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Published in:
Aquatic Conservation : Marine and Freshwater Ecosystems

Link to article, DOI:
10.1002/aqc.2795

Publication date:
2017

Document Version
Peer reviewed version

Shining a light on the loss of rheophilic fish habitat in lowland rivers as a forgotten consequence of barriers and its implications for management

In press in Aquatic Conservation: Marine and Freshwater Ecosystems as a Short Communication

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Running title: Habitat loss as a forgotten consequence of barriers

Abstract

1. The majority of rivers around Europe have been modified in one way or another, and no longer have an original, continuous flow from source to outlet. The presence of weirs and dams has altered habitats, thus affecting the wildlife that lives within them. This is especially true for migrating rheophilic fish species, which in addition to safe passage depend on gradient and fast flowing waters for reproductive success and early development.

2. Thus far, research has focused on investigating the impacts of weirs and dams on fish passage, with less attention paid to the loss of habitat entrained by such infrastructures. The loss of rheophilic habitat is particularly important in lowland streams, where gradient is limited, and dams and weirs can be constructed with less effort.

3. Denmark is considered a typical lowland country, where the landscape around streams and rivers has been modified by agriculture and other human activities for centuries, leaving management practitioners wondering how much change is acceptable to maintain sustainable fish populations and fisheries practices.

4. With examples from Denmark, we attempt to conceptualize the loss in habitat as a result of barriers in lowland streams and rivers, and the repercussions that such alterations may have on rheophilic fish populations. Furthermore, we emphasize the need for management to address habitat loss and its related consequences concurrently with the improvement of fish passage.

Keywords: river, stream, fish, river management, catchment management, indicator species, hydropower, impoundment

Introduction

The presence of barriers (such as weirs, dams and culverts) in rivers has grown immensely in the last centuries. These barriers are most often put in place to serve human needs, such as to generate electricity (Welcomme, 1995), though fish farming, irrigation and flood control are also common (Jungwirth, 1998; Jungwirth, Muhar, & Schmutz, 2000). When barriers were first established, the potential detrimental impacts to the surrounding environment were not considered (Hunt, 1988), but it quickly became apparent that they had severe consequences to river ecosystems and the organisms that live within them (e.g., Aarestrup & Koed, 2003; Alexandre & Almeida, 2010; Dynesius & Nilsson, 1994; Junge, Museth, Hindar, Kraabøl, & Asbjørn Vøllestad, 2014; Koed, Jepsen, Aarestrup, & Nielsen, 2002).

Many countries lack a complete inventory of water barriers and those that do typically register large barriers only (e.g., the United States National Inventory of Dams for dams above 10m). In Denmark, the Ministry of Environment and Food has recently generated an inventory of barriers to implement the EC Waterframe Directive (Council of the European Communities, 2000). Although quite comprehensive, even this inventory is unlikely to account for all Danish barriers given that smaller weirs and especially culverts often remain unregistered. While freshwater management have remedied some of the negative consequences of barriers associated with fish passage (e.g., through fish ladders, fish pass etc.), most of the habitat changes due to damming are still present and thus still threaten stream and river ecosystem sustainability. The need to take action is pressing given that riverine ecosystems are in the poorest condition of all ecosystems across the globe (WWF, 2016). To date, there has been tremendous focus on the impacts of barriers on fish passage (both upstream and downstream movements; e.g., Aarestrup & Koed, 2003), and finding ways to establish minimal flow to sustain fluvial habitat (Rood et al., 2005). While this approach has merit for management, it ignores some basic problems: (1) it does not account for the loss of habitat in the resulting “ponded” zone that results from damming, and (2) it typically ignores the small-scale migrations and movements of less known species (Larinier, 2001). Moreover, current management schemes tend to neglect effects on other aquatic organisms, such as plants and invertebrates, which are also affected by the presence of obstacles (Merritt & Wohl, 2005, Palmer, Arensburger, Botts, Hakenkamp, & Reid, 1995).

Here, we briefly describe the important consequences of barriers for rheophilic fish species (i.e., species that live in fast-moving, oxygen-rich water), with greater focus on (1) quantity of habitat lost due to a loss in gradient, and (2) lowland streams/rivers given that gradient is a limiting factor for rheophilic fish reproduction and development in such watercourses. We attempt to conceptualize the loss in habitat as a result of barriers, and present a “quick and dirty” method that could be applied to management scenarios which aim to restore the river continuum and natural habitats for rheophilic fish species.

Habitat changes as a consequence of barriers

Barriers result in fragmentation and decoupling of hydrological, geomorphological and ecological aspects of a river, thereby modifying habitat and restricting movement between them (Lucas & Baras, 2000; McCluney et al., 2014; Nilsson, Reidy, Dynesius, & Revenga, 2005; Poff et al., 1997; Ward & Stanford, 1983, 1995). Specifically, the upstream section becomes a “ponded zone” and the length of this zone depends on the height of the dam and the watercourse gradient (Petts, 1984; Poff et al., 1997; Stanford et al., 1996; Figure 1). In turn, this completely changes the river habitat upstream of the barrier, such as increasing homogeneity of substrates and vegetation (Nilsson & Jansson, 1995; Poff, Olden, Merritt, & Pepin, 2007), increasing depth, reducing current speed, reducing oxygenation, causing sedimentation and changing water temperatures (Petts, 1984; Poff & Hart, 2002). The downstream habitat also becomes altered, but for the purpose of this paper, we focus primarily on the upstream geomorphological changes induced by barriers.

Lowland streams and rivers: case studies from Denmark

In lowland streams, the areas with relatively high gradients are preferentially selected to construct barriers because of their greater relative potential for energy (Hoffman & Dunham, 2007). Damming effects also vary depending on the size of the watercourse and the location of the dam. Generally, a dam located closer to the source of a river will have fewer repercussions than one located further downstream (Figure 1), because the gradient of the river is typically greater in the upper regions, and therefore a smaller proportion of the watercourse is affected by the damming. Furthermore, upstream parts of a river tend to be narrower than downstream sections, thus the total damming impacts are considerably lower when a barrier is upstream (Figure 1), though may still have important consequences for local species.

In Denmark, a country consisting solely of lowland landscapes, rivers are typically small, and have smaller gradients than those from more mountainous countries. While a river in Norway, for example, can easily provide a drop of 500m, even the larger Danish rivers typically begin below 100m above sea level. Large gradients are therefore a limited resource in Denmark. Nonetheless, much of the wildlife in Danish rivers relies on these scarce habitats (especially rheophilic fish), making them especially important to protect. Within lowland rivers, the areas where the gradient is (relatively) large, there is greater potential for harnessing water power, often leading to the establishment of more than a single dam throughout the river course. For example, River Grejs (Vejle, Denmark) runs for approx. 15km, and has a total drop of 55m from source to outlet, where a total of 11 dams were established by 1986.

An altered flow regime caused by dams affects the wildlife present, typically reducing biodiversity (Bunn & Arthington, 2002; Power, Dietrich, & Finlay, 1996) and population size of migratory species (Hubbs & Pigg, 1976; Zhong & Power, 1996). This is especially true for rheophilic species (Hoffman & Dunham, 2007). Hence, the increase in water level (i.e., increased depth) and current decrease may be used as indicators of the loss in geomorphological variability and thus a river's ability to maintain biodiversity, as well as a rough measure of potential rheophilic habitat loss. This is important because a relatively large proportion of species that inhabit freshwater streams require relatively fast flowing and oxygen-rich water with varied substrate conditions in order to thrive; the most common threat to freshwater species (i.e., fish, amphibians, reptiles, mammals and birds) is habitat loss and degradation from anthropogenic activities (Freyhof & Brooks, 2011).

Given the extent of dam establishment in some lowland rivers, much of what used to constitute adequate habitats for these species is no longer available. For example, habitat quality indicator species in Danish rivers, such as Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*), spawn and grow (during early life stages) in stretches where habitat is typified as riffle areas with gravel or cobble substrate, with low gradients (Gibson, 1993, Gibson, Bowlby, & Amiro, 2008). Dammed rivers reduce the availability of such stretches, and have been shown to reduce overall salmonid populations (Welcomme, 1985).

Recognizing the consequences of barriers on freshwater ecosystems has led to the pursuit of mitigation strategies. For example, some municipal and governmental agencies have put in place new infrastructures to address environmental concerns (e.g., periodic high flows, fish ladders; Auer, 1996). A common approach is the installation of nature-like fish passes. These bypasses can be useful in allowing fish to move upstream and downstream of a barrier (e.g., Calles & Greenberg 2005) but do not remedy the underlying habitat alterations caused by barriers (Dadswell, 1996), and have been found to have limited success (Bunt, Castro-Santos, & Haro, 2012). Recent evidence suggests that dam removal provides an efficient management tool for ecological restoration of freshwater ecosystems (reviewed in Bednarek, 2001), and should be considered where possible. In fact, complete dam removal restores habitat quality, quantity *and* connectivity, thus restoring previously lost habitat (Pess, McHenry, Beechie, & Davies, 2008), enabling rheophilic fish populations to re-establish and also enabling fish to migrate (both on small and large scales), regardless of how much knowledge we have on a species.

Conceptualizing habitat loss: applications for management

In Table 1, we provide data for three Danish rivers that vary in size from 3m to 40m in width and from 20km to 149km in length. We present the total drop from spring to outlet, the summed drop resulting from barriers, the total length of the river, and the summed length of the ponded zone. This data was then used as a rough estimate of vertical and horizontal habitat loss (Table 1). This specific information was chosen given that it is typically easily accessed and could easily be applied to management strategies. We acknowledge that the habitat loss may not be proportional to the loss in gradient (as this approach suggests). In fact, the relationship between habitat loss and gradient is likely more complex, especially if barriers are present further upstream, but this approach has merit to rapidly address some of the management concerns we are currently facing.

This approach shows that a large proportion of the potential rheophillic habitat is lost in the ponded zones (Table 1). River Gudenaa, the longest river in Denmark, was historically one of the most important Danish rivers with large populations of anadromous salmonids. It has seven barriers in the main stem predominantly for hydro power generation, yielding a total relative loss of the potential spawning and juvenile development habitat of 36% (Table 1). This loss increases to approx. 60% if we exclude the upper 10% of the watercourse where the river is narrow, the gradient is significantly larger, and salmon production is historically non-existent. The smaller Rivers Villestrup and Omme, on the other hand, have barriers established for fish farming or old watermill purposes, but nonetheless result in a similar loss in habitat. Furthermore, this estimated habitat loss is likely underestimated at fish farm sites, because the stretch of the river between a weir and the outlet of a fish farm is often several hundreds of meters apart, with very little water flow during a large part for the year. The habitat quality in these stretches is limited as a consequence of the reduced water flow alone, but may also represent an area of high predation (Jepsen, Aarestrup, Økland, & Rasmussen, 1998; Poe, Hansel, Vigg, Palmer, & Prendergast, 1991; Ruggerone, 1986).

The three rivers discussed in the above paragraph run mainly through agricultural land. However, rivers running through urban areas may be subjected to even more severe habitat loss (Birnie-Gauvin, Peiman, Gallagher, de Bruijn, & Cooke 2016). River Mølleaa is approx. 13km long, and flows through Northern Copenhagen into the Øresund strait. The river has nine dams, which together remove an estimated 75% of the river gradient. There is virtually no natural gradient left, and thus no adequate habitat for rheophilic species.

Conclusions

The productive potential of rheophillic species in lowland freshwater rivers is greatly reduced by the presence of dams and weirs. Typical management interventions aim to address issues concerning fish passage, but often omit to consider the habitat that has already been lost as a result of barriers for which we lack empirical data (Abell, 2002). Given the relatively limited gradient available in Danish rivers (and in lowland rivers across the world in general) and the potential habitat loss associated with the latter, the overall effects of water barriers on habitat should be included in assessments of watercourses. These actions should be undertaken concurrently with the improvement of fish passage and other typical management-related challenges. To improve the state of regulated lowland rivers may mean that many of these river obstacles need to be removed in order to reinstate the former gradient and habitat, which may re-establish proper fauna passage in itself.

The purpose of this paper was to shine a light on a problem that is often ignored in traditional fish management to this day: rheophilic habitat loss resulting from barriers. Too often, the focus of management is on fish passage alone, ignoring other important effects of damming. This may be particularly true for lowland rivers. Given the number of dams and weirs in rivers across the world, we acknowledge that acquiring complete knowledge on habitat loss and fish passage is a daunting task. However, if the majority of rheophilic-appropriate habitat is lost, improving fish passage may be pointless. We therefore suggest the use of a “quick and dirty” method (Table 1) to evaluate the potential loss in habitat as a result of barriers. This approach may provide managers with an improved overview of the state of rivers, and allow for better management strategies to be implemented. Further studies should be undertaken to evaluate the validity of the approach.

Acknowledgements

This research was funded by the Danish rod and net fish license funds and the European Union (AMBER project).

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Table 1. Conceptualizing rheophilic habitat loss. Using three Denmark rivers, the ratio of the total drop as a result of barriers (m) to the total drop of the river from source to outlet (m) was used as a proxy for vertical habitat loss (%).The ratio of the summed ponded zones (km) to the total river length (km) was used as a proxy for horizontal habitat loss (%). This "quick and dirty" approach to estimate habitat loss from barriers provides managers with a low cost and effective method to get a rapid overview of the current state of freshwater streams and rivers, and may enable the implementation of more effective management strategies.

River (# of dams)	Total drop from source to outlet (m)	Summed drop from barriers (m)	Vertical habitat loss (%)	Total river length (km)	Summed ponded zones (km)	Horizontal habitat loss (%)
Villestrup (6)	22	8.8	40	20.0	5.8	29
Omme (14)	75	17.7	24	55.0	11.35	21
Gudenaa (7)	69	24.9	36	149.0	-*	-*

* Information not available given that the weirs and dams are too old to accurately estimate the length of ponded zones.

Figure 1. Effects of dams on rivers. Conceptualized diagram of the effects of dams on rivers showing two (A and B) identical weirs (i.e., same stemmed height). Depending on the gradient of the river, the ponded zone differs. As the gradient typically decreases, and the river size increases, from source to outlet, a similar sized weir closer to the outlet will have a larger ponded zone, both in terms of length and surface area. Downward-pointing arrows (↓) represent a decrease.