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Assessing environmental improvement options from a water quality perspective for an urban–rural catchment

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The ability of environmental systems to persist while experiencing sharp discontinuities is an issue of great importance to today's environmental managers and planners. This study quantified the relationship between land use and the total nitrogen (TN) load in a catchment using a mass balance model based on multivariate analysis. This model considered the spatial arrangement of observed data and the quantity of different land-use types to examine the relationship between the environmental improvement effects of various policy measures and the TN load in the Gyaku River basin, Japan. The distribution of the land uses was estimated from LANDSAT/TM data using ISODATA clustering. The aim was to develop concrete controls for improving the environment (*i.e.*, an environmental improvement policy). The TN load was governed largely by the distribution of human-related factors such as industrial wastewater discharge, agricultural production, population density, and livestock density. The optimal environmental state was determined by examining various factors influenced by human activities and natural phenomena. The analysis incorporated previously published data from the early stages of stand development. First, the boundaries of the self-governing bodies that would enforce the proposed measures were located on maps of the environment and settlements in the study catchment. A proposed plan was then developed based on concrete procedures. The study catchment contained a predominantly agricultural area and an urban area. Thus the environmental improvement policy had to consider both urban and rural characteristics of the catchment. The qualitative effects of various measures and combinations of measures were simulated, considering inflows and outflows from both the agricultural and urban areas. This study is particularly useful because many visible aspects of Japanese environmental management are not those that rationally based paradigms of decision making would associate with environmental improvement and resilience.

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1. Introduction

Water policies, such as those aimed at improving aquatic environments, are widely applied by local and central governments worldwide. Such policies can not only benefit the environment, but may also enhance water quantities and profit for certain users. Furthermore, regional or national policies may lead to better wastewater treatment, reduction in fertilizer use, and river infrastructure construction to further promote regional or national economic growth (Galloway et al., 2003; Kalavrouziotis et al., 2004).

Environmental decision making is extremely complex due to the intricacies of environmental systems and the competing interests of multiple stakeholders (Mysiak et al., 2005; Reichert et al., 2007; Healy, 2009; Kragt et al., 2010). Additional research is needed to better understand the various types of uncertainty (*e.g.*, knowledge, variability, decision, and linguistic uncertainties) inherent in environmental decision making and how these uncertainties affect the quality of decisions. Modelling and decision-support tools (*e.g.*, integrated assessment models and multi-criteria decision analysis tools) are being increasingly used for comparative analysis and uncertainty assessment of environmental management alternatives (Ascough II et al., 2008; Roberts et al., 2009; Bréchet and Tulkens, 2009). Decision making on a catchment scale is based on the internal state and the perception of the outside world as gained from information received during interactions with other agents and the environment.

Modelling for decision-making purposes may have to consider requests for transparency and participation (deliberation frames

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analysis), and the validity of model products will be judged according to their capacity to provide context-sensitive knowledge for specific decision problems that determines the most cost-effective solution (Haag and Kaupenjohann, 2001; Cools et al., 2011). Increasingly, formal scientific approaches have been developed and applied to assist with environmental management and decision making. Jakeman and Letcher (2003) demonstrated the importance of integrated models (*e.g.*, explicitly accommodating linkages between natural and human environments) in assessing the response of environmental systems to proposed management options. At the landscape level, such a system will require inputs from stand-level models. Such systems would be extremely useful for tactical and strategic decision making for sustainable forest management (Chertov et al., 2002). Vissikirsky et al. (2005) and Vieira and Lijklema (1989) developed a mathematical model for determining the optimal extent of regional water and wastewater treatment and wastewater diversion schemes and applied the model to regional water quality management in a river basin. Neumann et al. (2002) analysed water samples from an agricultural catchment in Germany and suggested that a sewage plant was the largest source of herbicides, contaminating streams almost continuously. In such streams, the low-water phase accounted for most of the contaminant load, and non-point sources were insignificant. Farmyard runoff was possibly the second most important source of herbicides. After heavy precipitation, farmyard runoff and non-point sources (field runoff) produced contamination peaks and accounted for most of the contaminant load of small streams (Neumann et al., 2002; Scholes et al., 2008). Kalavrouziotis (2011) and Chu et al. (2004) described a systematic framework for estimating wastewater reuse potential. Using the model, the effectiveness of different policy scenarios for water price changes was simulated and evaluated, providing information regarding water and wastewater management (Chu et al., 2004; Redmond et al., 2008; Kalavrouziotis, 2011; Kalavrouziotis et al., 2011). Environmental management decisions are often now made with the support of mathematical simulation models. Several such models have been proposed for pollutant transport and fate in surface waters (Reckhow, 1994; Assaf and Saadeh, 2008). Rice paddies can play a significant role in water quality, as noted by Takeda et al. (1997). In the watershed examined in their study, paddies seemed to have the desirable function of pollutant removal, with deposition in paddies being more effective than flushing by a river; the water retention time was sufficient for purification mechanisms to work in paddy fields. Although the circular rice irrigation system was originally designed not for purification but to supply enough water to the paddy, this system can help reduce non-point source pollutants. This finding suggests that small-scale water recycling use in agricultural watersheds may be a good alternative method for watershed management (Takeda et al., 1997; Heathwaite, 2003; Isendahl et al., 2010).

Given the prevalence of aquatic pollution in many regions worldwide, controlling non-point source pollution is desirable. Best management practices (BMPs) for agricultural non-point source pollution have been designed primarily for controlling sediment and include sedimentation ponds, grass and vegetative filter strips, and changes in tillage practices (Gallagher et al., 2001; Walter et al., 2003; Bishop et al., 2005; Kovacs et al., 2008). Graphical techniques, when combined with a resource simulation model, permit resource managers to explore the effects of different management options. This technique (in the form of a nomogram or response surface) also permits derivation of “optimal solutions” for particular objectives (Peterman, 1977). The effects of several types of uncertainties have been discussed, including uncertainties in model assumptions, management precision, future objectives, and system evolution. The graphical nature of nomograms helps managers and analysts to more easily grasp the complicated behaviour of ecological system models. As noted by Peterman (1977), computer models can play a useful role in decision making. Mouri et al. (2010) quantified the relationship between land use and total nitrogen load in a catchment using a mass balance model based on multivariate analysis that considered the spatial arrangement of observed data and the quantity of different land-use types. The reduction coefficient of velocity, which assessed change in the amount of a substance in the process, was expressed as a function of biomass, hydrological conditions, and weather or geographical feature factors.

2. Objectives

This research presents a scenario for radical environmental improvement based on the response relationship between individual environmental agents resulting from land use and human activities in a catchment including urban and agricultural land uses using a mass-balance model (Mouri and Oki, 2010; Mouri et al., 2010, 2011a). Given this situation, reducing the pollution load as much as possible is of utmost importance. In addition to discharge sources, flow control is required for pollution-load reduction. These features can be considered individual measures for environmental improvement. In this study, the nitrogen loads from point and non-point sources are calculated separately, and an integrated modelling of nitrogen transport and retention of typical Japanese rural–urban streams is proposed (Mouri et al., 2010, 2011a, 2011b). Subsequently, the next section provides an integrated model that aims to support integrated catchment management. The modelling and valuation techniques employed in this study are presented in Section 3. The selection of the study area and the conceptual model development are described in Sections 3.1, 3.2 and 3.3. Several challenges encountered in this interdisciplinary research are discussed in Sections 5 and 6. The final section provides conclusions and directions for future work.

3. Methods

3.1. Site and database descriptions

Management strategies were applied to the Gyaku River basin, a tributary basin of the Nagara River, Japan. Table 1 provides general information on the Gyaku River, which has a catchment area of 55 km^2 and main watercourse length of 38 km. The river's abundant waters are used to irrigate an area of 24 km^2, mainly from small tributaries and waterways. A land-use map was generated from Landsat Thematic Mapper (TM) images (21 October 1997; 30 March 1998) using a clustering method (ISODATA). On this map, none of the area was classified as mountainous, while 44% of the catchment area was occupied by arable land, and 55% was occupied by buildings. Most of the arable land was used as paddy fields, with more arable land found in the southern part of the catchment than in the northern part.

Table 1
General information on the Gyaku River.

Item	Description
Location	Central Honshu, Japan (N: 35°31′–35°35′, E: 136°69′–136°75′)
Area and length of main stream	55 km^2, 30.3 km
Origin and highest point	Yanaizu-cho (11 m)
Outlet	Ise Bay, Pacific Ocean
Main geological features	Holocene sediment
Main lakes	None
Mean annual precipitation	1915.3 mm (1979–2000) at Gifu
Mean annual runoff	116.5 m^3/s (1954–2001) at Chusetsu
Land use	Mountainous area (0.0%), Urban area (54.6%), Cultivated area (44.2%)
Population	105,432 (2006)

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