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Research article

Drawdown flushing of a hydroelectric reservoir on the Rhône River: Impacts on the fish community and implications for the sediment management

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ABSTRACT

Sediment flushings of hydropower reservoirs are commonly performed to maintain water resource uses and ecosystem services, but may have strong impacts on fish communities. Despite the worldwide scope of this issue, very few studies report quantitative *in situ* evaluations of these impacts. In June 2012, the drawdown flushing of the Verbois reservoir (Rhône River) was performed and subsequent impacts on the fish community were assessed, both inside the reservoir (fish densities by hydroacoustic surveys) and downstream (short-term movement and survival of radio tracked adult fish). Results showed that after the flushing fish acoustic density decreased by 57% in the reservoir, and no recolonization process was observed over the following 16 months. Downstream of the dam, the global apparent survival of fish to the flushing was estimated at 74%, but differed between species. The nine-year delay from the previous flushing and thus the amount of sediments to remove were too stressful for the low-resilience fish community of the Rhône River. Alternative flushing schedules are discussed to reduce these impacts.

1. Introduction

River fragmentation and regulation by damming are among the most severe human impacts on freshwater ecosystems worldwide (Dynesius and Nilsson, 1994). About 47% of world's large rivers (>1000 $m^3.s^{-1}$) are impacted by a cumulative upstream reservoir capacity which exceeds 2% of their annual flow (Lehner et al., 2011). Within these reservoirs, sediment trapping is one of the major issues managers have to face, with strong socio-economic and environmental outcomes (Owens et al., 2005). They have to maintain sedimentation at an acceptable level, and a common technical measure consists in releasing deposited sediment downstream (Kondolf et al., 2014).

Current hydropower development and the increasing number of dams raise severe questions about subsequent ecological impacts, especially concerning sediment flushing from reservoirs (Zarfl et al., 2015). Drawdown flushing involves eroding the deposited sediments and ensuring their transportation by flow through low-level gates of the dam (Kondolf et al., 2014). This requires the complete emptying of the reservoir to allow the resuspension of fine sediments and moving bedloads by increased flow erosivity, and finally a flow augmentation to flush away the sediment load. Suspended sediment concentrations (SSC) below dams can widely vary (Buermann et al., 1995; Brandt, 1999). When performed on a regular basis and synchronized with high flows, such an operation can be minimally harmful to the ecological functioning, with low mortalities and an ability to develop resilience in the downstream populations (Gutzmer et al., 2002; Owens et al., 2005). Conversely, when performed during base flow, the sediment load is generally excessive and causes substantial ecological impacts (Kondolf, 1995).

Many publications address the impacts of SSC on aquatic ecosystems, including fish (review by Kemp et al., 2011). Impacts on fish are various and may be direct, such as behavioural responses, metabolic changes, physiological and histological damages, or indirect through habitat modification. Impacts largely depend on the species and life stage through specific biological and ecological functional traits (Schwartz et al., 2011), but many other factors can interplay such as water temperature, the origin, composition and physical structure of sediment particles, presence of shelter, or the duration and intensity of the disturbance (Kemp et al., 2011).

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Because of these many sources of variation, predicting or empirically evaluating *in situ* biological responses to SSC is challenging. Newcombe and MacDonald (1991) combined the duration of exposure and concentration of the suspended sediment load to define a stress index, used as a proxy for the severity of the disturbance, while impacts on fish were categorized as behavioral, sub-lethal, or lethal. Accounting for taxonomy, fish size, life history and sediment particle size, Newcombe and Jensen (1996) showed that the 'severity of ill' effects (SEV) on fish depended on the concentration and duration of the disturbance. Salmonids are acknowledged to be more sensitive to SSC than other species such as cyprinids, and young fish are more sensitive than adults (Newcombe and Jensen, 1996; Crosa et al., 2010). Overall, most results come from laboratory experiments, and may not be realistic in nature. Also, investigations mainly focus on salmonid species due to their conservation or fisheries interest, while knowledge is much scarcer for other families. Despite the concern that management authorities, fishermen and environmentalists express about sediment flushings, their effects on fish communities in the field have as yet been poorly documented, especially inside reservoirs.

The aim of this paper is to evaluate the short and medium-term (*i.e.* up to 16 months) impacts on the fish community of a drawdown flushing of a hydropower reservoir, both upstream and downstream of the dam. Using an original combination of radio tracking and hydroacoustic approaches, we assessed the spatial-temporal changes in overall density of the fish community in the reservoir, and the behaviour and survival of the main common species of this river reach. We compared observed impacts to predicted ones using the SEV model (Newcombe and Jensen, 1996), and calculated expected impacts for past sediment flushings on the same reservoir. Results are discussed in the light of operational sediment management issues for hydropower reservoirs.

2. Methods

2.1. Study area

The study area was located on the Rhône River, 98,500 km^2 basin area, 812 km long, flow 1720 m^3.s^{-1} at its delta (Olivier et al., 2009), and focused on a 24 km long section from the outlet of Lake Geneva to the France-Switzerland border (Fig. 1). Three run-of-the-river hydropower dams have been erected along this section. The Seujet dam, which is at the outlet of Lake Geneva, regulates the lake level and the flow in the downstream Rhône River (annual mean flow = 251 m^3.s^{-1}). Approximately 15 km downstream, the Verbois dam is a 34 m high dam devoted to hydropower production. Its reservoir is 11.4 km in length, 13 Mm^3 storage capacity, and it has a mean width (±s.d.) of 116.2 m (±35.8 m) and a mean depth of 11.4 (±3.0 m) (Olivier et al., 2009). The Chancy-Pougny dam is located 7 km downstream of Verbois. It is 10.7 m high and its reservoir is 3.7 km long. At the time of the study, only the Seujet and Verbois dams were equipped with fish bypasses. Excluding reservoirs, lotic reaches are between 3 and 6 m in depth, depending on river bed morphology and flow regulation, and up to 114 m wide. The flow regime in this section of the Rhône River combines the water released from Lake Geneva through the Seujet dam and the water coming from the Arve River (mean flow = 79 m^3.s^{-1}; Fig. 1). This important tributary, characterized by a very high suspended sediment load, drains the Mont Blanc alpine massif and annually carries about 500,000 tons of flysch and molasse particles into the Rhône River (Bravard and Clémens, 2008), most of which are deposited in the Verbois reservoir. Two smaller tributaries (Allondon and Laire) flow into the Rhône River along the study area (Fig. 1). In these two rivers, pools were dug in gravel deposits at their mouths (65-m length and 1.5-m depth) prior to the flushing to provide fish refuge areas. The fish community in the study area is composed of 18 species, among which chub (*Squalius cephalus*), barbel (*Barbus barbus*), roach (*Rutilus rutilus*), European perch (*Perca fluviatilis*), and brown trout (*Salmo trutta)* are the most abundant (GREN, 2009). Little information is available about the composition and structure of the fish community in the reservoir, but limnophilic species such as tench (*Tinca tinca*), bream (*Abramis brama*), carp (*Cyprinus carpio*) or northern pike (*Esox lucius*) are present.

2.2. Verbois reservoir management and drawdown flushing operation

The Verbois reservoir was managed by means of triennial drawdown flushings from 1969 to 2003. Because of significant environmental impacts (e.g. water quality, fish behaviour and mortality, bird nesting perturbation: Roux, 1984; Hofmann et al., 2001; ECOTEC, 2003; GREN, 2003) and growing societal discontent, the next flushing was postponed to look for alternative, less harmful options, and was finally scheduled from 9 to 22 June 2012, with an estimated volume of 5.6 Mm^3 of trapped sediment (SIG and SFMCP, 2013a).

The flushing consisted of a three-step process. First, the reservoir was completely emptied from 9 to 12 June 2012, during which sediments were mainly swept away (Fig. 2). Second, from 11 to 15 June 2012, successive flow flushes were created by releasing water from the Seujet dam to remove more cohesive sediment benches. Third, the reservoir was refilled on 21 and 22 June 2012. Note that the water level remained low between 15 and 21 June (Fig. 2) because of heavy maintenance work. An estimated volume of 2.69 Mm^3 of deposited sediment was evacuated during this flushing (from bathymetric data, SIG and SFMCP, 2013a), the release lasting from 10 June at 03:50 to 21 June 2016 at 18:00. At the same time, a coordinated flushing operation was carried out at Chancy-Pougny dam. Reservoir water level was lowered from 9 to 10 June 2012, and maintained empty until 15 June 2012 to take advantage of flow flushes for eroding sediment in the Chancy-Pougny reservoir. Then, the Chancy-Pougny reservoir refilling was planned on 15 June 2012 as the expected sediment release beyond was negligible (SIG and SFMCP, 2013a).

2.3. Hydroacoustic data collection

Hydroacoustic surveys were performed on the Verbois reservoir using a zigzag sampling design on 33 consecutive transects, from one bank to the other, cruising at a speed of approximately 8 km.h^{-1} (Guillard and Vergès, 2007). The trajectory was determined before the study to obtain representative data according to Aglen (1983). The degree of coverage, defined as the ratio of the total length (km) of all transects over the square root of the reservoir area (km^2), equalled 8. A Simrad EK60 echosounder (SIMRAD, Oslo, Norway), 70 kHz, using a 256 ms pulse length (Godlewska et al., 2011) and pinging at 5 pings per second, was used to acquire data. The circular split-beam transducer, 11.16° × 11.46° at −3 dB, was fixed on the right side of a small aluminum boat, 0.30 m below the water surface and emitted vertically (Samedy et al., 2013). The transducer was linked to a computer with the Simrad ER60 software, connected to a GPS to record boat positions.

Two pre-flushing and nine post-flushing nocturnal hydroacoustic surveys were performed from May 2012 to October 2013 to determine the fish density evolution in the reservoir (Fig. 3). Acoustic data were analysed using Sonar 5-Pro software (v. 6.0.1; Balk and Lindem, 2011). Detection thresholds were set at −50 dB for individual targets, or 'Single Echo Detection' (*SED*), and at −56 dB for echo-integration in accordance with recommendations of standards (CEN, 2009; Parker-Stetter et al., 2009). These