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Stream modification patterns in a river basin: Field survey and self-organizing map (SOM) application

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ABSTRACT

In this study, stream modifications were surveyed in order to discover the relationships between geographical characteristics, human population distribution, and artificial stream alteration in the Nakdong River system, South Korea. Prior to this study, there was no comprehensive survey of stream modifications of the Nakdong River basin, even though the utilization of its water resources and ecosystem is recognized as an important issue. A total of 1655 stream sites were investigated by applying the Stream Modification Index (SMI), consisting of 12 parameters, comprising three characteristic factors of channels, land use, and levees (each characteristic factor contained four parameters). Those parameters were dichotomous (i.e. marked as 0 or 1), and a higher score of summing 12 parameters values (the SMI score) indicates a more modified state (maximum 12, minimum 0). This data was averaged in accordance with 265 unit catchments in the Nakdong River basin, and compared with population density, seven land coverage categories, elevation, and slope of each of unit catchments to discover general patterns of stream modification in the river basin by the application of a self-organizing map (SOM). A general tendency of increase in survey scores was observed in which unit catchments in urbanized area as well as high population density was found, and significant Spearman rank correlation coefficients were obtained for those relationship. However, though the statistical analysis exhibited significance, the relationship between survey results and socio-geographical information was unclear. SOM application clustered the 265 unit catchments into four groups on the map size of 9×6 plane (quantization error 0.329; topographic error, 0.000), such as catchments where streams were largely modified due to urbanization (cluster 4), relatively well preserved due to high elevation (cluster 2), moderately modified due to agricultural land coverage along with the main channel of the Nakdong River (cluster 1), and the remaining catchments with relatively moderately modified streams (cluster 3). The modification degree represented by the index scores was relatively high in which catchments in a highly urbanized area with large human population density exist, while scarce modification of stream occurred in relatively elevated and forested area. The results of this study suggest not only information and evidences of the general tendency of artificial stream utilization, but also the efficiency of SOM application to a basin-level characterization.

1. Introduction

Lotic ecosystems are recognized as important water resources and habitats. With the start of human agricultural activity, the riparian area of lotic ecosystems has been frequently utilized (Flannery, 1972; Weiss et al., 1993), with continuous development found inside and outside of the lotic systems. Even though seasonal flooding fertilizes the river basin (Moss, 1998), it can cause huge amounts of damage to human civilization, leading to frequent physical modification of streams and rivers. The alteration of streams and rivers has been accelerated with the development of industrial and socioeconomic technology (Wakeford and Walters, 1994). The demand for water resources (mainly for agricultural production) exceeded supply during the last few decades, and the need to protect a highly populated area (e.g. cities or villages) from great seasonal floods encouraged the modification of lotic systems (Moss, 1998).

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The physical modification of streams and rivers often causes serious degradation of habitats and loss of natural functions of the systems, causing diverse environmental problems (Moss, 1998). The structural alterations of streams and rivers by artificial factors are acute and the derivatives from these changes are quite different from those of natural processes (e.g. meandering by erosion). For example, Kissimmee River in Florida experienced serious eutrophication problems after channelization between 1960s and 1970s, and currently the river is undergoing restoration by creating new meanders that return the river back to a more natural state (Dahm et al., 1995; Koebel, 1995).

Stream restoration needs to consider numerous factors, and it is a fundamental point to understand ecological status on a target of the restoration among them we should take into account. Generally, the artificial alteration of stream structures involves the water channel (impoundment construction, dredging, and riparian modification), levee (artificial levee construction) and adjacent land coverage patterns (e.g. urbanization or agricultural area) (Jeong et al., 2008). The listed factors impede longitudinal continuity in streams and lateral interaction between streams and adjacent land habitat (Schlosser, 1991; Vannote et al., 1980). Therefore, comprehensive survey for those three factors will help understand the current characteristics of streams and rivers.

Typically, a large river basin consists of numerous tributaries, which tend to have diverse structural patterns. Therefore, a comprehensive survey for a river basin to abstract general patterns may need high cost (either time or expense). When a fast survey tool for the investigation of stream modification degree is available, the application results in a whole river basin will provide relevant information to the following restoration projects, which will apply in-depth quantitative methodology to the specific sites. The other problem, which needs to occur right after the completion of survey works, is the analysis of collected data. Because most environmental data is non-linearly associated, an efficient patterning method has to be adapted to the collected information. Catchment patterning is on the same line (e.g., Wagener et al., 2007), therefore, multivariate statistical analysis (e.g. principal component analysis) is popularly used. Alternative to those statistical methods, self-organizing map (SOM), a branch algorithm of artificial neural network, is increasingly applied to ecological sciences, especially for understanding non-linearly organized patterns (Jabiol et al., 2009; Lee et al., 2010; Rustum et al., 2008; Zhang et al., 2008). Despite the large number of application examples from an ecological point of view, SOM utility in river basin patterning is rare.

The Nakdong River basin lies in the monsoon climate region and is the second largest river system in South Korea. Especially from the 1960s to 1970s, the government's land use strategy was directed to increasing agricultural productivity, which resulted in the extensive loss of the natural characteristics of the river (Nakdong River Environment Research Center, 2008). These circumstances are completely exposed in the unique climate characteristics of Korea, i.e. seasonally heterogeneous distribution of rainfall (ca 60% of annual rainfall in summer, June to early September), and the protection of human-developed areas from flooding caused strengthening of levees (Joo et al., 1997). Expansion of the agricultural area and increase in population density in the middle to lower parts of the river basin caused the loss of riverine wetlands, and dredging in the water channel for flood prevention (by assuring water depth), often degrading in-stream habitat diversity (Nakdong River Environment Research Center, 2008). Consequently, high water demand for approximately 10 million residents cannot help weighing the pressure to modify the shape of the Nakdong River main channel and its tributaries.

Most of the stream structural characterizations or evaluation of stream modifications focus on one or several streams at once, but cases of investigating alteration degree at the large basin level is rare. If stream modification information is available at this level, this will provide useful information for the development of stream environmental management strategies. Therefore, in this study, over 1600 stream sites were explored in the Nakdong River in order to provide information about the current status of stream modification. The surveyed results from the stream sites were analyzed based on their catchment level, and socio-geographical information (e.g., population density, land coverage) was compared with the survey results. A SOM model was created to discover patterns of stream modification in relation with socio-geographical aspects, and further utility of this information was discussed.

2. Study sites and field data collection/processing

2.1. The Nakdong River basin and study site preparation

The Nakdong River flows ca 520 km and the basin area is ca 23,800 km^2, comprising one fourth of South Korea (Fig. 1). Several multi-purpose dams upstream, an estuarine barrage, and numerous small reservoirs and weirs were installed in the stream channels. Large quantities (ca 40 million m^3 per year) of water from the lower Nakdong River is pumped or conveyed to the cities or streams outside the Nakdong basin, therefore these adjacent basins are considered components of the Nakdong River basin (Water Management Information System, 2009). Water resource management is an important and complicated factor in the development of the river management strategy of the Nakdong River basin. Summer concentrated rainfall due to the monsoon climate from June to July and several typhoon events in the summer causes serious flooding. In addition, the riverbed slope has a shallow angle so hydrological stream management was the primary consideration.

In this study, a total of 1655 sites were established in the streams of the Nakdong River basin. Due to geographical morphology (i.e. mountains in eastern and southern area of the Nakdong River basin), streams flowing to the eastern and southern coasts were not originally included in the Nakdong basin. However, in this study those streams were also included in the survey. The streams surveyed in the study were based on the stream order information provided by the Water Management Information System (2009) maintained by the Ministry of Land, Transport and Maritime Affairs (MLTMA) of South Korea. This information system divides streams into four groups: national river (mostly 4th–9th order), regional 1st and 2nd level streams (mostly 4th to 7th and 1st to 5th orders, respectively), and miscellaneous tiny-scale streams (mostly 1st to 3rd order). In this study, all streams and rivers belonged to the first three groups as monitoring streams.

The selection of stream sites was as the following:

1. Site establishment: the first site was established 2 km upstream from its estuarine area when it flows to sea, or from the confluent point toward the same or higher order streams.
2. Distance between sites: 10 km for national rivers (mostly 4th–9th order, as aforementioned) and regional 1st streams (mostly 4th to 7th order) from the first site of the streams, and 5 km for regional 2nd streams (mostly 1st to 5th order) from the first site of the streams.
3. Exception: if length of a stream is lower than 5 km, then only one site was established at 2 km upstream of the estuarine area or confluent point (mostly for regional 2nd streams).

A total of 265 catchments comprise the Nakdong River basin region (including the coastal area), and mostly 5–10 sites were included from each catchment. The number of sites in the catchments relied on the size and number of streams in the catchments, and some catchments in the southwestern region (mainly in the Mt. Jiri Range) contained relatively large number of sites due to numerous small tributaries in the mountainous area (see Fig. 1).