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Research paper

Development and application of hydrological and geomorphic diversity measures for mountain streams with check and slit-check dams

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Abstract

Habitat diversity is frequently used as an indicator of ecosystem health, but it is still difficult to find a parameter that can indicate river health. In this study, we suggest methods for calculating both hydrological and channel-geomorphic-unit diversity as factors that represent the health of a habitat. Both factors were computed based on a modified Shannon diversity index. The suggested methods for calculating the diversities were applied to ten reaches of two mountain streams with slit-check and check dams, because the influence of slit-check and check dams on fluvial systems can cause them to become either simpler or more dynamic. The usefulness and ecological significance of the methods were verified through correlation analysis using the species diversity of macroinvertebrates.

Upstream reaches with check dams can appear to be reservoirs because of their slow velocity. Hydrological diversity, as the sum of the velocity and substrate diversities, is low for upstream reaches; the method also calculates the velocity and substrate diversities. Both the velocity and the substrate diversity showed significant correlation with species diversity, at 0.713 and 0.619, respectively. Channel geomorphic unit diversity (H'_{CGUD}) was highest at 1.80 for the upstream reach with a slit-check dam, while the diversity of the check dam was 1.05. The diversity index is improved by geomorphic unit change after dam slit construction, which reveals that the index is sensitive to changes. These parameters, namely, velocity, substrate and channel geomorphic unit diversity, are useful non-biological indicators for easily assessing river ecosystems. Channel-geomorphic-unit diversity is a particularly sensitive indicator for calculating and distinguishing various types of streams, and therefore, it can be useful for monitoring temporal changes at the reach scale.

Keywords: Slit-check dam; River restoration; Hydrological diversity; Channel-geomorphic-unit diversity; Species diversity

1. Introduction

Natural rivers and streams are temporally heterogeneous systems, but the quantity of homogeneous aquatic systems is often increased through habitat loss. Dam construction has been reported as one reason for habitat loss in rivers. An open-type check dam is one means of restoring river function, as it can partially remove obstacles to water and sediment transport. Open-type check dams are preferred in some countries where both river ecosystem recovery and control of sudden debris flow in mountain streams are required. The river's response after dam slit construction, which is an example of an open-type check dam strategy, includes degradation upstream of the dam. In addition, the continuity of the river system is also recovered by reducing the differences in the physical environment, such as velocity, particle size and bottom slope, between the reaches upstream and downstream of the slit-check dam (Kang, 2012). While a check dam creates a homogeneous habitat through sediment deposition, a slit-check dam recovers heterogeneous habitat through sediment transport. Therefore, a change in habitat diversity can be used as an index to assess river restoration because river habitat responds to changes in the environment.

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Various methods for measuring diversity have been used in the past. Initially, recognition of differences in river characteristics was used to analyze basic river diversity. A classification of physical habitats was suggested (Rosgen, 1985; Miller and Ritter, 1996). The river habitat survey methodology and the habitat mapping survey were also developed to evaluate river form based on field observations (Fox et al., 1996; Maddock and Bird, 1996). The concept of classified habitats became an important factor in river diversity research. Habitat classification using quantitative and statistical analysis has been made possible by advances in computer modeling. As a method for measuring hydrological diversity, the Instream Flow Incremental Methodology (IFIM) and the Physical Habitat Simulation System (PHABSIM) is a popular computer-based model of physical habitats in streams. The method is based on field measurements of channel shape, water depth, velocity and substrate (Maddock, 1999), but these measurements must be taken over a range of discharges because the method relies on measuring a flow variable that is dependent on discharge (Bartley and Rutherfurd, 2005). FRAGSTATS is a landscape structure analysis program that can calculate various landscape metrics including area, patch density and size, edge, shape and diversity (McGarigal and Marks, 1995). As one function of that program, landscape diversity can be computed using the Shannon diversity index, which is a well-known method for measuring species diversity in an ecosystem and can also be employed to measure the geomorphic and hydrologic diversity of a stream or river. However, one problem with the program is that it concentrates only on the patch pattern and the area of the patches. For this program, patch pattern and area are important parameters for measuring habitat diversity. However, other ecological functions should be considered in evaluating geomorphic unit diversity. For example, a mountain stream may have continuous habitat structures, such as riffle-pool or step-pool sequences. In addition, the meandering edge of a stream provides small spaces for spawning and sheltering aquatic life, in contrast to a straight-line channel. Therefore, not only patch pattern and area but also river sequence and the shape of each patch are important for measuring habitat diversity.

The purpose of this paper is to assess river restoration using the diversity of physical and geomorphic factors. Initially, a suitable indicator must be devised for measuring physical and channel-geomorphic-unit diversity; we develop and propose a method for calculating such an indicator. The method was applied to mountain streams with and without slit-check dams. As mentioned above, a homogeneous river with a check dam will be dynamically changed following slit-check dam construction. The difference in diversity of physical and geomorphic factors between check dams and slit-check dams offers a suitable case for assessing the proposed method. The usefulness of the proposed method is verified by looking at the species diversity of macroinvertebrates for the two mountain streams, which is a commonly used quantitative indicator of the health of river ecosystems. Additionally, this method's algorithm can contribute to river restoration and other projects that aim for ecological diversity.

2. Theory and analysis of hydrological and channel geomorphic unit diversity

The Shannon diversity index (H′) is defined using the probability density function p_i (N_i/N) (Equation (1)).

$$\mathrm{H}' = -\sum p_i \ln(p_i) \tag{1}$$

The term p_i represents the proportion of individuals of the i-th species (N_i) to the total number of individuals (N) and is usually used to quantify species diversity in an ecosystem (Pielou, 1967; Allan, 1975). In the same manner that the Shannon diversity index has been used to quantify species, it can also be used to quantify the diversity of habitats along a stream.

2.1. Hydrological diversity: velocity, substrate, cross-section and longitudinal section

First, the significant parameters for hydrological diversity must be selected. Velocity, substrate and channel shape are basic hydrological parameters that have been considered and monitored in many studies of river restoration after dam removal (Born et al., 1998; Pawloski and Cook, 1993; Burroughs et al., 2001). We selected the following four parameters to represent the hydrological condition of a river in our analysis: velocity, substrate, cross-section and longitudinal section. Among these parameters, we determined that the Shannon diversity index can be applied to velocity and substrate because substantial velocity and substrate data can be obtained at various sample points, even at the reach scale. However, cross- and longitudinal section data are limited to several transects or to one section. The cross- and longitudinal sections can be calculated using the 'sum of squared height difference' method, which is a summation of the squared differences between consecutive points along a topographic profile (Bartley and Rutherfurd, 2005). This method can be used to calculate the roughness of the river bottom and had already been applied in our previous research (Kang and Kazama, 2010). The original function is $\Sigma \mathrm{dh}^2$ (Equations (2) and (3)), where 'dh' is the difference in height from one point to the next on the cross- and longitudinal sections. In the case of the cross-section, this value is divided by 'n', the width of the wetted perimeter, because the stream width of each cross-section is different (Equation (2)).

$$\text{Cross}-\text{section diversity} = \frac{\Sigma dh^2}{n} \tag{2}$$

$$\text{Longitudinal section diversity} = \sum dh^2 \tag{3}$$

Then, defining P_i, that is, defining N_i (part i) and N (whole), and selecting the optimal resolution are important for calculating velocity and substrate diversity using the Shannon diversity index. The velocity and substrate are represented by numerical values. These continuous numerical values must be divided into categories of uniform resolution. For example, if velocities are measured at ten points at the reach scale using an