A cost-effective approach to predict dynamic variation of mesohabitats at the river scale in Norwegian systems

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ABSTRACT

This paper presents a cost-effective approach to predict dynamic variation of mesohabitat classes or hydromorphological units (HMU) in the context of a peaking scenario. Predicting dynamic mesohabitats has been a challenge in the last 20 years. This is mainly due to the fact mesohabitat changes do not show a simple relationship with varying discharges. The HMU Simulation Method, by using a one-dimensional hydraulic model as a basis, proved to be a promising tool to simulate HMUs at four varying discharges in a Norwegian river. Low flows and surface pattern criteria were the most challenging to simulate and best modeling results were achieved for the higher flows. Further development on this approach should follow, but at present the method shows promising results towards the prediction of dynamic HMUs at the river scale.

Keywords: Mesohabitats, HMUs, dynamics, one-dimensional hydraulic modeling, river scale, regulated rivers, hydropeaking

1 Introduction

In the context of increasing demand for renewable energy, hydropower has the potential to balance loads in energy system. To enable this load balancing, production should occur during peak demand periods whilst during surplus power periods, reservoirs should store water for future production. Storage capacity is therefore an important factor to make load balancing possible. A 50% of the European storage potential due to regulated reservoirs is found in Norway (Catrinu-Renström and Knudsen 2011). Potential load balancing will imply more frequent hydropeaking operations that will translate into sudden flow changes in rivers. Such hydropower operations will potentially have associated environmental consequences. Those have been reviewed in Bain (2007), Cushman (1985), Harby *et al.* (2001). However, further research is needed to fully understand the environmental effects of dynamic flow variations at the river scale and for the development of mitigation strategies. It is important for river managers to build a framework in which an easy and cost-effective method can be used to assess changes and propose responses to potential environmental issues at the broader scale (Borsányi 2005). This paper suggests an approach to use one-dimensional hydraulic models for the prediction of mesohabitat changes with flow variations at the river scale. This should provide baseline conditions to assess potential environmental effects of hydropower operations such as hydropeaking.

Specific objectives are: (i) to assess the changes in composition and spatial distribution of mesohabitats with varying discharges; (ii) to investigate the possibilities of modeling mesohabitats using a1D hydraulic model for varying discharges and (iii) to assess the performance of the above approach by comparing field mapped and modeled outputs at the cross section level.

2 Background

Understanding dynamic changes in the physical habitat can provide the template to assess ecological processes and establish important basis for links between the two (Maddock 1999). Research made to date shows the unquestionable link between hydraulic process, geomorphology and river ecology (Maddock 1999, Padmore 1998, Petts *et al.* 2006). Several studies (Kemp *et al.* 1999, Moir and Pasternack 2008, Padmore 1997, Parasiewicz 2007 and Wood *et al.* 1999) have proven relevant links between meso-scale physical habitat (including interactions of hydrological and geomorphic forces) and ecological processes, suggesting meso-scale as an adequate scale to study relevant ecological processes (Newson and Newson 2000), and at the same time a feasible scale for river management (Borsányi 2005).

Efforts to objectively characterize mesohabitat classes through physical parameters have been undertaken by Jowett (1993), Tickner *et al.* (2000), Wallis *et al.* (2012), Wood *et al.* (1999), and particularly for Norwegian rivers by Borsány*i et al.* (2004). When only physical descriptors are used, these areas are commonly named hydromorphological units (HMUs). Hydromorphological units are considered to help us to understand connections between different parts of the river which hold biotic relationships (Borsányi 2005).

Characterizing mesohabitats with physical descriptors has the potential to enable a simplified prediction. The prediction and modeling of such mesohabitat classes is a challenge for scientists and it has been achieved in some cases at the meso-scale (Hauer *et al.* 2009,Wallis *et al.* 2012). However, one issue when characterizing and predicting mesohabitats is to define the degree of detail for a valuable yet cost-effective assessment (Maddock 1999) and the ability to predict how mesohabitat changes with flow variations at a larger scale still remains a challenge (Nikora 2010).

Mesohabitat classification has been increasingly used to describe habitat composition in rivers and to investigate changing habitat composition with varying flows (Alcaraz-Hernández *et al.* 2011,Gosselin *et al.* 2012,Wallis *et al.* 2012). Further research on the relationship between mesohabitat composition and flow changes is needed to enable prediction of unmapped flows. One-dimensional (1D) hydraulic modeling is presently the most cost-effective way to model river hydraulics on a large scale in terms of both surveying and computing effort when comparing it to two- and three-dimensional models.

Although limitations such as the inability of simulating secondary flows, eddies and turbulence in a 1D hydraulic model; hydraulic parameters obtained such as mean velocity, depth, slope, Froude number can still be used to investigate the characteristics of habitats (i.e. HMUs). Thus predictions can be made and consequently a control of frequent fluctuations, developing into a potential tool to be used for mitigation of environmental impacts at the larger scale (Borsányi 2005).

3 Methods

3.1 Study site

The Lundesokna River is a regulated tributary to the Gaula River, located in Central Norway. The Lundesokna hydropower system consists of three regulated reservoirs and three power plants with an average production of 278 GWh per year. The study reach is 2.5 km long and located in the furthermost downstream part of the Lundesokna River before it meets the Gaula River, starting below the outlet of Sokna power plant (Figure 1B). At this site, the Lundesokna River is subject to regular hydropeaking operations with a typical flow range varying from 0.45 $m^3 s^{-1}$ to 20.6 $m^3 s^{-1}$.

3.2 HMU Classification

The Norwegian Mesohabitat Classification Method or NMCM (Borsányi 2005) was used to classify Hydromorphological Units (HMUs) in this project. Borsányi's system distinguishes 10 HMUs that describe mesohabitats by letters of the alphabet. Each HMU is defined by a total of 4 criteria (surface pattern, surface gradient, surface velocity and water depth) with established and measurable thresholds (Table 1). Established limits for each criteria are summarized in Table 2. Details on the method development and a full justification of its use can be found in (Borsányi *et al.* 2004).

3.3 Field data collection

Field data was collected in June 2010 and May and July 2011 comprising geometric surveys, mesohabitat mapping and hydraulic measurements.

A total of 41 cross sections were surveyed in June 2010 using differential GPS with reported accuracy of 10 mm. Cross section location responded to pronounced changes in the river morphology and bed slope. Mean distance between cross sections was about 50 m with a variation between 7 and 200 m with the aim to provide an appropriate geometry for the hydraulic 1D model. The morphology of the river was assumed to remain stable since 2010, with possible changes from that date being considered negligible.

Mesohabitat mapping was undertaken at several discharges between May and July 2011. Discharges at the time of surveying were steady flows at 0.45, 10.6, 16.4 and 20.6 m^3s^{-1}. The discharge was fully controlled by the hydropower production plants during the surveying period. Two surveyors walked along the whole site length to visually identify mesohabitat classes or HMUs according to the established thresholds of water surface pattern, gradient, velocity and depth in the NMCM method. A 1:25000 topographic map of the area was used to manually sketch the layout of the HMUs together with the differential GPS to locate the start and end of the surveyed HMUs in the longitudinal direction. A maximum of 3 HMUs were defined across the river width, considering the widest HMU as the dominant and the others as subdominant.

Discharge and water surface elevation data were collected for each of the HMU mapping surveys in 2011. Discharge was measured at the same spot (cross section 30, figure 1B) at all times with an ADCP. Water surface elevations were measured at the same time of the HMU mapping using the GPS as input for the 1D hydraulic model calibrations.

3.4 Spatial analysis of mapped HMUs

Field sketches on HMU distributions were digitized in ArcGIS 10 as polygon layers. The wetted edges of the HMUs matched at all times field GPS measurements. For the 2 highest discharges, at locations where GPS measurements were not possible, topographical map data was used, considering bankfull discharge as the wetted area edges. A total of 4 maps were digitized, depicting the number, type and distribution of HMUs for each of the surveyed discharges.

From the resulting maps, the total area occupied by each of the HMU was calculated at each discharge. Changes on HMUs area when flow was reduced were assessed by overlaying the map for the highest discharge with each of the other maps. Taking each of the HMUS polygon areas at 20.6 m^3s^{-1} as a reference, changes were quantified by comparing the amount of HMU area of the 16.4 m^3s^{-1}, 10.6 m^3s^{-1} and 0.45 m^3s^{-1} polygons present inside the reference area. Changes in HMUs with flow reduction were assessed by plotting the amount of areas containing fast *vs* slow, deep *vs* shallow and broken *vs* smooth HMU types. In addition, the Shannon and Weaver diversity index (*Shannon and Weaver* 1949) was used to calculate habitat diversity for each of the surveyed discharges.

3.5 One-dimensional hydraulic simulation

Hydraulic simulations were carried out for the four surveyed discharges using the one-dimensional HEC-RAS hydraulic model (*US Army Corps of Engineers* 2012). Calibration was made at steady flow for each discharge using a fully subcritical flow regime and downstream water level and upstream discharge as boundary conditions. Manning's n values were adjusted in order to calibrate the model to fit the observed water surface elevation at each of the surveyed cross sections. A maximum error of 0.05 m between the observed and HEC-RAS simulated water surface elevation was accepted.

3.6 HMUs Simulation Method

A total of 12 variables were extracted from the HEC-RAS output tables and utilized to investigate the potential simulation of each of the four NMCM criteria at the cross section level (Table 3). The output parameters were either used in direct comparisons or as a basis for further computation of variables used to define the NMCM criteria. Details on the final methodology for computing HMUs from HEC-RAS data is explained below with reference to each of the four criteria.

The HMUs Simulation Method describes the process to enable HEC-RAS output variables to be compared with the observed data. The HEC-RAS output variables listed in Table 3 were investigated for their use either in direct comparisons or as a basis for further computation of variables used to simulate each of the four NMCM criteria. Table 4 summarizes the HEC-RAS output parameters chosen for the simulation of each criteria and the changes made to them to enable the simulation of NMCM criteria. A full description of the process to enable simulation is presented below for each of the NMCM criteria.

3.6.1 Water surface pattern

In order to obtain a water surface pattern from the HEC-RAS simulation that could be compared with field data, a total of eight HEC-RAS output variables (Table 3) were investigated to establish a link to the observed surface pattern. These included the Froude number, Manning coefficient n, shear stress, hydraulic slope, stream power, discharge, velocity and Depth. Outputs of each variable were initially compared with the observed water surface pattern (defined as smooth or broken) through fitting minimal adequate binomial generalized linear models (GLM). Results of the initial assessment found that both Shear stress and manning' n were non-significant. Therefore only Slope, Stream power, Froude number, Discharge, Velocity and Depth were further investigated. All possible combinations of those six parameters were fitted in several minimal adequate binomial GLMs. Only five model combinations were found significant and their outputs were individually plotted against observed surface pattern data. A threshold range of values was tested for each of the models outputs to predict smooth or broken surface and then compared to the observed data. The number of coincidences between simulated and observed surface pattern was accounted for each model and each threshold combination. The final model choice was made according to the number of matches as well as the model Akaike's Information Criterion (AIC) as a measure of fit (*Crawley* 2007).

The summary of the tested GLM model formulations, their AIC, established thresholds and the resulting matches are summarized in Table 5. The first model combination, with the lowest AIC and the highest number of matches with the field data was finally chosen. A new threshold of 0.5 for the response function of the model (Surface pattern response function) was established to differentiate between smooth and broken surfaces. Figure 2 illustrates the output of the model and the new threshold.

3.6.2 Water surface gradient

Simulated water surface gradient was calculated at each cross section according to the formula: $m=\Delta H/\Delta x$, where: m is the simulated water surface gradient, ΔH is the water level difference to downstream cross section obtained from the simulated water surface elevation in meters and Δx is the distance to the immediate downstream cross section thalweg point.

3.6.3 Water velocity

Water velocity estimated in the field was based on the observed surface velocity, whilst water velocity provided by HEC-RAS refers to the mean velocity. According to a typical logarithmic water velocity profile in an open channel, velocity in the surface will always be higher than the mean velocity. Therefore, an adjustment to the mean velocity was done to provide a more reliable comparison. The formula for a standard logarithmic velocity profile in open channels was employed to find the surface velocity (*Von Karman* 1931):

$$u = \bar{u} + \left[\frac{1}{\kappa} v \left(1 + 2.3 \log \left(\frac{y}{d} \right) \right) \right] \qquad (1)$$

where: u: surface velocity; ū: mean velocity; κ: Von Karman constant (0.41); d: maximum depth; y= 0.95d; $v = \sqrt{9.81RI}$, R=A/P_w, R: hydraulic radius, A: flow area; P_w: wetted perimeter, and I: topographic downstream slope.

Adjustments were first applied to all discharges, but a preliminary comparison with field data revealed that the adjustment did not provide reliable results for the lowest of the discharge (0.45 $m^3 s^{-1}$), most likely due to the very shallow depth, which made it difficult to apply the logarithmic velocity profile model. Therefore, adjustments were not applied for the lowest of the discharges.

3.6.4 Water depth

Both average depth and maximum depth were preliminarily compared to the observed data for the potential simulation of the water depth criteria. Maximum depth proved the best results at the highest discharges and therefore this parameter was to be used for direct comparison. Although it did not show the best results for the lowest of the discharges, maximum depth was used for all discharges for consistency in the method.

Following changes to HEC-RAS output variables, the four criteria were finally simulated at each of the 41 cross sections for the four discharges. Together all simulated criteria resulted in predicted HMUs that could then be compared to the field observed HMUs.

The HMU Simulation method was based on the best match to simulate each of the four criteria. In addition to comparing the simulated HMUs, we also compared each of the individual criteria to assess potential errors and to improve the method. Simulated NMCM criteria and final HMUs are compared with the field observed data in section 4.3. The final number of matches with field observed data for each of the simulated criteria are presented in section 4.4.

3.7 Match and Mismatch analysis

The number of matches between simulated and observed data was calculated both for each of the simulated NMCM criteria and for the resulting HMUs at the cross section level for each mapped discharge.

An analysis on the causes of mismatches was carried out. The analysis of causes for a mismatch was considered as a tool to identify possible errors or/and inaccuracies of the HMU assessment method for further improvements in the future. The total number of mismatches by criteria was calculated for each discharge. Additionally, the potential cause of error due to the presence of more than one observed HMU at the mismatched cross sections was analyzed.

The magnitude of the mismatch error between observed and simulated data was calculated in order to analyze potential overestimation or underestimation in the modeled HMUs. Such error calculation was based on the defined threshold for each of the defining features (Table 2).

3.8 Final comparison with field observed data

Comparison between observed and simulated HMUs was carried out for all the discharges at the cross section level. Observed field data was considered the correct basis for comparison. The following data was compared: (i) Number of dominant HMUs (ii) Number of categories for each of the NMCM criteria (iii) accumulation of HMU classes and (iv) sequences of HMUs.

4 Results

4.1 Spatial analysis of mapped HMUs

Table 6 summarizes the total area occupied by each field mapped HMU for all surveyed discharges. Figure 3 illustrates the distribution of HMU areas along the river length. As expected, the 2 highest discharges show a dominant presence of G1 HMU class (deep, fast and broken), whilst at the lowest discharge, the water covered area is reduced and class D habitat (shallow, slow and smooth) is dominant. In the intermediate discharge of 16.4 m^3s^{-1}, some patches of B1 HMU class start to occupy the areas previously of type G1. And at 10.6 m^3s^{-1}, B1 becomes dominant. For all discharges, it is noticeable that the areas of major diversity of HMUs are concentrated in the river bends.

Figure 4 illustrates HMUs relationships with reduction of flow. It shows how an area originally occupied by an HMU type at the highest discharge change to become another HMU type at lower discharges.

From 20.6 to 16.4 m^3s^{-1} (Figure 4a), there is a very slight change in HMUs composition. The most significant changes were a transformation of some 12% G1 to B1 and most of the G2 becoming B2, meaning a change into smoother surface patterns in both cases.
Changes from 20.6 to 10.6 m^3s^{-1} (Figure 4b), shows an important transformation of 81% G1 into B1, becoming the dominant type. Some of the original B1 became C and B2 at 10.6 m^3s^{-1} and a total of 6% of the wet area was dried out.
Figure 4c shows a total of 33% of area dried out from 20.6 to 0.45 $m^3 s^{-1}$. G1 changed to become mostly D and also B2 and C, the latest becoming the dominant HMUs distributed in a mosaic along the river (Figure 3).

Figure 5 illustrates the percentage of HMUs occupied by each type in the NMCM criteria. Surface pattern shows a progressive evolution from high to low flows, going from broken to smooth types as the flow decreases. Surface gradient was considered mild in all cases from the field observations. In terms of velocity, there is a dominance of fast HMUs at the three highest discharges with a change in slow dominance at the lowest one. Deep HMUs also dominates at all discharges except for the lowest, where shallow HMU is dominant. However, some patches of shallow and deep HMUs can still be found at high and low flows respectively.

Table 7 summarizes landscape diversity results. Habitat diversity increases from the highest to the lowest flows, where it reaches the highest value. However, a reduction in diversity from the 16.4 to the 10.6 $m^3 s^{-1}$ discharges is observed due to a strong dominance of B1 flow types at 10.6 $m^3 s^{-1}$.

4.2 One-dimensional Hydraulic Model and HMU Simulation Method Outputs

Calibration of the HEC-RAS model for all the simulated discharges was achieved with an acceptable average error of 1 to 2.6 cm between observed and simulated water levels. Mean Manning's n values used for the calibrations were between 0.054 and 0.632 for all simulated discharges.

The average values of all HEC-RAS output parameters and those calculated through HMUs simulation method are summarized in Table 8. Those are presented for all simulated discharges. As expected, the lower the discharge, the smaller the average values of all the hydraulic parameters are, with the highest difference occurring between 10.56 and 0.45 $m^3 s^{-1}$. This occurs in all parameters except for hydraulic gradient, and the surface pattern response function. For the hydraulic gradient the higher gradients are found in the two middle discharges. The surface pattern response function decreases the most between 16.4 and 10.6 $m^3 s^{-1}$. The adjustment made to the average velocity to obtain surface velocity resulted in velocity values between 32% and 37% higher than the average velocity.

4.3 Match and mismatch analyses

Results of matches between observed and simulated data at the cross section level is shown in Table 9 and of mismatches in Tables 10 and 11.

Total number and percentage of matches between observed and simulated HMUs is summarized in columns two and three in Table 9. The highest discharge presents the highest number of matches, whilst the two lowest discharges present the lowest number of matching cross sections those being 25 out of 41.

The last four columns in Table 9 summarize the percentage of matches between observed and simulated data for each of the criteria after the adjustments and calculations explained in section 3. Surface pattern matched 75-98% with the observed data for all discharges, with the best matches at the highest and lowest discharges. The overall best results were shown for Surface gradient with matches of 95-100%; again the highest and lowest discharges showed the highest percentage of matches. Simulated surface velocity coincided with the observed data between 80-100%. The two highest discharges were the best matched with the observed surface velocity. Finally, water depth also showed the best results for the two highest discharges (95-98%), with the lowest match being 82%.

In total, 41 mismatches out of 164 simulated cross sections were identified (Table 10). For each discharge, the two highest present the lowest number of mismatches with main mismatches causes being surface pattern, water depth and surface gradient. In the lowest discharges, the number of mismatches increases and velocity is added as causes for mismatch. Surface pattern is the main cause of mismatch at 10.6, whilst it is velocity for the lowest discharge. Only 2 out of 164 causes of mismatch were due to combined causes and both occurred in the lowest discharge. In 24 cases the mismatch occurred in cross sections where more than one HMU type was observed.

High underestimations are shown for the surface gradient at the intermediate discharges (Table 11). The highest relative differences are shown in surface velocity for the 10.6 $m^3 s^{-1}$ discharge, showing a >3 times overestimation in the simulation. Both underestimations and overestimations are observed in the simulated results for the surface pattern.

4.4 *Comparison to field observed data*

Comparisons between field mapped and modeled HMUs at the cross section levels are shown in Table 12, Figures 6 and 7 and Table 13.

Table 12 summarizes the comparison between observed and simulated HMUs numbers for each of the discharges. Dominant HMU along the river length are coinciding between observed and simulated for all discharges. The total numbers of observed and simulated HMU classes are in the same range for all situations. However, observed numbers are higher than those simulated for the 20.6 and 0.45 $m^3 s^{-1}$ discharges; and lower for the 16.4 $m^3 s^{-1}$ discharge. In four occasions, one for each of the discharges, the simulation captured HMUs that had not been observed in the field. In the same way, also in four cases, observed HMU had not been captured by the simulation. But of those, three only observed HMU are found in the 10.6 $m^3 s^{-1}$ and the other in the 16.4 $m^3 s^{-1}$.

Figure 6 illustrates the comparison between observed and simulated surface pattern, surface gradient, surface velocity and water depth. For all criteria, categories numbers are very similar between observed and simulated, especially in the higher discharges. The highest difference between observed and simulated results is noticed for the velocity criteria, where simulation considers a major number of slow HMUs than those observed.

Accumulation of HMU classes with distance downstream is compared in Figure 7. The general tendency of HMU class accumulation is visually similar between observed and simulated for the three higher discharges. G1is progressively accumulated downstream for the two highest discharges and G2 for 10.6 $m^3 s^{-1}$. The accumulation of the D type HMU is however slightly overestimated for the lowest discharge.

Table 13 shows the class sequences for both observed and simulated data. It indicates the number of cross sections followed by a certain HMU type. For all discharges, the simulated data distribution is visually similar to the observed distribution and the dominant HMU in number coincides.

5 Discussion

In terms of the assessment of changes in the spatial distribution of HMUs, broken, faster and deeper HMUs decrease in dominance as discharge decreases, whilst smoother, slower and shallower HMUs increase (Figure 2). Whilst fast and deep HMUs show the most substantial change to slow and shallow at the lowest of the discharges; broken surface HMUs start to change to smooth surface HMUs at the intermediate flow, showing a higher sensitiveness in surface pattern changes. The most significant change in the HMU distribution is that an important part of the wet area becomes dry when discharge decreases, reducing the total available area.

Mesohabitat diversity does not change linearly with the flow increase, suggesting that there is no simple link between habitat diversity and flow. This confirms findings in Gosselin *et al.* (2012) and also supports the suggestion in Wallis *et al.* (2012) on river morphology being a template for potential hydraulic diversity, with discharge as the main driver for this potential to occur. The lowest diversity found in the second lowest discharge suggests that the combination of river morphology and discharge has an important role in mesohabitat composition and therefore on habitat diversity. In this study, only 4 discharges were possible to survey at the time, due to the constraints posed by the hydropower production. However, the range surveyed does encompass very high, minimum and intermediate discharges. To further control the results from the survey, photos were taken in the field and the results were further discussed with experienced surveyors to check for potential errors in the interpretation. Field subjectivity however is still a possibility when judging this work as it is for all mesohabitat assessments.

The HEC-RAS calibration results were satisfactory and the authors are confident on the reliability of the model predictions for the discharge range needed for this work. The chosen HEC-RAS output variables were used as a basis to enable the simulation of all NMCM criteria with further adjustments and calculations.

The results of the HMU Simulation Method are discussed below. The analysis of mismatches for each of the simulated NMCM criteria with regards of the observed data is also reviewed. Such analysis was undertaken at the cross section level only as it was considered the most realistic comparison.

The criteria presenting the major number of mismatches for all discharges are the surface pattern, followed by water depth, surface velocity and surface gradient. However, the magnitude of the error is higher in velocity followed by surface pattern and depth.

The variables used for the simulation of water surface patterns are found to be reasonable from a physical point of view. The Froude number, for example, has been used previously in literature to simulate surface patterns. Froude has been discussed in Mérigoux and Dolédec (2004) and Moir *et al.* (2002) as a relevant variable to characterize physical habitat for aquatic organisms. Hauer *et al.* (2009)

considered Froude number as a variable to include for the improvement of mesohabitats description. It has also been recognized as a criterion to distinguish between pools and riffles (Jowett 1993), where riffles indicated broken and wavy water surface respectively, and pools indicated smooth water surface similar to the surface pattern criteria in NMCM. However, Clifford *et al.* (2006) emphasized that a careful interpretation is needed for Froude number in a single reach under low and high flows because very different velocity-depth relationships could exhibit similar values. It is therefore not surprising that factors such as stream power and discharge adds information in the prediction of surface patterns. Although more tests should be done in other river types to confirm this, our results are promising for future dynamic mesohabitat simulations.

Water surface pattern adjustment proved to work in the majority of the cases with a very satisfactory result. The most challenging discharge to model regarding water surface pattern was the intermediate 10.6 $m^3 s^{-1}$. This can be explained by the fact that it is an intermediate flow where the line between B1 and G1 is very fine. Both HMUs classes have the same hydraulic characteristics, except for the surface pattern, making it difficult for the model to simulate this intermediate stage accurately.

Simulated water surface gradient was the most straight-forward of all variables to predict and the threshold of 0.04 fitted well with the observed data. This can be related to the river type, and this variable might be more complicated to differentiate in other river types.

Surface gradient, is a very objective measurement and easy to determine with high reliability in a hydraulic model. Although it was not an important cause of mismatch, influenced the simulation of A and E classes that were not captured by the field observations. Those had not been considered in the field due to the assumption of mildness for the whole river length.

The adjustment made to velocity in the higher discharges and not in the lowest of the discharges enabled a more realistic comparison to what was observed in the field. Velocity presented mismatches in the two lowest discharges only, with the lowest discharge presenting the highest mismatch numbers. A potential reason for the mismatching in velocity was considered to be the smoothing of HEC-RAS for several consecutive differentiated HMU classes. Looking through the relative location of the non-coinciding cross sections (at 0.45 $m^3 s^{-1}$), several patches combined long shallow glides (D type, slow) and narrow strips of shallow splash (B2 class, fast). HEC-RAS mainly takes into account the cross sections with a significant change of slope and, in general, the model smooth it out, then B2 type can be underestimated by the model. This could be the reason for some of the mismatched cross sections which lay in a B2 type and therefore were considered as fast in field but they are not reflected by the model. Moreover, a 0.45 $m^3 s^{-1}$ discharge is extremely low for the Lundesokna River, reaching the edge the hydraulic model simulation capacity.

The use of maximum depth for the all discharges was consistent and resulted in a satisfactory comparison between simulated and field observed data.

Combined causes of mismatches appeared to be rare. In most of the cases only one feature was the cause of the mismatch. However, in more than 50% of the mismatches, more than one HMU was observed at the cross section level. This suggests than in cross sections where more than one HMU was observed, the model averaged the simulated parameters across the cross sections, being more difficult to capture the physical parameters corresponding to the dominant HMU.

Final comparisons between the observed and simulated HMUs showed satisfactory results for all discharges. It resulted in more coincidences in the highest discharges both in terms of HMUs and NMCM criteria numbers. The number of HMU classes was similar between observed and simulated data. Observed data showed a higher number of HMU classes than those simulated for the highest and the lowest of the discharges but not for the middle discharges.

In terms of class accumulation with distance, the simulation of the dominant classes fits well with the observed data for the higher discharges, with less accuracy for the lowest of the discharges. The same can be observed for the class sequence analysis. Simulated results show the ability of the model to capture the dominant classes. However, the model is unable to successfully predict the observed variability (number of subdominant HMUs).

6 Conclusions

The spatial composition and diversity of mesohabitats with varying discharges has shown not to follow a simple relationship. From the highest to the lowest of the flows, the most significant change is the reduction on the total available area and at the same time an increase in number of HMU units. However, this increase in landscape diversity does not follow a linear increase from high to low flow, making apparent its complexity. According to the NMCM classification, surface pattern is the most sensitive criteria to detect changes in flow.
The use of a one-dimensional hydraulic model proved to be a promising method to simulate dynamic HMUs. The HEC-RAS 1D model provides the necessary output variables that with some adjustment

enabled the simulation of each of the four NMCM criteria needed to derive HMU classes at each of the surveyed discharges.

Finally, the performance of the HMU Simulation Method was considered satisfactory when compared to the field observed data, both in terms of individual NMCM criteria and overall HMU classifications. In terms of discharges and criteria, the lowest discharge and surface pattern were the most challenging to simulate. The best modeling results were achieved for the higher flows.

The further development of this approach is ongoing, and we suggest the test of the method to rivers with other dynamics and physical characteristics for further improvements to be incorporated. Nevertheless, at present, the method shows promising results to work towards dynamic prediction of HMUs at the river scale. It has the potential to provide river managers with a cost-effective prediction tool with a high applicability in the assessment of potential environmental impacts. This approach will allow simulating HMU maps using a relatively simple way such as the application a 1D hydraulic model. HMU maps can be then computed for a range of discharges without the need for field mapping at every discharge needed for the analysis. This will make it easier to predict HMU changes, especially for those discharges with rare occurrence or in which access to the river is limited. This provides a more efficient method for developing mesohabitat class maps for all interesting discharges, and an improved capability to describe habitat dynamics which previously have required considerable field work.

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Tables

Table 1. Decision tree for HMU classification (Borsányi 2005)

Surface pattern	Surface gradient	Surface velocity	Water depth	HMU type	NMCM name
smooth / rippled	steep	fast	deep	A	Run
			shallow	No existing combinations	
		slow	deep	No existing combinations	
			shallow		
	mild	fast	deep	B1	Deep glide
			shallow	B2	Shallow glide
		slow	deep	C	Pool
			shallow	D	Walk
broken / unbroken standing waves	steep	fast	deep	E	Rapid
			shallow	F	Cascade
		slow	deep	No existing combinations	
			shallow		
	mild	fast	deep	G1	Deep splash
			shallow	G2	Shallow splash
		slow	deep	No existing combinations	
			shallow	H	Rill

Table 2. Thresholds limits for each class of the four criteria for the HMU classification (Borsányi 2005)

Criteria	Categories	Thresholds
Surface pattern	smooth/rippled	wave height <0.05 m
	broken/unbroken standing waves	wave height >0.05 m
Surface gradient	steeper	> 4%
	less step	< 4%
Surface velocity	fast	>0.5 m s^{-1}
	slow	<0.5 m s^{-1}
Water depth	deep	>0.7 m
	shallow	<0.7 m

Table 3. Summary of output simulated hydraulic parameters from HEC-RAS used to investigate potential comparison with field data at the cross section level.

Simulated parameter obtained from HEC-RAS	Units	Description	Field observed criteria investigated
Froude	-	Froude number for the main channel.	Surface pattern
Mann Comp	-	Mannings n value for main channel	Surface pattern
Shear Chan	$N\ m^{-2}$	Shear stress in main channel	Surface pattern
E.G. Slope	$m\ m^{-1}$	Slope of the energy grade line at a cross section	Surface pattern
Power Chan	$N\ m^{-1}\ s^{-1}$	Total stream power in main channel	Surface pattern
Q Total	$m^3\ s^{-1}$	Total flow in cross section	Surface pattern
Vel Total	$m\ s^{-1}$	Average velocity of flow in total cross section	Surface pattern Surface velocity
Hydr Depth	m	Hydraulic depth in channel	Surface pattern
Distance downstream	m	Distance to downstream cross section	Surface gradient
W.S. Elev	m	Calculated water surface from energy equation	Surface gradient
W.P. Total	m	Wetted perimeter of total cross section	Surface velocity
Flow area	m^2	Total area of cross section active flow	Surface velocity
Max Chl Dpth	m	Maximum main channel depth	Water depth

Table 4. Summary of simulated parameters obtained from HEC-RAS and changes needed to enable comparison to the field observed criteria.

Field observed criteria	Simulated parameter obtained from HEC-RAS	Changes needed to HEC-RAS obtained parameters
Surface pattern	Total flow ($m^3 s^{-1}$) Froude number Average Velocity ($m\ s^{-1}$) Hydraulic Depth (m) Stream Power ($N\ m^{-1}\ s^{-1}$)	GLM response model and establishment of a new threshold according to the model output
Surface gradient	Water Surface Elevation (m) Distance to downstream transect (m)	Calculation
Surface velocity	Average velocity ($m\ s^{-1}$) Flow area (m^2) Wetted perimeter (m)	Adjustments to the parameter
Water depth	Maximum Depth (m)	Direct comparison

Table 5. Global Linear Model combinations and details of its AIC values, estimated threshold established and number of matches with observed data for the assessment of surface pattern prediction.

Model formulation	AIC	Model Output	
		Established threshold	Number of matches
Surface Pattern ~ Velocity + Depth + Froude + Stream power + Discharge	82.852	0.5	149
Surface Pattern ~ Stream power + Discharge	116.02	0.55	143
Surface Pattern ~ Velocity + Froude + Depth	136.9	0.5-0.6	142
Surface Pattern ~ Veocity + Froude	141.43	0.5-0.55	140
Surface Pattern ~ Depth + Froude	170.7	0.55	128

Table 6. Area occupied by each observed HMU type at each of the surveyed discharges

		20.6 m^3s^{-1}	16.4 m^3s^{-1}	10.6 m^3s^{-1}	0.45 m^3s^{-1}
HMU area (m^2)	G1: Deep splash	40410	31584	4433	0
	G2: Shallow splash	2385	278	0	949
	B1: Deep glide	1605	9587	33211	26
	B2: Shallow glide	1229	4318	5118	5223
	C: Pool	782	519	974	3595
	D: Walk	491	615	517	20918
	H: Rill	0	0	0	765
Total area (m^2)		46904	46901	44252	31475

Table 7. Landscape diversity along the river Lundesokna for the four surveyed discharges.

Discharge	Shanon-Weaver index
20.6 m^3s^{-1}	0.61
16.4 m^3s^{-1}	0.95
10.6 m^3s^{-1}	0.80
0.45 m^3s^{-1}	1.02

Table 8. Average values of key hydraulic parameters output from HEC-RAS used for the simulation of the HMU criteria.

Simulated parameter obtained from HEC-RAS	Units	Average values			
		20.6 $m^3 s^{-1}$	16.4 $m^3 s^{-1}$	10.6 $m^3 s^{-1}$	0.45 $m^3 s^{-1}$
Froude number	-	0.41	0.38	0.34	0.14
Stream Power	$N\ m^{-1}\ s^{-1}$	77.86	47.56	29.81	26.83
Average velocity	$m\ s^{-1}$	1.14	1.01	0.82	0.18
Hydraulic depth	m	0.85	0.80	0.68	0.31
Surface pattern Response Function*	-	0.93	0.72	0.13	0.06
Hydraulic gradient*	$m\ m^{-1}$	0.0033	0.0064	0.0051	0.0028
Wetted perimeter	m	23.31	22.63	21.23	13.16
Flow area	m^2	19.10	17.56	13.94	4.26
Surface Velocity*	$m\ s^{-1}$	1.70	1.55	1.32	-
Maximum depth	m	1.36	1.28	1.12	0.55

* Calculated parameters

Table 9. Total number and percentage of total matches between simulated and field observed dominant HMUs and percentage of matches with observed data for each of the simulated criteria. Percentages of matches are shown for each of the simulated discharges.

Discharge	Total number of matches	% of Total matches	% of matches by criteria			
			Surface pattern	Surface gradient	Surface velocity	Water depth
20.6 m^3s^{-1}	39	95.1	97.6	100.0	100.0	97.6
16.4 m^3s^{-1}	33	80.5	85.4	95.1	100.0	95.1
10.6 m^3s^{-1}	25	61.0	75.6	97.6	92.7	92.7
0.45 m^3s^{-1}	25	61.0	95.1	100.0	80.5	82.9

Table 10. Analysis on the mismatches causes. The table shows in the first column the total number of mismatches followed by the mismatches numbers by criteria. The "combined causes" column represents mismatches that are due to more than one criteria. And the ">1 HMU" column represents the number of mismatches that are occurring in a cross section where more than one HMU class was observed in the field. All data is represented for each of the four surveyed discharges and in total numbers.

Discharge	Number of mismatches	Mismatches numbers by criteria				Combined causes	>1 HMU
		Surface pattern	Surface gradient	Surface velocity	Water depth		
20.6 m^3s^{-1}	2	1	0	0	1	0	2
16.4 m^3s^{-1}	10	6	2	0	2	0	7
10.6 m^3s^{-1}	16	10	1	3	3	1	9
0.45 m^3s^{-1}	16	2	0	8	7	1	6
Total	44	19	3	11	13	2	24

Table 11. Maximum, minimum and average errors found in the simulated data for each of the simulated discharges. Error was calculated in relation to the established NMCM thresholds for each of the four criteria.

Discharge	Defining feature	Threshold	Maximum	Minimum	Average
$20.6\ m^3\ s^{-1}$	Surface pattern	0.5	-0.312	-0.312	-0.312
	Surface gradient	0.04	0.000	0.000	0.000
	Surface velocity	0.5	0.000	0.000	0.000
	Water depth	0.7	0.240	0.240	0.240
$16.4\ m^3\ s^{-1}$	Surface pattern	0.5	0.443	-0.070	0.246
	Surface gradient	0.04	-0.029	-0.030	-0.030
	Surface velocity	0.5	0.000	0.000	0.000
	Water depth	0.7	0.190	-0.030	0.080
$10.6\ m^3\ s^{-1}$	Surface pattern	0.5	0.181	-0.443	-0.289
	Surface gradient	0.04	-0.044	-0.044	-0.044
	Surface velocity	0.5	1.820	0.420	1.040
	Water depth	0.7	0.080	-0.050	0.010
$0.45\ m^3\ s^{-1}$	Surface pattern	0.5	-0.126	-0.416	-0.271
	Surface gradient	0.04	0.000	0.000	0.000
	Surface velocity	0.5	0.260	-0.230	-0.034
	Water depth	0.7	0.290	-0.190	0.027

Table 12. Comparison between number of observed and simulated dominant HMUs at the 41 cross section positions.

Discharge		A	B1	B2	C	D	E	G1	G2	H	Number of HMU classes
23.6 m^3 s^{-1}	Observed		2					38	1		3
	Simulated		3					38			2
16.4 m^3 s^{-1}	Observed		11	1				29			3
	Simulated	1	7				1	31	1		5
10.6 m^3 s^{-1}	Observed		32	2	3			4			4
	Simulated	1	29	3				8			4
0.45 m^3 s^{-1}	Observed			7	9	22			2	1	5
	Simulated			1	10	29				1	4

Table 13. Observed and simulated class sequences along the river Lundesokna for each of the surveyed discharges. At each table, the rows illustrate the number of cross sections with a certain HMU that are followed by the HMU represented in the columns.

20.6 $m^3 s^{-1}$ — Number of HMU classified transects followed by

Observed	A	B1	B2	C	D	E	G1	G2	H
A									
B1		1					1		
B2									
C									
D									
E									
G1							36	1	
G2							1		
H									

Simulated	A	B1	B2	C	D	E	G1	G2	H
A									
B1		1					2		
B2									
C									
D									
E									
G1		1					36		
G2									
H									

16.4 $m^3 s^{-1}$ — Number of HMU classified transects followed by

Observed	A	B1	B2	C	D	E	G1	G2	H
A									
B1		7					4		
B2							1		
C									
D									
E									
G1		3	1				24		
G2									
H									

Simulated	A	B1	B2	C	D	E	G1	G2	H
A		1							
B1	1	2					4		
B2									
C									
D									
E		1							
G1		2				1	26	1	
G2							1		
H									

10.6 $m^3 s^{-1}$ — Number of HMU classified transects followed by

Observed	A	B1	B2	C	D	E	G1	G2	H
A									
B1		25	1	1			4		
B2		1	1						
C		2		1					
D									
E									
G1		4							
G2									
H									

Simulated	A	B1	B2	C	D	E	G1	G2	H
A			1						
B1	1	20	2				5		
B2		2					1		
C									
D									
E									
G1		6					2		
G2									
H									

0.45 $m^3 s^{-1}$ — Number of HMU classified transects followed by

Observed	A	B1	B2	C	D	E	G1	G2	H
A									
B1									
B2					6				1
C				4	5				
D			7	3	10			1	
E									
G1									
G2				1	1				
H								1	

Simulated	A	B1	B2	C	D	E	G1	G2	H
A									
B1									
B2					1				
C				5	5				
D			1	4	22				1
E									
G1									
G2									
H					1				

Figure captions

Figure 1. Locations of the Lundesokna catchment (A) and the 41 surveyed cross sections along the study site (B).

Figure 2. Results of the GLM analysis to enable a response function for the simulation of the surface pattern criteria. The dotted line across represent the established threshold of 0.5 to differentiate between Smooth and Broken surface patterns.

Figure 3.Maps of observed HMU types at each of the surveyed discharges along the study site.

Figure 4. Change of HMU (in % of area) from the highest 20.6 m^3s^{-1} (area at this discharge taken as a reference) to the rest of surveyed discharges.

Figure 5.Percentage of total HMU area occupied by each type on the NMCM criteria (a) Surface pattern (b) Surface gradient (c) Surface velocity (d) Water depth, for each of the field mapped discharges.

Figure 6. Comparison between observed and simulated NMCM criteria (a) Surface pattern (b) Surface gradient (c) Surface velocity (d) Water depth, for each of the field mapped discharges.

Figure 7. Observed and simulated HMU type accumulation from the upstream (cross section 41) to the downstream (cross section 1), for all surveyed discharges.