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Soil erosion and non-point source pollution impacts assessment with the aid of multi-temporal remote sensing images

Shu-Kuang Ning[a], Ni-Bin Chang[b,*], Kai-Yu Jeng[c], Yi-Hsing Tseng[d]

[a]Department of Civil and Environmental Engineering, National University of Kaohsiung, Kaohsiung, Taiwan, ROC
[b]Department of Civil and Environmental Engineering, University of Central Florida, Orlando, FL 32826, USA
[c]Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, ROC
[d]Department of Surveying Engineering, National Cheng-Kung University, Tainan, Taiwan, ROC

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Abstract

Soil erosion associated with non-point source pollution is viewed as a process of land degradation in many terrestrial environments. Careful monitoring and assessment of land use variations with different temporal and spatial scales would reveal a fluctuating interface, punctuated by changes in rainfall and runoff, movement of people, perturbation from environmental disasters, and shifts in agricultural activities and cropping patterns. The use of multi-temporal remote sensing images in support of environmental modeling analysis in a geographic information system (GIS) environment leading to identification of a variety of long-term interactions between land, resources, and the built environment has been a highly promising approach in recent years. This paper started with a series of supervised land use classifications, using SPOT satellite imagery as a means, in the Kao-Ping River Basin, South Taiwan. Then, it was designed to differentiate the variations of eight land use patterns in the past decade, including orchard, farmland, sugarcane field, forest, grassland, barren, community, and water body. Final accuracy was confirmed based on interpretation of available aerial photographs and global positioning system (GPS) measurements. Finally, a numerical simulation model (General Watershed Loading Function, GWLF) was used to relate soil erosion to non-point source pollution impacts in the coupled land and river water systems. Research findings indicate that while the decadal increase in orchards poses a significant threat to water quality, the continual decrease in forested land exhibits a potential impact on water quality management. Non-point source pollution, contributing to part of the downstream water quality deterioration of the Kao-Ping River system in the last decade, has resulted in an irreversible impact on land integrity from a long-term perspective.

Keywords: Land use classification; Remote sensing; Environmental impact assessment; River basin management; Erosion control; Non-point source pollution

1. Introduction

With rapid socio-economic changes and various environmental perturbations during the last decade, land resources of populated areas, such as the Kao-Ping River Basin in South Taiwan, have been depleted and eroded significantly, resulting in increased ecological vulnerability and hydrological disruption. Furthermore, the instable geological structure resulting from earthquake impacts has led to accelerated soil erosion, increased turbidity of rivers, and more incidences of debris flow when storm events occur. Ecosystem integrity due to such variations also becomes an urgent focus for the prospective planning of the land exploitation in this river basin. Change detection of land use and land cover is one of the essential practices in many interrelated disciplinary areas, such as soil erosion, flood control, landscape conservation, ecosystem restoration, and water quality management via non-point source pollution control. Careful monitoring and assessment with different temporal and spatial scales in this regard would reveal a fluctuating interface, punctuated by changes in rainfall and runoff, movement of people, perturbation from environmental disasters, and shifts in agricultural activities and cropping patterns.

Many previous analyses focused on investigating the interactive relationship between soil erosion associated with

* Corresponding author. Tel.: +1 361 455 3179.
E-mail address: nchang@even.tamuk.edu (N.-B. Chang).

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non-point source discharge and ecosystem management. Some pinpointed the effects of environmental changes that would impact both the ecological characteristics of plant species and their distribution and abundance in specific landscapes (Hoffmann, 1998). Others assessed landscape changes in terms of landscape functions and conservation potential to form a comparative basis in the search for the optimal ecological management alternative (Bastian and Roder, 1998). The most susceptible factor that affects ecosystem functioning is actually the seasonal patterns of soil moisture distribution, inorganic nutrients, organic nitrogen, and soil erosion over the most abundant vegetation types in some typical watersheds around the world (Arhonditsis et al., 2000). In the past, environmental studies were often designed to determine the nutrient concentrations in runoff sediments in order to quantify the outflows of the ecosystem's nutrient budget for preserving agricultural productivity and diminishing non-point pollution (Arhonditsis et al., 2000). Some case studies explored socio-economic, climatic, and lithological components of the erosion processes leading to development of a risk-based map associated with the large-scale clearance of dispersive soils for arboriculture (Warren et al., 2001; Faulkner et al., 2003).

Best management practices (BMPs) have long been recognized as an integral part of water pollution prevention and control in river basins for controlling non-point source pollution using ecologically benign approaches. Simulation analyses of non-point source pollution impacts, which are instrumental to Total Maximum Daily Loads (TMDLs) programs, play an important role in decision-making (Shoemaker et al., 1997). They help planners identify, analyze, and simulate the impacts of alternative land use management policies and practices with respect to non-point source pollution control. Various types of non-point source numerical simulation models were employed to account for the integrated impacts of hydrological cycle and land use pattern in relation to nutrient yield (Bailey et al., 1974; Donigian et al., 1996). They can be further classified as distributed (i.e. grid-based approach) and lumped (i.e. semi-mechanistic approach) parameter hydrologic models. Two salient examples based on a monthly scale in each category include the generalized watershed loading function (GWLF) (Haith et al., 1992) and the Cornell non-point sources simulation model (CNPS) (Dikshit and Loucks, 1995, 1996). More elaborate grid-based numerical simulation models for assessing non-point source waste loads in the agricultural field may enable planners to assess detailed pros and cons of different policy options. They generally simulate rainfall, soil erosion, run-off sediment, temperature, wind speed, atmospheric pressure, and non-point source processes leading to estimate pollutant loading at the watershed outlet. Existing examples include ANSWERS (Beasley and Huggins, 1982), HSPF (Donigian et al., 1980), and AGNPS (Young et al., 1989). Synergy of different models is sometimes anticipated for designated applications with various temporal and spatial scales. For instance, the Spatially Integrated Models for Phosphorus Loading and Erosion (SIMPLE) model was developed to evaluate the potential phosphorus loading to streams from areas with various soil and management practices. This model operates on a daily time step and independent simulations are based on factors such as rainfall, soil characteristics, fertilizers and animal waste applications, and topographic characteristics (Kornecki et al., 1999). It is often connected with the Erosion Productivity Impact Calculator (EPIC) which is a physically based model designed to simulate the effect of different management practices on crop yield and on chemicals, including phosphorus losses by surface runoff, sediment movement, and leaching below the root zone to accomplish an integrated study. Recent efforts using a neural network model demonstrate an additional dimension for soil erosion modeling (Licznar and Nearing, 2003). With the aid of various environmental models, the improvement of the estimation and control of non-point sources in some reservoir watersheds was greatly enhanced in recent years (Safe and Choudhury, 1998; Yool, 1998; and Miller et al., 1998).

The integration of grid cell information in the study area of interest in geographic information systems (GIS) with various environmental models has been fully implemented (Liang and Chen, 1995; Goodchild et al., 1996; Dikshit and Loucks, 1995, 1996). In many cases the grid-based non-point sources modeling analysis is prohibitively hindered because of insufficient information and unbearable data-intensive requirements. However, land use characterization and change detection analysis based on remote sensing are able to provide planners with sufficient background information for model parameterization (Helmschrot and Flügel, 2002). Recent applications with different spatial scales range from a continental scale to a river basin scale and to an urban scale (Cohen et al., 2003; Hashiba et al., 2000; Tapiador and Casanova, 2003). With such a need, advanced and improved remote sensing data analysis and land use classification techniques are anticipated (Steele, 2000; Foody, 2002; Pal and Mather, 2003).

The goal of this study is to assess the long-term impact of soil erosion and nonpoint source pollution in a fast growing river basin in Taiwan via the integrative use of remote sensing, global positioning system (GPS), GIS, and numerical simulation models. While a companion study (Ning et al., 2002) addressed available data, choices of method, and what has been done with these data in a short-term analysis for the Kao-Ping River Basin, this paper focuses on the application of multi-temporal remote sensing images to aid in soil erosion and non-point source pollution assessment within the same study area from a long-term perspective.

2. Study area

The Kao-Ping River Basin is located from 120° and 22 min (122°22′) north longitude and 22° and 28 min