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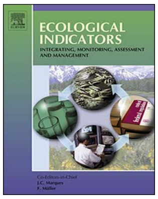

Original Articles

# Periphyton and ecosystem metabolism as indicators of river ecosystem response to environmental flow restoration in a flow-reduced river

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## ABSTRACT

Tracking river ecosystem responses to river flow restoration is a necessary and important step for adaptive management of environmental flow. In this study, we used a unique experimental scheme to investigate the responses of water quality, periphyton, and river metabolism to a new environmental flow in a flow-reduced river in Japan. After implementing the new environmental flow, water quality improved. Periphyton biomass increased substantially in terms of both chlorophyll a and ash-free dry mass. However, the new flow also promoted the growth of filamentous species that could deteriorate the river environment. River metabolism was determined by continual measurement of the diel oxygen concentration. Gross primary production and ecosystem respiration both increased after the increase in environmental flow. These results indicate that the periphyton and metabolism can potentially be used as indicators for monitoring river ecosystem response to increased minimum environmental flow.

## 1. Introduction

Intensive use of water resources such as hydropower plants and large irrigation fields, which alter flow regimes, has had a pervasive and damaging effect on many river ecosystems and species (Poff and Allan, 1995; Stanford et al., 1996; Poff et al., 1997; Bunn and Arthington, 2002; Nilsson et al., 2005), particularly ecosystems in flow-reduced rivers (Dewson et al., 2007). Much effort has therefore been devoted to restoration of altered river flow regimes by implementing environmental flow (Arthington, 2012). The environmental flow has been widely accepted as a very important issue in sustainable river management (Pahl-Wostl et al., 2013). However, few monitoring studies have considered the response of the river ecosystem to new environmental flows; as a result, there is a need to improve our knowledge of the links between flow regime restoration and biological aquatic responses. (Souchon et al., 2008; McCoy et al., 2017). There is a growing awareness that tracking river ecosystem responses to environmental flow with appropriate indicators is essential; it is an important aspect of the ecological limits of hydrologic alteration (ELOHA; Poff et al., 2010), is critical for assessing the effect of flow restoration, and guides further environmental flow restoration decisions (Reich et al., 2010; Konrad et al., 2012; Davies et al., 2014).

Many aspects of river ecosystems have been examined in response to river flow restoration or alteration. For example, Dewson et al. (2007a, 2007b) reviewed macroinvertebrate response to decreased flow in streams and found that invertebrate abundance increases or decreases in response to reduced flow. Certain invertebrate taxa are especially sensitive to flow decreases and might be useful indicators of reduced flow or flow restoration. Mérigoux et al. (2015) tested predictions of changes in benthic invertebrate abundance and community structure after flow restoration in a large river. Kakouei et al. (2017) performed a large-scale analysis of the distribution of stream invertebrates at stream monitoring sites to determine their responses to various hydrologic conditions. Daufresne et al. (2015) investigated fish community guilds and size structure response to flow restoration in several artificial channels, finding that flow restoration benefits species that prefer deep and fast-flowing microhabitats. Phelan et al. (2017) investigated fish and invertebrate responses to flow alteration in the North Carolina (USA). They indicated that all relationships were linear and therefore did not provide clear thresholds to support ecological flow

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determinations and prescriptions to prevent the degradation of fish and invertebrate communities in North Carolina rivers and streams. Lee et al. (2016) used vegetation, invertebrate, and fish communities to assess how past regulation and current experimental releases were affecting ecological conditions on floodplains. Although these studies provide valuable information on the response of river ecosystems to flow restoration, they mainly focused on biotic communities and structural attributes such as fish, macroinvertebrates and periphyta, supplying little information on stream ecosystem functioning processes such as metabolism (Dewson et al., 2007; Young et al., 2008; Masese et al., 2014).

Recently, some have argued that structure and function, and ideally both, should be considered when assessing ecological integrity (Bunn and Davies, 2000; Young et al., 2008; Aristi et al., 2014). Some structural and functional indicators have been developed and applied to test river ecosystem responses to flow restoration. For instance, periphyton and stream metabolism were used to study the response to experimental flood regimes, and the results showed that such regimes increased ecosystem dynamics (Uehlinger et al., 2003). Macroinvertebrates, periphyton, water chemistry, and seston were used to investigate multiple experimental floods (Robinson et al., 2004), showing that these floods, an important component of environmental flow, potentially change communities to a more natural composition. Colangelo (2007) estimated gross primary productivity (GPP), community respiration (CR), the ratio GPP/CR (P/R), and net daily metabolism before and after restoration of continuous flow, plus the response of these functional indicators. This indicated that the flow restoration had a positive effect. Feio et al. (2010) assessed river ecosystem healthy conditions based on a set of structure and function indicators, including leaf-litter decomposition, sediment respiration, biofilm biomass, growth, chlorophyll a concentration, and the autotrophic index. The authors stated that the combined use of functional and structural variables can give a more holistic measure of stream health. River metabolism was used to examine the effect of flow regime regulated by large dams on Mediterranean rivers, showing that both GPP and ER increased during dampened floods, increasing the duration of inter-flood periods (Aristi et al., 2014). Obviously, increasing attention has been paid to tracking river ecosystem response to flow restoration or related practices, and periphyton and river metabolism have been increasingly used as indicators to detect the effect of that restoration. The reason is that periphyton is the primary producer in river ecosystems and is sensitive to human-induced stresses and disturbances (Burns and Ryder, 2001). Moreover, it can serve as both structural and functional indicators. River metabolism can provide relatively comprehensive and broad information on ecosystem conditions, and has been increasingly used to evaluate river conditions (Bunn et al., 1999; Fellows et al., 2006; Feio et al., 2010). However, much less is known regarding periphyton and river metabolism in terms of environmental flow restoration.

In the present study, a unique experimental environmental flow was implemented to restore a damaged river ecosystem. We investigated water quality, periphyton, and river metabolism (which served as structural and functional indicators) response to the restoration of environmental flow. The main objectives were to determine whether periphyton and metabolism could be useful indicators to detect minimum environmental flow restoration using a similar Before-After-Control-Impact (BACI) design in monitoring.

## 2. Methods

### 2.1. Study area

This study was conducted in the Ohyama River, a first-order tributary of the Chikugo River, Kyushu, Japan (Fig. 1). The river hosts three dams for multipurpose use (flood control and hydropower generation). Shimooke Dam and Matsubara Dam are large dams with heights of 98 and 83 m, and total water storage capacities of 59,300,000 and 54,600,000 $m^3$, respectively. Ohyamakawa Dam is a diversional dam, at which water is transferred to generate hydropower through two large pipes (Fig. 1). After completion of the three dams, the environmental flow downstream was set according to the method used in Japan (0.1–0.3 $m^3/s$ per 100 $km^2$; Nakamura, 2008). The year-round environmental flows were set to 0.5$m^3/s$ and 1.5$m^3/s$ below the Matsubara Dam and Ohyamakawa Dam, respectively. However, these flows significantly deviate from the natural flow regime and have severely damaged the downstream riverine ecosystem. In 2002, a program was initiated to rehabilitate the degraded environment. The first phase was to increase the minimum flow. Following negotiations with several interested groups (e.g., local government, electrical power company, local residents), a restoration flow regime scheme was planned (Fig. 2).

### 2.2. Experimental design

Three sites (Fig. 1), respectively representing natural, pre-restoration, and post-restoration conditions, were selected for survey. Site 1 (natural flow) was located above the upper dam and served as the reference site. Site 2 (pre-restoration condition) was located between Mastubara Dam and Ohyamakawa Dam and was used to represent pre-restoration conditions because it experiences the same flow regime as Site 3 prior to flow restoration. Site 3 (post-restoration condition) was located below the Ohyamagawa Dam. These sites have comparable physical conditions (Table 1). Sampling and measurements were carried out at the three sites at approximately bi-weekly intervals from March 2006 to November 2006. Continual measurement of dissolved oxygen concentration was carried out from May to June 2006 (i.e., the typical period for primary production).

### 2.3. Sample collection

Flow data were provided by gauging stations located near the sampling sites. For nutrient analysis of total nitrite (TN) and total phosphorus (TP), unfiltered water was collected in a plastic bottle during each site visit and 40 ml of water was immediately filtered through 0.45 μm cellulose acetate filters for the analysis of dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP). Other water quality variables (i.e., turbidity, pH, conductivity, and temperature) were measured by using a YSI 6000 (YSI, Yellow Springs, Ohio, U.S.A). Water velocity and water depth were measured using an electromagnetic current sensor (AEM213-D).

Periphyton was collected from three to five representative rocks (diameters ~15–25 cm) during each site visit. Periphyton was removed from a designated area on the top surface of the rock using a brush and was then rinsed into plastic specimen containers with drilled water. All samples were transported on ice and in the dark and were within the laboratory in not more than 4 h. In the laboratory, samples were stored at −25 °C and were processed within 3 weeks of sampling. For analysis, each sample was equally divided into three subsamples for determination of Chlorophyll a, ash-free dry mass (AFDM), and species identification. After being filtered (using Whatman GF/C filters), Chlorophyll-a was determined by extraction using 90% acetone, steeping in the dark at 4 °C for 24 h, and then spectrophotometric measurement according to APHA (1995). AFDM was determined by filtering the subsample through pre-ashed Whatman GF/C filters, drying for 24 h at 105 °C, weighing, ashing for 4 h at 550 °C, and reweighing (Biggs, 1989). Chlorophyll a concentration and AFDM were converted to biomass per unit area ($mg/cm^2$ for AFDM, and $\mu g/cm^2$ for Chlorophyll a), where the sampled area was determined from pictures taken in the field. The relative importance of autotrophs versus heterotrophs and detritus of the periphyton was calculated as the autotrophic index APHA (1995). Subsamples for species identification were preserved with 5% formalin and were sent to a technical laboratory for analysis.