Chin. Geogra. Sci. 2012 Vol. 22 No. 2 pp. 127–143
doi: 10.1007/s11769-012-0524-2
www.springerlink.com/content/1002-0063

Spatial Scale Effects of Water Erosion Dynamics: Complexities, Variabilities, and Uncertainties

WEI Wei, CHEN Liding, YANG Lei, FU Bojie, SUN Ranhao

(*State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China*)

Abstract: Severe water erosion is notorious for its harmful effects on land-water resources as well as local societies. The scale effects of water erosion, however, greatly exacerbate the difficulties of accurate erosion evaluation and hazard control in the real world. Analyzing the related scale issues is thus urgent for a better understanding of erosion variations as well as reducing such erosion. In this review article, water erosion dynamics across three spatial scales including plot, watershed, and regional scales were selected and discussed. For the study purposes and objectives, the advantages and disadvantages of these scales all demonstrate clear spatial-scale dependence. Plot scale studies are primarily focused on abundant data collection and mechanism discrimination of erosion generation, while watershed scale studies provide valuable information for watershed management and hazard control as well as the development of quantitatively distributed models. Regional studies concentrate more on large-scale erosion assessment, and serve policymakers and stakeholders in achieving the basis for regulatory policy for comprehensive land uses. The results of this study show that the driving forces and mechanisms of water erosion variations among the scales are quite different. As a result, several major aspects contributing to variations in water erosion across the scales are stressed: differences in the methodologies across various scales, different sink-source roles on water erosion processes, and diverse climatic zones and morphological regions. This variability becomes more complex in the context of accelerated global change. The changing climatic factors and earth surface features are considered the fourth key reason responsible for the increased variability of water erosion across spatial scales.

Keywords: water erosion; spatial variation; scale effect; driving force; uncertainty; complexity

Citation: Wei Wei, Chen Liding, Yang Lei, Fu Bojie, Sun Ranhao, 2012. Spatial scale effects of water erosion dynamics: Complexities, variabilities, and uncertainties. *Chinese Geographical Science*, 22(2): 127–143. doi: 10.1007/s11769-012-0524-2

1 Introduction

As one of the major types of land degradation on the earth surface, soil erosion caused by water has induced large-scale environmental deterioration and widespread declines in land productivity, which threatens the health and sustainability of human-earth systems (Fu, 1989; Kheir *et al.*, 2006). For example, accelerated overland flow and water erosion have led to considerable on- and off-site damages, including the pollution of drinking water resources and flooding of rural and urban areas (Cerdan *et al.*, 2004; 2010). New researches indicate that severe erosion caused by rainwater runoff might contribute significantly to global climate change owing to larger amounts of carbon releasing from the soil to the atmosphere (Lal, 2004; Gaiser *et al.*, 2008). These factors have made water erosion a critical issue in many countries due to its negative impacts on crop systems, water bodies and other ecosystems, and related ecological services (Bryan, 2000; Renschler and Harbor, 2002). Accurate estimation of water erosion is thus extremely important in a number of environmental contexts, such as the assessment of potential soil loss, the evaluation of water storage capacity losses in reservoirs due to sedi-

---

Received date: 2011-06-28; accepted date: 2011-09-12
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 40925003, 40930528, 40801041)
Corresponding author: CHEN Liding. E-mail: liding@rcees.ac.cn

ment deposition, and the effects of water erosion on environmental quality across different regions and scales (Nearing *et al.*, 2000; Amore *et al.*, 2004; Xu and Yan, 2005).

However, the dynamics and consequences of water erosion have proven to be quite complex (Yair and Raz-Yassif, 2004). This complexity consequently increases the variability and uncertainty of water erosion potentials and risks over time and space in the real world, which are referred to as the scale effect (García-Ruiz *et al.*, 2010). This effect is one of the biggest obstacles for correctly dealing with water erosion issues across a range of scales (Xu and Yan, 2005). Generally, scale issues are critical in soil erosion sciences and related fields such as physical geography and hydrology because of their significance to data availability and quality, model development, and the output of important information and valuable references for policymakers (Vigiak *et al.*, 2006).

Due to scale effects, conducting water erosion assessments across a wide range of spatial scales is quite difficult (Cerdan *et al.*, 2010). For example, spatial heterogeneity often constrains the ability to translate information from one scale to another in certain landscapes (Peeters *et al.*, 2008). Specific runoff and sediment yields generally decrease with the increase in the area (Yair and Raz-Yassif, 2004), and Xu and Yan (2005) found that sedimentation first increases with the increaseing area of the Huanghe (Yellow) River basin, reaches a maximum, and then declines, and the reasons for this trend are not independent of the scale. Therefore, monitoring data based on real-time measurements *in situ* from relatively small scales can not simply be used for larger-scale erosion quantification as well as prediction, and vice versa (Chen *et al.*, 2009). Other researchers have drawn similar conclusions. For instance, Boix-Fayos *et al.* (2006) pointed out that soil loss data obtained from plot scales are very hard to extrapolate at catchment levels, mainly because the heterogeneity of a catchment is always much higher than that of a plot.

Exploring the complex driving forces and dynamic rules of water erosion across different scales, therefore, is urgent for soil-water loss disaster assessment, management, and policy readjustment (Wang *et al.*, 2002; Wei *et al.*, 2007; Tefera and Sterk, 2010). In order to achieve this purpose, water erosion processes at three typical spatial scales (i.e., plot, watershed, and region) are the focus of this paper. A better understanding of water erosion variation across scales is expected, which is helpful for sustainable land management strategies targeting spatial hazard evaluation and minimization, and consequently providing benefit to erosion control in practice.

2 Water Erosion Dynamics Across Various Spatial Scales

Water erosion is generally shown to be highly scale-dependent and to vary significantly across different spatial scales, such as plot, small and large watersheds, and regions (Table 1). The major targets, advantages and disadvantages, mechanisms and drivers, and specific processes of runoff volumes and soil loss rates might all change with alterations in the spatial scale (Fig. 1). Herein, in order to get a better understanding of water erosion issues, the scale effects of water erosion processes are discussed based on three major spatial levels.

2.1 Plot scale

2.1.1 Purpose and objectives of water erosion study

The purpose and objectives of water erosion studies at the plot scale are specific and multiple, and are mainly determined by the focus of the researchers. For example, some researchers make great efforts to determine the quantitative relationships between rain-runoff-erosion, and some focus on developing conceptual or mathematical models to depict and predict different water erosion responses based on the measured data *in situ*, while others are likely to focus on the real roles of multiple influencing factors, such as land use, tillage, rotation, mulching, plot length, slope gradients, morphology of plant species, and micro-topography, on runoff-erosion rates (Bochet *et al.*, 1998; Boix-Fayos *et al.*, 2006; Xu *et al.*, 2008). In general, however, soil erosion induced by rainwater at the plot scale have proven to be extremely important since the very beginning of erosion research (Nearing *et al.*, 2000; Cerdan *et al.*, 2004; Wei *et al.*, 2007; Jin *et al.*, 2008). Discoveries found at the plot scale have been used to reflect key changes in direction or trends at higher scales, including regional or even global levels. Meanwhile, consecutive field measurements provide large quantities of basic data and important parameters for model calibration and validation (e.g., universal soil loss equation (USLE), revised uni-

Table 1 Major progress in spatial water erosion studies around the world

Key study areas	Spatial scale levels	Methodology	Major conclusions	References
Sicilian basins, Italy	Watershed	USLE/WEPP model	Neither USLE nor WEPP was sensitive to the size or covered area of the hill-slope	Amore *et al*., 2004
Western Sicily, Italy	Plot	Field observation	Soil loss did not vary significantly with slope length	Bagarello and Ferro, 2010
Almería, Spain	Watershed	Field observation	Runoff and soil erosion were controlled by the soil surface type	Cantón *et al*., 2001
Madrid, Spain	Plot	Rainfall simulation experiment	Plant cover was the main factor reducing surface runoff and the movement of sediment	Casermeiro *et al*., 2004
Western Sierra Madre, Mexico	Watershed	Field observation	Runoff and soil loss within the extension of a considered area varied with the spatial distribution of land use and the geological context	Descroix *et al*., 2008
Spain	Region	WATEM-SEDEM/ PESERA/SPADS model	Gully erosion, river channel erosion, and sediment transport processes were much more important than sheet and rill erosion for regional scale sediment yield	de Vente *et al*., 2008
Iberian Peninsula, Spain	Plot	Field observation	Land use/cover, farmland set aside, and land misuse greatly affected the runoff and soil erosion	Dunjo *et al*., 2004
Almeria, Spain	Region	SPEROS model	Land abandonment decreased water erosion and the conversion of abandoned land to intensively cultivated arable land increased water erosion	Govers *et al*., 2006
Embu, Kenya	Watershed	LISEM model	The effect of soil and water conservation on a watershed scale was different from that on a pixel scale	Hessel and Tenge, 2008
Luoyang, China	Plot	Rainfall simulation experiment	No till with mulch was the best alternative as compared with other soil management practices in terms of soil erosion control	Jin *et al*., 2008
Belgium	Plot	Laboratory experiment	Effect of transmission losses on runoff and erosion on arable land was highly significant	Leys *et al*., 2010
USA	Plot	Field observation	Variances between replicates decreased as a power function of measured soil loss, and were independent of whether the measurements were event, annual, or multi-year values	Nearing *et al*., 1999
Central Europe	Plot	Field observation/ laboratory experiment	Plot length was important in determining the effectiveness of mulch cover in reducing soil erosion	Smets *et al*., 2008b
Jiangxi, China	Watershed	Field observation	The spatial variation of surface crust and/or the vegetation cover controlled the source of sediment	Uchida *et al*., 2000
Indonesia	Plot/ Watershed	Field observation	Landslides, river bank erosion, and the concentrated flow erosion of small footpaths were the main reasons for a difference between the plot and watershed scales	Verbist *et al*., 2010
Kwalei, Tanzania	Watershed	MMF/LISEM/Vigiak/ Okoth/FIT model	Spatial scale of erosion distribution coincided with the overland flow distribution at short re-infiltration length	Vigiak *et al*., 2006
Valencia Spain	Watershed	Field observation	The bare road embankments contributed 30 times more soil erosion than the vegetated ones	Cerdà, 2007
Huanghe River basin, China	Region	Field observation	With increasing basin area, the sediment yield increased, reached a maximum, and then declined	Xu and Yan, 2005
Maoxian, China	Plot	Field observation	Relatively small leaf area but low height and dense canopy controlled runoff and soil loss	Xu *et al*., 2008
Sede Boquer, Israel	Watershed	Field observation	Positive relationships between slope length and deposition rates, regardless of slope angles	Yair and Raz-Yassif, 2004
West Africa	Plot/ Watershed	Field observation	Temporal dynamics of the rainfall-runoff process determined the reduction of runoff coefficients from longer slopes	de Giesen *et al*., 2011
Meuse basin, Europe	Region	WATEM-SEDEM model	Sensitivity of sediment yield changes in climate increased as the percentage of deforested land increased	Ward *et al*., 2009

Notes: USLE: universal soil loss equation; WEPP: water erosion prediction project; WATEM-SEDEM: a spatially distributed soil erosion and sediment delivery model; PESERA: pan- European soil erosion risk assessment model; SPADS: spatially distributed scoring model; LISEM: limburg soil erosion model

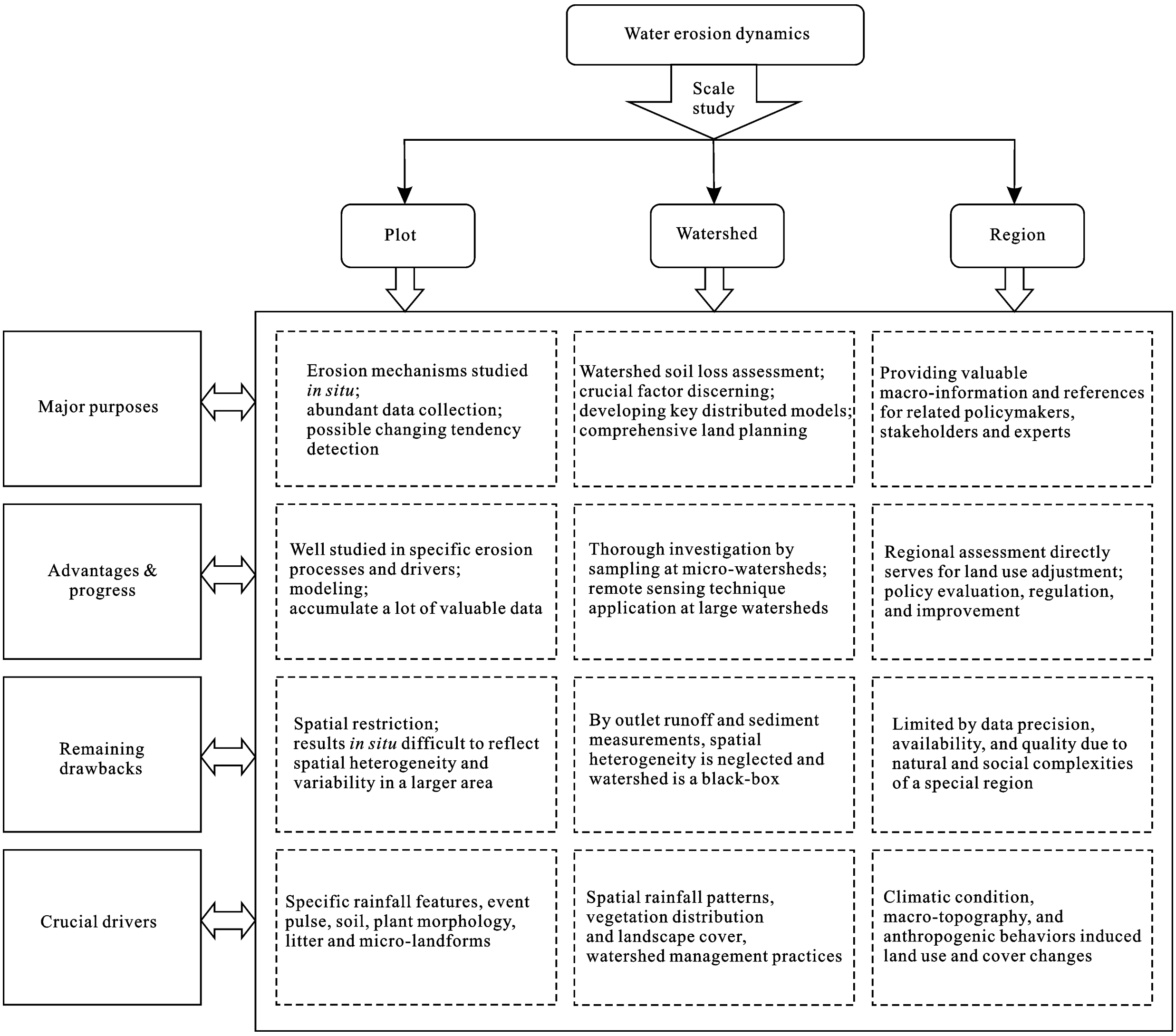

Fig. 1 Important characteristics of water erosion studies on three typical spatial scales

versal soil loss equation (RUSLE), and water erosion prediction project (WEPP)) as well as larger-scale predictions.

In general, three major objectives of water erosion researches at plot scale are valuable: 1) finding and understanding the mechanisms and phenomena regarding water erosion dynamics and related influencing factors *in situ*; 2) collecting abundant experimental data and providing for the establishment, validation, and calibration of soil erosion models as well as trend forecasting across higher scales; and 3) uncovering important evidence about specific regional backgrounds, such as a potential variable tendency of surface runoff volumes or soil loss rates with changes in natural rainfall in the context of possible human-induced global warming or changing environmental conditions.

2.1.2 Major advantages and disadvantages

During the past several decades, many researches regarding water erosion processes at the plot scales have been conducted. Some experimental techniques and (semi-) quantitative methods have been involved. As a result, all of these efforts have greatly accelerated advances in water erosion research and soil conservation science. Several major aspects of these water erosion advances and remaining problems at the plot scale are addressed systematically in the following paragraphs.

The major advantages and progresses of water erosion research at the plot level are fourfold. First, the driving forces and specific processes of water erosion in plots have been adequately studied. For instance, runoff generation and sediment production are confirmed to be directly correlated with vegetation (Rey, 2004; Kakembo, 2009). However, huge uncertainties remain because different plants show different results regarding soil erosion control (Imeson and Prinsen, 2004; Seeger, 2007). Interrelations between erosion rates and other specific variables such as rain, land use, and slope gradients as well as field management measures like tillage, mulching, and cultivation increase this uncertainty (Lundekvam, 2007; Smets *et al.*, 2008b; Cerdan *et al.*, 2010). These processes, however, are of significance (at least at field scales) for land structure readjustment, plant species selection, and vegetation community protection as well as soil erosion reduction. Second, the concept of a so-called 'standard unified plot' has been developed and implemented in practical studies, which is significant and necessary for erosion prediction, data utilization, and related scale transformation (Zhang *et al.*, 2000). Due to diversity in the plot sizes used in different studies, researchers indicate that standard plot sizes should be established according to the specific features of different locations. For example, the unified plot in China was suggested as fallow lands of 20 m length and 5 m width with a 15℃ slope gradient (Zhang *et al.*, 2000), which is different from the U.S. standard (Amore *et al.*, 2004). Third, long-term consecutive measurements at the plot level are quite significant for collecting sequential data and reflect event-based erosion dynamics, secular rainfall change, and vegetation succession as well as soil loss fluctuation at a series of temporal scales (Boix-Fayos *et al.*, 2006). Last, based on data collected and measured at the plot level, many conceptual, semi-quantitative, quantitative, and physical-based mathematical models (USLE, RUSLE and WEPP) have been developed and widely used in climatic and geographical zones around the world (Nearing *et al.*, 2000; Renschler and Harbor, 2002; Yan and Xu, 2006).

The major drawback of soil erosion study at the plot level, however, is the spatial restriction owing to the relatively smaller experimental area. It is usually not possible to reflect the spatial heterogeneity and variability of a certain region only through the analysis of field data (Blöschl and Sivapalan, 1995) (Fig. 1). Due to the existence of the scale effect, the phenomena and rules discovered at the plot scale do not always fit with those found at larger spatial scales. Furthermore, there are several water erosion types in real landscapes and eco-environments. Studies based on plots, however, only concentrate on splash, rill, and inter-rill erosion in certain gradients and slope lengths. Other erosion types such as ephemeral/permanent gully, bunk, and channel erosion do not occur and can not be taken into account. Thus, greater efforts need to be made to better understand soil erosion dynamics and to solve related problems across various scales.

2.1.3 Driving forces and mechanisms

In micro-plots (plant scale) with covered areas less than 1 m^2, the water erosion process is mainly affected by rainfall and the morphological conditions of isolated plant species on the site (Renschler *et al.*, 1999; Dunjo *et al.*, 2004). In addition to rainfall, isolated plants in micro-plots, which consist of various types, covers, growing stages, and morphological features, play important roles in decreasing the walloping energy of raindrops on surface soil in a variety of environments (Bochet *et al.*, 1998; Smets *et al.*, 2008b; Xu *et al.*, 2008) and inducing high spatiotemporal variations of soil erosion rates and sediment outputs (Sánchez and Puigdefábregas, 1994; Xu *et al.*, 2008; Vásquez-Méndez *et al.*, 2010). Meanwhile, in small plots (i.e., 0.1–0.4 m^2; 0.1 m < plot length < 0.61 m), only splash detachment (sometimes inter-rill erosion) was observed (Smets *et al.*, 2008a). Rill erosion, concentrated flow, and gully erosion generally have no developing chance mainly due to the extreme shortness of the plot length, especially under high plant coverage.

In meso-plots (area of 0.01–100 m^2) and macro-plots (area of 10–10 000 m^2), the factors that affect water erosion are more complex than those found in micro-scale plots (Poesen *et al.*, 1994; Descroix *et al.*, 2008). Rain erosivity is a basic factor governing the risks, extents, magnitudes, rates, and frequencies of water erosion *in situ* (Renschler *et al.*, 1999; Wei *et al.*, 2007), and four other aspects regarding the surface features of the earth may play key roles. First, the growing status, canopy covers, types, morphological shapes, and landscape positions of vegetation in plots all contribute to uncertainties and variations in soil loss rates (Sánchez and Puigdefábregas, 1994; Zhang *et al.*, 2006). For example, Rey (2004) found that 20% canopy coverage of grasses and under-shrubs at the bottom of a plot prevents most soil erosion and water loss. Based on rainfall simulations on 29 natural plots, Casermerio *et al.* (2004) found that high canopy coverage effectively controlled runoff and soil erosion rates. The result of another study indicates that vegetation at the bottom of the plots plays a more powerful role in controlling soil loss than vegetation at the upper and other parts of the plots (Rao and Cui, 2008).

Soil surface coverage also affects the dynamics of water erosion. The spatial variations of rock fragment cover influence water erosion rates and patterns, and high rock fragment cover on steep slopes leads to a reduction in local rill and inter-rill erosion (Poesen *et al.*, 1994; 1998; Govers *et al.*, 2006). The second aspect regarding the surface features the earth is the microtopography on slopes. The undulation of micro-landforms and the specific convex-concave structures of hillslopes are the major drivers for the 'source-sink' role of water erosion dynamics (Kirkby, 2001; Zhang *et al.*, 2006). The third aspect is slope length. Due to the short plot length, it is generally not an important factor for overland flow at the micro-plot scale, unlike meso- and macro-plots (Fig. 2). Uncertainties, however, still remain. Although the majority of studies consider that runoff, soil loss rates, and sediment transportation increase as slope length increases (Kinnell, 2000; Bagarello and Ferro, 2010), contrasting experimental results can be found in the recorded literature. For example, the result of a field observation in the Negev Highlands shows a positive relationship between deposition and slope length (Yair and Raz-Yassif, 2004). The longer the plot length, the higher the uncertainty that deposition and sediment yield will appear. The fourth aspect is local soil conditions. Soil sealing and crusting, aggregate stability, antecedent soil moisture, and organic matter content may all play a role in the degree of infiltration capacity, runoff generation, and soil loss. These parameters are also confirmed to be highly variable across time and space (Seeger, 2007; Smets *et al.*, 2008a).

2.2 Watershed scale

2.2.1 Purpose and objectives of water erosion study

There are three major purposes of water erosion studies at the watershed scale. First, it enables a better understanding of the mechanisms and processes of water erosion across different types and sizes of watersheds in different regions. In other words, watershed diversity and variability are very high, mainly because of the adaptability and complexity of natural factors (e.g., topography, climate) and human activities (e.g., deforestation/reforestation, cultivation, and infrastructure construction) in different areas. These differences alter the surface properties of the earth and eventually induce higher soil erosion variation. Much attention has been paid to the role of changes in vegetation cover and landscape patterns on runoff, soil loss, and sediment delivery ratios at the outlets of watersheds. Moreover, much attention has also been paid to the spatiotemporal effects of natural rainfall and its role, along with landscape conditions, in the water erosion dynamics of the whole watershed. Studies on the response of water erosion to rainfall variability over time and space, however, are restricted by the actual covered areas and climatic locations of watersheds in many cases. For example, precipitation and related hydrological processes may not experience high spatiotemporal variations in micro-watersheds (less than 1 km^2) as compared with large

Plot 1: 1.2 m × 1.2 m; Plot 2: 2 m × 4 m; Plot 3: 5 m × 10 m; Plot 4: 5 m × 20 m; location: semi-arid loess hilly area in China
Splash erosion is reduced by effective plant coverage in plots 1 and 2. Meanwhile, with the shortness of plot length, overland flow did not occur in these two plots. On the contrary, rill and ephemeral gully erosion were well developed due to the erosive rainfall, bare soil, and long plot length in Plot 4.

Fig. 2 Different sizes and lengths of experimental plots watersheds (over several hundreds of km^2) with fragmentized landforms. Moreover, the heterogeneity and complexity of landscapes and topographies may vary widely across different climatic zones and geographical regions, subsequently causing various water erosion consequences.

Secondly, water erosion research at the watershed scale aims to provide valuable information and references for comprehensive watershed management, hazard minimization, landscape planning, and land optimization. This is because landscapes and ecosystems in certain watersheds are relatively integrated and independent as compared with plots or a whole slope. Therefore, erosion hazard assessments are often carried out for the planning of soil loss control on a watershed scale (Stroosnijder, 2005).

Third, researches at the watershed level often involve attempts to develop feasible indices (location-weighted landscape-contrast index, multi-scale soil-loss evaluation index) or spatially-distributed/process-based soil erosion models (e.g., the European soil erosion model (EUROSEM), a kinematic runoff and erosion model (KINEROS), areal nonpoint source watershed environmental response simulation (ANSWERS), limburg soil erosion model (LISEM), soil and water assessment tool (SWAT), agricultural non-point source (AGNPS), WEPP, and so on) for quantitative water erosion assessments and forecasts at the watershed level (Nearing *et al.*, 1999; Poesen *et al.*, 2003; Chen *et al.*, 2009). These indices and models, however, are focused on evaluating soil erosion hazards and thereby launching practical comprehensive land management plans.

2.2.2 Major advantages and disadvantages

The major advantage/progress in soil erosion science at the watershed level can be summarized in two aspects. At micro-catchments (62–255 m^2, 5775 m^2, and 18 796 m^2 according to Cantón *et al.* (2001)) and other types of small watersheds (less than several square kilometers in size), it is much easier for researchers to launch a thorough investigation by setting sampling plots or establishing ecological transects throughout the whole area, considering different slope conditions, vegetation types, and human disturbances on the site, plot, slope, and watershed scales. The related soil, vegetation, and water samples can all be collected for further analysis. In larger, more complex watersheds (over hundreds or even thousands of square kilometers), however, it becomes very difficult and even impossible to launch detailed surveys through artificial investigations due to the large covered areas and high spatial heterogeneity. Technologies such as remote sensing (RS) and Geographical Information Systems (GIS) then become the most powerful tools (Renschler and Harbor, 2002; Vireling, 2006).

Generally, the disadvantages (or drawbacks) of water erosion research at the watershed scale are related to three main things. First, it is quite difficult to monitor the spatial changes from relatively long-term consecutive temporal scales, mainly because of the large size of the covered area and landform complexity in addition to the diverse land use consequences induced by human disturbances. To date, the most common method is to collect runoff and sediment yield at the outlet of a watershed, while the spatial variability within the watershed can not be detected without spatially distributed data collection. Second, monitoring and collecting spatial hydrological erosion data for a whole watershed is difficult. Data at the outlet is not enough to analyze the dynamics of specific erosion processes within the watershed. In this case, a watershed can only be considered as a black-box and no other information is available. Fortunately, many researchers have tried to analyze the spatial variability of water erosion consequences within certain watersheds by considering spatiotemporal differences in rainfall, landscape, and topography. However, this is a huge task due to the complexity of hydrological dynamics, especially in fragmented semiarid ecosystems. Third, in order to assess and predict water erosion dynamics in large watersheds, different models must be developed and used. However, model uncertainty becomes one of the key error sources for prediction and evaluation, possibly providing misleading messages for stakeholders, researchers, and policymakers.

2.2.3 Driving forces and mechanisms

In general, soil erosion dynamics at the plot scale are more propitious for studying the mechanisms of specific water erosion processes (Boix-Fayos *et al.*, 2006). At a watershed scale, however, soil erosion becomes more complicated due to the interactive multi-factors and diverse erosion types (splash, rill, sheet, gully, and bunk erosion) (Cammeraat, 2004; Govers *et al.*, 2006; Leys *et al.*, 2010). Large-scale land use/land cover change may become a key driving force inducing erosion variations at the watershed scale as compared with what is found with experimental plots of various sizes (Poesen *et al.*, 2003). In practice, reforestation and other forestry management techniques as well as soil and water conservation management can impact horizontal/vertical vegetation distribution and consequently hydrological erosion processes (Zhang *et al.*, 2006; Hessel and Tenge, 2008; Tefera and Sterk, 2010).

In most cases, a decreasing trend of water erosion rates was found with increasing watershed area (Xu and Yan, 2005; Chen *et al.*, 2009), although de Vente *et al.* (2007) have drawn different conclusions. It indicates that a complete catchment can not be simply considered as the sum of each individual field (Cerdan *et al.*, 2004). As compared with erosion rates measured in experimental plots *in situ*, the likelihood of sediment deposition increases when the drainage area becomes larger, which may eventually result in a lower sediment delivery ratio and yield (SDY) at the outlet of a watershed (Boix-Fayos *et al.*, 2006). Therefore, simple extrapolations based on data from plot scales will, in most conditions, lead to an overestimation of water erosion at watershed or larger levels. Moreover, gully, channel, and gravity erosion as well as sediment transportation processes may become more dominant than sheet and rill erosion for watershed scales, especially in watersheds characterized by high landscape heterogeneity and fragile ecosystems (e.g., the loess hilly and gully area in China). In general, however, common factors such as rainfall variability, land use patterns, mean slope gradient, slope length, gully density, soil features, and vegetation cover can interact with each other and play complex roles in determining the variations and heterogeneities of water erosion, regardless of the specific watershed area.

2.3 Regional scale

2.3.1 Purpose and objectives of water erosion study

Unlike soil erosion studies at the plot or watershed level, the key purposes and objectives of water erosion assessment at regional or larger scales are different. In general, research and evaluation on soil erosion at a regional scale are mainly helpful for assessing and predicting current and future erosion status and hazard potentials in certain regions as a whole (Kheir *et al.*, 2006), providing valuable information for policymakers, stakeholders, and related experts. Research and assessment on soil erosion at this scale directly influence the public in terms of providing advice on natural hazards and human impacts, and also serve as the basis for regulatory policy for comprehensive land use management (Renschler and Harbor, 2002).

2.3.2 Major advantages and disadvantages

The major advantage for assessing regional soil erosion is that it can provide an important reference point for policymakers and community stakeholders in order to detect macro-scale water erosion potentials and degradation trends (Gobin *et al.*, 2004; Vrieling, 2006). It also can provide valuable information on historical/current land management problems and the effects of related policies (Gobin *et al.*, 2004; Chen *et al.*, 2009). Then, as positive feedback in practice, corresponding comprehensive treatments regarding erosion control can be planned and implemented based on these assessment reports.

As compared with soil erosion studies at the plot or watershed level, the major disadvantages of regional studies are related to the difficulties in quantifying specific relationships between soil erosion processes and influencing factors. Due to the relatively larger areas of plots and watersheds, regional erosion assessment is always limited by data availability and quality (Boardman, 2006). Thus, satellite remote sensing techniques are frequently used for the evaluation and analysis on potential erosion. The results and conclusions, however, are always too general, qualitative, and imprecise, and sometimes even full of errors. Moreover, water erosion assessment at the regional level is not sufficient enough to explain the detailed mechanisms of water erosion dynamics and its evolvement.

2.3.3 Driving forces and mechanisms

Monitoring and assessing water erosion at the regional level have received more attention since the 1990s, mainly because it can directly provide valuable information for policymakers (de Vente *et al.*, 2008). However, water erosion analyses on regional scales generally have essential differences from those on watershed scales. The concept of a region is always defined and classified by the related administrative departments and thus contains political meanings. From the physical geography point of view, the regional scale has no entirely clear integrated, independent boundaries, whereas a watershed does. Therefore, different watersheds and climatic zones may be involved in a single region, and are mainly determined by the actual area of this region (Yan and Xu, 2006). The diversity and complexity of the influencing factors and driving forces are much higher than those at plots and watersheds. As a result, different hydrological and soil erosion processes and consequences are found.

The driving forces and mechanisms of water erosion processes at the regional level are closely connected with three major factors: climate condition, macro-topography, and anthropogenic behaviors induced by land use changes (Descroix and Gautier, 2002; Poesen *et al*., 2003; Aksoy and Kavvas, 2005). For instance, regional rainfall erosivity is the main factor in inducing potential water erosion risk in certain geographical areas (Renschler *et al*., 1999; Wang *et al*., 2002; Ward *et al*., 2009). Widespread land use changes coupled with huge losses of protective vegetation coverage (i.e., deforestation, overgrazing, man-made fires, and cultivation of steep slopes) is often considered as the major human behavior causing erosion (Barthès *et al*., 2000). On the other hand, wise land use policy and its successful implementation in practice can contribute to the improvement of vegetation communities and land covers as well as landscape conditions, which may reduce the degree and frequency of erosion destruction (Renschler and Harbor, 2002; Gobin *et al*., 2004; Tefera and Sterk, 2010).

3 Discussion

As discussed above, the drivers, influencing factors, types, and specific processes of water erosion are quite variable with the changes in spatio-temporal scales. In addition to these facets (e.g., high variation in rainfall patterns, soil parameters, and human activities), three other major contents are stressed as follows (Fig. 3). These factors contribute to the complexities, variabilities, and uncertainties of water erosion over time and space in most cases.

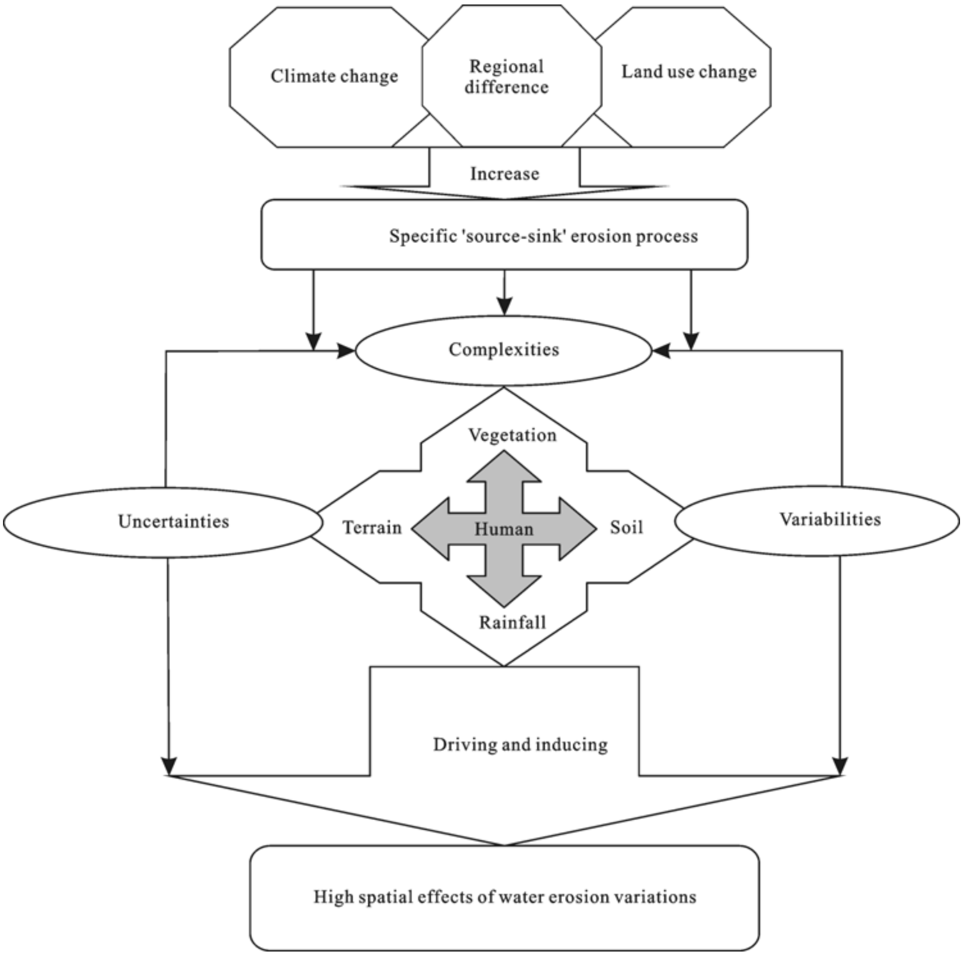

Fig. 3 Framework for understanding spatial scale effect of water erosion

3.1 Differences in methodologies across different scales

Generally, in order to study hydrological and erosional processes across different spaces, multiple approaches and methodologies are used in various spaces and locations, including experimental measurements and long-term observations *in situ* (Wei *et al*., 2007; Cerdan *et al*., 2010), rainfall and hydrological simulations in controlled conditions (Bryan and Luk, 1981; Seeger, 2007), artificial neural networks for quantitatively predicting soil loss rates from natural runoff plots (Licznar and Nearing, 2003), multiple-scale soil erosion evaluated indices (Chen *et al*., 2001; Chen *et al*., 2009), conceptual/mathematical modeling (Blöschl and Sivapalan, 1995; Baffaut *et al*., 1996; Kirby, 2001; Aksoy and Kavvas, 2005; Vigiak *et al*., 2006; Dymond *et al*., 2010), aerial photographs, images, and satellite remote sensing (Vrieling, 2006), and spatial analysis based on GIS and Global Positioning Systems (GPS) (de Vente and Poesen, 2005; Kheir *et al*., 2006).

The differences among these methods bring great uncertainties and complexities to specific water erosion responses across different scales (Renschler and Harbor, 2002; Bagarello and Ferro, 2004; Boix-Fayos *et al*., 2006). Moreover, current approaches regarding soil erosion measurements and analysis have experienced many drawbacks, limitations, and uncertainties (Boardman, 2006). For example, although rainfall simulation techniques have been widely used to characterize the magnitude of soil loss at the plot scale, there is enough evidence to show that such simulations always induce extra uncertainty and distortion in contrast to what occurs in the real world (Bryan and Luk, 1981; Seeger, 2007). According to this discovery, water erosion has been greatly underestimated in rainfall simulation experiments as compared with natural rainfall conditions (Nearing *et al*., 1999; Boix-Fayos *et al*., 2006). The kinetic energy of raindrops produced by the nozzles of simulated rainfall is always said to be lower and more constant as compared with that of natural raindrops, which is believed to be the key reason of inducing greater anamorphic and unauthentic erosion consequences than those in reality (Boix-Fayos *et al*., 2006). Moreover, the accepted method of rainfall simulation is more suitable for plot-scale water erosion studies, but not very convenient for soil erosion research at the watershed or regional scale due to the large covered areas.

Methods for scaling up or down are still less developed to date (Blöschl and Sivapalan, 1995; Boardman, 2006). For example, almost all current soil erosion models are developed based on a certain spatial scale (Vigiak *et al*., 2006). The structures, parameters, and operation types of these models all change significantly with the varied scales, and are only suitable for water erosion assessment and evaluation at the corresponding scale but not for other scales (Aksoy and Kavvas, 2005). For example, experiential and empirical soil erosion models based on large quantities of runoff measurements (such as USLE and RUSLE) mainly consider the influencing factors of sloping plots and hill slopes (Wang *et al*., 2002; Lundekvam, 2007). Different models including physical, empirical, or distributed models have been applied across a range of spatial scales (Blöschl and Sivapalan, 1995; Van de Giesen *et al*., 2000; Amore *et al*., 2004), so it is difficult to distinguish the relevant driving factors of water erosion processes and launch scale transformation studies across these spatial scales. For instance, the scaling up of runoff and soil loss from models at the plot scale to larger scales always causes inaccurate outcomes, mainly because different erosion processes occur and even become dominant when the spatial scale changes (Cerdan *et al*., 2004). These involved surface processes may be rill, gully, or bunk erosion, or mass movement, and it is difficult to monitor them accurately only through plot measurement methods (Verbist *et al*., 2010).

3.2 Role of 'source-sink' in water erosion variations at various scales

The so-called 'source–sink' in hydrological processes at the surface of the earth also causes high variability and complexity of water erosion across different spatial scales (Fig. 3). For example, in semiarid and arid ecosystem zones, landscapes at convex-concave hill slopes are shaped by patchy vegetation clusters (Sánchez and Puigdefábregas, 1994; Kakembo, 2009). These vegetation-bare soil mosaics are key bio-geo-indicators for identifying the magnitude and connectivity of runoff and sediment source-sink areas (Imeson and Prinsen, 2004). On the one hand, soil crusting and sealing always occur at bare-soil sites with no vegetation cover, leading to a reduction of infiltration capacity and thus an increase in surface runoff generation (Uchida *et al*., 2000). In vegetated patches, on the other hand, soil infiltration capacities are markedly improved and precipitation is absorbed, resulting in low soil erosion rates (Cammeraat, 2004; Lesschen *et al.*, 2008). These two conditions are therefore defined as the source and sink landscapes and play distinct roles in water erosion processes (Zhang *et al.*, 2006). Moreover, previous studies indicate that the dynamics and inter-translations of erosion 'source' or 'sink' greatly increase the uncertainties and complexities related to hydrological erosion (Kirkby, 2001; Chen *et al.*, 2009).

All of these previous studies have mainly focused on the roles of vegetation patterns and specific micro-opographical conditions on soil and water loss in addition to sediment yields. For instance, in patchy arid and semiarid lands, the 'source-sink' areas driven by vegetation patterns play a key role in surface water flow and soil erosion dynamics (Cammeraat, 2004). Plants and their distribution in real landscape conditions serve as a function of water absorbing patches and can be regarded as an important buffer for controlling soil and water loss, which is thus considered a 'sink' area in runoff and soil erosion processes (Imeson and Prinsen, 2004). The micro-topography, however, is more complicated due to its scraggly and undulant surface features (Kirkby, 2001). In general, the convex part of the surface of the earth can sometimes accelerate an overland flow and play the 'source' role, while at other times it may play a sink (as erosion 'controlling buffers' in a sense) role to reduce runoff velocity and collect water sediment yields due to the relatively high number of micro-landforms (Zhang *et al.*, 2006; Xu *et al.*, 2008). Similar conditions occur at the concave soil surface (i.e., sometimes a source while other times a sink). Ludwig *et al.* (2005) found that three patchy lands, including different vegetations, bared soil vegetation mosaics, and banded vegetation patterns, play various roles in the patterns and processes of soil erosion and water loss. Moreover, the areas for source and sink erosion always transform from each other (Chen *et al.*, 2008). Under certain conditions, a source area may change into a sink area while in other cases an erosion sink will be a source for soil erosion (Imeson and Prinsen, 2004). These inter-transformations consequently increase the variability, complexity, and uncertainty of hydrological and soil erosion processes.

3.3 Differences in various scales by geographical region

Changes in geographical units and climatic zones are another major reason for an increase in the variability and complexity of water erosion dynamics across different spatial scales (Cerdan *et al.*, 2010). It is not difficult to understand that climates, landscape units and elements, landforms, land management behaviors (sloping cultivation, over-gazing, reforestation, afforestation, deforestation, types and stages of land abandonments), and socioeconomic status (population densities, economic levels, industrial distributions, *etc.*) may vary markedly with the changes in natural geographical regions (Descroix and Gautier, 2002; D'odorico and Porporato, 2005; Lesschen *et al.*, 2008) (Fig. 4). In these typical regions, different climatic zones, topography, vegetation dynamics and cover, land use, and human factors are involved, which highly increase the variability and complexity of water erosion responses. Such variations are confirmed to be scale-dependent (Blöschl and Sivapalan, 1995), leading to higher complexities and uncertainties of water erosion responses across time and space.

At the plot scale, there are two typical situations. First, when the rainfall-runoff-erosion plots are established in very similar eco-environments (e.g., on the same hill slopes or locations), variations in the geographical and climatic zones are not involved. However, even under these conditions, the specific soil properties (e.g., previous soil moisture, aggregate stability, organic matter, crusting and sealing), plants (e.g., morphology, type, stage, and structure), micro-landforms (e.g., convexity and concaves), and site management techniques (e.g., mulching, tillage, weeding, *etc.*) may differ, thus inducing variations in specific water erosion processes (Smets *et al.*, 2008b; Cerdan *et al.*, 2010). Second, when these experimental plots are established in different regions, the variations in soil types (different classes) and climatic factors such as rainfall erosivity play a dominant role (Boix-Fayos *et al.*, 2006). As a result, the uncertainty and variability of water erosion calculated from these plots increases. These variations, however, should be considered as water erosion changes within the same spatial scale, and not among different scales.

At the watershed scale, the local landforms, soil conditions, landscape diversity, and vegetation communities become more complicated when compared with those at the plot scale (Ward *et al.*, 2009). Two different conditions also appear. On the one hand, at micro and very small watersheds (less than several square kilometer), different geographical regions may not be involved due

a: a typical watershed in the Loess Plateau of Northwest China; b: a landscape in Tucson, the semiarid region in America; c: a typical tillage area in Northeast China, where tillage erosion and ephemeral erosion occur frequently; d: a small watershed in Germany with a landscape covered by grasses and patchy shrubs

Fig. 4 Several typical landscapes in different regions of the world

to the small size of the covered areas. The spatio-emporal variations of topography and soil systems as well as climatic variables in such types of watersheds are low. As a result, a relatively uniform response of runoff and erosion is possibly induced between similar watersheds if the intensity of landscape heterogeneity and human disturbance are low. On the other hand, for very large watersheds (hundreds or even thousands of square kilometers), things may be more complicated, especially when the watershed is located in a typical climatic transaction zone (Gao and Mu, 2004). In this situation, without taking into account the diversity and intensity of human activities, different climate statuses, changeable landforms, and variable soil features may become major contributors to higher variability and complexity in water erosion responses.

At the regional scale, the diversity and variation of climates and topographies as well as land use/cover changes induced by anthropogenic activities notably increase with the expansion of geographical areas (Cammeraat, 2004; Kheir *et al*., 2006; Piao *et al*., 2007; Dymond *et al*., 2010). As with those in large watersheds, different sub-geographical regions may be involved in certain regions, such as the typical Mediterranean area or the Loess Plateau region in China (Fu, 1989; Yan and Xu, 2006; de Vente *et al*., 2008). Meanwhile, the coupled effects of human and nature on the eco-environents play more marked and interacted roles in the features and surface processes of the earth (Descroix and Gautier, 2002; Govers *et al*., 2006). Therefore, different specific responses of surface runoff volumes and soil erosion rates possibly appear within these regions (Yan and Xu, 2006). These facets mentioned are thus considered as the major drivers for the variabilities and complexities of water erosion processes across changing scales and spaces.

3.4 Accelerated rainfall variations and earth surface changes across scales

Climate change and human intervention are expected to strongly reshape regional and even global surface water flows and hydrological cycles in the coming decades (Piao *et al*., 2007), greatly influencing rainfall patterns and soil erosion processes. To date, the changes in rainfall have taken place and have been monitored across different spatiotemporal scales worldwide (Weltzin *et al*, 2003; Richard, 2007). The changes in precipitation variables, frequencies, and distribution are not uniform throughout the world with short or long time spans, or on small or large scales. Responses of water erosion outputs to each changing scale, therefore, differ from each other (Wei *et al*., 2009).

Water erosion dynamics, on the other hand, are the coupled consequence of climate changes (especially rainfall) and earth surface evolvements (vegetation succession, topographic variation, *etc*.) (Govers *et al*., 2006) (Fig. 4). Changes in climatic factors have been found in many key arid and semiarid regions, causing different spatiotemporal changes in rainfall features and vegetation distributions across various spatial scales. For example, using the Mann-Kendall method, it was found that the temperature in the Loess Plateau increased, whereas natural rainfall amounts decreased. This trend is especially obvious since the 1990s (Tian, 2010). The results showed that rainfall varied highly across different spatial scales, especially in arid and semiarid regions (Weltzin *et al*., 2003; Wei *et al*., 2009). Furthermore, due to accelerated human activities, great changes in land use, surface vegetation covers, and topographical characteristics have taken place. As a result, water erosion responses at different spatial scales have become more complex, uncertain, and nonlinear.

4 Concluding Remarks

In summary, the so-called 'spatial scale effects' of water erosion share some similarities and differences across a range of scales. Three major facets in these relationships are elaborated below.

(1) From an objective point of view, the purposes of water erosion research across different scales differ. The studies of water erosion at the plot scale are generally focused on uncovering the specific mechanisms and drivers at sloping conditions, while those at the watershed scale are mainly beneficial for comprehensive land hazard management. Regional erosion assessment, however, is more helpful for assessing the risks of erosion hazard and testing the effects of related policy implementations.

(2) From the mechanism standpoint, rainfall characteristics are the common drivers responsible for water erosion generation and dynamics, regardless of the specific scale. However, due to the high stochastic character and variability of rain erosive events, puzzles regarding water erosion measurements and assessments remain. Topography, soil, vegetation, and anthropogenic management all play roles in these surface erosion processes. Different contributions by these factors, however, exist across different scales. Moreover, specific erosion types may vary across these spatial scales owing to different biophysical controlling factors and processes.

(3) From the methodological point of view, distinct methods regarding water erosion research at multiple scales are used. The studies at the plot scale are mainly dependent on traditional data collection by monitoring *in situ*. The studies at the watershed scale are generally done by sampling belt investigation or aerial photograph analysis, while those at the regional scale are usually done through remote sensing images for quick assessments at one point in time.

More attention has been paid to the scale-effect issue by researchers in the previous references. Meanwhile, great efforts have been made toward the development of scale transformation methodology, and multiple-scale investigations (i.e. site, plot, hillslope, watershed, region, nation, *etc*.) and predictions based on different measures are ongoing in many areas of the world. However, due to the complexities and remaining uncertainties of the scale effect, the key obstacle in targeting accurate erosion assessments and predictions over time and space is still a big drawback in the real world. As a result, several key aspects regarding the scale effects of water erosion responses need to be enhanced. First, much attention should continue to be paid to the specific drivers and influencing factors of water erosion across different scales. It is important to develop new methodology for distinguishing and quantifying the roles of climatic factors (e.g., rainfall variability) and the surface features of the earth (e.g., vegetation dynamics and topography) as well as their interactive effects on soil erosion. Second, the absence of systematic models and other quantitative methods induce uncertainties and even errors caused by the limitations of current methodologies. Herein, the well-documented source-sink landscape theory and related approaches are possibly helpful in dealing with the scale effect issue. Third, water erosion across different scales will inevitably become more complicated and changeable under a background of accelerated human disturbances and changing climatic conditions.

References

Aksoy H, Kavvas M L, 2005. A review of hill-slope and watershed scale erosion and sediment transport models. *Catena*, 64(2–3): 247–271. doi: 10.1016/j.catena.2005.08.008

Amore E, Modica C, Nearing M A *et al.*, 2004. Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. *Journal of Hydrology*, 293(1–4): 100–114. doi: 10.1016/j.jhydrol.2004.01.018

Baffaut C, Nearing M A, Nicks A D, 1996. Impact of CLIGEN parameters on WEPP-predicted average annual soil loss. *Transactions of American Society of Agricultural Engineers*, 39(2): 447–457.

Bagarello V, Ferro V, 2004. Plot-scale measurement of soil erosion at the experimental area of Sparacia (southern Italy). *Hydrological Processes*, 18(1): 141–157. doi: 10.1002/hyp.1318

Bagarello V, Ferro V, 2010. Analysis of soil loss data from plots of differing length for the Sparacia experimental area, Sicily, Italy. *Biosystems Engineering*, 105(3): 411–422. doi: 10.1016/j.biosystemseng.2009.12.015

Barthès B, Azontonde A, Boli B Z *et al.*, 2000. Field-scale run-off and erosion in relation to topsoil aggregate stability in three tropical regions (Benin, Cameroon, Mexico). *European Journal of Soil Science*, 51(3): 485–495. doi: 10.1023/A:1006946027619

Blöschl G, Sivapalan M, 1995. Scale issues in hydrological modeling: A review. *Hydrological Processes*, 9(3–4): 251–290. doi: 10.1002/hyp.3360090305

Boardman J, 2006. Soil erosion science: Reflections on the limitations of current approaches. *Catena*, 68(2–3): 73–86. doi: 10.1016/j.catena.2006.03.007

Bochet E, Rubio J L, Poesen J, 1998. Relative efficiency of three representative matorral species in reducing water erosion at the microscale in a semi-arid climate (Valencia, Spain). *Geomorphology*, 23(2–4): 139–150. doi: 10.1016/S0169-555X(97)00109-8

Boix-Fayos C, Martínez-Mena M, Arnau-Rosalén E *et al.*, 2006. Measuring soil erosion by field plots: Understanding the sources of vartiation. *Earth-Science Reviews*, 78(3–4): 267–285. doi: 10.1016/j.earscirev.2006.05.005

Bryan R B, 2000. Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, 32(3–4): 385–415. doi: 10.1016/S0169-555X(99)00105-1

Bryan R B, Luk S H, 1981. Laboratory experiments on the variation of soil erosion under simulated rainfall. *Geoderma*, 26(4): 245–265. doi: 10.1016/0016-7061(81)90023-9

Cammeraat E L H, 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in Southeast Spain. *Agriculture*, *Ecosystems and Environment*, 104(2): 317–332. doi: 10.1016/j.agee.2004.01.032

Cantón Y, Domingo F, Solé-Benet A *et al.*, 2001. Hydrological and erosion response of a badlands system in semiarid SE Spain. *Journal of Hydrology*, 252(1–4): 65–84. doi: 10.1016/S0022-1694(01)00450-4

Casermeeiro M A, Molina J A, Cravaca M T *et al.*, 2004. Influence of scrubs on runoff and sediment loss in soils of Mediterranean climate. *Catena*, 57(1): 91–107. doi: 10.1016/S0341-8162(03)00160-7

Cerdà A, 2007. Soil water erosion on road embankments in eastern Spain. *Science of the Total Environment*, 378(1–2): 151–155. doi: 10.1016/j.scitotenv.2007.01.041.

Cerdan O, Bissonnais Y L, Govers G *et al.*, 2004. Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. *Journal of Hydrology*, 299(1–2): 4–14. doi: 10.1016/j.jhydrol.2004.02.017

Cerdan O, Govers G, Bissonnais Y L *et al.*, 2010. Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. *Geomorphology*, 122(1–2): 167–177. doi: 10.1016/j.geomorph.2010.06.011

Chen L D, Fu B J, Zhao W W, 2008. Source-sink landscape theory and its ecological significance. *Frontiers of Biology in China*, 3(2): 131–136. doi: 10.1007/s11515-008-0026-x

Chen Liding, Tian Huiying, Fu Bojie *et al.*, 2009. Development of a new index for integrating landscape patterns with ecological processes at watershed scale. *Chinese Geographical Science*, 19(1): 37–45. doi: 10.1007/s11769-009-0037-9

Chen S C, Chien S, Cheng D H, 2001. Development of soil erosion index model in Taiwan watersheds. *International Journal of Sediment Research*, 16(1): 80–90.

de Giesen N V, Stomph T J, Ajayi A E *et al.*, 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: Fied data and models. *Agriculture, Ecosystems and Environment*, 142(1–2): 95–101. doi: 10.1016/j.agee. 2010.06.006.

Descroix L, Barrios J L G, Viramontes D *et al.*, 2008. Gully and sheet erosion on subtropical mountain slopes: Their respective roles and the scale effect. *Catena*, 72(3): 325–339. doi:10.1016/j.catena.2007.07.003

Descroix L, Gautier E, 2002. Water erosion in the southern French alps: Climatic and human mechanisms. *Catena*, 50(1): 53–85. doi: 10.1016/S0341-8162(02)00068-1

de Vente J, Poesen J, 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. *Earth-Science Reviews*, 71(1–2): 95–125. doi: 10.1016/

j.earscirev.2005.02.002

de Vente J, Poesen J, Arabkhedri M *et al*., 2007. The sediment delivery problem revisited. *Progress in Physical Geography*, 31(2): 155–178. doi: 10.1177/0309133307076485

de Vente J, Poesen J, Verstraeten G *et al*., 2008. Spatially distributed modeling of soil erosion and sediment yield at regional scales in Spain. *Global and Planetary Change*, 60(3–4): 393–415. doi: 10.1016/j.gloplacha.2007.05.002

D'Odorico P, Porporato A, 2006. *Dryland Ecohydrology*. Netherlands: Springer, 1–335.

Dunjo G, Pardini G, Gispert M, 2004. The role of land use-land cover on runoff generation and sediment yield at a micro-plot scale, in a small Mediterranean catchment. *Journal of Arid Environment*, 57(2): 239–256. doi: 10.1016/S0140-1963(03)00097-1

Dymond J R, Betts H D, Schierlitz C S, 2010. An erosion model for evaluating regional land-use scenarios. *Environmental Modeling & Software*, 25(3): 289–298. doi: 10.1016/j.envsoft.2009.09.011

Fu B J, 1989. Soil erosion and its control in the Loess Plateau of China. *Soil Use and Management*, 5(2): 76–82. doi: 10.1111/j.1475-2743.1989.tb00765.x

Gaiser T, Stahr K, Billen N *et al*., 2008. Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion. *Ecological Modeling*, 218(1–2): 110–120. doi: 10.1016/j.ecolmodel.2008.06.025

Gao Zhaoliang, Mu Xingmin, 2004. Spatio-temporal change of land use/coverage in Loess wind-water erosion crisscross region—Take Liudaogou watershed as example. *Journal of Soil and Water Conservation*, 18(5): 146–150. (in Chinese)

García-Ruiz J M, Lana-Renault N, Beguería S *et al*., 2010. From plot to regional scales: Interactions of slope and catchment hydrological and geomorphic processes in the Spanish Pyrenees. *Geomorphology*, 120(3–4): 248–257. doi: 10.1016/j.geomorph.2010.03.038

Gobin A, Jones R, Kirkby M *et al*., 2004. Indicators for pan-European assessment and monitoring of soil erosion by water. *Environmental Science & Policy*, 7(1): 25–38. doi: 10.1016/j.envsci.2003.09.004

Govers G, Oost K V, Poesen J, 2006. Responses of a semiarid landscape to human disturbance: A simulation study of the interaction between rock fragment cover, soil erosion and land use change. *Geoderma*, 133(1–2): 19–31. doi: 10.1016/j.geoderma.2006.03.034

Hessel R, Tenge A, 2008. A pragmatic approach to modeling soil and water conservation measures with a catchment scale erosion model. *Catena*, 74(2): 119–126. doi: 10.1016/j.catena.2008.03.018

Imeson A C, Prinsen H A M, 2004. Vegetation patterns as biological indicators for identifying runoff and sediment source and sink areas for semiarid landscapes in Spain. *Agriculture, Ecosystems and Environment*, 104(2): 333–342. doi: 10.1016/j.agee.2004.01.033

Jin K, Cornelis W M, Gabriels D *et al*., 2008. Soil management effects on runoff and soil loss from field rainfall simulation. *Catena*, 75(2): 191–199. doi: 10.1016/j.catena.2008.06.002

Kakembo V, 2009. Vegetation patchiness and implications for landscape function: The case of *Pteronia incana* invader species in Ngqushwa Rural Municipality, Eastern Cape, South Africa. *Catena*, 77(3): 180–186. doi: 10.1016/j.catena.2008.12.014

Kinnell P I A, 2000. The effects of slope length on sediment concentration associated with side-slope erosion. *Soil Science Society of America Journal*, 64(3): 1004–1008.

Kirkby M, 2001. Modeling the interactions between soil surface properties and water erosion. *Catena*, 46(2–3): 89–102. doi: 10.1016/S0341-8162(01)00160-6

Kheir R B, Cerdan O, Abdallah C, 2006. Regional soil erosion risk mapping in Lebanon. *Geomorphology*, 82(3–4): 347–359. doi: 10.1016/j.geomorph.2006.05.012

Lal R, 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677): 1623–1627. doi: 10.1126/science.1097396

Lesschen J P, Cammeraat L H, Kooijman A M *et al*., 2008. Development of spatial heterogeneity in vegetation and soil properties after land abandonment in a semiarid ecosystem. *Journal of Arid Environments*, 72(11): 2082–2092. doi: 10.1016/j.jaridenv.2008.06.006

Leys A, Govers G, Gillijns K *et al*., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. *Journal of Hydrology*, 390(3–4): 143–154. doi: 10.1016/j.jhydrol.2010.06.034

Licznar P, Nearing M A, 2003. Artificial neural networks of soil erosion and runoff prediction at the plot scale. *Catena*, 51(2): 89–114. doi: 10.1016/S0341-8162(02)00147-9

Ludwig J A, Wilcox D D, Breshears D D *et al*., 2005. Vegetation patches and runoff-erosion as interacting eco-hydrological processes in semi-arid landscapes. *Ecology*, 86(2): 288–297. doi: 10.1890/03-0569

Lundekvam H E, 2007. Plot studies and modeling of hydrology and erosion in southwest Norway. *Catena*, 71(2): 200–209. doi: 10.1016/j.catena.2007.03.004

Nearing M A, Govers G, Darrell Norton L, 1999. Variability in soil erosion data from replicated plots. *Soil Science Society of America Journal*, 63(6): 1829–1835.

Nearing M A, Romkens M J M, Norton L D *et al*., 2000. Measurements and models of soil loss rates. *Science*, 290(5495): 1300–1301. doi: 10.1126/science.290.5495.1300b

Peeters I, Van Oost K, Govers G *et al*., 2008. The compatibility of erosion data at different temporal scales. *Earth and Planetary Science Letters*, 265(1–2): 138–152. doi: 10.1016/j.epsl.2007.09.040

Piao S X, Friedlingstein P, Ciais P *et al*., 2007. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America*, 104(39): 15242–15247. doi: 10.1073/pnas.0707213104

Poesen J, Nachtergaele J, Verstraeten G *et al.*, 2003. Gully erosion and environmental change: Importance and research needs. *Catena*, 50(2–4): 91–133. doi: 10.1016/S0341-8162(02)00143-1

Poesen J, van Wesemael B, Bunte K *et al.*, 1998. Variation of rock fragment cover and size along semiarid hill-slopes: A case-study from Southeast Spain. *Geomorphology*, 23(2–4): 323–335. doi: 10.1016/S0169-555X(98)00013-0

Poesen J W, Torri D, Bunte K, 1994. Effects of rock fragments on soil erosion by water at different spatial scales: A review. *Catena*, 23(1–2): 141–166. doi: 10.1016/0341-8162(94)90058-2

Rao Liangyi, Cui Jianguo, 2008. Research advances on the eco-hydrological functions of riparian buffer. *Science of Soil and Water Conservation*, 6(4): 121–128. (in Chinese)

Richard A K, 2007. Global warming is changing the world. *Science*, 316(5822): 188–190. doi: 10.1126/science.316.5822.188

Renschler C S, Harbor J, 2002. Soil erosion assessment tools from point to regional scales—The role of geomorphologists in land management research and implementation. *Geomorphology*, 47(2–4): 189–209. doi: 10.1016/S0169-555X(02)00082-X

Renschler C S, Mannaerts C, Diekkrüger B, 1999. Evaluating spatial and temporal variability in soil erosion risk-rainfall erosivity and soil loss ratios in Andalusia, Spain. *Catena*, 34(3–4): 209–225. doi: 10.1016/S0341-8162(98)00117-9

Rey F, 2004. Effectiveness of vegetation barriers for marly sediment trapping. *Earth Surface Processes and Landforms*, 29(9): 1161–1169. doi: 10.1002/esp.1108

Sánchez G, Puigdefábregas J, 1994. Interactions of plant growth and sediment movement on slopes in a semi-arid environment. *Geomorphology*, 9(3): 243–260. doi: 10.1016/0169-555X(94)90066-3

Seeger M, 2007. Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulation. *Catena*, 71(1): 56–67. doi: 10.1016/j.catena.2006.10.005

Smets T, Poesen J, Bochet E, 2008a. Impact of plot length on the effectiveness of different soil-surface covers in reducing runoff and soil loss by water. *Progress in Physical Geography*, 32(6): 654–677. doi: 10.1177/0309133308101473

Smets T, Poesen J, Knapen A, 2008b. Spatial scale effects on the effectiveness of organic mulches in reducing soil erosion by water. *Earth-Science Reviews*, 89(1–2): 1–12. doi: 10.1016/j.earscirev.2008.04.001

Stroosnijder L, 2005. Measurement of erosion: Is it possible? *Catena*, 64(2–3): 162–173. doi: 10.1016/j.catena.2005.08.004

Tefera B, Sterk G, 2010. Land management, erosion problems and soil and water conservation in Fincha′a watershed, western Ethiopia. *Land Use Policy*, 27(4): 1027–1037. doi: 10.1016/j.landusepol.2010.01.005

Tian Junliang, 2010. *Edits Study on the Environmental Effects of Ecological Construction in the Chinese Loess Plateau*. Beijing: China Meteorological Press, 16. (in Chinese)

Uchida T, Ohte N, Kimoto A *et al.*, 2000. Sediment yield on a devastated hill in southern China: Effects of microbiotic crust on surface erosion process. *Geomorphology*, 32(1–2): 129–145. doi: 10.1016/S0169-555X(99)00080-X

Van de Giesen N C, Stomph T J, de Ridder N, 2000. Scale effects of Hortonian overland flow and rainfall dynamics in a West African catena landscape. *Hydrological Processes*, 14(1): 165–175. doi: 10.1002/(SICI)1099-1085

Vásquez-Méndez R, Ventura-Ramos E, Oleschko K *et al.*, 2010. Soil erosion and runoff in different vegetation patches from semiarid Central Mexico. *Catena*, 80(3): 162–169. doi: 10.1016/j.catena.2009.11.003

Verbist B, Poesen J, van Noordwijk M *et al.*, 2010. Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape. *Catena*, 80(1): 34–46. doi: 10.1016/j.catena.2009.08.007

Vigiak O, van Loon E, Sterk G, 2006. Modeling spatial scales of water erosion in the West Usambara Mountains of Tanzania. *Geomorphology*, 76(1–2): 26–42. doi: 10.1016/j.geomorph.2005.09.002

Vrieling A, 2006. Satellite remote sensing for water erosion assessment: A review. *Catena*, 65(1): 2–18. doi: 10.1016/j.catena.2005.10.005

Wang G X, Gertner G, Singh V *et al.*, 2002. Spatial and temporal prediction and uncertainty of soil loss using the revised universal soil loss equation: A case study of the rainfall-runoff erosivity R factor. *Ecological Modelling*, 153(1–2): 143–155. doi: 10.1016/S0304-3800(01)00507-5

Ward P J, van Balen R T, Verstraeten G *et al.*, 2009. The impact of land use and climate change on late Holocene and future suspended sediment yield of the Meuse catchment. *Geomorphology*, 103(3): 389–400. doi: 10.1016/j.geomorph.2008.07.006

Weltzin J F, Loik M E, Schwinning S *et al.*, 2003. Assessing the response of terrestrial ecosystems to potential changes in precipitation. *Bioscience*, 53(10): 941–952. doi: 10.1641/0006-3568(2003)053

Wei W, Chen L D, Fu B J *et al.*, 2007. The effect of land use and rainfall regimes on runoff and erosion in the loess hilly area, China. *Journal of Hydrology*, 335(3–4): 247–258. doi: 10.1016/j.jhydrol.2006.11.016

Wei W, Chen L D, Fu B J, 2009. Effects of rainfall change on water erosion processes in terrestrial ecosystems: A review. *Progress in Physical Geography*, 33(3): 307–318. doi: 10.1177/0309133309341426

Xu J X, Yan Y X, 2005. Scale effects on specific sediment yield in the Yellow River basin and geomorphological explanations. *Journal of Hydrology*, 307(1–4): 219–232. doi: 10.1016/

j.jhydrol.2004.10.011

Xu X L, Ma K M, Fu B J *et al*., 2008. Influence of three plant species with different morphologies on water runoff and soil loss in a dry-warm river valley, SW China. *Forest Ecology and Management*, 256(4): 656–663. doi: 10.1016/j.foreco.2008.05.015

Yair A, Raz-Yassif N, 2004. Hydrological processes in a small arid catchment: Scale effects of rainfall and slope length. *Geomorphology*, 61(1–2): 155–169. doi: 10.1016/j.geomorph.2003.12.003

Yan Yunxia, Xu Jiongxin, 2006. Research on scale effect of soil erosion and sediment yield in the Yellow River Region. *Science in China* (*D*): *Earth Sciences*, 36(8): 767–776. (in Chinese)

Zhang Keli, Liu Baoyuan, Cai Yongming, 2000. The standard of unit plot in soil loss prediction of China. *Geographical Research*, 19(3): 297–302. (in Chinese)

Zhang Zhiqiang, Wang Shengping, Sun Ge *et al*., 2006. Runoff and sediment yield response to vegetation change at multiple scales: A review. *Acta Ecologica Sinica*, 26(7): 2356–2364. (in Chinese)