Performance of a one-dimensional hydraulic model for the calculation of stranding areas in hydropeaking rivers

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ABSTRACT

Fish stranding is a critical issue in rivers with peaking operations. The ability to accurately predict potential stranding areas can become a decisive factor to assess environmental impacts and for mitigation planning. The presented works shows that common procedures suggested in the literature in the use of one-dimensional (1D) models to for flood zone mapping are not always applicable to compute stranding areas. More specific guidance need to be given for such smaller issues. We provide specific guidelines to accurately predict potential stranding areas in a cost-effective manner. By analyzing four different river morphologies in detail in a peaking river we find that the optimal geometry effort (number of cross sections) will vary between channel types according on river physical characteristics such as sinuosity and channel complexity. The use of a 1D model can provide good estimates with an optimal geometry layout.

Keywords: stranding area estimation, 1D hydraulic modeling, hydropeaking, hydropower

1 Introduction

In the future European energy market, hydropower is expected to play a key role due to its storage potential and flexibility to balance the load of other renewables. Norway has to date approximately 50% of the storage potential in Europe and shows a potential for further increase (Catrinu-Renström and Knudsen 2011), and research on using such storage capacity is currently ongoing. In parallel, the implementation of the Water Framework Directive (WFD) and revisions of hydropower licenses are big scale processes defining hydropower scenario in Norwegian rivers. Load balancing will lead to more variable production including hydropeaking and potentially induce more frequent accidental stops in hydropower plants. This will translate into more severe and unpredicted fluctuating levels in the receiving water bodies and might strongly affect the riverine habitats.

Potential ecological implications of hydropeaking have been reviewed in (Harby et al. 2001, Cushman 1985, Bain 2007) . Drifting of macroinvertebrates (Lauters et al. 1996, Bruno et al. 2009), and especially the stranding of juvenile fish are the most relevant examples. Fish stranding has been described as any event in which fish are restricted to poor habitat as a consequence of physical separation from a main body of water as a consequence of a sudden decrease in flow (Nagrodski et al. 2012). Studies on fish stranding as a consequence of hydropeaking are found in Norway and elsewhere (Vehanen et al. 2000, Stillwater Sciences 2006, Scruton et al. 2003, Saltveit et al. 2001, Irvine et al. 2009, Halleraker et al. 2003, Flodmark, VØllestad and Forseth 2004, Flodmark et al. 2006, Bradford 1997, Berland et al. 2004). They indicate that physical habitat factors such as slope, substrate and bathymetry are among the factors influencing stranding of juvenile salmon and trout. These species, not being able to follow the declining water line when a rapid decrease in flow occurs may strand on flat river banks or be trapped in pools disconnected from the main channel which are gradually dewatered. Most of the studies of fish stranding have been done in laboratories (Bradford 1997, Halleraker et al. 2003), or in confined areas in rivers (Saltveit et al. 2001). Very few studies exist on larger-scale in rivers and on the causes and effects of stranding on fish populations, being a significant drawback for the assessment of impacts of peaking operation on fish mortality.

Stranding of fish and other organisms has been recognized as a potential issue that hydropower plants with peaking operations must take into account in the form of mitigation strategies (Harby et al. 2001, Harby et al. 2004), linked to environmental impact assessments

(EIA) and therefore relevant when working with the WFD, hydropower revisions and balance capacity assessment.

In order to develop measures to avoid and/or mitigate stranding it is important to have adequate tools which allow estimating the stranding risk at the larger scale, (Forseth et al. 2008) devised a method to estimate stranding mortality of juvenile Atlantic salmon at the river scale. They combined fish density data from various mesohabitats, stranding mortality and critical dewatering speeds from cage experiments, and simulated dewatering and drying rates for the river from a 1D hydraulic model. The study showed that a low amount of geometry data increases the inaccuracy of the 1D hydraulic model results, especially at low flows. At the same time, it raised the question of what the minimum amount of geometry data is needed for the 1D model to be as accurate as possible.

Some examples of computing dewatered areas using 1D hydraulic models and GIS are found in literature looking at the effect of topographic data and geometric configuration in the context of flood inundation mapping (Werner 2001, Richmond and Perkins 2009, Cook and Merwade 2009). (Castellarin et al. 2009) suggested some general guidelines to decide the optimal cross-sectional spacing in 1D models to obtain the highest accuracy but emphasized that the final optimal number will depend on the problem under investigation. In all cases, no specific guidelines are shown. Therefore, recommendations for an optimum geometry mapping effort in order to cost-effectively calculate the stranding areas still remain. In addition, there is a knowledge gap in the understanding of the physical mechanisms that induce stranding, in regard to the application of stranding models as tools for water management groups. In order for water managers to utilize stranding model tools with low uncertainty, in the context of a growing demand for renewable energy and potentially more hydropeaking, more knowledge is needed for the establishment of scientifically sound guidelines for hydropower operations.

The aim of the present work was to study the accuracy of predicting potential stranding areas obtained from a steady flow analysis in a one-dimensional (1D) hydraulic model. The performance of the 1D model and its capacity to predict potential stranding areas was assessed in terms of optimal geometry density or amount of cross sections needed. Outputs of the 1D hydraulic model were compared with field observed data for several combinations of geometry densities. The objective of the work is to assess river scale impacts of stranding in line with (Forseth et al. 2008), a task where a 1D tool still has an edge over 2/3D models due to data needs and computational efficiency. This study will provide with an objective, reproducible and easy to use methodology for the study of dry out areas as potential stranding areas due to hydropeaking or accidental hydropower plant shut downs.

A total of four river stretches with different morphologic characteristics in river Lundesokna were investigated. The four river sections include two straight channels, and a sharp bend and a smooth bend with varying configurations of exposed gravel bars at low flows. By simulating each of the sections with an increasing density of cross sections and comparing the results to detailed field surveys of stranding area, we estimated the minimum number of sections needed to get an accurate computation of the stranding area.

The results from this work will help improve current available guidelines on the optimal number of cross section selection (Castellarin et al. 2009), specifically in designing data collection procedures for stranding studies and for evaluating the accuracy in existing data sets before further studies are carried out. This will also contribute to a more secure estimate of fish mortality due to stranding as emphasized in (Forseth et al. 2008), and to an improved methodology for large scale impact assessment studies in hydro peaked rivers.

2 Methods

2.1 Study site

The Lundesokna River, a tributary to the Gaula river, is located in Central Norway (Figure 1A). The Lundesokna hydropower system consists of three regulated reservoirs, three interbasin transfers and three power plants with a total average production of 278 GWh per year. The study reach is located at the furthermost downstream part of the Lundesokna before it meets the Gaula River, 2.5 km below the outlet of Sokna power plant. At this reach, the Lundesokna River is subject to regular hydropeaking operations with a typical flow range varying from 20m^3 s-^{1} to 0.45m^3 s-^{1} in some 20 minutes.

A total of four sites along the lower 2.5 km of the Lundesokna river were selected for this study (Figure 1B). Physical characteristics of each of the sites are summarized in Table 1. They presented different lengths, widths, slope, degree of sinuosity, the (O'Neill and Thorp 2011) River Channel Complexity Ratio (RCCR), and side bars types. Side bars in all cases appeared fully exposed during low flows and were identified as potential stranding areas due to their small slope (Bradford 1997).

2.2 Field data collection

As an input for the 1D hydraulic model, both geometric and hydraulic data were collected between 2010 and 2011 at the four selected sites.

Fine resolution river bed geometry were obtained during several low flow events in 2010 and 2011. The banks and water uncovered areas were surveyed using a laser scanner (Topcon^{TM} GLS-1000) with a resolution of 0.03-0.2 m distance between sampling points. The areas covered with water at low flow were surveyed using a RTK-GPS (Topcon^{TM} Legacy E+) and total station (Topcon^{TM} GPT3107N) where GPS reception was not possible. Average sampling point distances were between 0.5 and of 2 m.

For the acquisition of hydraulic data, high and low constant flow events were surveyed obtaining data on discharge, water level elevations and water edges at both banks. Steady river flows were measured for all sites at 0.87 (low flows) and 16.92 $m^3 s^{-1}$ (high flows) in summer 2011.

An Acoustic Doppler Current Profiler (Son Tek River Surveyor M9) was used on a floating platform to measure discharges. A rope was placed across the channel and two pulleys were placed at each end, and the ADCP was pulled across the river to measure discharge.

Water level elevations and water edges positions were surveyed together at both banks at different length intervals along the sites, according to the change of slope and the geometric complexity of the channel using the GPS and total station.

2.3 Cross section extraction

2.3.1 Establishment of cross sections density combinations

In order to have a reproducible way to progressively change the resolution of the geometry effort or cross section density, two cross sections at each of the sites extremities constituted the Base geometry regardless their morphology. The cross section density was progressively increased by halving the distance between cross sections. Successive divisions resulted in 2, 4, 8, 16 and 32 sections, translated in five additional geometry combinations named Add 1, Add 3, Add 7, Add 15, Add 31, which described the number of cross sections added between the two initial cross sections that created the Base geometry (Figure 2).

Distances between cross section were calculated from a presumed mid-river longitudinal line and were kept constant between the successive divisions. Average distances ranged from 123 m in the Base geometry to 4 m in the Add 31 geometry.

2.3.2 DEM creation and cross section extraction

From the high density geometry obtained in the field, a digital elevation model (DEM) was created thought kriging interpolation in ArcGIS 10 for all the sites. A total thirty-three cross sections were drawn as polylines on top of the DEMs and the endpoint coordinates were extracted. Further, cross section coordinates at an interval of 0.5 m where computed, and the corresponding z values were obtained from the DEM at each of the four sites. A comparison of cross sections from direct measurements and cross sections derived from the DEM was made and showed minimal differences (Boissy 2011), assuring a highly reliable geometry representation at all the sites.

2.4 Data Analysis

2.4.1 Creation of observed wet and dry area polygons

As a basis for latter comparison, both wet and dry area polygons were drawn for each of the sites based on observed data using ArcGIS 10. A total of eight polygons representing wet areas (high flows and low flows for each of the four sites) were made. At low flows, isolated wet areas of less than 1 m^2 were excluded from the calculation. Four dry area polygons were then made by subtracting the low flow polygon from the high flow polygon.

2.4.2 One-dimensional hydraulic simulation and creation of simulated wet and dry area polygons

The HEC-RAS v.4.1. computer program was used for the simulation of high and low steady discharges, resulting in a series of simulated water edges. Model calibration was achieved by adjusting the Manning n until simulated and observed water elevations fit. The R^2 correlation coefficient and the Mean Absolute Error (MAE) were computed to measure the accuracy of the model. A total of 12 steady flow simulations were carried out with HEC-RAS for the whole river length, for each of the six density combinations at both low and high flows.

The simulated cross sectional water edges at each of sites were geo-referenced and input into ArcGIS 10 and joined together in polygons using the same procedure as for the observed data. When HEC-RAS computed divided flow at a cross section, the points representing a dry area were connected to both the upstream and the downstream cross section creating a triangular shape. A total of 48 simulated wet area polygons were obtained representing the four sites at both flows and for each of the six geometry densities. Twenty four simulated dry area polygons were finally obtained by subtracting the low flows to the high flows simulated polygons.

2.4.3 Comparison between Observed and Simulated polygons

To enable comparison, all the observed and simulated polygons were first individually rasterized. The rasterization process resulted in a negligible (<0.02%) difference in area from polygon to raster features. The obtained observed and simulated rasters were then overlapped in ArcGIS 10 which resulted in the computation of three different areas (Figure 3): (i) areas only found in the observed data, indicating model underestimation of the flow area; (ii) areas only found in the simulated data, indicating model overestimation of the flow area and (iii) areas found both in the modeled and observed data, hereafter called “matching areas”.

Three types of comparisons as indicators of accuracy were carried out between observed and simulated areas. Those are explained below. Comparisons were carried out separately for high flows, low flows and resulting dry areas, using each of the observed areas and the six simulated geometry densities.

Area estimation

The resulting raster areas (i), (ii) and (iii) were quantified. Model overestimation and underestimation was estimated by comparing the total simulated (only simulated and matching areas) with the total observed (only observed and matching) areas.

Matching area

The percentage of coinciding area between simulated and observed areas was calculated and used to indicate the model ability to represent the shape of the observed areas. It illustrated the spatial overlap between simulated and observed areas.

F criteria

F statistics (eq. 1 after (Tayefi et al. 2007, Horritt, Bates and Mattinson 2006, Cook and Merwade 2009, Bates, Marks and Horritt 2003)) was chosen as an "all factors inclusive" indicator of the ability of the model to simulate the observed areas, including both the matching area, the extent of overestimation and underestimation and the spatial coincidence. The closer the criterion value is to 100 the highest is the fit between simulated and observed areas and a lower F indicates disparity between the two.

$$F = 100x \frac{A_{Obs\&Sim}}{A_{Obs} + A_{Sim} - A_{Obs\&Sim}} \quad (1)$$

where: $A_{Obs\&Sim}$ is the matching area in square meters, A_{Obs} is the total observed area (m^2) and A_{Sim} is the total simulated area (m^2).

2.4.4 Optimal geometry density for the simulation of potential stranding areas

The optimum geometry density (number of cross sections) for accurate simulation of potential stranding areas was explored by using the metrics described above. All geometry combinations and sites were considered and some best-fit to the data rules were established for the prediction of the optimum geometry density.

3 Results

3.1 Steady simulation performance

The 12 HEC-RAS simulations for different geometry combination in Lundesokna were calibrated with good accuracy. The mean absolute error (MAE) for all geometry densities ranged from 0.008 to 0.01for high flows and 0.003 to 0.01 for low flows. The correlation coefficient R^2 for all simulations was >0.99. Mean Manning's n values used for the calibrations were 0.046 and 0.085 (low and high flows respectively) for all geometry densities.

3.2 Comparison between Observed and Simulated areas

3.2.1 Area estimation

Figures 4 and 5 illustrate sites 2 and 4 examples of the outputs obtained after overlapping simulated and observed data for wet and dry areas. As should be expected, the matching areas increase with the detail in geometry.

The percentages of model underestimation or overestimation in relation to the observed area can be observed in Figure 6 for all sites at high and low flows and for dry areas. The total simulated area in relation to the total observed (100%) shows the highest differences (either underestimation or overestimation) at the base geometry. Such differences slowly decrease as the geometry density increases, as expected, but more evident for Site 2 than 4, with a higher sinuosity.

The model underestimates the amount of simulated wet areas in all except two cases. The simulated dry areas were underestimated in half of the cases and presented the highest underestimation percentages at the initial geometry densities.

3.2.2 Matching area and F criteria results

Figure 6 also illustrates the percentage of simulated area that matches with the observed at high and low flows and for the dry areas. For all sites and geometry combinations, as the geometry density increases, the ability of the simulation to match the observed wet and dry area increases.

At high flows, the matching area reached up to 98.4% at the maximum density combination. From Add1 to Add3, the matching area increased on average 7% and between Add7 and Add15 <1%.

For low flows, it reached up to 93.9% at the Add31 geometry. Between Add1 and Add 3, an average increase of 9% was found. From Add7 to Add15, the matching area increased <2%.

The dried areas reached 91% at the highest geometry density. The matching area increased 27% between Add1 and Add3 and <5% from Add7 to Add15.

Figure 7 illustrates the results of the F criteria calculation for each of the sites at high flows, low flows and for the dry areas.

The F values tend to increase as the geometry density increases for all cases, as occurring for the matching areas, but with lower values At high and low flows, F values were <3% and <6% respectively lower to those find for the matching areas.

At high flows, F reached up to 97.8% at the maximum density combination. From Add1 to Add3, F increased on average 9.7% and between Add7 and Add15 <1%.

For low flows, F reached up to 92.7% at the Add31 geometry. Between Add1 and Add 3, an average increase of 15% was found. From Add7 to Add15, the F value increased <2%.

F values for simulated dried areas showed an average decrease of 11.4% in relation to matching areas with a maximum F value of 82.5% at the Add31 geometry density. This indicated the high over and underestimation influence on the dried areas F calculation.

F increased 27% between Add1 and Add3 and <5% from Add7 to Add15, showing a bigger difference between geometry density inputs in comparison to F values for low and high flows.

When comparing between sites, both the matching area and the F criteria illustrate the same result. Site 4, with the lowest sinuosity but highest RCCR, presented the highest percentage of matching area and F values at the Add31 geometry density. At the base geometry, >54% of the simulated dried area matched with the observed and the F value was >47%.

Site 1 presented the lowest percentage of matching areas and F values at the Add31 geometry density. Site 2, with the highest sinuosity, presented the lowest percentage of matching area and F at the base geometry.

3.2.3 Optimal geometry density

Figure 8 shows the matching area and F criteria percentages with the over and underestimation for each of the sites as the geometry density increase. The matching area is the main influence on the F criteria, with a positive linear relationship of 0.978 in R square. However, since the F criteria also takes in account underestimation and overestimation, this was the solely indicator to establish the optimal geometry density. The matching areas and F criteria tendency in all sites follows the same pattern, with a sharp increase on accuracy at the lowest geometry densities and flatten down towards as the density increases. In the light of these results, the following rules were established to find the optimum geometry density for the accurate estimation of potential stranding areas:

(i) It should predict >50% F criteria
(ii) Its increase in F in relation to the previous geometry density should be <15%

According to the above rules, Figure 9 illustrates the optimum geometry density for each of the sites in relation to their RCCR and Sinuosity index. The optimum geometry density was found: at Add15 in Site 2 with the highest sinuosity and the second highest RCCR; at Add7 in Sites 1 and 3 with moderate sinuosity and RCCR; and sinuosity and RCCR; and at Add 3 at Site 4, with the lowest sinuosity but highest RCCR.

4 Discussion

Fish stranding is a critical issue in rivers with peaking operations. The ability to accurately predict potential stranding areas can become a decisive factor to assess environmental impacts and for mitigation planning. We provide specific guidelines on the optimal amount of cross sections (or geometry) to be used in a1D model for the accurate prediction of potential stranding areas in a river wide stranding assessment. We show how the use of a 1D model can provide with the best possible prediction of potential stranding areas by selecting the optimal geometry density (number of cross sections) depending on river physical characteristics. We can summarize the main findings as:

1. The optimal geometry is not necessarily found at the highest density and varies with site-specific physical characteristics. Sinuosity combined with channel complexity influences the geometry density needed. This can be used to determine the optimal measurement strategy to accurately estimate stranding areas.

Add3 was found to be the optimal geometry density for straight channels regardless of their complexity; Add7 for slight sinuous channels with a low RCCR and Add15 for very sinuous channels regardless their RCCR. These results showed that the effort of adding extra cross sections does not bring substantial improvement on the model accuracy.

2. Both over- and underestimation of simulated dry areas were observed when compared to field data. The general tendency, however, was to underestimate with lower geometry density in all river morphologies.

Underestimation at low geometry densities was also observed by (Cook and Merwade 2009), when assessing the effect of geometric configuration on flood inundation mapping with 1D and 2D models. Higher geometry densities induce a better estimation of dry areas, with less likelihood of underestimating the environmental effect. This is a cost-effective decision that needs to be taken in account by managers when deciding on resource use.

3. The F criteria proved to be an “all inclusive” factor to assess the accuracy of the model reflecting the matching area, spatial distribution and the over and underestimation of the simulations. It proved to be a relevant factor to determine the optimal geometry density.

As an example of how to apply the methodology, if we imagine a potentially stranding reach of a 900 m length, with a sinuosity value of 2 and 1.3 in RCCR, we should use the Add15 geometry density, which translates into dividing the 900m in 16 equidistant parts separated ca. 56m. A total of 17 cross sections should be surveyed in such reach to achieve the optimal results for the calculation of stranding.

The performance of the 1D hydraulic model proved to be adequate and was able to simulate both high and low flows separately in an accurate manner based on our comparisons. Low flows proved to be more challenging to model with lower percentage of matching areas and lower F-criteria. When computing potential stranding areas from high and low flows the combination of both simulations inaccuracies, even if they were minimum, brought uncertainties in the data. In this study, potential errors were minimized by using high resolution field data. A high density of points was used at the cross section level and water levels were collected by the same surveyors at each cross section to allow a reliable calibration and verification. However, the difficulty to identify the exact location of the water edge in the field was a challenge difficult to overcome.

The use of 1D model for the estimation of stranding areas proved to be a cost-effective approach to accurately predict potential stranding areas in the case studies considered in this work, all cases with gentle slope and similar reach length. The use of 1D can be limiting in more complex river systems as suggested by (Werner 2001). However, the use of 1D model was the approach chosen in this paper to fit the purpose or cost-effectiveness. 1D modeling prevails over more complex modeling when assessing its users time and computing power (Cook and Merwade 2009).

(Richmond and Perkins 2009) examined the influence of fluctuating discharge on the physical river environment with the use of a 1D model. Their study presents similar methodological approaches with the present work. Both studies are based on steady state simulations. However, the present study considers only the dry areas as potential stranding areas, not taken in account large entrapped areas. In addition, the works presented do not take in account a range of discharges for the calculation of several potential stranding areas, but it focuses on the two extreme discharges on which hydropeaking operations occur most regularly. A systematic approach on the placement of cross sections was chosen to avoid to site-specific outcomes. The focus is not on optimal location of cross sections as shown in (Werner 2001) in his study on the impact of grid size on flood mapping, but on the optimal number and distancing between them. This approach is also shown in (Castellarin et al. 2009). They took as a reference the highest number of cross sections, whilst in this paper observed data is taken as a reference. They focus on flood computations with a coarser detail than that required for the present study. However, as in the present study, they concluded that optimal spacing between cross sections depends on the river bed geometry and that the inclusion of additional cross sections does not necessarily improve the model accuracy.

This study represents an improvement to the method devised by (Forseth et al. 2008). By utilizing the suggested method, we can ensure a more accurate representation of potential stranding areas in future applications and we can devise a strategy for the measurement of sections which can improve the cost-efficiency of the method in Norwegian rivers. The works presented suggest that common procedures from the literature on the use of 1D models such those for flood zone mapping (Castellarin et al. 2009) might not be enough for stranding area computations.

The proposed approach for a simplification of stranding potential assessment can be utilized by water managers to more easily investigate one or several rivers and river sections using fewer resources for physical analysis. Water managers can use this tool to calculate potential fish mortality in an area subject to rapid fluctuations. The proposed methodology can also be used as starting point template to build in more potential physical and biological factors affecting stranding. Further criteria can be applied to this approach. This can be used as a template and as a starting point to build upon. It is possible to add up additional criteria such as a more detailed definition of entrapped and dewatered areas, substrate characteristics, rate of change, behavior, physical habitat conditions, for a more specific calculation of the stranding potential.

The proposed improvement of the method can provide an important tool for future environmental impact assessments of regulated rivers. The potential use of Norwegian hydropower as energy storage will increase the variability in the hydrologic regimes of rivers and thus influence the ecology in the same systems. With an easy-to-implement methodology based on effective measurement with result significance, the tool for reducing the amount of field work necessary for conducting sound stranding potential research will help water managers to a quicker step-by-step analysis of hydropeaked rivers. Using transect density optimization will aid in reallocating resources to other parts of an EIA. The methodology proposed can also be utilized in mitigation analysis. River bed morphology alteration to improve river ecology through installment of flow altering thresholds and other means can more effectively be verified using optimized transect density in pre and post analysis.

5 Conclusions

In this paper we provide specific guidelines on the optimal geometry to be used in a1D model for the accurate prediction of potential stranding areas in a river wide stranding assessment. The optimal geometry is not necessarily found at the highest density and varies with site-specific physical characteristics. The general tendency was to underestimate with lower geometry density in all river morphologies. The F criteria proved to be an “all inclusive” factor to determine the optimal geometry density.

This study represents an improvement to the available methods in the literature on optimal geometry usage, ensuring a more accurate representation of potential stranding areas in future applications. The proposed improvement of the method translates into a useful tool for managers that can provide an important tool for future environmental impact assessments of regulated rivers and mitigation analysis.

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