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Dynamic ice formation processes in two Norwegian rivers – implications for the environment and hydropower

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Dynamic ice formation in the form of frazil and anchor ice is a key component in the ice regime in most Norwegian rivers. In the larger rivers dynamic formation is mostly seen during freeze up in steeper sections while in steep small streams anchor ice formation is the key driver for the formation of a static ice cover. During dynamic ice formation large hydraulic heterogeneity and frequent changes in hydraulic conditions are observed, even with stable discharge conditions. Furthermore, prolonged or even full seasonal dynamic ice formation in regulated rivers can be experienced, which in some cases may increase the total ice volume produced over the winter and lead to challenges towards operating hydropower systems and for aquatic ecology. In this paper we report on studies of dynamic ice formation in two Norwegian rivers. In the regulated river Orkla we conducted studies on detailed dynamic ice formation during a cold period with variable flow conditions, and in addition behavioral responses of juvenile Atlantic salmon using radio telemetry. We observed deep penetrating anchor ice into the interstitial spaces of the bottom substrate. Observations of fish behavior are in contrast with many previous findings on winter behaviour, showing large home ranges and all day movements with strong individual differences. In river Sokna, which is unregulated, smaller and steeper compared to Orkla, we observed large variability in hydraulic conditions during freeze up and the formation of a static ice cover is dependent on anchor ice dam formation, and we observe several anchor ice dams forming along the reach either at shallow areas or in areas where emergent boulders aid the ice formation.

1 Introduction

Dynamic ice formation in the form of frazil and anchor ice is common feature in Norwegian rivers during winter, and a key driver for freeze-up in steep streams. In addition, in many regulated rivers dynamic ice formation is prolonged or even occurs regularly during the entire winter season due to warm water releases from hydro power reservoirs over the entire winter season. This makes knowledge of dynamic processes important both for infrastructure operation, for winter hydrology and for studies of winter ecology. Recently, some studies have focused on small river freeze up (Stickler et al. 2010; Turcotte and Morse 2011), showing the importance of anchor ice and the formation of anchor ice dams on the ice formation. Further, these studies also indicate the importance of ice on the hydrologic regime and the river hydraulics during winter. This is information important for any work on infrastructure, e.g. (Nøvik et al. in review) or studies of small stream ecology e.g. (Linnansaari and Cunjak 2010). In Norway, hydropower structures are an important river infrastructure and dynamic ice formation is important both for the structures themselves and for the operation of the power plants (Gebre et al. 2013). In a typical high head system the increased production of frazil ice may lead to blocking of hydropower intakes, increased ice accumulation in the river and influence the river environment. Another typical effect is the need to constrain the production of energy to mitigate severe ice problem leading to reduced energy output and income to the operator.

Studies on dynamic ice have been performed over the latest years in Norway, particularly in regulated rivers and in rivers with slopes too high for direct surface ice formation. The focus of the studies have been to:

1. Understand the processes of ice formation in rivers with steep slopes.
2. Impacts on ice formation on stream heterogeneity in winter – implications for environment and management.
3. Study the effect of prolonged dynamic ice formation periods in regulated rivers
4. The impact of dynamic ice on winter habitat and behavior of Atlantic salmon.

This paper will summarize findings on dynamic ice formation in rivers Orkla and Sokna in Norwegian rivers, and for the Orkla case relate the results to hydropower production and winter behaviour in Atlantic salmon.

2 Materials and methods

Study sites

The data presented in this paper are collected at two different study sites. The river Orkla in mid Norway (63°17´N, 9°50´E) is regulated for hydropower through several power plants fed from high elevation reservoirs (Figure 1). The release of warmer reservoir water will in most winters keep the river open downstream of the power plant outlets and create long periods with heavy production of frazil and anchor ice during winter. The average regulated winter flow in Orkla is 50 m^3/s. The study site is located at Hårråøya which is approximately 17 km downstream of the outlet of the Grana power plant, and about 3 km upstream of the intake to Svorkmo power plant. The study reach is 300 meters long, and two-thirds of the reach consists of a deep, slow flowing section (pool) which is going into a fast flowing section (riffle) at the downstream end. River Orkla is designated a national salmon river and one of the largest producers of Atlantic salmon annually in Norway (Hvidsten et al. 2004). The second is the river Sokna (62°98´N, 10°23´E) located in the neighbouring catchment to Orkla (Figure 1). Sokna is a small, unregulated stream with an average slope of 1.8 % and a winter discharge of 2 m^3/s. River Sokna freeze-up is in large parts controlled by anchor ice damming and subsequent freeze over of the anchor ice dams. Two study sites are monitored in Sokna, the first at Stavilla (100 m long) and the second at Korporal bridge (300 m long). Both sections are steep (gradients of 1.2% and 1.7% respectively) with fast flowing water (riffles) with emergent boulders. In both Korporal bridge and Stavilla the ice cover formation controlled by anchor ice dams.

Field procedures

The distribution and thickness of anchor ice and anchor ice dams in both cases was mapped in most cases using total stations or RTK-GPS receivers. For Orkla and the Stavilla case, coverage of anchor and border ice was also noted every day of the experiment period in relation to a number of predefined cross sections as a faster alternative to the detailed measurements. In addition, a time-lapse camera was used in Stavilla to record the ice formation. The density of anchor ice and the degree of ice intrusion into the substrate was recorded in river Orkla (Stickler and Alfredsen 2009). To assess impacts on Atlantic salmon, a total of 24 juvenile Atlantic salmon were marked with Lotek radio tags in the Hårråøya reach of Orkla and tracked manually four times a day for a period of 14 days. For further information of the experiment setup, see Stickler et al. (2007).

3 Results

Ice formation in river Sokna

For the study periods, ice formed in both reaches by the development of anchor ice dams, often located where one or more boulders restricted the flow (Figure 2). It was also observed some border ice and spray ice on emergent boulders and along the bank. For the Stavilla site, 8 anchor ice dams with height up to about one meter was observed, while at the Korporal bridge site a total of 18 anchor ice dams developed with a max height of 1.90 meters. For both sites the largest dams appeared in the fastest areas. Ice cover then started to form behind the ice dams, and eventually an ice cover was established in both reaches. During freeze up the river was transformed from a mostly riffle dominated reach into a type of stair-step reach with increasing amount of slow flowing areas. Figure 3 shows the development of the water level with time, and figure 4 shows the flow pattern characterized using a meso-habitat classification system (Borsanyi et al. 2004).

Ice, hydropower and Atlantic salmon in river Orkla

Anchor ice was observed at the reach in Orkla over the entire study period, with an extent that varied from covering only turbulent riffle areas and to covering the entire reach including deeper areas. Release of anchor ice was typically observed in mid morning, and accumulation of released anchor ice at the downstream ice edge could temporarily increase the water level at the downstream end of the study site approximately 0.4 meters. In the turbulent riffles anchor ice penetrated the bottom substrate and became compacted, while in the slow flowing areas ice formed on top of the substrate. Later measurements of anchor ice density revealed a significant difference from the riffle to the slower flowing areas, with more dense anchor ice formed in the riffle areas (Stickler and Alfredsen 2009)

Based on tracking data, movement of the juvenile Atlantic salmon was calculated between each tracking period and recorded together with their position in the river. This was then combined with the ice data to study the effects of ice on behavior and position choice. Home ranges for the fish was computed (minimum spanning polygon of all points) and show a large variability between individuals, ranging from 112 m^2 to 9337 m^2 with a mean of 2127 m^2. Further, frequent movements were observed for each fish (mean 18.1±8.3 SD) and no significant difference were found between day and night. Figure 5 shows the movement between each tracking period for each individual, which is identified by the frequency of the radio tag. The reach provides shelter for the fish both in the form of border ice, large boulders along banks and complete ice cover at a pool just downstream of the study site, and some of the tagged fish would utilize this shelter for longer or shorter periods during the study. It is evident that the group of fish that used the shelter shows less movement than the group fish that is located mostly in open water areas (access to substrate shelter on the river bottom). This indicates that open water physical processes e.g. anchor ice formation influences fish movement, possibly by penetration into the sheltered areas as was seen at several occasions in Orkla. Figure 6 shows an example of movements in relation to shelter access for a single fish.

Large production of frazil and anchor ice influences the hydro power production in Orkla, both directly as frazil may clog the trash rack of the intake to Svorkmo power plant and indirectly since the presence of ice in the river puts constraints on the operation of the power plant during the winter season. The accumulation of ice on the trash rack leads to increased head loss through the intake and reduced production. In the current regime, as the cold season starts production is as even as possible to build a stable ice cover on the intake dam to Svorkmo and thereby prevent super cooled water and frazil from reaching the intake. This works in periods, but there are still situations where ice will build on the intake. In these cases, the power plant must use heavy machinery to clear the ice.

4 Discussion

The river Sokna freeze-up shows that anchor ice dams are crucial in the establishment of an ice cover in the river. In contrast to observations in Orkla and other observations in literature (Arden and Wigle 1972; Kempema and Ettema 2011), Sokna also shows anchor ice formation that last over long periods, most likely due to the high valley sides that shelters short wave radiation. Eventually exposure to air froze parts of the anchor ice into solid ice. Something that is evident from our data from in both sites in Sokna is large variability in in-stream habitat (in our case measured on a meso-habitat scale) for a stable discharge during ice formation. Since most methods for environmental impact assessment is discharge driven, and since impact mitigation also often relies on setting a discharge neglecting effects of ice formation might cause errors in such procedures. It is therefore important to convey these findings to management and integrate them in the assessment methodologies currently in use.

Ice formation in Orkla has changed due to the regulation resulting in longer reaches with open water, less surface ice cover and increased frazil and anchor ice formation. The river can have heavy anchor ice formation events, and studies show ice with high density and a large degree of packing into the substrate. Looking at the juvenile Atlantic salmon, the data from the Orkla study shows no clear pattern of nocturnal behavior in the salmon which is seen in several other studies (Huusko et al. 2007), and combined with the data showing increased movement in fish utilizing substrate shelter in the open areas it is reasonable to assume that the ice formation processes influences the fish behavior. The data from Orkla indicates that the exposure to anchor ice forces movement in the juveniles located in open water, which is in contrast to other findings on juvenile Atlantic salmon where anchor ice formation is encountered in habitat for juvenile fish (Roussel et al. 2004; Stickler et al. 2008). Further, home ranges in the Orkla are larger than those reported in literature for winter conditions. These findings is an indication that the actual formation process of anchor ice with density and substrate penetration will influence behavior and habitat selection in juvenile fish, and that behavior might vary with the type of anchor ice encountered.

With increasing focus on renewable energy in the future and an increased hydro power potential in cold climate areas (Hamududu and Killingtveit 2012), handling ice problems like the ones seen in Orkla may increase in importance. Even if a changing climate decreases winter duration, there will still be periods with ice that will influence production, and whether the total problems will be reduced or maybe more severe due to more variability in winter conditions needs to be assessed further (Beltaos and Prowse 2009; Prowse et al. 2011). But it is reasonable to assume that in a more unstable winter situation knowledge of dynamic ice formation will play an important role in planning and operation of hydropower plants.

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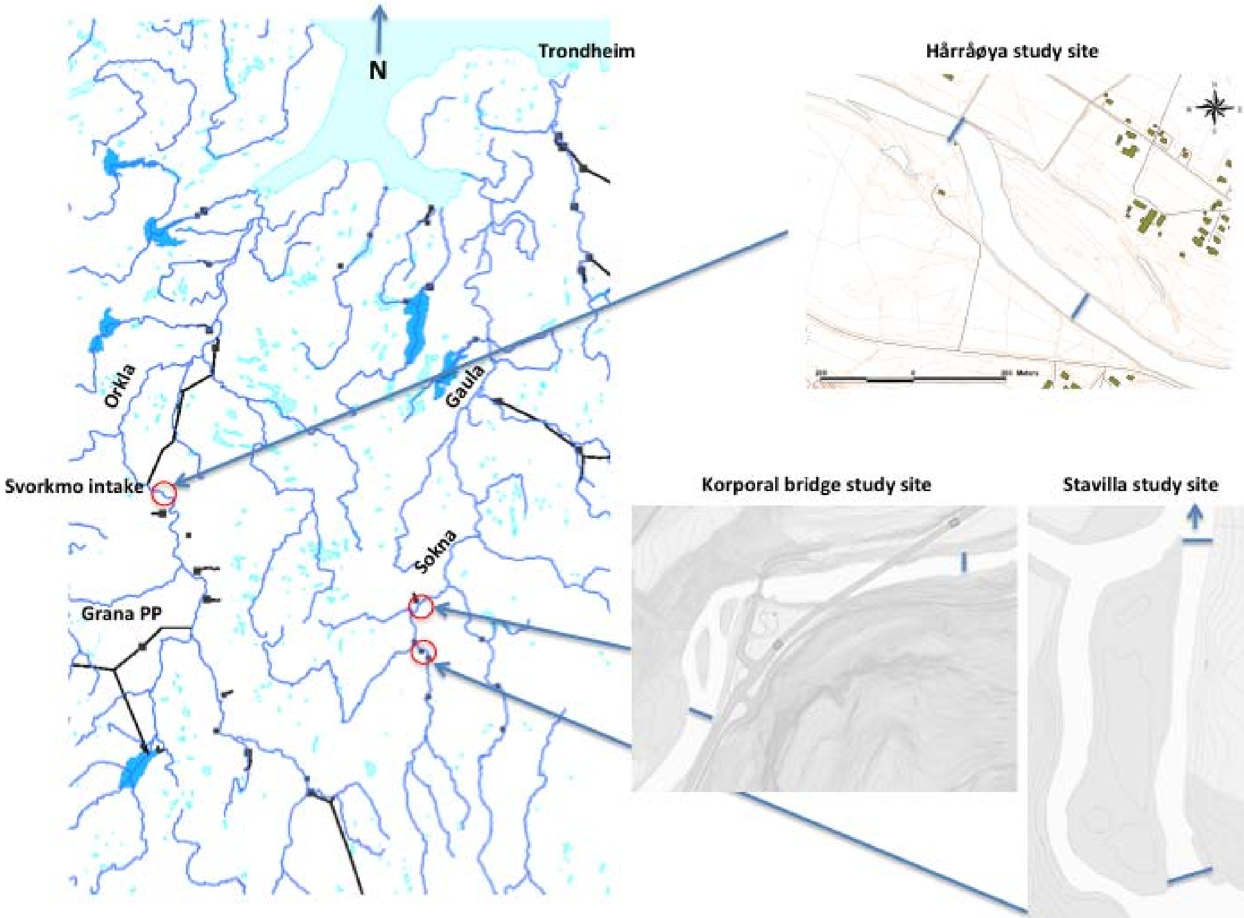

Figure 1 Study sites

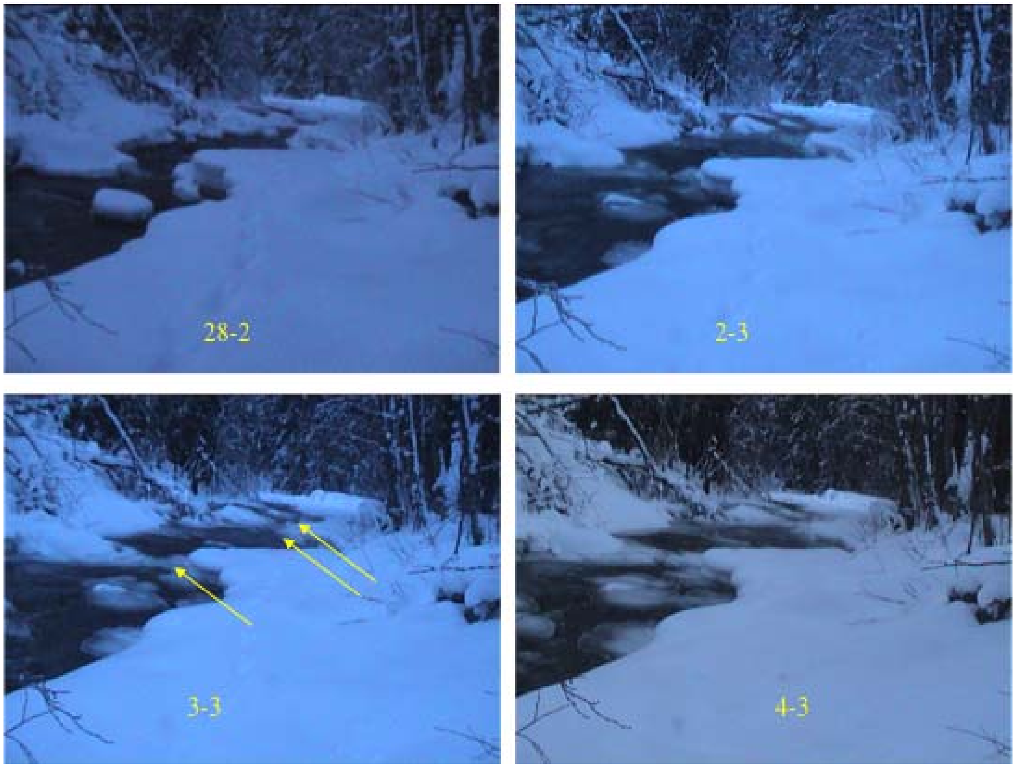

Figure 2 Formation of anchor ice dam in the Stavilla reach of the river Sokna.

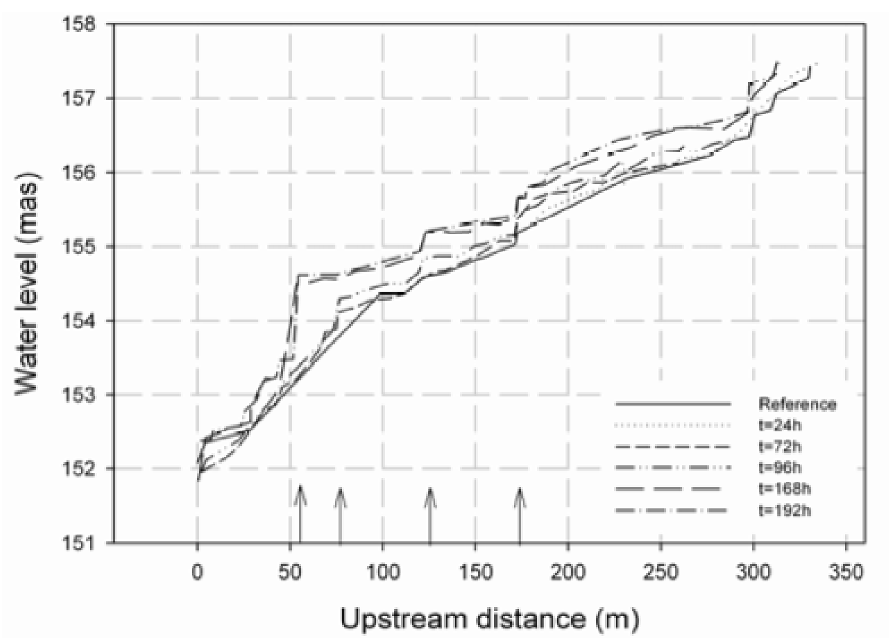

Figure 3 Water levels recorded at Korporal bridge study site as anchor ice dams developed. Arrows on the figure indicate the location of major dams. Adapted from (Stickler 2008)

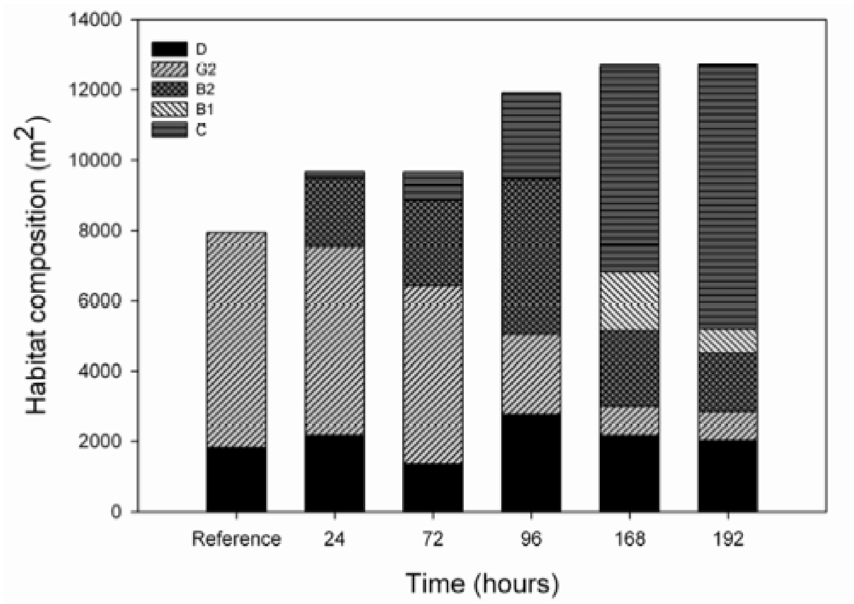

Figure 4 Composition of meso-habitats with time as anchor ice dams develop at the Korporal Bridge study site. Type D/C indicate slow flowing areas, while G2/B2/B1 is faster flowing areas. Adapted from (Stickler 2008)

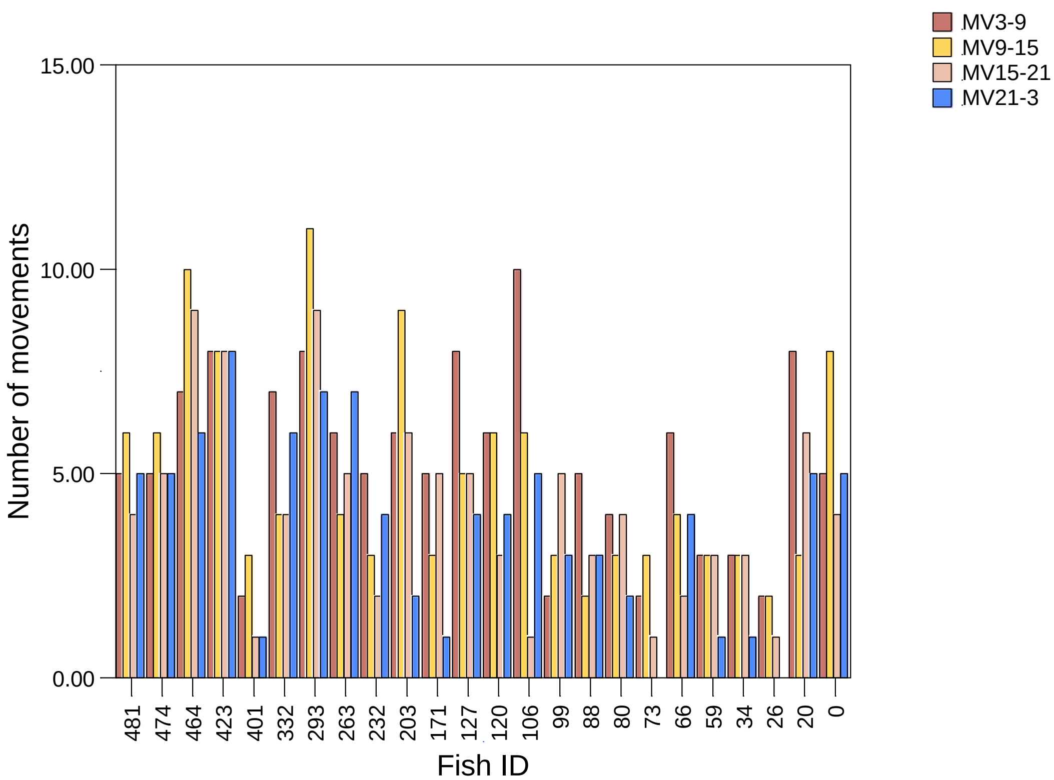

Figure 5 Fish movements between the four tracking periods (03:00, 09:00, 15:00 and 21:00)

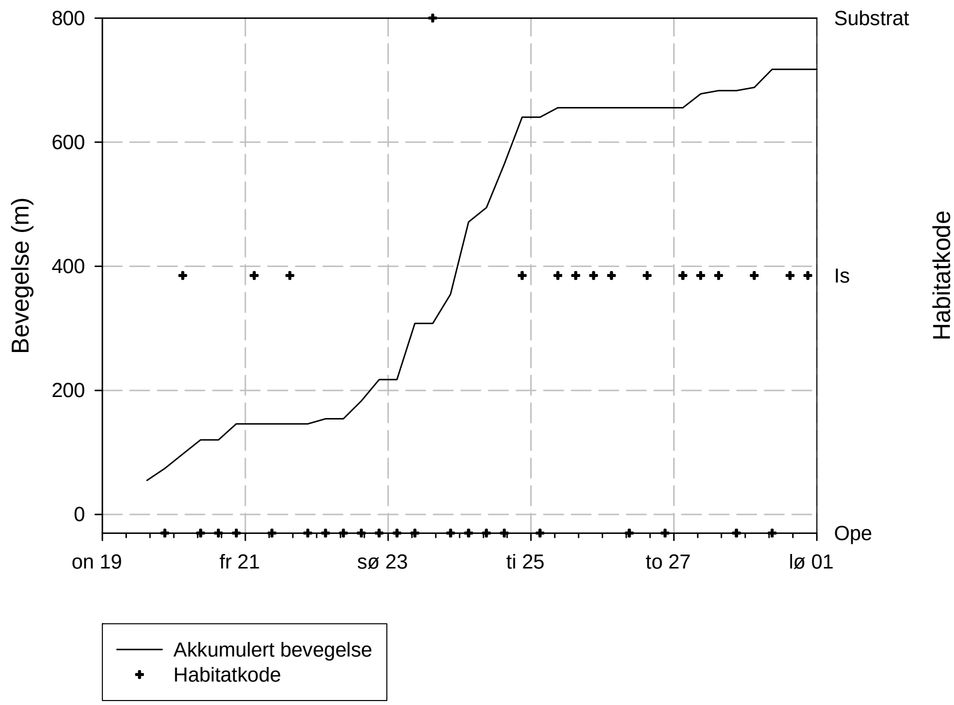

Figure 6 Accumulated movement in a juvenile Atlantic salmon exposed to varying shelter. Crosses indicate if the fish was in the open (typically shelteringing in bottom substrate) or if it was under ice or under bankside large boulders.