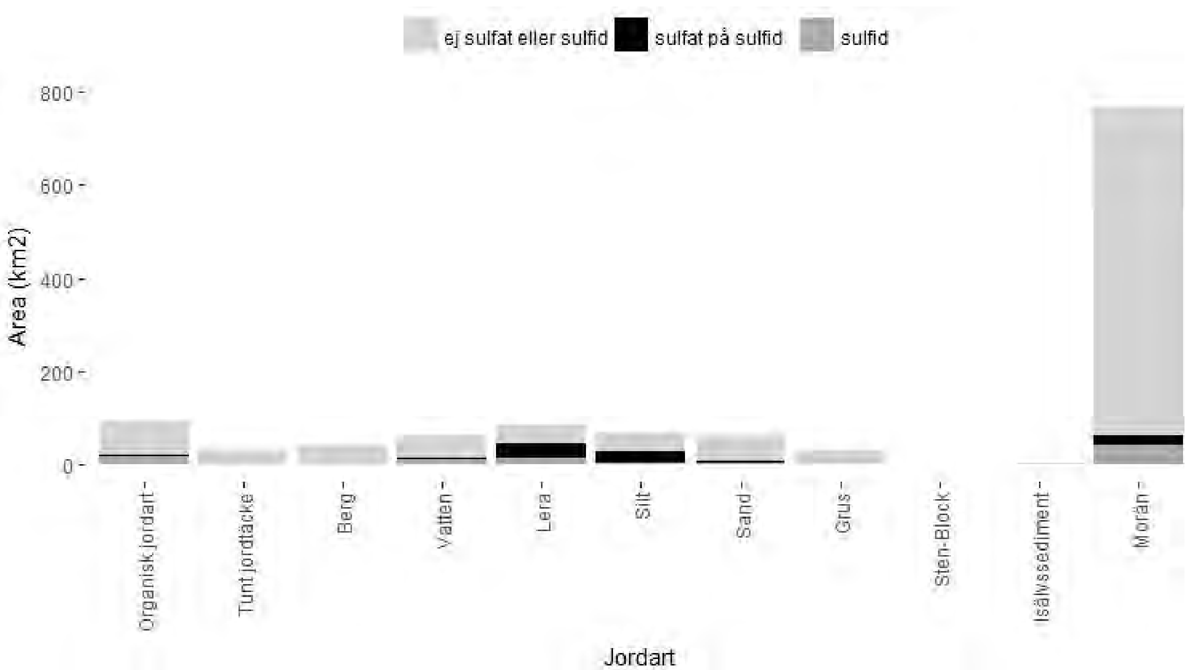

Figure 29. The area of the catchment area of the Alterälven, Alån, and Rosån rivers classed as 'not sulphate or sulphide', 'sulphate on sulphide' and 'sulphide' on each soil type (according to the SGU soil type map).

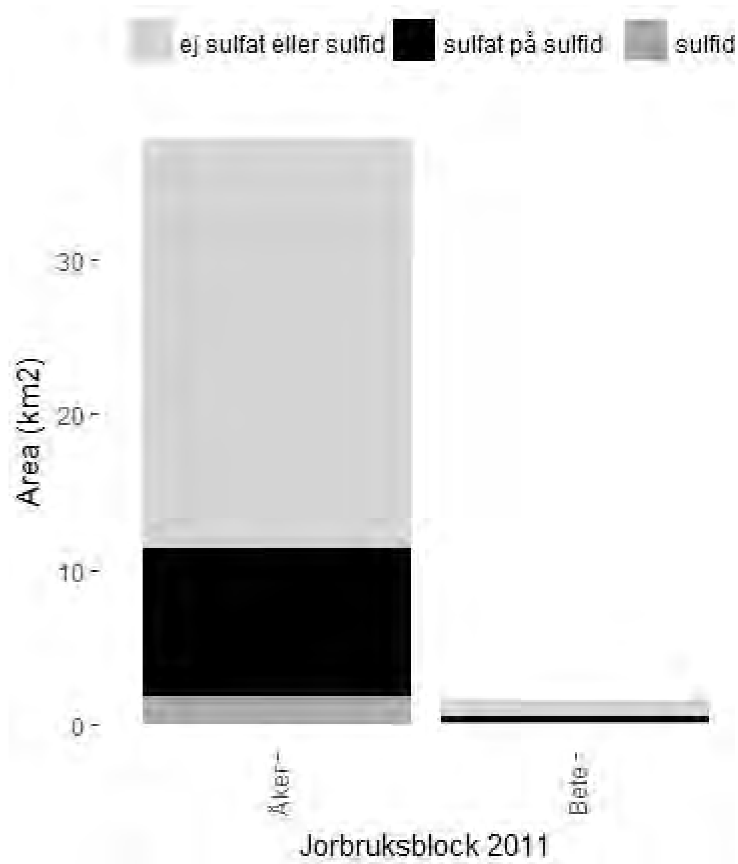

Figure 30. The area of arable land and pasture in the catchment area of the Alterälven, Alån, and Rosån rivers classified as 'not sulphate or sulphide', 'sulphate on sulphide' and 'sulphide'.

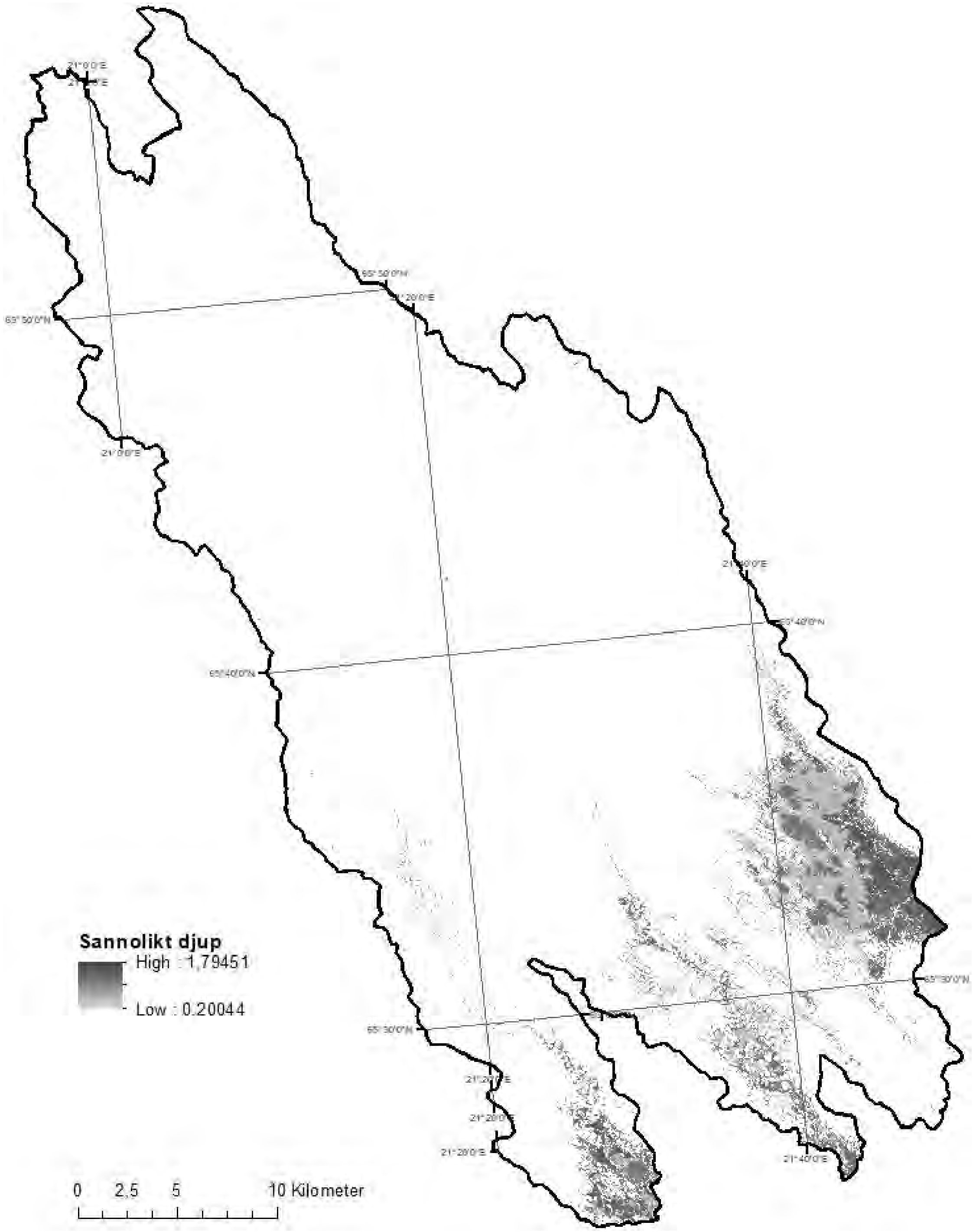

Figure 31. Map of the probable depth of acid sulphate in the catchment area of the Alterälven, Alån, and Rosån rivers.

The catchment area of the Simo Älv river

The model of the catchment area of the Simo Älv river (Finnish *Simojoki*) had a total accuracy of 85% and a kappa of 0.58. The model predicts the two classes 'not sulphate or sulphide' and 'sulphide' correctly about 70-85% of the time, and because no sampling localities classed as 'sulphate on sulphide' have been observed, this class has not been modelled.

The Simojoki river catchment area runs north east to south west where the incidence of 'sulphide' is predominantly in the valley with patches of incidence on peat (Figures 32 and 33). This class occurs mainly on postglacial gravel and sand and peat (Figure 33) up to 100 masl (Figure 34).

Observations in the catchment area have previously been used to prepare a sketch map of the incidence of acid sulphate soils. In a visual comparison the modelled and sketch maps correspond (Figure 35).

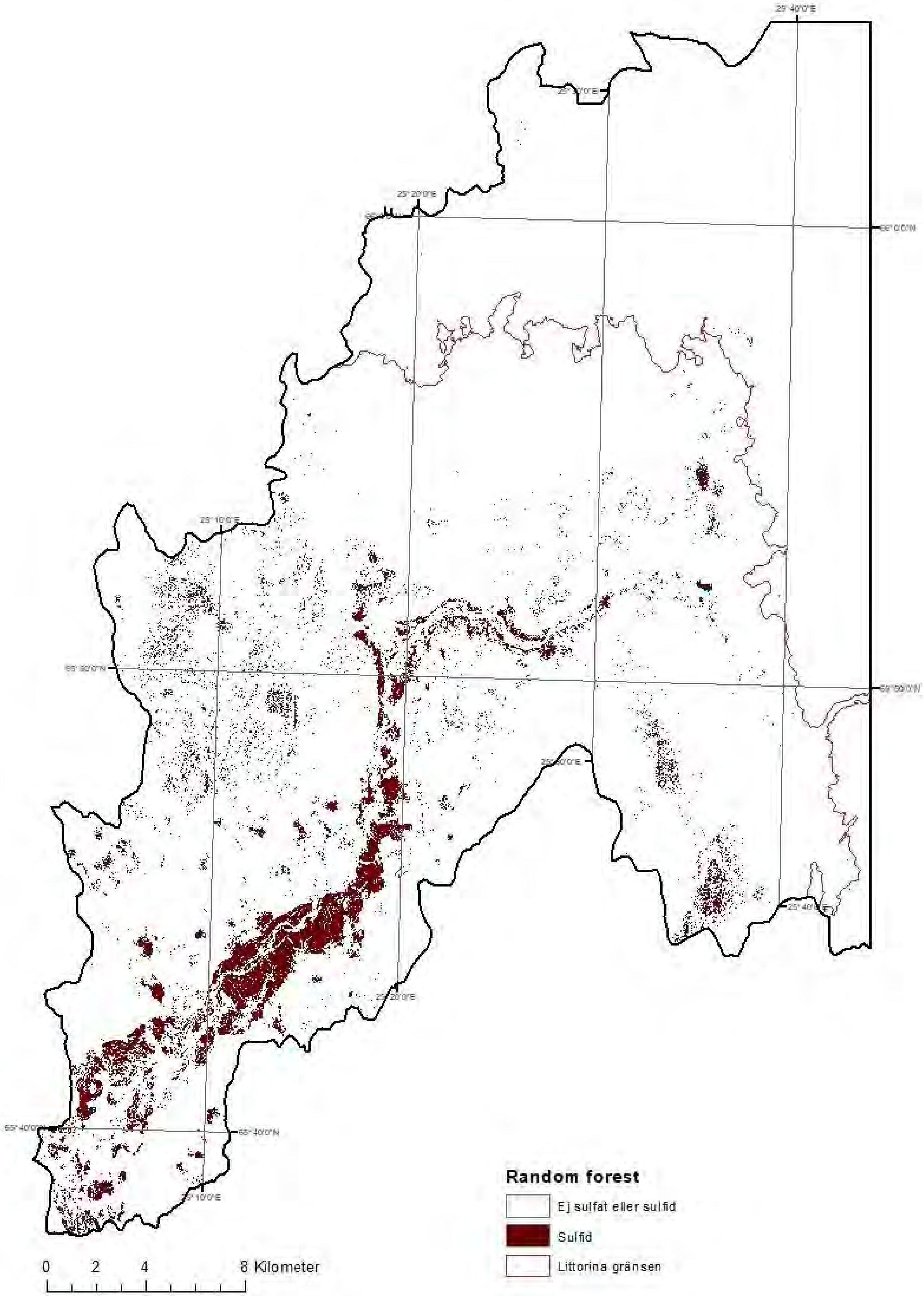

Figure 32. Map of the incidence of acid sulphate soils in the catchment area of the Simo Älv river (Finnish Simojoki). Each pixel/location has been assigned the class which has the highest probability for the location based on the numerical modelling.

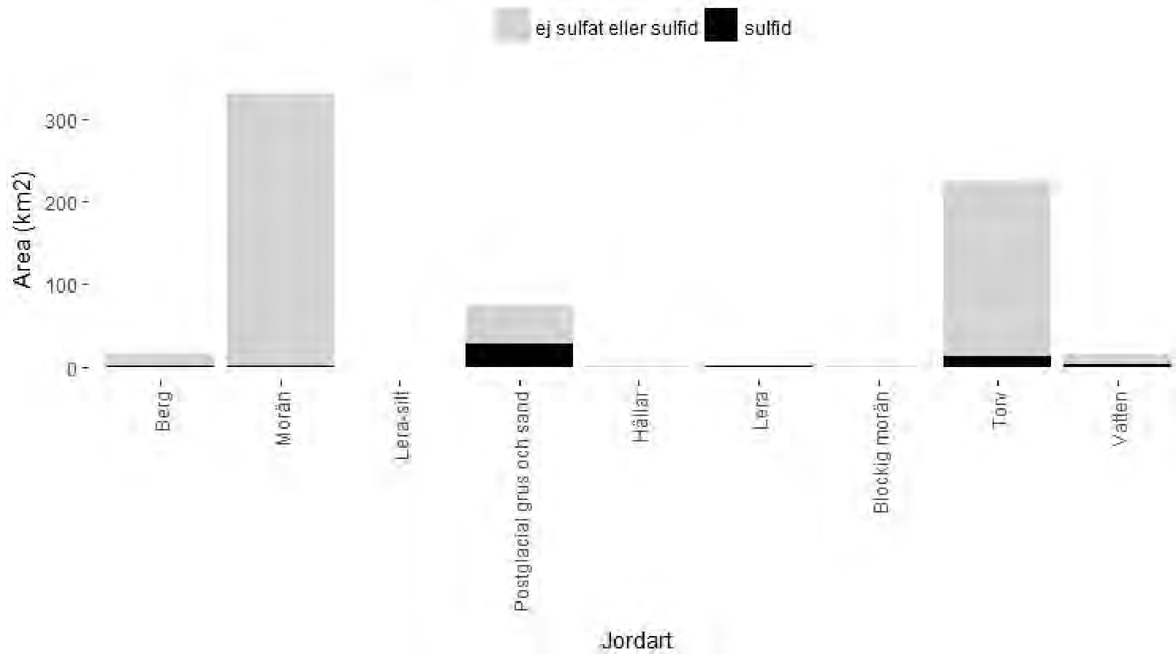

Figure 33. The area in the catchment area of the Simo Älv river (Finnish *Simojoki*) classified as 'not sulphate or sulphide' and 'sulphide' for each soil type (according to the GTK soil type map). No localities with 'sulphate on sulphide' were encountered.

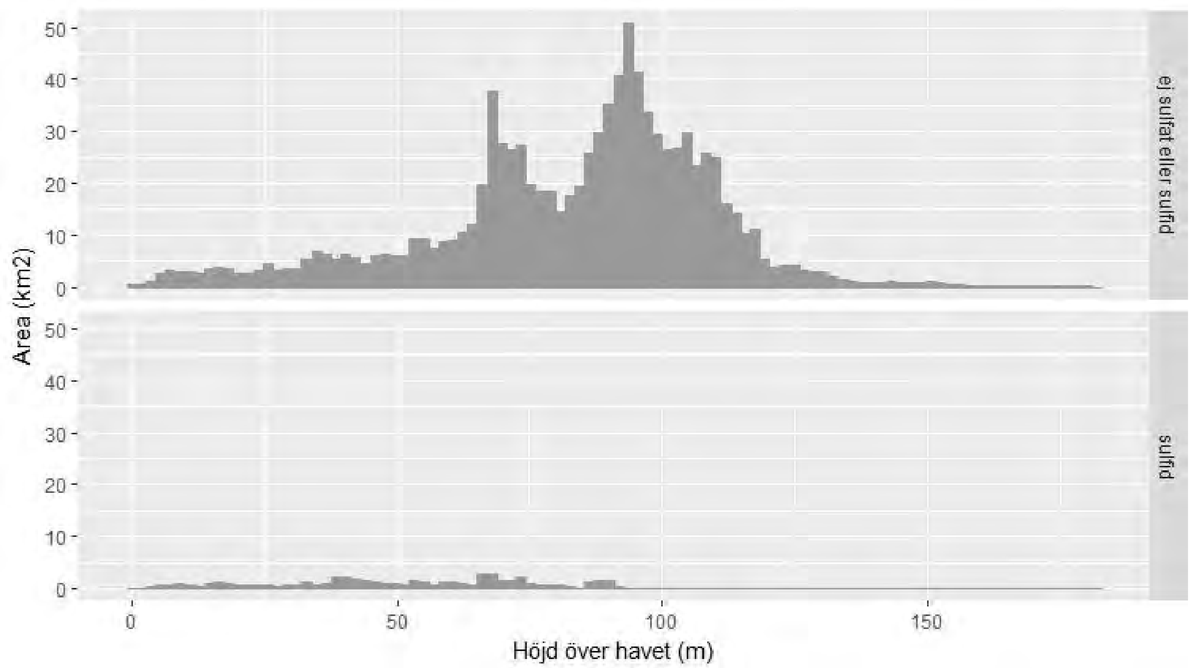

Figure 34. The distribution of the number of pixels in the two classes against height above sea level in the catchment area of the Simo Älv river (Finnish *Simojoki*).

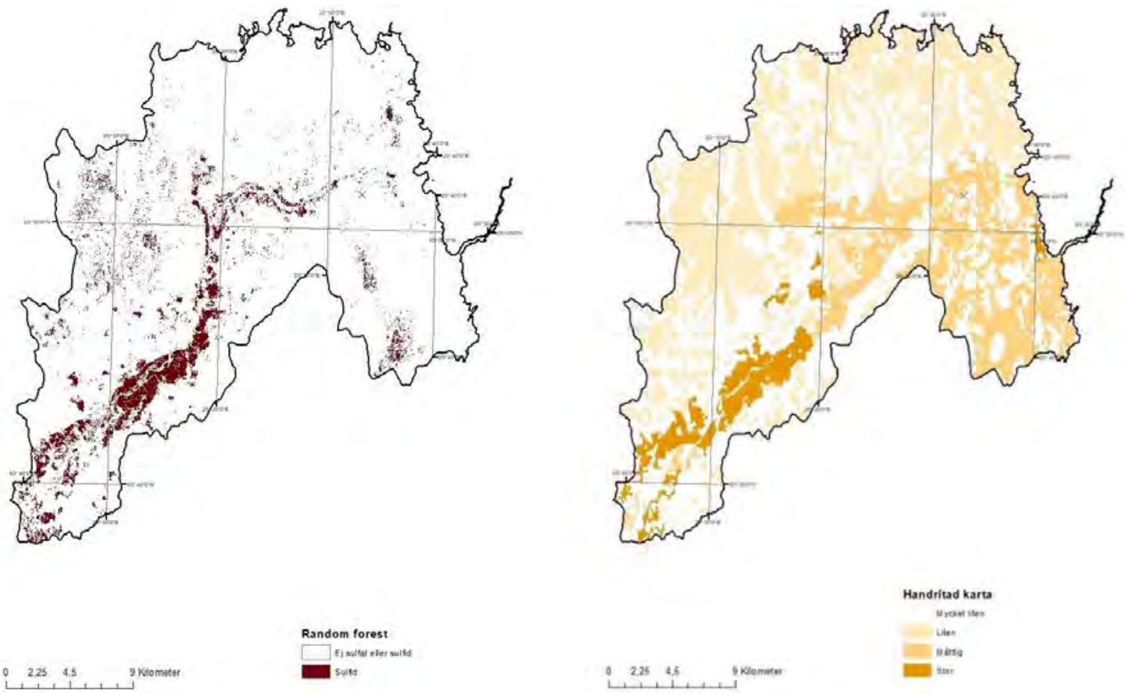

Figure 35. Modelled (on the left) and sketched (on the right) distribution maps of acid sulphate soils in the catchment area of the Simo Älv river (Finnish *Simojoki*). The modelled map shows the class which has the highest probability for the location based on the numerical modelling. The sketch map shows the "probable" chance of encountering acid sulphate soils in the area.

Calculation of metal leaching in the catchment area of the Alterälven, Alån, and Rosån rivers

In order to assess the amount of metals leached from the active acid sulphate soils occurring in the area, the average content of some of the analysed substances has been calculated for active acid sulphate and potentially acid sulphate soils (See Table 9). When modelling, the volume of active acid sulphate soils in the three studied catchment areas was calculated to be 0.065 km^3 (see above). By calculating the difference in metal content between active and potentially acid sulphate soils, the mass of the substances leached from active acid sulphate soils has been calculated. For this dry density has been estimated at 160 kg/m^3, which is based on the results of analyses of samples from agricultural land where the soil types have a similar grain size composition to here (Etana 2017). There are a large number of uncertainties in these calculations. For example, the levels of substances vary between localities and it is difficult to know how representative the average values used are. In some cases, the difference between the average values for active acid and the potentially acid sulphate soils is significantly less than the standard deviation (e.g. for Ti and Cr, which is expected as these substances are not mobilised from acid soils to any significant degree). It should also be noted that these analysed levels are not total levels, but correspond to the proportion of the analysed substances leached out using HNO_3. However, this should not impact too greatly on the results as the slightly soluble phases cannot be expected to be affected by the acidic conditions prevalent in active acid sulphate soils. Accordingly, the results of the analyses of potentially acid sulphate soils should include the phases that can be mobilised if potentially acid sulphate soils oxidise.

Table 9. The average content of a variety of metals in active and potentially acid sulphate soils. The difference in levels between the two layers has been used to calculate the amount of these metals mobilised from active acid sulphate soils. In modelling, the volume of active acid sulphate soil found in the three catchment areas was calculated. This volume has been used to calculate how many tonnes of the various elements that have been mobilised from the active acid sulphate soils in the area.

	Active acid sulphate soils			Potentially acid sulphate soils			
Chemical element	Quantity	Average (mg/kg)	std	Quantity	Average (mg/kg)	std	Tonnes leached from the three catchment areas
Cr	39	32.1	8.72	25	33.2	6.0	114
Co	39	4.18	1.56	25	9.71	2.69	575
Ni	39	9.95	2.91	25	20.0	4.6	1,045
Cu	39	14.0	8.4	25	18.6	4.4	474
Zn	39	32.3	10.2	25	58.6	8.90	2,740
Cd	39	0.074	0.171	25	0.109	0.033	3.6
Dy	39	2.55	1.24	25	3.84	0.51	134
Ho	39	0.50	0.240	25	0.76	0.111	27.6
Pb	39	8.61	4.00	25	8.32	1.30	-30
Mg	39	4,340	1,090	25	6,830	940	259,000
Al	39	9,530	2110	25	12,100	2,020	267,000
K	39	2,580	774	25	3,310	463	75,900
Ca	39	2,060	426	25	4,360	534	239,000
Ti	39	1,160	195	25	1210	106	5,200
Mn	39	163	50	25	618	293	47,300
Fe	39	32,900	13,200	25	37,300	6,160	458,000
Y	39	11.3	5.85	25	34.0	8.2	2,360
La	39	26.0	15.1	25	37.3	9.7	1175.2
Ce	39	47.8	23.1	25	67.4	12.4	2038.4

Establishing a test field with controlled drainage

Controlled drainage was implemented in the Bäverfältet field in July – October 2016. When this measure was planned it was assumed that the field previously had subsurface drainage installed. There is an old subsurface drainage plan from 1975, however, during construction work in 2016 no old pipes were found in the ground. No outfall pipes were found in the surrounding open ditches. The conclusion was that there was no old subsurface drainage, which in turn suggested that for a long time Bäverfältet had been drained by the open ditches because the field, despite everything, had well-developed active acid sulphate soil. According to the landowner, before the measure was installed the lower part of Bäverfältet was so wet that cultivation had in practice been impossible. The plan was to cultivate the field during the 2017 growing season. Because the ground was frozen for an unusually long period in May 2017, it was not possible to sow the field that year. The field was sown for the first time after the measure was installed in the spring of 2018. It is not possible to reach any conclusions about harvest and yield for this reason. However, because the lower part of the field now has working drainage, it is likely that, compared to before drainage was installed, cultivation of Bäverfältet will now work normally.

Before the logging of levels began in June 2017, a circumstance was discovered that could have affected the measurements in sub-area 2; the control valve had been left open in well 2 (BR2) throughout the winter; this meant that the groundwater level in sub-area 2 was lower than planned during the winter of 2017. This was discovered during a visual inspection of the wells in early May 2017, at which time no levels could be measured. Because of this there are unfortunately no data showing the levels, instead the difference in levels between BR2 and BR3 have only been inspected and evaluated visually. One possible outcome of this circumstance is that the oxidation of sulphide soil has not been inhibited in sub-area 2 in the same way as for sub-area 3 in the winter of 2017. This should be taken into account when conductivity and level data from later periods are being interpreted.

Measurement of groundwater levels

Groundwater levels were measured continuously during the period 14 June 2017 – 16 May 2018. Data from the uncontrolled sub-area 4 which did not have a plastic barrier installed, shows how the groundwater level varies in a field with normal drainage installed (Figure 36). The groundwater level in sub-area 4 has always followed runoff during the measuring period, with slow decline in winter until snow melt. Periods with the highest groundwater level occur in the autumn and spring, which is to be expected, given that runoff was high due to autumn rain and snow melt during these periods. The lowest groundwater levels were measured in summer and winter as no water fell on the ground during these periods. The level is sometimes lower than the installation depth of the subsurface drainage pipes (about 120 cm), this can result in the pipes being blocked due to iron deposits.

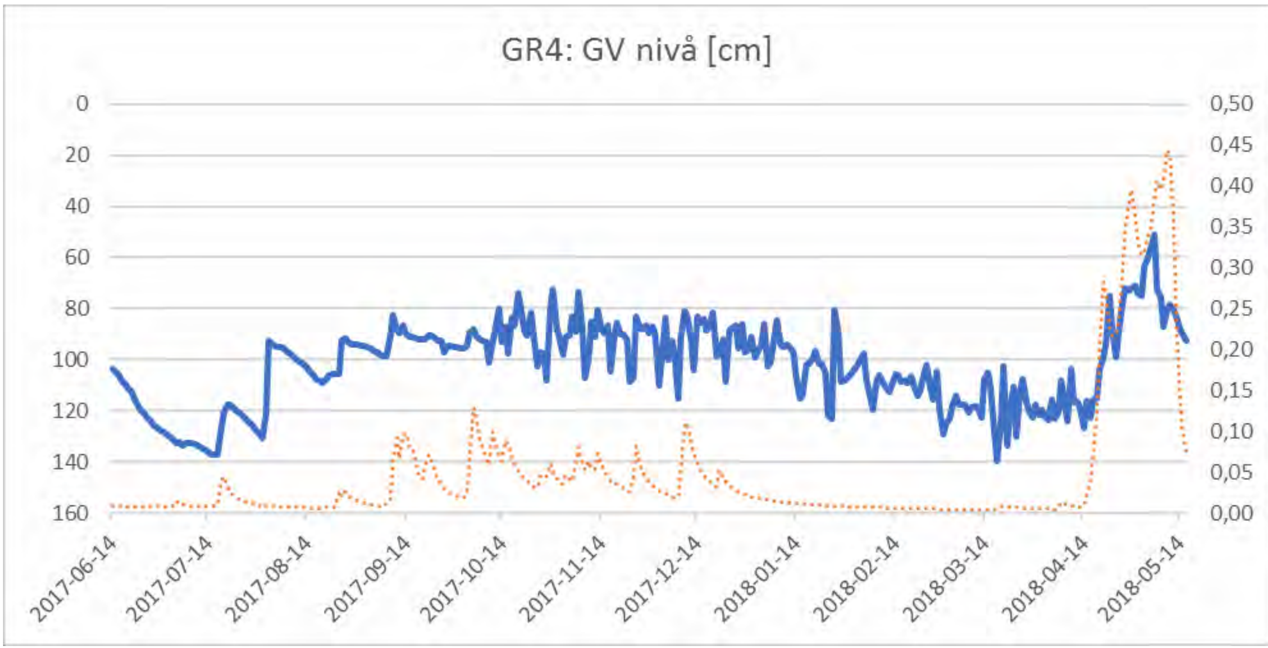

Figure 36: Groundwater level in cm dbg (left Y axis) for sub-area 4 (solid line) and daily average values for runoff in m^3/s (right Y axis) according to the SMHI water web (dotted line).

The variations in groundwater levels in sub-areas 2 and 3 (Figure 37) correlate well with each other (coefficient of determination = 0.9). This is expected because the areas have a similar slope, size, and have the same drainage system in place (except that sub-area 3 has an intake well, which has not been used during the data collection period for this report). The groundwater levels in sub-areas 2 and 3 however, do not correlate well with the levels in sub-area 4 (coefficient of determination = 0.42 and 0.58 for sub-areas 2 and 3). This is probably due to sub-area 4 having neither a control well nor plastic film installed, and that the ground has a greater incline in area 4. In general there is a tendency for the groundwater levels in sub-areas 2 and 3 (as well as sub-area 1) to rise more than sub-area 4 during of peak flow episodes. This is probably due to the plastic film in sub-areas 2 and 3 preventing lateral leakage, while sub-area 4 drains faster as the peak flow episode tails off.

The level is generally higher in the lower lying sub-area 2, probably due to its proximity to the wetland area where the slope is very slight. The groundwater levels in sub-areas 2 and 3 have not fallen below the depth of the subsurface drainage pipes except during the summer of 2017. This is due to the control being open too long following spring flood so that the groundwater level could be kept sufficiently high during the summer.

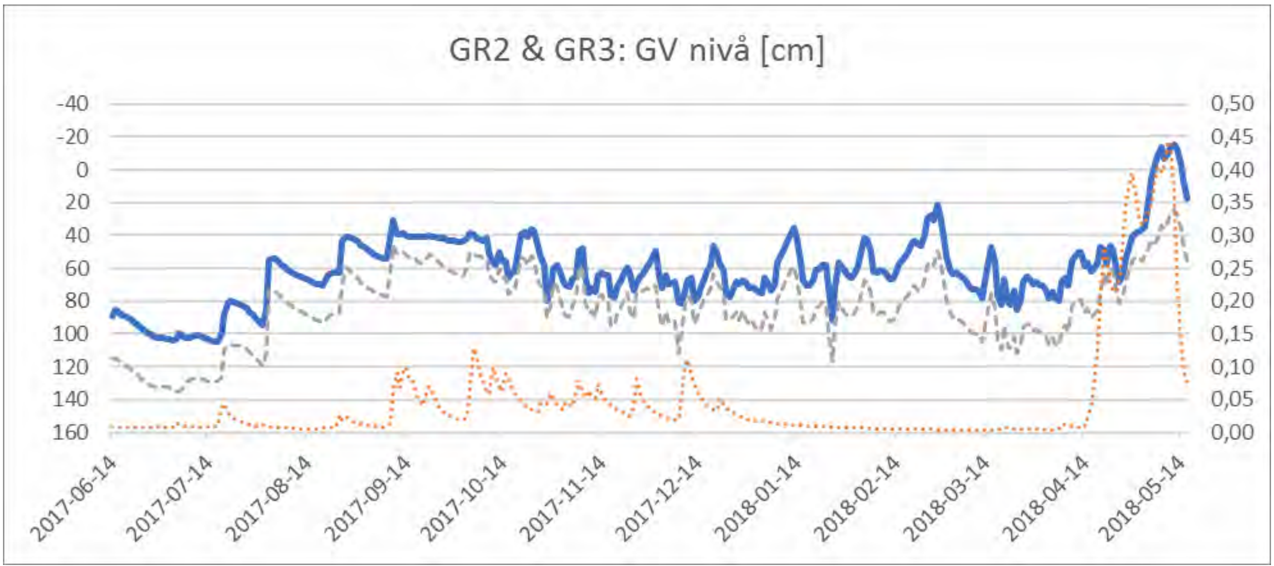

Figure 37: Groundwater level in cm dbg (left Y axis) for sub-area 2 (solid line) and sub-area 3 (dashed line) and daily average values for runoff in m³/s (right Y axis) according to the SMHI water web (dotted line).

The groundwater level in sub-area 1 appears to correlate well with changes in the runoff (Figure 4

38). However, the coefficient of determination is relatively low (R^2 = 0.56) but clearly higher compared to sub-areas 2 – 4 (R^2 = 0.26 – 0.32). Sub-area 1 is very low lying – the adjacent wetlands in the to the south west is very flat and is 1 – 1.5 metres higher than the coastal area by the Alterälven river is about 300 m farther away). Sub-area 1 has an outfall well with no control, this means that the drainage water runs straight into the open ditch.

The difference compared to sub-area 2 – 4 is particularly apparent in the winter. The groundwater level fluctuates somewhat in sub-areas 2, 3 and 4 during the winter period January – March 2018, despite the runoff being low, slowly tailing off and varying minimally. The level in sub-area 1, on the other hand, does not exhibit the same variation at all. Since the fluctuations that can be seen in data from sub-areas 2 – 4 are not present in sub-area 1, systematic errors in the measuring equipment can be ruled out. It is possible that the level in sub-area 1 is more stable because the area is the most low lying and is close to the wetland area adjacent to the test field to the south west. In isolated observations the groundwater level has been found to be very close to ground level in the wetland area, as the surface is very wet almost all year round. The fluctuations in sub-areas 2 – 4 show that the groundwater is running to the test field from higher areas even in winter, while the more stable level in sub-area 1 is likely to be due to groundwater levels generally varying little close to the lowest lying point in the landscape.

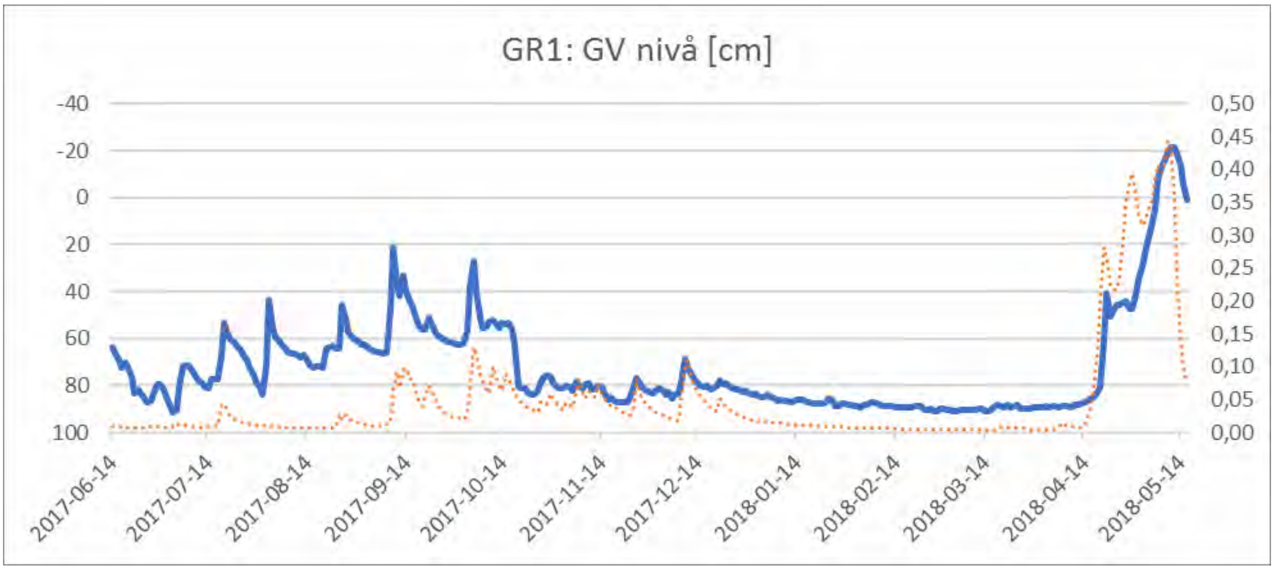

Figure 38: Groundwater level in cm dbg (left Y axis) for sub-area 1 (solid line) and daily average values for runoff in m³/s (right Y axis) according to the SMHI water web (dotted line).

The control and monitoring of groundwater levels seems to work well. There is a clear difference in groundwater level between the areas enclosed in plastic 1 – 3 and sub-area 4. The average values for groundwater level in sub-areas 1 – 4 during the period 14 June 2017 – 16 May 2017 were 72, 61, 83 and 102 cm respectively. In theory this should mean that the leaching of acidifying substances and metals from sub-area 4 takes place to a greater extent (per unit of surface area) compared to sub-areas 1 – 3.

Groundwater levels have also occasionally been measured by a water level meter at GR0, both before and after installation work (Table 10). The results indicate that the groundwater level at GR0 was lower in the summer of 2017 (after the measure) compared to the summer of 2016. The average values for summer periods were 73 cm dbg for the summer of 2016 and 113 cm dbg for the summer of 2017 (calculated on the basis of the underlined values in the table). What could have affected the difference in groundwater level between the two years is primarily the overall hydrological status of the area, but also that the new drainage was becoming more efficient. GR0 is located in sub-area 1 where the groundwater level cannot be controlled. The snow melt in 2017 did not cause as much runoff as in 2016 (Figure 39), this contributed to drier conditions in the summer of 2017 than in 2016. Preliminary data from 2018 show that the groundwater level had been even lower (on average 129 cm dbg based on two measurements in the period June-July). The hydrological status of the area can generally be said to be even drier than 2017, which is a likely explanation.

Measurement of water chemistry parameters

In the groundwater pipe GR0, conductivity was continuously measured by a logger from 22 March 2016 to 16 May 2018. The measuring period covered three snow melts, two summer periods and one winter period. The aim has been to collect data before and after the implementation of controlled drainage. Data indicate that conductivity has been stable for long periods with specific conductance values of just below 1000 µS/cm@25 °C (Figure 39). Data loss occurred in the periods 26 – 30 September 2016 and 18 December 2016 – 3 April 2017. Our assessment is that the groundwater level at that time was so low that the logger was above it. Unfortunately, these episodes occurred before the continuous measurement of groundwater levels was started.

During the snow melt and subsequent spring flood, flows and runoff are their greatest. Large volumes of melt water are transported in the upper soil horizons. However, this does not seem to have affected conductivity in groundwater in the Bäverfältet field – data from the winter of 2018 indicate that conductivity was stable at just below 1000 µS/cm@ 25 °C.

Table 10: Groundwater levels at groundwater pipes GR0 in cm below ground level. Data from field measurements using a water level meter. Underlined rows indicate the values used for averaging for the summer periods 2016 and 2017. Rows in italics indicate preliminary values for 2018 used for averaging.

Date	***GWL cm dbg***
22/03/2016	*67*
20/04/2016	*61*
13/05/2016	*43*
31/05/2016	*77*
14/06/2016	*81*
28/06/2016	*60*
09/08/2016	*112*
10/08/2016	*102*
15/09/2016	*119*
26/09/2016	*124*
26/10/2016	*113*
21/11/2016	*111*
30/05/2017	*96*
21/06/2017	*116*
17/07/2017	*126*
09/10/2017	*90*
16/05/2018	*22*
13/06/2018	*121*
27/07/2018	*136*

Summer values have shown varying results. In the summer of 2016, conductivity was stable at values just below 1000 µS/cm@ 25 ˚C, while in the following summer in 2017 it was significantly higher with sharp variations. The summer of 2017 was the first summer after the implementation of controlled drainage, which could have affected conductivity at GR0. Because it was discovered that the ground had not previously had subsurface drainage, the new drainage resulted in increased sulphide oxidation in the underlying soil horizons, which in turn caused elevated levels of sulphate and thus elevated conductivity levels in the groundwater.

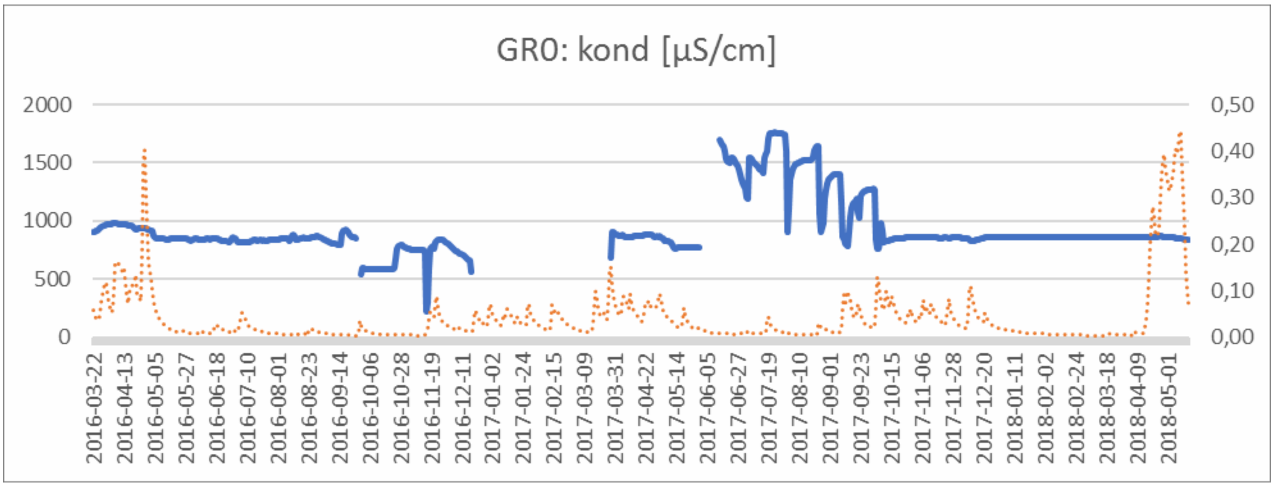

Figure 39: Conductivity as a specific conductance in µS/cm@25 °C (left Y axis) in groundwater from pipe GR0 (solid line) and daily average values for runoff in m^3/s (right Y axis) according to the SMHI water web (dotted line).

Conductivity has been measured continuously at wells BR1 – BR3 during the period 14 June 2017 – 13 June 2018 (Figures 40 – 42). Data loss occurred until 9 October 2017 from BR3 when an unidentified error occurred when the logger was being read off in the field. Conductivity was high in all wells during the period and the variations occurring in the data coincided with high runoff episodes. This indicates that the water in the wells is affected by water with lower conductivity during these episodes, which was not the case for groundwater (GR0).

All transient decreases in conductivity in data from BR1 – BR3 coincide with an increase in runoff, with the exception of the sharp decrease in conductivity in BR1 that occurred between 6 – 18 March 2018, almost one month before the spring flood. The lower values during this period show that water with a lower conductivity is mixing with drainage water from sub-area 1. However, it is impossible to say anything about where the water originated from based on the collected data. One guess is that this is melt water that has been pushed into BR1 from the wetlands bordering the test field to the west or from the area south of the test field. This melt water would reach BR2 and BR3 later, because the outfall from these wells is higher than BR1. Where a decrease in conductivity coincided with increased runoff, the decrease is probably due to rainwater or melt water with a low conductivity diluting the highly conductive groundwater.

Average values for conductivity were calculated for the winter period 1 January – 1 March 2018, and were 1305, 1200 and 1069 µS/cm (for BR1, BR2 and BR3 respectively) according to logger data. Preliminary data from 2018 show that conductivity from field measurements was clearly lowest in BR3 in comparison with BR1 and BR2 (Table 11). Logger data and data from these field measurements together indicate that conductivity in BR3 is lower than in BR1 and BR2. Because the conductivity in the wells drops at runoff peaks, the lower conductivity in BR3 may indicate more water passing or being stored in sub-area 3 than, for example, sub-area 2. In turn this may be because the slope of these sub-areas is different, or because the groundwater levels have been higher in sub-area 3 than in sub-area 2. Another explanation may be that the well control was open in BR2 during the winter of 2017 (see above) and that this is still affecting the water chemistry in the well water in BR2.

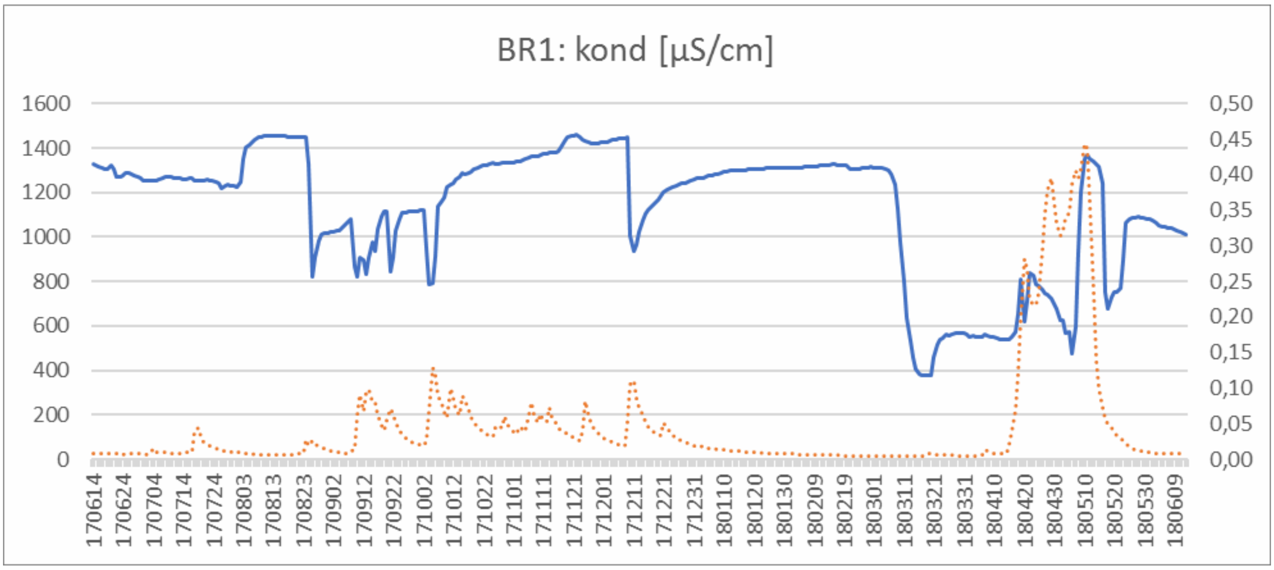

Figure 40: Conductivity as a specific conductance in µS/cm@25 ◦C (left Y axis) in water from well BR1 (solid line) and daily average values for runoff in m^3/s (right Y axis) according to the SMHI water web (dotted line).

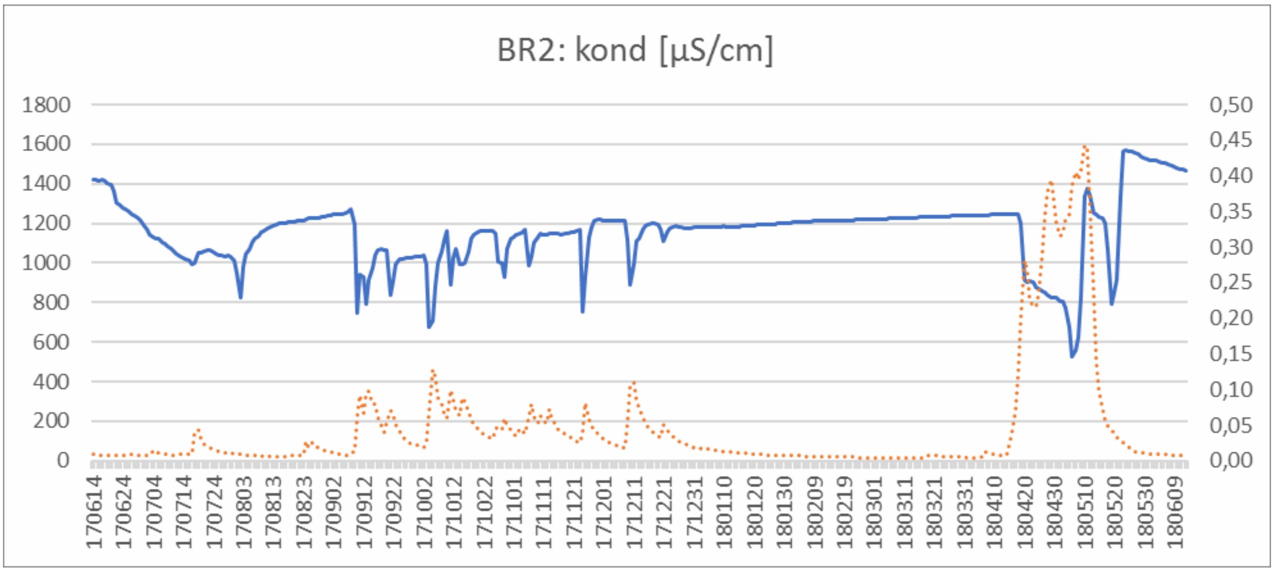

Figure 41: Conductivity as a specific conductance in µS/cm@25 ◦C (left Y axis) in water from well BR2 (solid line) and daily average values for runoff in m^3/s (right Y axis) according to the SMHI water web (dotted line).

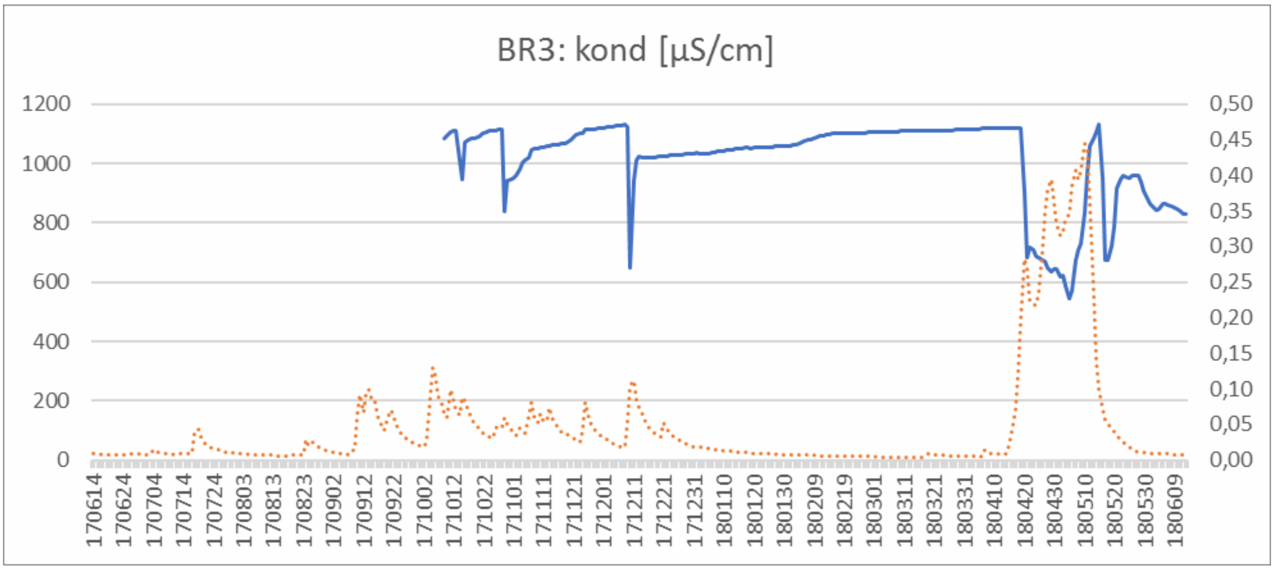

Figure 42: Conductivity as a specific conductance in µS/cm@25 °C (left Y axis) in water from well BR3 (solid line) and daily average values for runoff in m^3/s (right Y axis) according to the SMHI water web (dotted line).

Table 11: Field measurements of pH and conductivity in wells BR1-BR3.

	Measurement 25/10/2017		***Measurement 13/06/2018***		***Measurement 26/07/2018***	
Locality	*pH*	*EC (µS/cm)*	*pH*	*EC (µS/cm)*	*pH*	*EC (µS/cm)*
BR1	*3.6*	*1232*	*4.3*	*1115*	*4.0*	*1171*
BR2	*3.6*	*916*	*4.2*	*1347*	*3.7*	*1423*
BR3	*3.4*	*905*	*3.9*	*656*	*5.7*	*326*

Measurement of pH has only taken place in the field at measuring points GR0, GR1-4 and BR1 - BR3. The pH values measured were generally higher in groundwater than well water (Tables 11 and 12). Conductivity in the groundwater pipes GR1 – GR4 has only been measured in the field. These measurements show that conductivity in groundwater did not vary greatly between the different sub-areas of the field.

Table 12: pH values and conductivity from groundwater pipes on the test field 2016 - 2018

Locality	***pH interval***	***EC interval (µS/cm)***
GR0	*3.7- 6.2*	*(see diagram above)*
GR1	*5.2- 6.7*	*475- 770*
GR2	*4.7- 6.6*	*292 – 780*
GR3	*4.0 – 6.4*	*398 – 832*
GR4	*4.4- 6.4*	*565 – 924*

Transect measurement in the open outfall ditch

The measurement of pH and conductivity in the open outfall ditch south east of the field has been carried out in transects on three occasions (Table 13). The results show that conductivity is highest and pH lowest in the upper areas of the field (sub-areas 3 and 4). The reverse applies to the outfall point downstream of sub-area 1. This is contrary to what was measured in wells BR1 – BR3 where conductivity was lower in the upper sub-areas of the field (sub-area 4 has no well). This is probably because the drainage water from the test field is gradually diluted with low conductivity water originating from nearby land areas where sulphide oxidation does not affect the ground water to the same extent as in the test field.

Table 13: pH values and conductivity from field measurements in the open outfall ditch of the test field. YTV1 is a point at the outfall from sub-area 1, YTV2 is located at the outfall from sub-area 2, etc.

	Measurement 25/10/2017		***Measurement 13/06/2018***		***Measurement 26/07/2018***	
Locality	*pH*	*EC (µS/cm)*	*pH*	*EC (µS/cm)*	*pH*	*EC (µS/cm)*
YTV1	*4.7*	*321*	*7.3*	*233*	*6.9*	*231*
YTV2	*4.7*	*335*	*7.2*	*248*	*7.4*	*254*
YTV3	*3.6*	*446*	*3.7*	*420*	*6.7*	*246*
YTV4	*3.7*	*388*	*3.5*	*577*	*3.6*	*395*

Investigation of the transition zone between active and potentially acid sulphate soil

SGU has undertaken soil sampling in order to map the transition zone between the active and potentially acid sulphate soils. The soil type is determined for each profile and the pH is measured every 10 cm. Data from a total of 23 localities in the test field (Appendix 4) are presented here as an average profile showing how pH typically varies with the depth of the soil in the field (Figure 43). These profiles have been sampled both before and after the implementation of the measure, but no difference in the location of the transition zone has been observed. However, this was expected, as it will probably take a long time before sulphide oxidation in the ground decreases to an extent that moves the transition zone.

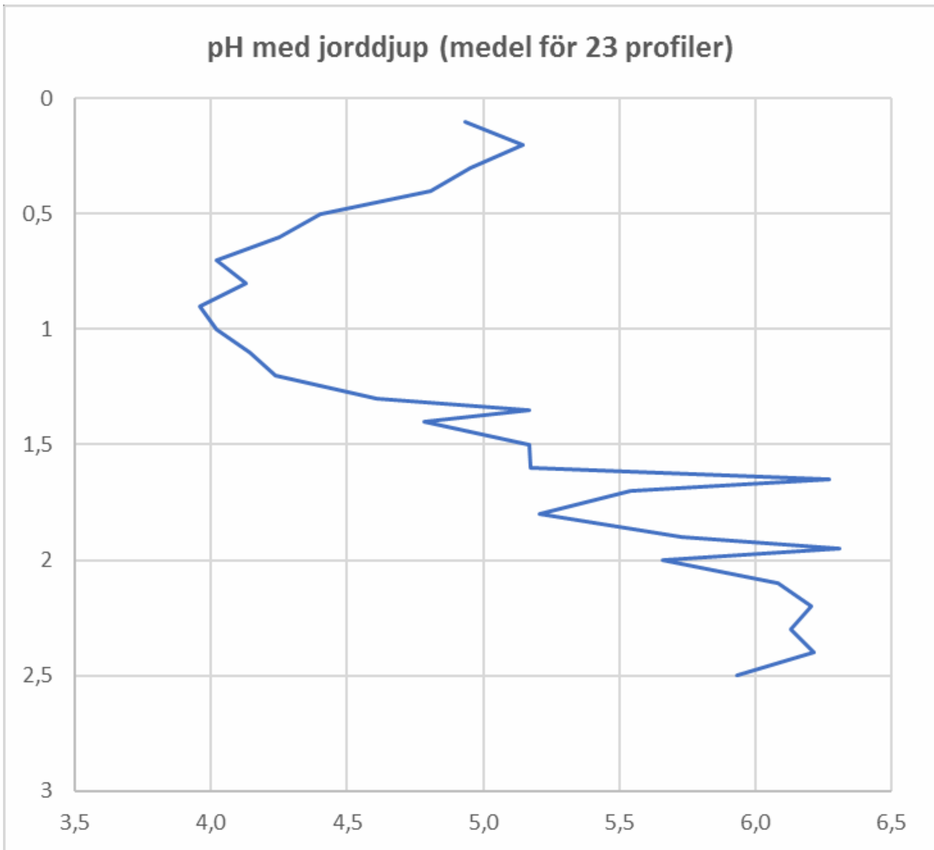

Figure 43: pH change (X axis) with depth (Y axis) in a typical soil profile from Bäverfältet (average of 23 profiles).

DISCUSSION

Modelling

The results of the modelling of acid sulphate soils in the catchment areas of the Simo Älv, Alån, Rosån and Alterälven rivers show that it is possible to use modelling to prepare maps showing where active and potentially acid sulphate soils are likely to occur. Such maps are useful for identifying areas where it is important to avoid land use that will lead to a negative impact from acid sulphate soils. However, it is important to remember that these maps do not show areas where it is certain that acid sulphate soils occur, instead they show areas where such soil is likely to occur, and conversely, acid sulphate soils occurring in certain locations where, according to the map, this is unlikely, cannot be ruled out. In order to accurately assess the conditions in a particular location, it is therefore important to characterise the soils. However, these maps can be used to assess whether such a characterisation is justified.

Naturally, the reliability of the model in a certain area depends on the amount, resolution and quality of the data used (input data). The soil type map is an important parameter in the model of the Swedish catchment areas. And when the soil type map is a generalisation of the actual situation, and the boundaries are not exact, the class of each sampling point in the field and on the soil type map need not always agree. For example, localities classified as 'sulphate on sulphide' have been sampled in areas that, according to the soil type map, are made up of till, though they are in fact made up of a fine-grained sediment. However, it is noteworthy that the model in the Swedish catchment areas predicts the presence of "sulphide" and "sulphate on sulphide" in relatively large areas that, according to the soil type map, are made up of till. It is unlikely that such a large proportion of the soil types on the map is incorrectly classified as till. In all probability these areas are instead flat till which has been incorrectly modelled as "sulphide" or "sulphate on sulphide". It is possible that the national elevation model can be used to better characterise these flat till areas and developing a model in which these areas are not characterised as acid sulphate soil.

The reliability of the model also varies between different soil types and types of land use. For example, it is highly probable that acid sulphate soils occur within the large flat areas with ditched, cultivated, postglacial fine sediment near the coast. On the other hand, it is harder to predict the extent to which potentially acid sulphate soils occur in other, younger soil types. For example, some peatland in an area may be underlain by potentially acid sulphate soils while other peatland is not. Furthermore, some reduced sandy soils may be potentially acid sulphate soils, while other sandy soils do not contain potentially acid sulphate soils. And it is hard to predict which case applies the sandy soils in a specific location.

In the three Swedish catchment areas, the frequency of active acid sulphate soils, based on the results of modelling, is greatest closest to the coast and decreasing at higher altitudes. This corresponds to the fact that the vast majority of localities with acid sulphate soils have been found in areas less than 40 masl (Figure 14 and 28). The large areas of active acid sulphate soils are found in the flat clay area that occur near the coast; often consisting of active or abandoned agricultural land. On the other hand, small areas of potentially acid sulphate soils (sulphide soil) occur at higher altitudes, for example in small wetlands where the sulphide soil is overlain by peat. In Finland, in the catchment area of the Simo Älv river, there are no active acid sulphate soils, while there are potentially acid sulphate soils, overlain by other, younger soil types such as sand or peat. One reason for the lack of active acid sulphate soils may be that the area is so far north that it was not worth ditching the wetlands to obtain agricultural land. It is therefore unlikely that the water chemistry in this area would be adversely affected by acid soils but potentially this could occur if sulphide soils were exposed to air, as a result of ditching for example.

As regards the map in Figure 26, which shows the probability of the incidence of acid sulphate soils around the northern Gulf of Bothnia, it is reasonable to assume that the reliability of the map in the modelled area varies. However, we consider that it gives a good overview of the distribution of acid sulphate soils around the northern Gulf of Bothnia, which is confirmed by the appearance of large areas of identified acid sulphate soils on the map. The map indicates that the area of acid sulphate soils is considerably larger in Finland than on the Swedish side, which explains why the environmental problems associated with these soils have been observed more widely in Finland. One reason for uncertainty is that the model of the northern Gulf of Bothnia represents a large area with varying geological conditions. For example, there are differences in the topography today and the current and previous extent of land uplift. In Sweden there are large areas where there are no observations at all, while there are a large number of observations on the Finnish side. This means that conditions in areas with Finnish acid sulphate soils have great importance to the model. Although the border between Sweden and Finland does not in any way constitute a geological boundary, there are general differences in the topology between the two countries. This means that the model is probably subject to major uncertainties on the Swedish side. On the Swedish side, for example, the model predicts the incidence of acid sulphate soils in areas located at relatively high altitudes, where we did not encounter such soils. One way to improve the map may be to model smaller areas separately, and then put them together in a larger map. Another way would be to use the entire soil type map as input for the model. This was not carried out for the model presented here. The electrical conductivity of the water in both Norrbotten and Västerbotten has been measured in a large number of small watercourses. High conductivity indicates the presence of active acid sulphate soils, and this data could therefore be used to verify and improve the map. Additional data, such as data collected by Skogsstyrelsen [*the Swedish Forestry Agency*] as part of VIMLA, will soon be available, and SGU will continue to work on improving the map.

Geochemistry

As mentioned above the results of the chemical analyses, show that many elements harmful to the environment are mobilised from areas with active acid sulphate soil. Only the results from four localities are reported here. Two of these are made up of active acid sulphate soils. However, results from other localities investigated as part of this project and in other studies show similar results. The results of this and previous studies (e.g. Nordmyr et al. 2008, Åström 2001b) also show that many of the elements mobilised from acidic soil are found in high concentrations in the transition between active and potentially acid sulphate soils (e.g. Sohlenius & Öborn 2004). This is an effect of substances being mobilised from the upper layer of active acid soil and accumulating further down in the soil profile. This means that environmentally harmful mobile substances remain in the profiles. The results of other studies show that the metals in these peaks occur in a soluble phase (e.g. Sohlenius & Öborn 2004) and can easily leach into surrounding water. The substances shown in the figures are just some of those analysed, and the results show that many other substances are leached from acid sulphate soils. For example, all rare earths, including Y (as shown in the figures), show a similar pattern, which has been demonstrated in several previous studies (e.g. Nordmyr et al. 2008, Åström 2001b).

The results section details an attempt to calculate the amount of the different elements that could have been mobilised from active acid sulphate soils in the three catchment areas investigated in Norrbotten. Although there are major uncertainties, we consider that the results show the magnitude of metal leaching from areas with acid sulphate soils. However, it is important to point out that this is an ongoing process and, to some extent, substances mobilised from active acid sulphate soils are likely to remain in the soil, but in a relatively soluble form (see Sohlenius and Öborn 2004). As mentioned above, many elements appear in high levels in the transition between oxidized and reduced soil. Data from these peaks were not used to calculate the average values of active and potentially acid sulphate soils. These peaks are probably equivalent of metals leached from the acidic soil and can be mobilised into the surrounding waters. Calculations show that the difference between the levels of active and potentially acid sulphate soils indicates that very large amounts of elements harmful to organisms have been mobilised from the acidic soils. Although the values contained in the table may be an overestimate, it is likely that large amounts of metals were mobilised from active acid sulphate soils into surrounding water as a result of the lowering of groundwater levels in many areas with potentially acid sulphate soils over the last century. The results of a degree project recording the concentrations of metals in ditches and watercourses with acid sulphate soils in coastal areas in Norrbotten, also show that concentrations of Co, Ni, Cd, Zn, Al and Mn are significantly higher in these waters compared to concentrations in average Swedish watercourses (Wennström 2017), which further supports the interpretation that active acid sulphate soils are a significant source of these substances.

On the Finnish side there are studies showing that elements mobilised from active acid sulphate soils largely accumulate in sediments deposited outside the mouths of watercourses affected by these soils (e.g. Nordmyr et al. 2008). The results of studies of sediment deposited near the Rosån river, show that elements mobilised from acid sulphate soils are, at least in part, laid down in marine sediments in proximity to the watercourse instead of being transported out to sea by the watercourse. However, it is not possible to determine from this study what proportion of the metals accumulate in the sediments, and what proportion that could be transported farther out into the Baltic, and for certain elements it is difficult to determine whether the elevated levels are an effect of the impact of acid sulphate soils. This applies, for example, to the increased levels of cadmium in sediments deposited in coastal areas. It is conceivable that sediments that exhibit high concentrations of certain metals in the Övre Träsket and Nedre Träsket lakes have been deposited in conjunction with acid shocks, as acidic water causes clear water with high concentrations of metals. A study of Persöfjärden fjard just north of Luleå shows that during certain periods the water is characterized by a low pH, when this is the case organic matter flocculates with iron and sinks to the bottom (Erixon 2009). This causes the water to become very clear. Similarly, periods of very clear acidic water have been observed in the Rosån river (see Erixon 2009). In other words the process described by Erixon (2009) can explain the peaks with a high organic content and with high levels of Al and Fe, among other elements, occurring in the two lakes. These acid shocks occur during periods when a low groundwater level that has resulted in sulphide oxidation, is followed by a period of high flows, as a result of which acidic metal-rich water can be mobilised from the soils. That interpretation is supported by the results of lead dating, which show that the sediments with high levels of iron and aluminium were probably deposited after drainage was started, and thus when active acid sulphate soil was present in the catchment area.

One difficulty with sediment investigations is that the levels of metals and other elements are not always directly linked to the amount of those elements available in the water. For example, the results of this study show that the levels of lead in certain sediment samples from the Övre Träsket lake are relatively high, despite this element not exhibiting high concentrations in water impacted by active acid sulphate soils (see Wennström 2017, Åström 2001b for example). Although some elements occur in relatively high concentrations in the sediments off the mouth of the Rosån river, the levels are far from as high as those encountered on the Finnish side (e.g. Nordmyr 2008). A study of sediment off the mouth of the Hertsångerälven river in Västerbotten, also found no high concentrations of metals mobilised from active acid sulphate soils (Thomas 2016). In order to determine how efficiently metals from acid sulphate soils are laid down in maritime and coastal sediments, further investigations would therefore be required, and sediments from additional catchment areas with acid sulphate soils would have to be investigated. In addition, water chemical analyses would have to be undertaken to study whether concentrations of metals decrease in the areas in which sediments are deposited, and the redox conditions in the sediments should be investigated as these have a major influence on the bonding and solubility of different metals.

Conclusions regarding the test field results

It is probable that it will take several years before any soil and water chemistry changes can be observed as a result of the measure. The results presented here must therefore be seen as a starting point for continued monitoring. The County Administrative Board of Norrbotten plans to continue monitoring for at least five years. Monitoring has focused on conductivity measurement, groundwater level measurement and soil sampling, which in this case is relatively cost effective. The measurement of conductivity and groundwater levels will continue using loggers, requiring minimal personnel resources in the field. Soil sampling need not to be carried out every year, instead fairly sporadic initiatives are required every 2 to 3 years.

Water chemistry data suggest that the groundwater in the field is acutely affected by sulphide oxidation. The groundwater chemistry is relatively stable, while the water chemistry in the wells and outfall ditches appears to fluctuate more. The assessment is therefore that the effect of water chemistry in the future is best monitored by measuring water quality in the open ditches and outfall wells. The disadvantage is that sub-area 4 will be difficult to monitor because it has no outfall well and because the water supply in the open ditch level with sub-area 4 is often too small to carry out measurements. One possible method would be to put groundwater pipes close to the outfall pipes for the various sub-areas so as to establish localities that can be sampled and that are comparable. This would minimise the effect of low conductivity drainage water from nearby land.

The conditions for cultivation have been considerably improved following the implementation of controlled drainage. It will be interesting to follow the performance of subsurface drainage in the future in view of the risk of blockage due to iron precipitation when subsurface drainage is implemented in acid sulphate soils. The purpose of controlled drainage is to reduce that risk, and thus reduce the need for maintenance of the drainage system.

Because the intake chamber in sub-area 3 was installed late in the project, no water supply trials have been carried out. The purpose of the chamber is to supply water to the field during dry periods to reduce the risk of sulphide oxidation in the soil horizon and to water crops from below. Our assessment is that supplying water to the water reservoir in sub-area 3 in this manner will not be a problem.

It is possible to use the subsurface drainage system to lime the soil from below. This has been tested as part of the Finnish project Precikem II, conducted by the Novia University of Applied Sciences (leaderpohjanmaa.fi, 2018). Drainage systems with controlled drainage have been used here to pump a lime solution through the outfall wells instead of spreading lime on the surface of the cultivated land. The idea is that the lime will be able to penetrate the soil in order to more effectively buffer the acidity leaching out from acid sulphate soils. This method has the potential to reduce amount of lime needed per unit of surface area, reduce costs and increase efficacy. The soil in the test field has not been limed for many years, but it is common for agricultural land in the coastal Norrbotten to be surface limed to raise the pH of the soil.

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Product description GSD Digital elevation model. Grid 2+ Gävle. The Swedish

Mapping, Cadastral and Land Registration Authority 2017b: Product

description GSD Orthophoto and orthophoto25. Gävle.

The Swedish Mapping, Cadastral and Land Registration Authority 2017c: Product description GSD Property map, unified raster. Gävle.

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APPENDIX 1 – CLASSIFICATION OF ACID SULPHATE SOILS IN FINLAND AND SWEDEN

Classification of acid sulphate soils in Finland and Sweden

Version 2.2018

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1. Introduction

This document describes the classification of acid sulphate soils in Finland and Sweden The classification methodology has been developed in collaboration between the projects "Kustmynnande Vattendrag i Bottenviken - Metodutveckling och ekologisk restaurering. Ett gränsöverskridande Svenskt-Finskt samarbetsprojekt" [*Watercourses discharging into the Bay of Bothnia - Methodological development and ecological restoration. A cross-border Swedish-Finnish joint project*] (financed by the Interreg North programme) and "Water and Man in the Landscape" (VIMLA, funded by the Interreg Botnia-Atlantica programme). The purpose of these guidelines is for Finland and Sweden to use the same classification methodology for acid sulphate soils, allowing for the cross-border mapping of acid sulphate soils.

The general definition of acid sulphate soils is soils containing sulphidic material (i.e. hypersulphidic material, Chapter 2.2) in such quantities that the soil pH has fallen, or may fall, below 4 as a result of sulphide oxidation and the formation of sulphuric acid. Added to Swedish-Finnish definition is that for organic soil material (e.g. peat and organic clay) the pH falls below 3 on oxidation. The reason for this is to distinguish between pH reduction due to sulphide oxidation and pH reduction due to the presence of organic acids (Hadzic et al. 2014).

The terminology and definitions used for the classification of soil horizons in acid sulphate soils, follow, in as far as it is possible, the proposals of the international working group on acid sulphate soils, published in Sullivan et al. (2010). Parts of the working group's publications have also been included in existing international classification systems such as the "World reference base for soil resources, WRB" (IUSS Working Group WRB, 2015) and the Australian soil type classification (Isbell, RF and National Committee on Soils and Terrain, 2016). Minor modifications to some definitions of materials have been included in the Swedish-Finnish classification for certain important acid sulphate soil materials (e.g. peat) that occur in Finland and Sweden. Some new terms and materials have also been included in the Swedish-Finnish classification.

Acid sulphate soils usually consist of layers of **minerogenic soils** of varying grain sizes (e.g. clay, silt, sand etc.) and/or **organic soils** (e.g. peat and organic clay). It is sufficient for one of these layers to consist of diagnostic material for the locality to be classified as an acid sulphate soil (see Chapter 3 for the classification of acid sulphate soils). Minerogenic soils are further divided into **sorted** and **unsorted material**. Sorted material has usually been transported by water and wind and deposited in "sorted" layers. Unsorted material, such as till, consist of materials deposited through the activity of the continental ice sheet and usually consist of different grain sizes. A large proportion of the soil material that forms acid sulphate soil in Finland and Sweden therefore has a sedimentary origin, and is either deposited directly as a result of the latest activity of the continental ice sheet, i.e. till (glacial sediment), or deposited after the melting of the last continental ice sheet (postglacial sediment). The largest areas of acid sulphate soil in Sweden and Finland that affect, or potentially affect, the aquatic environment are postglacial fine sediments, deposited on the bottom of the Baltic and later raised above the land due to uplift. Till is the most common soil in Finland and Sweden, and underlies most acid sulphate soils. In nature, a peat cover often forms on top of the mineral soil, and virtually all acid sulphate soils in Finland and Sweden were probably covered with peat which, but due to land use, that peat cover has generally been removed.

The Swedish-Finnish classification has a separate group defined for such soils which, according to current criteria, are not classified as acid sulphate soils, but are on the boundary of being classified as such. In these pseudo acid sulphate soils there is probably an increased risk of environmental problems. These soils are important when assessing the environmental risk potential of different types of acid sulphate soils. Research has shown that the environmental risk potential can vary widely between different types of acid sulphate soil. For example, coarse grained acid sulphate soils usually contain lower levels of sulphides and metals than fine grained acid sulphate soils, which means that the environmental risk of a coarse acid sulphate soil is probably less than a fine grain soil. A fine grain (clay, silt for example) pseudo acid sulphate soil will probably be a greater environmental problem than a coarse (e.g. sand) acid sulphate soil. The difference being that the greater environmental problem in this example is not classified as a "true" acid sulphate soil while the one posing a minor environmental risk is.

2. Definition of acid sulphate soil material

The term "acid sulphate soil material" refers to soil types (minerogenic and organic) containing sulphides (reduced material) and/or sulphates (oxidised material) (Chapters 2.1-2.7). Acid sulphate soil material that is diagnostic for acid sulphate soils is called "diagnostic material" and includes ***hypersulphidic material*** (Chapter 2.2), ***hypermonosulphidic material*** (Chapter 2.5) and ***sulphate material*** (Chapter 2.6). Wherever possible, the definitions and terminology of acid sulphate soil material as established by the international working group on acid sulphate soils have been used. However, new terms and modifications do occur and are described in detail below.

2.1. Sulphidic material

The existing definition used in the IUSS Working Group WRB (2015) and in the Australian classification (Isbell, RF and National Committee on Soils and Terrain, 2016).

Sulphidic material refers to soils (minerogenic and organic) containing ≥0.01% (dry weight) sulphur in sulphide form. The sulphide concentration can be determined using the chrome reduction method described in among others Backlund et al. (2005), Boman (2008) and Dalhem et al. (2016). For fine grained minerogenic soils (e.g. clay and silt), the analysis of total sulphur (e.g. aqua regia dissolution and ICP-OES/MS detection) can be sufficient, because previous studies have shown that the majority of sulphur in such materials is usually in sulphidic form (Boman 2008). For organic soils (e.g. peat), it is not possible to use total sulphur as a significant proportion of the sulphur can be organically bound.

2.2. Hypersulphidic material

Existing term for minerogenic soils but also includes organic soils. Synonym: Potentially acid sulphate soil material, sulphide soil material.

Hypersulphidic material is a diagnostic material for acid sulphate soils and is defined as a sulphidic material capable of strong acidification as a result of sulphide oxidation. Hypersulphidic material has a field pH of >4.0 for minerogenic soils and >3.0 for organic soils, and is identified by a sharp decrease* of pH to <4.0 for minerogenic material and <3.0 for organic material when a 2–10 mm thick layer of material is incubated (oxidised) under field capacity. The length of incubation is either: **a)** until the pH of the material has changed by at least 0.5 pH units to a pH value <4.0 for mineral soil material or <3.0 for organic soil material, or **b)** until a stable** pH value has been reached after at least an eight week incubation.

*******A sharp decrease during incubation is characterised by a reduction of 0.5 pH units or more.*

***A stable pH is assumed to have been reached after eight weeks incubation when either the pH reduction is < 0.1 pH units over a 14 day period, or when the pH starts to increase.*

2.3. Pseudo hypersulphidic material

New term that includes sulphidic material on the threshold of being classified as hypersulphidic material. In Fitzpatrick et al. (2008) the term "pseudo sulphidic" is used for sulphidic material with an incubation pH value between 4 and 5.

Pseudo hypersulphidic material is sulphidic material that is capable of moderate acidification as a result of sulphide oxidation. Pseudo hypersulphidic material has a field pH of >4.0 for minerogenic soils and >3.0 for organic soils and is identified by a very sharp reduction* in pH value to 4–4.5 for minerogenic soils and 3–3.5 for organic material when a 2–10 mm thick layer of material is incubated (oxidised) under field capacity to a stable ** pH value has been reached after at least an eight week incubation

*******A very sharp decrease during incubation is characterised by a reduction of 1.0 pH units or more.*

***A stable pH is assumed to have been reached after eight weeks incubation when either the pH reduction is < 0.1 pH units over a 14 day period, or when the pH starts to increase.*

2.4. Hyposulphidic material

Existing term with a somewhat modified threshold for the incubation pH for minerogenic soils and the inclusion of organic soils (however, with another threshold for incubation pH).

Hyposulphidic material is sulphidic material that is not capable of moderate acidification as a result of sulphide oxidation. Hyposulphidic material has a field pH of 4.0 or more for minerogenic soils and 3.0 or more for organic soils and is identified by the pH not decreasing to less than 4.6 for minerogenic material and less than 3.6 for organic material when a 2–10 mm thick layer of material is incubated (oxidised) under field capacity until a stable pH value has been reached after at least an eight week incubation

A very sharp decrease during incubation is characterised by a reduction of 1.0 pH units or more.

***A stable pH is assumed to have been reached after eight weeks incubation when either the pH reduction is < 0.1 pH units over a 14 day period, or when the pH starts to increase.*

2.5. Monosulphidic material

Existing term Synonym: Sulphidic soil

Monosulphidic material refers to sulphidic material that contains >0.01% (dry weight) acid volatile sulphides, AVS. The acid volatile sulphide concentration can be determined using the AVS method described in among others Backlund et al. (2005), Boman (2008) and Dalhem et al. (2016). Monosulphides cover inorganic ferrous sulphides such as mackinavite (FeS) and greigite (Fe_3S_4) (Boman et al., 2008) and is usually the reason for the dark or black colour of sulphidic material. In coarse grained (e.g. sand) minerogenic soils it can be difficult in the field to demonstrate the incidence of monosulphidic material while this is simpler in fine-grained (e.g. clay and silt) minerogenic soils. It is proposed that the term monosulphidic material be used only when the material exhibits a very dark colour (according to the Munsell colour chart) and the incidence for monosulphides has been demonstrated using an approved analysis method.

Monosulphidic material is divided in the same way as sulphidic material depending on how its pH value develops during incubation:

- ***Hypermonosulphidic material***, if the material consists of both monosulphidic material and hypersulphidic material (Chapter 2.2). Diagnostic material
- ***Pseudo hypermonosulphidic material***, if the material consists of both monosulphidic material and pseudo hypersulphidic material (Chapter 2.3).
- ***Hypomonosulphidic material***, if the material consists of both monosulphidic material and hyposulphidic material (Chapter 2.4).

2.6. Sulphate material

Existing definition for minerogenic soils but including organic soils (however, with a lower field pH threshold). Synonym: Actively acid sulphate soil material

Sulphate material is a diagnostic material for acid sulphate soils and is defined as soil types that, due to sulphide oxidation, have a field pH <4.0 for minerogenic material and <3.0 for organic materials. Evidence for sulphide oxidation is one of the following:

- Enrichment of jarosite ($KFe_3(OH)_6(SO_4)_2$) or other ferrous and aluminium sulphate mineral or hydrosulphate mineral such as natrojarosite ($NaFe_3(SO_4)_2(OH)_6$), schwertmannite ($Fe_{16}(OH,SO_4)_{12-13}O_{16} \times 10\text{-}12H_2O$), sideronatrite ($Na_2Fe(SO_4)_2(OH) \times 3H_2O$), tamarugite ($NaAl(SO_4)_2 \times 6H_2O$) etc.
- ≥0.05% (% by weight) water soluble sulphate.
- Underlying hypersulphidic material (Chapter 2.2).

2.7. Pseudo sulphate material

New term that includes "sulphate material" with a pH value between 4 and 4.5. Only applies to minerogenic soils.

Minerogenic material that, due to sulphide oxidation, has a field pH of between 4.0 and 4.5 and that can constitute an environmental problem when aluminium becomes soluble and is leached out. See the definition of "sulphate material" for evidence of sulphide oxidation. Pseudo sulphate material on its own is not a diagnostic material for acid sulphate soils, it also requires underlying hypersulphidic material (Chapter 2.2.) in order for the entire profile to be classed as am acid sulphate soil.

3. Classification of acid sulphate soil localities

The collective name acid sulphate soils is broad and includes localities where sulphate, hypersulphidic and/or hypermonosulphidic material occurs in the profile. As the various different materials can cause different environmental problems there is a need for further classification in which each level is more descriptive than the preceding one (see Figure 1). This manual describes the three first levels that are important at a local level and in the overview mapping of acid sulphate soils. Level 1 is made up of the main group "acid sulphate soil" (Chapter 3.1), level 2 is made up of active and potentially acid sulphate soils (Chapter 3.2), while level 3 (Chapter 3.3) describes the diagnostic material that occurs in the soil (Table 1).

Soils that are not classed as acid sulphate soils based on the criteria described in this manual but that are on the threshold have been given their own class and are called **"pseudo acid sulphate soils"** (Chapter 3.1.1).

Table 1. Classification of acid sulphate soils.

Level 1	Level 2	Level 3
Acid sulphate soil	Active acid sulphate soil	Soil with sulphate material
		Soil with sulphate and hypersulphidic material
		Soil with pseudo sulphate and hypersulphidic material
	Potentially acid sulphate soils	Soil with hypersulphidic material
(Pseudo acid sulphate soil)		

3.1. Level 1: Acid sulphate soil

Encompasses the main group *acid sulphate soil* and includes all types classified as acid sulphate soils. In order to classified as an acid sulphate soil, the soil must contain at least one diagnostic material, i.e. either *sulphate material* and/or *hypersulphidic material* (including hypermonosulphidic material). If the soil contains *pseudo sulphate material* (pH 4.0–4.5, Chapter 2.7), there must also be hypersulphidic material in underlying layers in order to classify the entire profile as an acid sulphate soil.

3.1.1. Pseudo acid sulphate soil

New term Note! Does not meet the requirements to be classified as an acid sulphate soil but may constitute a potential environmental risk given particular circumstances and environments.

Defined as soils that are on the threshold of being classified as acid sulphate soils, based on the criteria set out in this manual. A pseudo acid sulphate soil contains either: **1)** a moderately acid soil horizon, where the pH is between 4 and 4.5 (pseudo sulphate material, Chapter 2.7) in the minerogenic material, but where underlying material does not meet the criteria for hypersulphidic material (Chapter 2.2) (i.e. an active pseudo acid sulphate soil), or **2)** non-sulphate material (pH >4.5) together with underlying pseudo hypersulphidic material (Chapter 2.3) (i.e. a potential pseudo acid sulphate soil).

Pseudo acid sulphate soils can be further divided into subgroups in the same way as acid sulphate soils. However, this has not been included in this manual.

3.2. Level 2: Active and potentially acid sulphate soils

In an active acid sulphate soil, sulphide oxidation has started and the pH in the field meets the diagnostic requirements for sulphate material and/or pseudo sulphate material with underlying hypersulphidic material. A potentially acid sulphate soil can develop into an active acid sulphate soil if the hypersulphidic material is exposed to oxygen in the air. It is important to note that a potentially acid sulphate soil may contain an oxidised horizon that previously met diagnostic criteria for sulphate material and/or pseudo sulphate material, but that has been leached to such an extent that these criteria are no longer met. In such cases, an active acid sulphate soil has transitioned into a potentially acid sulphate soil, which in turn can develop into an active soil if the groundwater level is further lowered.

3.3. Level 3: Diagnostic materials in acid sulphate soils

Describes the diagnostic materials occurring in the soil. Example: *Soil with sulphate material* and *soil with sulphate and hypersulphidic material*.

At this level, no distinction is made between mineral soils and organic soils, so there can be mineral soil material and organic soil material that meet diagnostic criteria in the same profile. Note that the term "monosulphidic" is not used in the locality name, but that the term can be used for a more detailed classification of the soil profile (higher level).

4. Sampling acid sulphate soil material

The purpose of sampling is to determine if the sampling locality consists of acid sulphate soils or not. Below is a suggestion of how the sampling of acid sulphate soils can be used for overview mapping. If sampling has a different purpose, the guidelines below can be modified as necessary. Soil samples are always taken from each locality, except if the locality contains stony till (or rock) which causes problems for the sampler.

Observations prior to sampling:

1. Prior to sampling check that there are no drainage pipes, electrical power cables, gas pipes, water pipes etcetera, in the vicinity, which could be damaged or expose people in the surrounding area to risk.
2. The environment at the sampling locality is photographed and the photo is saved together with the sampling result.

Sampling:

1. The soil profile is photographed (in 1 m long sections for example) and the photos are saved together with the sampling result. Use a ruler or tape measure to mark the depth of the soil material being photographed.
2. If possible, sample from the surface (e.g. O, A horizon) and down to reduced material (C horizon). This depth is often found within 2-3 m but in peatland can be found at even greater depths. In peatland it is important to try to reach underlying minerogenic material.
3. Describe the colours of the soil type, texture, contacts, start and end depth and any odour of sulphur or hydrogen sulphide. Also make a note of other observations that could be useful for mapping or research (e.g. the incidence of jarosite or other interesting minerals). Always make a note of oxidation depth (transition layer) observations based on colour (e.g. colour variations from reddish to grey) and/or pH measurements. Also note how sharp the transition is, e.g. "sharp", "gradual" or "gradual 40 cm".
4. pH measurements from the oxidised soil horizon and the transition layer are made at 10–20 cm intervals.
5. Routine samples for incubation and any multi element analyses, are generally taken from the upper, clearly reduced soil. Soil samples can also be taken from the oxidised section of the soil. Depending on the purpose of sampling, different thicknesses of sample can be taken. For overview mapping 20 cm thick samples were taken, with a particular focus on reduced parent material. In some type profiles, 20 cm thick samples are continuously

sampled throughout the soil profile starting from ground level and down to unoxidised parent material. An attempt should be made to sample each individual soil type in the reduced parent material. Take into account the redox depth and the contact between various soil types and avoid mixing different soils. Remember to measure the soil sample pH immediately in the field when these have been homogenised and transferred into sample bags, chip trays or other incubation containers (see Figure 2). The thickness of the incubation samples should be between 2–10 mm. Although the pH of the oxidised layer is <4.0 for minerogenic material or <3.0 for organic matter (i.e. active acid sulphate soil), samples are always taken from the underlying reduced soil types.

Figure 1. Incubation of soil samples in a chip tray. Photograph: Pentti Kouri, GTK.

- Soil samples are used from about 10% of sampling localities for multi element analyses and for quality control of the incubation method (when overview mapping in Finland for example). Every soil sample is divided into two incubation samples (one routine and one duplicate sample) that are incubated in parallel. In practice, each sample can be transferred to a sample bag and then kneaded to homogenise it, then moving material from the sample bag to two containers for incubation. Ensure that there is enough material left in the multi element analysis sample bag. Remember to measure the soil sample pH immediately in the field when the incubation samples have been homogenised and transferred into sample bags, chip trays or other incubation containers.

6. If the soil profile is oxidised right down to the end depth of sampling, a sample should always be taken from the lowermost soil horizon. If necessary, soil samples can also be taken from the overlying oxidised soils.
7. In about 5% of the sampling localities (every 20^{th} locality), a replicate sample for the quality control of mapping is taken (when overview mapping in Finland for example). This means that a new soil observation is made within 1 m of the previous sampling point and this sampling point is described again (wholly independently of the previous observation).

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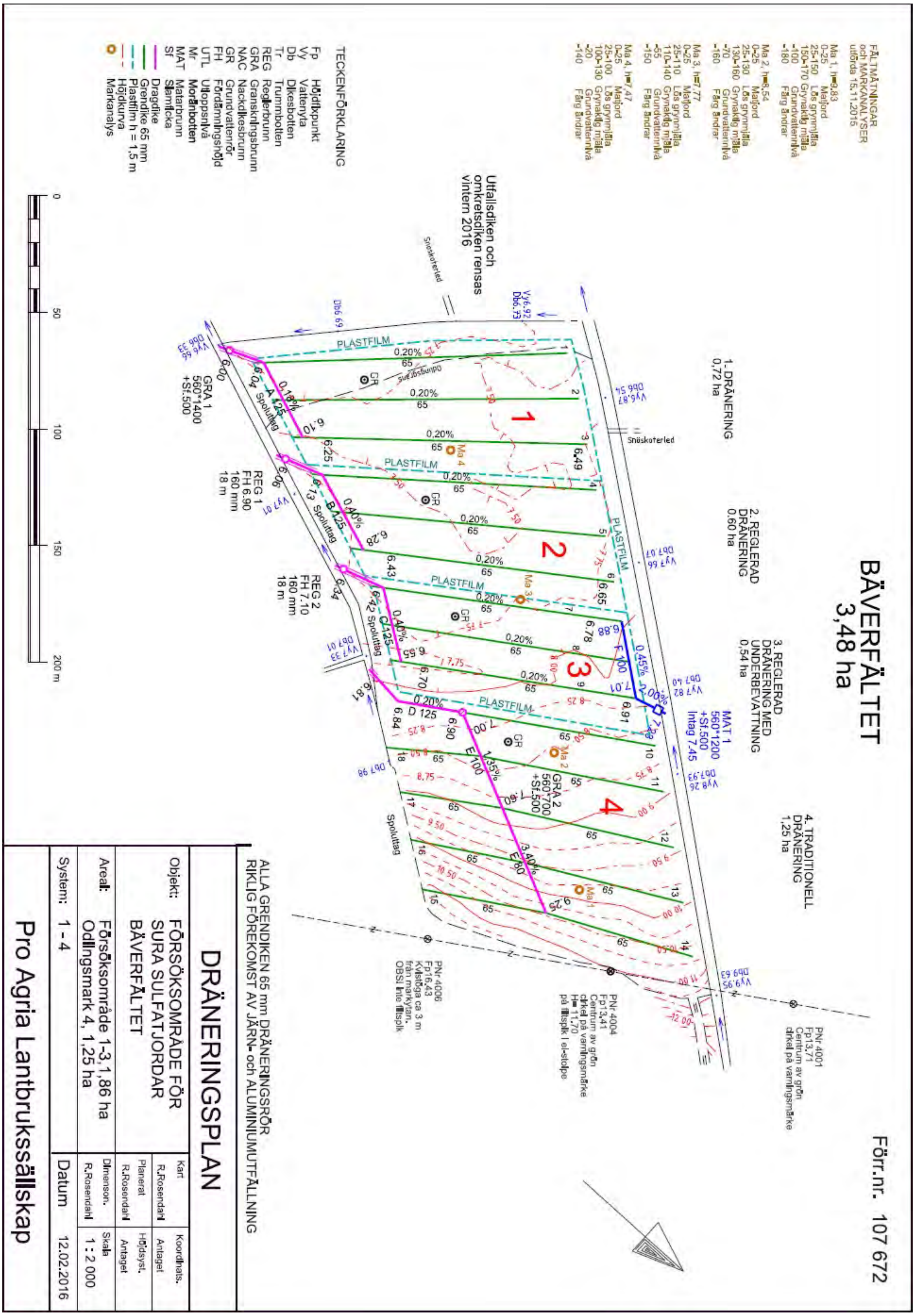
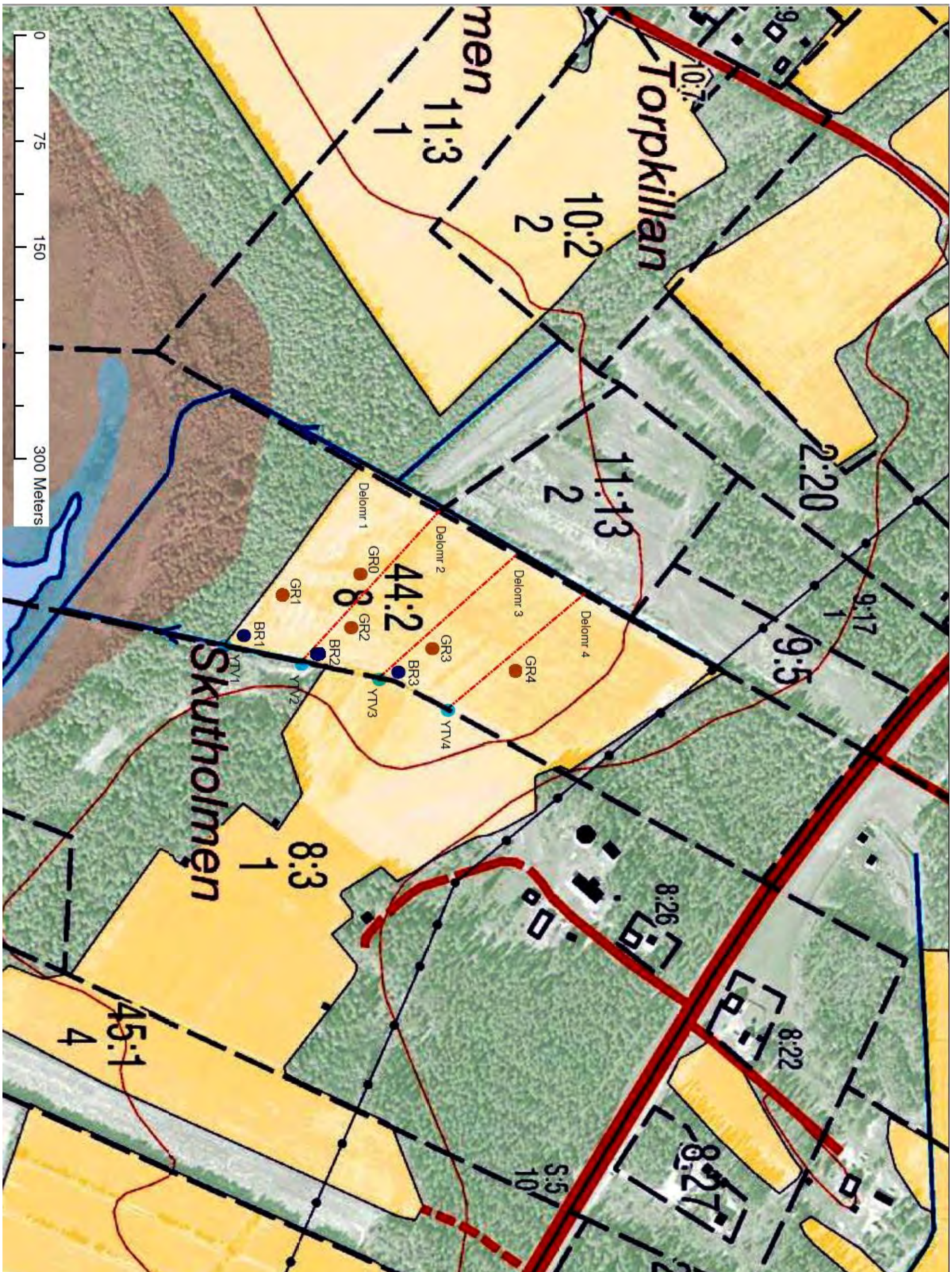
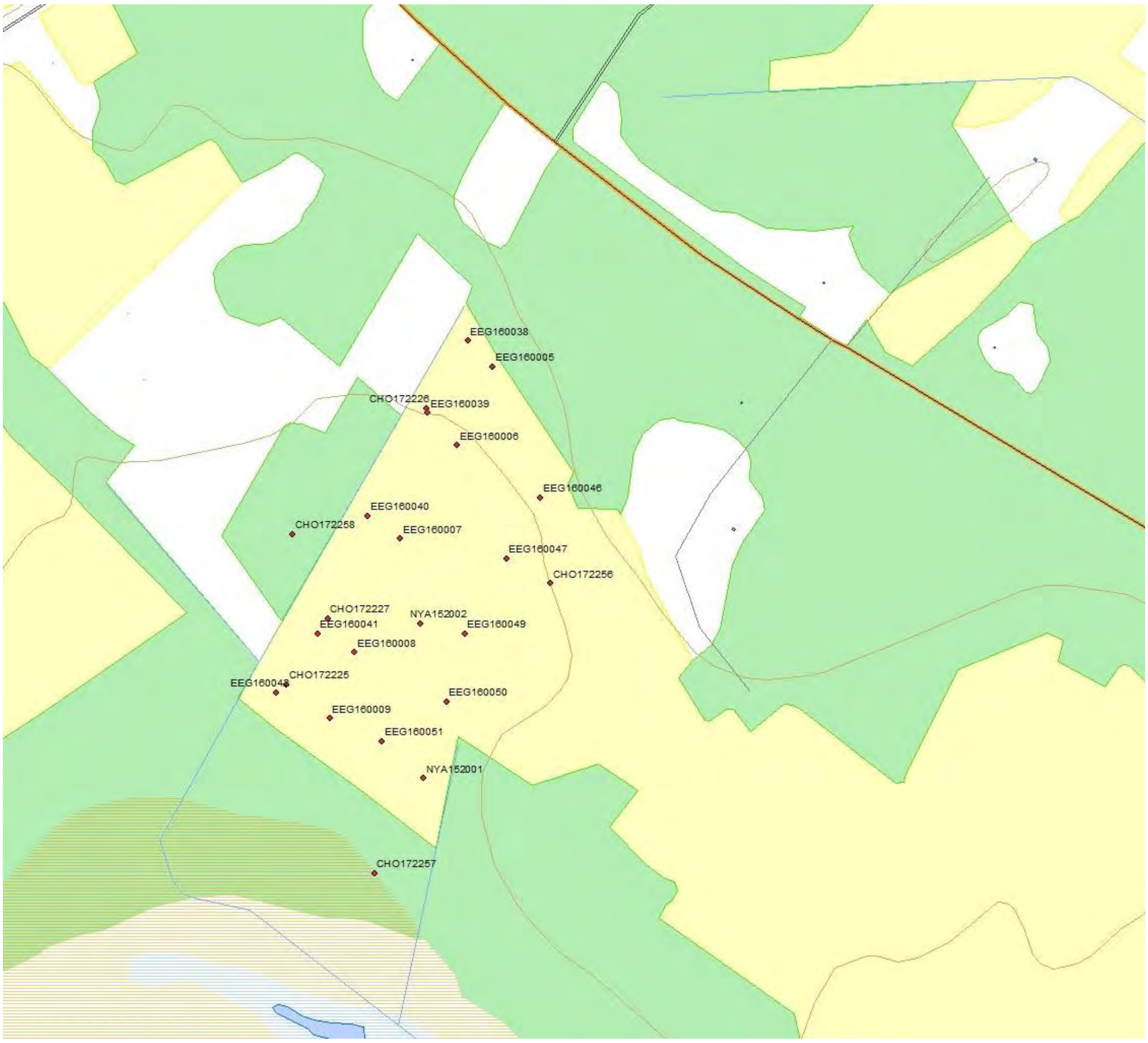
APPENDIX 2 – PLAN OF THE TEST FIELD DRAINAGE IN LAKAFORS



APPENDIX 3 – LAKAFORS TEST FIELD WITH SUB-AREA AND MONITORING LOCALITIES



APPENDIX 4 – BÄVERFÄLTET WITH SOIL SAMPLING LOCALITIES



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