Science of the Total Environment 505 (2015) 927–938

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Coupled analysis on landscape pattern and hydrological processes in Yanhe watershed of China

J. Li *, Z.X. Zhou

College of Tourism and Environment, Shaanxi Normal University, Xi'an, Shaanxi 710062, China

HIGHLIGHTS

- We simulated ecological hydrological processes in Yanhe watershed based on SWAT model.
- We quantitatively described the coupling relationship between regional landscape pattern change and soil erosion.
- We define a new Slope-HRU landscape index (SHLI) which closely related to soil erosion.
- SHLI is significantly negatively correlated with annual sediment.

ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 7 October 2014
Accepted 19 October 2014
Available online 7 November 2014

Editor: Simon Pollard

Keywords:
Yanhe watershed
Landscape pattern
Hydrological processes
Hydrological response unit (HRUs)
Slope-HRU landscape index (SHLI)

ABSTRACT

As a typical experimental Soil and Water Conservation District, Yanhe watershed has long been plagued by soil erosion due to severe human disturbances. Exerting remote sensing (RS) and geographic information system (GIS) technology, this paper firstly analyzed and simulated ecological hydrological process in Yanhe watershed based on SWAT model, constructed a comprehensive landscape indices which was closely related to soil erosion, and reflected the coupling relationship between regional landscape pattern change and soil erosion. The results are as follows: (1) Areas of different land use types remained relatively stable from 1990 to 2000 and then changed drastically from 2000 to 2010, which was characterized by lawn expansion and cultivated land shrinkage. (2) In terms of the spatial heterogeneity of hydrological response unit (HRUs), the correlation coefficient of seven selected landscape indices and runoff was very small, and cannot pass all significant testing. But correlation between the indices and sediment yield except for Total Core Area (TCA) and Interspersion and Juxtaposition Index (IJI) was remarkable. (3) According to 'the source–sink' theory of soil erosion, new landscape index—slope-HRU landscape index (SHLI) was built, and reflected the relationship between landscape pattern and soil erosion processes to a certain extent. (4) Coupling relationship between SHLI in 2010 and annual sediment was very prominent. In the sub-basin scale, SHLI has obvious regional differentiation from annual sediment.

1. Introduction

Understanding the coupled relationship between spatial landscape pattern and ecological processes has become the international research frontier in landscape ecology (Wu, 2007), which is critical for any in-depth research in landscape ecology. Land-use is closely related to the characteristics of human activities, which in turn determine the anthropogenic substances carried into erosion systems through soil detachment, runoff process, sediment transport (Shi et al., 2013). Watershed is the important research unit. Previous studies have often focused on land use change within the watershed to explain variations in soil erosion (Fohrer et al., 2005; Bakker et al., 2008; Cuo et al., 2008; Xu et al., 2009; Shi et al., 2013; Zhang et al., 2013). From a landscape ecology perspective, landscape pattern is significant to range of issues of environment phenomena, including hydrological connectivity processes, the temporal storage of runoff and run-on, and sediment delivery (Popp et al., 2009; Hou and Fu, 2014). At the same time, landscape pattern exerts a significant influence on the relations of rainfall–runoff and runoff–sediment (Zhao et al., 2004; Bakker et al., 2008; Van Nieuwenhuyse et al., 2011), and alters soil and water loss accordingly. Therefore, it is practical importance to understand the relationship between landscape patterns and erosion processes for watershed planning and management.

The spatial pattern, including the extent, distribution, and intensity of land uses, is an important factor in understanding the erosion processes (Shi et al., 2013). Bartley et al. (2006) found that similar cover can have different water and sediment yields depending on the arrangement of cover on the hillslope and cover patches in close proximity influence runoff and sediment yield. Shi et al. (2013) indicated that soil erosion and sediment yield in watershed are closely associated with the landscape patterns. Jordan et al. (2005) investigate impact of

* Corresponding author.
E-mail address: lijing@snnu.edu.cn (J. Li).

http://dx.doi.org/10.1016/j.scitotenv.2014.10.068
0048-9697/

historical land use changes on soil erosion and sediment transport using the SEDEM/WATEM model.

Spatial statistics and landscape indices are two popular tools to analyze landscape pattern and to quantify land use changes (Wu and Hobbs, 2002; Su et al., 2011). Many common landscape metrics concerning fragmentation, shape, diversity and connectivity characteristics have been used to delineate relationships between landscape pattern and soil loss process (Long et al., 2010; Yang et al., 2012). Not surprisingly, many studies have utilized landscape metric approach to examine the soil erosion and sediment yield response to different landscape patterns (Kepner et al., 2000; Tischendorf, 2001; Chen et al., 2009; Aguilera et al., 2011; Alhamad et al., 2011; Belda et al., 2011; Liu and Weng, 2013; Fan and Myint, 2014; Plexida et al., 2014). Despite the great potential of these landscape metric approaches, they also present particular analytical challenges which many landscape metrics are highly correlated (Wu, 2007). In order to affect the ecological process, many people defined some new landscape indices in different regions all over the world (Jackson et al., 2005; Borselli et al., 2008; Mayor et al., 2008; Hartel et al., 2010; Benedek et al., 2011; Brown and Reed, 2012). For example, Borselli et al. (2008) operatively defined two indices of connectivity: index of connectivity (IC) can be calculated in a GIS environment and represents a connectivity assessment based on landscape's information, and field connectivity index (FIC) that can be evaluated in the field through direct assessment. Mayor et al. (2008)) used flowlength for quantifying the connectivity of runoff source areas considering both vegetation pattern and topography. Hartel et al. (2010) connectivity indices and niche modeling were used to predict the occurrence of the northern crested newt in a rural landscape. Hou et al. (2014) investigated nutrient transport in runoff and eroded sediments. Ziegler et al. (2007) explored the influence of land-cover distribution on the generation and buffering of flow used a landscape index. These new indices effectively solved the ecological process in different environment features.

"Source–sink" theory refers to the role of the "source" and the "sink" played by landscape (Chen et al., 2003). Recognition of the "source" or "sink" landscape in landscape ecology should be integrated with a specific ecological process. "Source" landscapes are ones that may promote the development of an ecological process, while the "sink" landscapes are those that may delay or retard the development of an ecological process (Chen et al., 2008). According to this theory, if "source" and "sink" landscapes balanced in spatial distribution and possessed reasonable spatial distribution, less environmental destructions would be produced; otherwise, more environmental destructions would be produced. The "source–sink" theory is mainly used to study the influence of spatial dynamic balance of land use landscape types on ecological process, and also to pursue suitable landscape spatial pattern (Chen et al., 2006). Some studies focus on specific ecological process using "source–sink" theory (Boeken and Shachak, 1998; Walters, 2001; Imeson and Prinsen, 2004; Jiang et al., 2013). Chen et al. (2009) developed a location-weighted landscape index (LWLI) to highlight the role of nutrient losses. Jiang et al. (2013) quantified the spatial difference of non-point source pollution contribution of landscape type. Otherwise, few landscape indices aim at the specific ecological hydrological process.

Soil loss from a watershed can be estimated on an understanding of the underlying hydrological processes, climatic conditions, landforms, land management, and soil factors (Easton et al., 2010). Watershed models are capable of capturing the complex processes in a dynamic manner and can be used to understand the relationship between hydrologic processes, sedimentation, and management options. Soil and water assessment tool (SWAT) model is a basin scale model where runoff is based on land use and soil type, and develops to predict the impact of land management practices on water, sediment and agricultural chemical yields over long periods of time (Easton et al., 2010). In recent years, several studies in the Blue Nile basin or nearby watersheds have suggested that runoff, erosion excess processes control in large complex watersheds that support more effective watershed management (Arnold et al., 2010; Easton et al., 2010; Thampi et al., 2010; Githui and Thayalakumaran, 2011; de Vente et al., 2013; Bonuma et al., 2014; Park et al., 2014; Yasin and Clemente, 2014).

Exerting RS and GIS technology, this paper analyzed simulated ecological hydrological process in Yanhe River basin based on SWAT model; on this basis, applied landscape indices method, land use change on eco-hydrological processes was quantitatively described, particularly those soil erosion influences caused by the change of landscape pattern with the complicated topography and soil type status; then we defined the hydrological response unit (HRUs) including topography, soil and land use/land cover change (LUCC) information, constructed a comprehensive landscape indices (SHLI) which was closely related to soil erosion, and reflected the coupled relationship between regional landscape pattern change and soil erosion.

2. Method

2.1. Study area

The case study area is the Yanhe River Watershed which is located in the central Loess Plateau (Fig. 1) and covers an area of 7725 km^2. The elevation of this area varies from 500 to 1700 m. The region has a semi-arid continental climate, with an annual average precipitation of 495 mm, over 65% falls from June to September; such concentrated rainfall pattern is apt of forming storm lit with strong energy of runoff. The most common soil in the watershed is loess, a fine silt soil, which is prone to soil erosion (Zhao et al., 2012). The multi-year mean annual runoff in the watershed is 0.289×10^9 m^3, with runoff and sediment transportation of 36,425 m^3/km^2 and 78.0×10^3 t/km^2 respectively. Runoff is concentrated after storm rains and is often with high sediment concentration (Li et al., 2004). The study area has a very rugged topography: over 90% of the territory is composed by gullied and ridges. There are 35 townships in four counties within the study area (Fig. 1). Land use in this watershed comprises of construction land, terrace construction land, orchard, sparse forestland, forestland, cultivated land, water, lawn etc.

2.2. Data sources

The topographical information used in this study was derived from a Digital Elevation Model (DEM) with a resolution of 25 m × 25 m, which was purchased from the National Geomatics Center of China. The soil data, including a soil type map (1:100,000) and information on related soil properties, were obtained from the Soil Survey Office of Shaanxi Province. Watershed management information was added to improve the modeling accuracy. The watershed climatic features were simulated based on daily historical monitoring data from 3 weather stations (Ansai station, Yan'an station and Ganguyi station) from the period of 1954 through 2010. The daily averages of runoff and sediment yield at the Ganguyi station (the watershed outlet) were used to calibrate and validate the SWAT model. A vegetation map of China is at a scale of 1:100,000. The data used in this case study to provide actual three land use maps were generated from the classification of Landsat TM5 images, acquired during the summers of 1990, 2000 and 2010 at the spatial resolution of 30 m.

2.3. CA-Markov-based model

CA-Markov models represent an urban area with a lattice of cells, each of which exists in one of a finite set of states. The progression of time is modeled as a series of discrete steps with future patterns determined by transition rules which specify the behavior of cells over time (Kityuttachai et al., 2013) The IDRISI Sleva from Clark Lab (Clark University) is the software for simulating the land use change and the CA-Markov analysis. The CA-Markov analysis was run to test a pair of land cover images and outputs a transition probability matrix and a transition areas matrix. The transition probability matrix would explain the probability that each land cover category will change to every other