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

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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

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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

(22°28′) east latitude to 121° and 3 min (121°3′) north longitude and 22° and 30 min (22°30′) east latitude. The mainstream flows through approximately 140 km and drains towards Southern Taiwan Strait. With an area of 3256 km^2, the mainstream of the Kao-Ping River originates from four small tributaries: Chi-San River, Liao-Nung River, Cho-Kou River, and Ai-Liao River (Fig. 1). From the confluence to the union with those tributaries at the location of Li-Ling Bridge, the river carries the name Kao-Ping River. The river basin elevations range from sea level near the estuary region to 3293 m upon the headwater with the average slope of about 1/150. Five soil types appear in this river basin. Entisols, which are Lithosols, are spread around the northern and eastern mountainous area. Inceptisols and Alfisols that come from the older alluvial soils are distributed over the southwestern plain. Ultisols and Oxisols, which constitute the red soils, cover the southern region. Inceptisols and Ultisols that represent most yellow soils are dominant soils around the midwestern area. The land use pattern is quite distinct. Forested land covers the northeastern mountainous region in the upper portion of the river basin. Residential districts are mostly located downstream in this river basin. While many groves are located along the river corridor, agricultural land spreads around

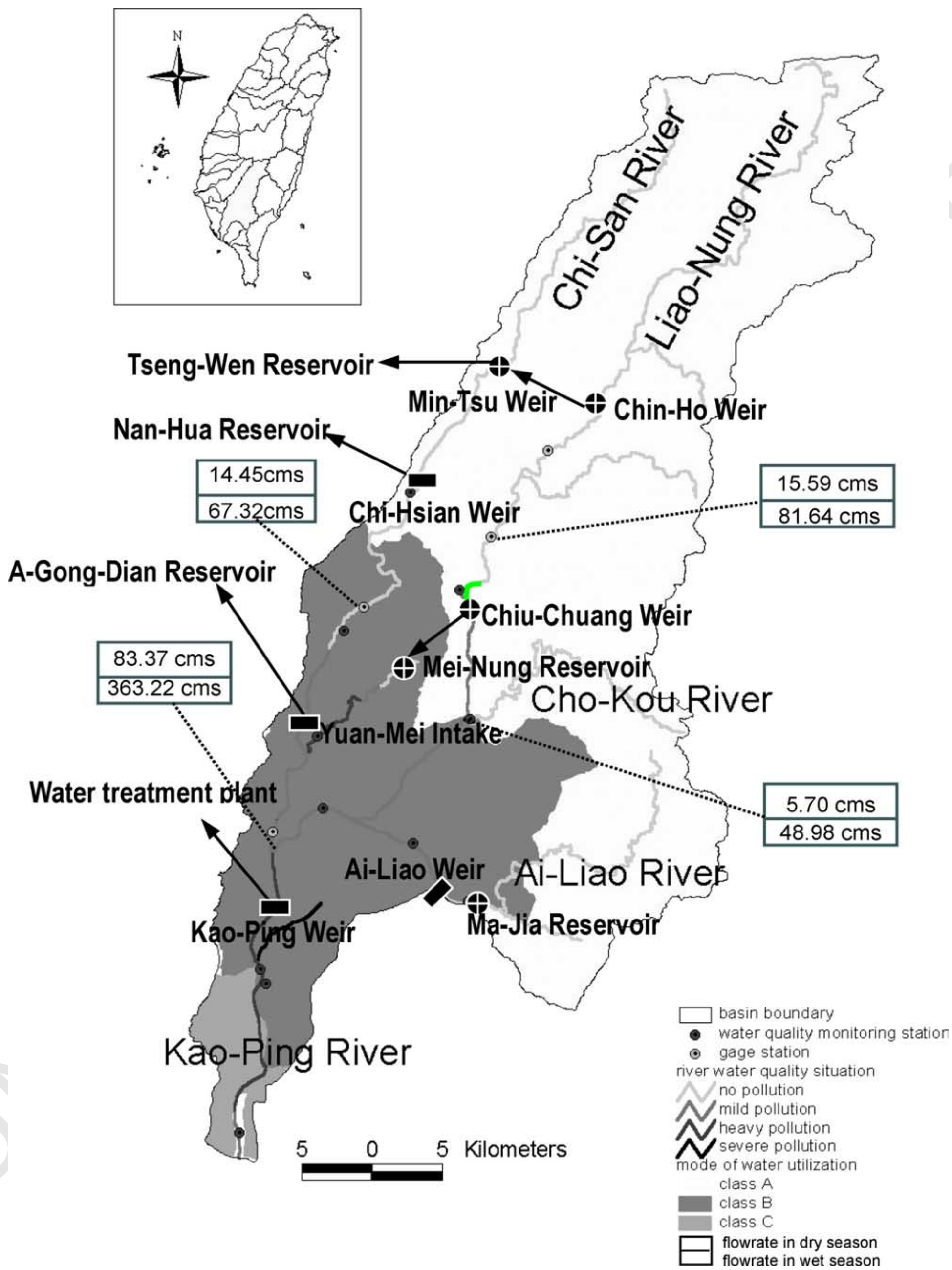

Fig. 1. System environment of the Kao-Ping River Basin, South Taiwan.

the western portion of the river basin. There are also a number of small- and medium-scale industrial parks in the populated region downstream.

The mean annual rainfall in this river basin is close to 3000 mm, over 90% of which precipitates in the wet season from May to September. The period of high flow rate in the stream usually occurs in late spring and summer due to the impacts of monsoons and typhoons. In this time period, the Kao-Ping River flow increases to a level approximately 8–12 times higher than the dry season flow. Uneven rainfall over seasons has resulted in severe issues of water resources redistribution in the winter and early spring that inevitably requires building more reservoirs for water storage. Land subsidence occurred in some coastal areas due to the abuse of groundwater resources.

The drainage area of the Kao-Ping River Basin is primarily planned for agricultural production. Crops that are produced from the agricultural fields include rice, sugarcane, pineapple, and a variety of vegetables. Stock farming is an active agricultural activity. In addition to the use of water for agricultural production and industrial manufacturing processes, water is also essential for drinking and personal hygiene in this area. The Kao-Ping River system, however, has a long history of higher BOD and NH_3–N concentrations due to careless landfill operations, inadequate disposal of manure from stock farming, and continuous discharges of industrial and domestic wastewater effluents. These discharges in the middle and downstream areas of the Kao-Ping River system, where most water intakes are located, have resulted in acute needs for promoting a new management policy to improve the water quality condition. The attainable use of river water is officially classified into three categories for management and control purposes. Several pollution prevention programs have been put into practice by the government agency (Ning et al., 2001). These include a large-scale livestock subsidy program for removing almost half of the domestic livestock in the upstream and middle stream areas and a series of collective sewer construction projects in several cities along the river corridor. On the other hand, controlling the agricultural run-off would require a complete assessment of soil erosion and associated non-point source pollution impacts in the river basin from a long-term perspective.

3. Methods

The analysis of soil erosion associated with non-point source pollution impacts includes three stages (Fig. 2): (1) land use pattern classification, (2) data acquisition for modeling analysis, and (3) simulation analysis for non-point source pollution impact assessment. The classification of land use pattern is viewed as one of the prerequisites for applying the subsequent simulation analysis. Thus, the initial focus of this study was on classifying eight types of land-use patterns in the watershed with the aid of SPOT satellite images that were generated during the time period of

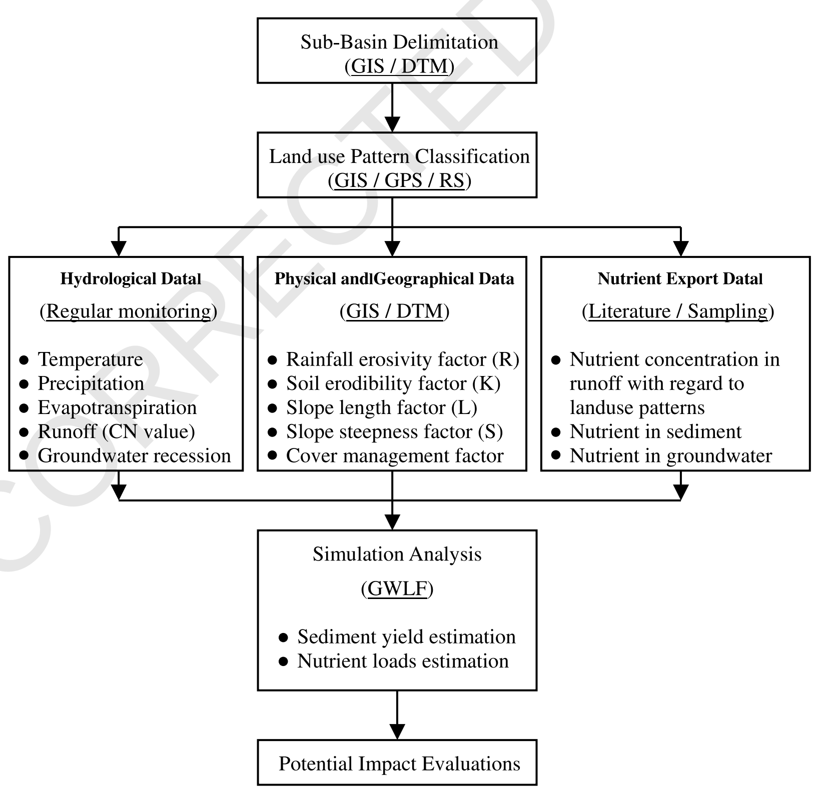

Fig. 2. The analytical framework.

1991–2001. A change detection analysis of decadal land use patterns in the river basin was then performed. To support the impact analysis of soil erosion and associated non-point sources, it requires a series of essential databases integrating both remote sensing and non-remotely sensed data for modeling analysis. In the end, the GWLF model provides predictions of monthly nitrogen and phosphorus loads in stream flow within the time frame based on the given rainfall and runoff patterns and the projections of soil erosion and sediment transport. They are described in detail below.

3.1. Land use pattern classification

Many shifting land use patterns, driven by a variety of social causes, result in land cover changes that affect biodiversity, water balance, radiation budgets, trace gas emissions, and other processes that, cumulatively, affect the global climate and biosphere (Riebsame et al., 1994). A primary component of mapping land use and land cover is to develop a land use classification system. The supervised classification approach was applied in the land use pattern classification of this study. It needs to be carried out in sequence including satellite image mosaic, classification, and verification.

Supervised image classification is a method in which the analyst defines training sites on the image that are representative of each desired land cover category. The delineation of training areas representative of a cover type is most effective when an image analyst has knowledge of the geography of a region and experience with the spectral properties of the cover classes (Skidmore, 1989). The image analyst then trains the software to recognize spectral values or signatures associated with the training sites. After the signatures for each land cover category have been defined, the software then uses those signatures to classify the remaining pixels (ERDAS, 1999). Fig. 3 indicates the detailed steps of this procedure. They can be described using a SPOT satellite image as follows:

3.1.1. (1) Select and mosaic satellite image

At first, an overlay is used when it is desirable for a block of content of a SPOT image and GIS themes of the study area to be shared with respect to the 2°-Zone Transverse Mercator (TM) projection coordinates. The SPOT has high-resolution visible (HRV) imagery, which includes three bands with 20-m resolution color mode and 10-m resolution panchromatic mode. Colorful images include infrared, red, and green bands corresponding to the wavelengths of 0.79 ∼ 0.89 μm, 0.61 ∼ 0.68 μm, and 0.50 ∼ 0.59 μm, respectively. Satellite image reception, archiving, and validation were carried out by the Center for Space and Remote Sensing Research in Taiwan. Current HRV data

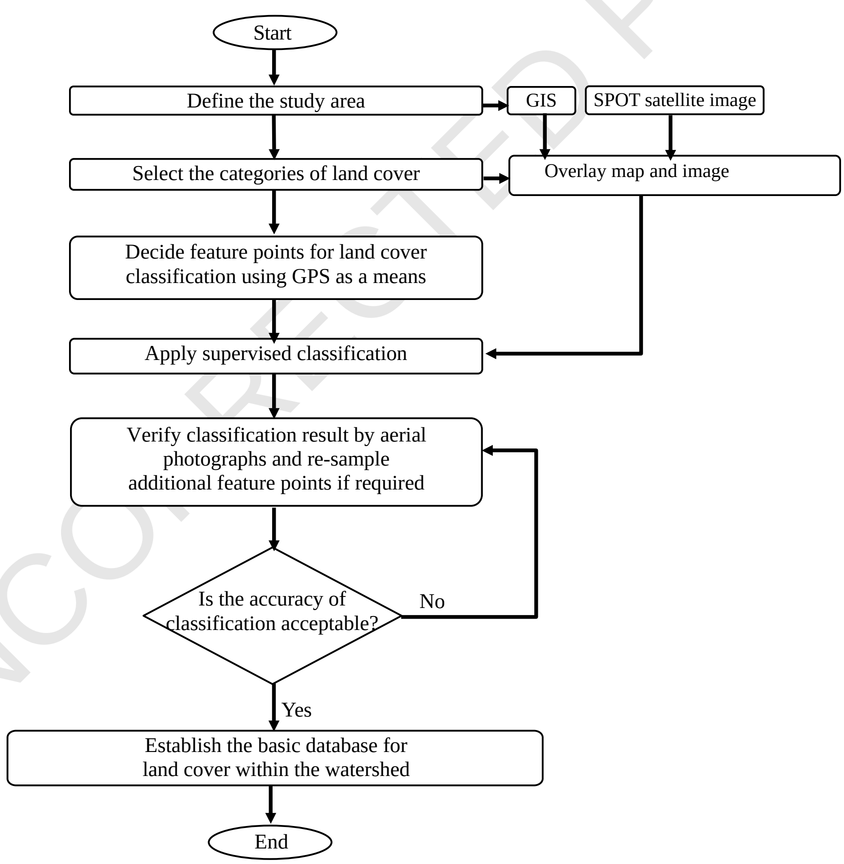

Fig. 3. The procedures of land use classification.

precision (80 bit) appears suitable for land cover identification on a river basin scale.

The entire analysis for land use identification and classification in the watershed of the Kao-Ping River Basin was designed based on a practical scale GIS framework. The study area has been further classified by the authors using three bands of SPOT satellite images in the spectrum that were collected during the time periods of 1994 (i.e. November, 1994), 1996 (i.e. June, 1996 and August, 1996), 1997–1998 (i.e. November, 1997 and January, 1998), and 2001 (i.e. January, 2001). Fig. 4 shows the decadal SPOT satellite images of the Kao-Ping River Basin. These SPOT scenes selected for land use pattern identification covering the portions of the Kao-Ping River Basin in South Taiwan must be first verified to a status of GICS level 10 by the Center for Space and Remote Sensing Research before performing various environmental applications. Automatically matching conjugate features in overlapped images was required first. Due to time differences when producing these satellite images, direct matching of them was impractical. Instead of using advanced direct matching algorithms, this study applied a different method in which each satellite image acquired at a different time was used for land use classification independently and individual outcomes were then integrated together as a whole for final evaluation via the use of Erdas Imagine® image processing software.

3.1.2. (2) Classification of land use patterns

Application of GPS helps verify the effectiveness of land use classification based on SPOT satellite image. The information gained from GPS can be divided into two groups. One group is prepared as a set of feature points that is designed for a direct calibration of land use classification in the Erdas Imagine® image processing system. The other group is prepared as an additional set of feature points or ground-control points (GCPs) for validation purposes. Fig. 5 shows the locations of all GPS feature points prepared for ground truth verification in 2001. Partial feature points expressed as dots were used for supervised land use

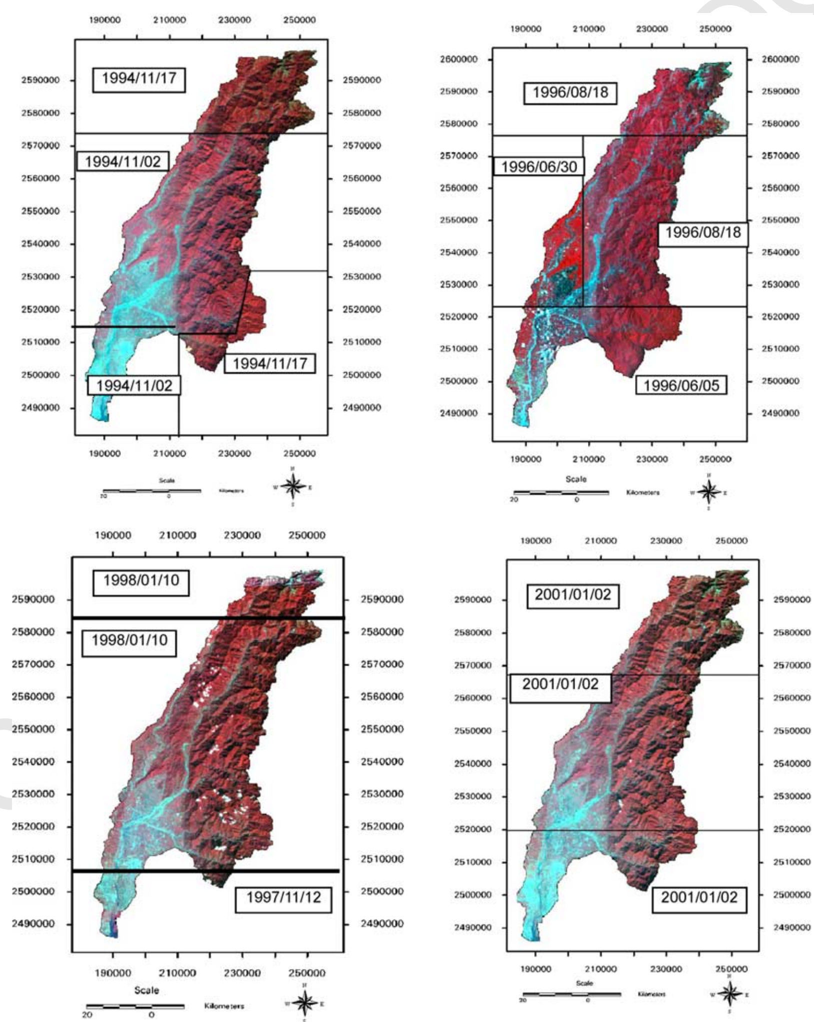

Fig. 4. Decadal SPOT satellite images of the Kao-Ping River Basin.

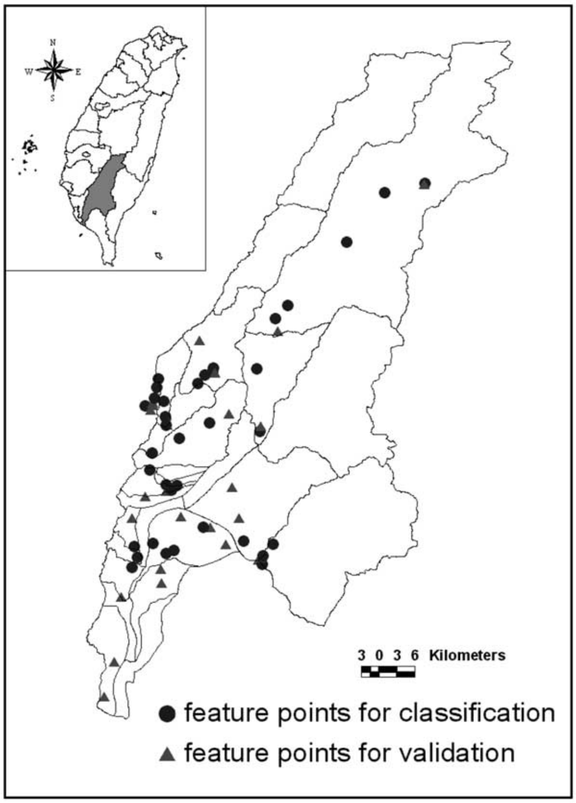

Fig. 5. The distribution of feature points for calibration (2001).

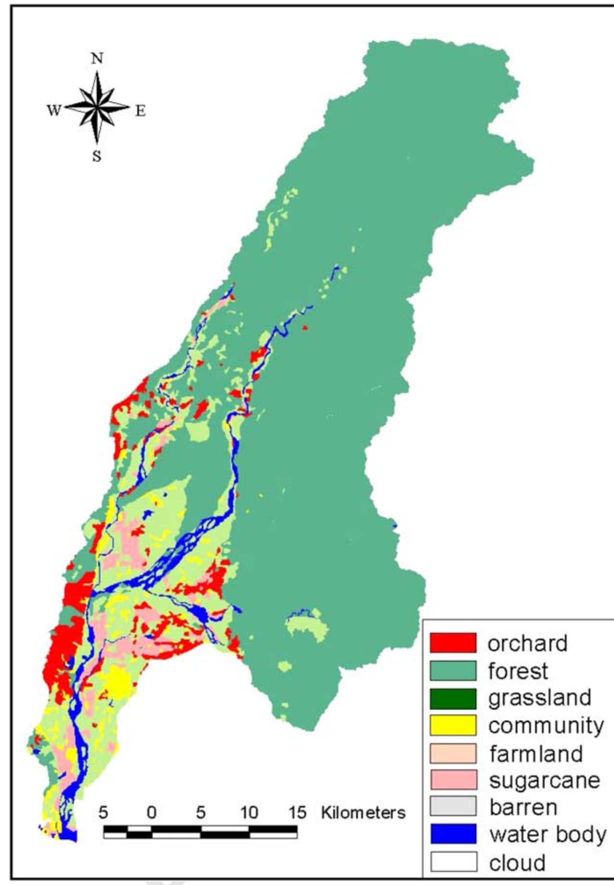

Fig. 6. The surveyed land use patterns in the Kao-Ping River Basin (1991).

classification, while those expressed as triangles were saved for final validation of land use patterns. The overall supervised ground truth classification process can therefore be trained based on the first set of feature points in the first stage and then be validated by the given land use pattern in the watershed with the aid of the second set of feature points in the second stage. An independent survey of land utilization in 1991, as shown in Fig. 6, was selected as the baseline information to track down the variations within a ten-year time frame when looking for the temporal variations of land use on a long term basis.

3.1.3. (3) Verification of land use pattern by local aerial photographs

Final accuracy can be confirmed by using some available aerial photographs as a kind of supplementary ground truth verification. A geometrical rectification procedure is required to map the aerial photographs onto the ground coordinate system. In this paper, the aerial photographs were rectified using an ortho-rectification procedure. The original hardcopy photographs were digitized first for digital processing. The photogrammetric procedure of Digital Aerial Triangulation was then performed to recover the exterior orientation. Because the correction for terrain displacement requires a Digital Surface Model (DSM), automatic stereo image matching was carried out to generate DSM. Then, the images were ortho-rectified according to the perspective geometry and terrain displacement. Finally, all rectified images were mosaiced together to compose an overall rectified image, which enabled us to overlap the aerial image on the satellite images. This eventually led to the accuracy assessment for the outputs of land use pattern classification. To achieve this goal, Kappa statistics are normally selected to express the proportionate reduction in error generated by a classification process, compared with the error of a completely random classification (Congalton, 1991). Fig. 7 indicates the area picked up for accuracy assessment points, in which a stratified random sampling method was applied. It uniquely allows us to evaluate a classified image file for evaluating diagnostic imaging methods.

3.1.4. (4) Change detection analysis of decadal land use in the designated river basin

An increasingly interesting application of remotely sensed data in the context of land use pattern classification is for change detection. Change detection is an important process in monitoring and managing land resources because it provides quantitative analysis of the spatial variations of the land use patterns within the designated time frame. Based on the remote sensing efforts aforementioned, this paper is also designed to summarize all the spatial variations

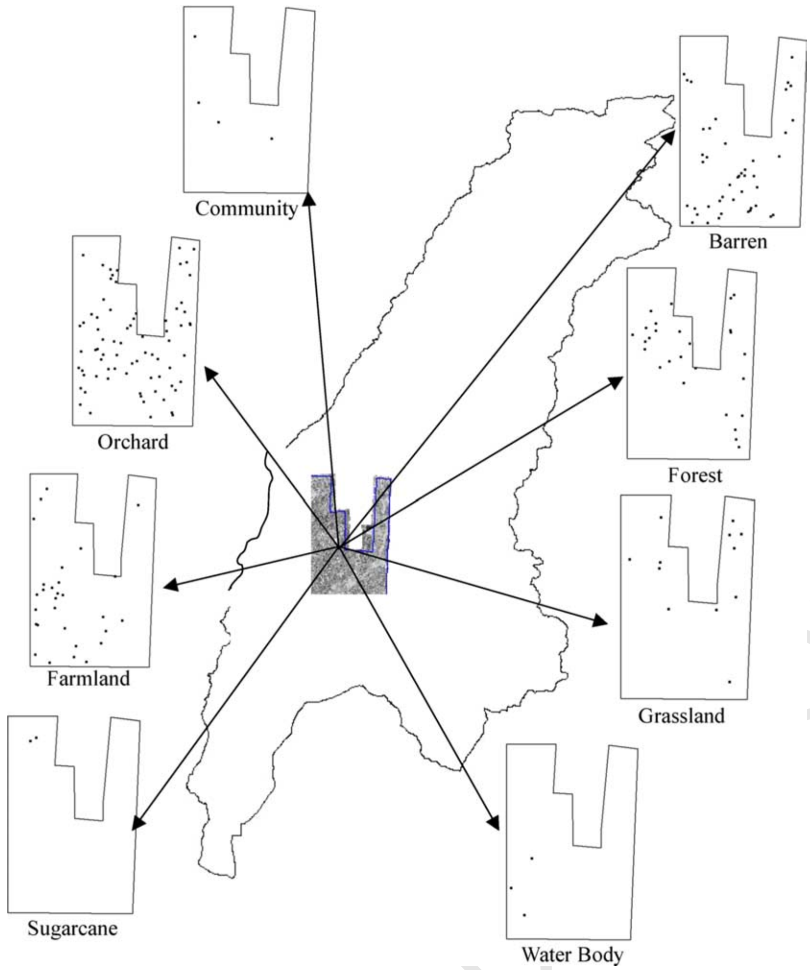

Fig. 7. The accuracy assessment selected by stratified random sampling.

with respect to seven land use categories that provide a clue to decadal shifts in agricultural activities and cropping patterns.

3.2. Data acquisition for modeling analysis

The input data needed for non-point source modeling analysis covers physical, topographical, meteorological, hydrological, and geological features, and nutrient export data. Precipitation, temperature, and evapotranspiration data can be obtained from regular meteorological observations. Runoff Curve Numbers (RCU) can be acquired from a technical report published by the US Soil Conservation Service (1986). The RCU were designed based on the information of land cover, soil groups, and hydrologic condition. Erosion and sediment parameters described by the Universal Soil Loss Equation may be obtained from the investigation of soil erosion, digital

Table 1
The nutrient concentration applied in this analysis (Ning et al., 2002)

Nutrient content in the runoff

Land use patterns	Forest	Community	Orchard	Agricultural land	Grassland	Sugarcane
TN (mg/L)	1.925	1.806	1.709	17.74	0.3	10.69
TP (mg/L)	0.18	1.17	0.46	9.56	0.15	4.66

Nutrient content in the sediment

Soil classification	Podzolic soils Red soils	Mudstone, silt-shale stone			Regosol
		Non-weathering	Semi-weathering	Weathering	
TN (mg/kg)	877	78	136	397	318
TP (mg/kg)	859	141	305	518	233

terrain modeling (DTM) information, mode of cover and management types for handling field crops, and the condition of agricultural practices in the field. But the representation of flow directions and calculation of upslope areas using rectangular grid digital elevation models must be applied (Tarboton, 1997). Finally, the mean concentrations (i.e. export coefficients) of nutrients in runoff and sediment transport from both rural and urban regions were collected and combined based on several previous sampling practices in Taiwan (Ning et al., 2002). They are summarized as part of the semi-empirical inputs in this model (see Table 1) (Ning et al., 2002).

3.3. Simulation analysis

The GWLF model was selected as a baseline tool to estimate the non-point source waste loads reflecting the impacts from soil erosion processes and nutrient cycles in the watershed of the Kao-Ping River Basin. The GWLF model describes non-point sources for runoff, erosion and

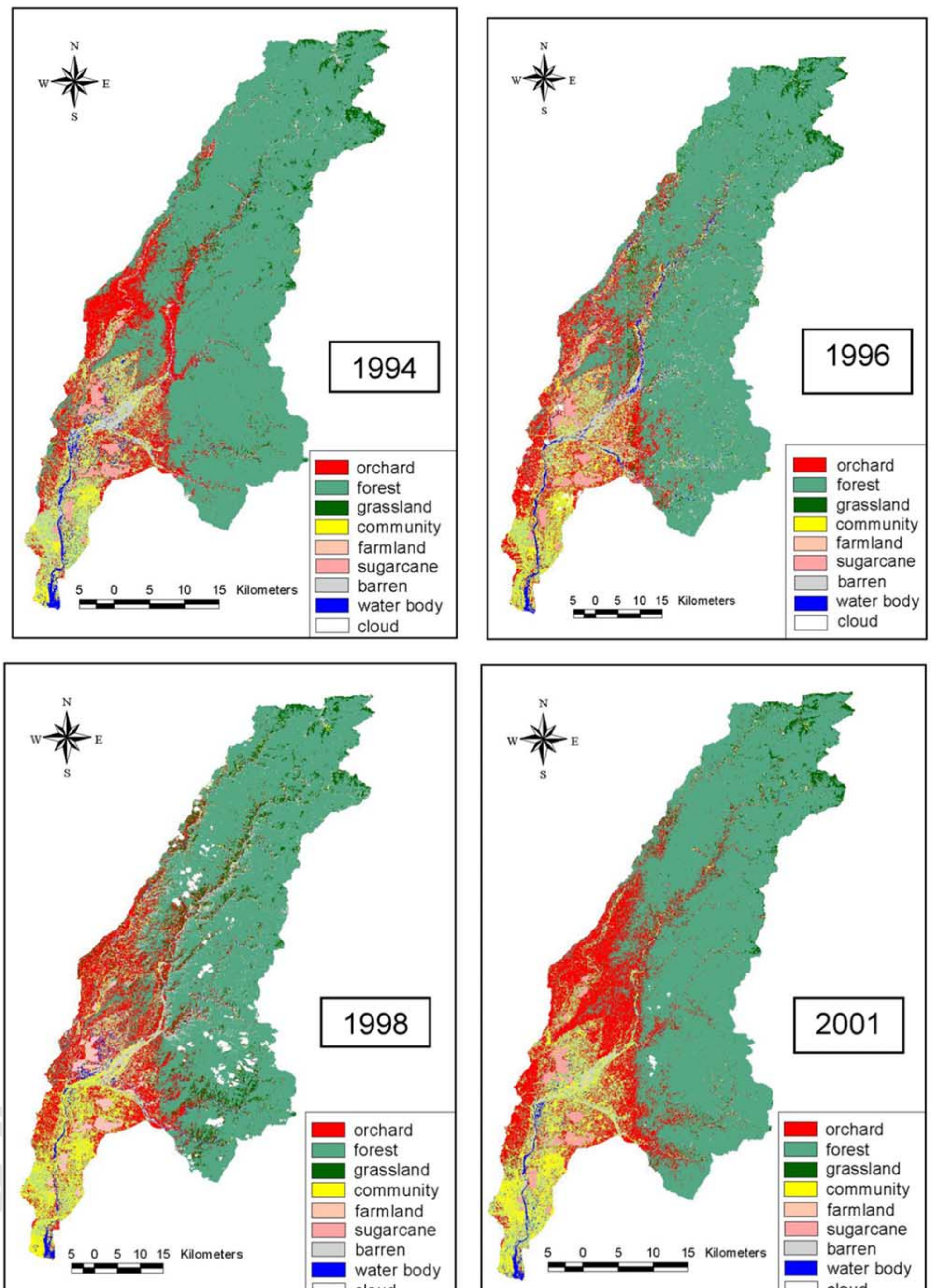

Fig. 8. The identified decadal land-use patterns in the Kao-Ping River Basin.

urban wash off, and a lumped parameter linear reservoir groundwater model. The delivery ratio concept was defined based on the Runoff Curve Numbers and the Universal Soil Loss Equation methods (Vanoni, 1975). It helps to yield an estimation of non-point source waste loads with respect to soil erosion, sediment transport, and resulting nutrient fluxes, such as total phosphorus (TP) and total nitrogen (TN). Eight types of land use patterns that have been classified in the previous step can be incorporated to track down long-term non-point source impacts.

All data from the SPOT satellite images were eventually integrated into the ArcView® system, in which land use and land cover information can be extracted from the GIS database to help in the estimation of soil loss and non-point pollutant loading in the watershed. The GIS expresses the geographic area as a matrix of grid cells of which each grid cell stands for a parcel of land of certain size and serves as the basic unit for quantification of various physical, topographical, meteorological, hydrological and geological features. Thereafter, the spatial analyst module in GIS can be applied for the prediction analysis with respect to each type of land use pattern in the watershed in a way that enables us to estimate individual impacts due to each type of non-point source of interest. Total impacts of soil erosion and non-point sources can then be integrated with respect to all land use patterns identified by SPOT satellite images and associated GIS operations.

4. Results and discussion

4.1. Assessment of long-term land use variations

The spatial analyst module embedded in the ArcView® system enables us to compute the land use statistics corresponding to each drainage sub-basin. Except for the area covered by clouds in the satellite image, the land use patterns being categorized include orchard, farmland, sugarcane farm, forest, grassland, barren, community, and water body in each sub-basin. These land-use patterns can be delineated as an ArcView® cartographic output as shown in Fig. 8.

Table 2
The kappa coefficient

Class name	Reference points	Kappa coefficient
Orchard	78	0.8449
Forest	27	0.6917
Grassland	12	0.8670
Community	5	0.2308
Farmland	29	0.8051
Sugarcane	2	1.0000
Barren	44	0.8397
Water body	3	0.7462
Total	200	0.7648

For the sake of further assessment of classification accuracy, GPS feature points and aerial photographs were used as real ground truth for final confirmation. Table 2 shows the number of points in the assessment and the associated Kappa coefficient for each land use pattern. The Kappa agreement test was applied and an average accuracy of 0.7648 was achieved with respect to different Kappa coefficients associated with different land use patterns.

Table 3 summarizes land use patterns on a comparative basis and covers the time period from 1991 to 2001. The survey of land use patterns in the year 1991 was manually digitized for comparison. At present, forested land occupies approximately 60.3% of the total area of the river basin. It spreads out along the eastern mountainous area in the watershed. Orchard areas that keep increasing over time are scattered around on both sides of the river corridor. They occupy approximately 17.7% of the total area in this river basin. Farmland, grassland, barren, and community constitute approximately 9.9, 3.3, 2.2 and 4.1% of the total area, respectively. They are normally located at the southwest region of the river basin. Because barren was not included in the classification, the dry riverbed was classified as part of the water body, which results in some inaccuracy. The stream flow rate in the wet season may be ten times higher than that in the dry season. Such seasonal stream flow variations were so phenomenal that they increased classification inaccuracy with respect to the water body. Due to the effect of clouds, inevitable discrepancies arise from the adoption of different satellite images acquired in the wet seasons in 1994 and 1996 and the dry seasons in 1998 and 2001. On the other hand, the increasing withdrawal of water flows from the river to satisfy the rising demand for water resources over time could affect the area of the water body (Ning et al., 2002). In 1998, clouds covered an area of about 62 km^2, which also impacts the classification of forested land in the watershed.

Fig. 9 summarizes the decadal variations of land use patterns in the Kao-Ping River Basin. From 1994 to 2001, the land use for orchard had increased dramatically due to

Table 3
The area of land use patterns identified in the Kao-Ping River Basin (km^2)

Land-use patterns	1991	1994	1996	1998	2001
Orchard	132.44	385.90	389.60	471.44	576.22
Forest	2242.30	2182.28	2048.55	1816.97	1962.52
Grassland	169.48	114.53	132.68	206.51	106.99
Community	69.74	71.96	108.55	153.44	133.59
Farmland	442.84	267.80	285.71	255.17	323.10
Sugarcane	102.06	47.26	47.91	46.19	45.89
Barren	0.00	132.98	191.60	207.06	70.70
Water body	91.71	48.72	41.97	38.08	29.30
Cloud	0.00	0.86	9.80	61.71	3.99
Total	3250.58	3252.30	3256.38	3256.57	3252.30

fast economic growth region wide. The capacity for production of versatile fruits contributed to both domestic and foreign target markets from which the income supports the local socio-economical system basin wide. In addition, the local pork industry, which counts heavily on stock farming, has enormous implications for the international trade surplus due to steady export demand. As a result, the total area of grassland and community also presented an increasing trend over time in the last decade. Yet forested land decreased substantially in the last decade. Fig. 10(a) explains the distribution of forest versus non-forested land in Taiwan. However, non-forested land only occupies 41.47% of the total area. Fig. 10(b) reveals observational evidence that while the per capita GDP and the export volume of the timber remained the same within the last decade, the reforestation efforts decreased over time in the same time period. A considerable area of forested land might be eradicated and transferred into golf courses, recreational parks, orchard farms, tea farms, and residential areas. The destabilization of fragile mountain slopes, through deforestation, agricultural expansion, excessive and indiscriminate grazing and expansion of the road network, disrupted the hydrological cycle in the river basin. It also caused the ecosystem irretrievable changes, such as vegetation area reduction and protozoan and protophyte disappearance affecting biodiversity in the long run. The intelligent use, extraction, conservation, and reuse of forest resources, and the design of long-term strategies require not only comprehensive understanding of the changes in the forested land, but also new and appropriate technology and solutions. To identify the susceptible spots for managerial use, Fig. 11 further pinpoints the long-term variations in forested land in the Kao-Ping River Basin (1994–2001). Overall, the long-term change detection analysis in this study showed that the land development programs in the last decade significantly changed the land use patterns in this region such that the land management, ecological conservation, and pollution control actions have become a new challenge to the environmental decision makers in the river basin.

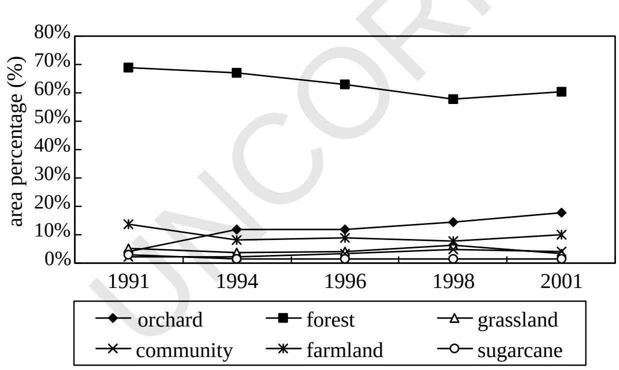

Fig. 9. Decadal change detection of land use in the Kao-Ping River Basin (1991–2001). (a) Forest versus non-forest land distribution. (b) Reforest area versus timber export and per capita GDP

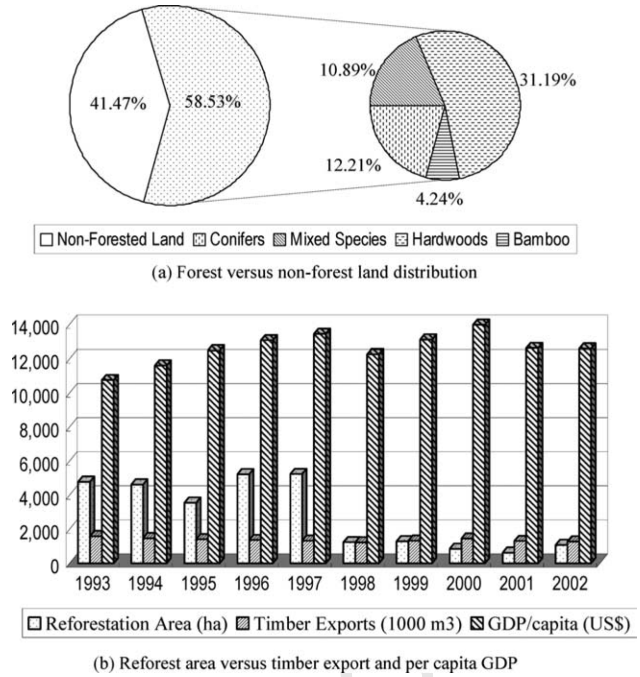

Fig. 10. The statistics of forest change versus timber export in Taiwan (1993–2002).

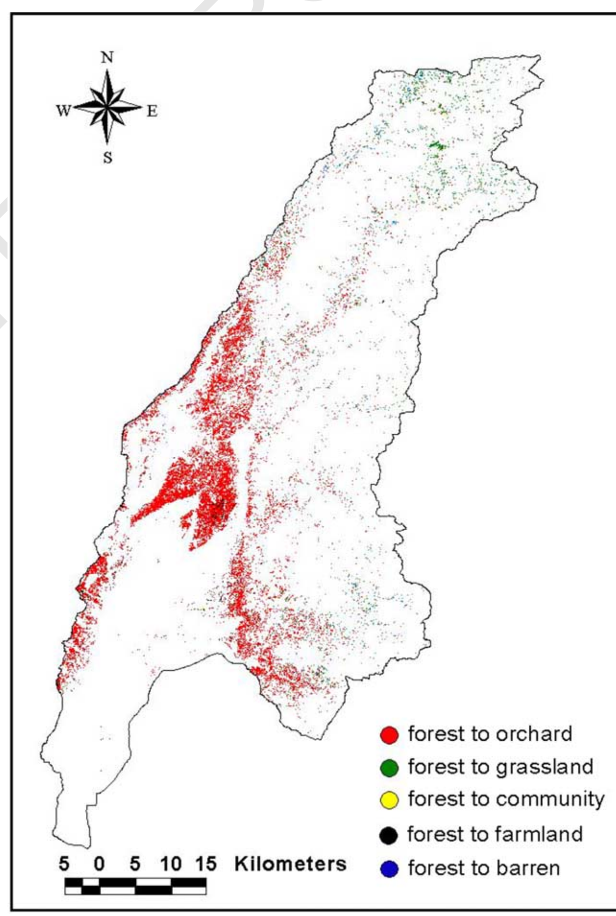

Fig. 11. The variation of forest regions in the Kao-Ping River Basin (1994–2001).

4.2. Assessment of soil erosion and non-point source pollution impact

Simulation outputs using the GWLF model reveal that more than ninety percent of the total impacts of TN and TP appear from June to September within a year when rainfall goes up in the summer. The long-term change detection analysis with regards to soil erosion and associated non-point source pollutant loading between years can also be explored based on the land use patterns in different years. Table 4 summarizes the decadal changes in total nutrient fluxes and soil erosion impacts. The impacts of non-point source pollution over the years result from a complex environmental process due to movement of people, changes in land use patterns, and shifts in agricultural activities and cropping patterns. The positive correlations between rainfall and soil erosion obtained quantitatively in the analysis may further verify the complex, dynamic, and interdependent relationships between them.

The combination of Figs. 12 and 13 would enable us to graphically demonstrate the possible cross linkages of spatial and temporal changes in soil erosion associated with non-point source pollution in the study area. While Fig. 12 delineates the temporal variations in soil erosion associated with varying nutrient loading in the last decade, Fig. 13 further categorizes the distribution of non-point source pollution in terms of different land use patterns using the year 2001 as a representative case. It clearly shows that the levels of annual soil erosion fluctuate stepwise in association with the variations in annual precipitation, and are associated with continuous land cultivation over the years. Within the seven identified land use patterns, excluding water body, in 2001, farmland is recognized as the most important one contributing to the biggest portion of nutrient sources in the river basin owing to a great deal of manure spreading. This also resulted in a critical situation for water quality management since most of those farms are situated alongside of the Kao-Ping River corridor. Furthermore the total area of forested land has been gradually decreasing, accompanied by increasing orchard and farmland. As a consequence, nutrient flux is anticipated to increase as intensive applications of fertilizers in most agricultural regions and inadequate disposal of animal waste in livestock farming communities continue.

Table 4
The estimate amounts of nutrient loading and soil erosion in the Kao-Ping River Basin

Year	Rainfall (mm)	TN (ton/year)	TP (ton/year)	Erosion (million-ton/year)
1991	2601.4	1407.6	260.0	213.2
1994	3349.3	2021.0	332.4	275.3
1996	2329.7	1935.0	310.3	264.9
1998	3017.3	2070.8	348.3	289.2
2001	3769.3	2386.1	451.1	356.0

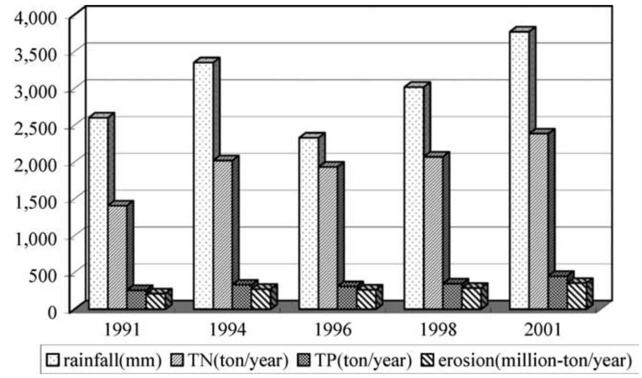

Fig. 12. The variation of nutrient loadings and soil erosion in the Kao-Ping River Basin.

4.3. Management policy

Risk maps of nutrient loading and soil erosion impacts may be produced for essential assessment and policy decision-making (Khawlie et al., 2002). To ease the management efforts, Fig. 14 exhibits the ranking of risk of nutrient loading and soil erosion impacts in the Kao-Ping River Basin. It involves using three regional patterns, consisting of high, middle, and low levels, to address how the resultant changes in land use patterns affect people in the coupled human and natural systems. While a significant number of non-point sources are spread around the middle stream and downstream areas, the regions with critical soil erosion are located at the upland area in the watershed. In particular, these regions with high-level potential for soil erosion are mostly located at the eastern and northern mountainous areas where the slope is steeper and the local rainfall is relatively higher than the other regions. Agricultural activities for crop and orchard farming have already been extended to those marginal and sub-marginal areas nearby the forest without taking the sustainability issue into consideration. This will eventually lead to the consequences of increased sediment transport in the river channel and impact the ecosystem

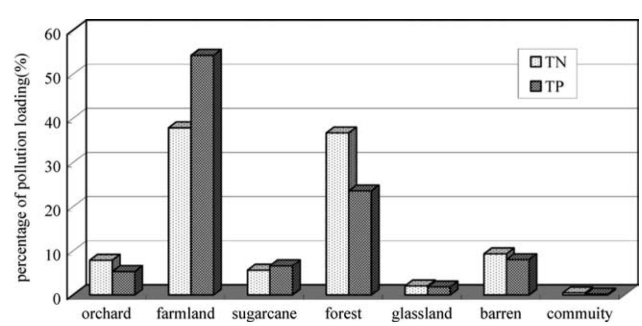

Fig. 13. The non-point sources distribution in the Kao-Ping River Basin in 2001.

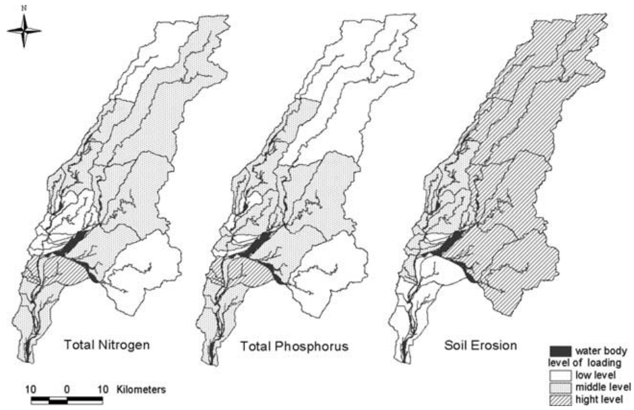

Fig. 14. The potential of nutrient loading and soil erosion in the Kao-Ping River Basin.

integrity in the estuary region. To handle the interrelated challenges, the non-point source critical map analysis obtained from this multidisciplinary study would allow decision makers to identify, describe, rank, and then visualize site options in collaborative spatial decision making. A 'consensus map' is thus devised for future decision making to visualize both the priority of the critical area as well as the consensus status about those priorities in a management sense, which should be instrumental to land development and environmental management programs (Sivertun and Prange, 2003).

Parks, including golf courses, designed for recreational use, could be another vital non-point source in some of the middle and upstream areas. The continuous development of golf courses is thus deemed very important in non-point source pollution control in the context of land use management. In the presence of so many golf courses in this region, advanced remote sensing images, such as IKONO images, should be used to access the corresponding non-point source impacts in the future. On the other hand, it is also worthwhile paying attention to the pesticides discharged from agricultural practices. The methods discussed in this study, such as GIS, remote sensing and the GWLF model, are not suitable for estimating the impact of pesticides.

5. Conclusion

With the rapid increase in population during the last decade in the Kao-Ping River Basin, the demand for land and food has increased considerably, putting increased biotic stress on the critical environmental components, like soil, water and forests. Consequently, this human transformation process has brought about drastic changes in the resource-use practices and land-use pattern of the region. This study builds on, supports, and integrates many existing disciplines and tools and provides new insight for river basin management. It quantifies the decadal changes in land use patterns via the use of multi-temporal remote sensing images and non-point source numerical modeling, thereby providing a firm basis for assessing the impacts of soil erosion and non-point source pollutant loading in the coupled human and natural system. It involves consideration of the natural and human dimensions of environmental changes, including different configurations of socio-economic systems, changes in rainfall and runoff, movement of people, and shifts in agricultural activities and cropping patterns.

Research findings indicate that while the decadal increase in orchards poses a significant threat to environmental quality, the continual decrease in forested land has a potential impact on non-point source pollution. Land degradation along with soil erosion and 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 the natural system. It can be concluded that sustained monitoring with respect to ecosystem features, environmental quality indices, and climate change symptoms using remote sensing should be a meaningful tool to aid in various land use management programs. This multidisciplinary approach using remote sensing to aid in decision making can save time when planners are required to assess the land use management policy with respect to soil erosion and non-point source pollution impacts. Such information should prove useful to watershed managers in the nexus of sustainable development.

6. Uncited reference

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