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Report

Water-covered area and meso-habitats of the river Vassbygdelvi

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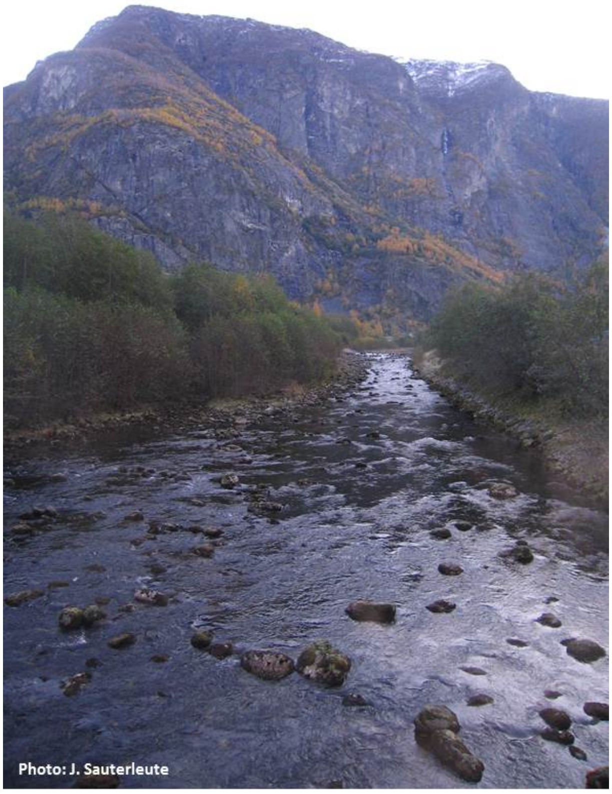

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ABSTRACT

The purpose of this study was to assess how the water-covered area and meso-habitats change with discharge in the river Vassbygdelvi in Aurland, Sogn and Fjordane county, with focus on low discharges. The river stretch from Vassbygdvatn to Jørve was divided into two reaches. In the lower reach water lines were measured and meso-habitats were mapped at three different discharges. In the upper reach water lines were measured at one discharge. In addition to the measurements by the use of differential GPS, aerial images were analysed to calculate the water-covered area at discharges given by the images. The measurements show that the water-covered area increases rapidly up to a discharge of 0.5 m^3/s. At higher discharges the area rises less strongly at the same increase in discharge. Especially in the lower reach the increase in area is relatively small when the discharge rises from 0.7 m^3/s to around 7 m^3/s. This is an effect of the weir and pool constructions in the lower reach. It is recommended to increase the minimum flow in Vassbygdelvi from 0.3 m^3/s to between 0.5 m^3/s and 0.6 m^3/s. This discharge range leads to app. 10 % larger water-covered area and maintains a more homogeneous distribution of habitats compared to a discharge of 0.3 m^3/s. Furthermore, a minimum flow of 0.5 m^3/s during winter time would avoid longer continuous periods of very low discharge as they occur under the current flow regime and might contribute to greater winter survival of juvenile fish.

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Table of contents

APPENDICES

1 Introduction

This report is a deliverable of the project EnviDORR (Increased power and salmon production with environmentally designed operation of regulated rivers) under the research centre CEDREN (Centre for Environmental Design of Renewable Energy). The Aurland watercourses are demo-rivers in EnviDORR. The objective of the work in Aurland is to establish biological and physical models for scenario modelling of alternative revisions and operations of the Aurland hydropower facilities, looking for solutions to benefit both salmon and power production. For this purpose, the physical and biological conditions of the rivers Aurlandselvi and Vassbygdelvi were investigated. The characteristics of the aquatic habitats and the relationship between discharge and inundated area provide important input to the scenario modelling, decisions on environmental operation design and potential mitigating measures. Results for the river Aurlandselvi were earlier documented in [1]. This report is the second deliverable within the study "Aurland - physical conditions" and presents the results for the river Vassbygdelvi.

2 Study area

The rivers Aurlandselvi and Vassbygdelvi are situated in the municipality of Aurland in Sogn og Fjordane county in West-Norway. The region is characterised by steep and high mountains where water drains through steep valleys into the fjords. The Aurland basin has been regulated since 1973, when the first hydropower plant (Aurland I) started to operate (cf. Figure 2.1). Further three power plants were taken into operation until 1983. The power plants are operated on several reservoirs situated on high elevation, which receive water by various abstractions within the river basin.

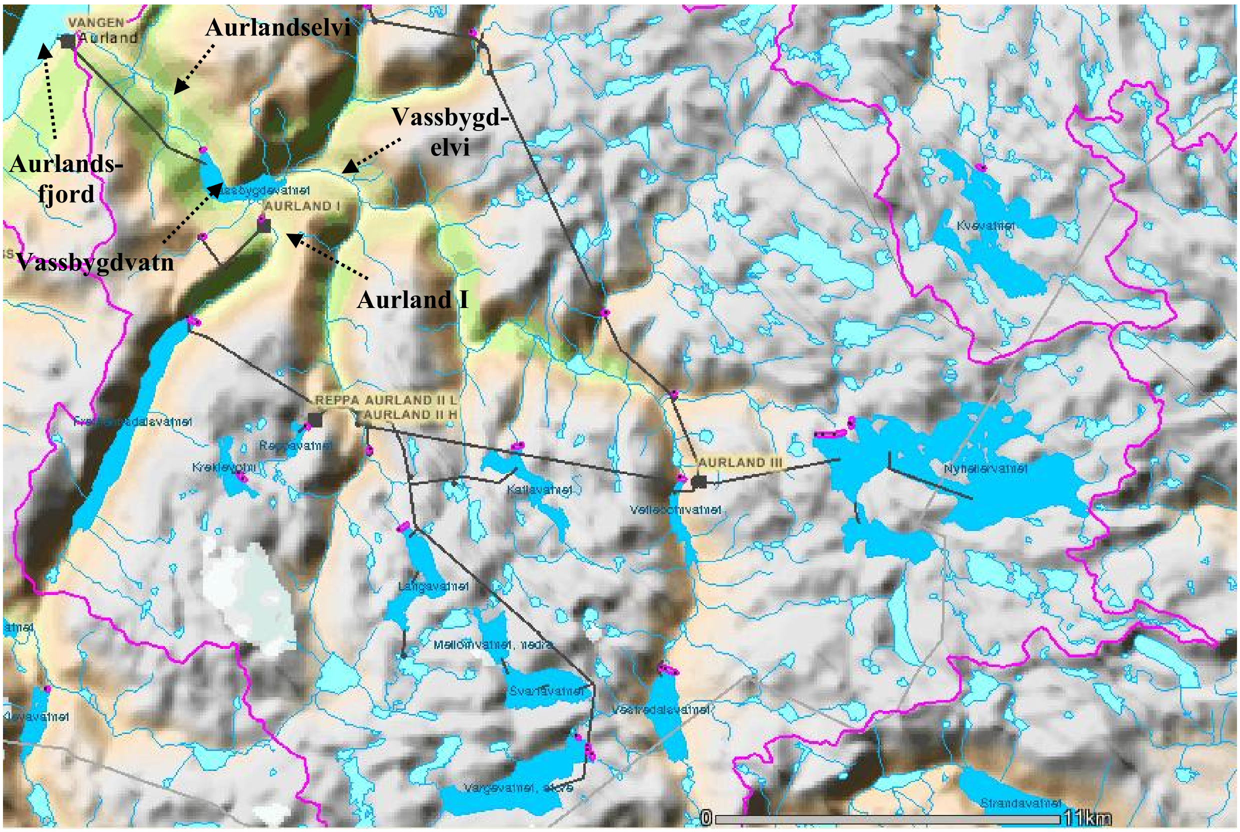


Figure 2.1 Overview on the hydropower system in the basin of Aurlandselvi and Vassbygdelvi. Power stations are indicated by black squares, water transfers by black lines. Source: NVE-Atlas [2].

The river basin of Aurlandselvi and Vassbygdelvi covers an area of 802 km^2 [2]. Aurlandselvi flows from the lake Vassbygdvatn over a distance of 6.8 km into the Aurlandsfjord. Vassbygdelvi is located upstream and flows into Vassbygdvatn (cf. Figure 2.2). The mean flow of Aurlandselvi was 16.6 m^3/s in the period 1990 to 2008. Vassbygdelvi had a mean flow of 3.9 m^3/s in the years 2004 to 2009. Before regulation, both rivers had a mean annual flow about 40 m^3/s [3].

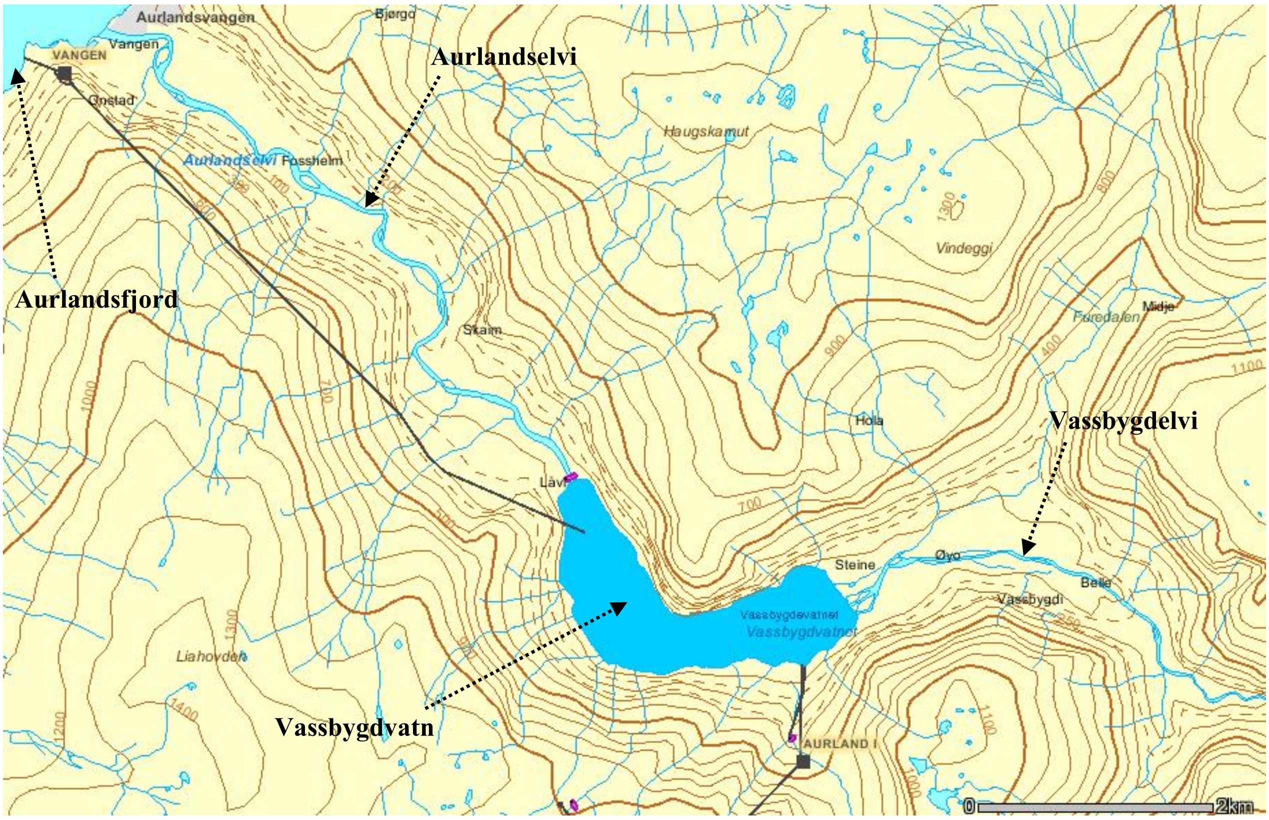


Figure 2.2 Vassbygdelvi runs west-wards from the Eastern part of the basin and into Vassbygdvatn. The positions of the hydropower plants Vangen and Aurland I, as well as their transfer tunnels, are indicated by black squares and lines, respectively.
Source: NVE-Atlas [2].

The licensed minimum flow in Aurlandselvi varies over the seasons, from 3 m^3/s during winter to 30 m^3/s in summer [3], while there are no minimum flow requirements in Vassbygdelvi. However, the hydropower company ensures 0.3 m^3/s to prevent too low discharges during winter time [3]. The hydrograph of Vassbygdelvi is shown in Figure 2.3.

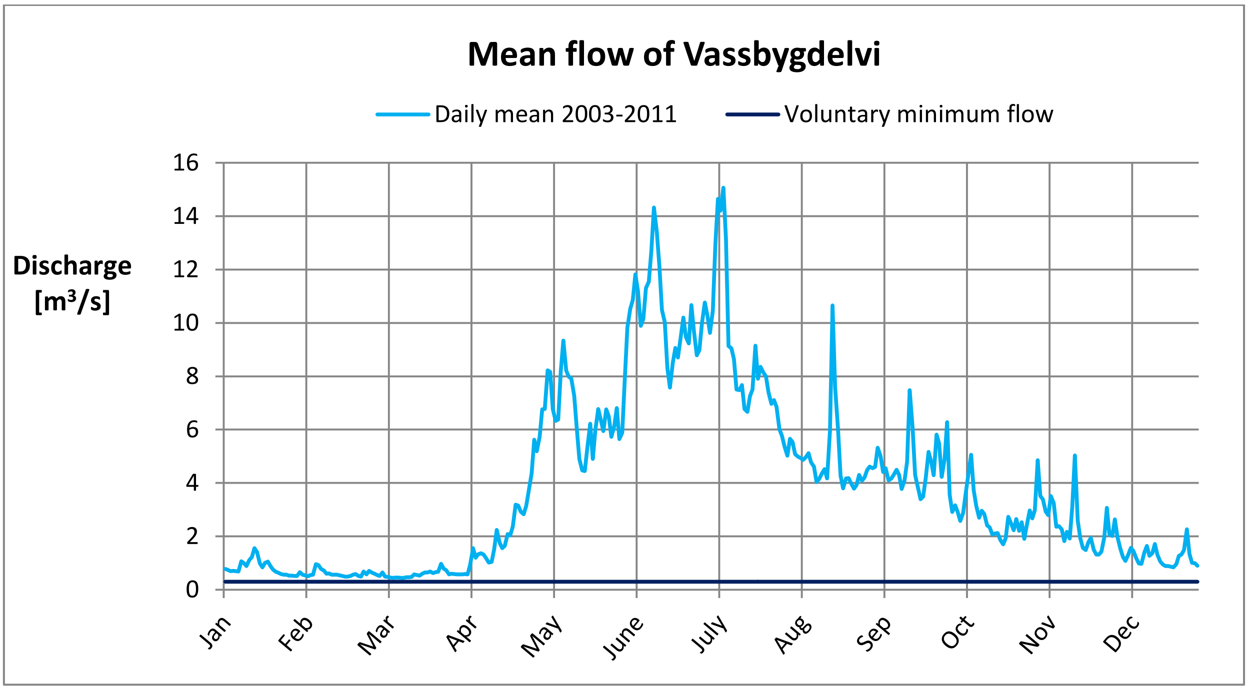


Figure 2.3 Mean daily flow of the years 2003-2011 (data from E-CO's gauging station) and voluntary minimum flow in Vassbygdelvi.

3 Data and methods

Field data were collected at high flows (around 16 m^3/s) in June 2011 and at two occasions at low flows (app. 0.7 m^3/s in October 2009; app. 0.3 m^3/s in January 2012). Figure 3.1 shows Vassbygdelvi at minimum, low and high flow conditions. During these three field campaigns the edges of the water (water lines) were measured and meso-habitats were mapped [4]. For a description of the methods, see [1]. For the analysis of the field data, time series of discharge from the gauging station in Vassbygdelvi, owned by E-CO, were used (hourly interval from 13/06/2003 to 05/02/2013). Based on the hourly discharge record daily mean values were calculated to examine durations of periods with low discharge occurring during winter time. The collected data are summarised in Table 1. Due to ice formation in the river during the minimum flow survey in January 2012, measurements could not be carried out upstream of the artificial pools, app. 600 m upstream of the bridge at Vassbygdi. Ice formation increased in upstream direction. Upstream of the uppermost artificial pool the water-covered area was significantly influenced by the ice. Consequently, the river was divided into two reaches for the data analysis. The mapping of meso-habitats was restricted to the lower river reach of Vassbygdelvi, from Vassbygdvatn to the uppermost artificial pool (cf. Appendix A2).

In the upper reach of Vassbygdelvi another survey with focus on the water-covered area at low flows was carried out in May 2013 (app. 0.46 m^3/s). Water lines were measured in the upper reach of Vassbygdelvi, from the uppermost artificial pool to the narrow, steeper section at "Jørve"(cf. Appendix A3).

In addition, aerial images from Norge i Bilder [5] were used to calculate the water-covered area at higher discharges than 0.46 m^3/s. Two aerial image series were analysed ("Aurland 2008" and "Indre Sogn 2007"). The discharge at the time when the images were taken was around 7.35 m^3/s and 5.05 m^3/s, respectively. The images of the series "Indre Sogn 2007" could only be analysed for the upper reach because of low resolution and contrast of the images in the lower reach.

Figure 3.1 Lower reach of Vassbygdelvi seen in upstream direction from the road bridge at Vassbygdi at minimum flow around 0.3 m^3/s (left), low flow around 0.7 m^3/s (middle) and high flow around 16 m^3/s (right).

Table 3.1 Overview of the field data collected in the years 2009 to 2013, discharge in Vassbygdelvi during data collection and aerial images used.

River reach/ field data/ flow conditions	Date	Discharge [m^3/s]
Lower reach/ meso-habitats/ low flows	29/10/2009	0.66 +/- 0.01
Lower reach / water line/ low flows	29/10/2009	0.69 +/- 0.03
Lower reach / meso-habitats/ high flows	30/06/2011	16.0 +/- 1.5
Lower reach / water line/ high flows	30/06/2011	16.0 +/- 1.5
Lower reach / meso-habitats/ minimum flow	01/02/2012	0.29 +/- 0.01
Lower reach / water line/ minimum flow	31/01/2012-01/02/2012	0.30 +/- 0.02
Upper reach/ water line/ low flows	03/05/2013	0.46 +/- 0.01
Upper and lower reach/ aerial images/ medium flows	10/07/2008	7.35 +/- 0.15
Upper reach/ aerial images/ medium flows	22/08/2007	5.05 +/- 0.05

4 Results

4.1 Discharge

Apart from the influence by hydropower regulation the flow regime of Vassbygdelvi is dominated by a nival regime. Discharge during winter time is low since precipitation is largely bound as snow and does not come to run-off until the snow melt starts in spring. The discharge reaches low values from October on and the period with lowest values typically lasts from January to March (Figure 2.3). The distribution of winter discharges compared to discharges over whole years is shown in Figure 4.1. Between autumn 2003 and autumn 2011 the median of the winter discharges (October to March) was 0.65 m^3/s while it was 2.24 m^3/s for the whole period. High flows (> 10 m^3/s) were rare during winters, and floods (> 30 m^3/s) did only occur during the summer half-year. Except from winter 2006/2007 all winters had periods with daily mean discharges below 0.5 m^3/s lasting for seven days or longer (Table 2).

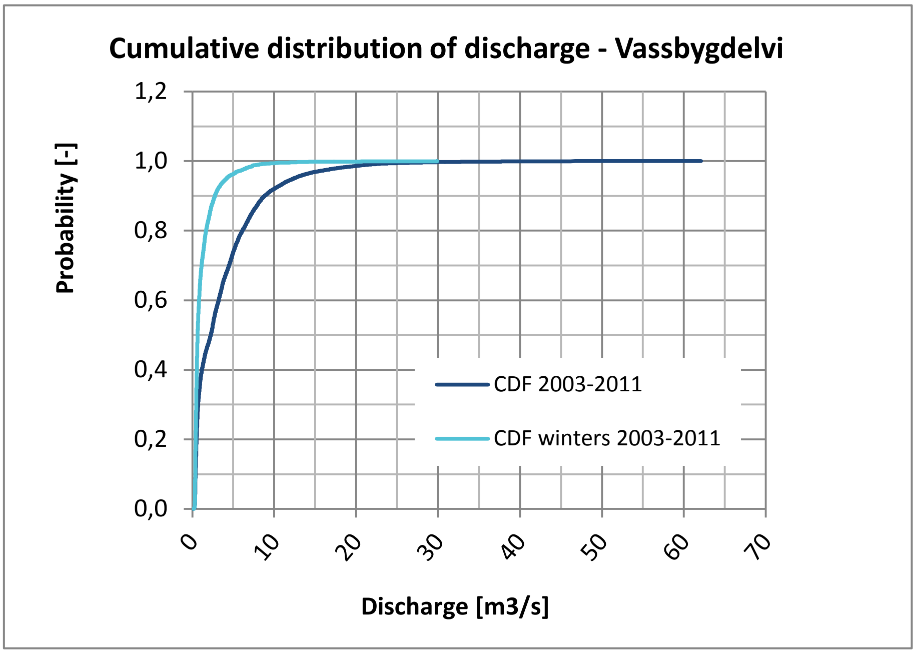


Figure 4.1 Cumulative distribution of the discharge of Vassbygdelvi; hourly records 01/07/2003-01/07/2011; winter: 01/10-31/03.

Table 4.1 Statistics of winter discharges of the years 2003 to 2011.

Number of days with daily mean discharge less than … during winters 2003 to 2011	**Count**	**% of all days**
< 0.3 m^3/s	18	1.2
< 0.4 m^3/s	269	18.4
< 0.5 m^3/s	478	32.8
< 0.6 m^3/s	651	44.7
< 0.7 m^3/s	769	52.7

Number of days in a row with daily mean discharge < 0.5 m^3/s for one week or longer:								
Winter of year	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
	8	7	8		17	62	78	16
	31	12	24					18
	23		51					41

4.2 Water-covered area

The water-covered area in the lower reach of the river Vassbygdelvi increases strongly with changing discharge up to 0.7 m^3/s compared to higher discharges (Figure 4.2 and Appendix A2). The increase in water-covered area is lower at discharges between 0.7 m^3/s and 7 m^3/s, while it is higher again between 7 m^3/s and 20 m^3/s. It can be assumed that the water-covered area-discharge-relationship flattens out above 20 m^3/s. It is important to mention that some area will still be inundated at zero discharge, as the pools and holes in between boulders can include sections with standing water. These pools originate from construction works in winter 1999/2000, when weirs were established in the lower reach of Vassbygdelvi in order to maintain the inundated area at low flows [6]. Further, it is important to mention that the measurement at 0.3 m^3/s is likely to be overestimated because ice had started to build up on the river bed, leading to a slightly higher water level than under normal conditions.

In the upper reach of Vassbygdelvi the increase in water-covered area with increasing discharge is high at discharges up to 0.5 m^3/s (Figure 4.3 and Appendix A3). Between 0.5 m^3/s and 10 m^3/s the increase in water-covered area is lower and can be assumed to further decrease with higher discharges.

The relationships between water-covered area and discharge of the two river reaches cannot be directly compared with each other because the area is given in absolute values. Therefore, the water-covered area was divided by the river reach length to calculate the mean wetted width for the different discharges (Figure 4.4). The comparison of the two curves shows that the wetted width of the upper reach decreases continuously down to a discharge of 0.5 m^3/s before it drops strongly, while the wetted width of the lower reach decreases less between 7 m^3/s and 0.7 m^3/s before it drops. This effect can be related to the weirs and pools which were constructed in the lower reach of Vassbygdelvi (Figure 4.5). When the discharge decreases the weirs maintain a larger wetted width. This effect applies to a decrease in discharge to 0.7 m^3/s in the lower reach of Vassbygdelvi. Below this discharge the wetted width drops strongly. At 0.7 m^3/s the wetted width is around 20 % higher thanks to the effect of the weirs and pools. The effect of the weir and pool structures in the lower reach is described more detailed in chapter 4.4.

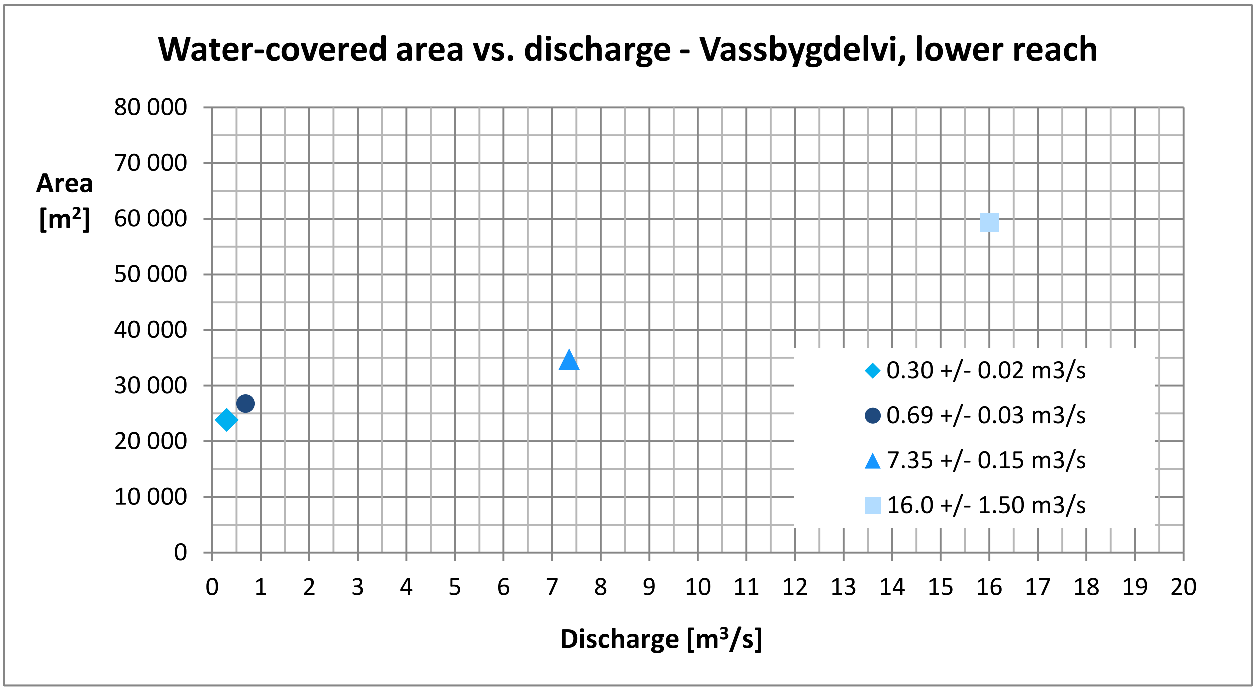


Figure 4.2 Relationship between water-covered area and river discharge. The figure shows the measurements of water-covered area in the lower reach of Vassbygdelvi at various discharges.

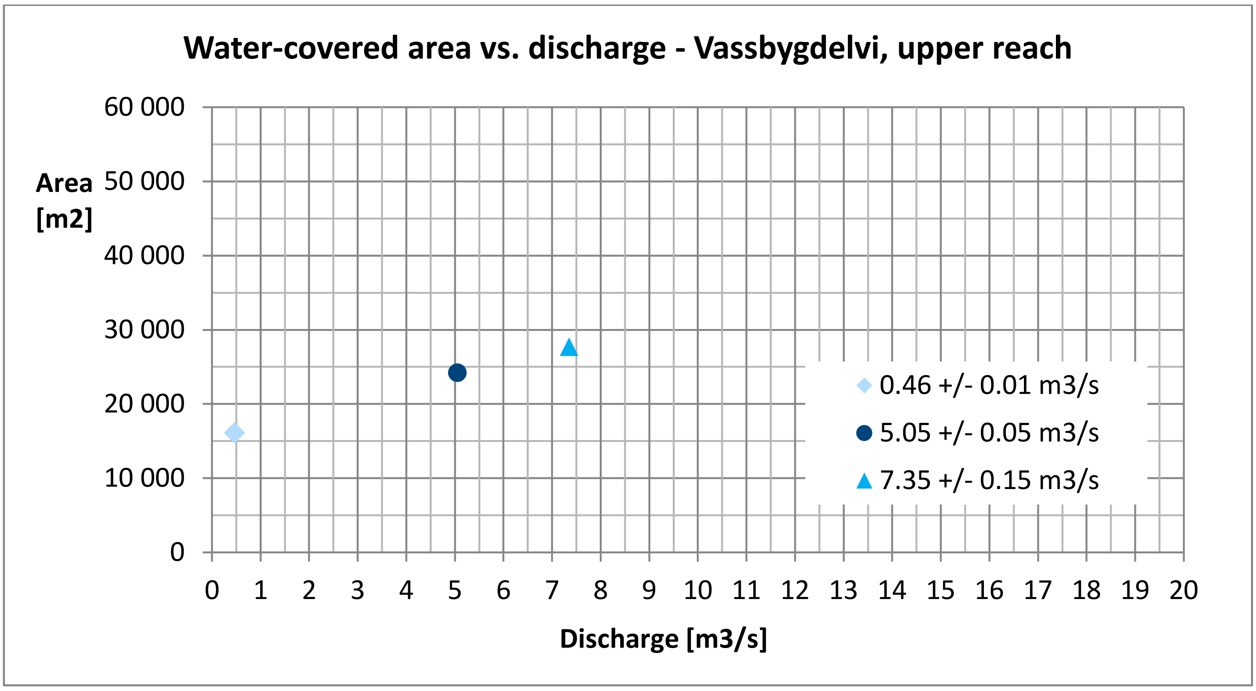


Figure 4.3 Relationship between water-covered area and river discharge. The figure shows the measurements of water-covered area in the upper reach of Vassbygdelvi at various discharges.

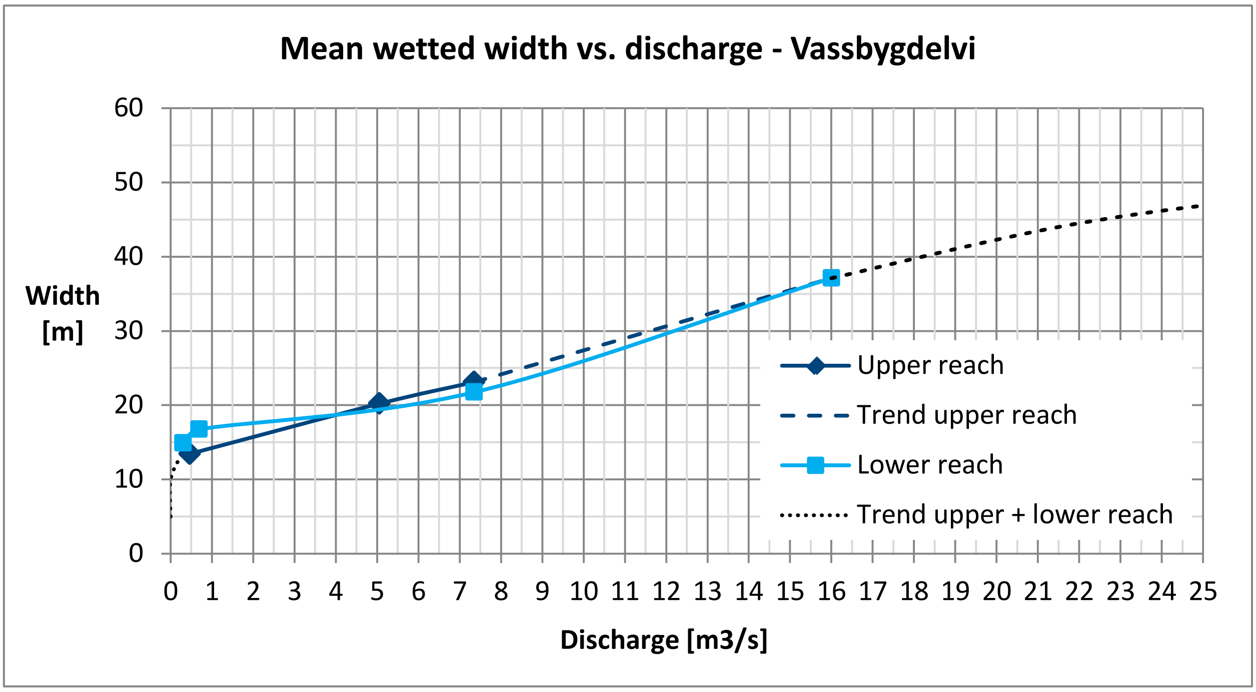
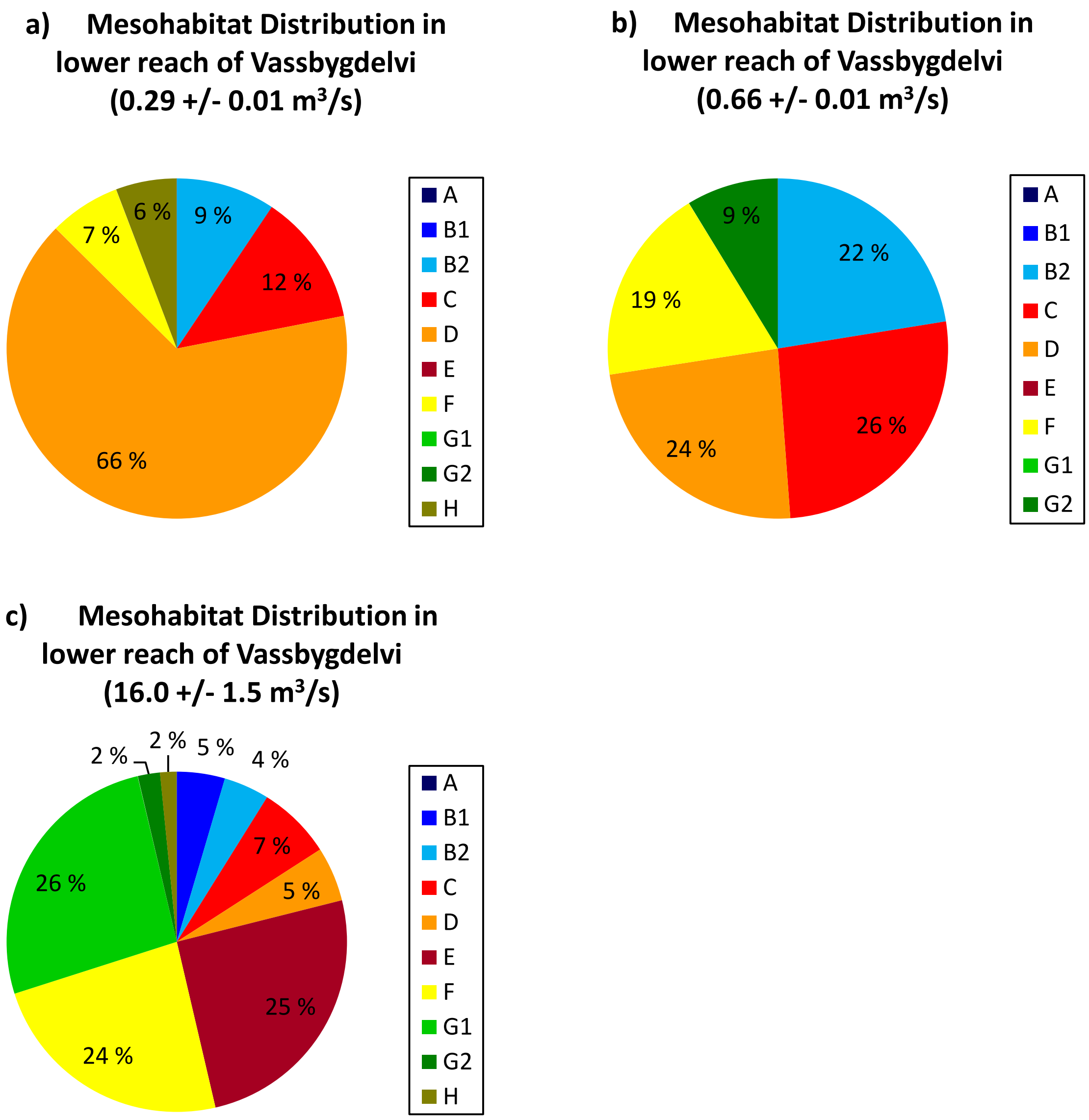


Figure 4.4 Comparison of the relationship between mean wetted river width and discharge of the lower and upper reach of Vassbygdelvi. The figures shows the change of wetted width with increasing discharge, calculated from the measurements of water-covered area. Based on the measurements marked in the graph, trend lines were drawn.

Figure 4.5 Artificial weirs and pools in Vassbygdelvi at high flow around 16 m^3/s.

4.3 Meso-habitats

At minimum flow (around 0.3 m^3/s) two thirds of the water-covered area is habitat with smooth surface, moderate gradient, low velocity and small depth (type D, cf. Figure 4.6a and Appendix A1). Slow-flowing habitats account for three quarters of the area, while the remaining quarter is fast-flowing, shallow habitat. At low flow conditions (around 0.66 m^3/s) the share of slow-flowing habitats decreases from 75 % to 50 %, while the area of fast-flowing, shallow habitats and areas with broken surface increase (cf. Figure 4.6b). Type H (typically small amounts of water running over gravel bars with steeper gradient) does not longer occur, but fast-flowing, shallow areas with waves and moderate gradient (type G2) as well as more rapids (F) occur. At high flow (around 16 m^3/s) slow-flowing habitats are reduced to around 10 % (cf. Figure 4.6c). Deep and fast-flowing habitats with waves dominate (> 50 %). In contrast to minimum and low flow conditions, fast-flowing, deep habitats with waves and steep or moderate gradient (type E and G1) occur and make up half of the inundated area. The meso-habitat maps are included in Appendix A4 to A6.


a) Mesohabitat Distribution in lower reach of Vassbygdelvi (0.29 +/- 0.01 m^3/s)

b) Mesohabitat Distribution in lower reach of Vassbygdelvi (0.66 +/- 0.01 m^3/s)

c) Mesohabitat Distribution in lower reach of Vassbygdelvi (16.0 +/- 1.5 m^3/s)

Figure 4.6 Percentage of meso-habitats of the total inundated area in the lower reach of Vassbygdelvi at minimum flow (a), low flow (b) and high flow (c).

4.4 Comparison of water-covered area in pool section

The water-covered area was analysed and compared separately for two pools in between weirs. This separate analysis of the two uppermost artificial pools was carried out with respect to three purposes: Firstly, this short river section is the only one that is covered by our measurements both in the lower reach and upper reach of Vassbygdelvi, i.e. most measurements of water-covered area are available in this section. Secondly, the effect of the pool-weir constructions in the lower reach could be examined explicitly. Thirdly, it allowed for checking the influence of the ice formation on the water-covered area, since another measurement close to the minimum flow was available for this section (0.46 m^3/s) in addition to the measurement around 0.3 m^3/s when ice built up in the river channel.

Figure 4.7 shows the areas of the two pools for various discharges. The influence of the ice formation during the measurement at the lowest discharge can be seen by comparing the water lines of 0.3 m^3/s and 0.46 m^3/s. The area of the pools at 0.3 m^3/s is larger than at 0.46 m^3/s, i.e. it is over-estimated due to higher water levels than usual for this discharge. Ice had built up with increasing intensity in upstream direction, i.e. the effect of the ice was largest at the location of the two pools, which is at the upstream end of the lower reach of Vassbygdelvi.

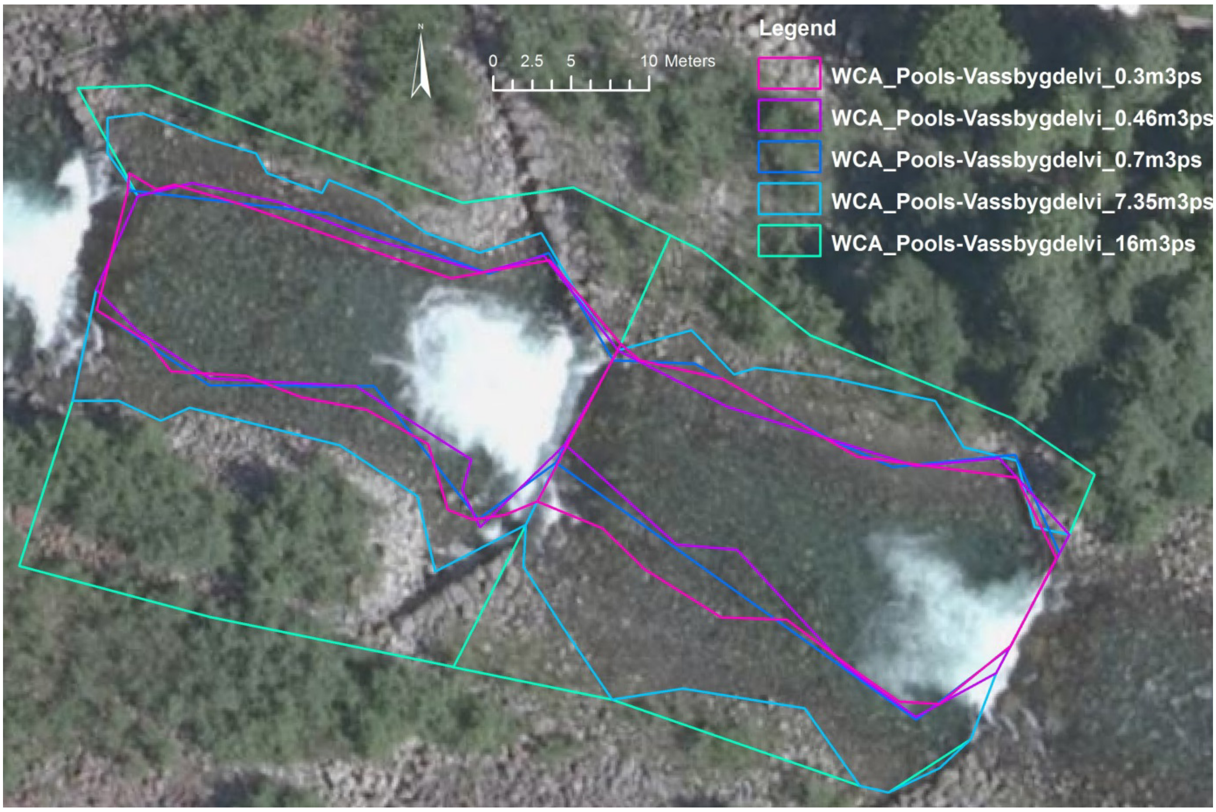


Figure 4.7 Comparison of the water-covered area for the two uppermost pools in Vassbygdelvi. The area of the lowest discharge (0.3 m^3/s) is larger than the one of 0.46 m^3/s. This is due to higher water level caused by ice build-up during the measurement.

The effect of the pool and weir constructions on the change of water-covered area with varying discharge is visible in Figure 4.8. Compared to a typical area-discharge-relationship of a regular river channel the curve shows a part with steeper slope, followed by a low gradient before it drops at a discharge reaching zero. At very low discharges the area increases rapidly due to the flat base of the pools. In the discharge range of the pool edges the area hardly increases (flat part of the curve). Once the water level reaches the top of the pool edges, the area increases more rapidly again (steeper slope) and then flattens out with increasing discharge.

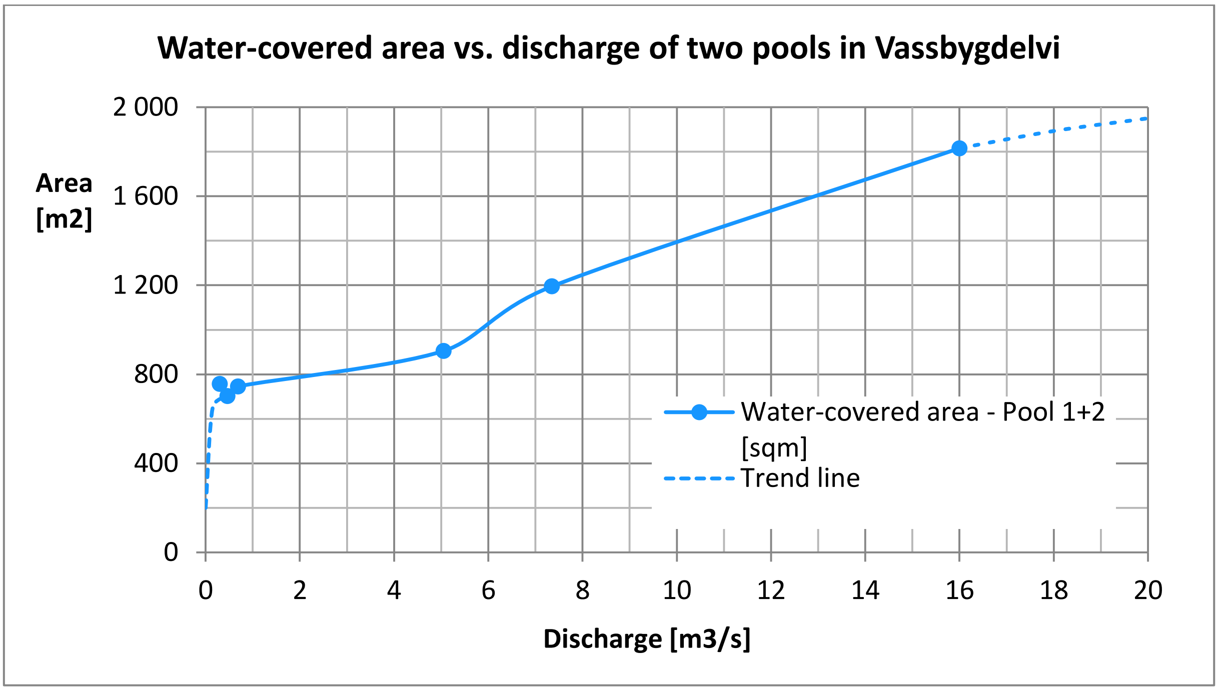


Figure 4.8 Relationship between water-covered area and discharge in the two uppermost pools of the lower reach of Vassbygdelvi. The figure indicates the influence of the weirs and pools on the change of water-covered area with varying discharge.

5 Discussion and conclusion

Measurements in Vassbygdelvi from Vassbygdvatn to Jørve show that the water-covered area increases rapidly up to a river discharge of 0.5 m^3/s. At higher discharges than 0.5 m^3/s the area rises less strongly at the same increase in discharge. Especially in the lower reach the increase in area is relatively small when the discharge rises from 0.7 m^3/s to around 7 m^3/s. This is an effect of the weir and pool constructions in the lower reach. They provide a larger wetted width when the discharge decreases. At 0.7 m^3/s this leads to an increase in the wetted width of approximately 20 % compared to without weirs. The influence of the weirs and pools on the change of water-covered area with varying discharge was also illustrated by comparing all measurements in two pools at the upper end of the lower reach.

In contrast, there is a great change in the distribution of meso-habitats at a rising discharge from 0.3 m^3/s to 0.7 m^3/s in the lower reach of Vassbygdelvi. At a discharge of approximately 0.7 m^3/s, the proportion of pools in area (type C) is twice as large as at discharges around 0.3 m^3/s, while the slow-flowing, shallow habitat area declines to a third (type D), and there is much more fast-flowing, shallow habitat with waves or smooth water surface (type B2, G2). The distribution is no longer clearly dominated by slow-flowing habitat. However, discharges around 0.7 m^3/s lack deep, fast-flowing habitats. At a change from 0.7 m^3/s to 16 m^3/s in the lower reach, the increase in water-covered area as well as the change in meso-habitat composition and distribution is obvious. The inundated area approximately doubles. Diversity of meso-habitats is high; except from fast-flowing, deep habitat with steep gradient and smooth surface (type A), all meso-habitat types occur, where deep, fast-flowing habitats and rapids dominate three quarters of the water-covered area and the proportion of pools declines. Compared to the lower reach, the proportion of slow-flowing deep and shallow habitats in the upper reach can be expected to be lower at minimum and low flow conditions, in favour of shallow, fast-flowing habitats.

It is important to mention that the amounts of ice during the minimum flow survey around 0.3 m^3/s in the lower reach affected the measurements. The ice formation grew in intensity in upstream direction, i.e. the influence of the ice on the water level was largest at the upper end of the lower reach of Vassbygdelvi. The water-covered area in the two uppermost pools showed to be overestimated by app. 10 %. Hence, it is assumed that the area for the lower reach in total at a discharge around 0.3 m^3/s was overestimated by up to 5 %. In general, there is a certain inaccuracy in the results arising from varying discharge during measurements and mapping, uncertainty in the differential GPS measurements, georeferencing of the aerial images and calculation of water-covered area from the aerial images.

Based on the above presented results it is recommended to increase the minimum flow in Vassbygdelvi from 0.3 m^3/s to between 0.5 m^3/s and 0.6 m^3/s. This discharge range leads to a larger amount of water-covered area and maintains a more homogeneous distribution of habitats than at a discharge of 0.3 m^3/s. Considering the overestimation of the water-covered area at 0.3 m^3/s in the lower reach, the increase in area between 0.3 m^3/s and 0.7 m^3/s discharge is larger than indicated by the results above, i.e. keeping the discharge higher than 0.3 m^3/s to maintain inundated area would have a larger effect. It is estimated that the increase in discharge to between 0.5 m^3/s and 0.6 m^3/s would lead to about 10 % larger water-covered area (ca. 3,500 to 4,200 m^2) compared to at a discharge of 0.3 m^3/s. Furthermore, maintaining a minimum flow of 0.5 m^3/s during winter time would avoid longer continuous periods of very low discharge, as they are likely to occur under the current flow regime with durations of up to more than seventy days. In other studies low discharge during winter was found to be an important parameter for survival of juvenile salmon [7], [8], [9]. In the rivers Alta [10] and Orkla [11] a positive correlation between values of the lowest weekly or daily mean discharge during winter and density of juveniles and smolt production, respectively, was found. Hence, increasing the minimum discharge to between 0.5 m^3/s and 0.6 m^3/s might contribute to greater winter survival of juvenile fish in Vassbygdelvi.

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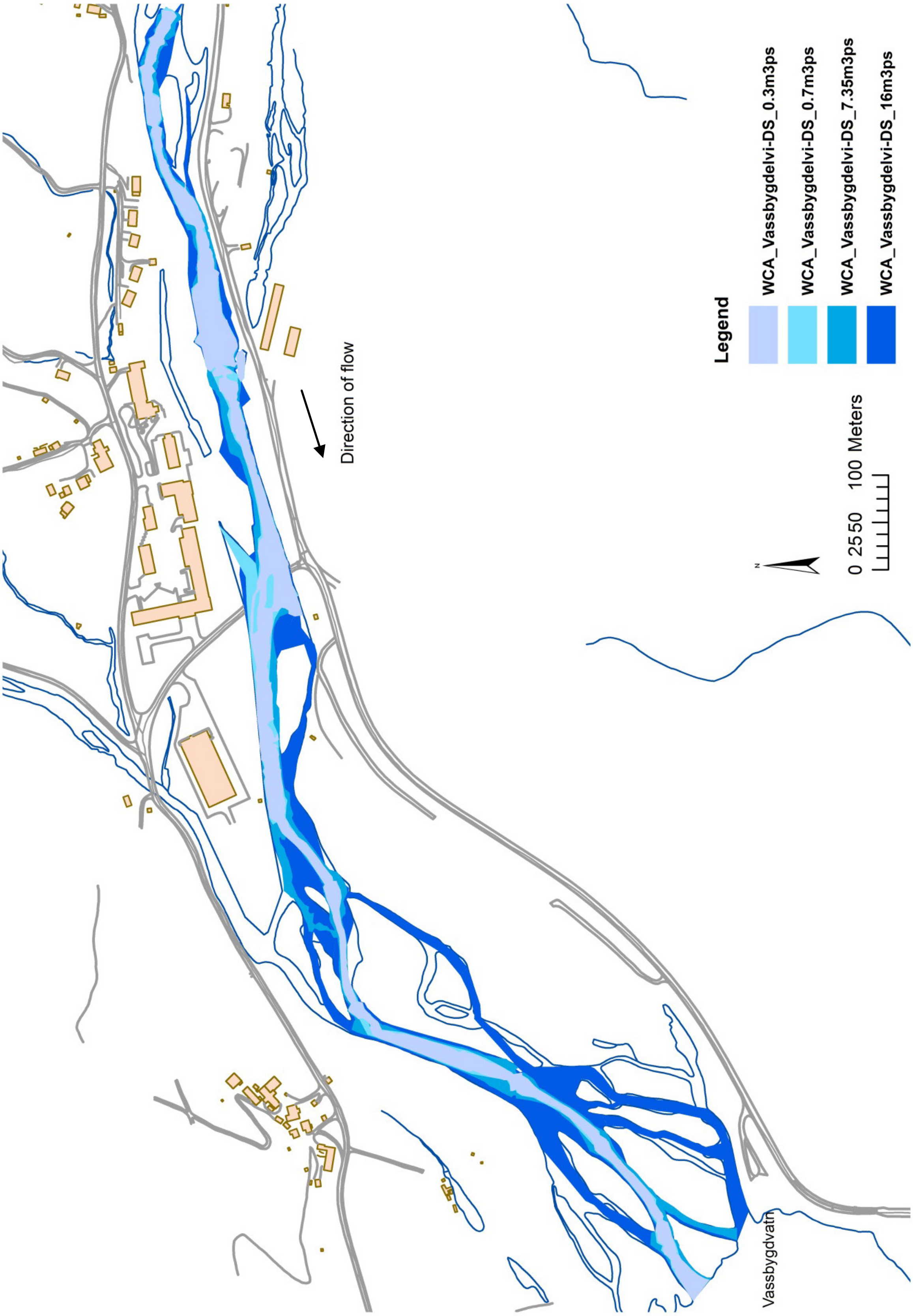
7 Appendices

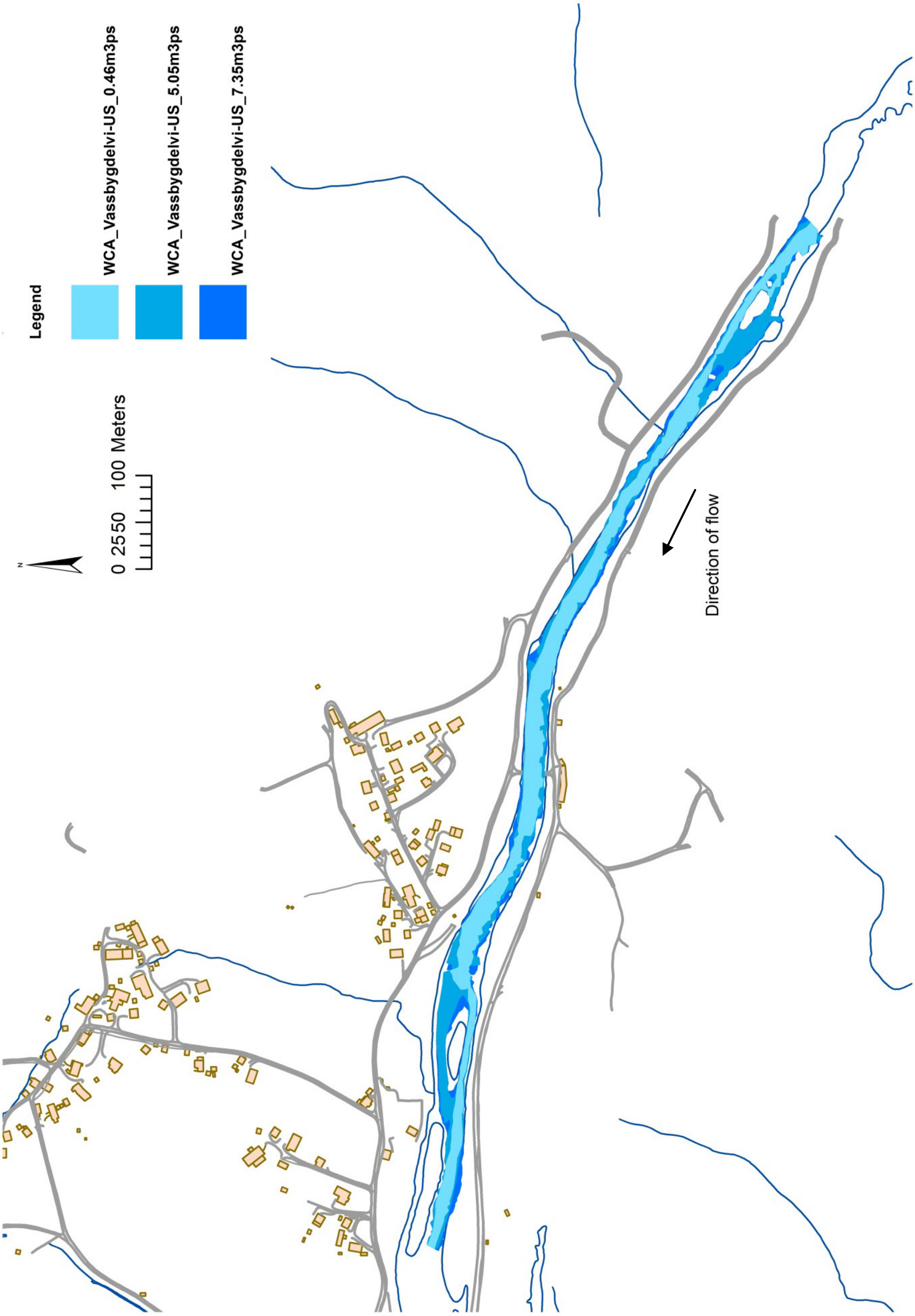
A1 Table for meso-habitat mapping based on combinations of the parameters surface pattern, surface gradient, water velocity and depth. Some combinations do naturally not occur. According to [4].

Surface pattern	Surface gradient	Surface velocity	Water depth	Code
Smooth / rippled surface	Steep	Fast	Deep	A
			Shallow	☒
		Slow	Deep	☒
			Shallow	☒
	Moderate	Fast	Deep	B1
			Shallow	B2
		Slow	Deep	C
			Shallow	D
Broken surface / unbroken standing waves	Steep	Fast	Deep	E
			Shallow	F
		Slow	Deep	☒
			Shallow	☒
	Moderate	Fast	Deep	G1
			Shallow	G2
		Slow	Deep	☒
			Shallow	H

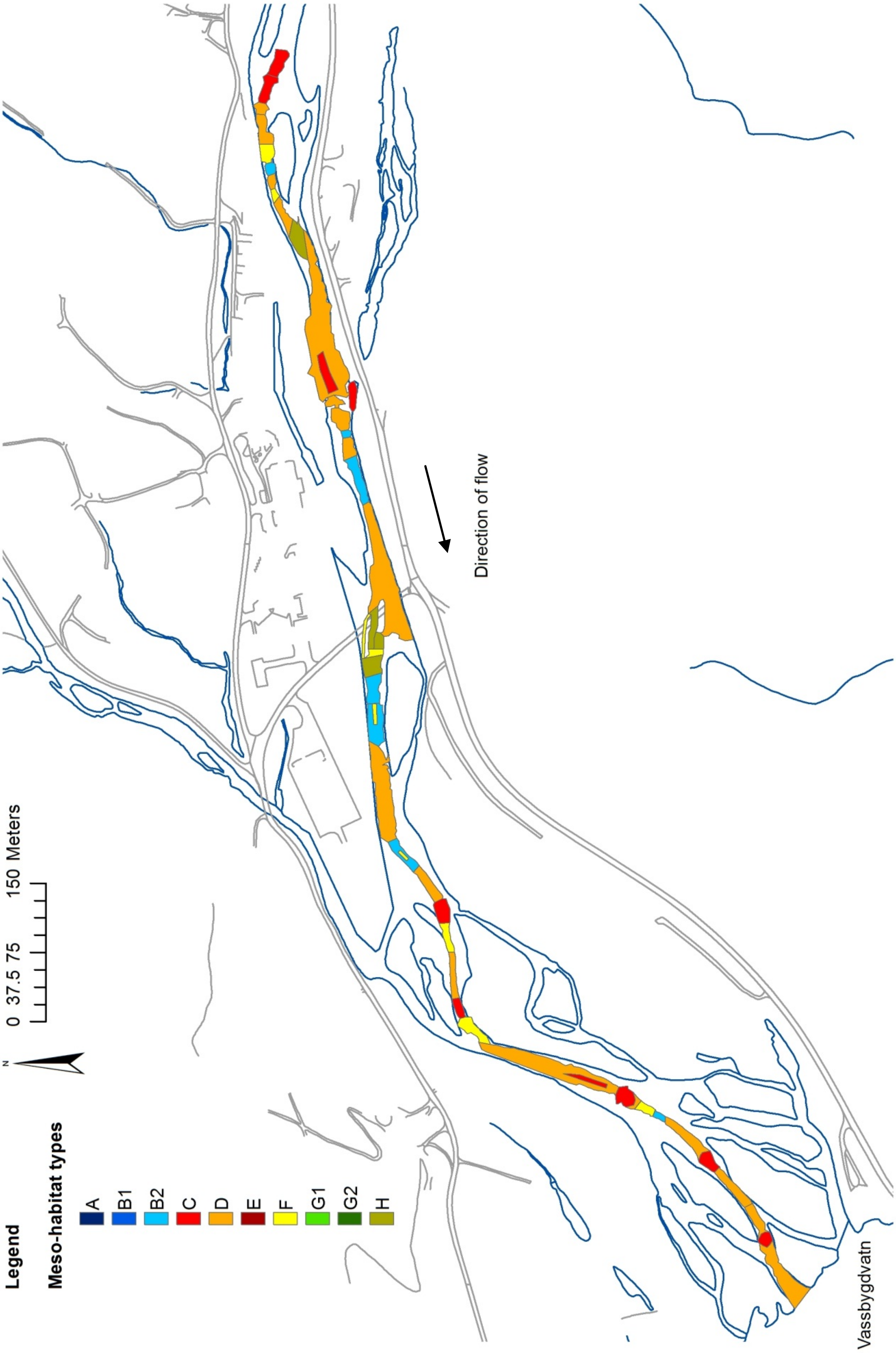
A2 Water-covered area in lower reach of Vassbygdelvi at 0.3 +/- 0.02 m^3/s, 0.69 +/- 0.03 m^3/s, 7.35 +/- 0.15 m^3/s and 16.0 +/- 1.5 m^3/s.



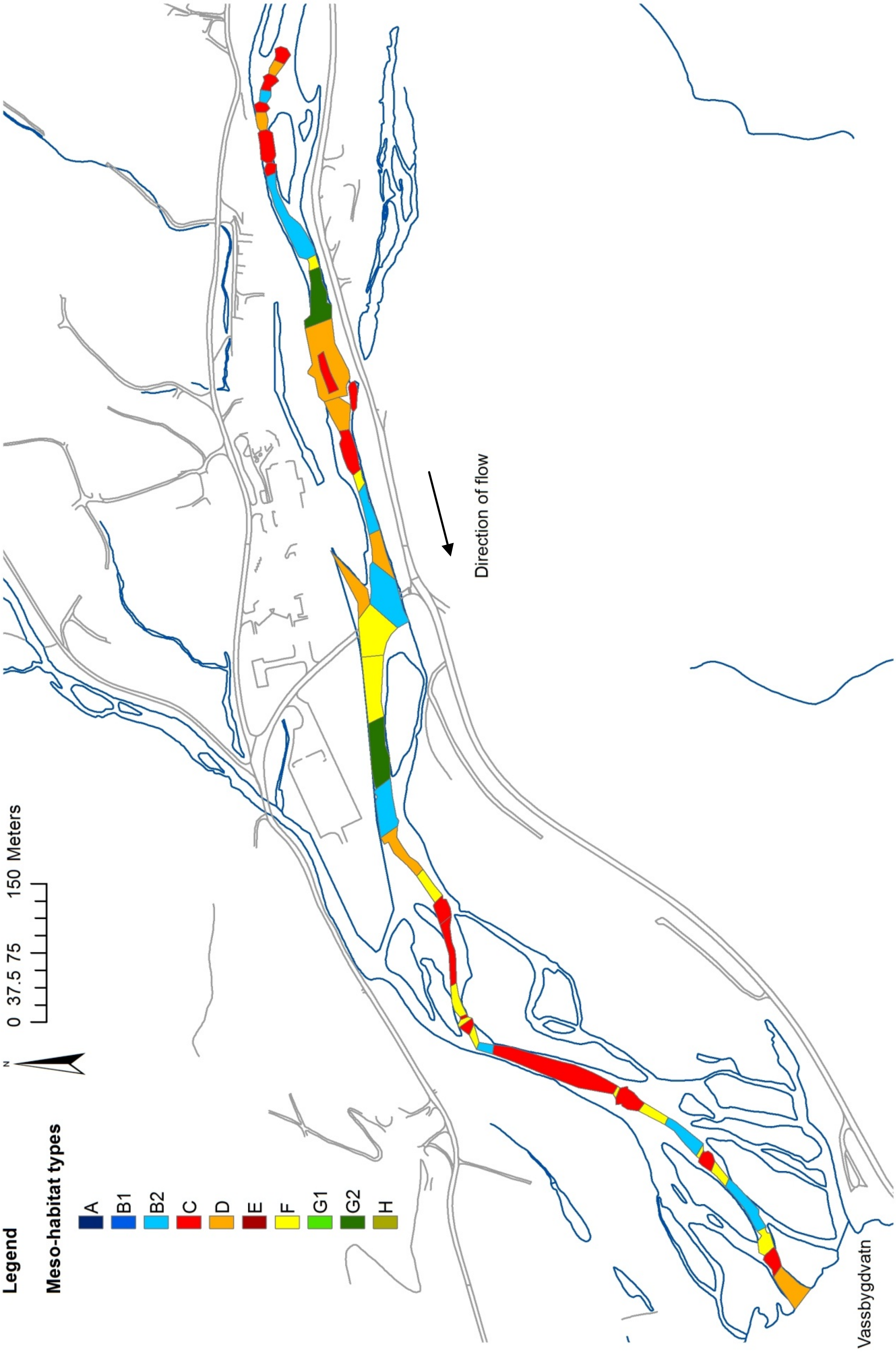
A3 Water-covered area in upper reach of Vassbygdelvi at 0.46 +/- 0.01 m^3/s, 5.05 +/- 0.05 m^3/s and 7.35 +/- 0.15 m^3/s.



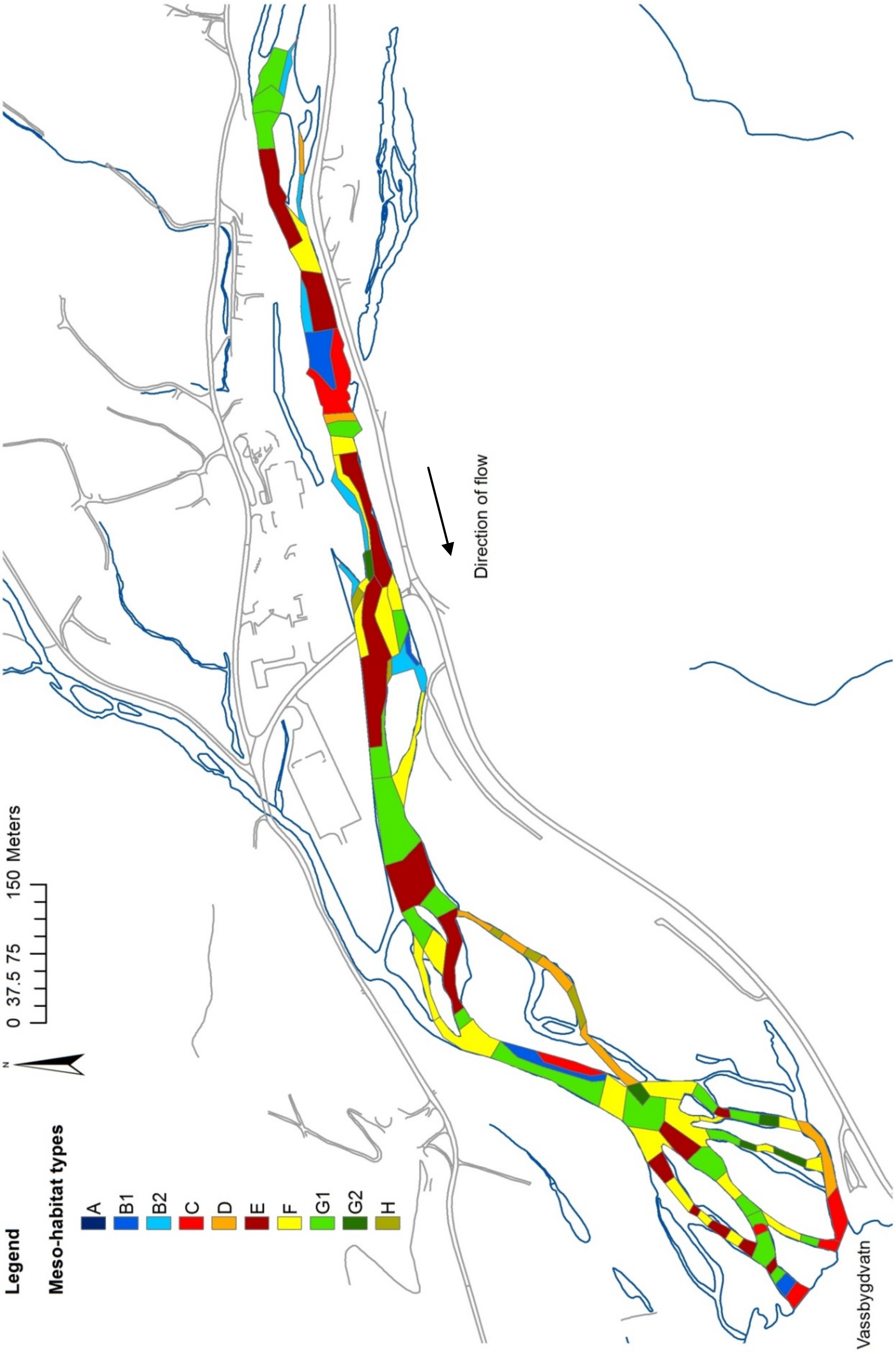
A4 Meso-habitat map: lower reach of Vassbygdelvi at minimum flow (0.29 +/- 0.01 m^3/s).



A5 Meso-habitat map: lower reach of Vassbygdelvi at low flow (0.66 +/- 0.01 m^3/s).



A6 Meso-habitat map: lower reach of Vassbygdelvi at high flow (16.0 +/- 1.5 m^3/s).



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