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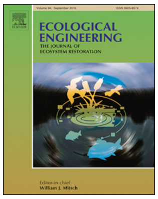

Silver eel downstream migration in the River Rhine, route choice, and its impacts on escapement: A 6-year telemetry study in a highly anthropized system

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ABSTRACT

Several routes are available for the downstream migration of silver eels in the river Rhine system. Very different effects on migration success can result from this choice, such as speed and migration duration or escapement rate. We studied the downstream migration of silver eels in a river section with two different routes. The first route is the initial and old riverbed, with two dams equipped with two rather small or medium sized hydropower plants (HPPs) located at the beginning and at the exit of the bypass stretch. Both HPPs have small bar spacing (10 mm and 20 mm, respectively) and the second HPP has two downstream bypasses. The second route is a power canal, supplying four major HPPs (maximum discharge capacity = 1400 $m^3 s^{-1}$) and a nuclear power plant with cooling water. Firstly, this study focused on highlighting the factors influencing route choice. Secondly, we focused on the consequences of this choice. We demonstrate that water current management in the old riverbed at the study site had a 40% higher negative effect on eel survival than that by a consecutive passage in four turbines.

1. Introduction

The European eel is a catadromous species widely distributed in Europe and northern Africa with an outstanding life cycle consisting of a single breeding in the Sargasso Sea, a first transatlantic migration as larvae, called leptocephali, which use oceanic currents that lead them from the spawning area to the continental shelf, and a growth stage in coastal and inland habitats where they remain and grow for 5–25 years (Tesch, 2003). Then, the silver eels swim downstream and undertake their breeding migration back to the Sargasso Sea, some 5000 km away from their growth habitats (Righton et al., 2016).

Because of the complexity of their life cycle, European eels are exposed to a number of threats, all caused by human activity (oceanographic regime shifts, river management, habitat destruction and related connectivity disruption, organic and metallic contaminants, fisheries, etc.) (Feunteun, 2002; Miller et al., 2016). Consequently, the recruitment of European eels is currently estimated below 10% of the maximum level recorded in the late seventies (ICES, 2018), and the species is now far outside its safe biological limits, and thereby considered by the IUCN as an endangered species (Jacoby and Gollock, 2014). In order to protect the European eel (Dekker and Casselman, 2014), the European Union has demanded that measures be taken to allow at least 40% escapement of reference silver eel biomass, relative to unexploited, unpolluted circumstances in unobstructed rivers (European Commission, 2007). A full understanding of the eel downstream migration biology and behavior are, thus, an absolute requirement to complete these objectives, and numerous studies have been conducted.

At the end of the growth stage, a complex hormonal activity enhances the silvering metamorphosis (Dufour, 2003; van den Thillart et al., 2009). The silver eels are then ready as potential migrants, but external cues are needed to trigger the downstream migration. In

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unobstructed European rivers, the main downstream migration peaks occur in November with great regional and interannual variations (David Righton et al., 2016). Numerous environmental parameters are known to trigger downstream migration of silver eels: rainfall, river flow, temperature, lunar phase, wind, atmospheric pressure, turbidity, and conductivity (see reviews in Haro, 2003; Bruijs and Durif, 2009; Trancart et al., 2013).

The impacts of hydroelectric complexes are well known: they can cause injuries (Bruijs and Durif, 2009), direct mortality (Winter et al., 2006; Bruijs and Durif, 2009), delay (Behrmann-Godel and Eckmann, 2003), or stop downstream migration (Durif et al., 2003). Navigation canals or bypassed stretches of rivers may also be used as routes during silver eel downstream migration (Klein Breteler et al., 2007; Verhelst et al., 2018). Heavily managed rivers are often transformed into complex networks of river sections regulated by dams that provide a wide range of routes for silver eels on their downstream migration to the sea. The consequences of route choice on migration success of silver eels has been poorly documented.

In the complex aquatic network of the lower Rhine, Klein Breteler et al. (2007) showed that numerous different routes were used by silver eels but with great temporal differences. In the same study site, Breukelaar et al. (2009) concluded that the route choice cannot simply be explained by the river water discharge. In a highly regulated river (river Stour, Southeast England), the gate position and the upstream water level had significant effects on the migration routes selected by eels (Piper et al., 2013).

The Rhine is one of the most important rivers in Northern Europe (1240 km long, 198,000 km^2 catchment area, 1053 m^3 s^{-1} mean water flow at Rheinalle). For a long time, this high discharge has been used for hydropower and cooling water purposes: 28 hydropower plants (HPPs) (including 10 large plants in France) and 5 nuclear plants have been built along the river between 1898 and 2012. On the Rhine, the historical riverbed has been diverted to create navigation canals. Numerous pathways have become available for eel migration, and this route choice can have very important consequences. For example, in the case of the upstream part of the upper Rhine, where the river is diverted to the Grand Canal d'Alsace (GCA) in Kembs, a passage by GCA will induce turbine mortalities (8–27% depending on HPP (De Oliveira, 2012a)). On the other hand, a passage by the almost turbine-protected bypassed stretch, called the Vieux Rhin (two rather small or medium HPPs, both equipped with fish-friendly racks [10 and 20 mm] and with downstream bypasses for the second one), may probably induce higher survival probabilities rates.

A large and long telemetry experiment was conducted to study the migration behavior and success of silver eels on their downstream migration of one the largest hydropower complex of the Rhine River located in France. Silver eels could either choose the hydropower canal (the Grand Canal d'Alsace, hereafter called GCA) and the bypassed riverbed (Vieux Rhin, hereafter called VR). Our aim was to assess the consequences of route choice on the downstream migration of silver eels. In order to accomplish this, we specifically addressed the following objectives: 1) investigate the factors triggering the downstream silver eel migration; 2) to analyze the proportion of eels in each of the pathways (GCA and VR) and the factors controlling route choice; and 3) to investigate the migration characteristics (duration and speed) and the escapement rates in the two possible routes.

2. Material and methods

2.1. Study site

This study was conducted on the large and complex river Rhine system (1320 km long, 185000 km^2, across 6 countries, Fig. 1). This river is extensively used for freight transport and hydro-electrical production (10 large power plants (> 100 MW) in France). The fish were released downstream Bâle (47.613°N, 7.578°E, Swiss, PK 170), 3–4 km upstream Kembs. Seven kilometers further downstream (Kembs, Kilometer Point 163), the Rhine river divides into 2 sections: the "Grand Canal d'Alsace" (GCA) and the "Vieux Rhin" (VR) (Fig. 1).

A dam is located at the beginning of VR in order to control the flow in the GCA (Kembs dam), which has a maximum discharge capacity of 1400 m^3 s^{-1} and is 50 km long, from Kembs to Vogelgrun (Kilometer Point 120). There are four HPPs along the GCA: Kembs, Ottmarsheim, Fessenheim, and Vogelgrun, all managed by Electricité De France (EDF).

The second pathway for downstream migration is the VR section. This section is 50 km long and is the historical natural Rhine riverbed. The minimum flow in this stretch of the river changed during the course of this study due to relicensing of the Kembs hydroelectric complex. Before 2011, the minimum flow was set at 20 or 30 m^3 s^{-1}, depending on the period of the year: 20 between December and February; 30 the rest of the year. Since 2011, the minimum flow in the bypass stretch has been raised to 52 m^3 s^{-1} in the winter period (November-March) and a maximum of 115 m^3 s^{-1} in the summer period (June-August), with intermediate discharge thresholds in the periods in between. The first major dam of VR (Kembs' dam) located upstream is equipped with a small HPP ($Q_{max} = 27$ m^3 s^{-1}) which used to deliver nearly all of the minimum flow in the bypass stretch (the complement being supplied by a fishway). The screen of this HPP has a small bar spacing (10 mm) which physically blocks the eels at this part of the river basin (Courret and Larinier, 2008). Since the raise of the minimum flow in 2011, this HPP continues to drive the turbine, although at a lower ratio of the minimum flow (from 23% to 52%). A second dam, built for agricultural purposes, is located at the end of the VR (Brisach dam). This dam is also equipped with an HPP ($Q_{max} = 60$ m^3 s^{-1}) whose screen has a small bar spacing (20 mm) to prevent fish from entering turbines and which is also equipped with two fishways for upstream and downstream migration. The four gates (45 m wide each) of the Brisach dam (190 m wide) begin to open only when the HPP is at full capacity (60 m^3 s^{-1}). The VR river stretch remains relatively "pristine" compared to the GCA, despite the regulation of the water flow and the alteration of sediment transport. However, as mentioned above, minimum flow has been raised since 2011 and a major renaturation program has been conducted (sediments reinjections, habitats creations) (Garnier and Barillier, 2015). The canal and the river then reconnect just downstream of Vogelgrun (48.036°N, 7.568°E).

2.2. Tracking technology

The tracking technology used in the present study was Radio Frequency Identification (RFID), with the NEDAP Trail System (www.nedaptrail.com). This telemetry system consists of active transponders (including a battery), each with a unique code, implanted in the fish and a network of detection and recording stations. A detection station is composed of antenna cables stretched across the entire width of the river bed and the recording station. Preliminary tests showed a 10–20 m mean detection range in some NEDAP sites used in this study (Tétard, 2013). High non-detection rates are possible with this technology, as for instance 43% of fish were never detected in Breukelaar et al. (2009).

2.3. Location of the NEDAP sites

The tagged fish were recorded in the passage at several detection points distributed along the study site. The first NEDAP loop (called hereafter NEDAP 1) was located upstream from the diversion between the VR and the GCA (47.616°N, 7.573°E, Fig. 2). The second NEDAP loop (NEDAP 2, 47.627°N, 7.569°E) controlled the entry in the VR (located at about one hundred meters downstream of the Kembs dam). The entry in the GCA was controlled by two NEDAP loops (3 and 4, 47.652°N, 7.525°E) located downstream of the Kembs hydropower plant. The output of these two sections was controlled in the unified Rhine River, near Marckolsheim (NEDAP 5, 48.065°N, 7.573°E) (Fig. 2),

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