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Estimation of periphyton dynamics in a temperate catchment using a distributed nutrient-runoff model

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ABSTRACT

This study develops a model to estimate the spatiotemporal distribution of stream algae on a basin scale by integrating an existing periphyton model into a distributed hydrothermal model to calculate the daily periphyton biomass throughout the Natori River basin. The influence of inorganic phosphorus on periphyton growth is incorporated into the periphyton model. The inorganic phosphorus concentration is simulated using the distributed pollute model depending on land use data to determine the phosphorus load. The model had a root mean square error (RMSE) = 14.1 mg/m^2 for periphyton biomass in the entire basin. This model shows that periphyton biomass tends to increase in the summer season with high water temperature and to decrease in the spring season with high discharge. This model can be applied to understand large spatial and temporal areas of the environment in a temperate catchment.

1. Introduction

Stocking and overfishing are known causes of biodiversity loss in freshwater ecosystems through extinction of the regional population or hybridization (Naylor et al., 2000). To reduce the negative impacts, it is necessary to understand the potential biomass in the river and to determine an appropriate level of stocking. Additionally, because river organisms determine their habitat distribution depending on local environmental factors, to estimate the biomass or biological density in a river, it is necessary to quantify the relationship between river organisms and environmental factors. For this purpose, the two following studies are given as examples. First, Huet (1954) showed an association between the flow rate and fish fauna. Second, Arai et al. (2015) demonstrated the variation of benthic invertebrates in headwaters associated with water temperature variation. It is especially significant to estimate the biomass of periphyton, which are a primary producer in stream ecosystems, to estimate the macroinvertebrates and fishes located at the upper trophic levels of the ecosystem pyramid (Mark et al., 1998).

There have been many attempts to estimate the temporal periphyton and phytoplankton biomass based on physicochemical processes (e.g., photosynthesis, assimilation, detachment) in a given stream reach. For example, Biggs and Close (1989) also showed the model of periphyton biomass dynamics with velocity and nutrient in time series and concluded the importance of the flow history. Chapra et al. (2014) used a simple model expressing the impact of nutrient for periphyton biomass well. To evaluate the features of periphyton growth at survey points in the midstream of the Yahagi River in Japan, Toda et al. (2007) developed a model to estimate the periphyton biomass in consideration of the carrying capacity at those points. Matsunashi et al. (2012) developed a similar model using the nutrient concentrations, suspended substance (SS) and dissolved organic carbon (DOC) and applied this model to urban rivers and mountain stream rivers.

Most previous studies have only focused on exploration at a smaller scale, such as the reach scale, since the availability of factors conventionally used to estimate periphyton dynamics (e.g., discharge and nutrients) is limited in space and time within a river network, resulting in limited predictions of periphyton as well. Observed values of various influencing factors were used in most of the previous studies to simulate periphyton biomass in streams (Horner et al., 1983; Saravia et al., 1998). In few studies, lumped or empirical models were used to simulate nutrient concentrations to predict dynamics of periphyton (Toda et al., 2007; Matsunashi et al., 2012; Chapra et al., 2014). However, the distribution of the factors that influence periphyton biomass in streams such as, stream discharge, water temperature, nutrient concentrations, and others in space and time depend on spatial and temporal variation of rainfall, temperature and various physical properties of catchment. Therefore, a better simulation for prediction of periphyton dynamics in stream can be done coupling a nutrient simulation model with a distributed hydrological model.

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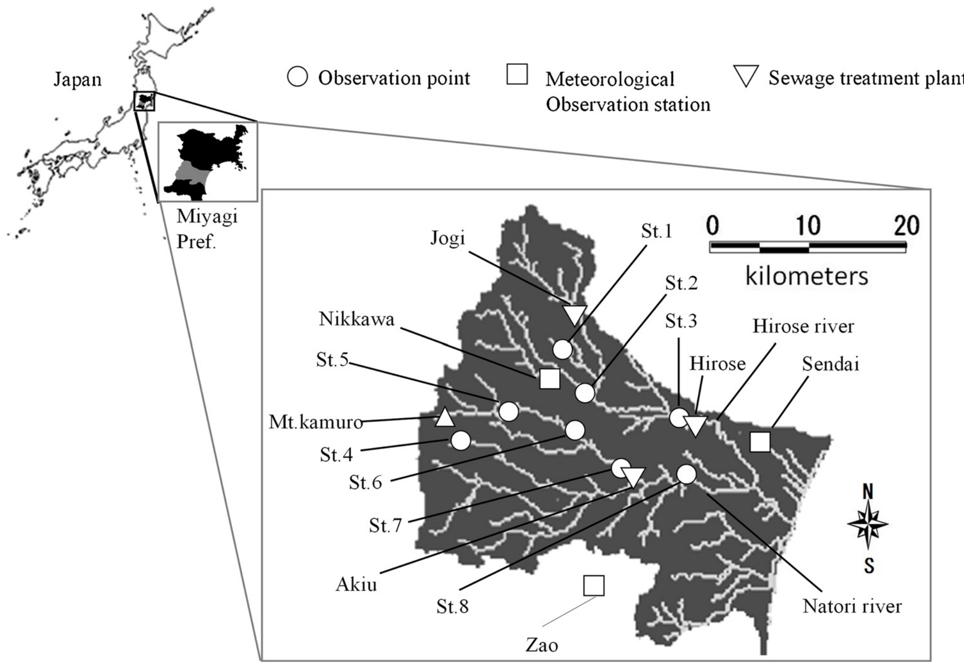

Fig. 1. Natori River basin in northeast Japan: There are 8 observation stations for ecological and water quality data in Natori River and Hirose River and 3 meteorological stations; Sendai is the capital city in this district.

Here, we developed a spatiotemporal distribution model of stream periphyton throughout the Natori River catchment in northeastern Japan using an existing dynamic periphyton model (Uehlinger et al., 1996) and distributed hydrological model (Kazama et al., 2007) coupled with a nutrient simulation in order to facilitates the sptiotemporal simulation of periphyton biomasses in stream due to spatiotemporal changes in climate and physical properties of catchments. Water velocity, water temperature and nutrient concentrations are among the most important factors influencing the periphyton biomass in streams (McIntire, 1973; McIntire and Colby, 1978; Horner et al., 1983). We estimated the daily periphyton biomass using the inputs of discharge or the volumetric flow rate of water through a given cross-sectional area, water temperature and nutrient concentration computed using the hydrological model. The model was calibrated by estimating parameters using the observed data of stream periphyton. Estimated periphyton biomasses were then compared with the observed data from different stream reaches and seasons within the catchment. We finally applied these parameters to the entire river meshes on the catchment and estimated the spatiotemporal periphyton biomass on the catchment scale.

2. Study area and observation

We studied the Natori River catchment (Fig. 1) located in Miyagi Prefecture, northeastern Japan (38°10′20″N, 140°30′58″E). The catchment area is 939 km^2, and the length of the Natori River is 55.0 km. The water source of the river is Mt. Kamuro, which is located along the border of Miyagi Prefecture and Yamagata Prefecture. The Natori River merges with the various sizes of tributaries whose water source is the Ou Mountains and flows through Sendai City to the east, eventually reaching the Pacific Ocean. In the upstream region, a large quantity of snow accumulates in the winter as the mountainous area exceeds 1000 m altitude. Midstream region is an urban area of Sendai City, and the downstream region is low altitude plains, with prevailing paddy field. The nutrients generated from residential and agricultural activities in the middle and lower reaches of the river have significant impact on periphyton biomass in the stream. This nutrient term is the advantage point in a basin with different land uses such as Natori River Basin. Modeling periphyton variability is important for ecological management of the basin.

We observed periphyton on 8 stream reaches in the same catchment from July 2014 to July 2016, excluding the winter season. We set a quadrat (5 × 5 cm) on the flat part of the cobbles to quantitatively collect the periphyton within the quadrat with a nylon brush. After collection, we placed the periphyton into a bottle filled with tap water without chlorine. We poured neutral formalin into the bottle to maintain the periphyton longer. The formalin concentration in the bottle was approximately 5%. We also collected river water to analyze the nutrient concentration. In our laboratory, we analyzed the total nitrogen (TN) and total phosphorous (TP) using a QuAAtro-2HR (BLTEC corporation). This is one of the most popular equipment for water quality analysis and is used widely in Japanese agencies. The periphyton biomass was estimated by analyzing chlorophyll a using the acetone extraction method with a spectrophotometer (UV-1800, Shimadzu corporation). The acetone extraction method is a fundamental method. Fluorescence spectrophotometer is often used to know the periphyton biomass roughly but the main purpose is to separate Diatoms, Green algae and Blue-green algae. To evaluate the amount, the acetone extraction is common. We calculated the chlorophyll a biomass using the formula developed by Jeffrey and Humphrey (1975).

The inorganic nitrogen and phosphorus concentrations were observed at 8 survey points in the Natori River basin from July 2014 to July 2016. Fig. 2 shows the observation results. The periphyton in the river take in inorganic nitrogen and phosphorus at a rate of 17:1 (Hillebrand and Sommer, 1999). Phosphorus was the limiting factor of periphyton growth at 67 observation times, which was more than half of the total 110 observations in Fig. 2. Therefore, phosphorus can be considered the limiting factor in the Natori River basin, and we estimated the periphyton biomass using the inorganic phosphorus concentration. However, nitrogen was the limiting factor of periphyton growth at Station (St).1, St.4, St.6 and St.8 in Fig. 2. The cause for the nitrogen limiting at St.1 and St.4 (which are located in the mountains) depends on the geological