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Soil erosion risk in Korean watersheds, assessed using the revised universal soil loss equation

Soyoung Park [a], Cheyoung Oh [a], Seongwoo Jeon [b], Huicheul Jung [b], Chuluong Choi [a,*]

[a] Dept. of Geoinformatic Engineering, Pukyung National University, 599-1 Daeyeon 3-Dong, Nam-Gu, Busan 608-737, South Korea

[b] Korea Adaptation Center for Climate Change, Korea Environment Institute, 290 Jinheung-Ro, Eunpyong-Gu, Seoul 122-706, South Korea

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SUMMARY

Soil erosion reduces crop productivity and water storage capacity, and, both directly and indirectly, causes water pollution. Loss of soil has become a problem worldwide, and as concerns about the environment grow, active research has begun regarding soil erosion and soil-preservation policies. This study analyzed the amount of soil loss in South Korea over a recent 20-year period and estimated future soil loss in 2020 using the revised universal soil loss equation (RUSLE). Digital elevation (DEM) data, detailed soil maps, and land cover maps were used as primary data, and geographic information system (GIS) and remote sensing (RS) techniques were applied to produce thematic maps, based on RUSLE factors. Using the frequency ratio (FR), analytic hierarchy process (AHP), and logistic regression (LR) approaches, land suitability index (LSI) maps were developed for 2020, considering the already established Environmental Conservation Value Assessment Map (ECVAM) for Korea. Assuming a similar urban growth trend and 10-, 50-, and 100-year rainfall frequencies, soil loss in 2020 was predicted by analyzing changes in the cover-management factor and rainfall–runoff erosivity factor. In the period 1985–2005, soil loss showed an increasing trend, from 17.1 Mg/ha in 1985 to 17.4 Mg/ha in 1995, and to 20.0 Mg/ha in 2005; the 2005 value represents a 2.8 Mg/ha (16.6%) increase, compared with 1985 and is attributable to the increased area of grassland and bare land. In 2020, the estimated soil loss, considering the ECVAM, was 19.2–19.3 Mg/ha for the 10-year rainfall frequency, 36.4–36.6 Mg/ha for the 50-year rainfall frequency, and 45.7–46.0 Mg/ha for the 100-year rainfall frequency. Without considering the ECVAM, the amount of soil loss was about 0.4–1.6 Mg/ha larger than estimates that did consider the ECVAM; specifically, the values were 19.6–19.9 Mg/ha for the 10-year rainfall frequency, 37.1–37.8 Mg/ha for the 50-year frequency, and 46.7–47.5 Mg/ha for the 100-year frequency. In 2010, without considering the ECVAM, the soil loss was 0.3–1.8 Mg/ha more than that estimated when considering the ECVAM. These results indicate that if urban areas are developed such that they damage areas of high value, as defined environmentally and legislatively, the amount of soil loss will increase, whereas if such areas are preserved, erosion will decrease slightly. Thus, when planning urban development, the environmental and legislative value of preservation should be considered to minimize erosion and allow for more sustainable development.

1. Introduction

In recent decades, soil erosion by water has become a worldwide issue, with climate change and progressive declines in the ratio of natural resources to human populations. Moreover, various practices expose soils to greater risks of erosion, including inappropriate agricultural practices, deforestation, overgrazing, forest fires, and construction activities (Terranova et al., 2009). Soil erosion has negative impacts on ecology and can lead to reduced crop productivity, worsened water quality, lower effective reservoir water levels, flooding, and habitat destruction (Oh and Jung, 2005). Concern for the environment has also increased worldwide and, thus, various studies have examined soil conservation. In particular, the need for environmentally sensitive development alternatives in watersheds with multiple usage pressures and the need to forecast erosion and minimize the environmental impacts of development have been noted (KMOE, 2001).

To calculate the risk of soil erosion and identify ways to control erosion, quantitative analysis is required to calculate how quickly soil erodes in its natural state. However, precise predictions are difficult because soil loss is influenced by complex factors, such as soil conditions, surface cover, and environmental factors. Thus, various forecasting formulae based on statistical and basic approaches have been developed (Oh and Jung, 2005).

* Corresponding author. Tel.: +82 10 7747 6272; fax: +82 51 629 6653.
E-mail addresses: 100yac@hanmail.net (S. Park), leeieel@nate.com (C. Oh), swjeon@kei.re.kr (S. Jeon), hchjung@kei.re.kr (H. Jung), cuchoi@pknu.ac.kr (C. Choi).

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Techniques for predicting soil erosion are classified as physical, analog, and digital types, with the digital type further subclassified into physically based, stochastic, and empirical types. Most models for calculating the amount of soil loss belong to the "gray-box" type of the empirical approach. These models select only the most important factors related to soil erosion and predict the amount of soil erosion using statistical techniques with materials observed and calculated in the field and laboratory. Recently, there has been tremendous effort to develop a "white-box" or physically-based model after issues regarding a mechanical understanding of the erosion process were raised (National Institute for Disaster Prevention, 1998).

Major empirical models include the Pacific Southwest Interagency Committee (PSIAC, 1968), universal soil loss equation (USLE) (Wischmeier and Smith, 1978), soil loss estimation for Southern Africa (SLEMA) (Elwell and Stocking, 1982), and Morgan and Finney methods (Morgan et al., 1984). Among these models, the USLE was the first and most important empirical model; it was developed based on thousands of experimental data points collected by the Soil Conservation Service and the Agricultural Research Service in 37 US states. A revision of the USLE model, called RUSLE (Renard et al., 1997), has been applied to erosion over extended areas and in different contexts, including forests, rangeland, and disturbed areas (Terranova et al., 2009).

Physically-based models, based on physics, include the areal non-point source watershed environment response simulation (ANSWERS) (Beasley et al., 1980), Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989), chemical, runoff, and erosion for agricultural management system (CREAMS) (Knisel, 1980), and the European soil erosion model (EuroSEM) (Morgan et al., 1990).

Because most models deal with many variables displaying great spatial and temporal variability, the use of remote sensing and geographical information system (GIS) techniques makes soil erosion estimation and its spatial distribution feasible, with reasonable costs and accuracy over large areas (Millward and Mersey, 1999; Wang et al., 2003).

The target area of this study was the Korean peninsula, located at the far eastern part of the Asian continent. As South Korea has undergone rapid industrialization and urbanization since the 1960s, the population has become intensively concentrated in urban areas, as shown by the increase in the urbanization ratio from 39.1% in the 1960s to 90.1% in 2005. Urbanization has been accompanied by reckless large-scale residential land development, with continuous destruction of agricultural and forest lands. Looking at trends in land use for individual categories surveyed by Statistics Korea, the area of rice paddy decreased from 7596 km^2 in 1980 to 1421 km^2 in 2005. In the same period, the area of farmland was reduced by 570 km^2 from 12,152 km^2, and the forest area was reduced by 1324–64,805 km^2 (Statistics Korea Homepage, http://www.index.go.kr). In addition, extraordinary weather conditions have brought unusually heavy local rain. For example, Inje-gun in Gangwon Province recorded a maximum daily rainfall of 350 mm during Typhoon Ewiniar in 2006; this amount corresponds to a rainfall event of 80–500 year frequency and was the largest daily rainfall recorded in Korea since meteorological observation began (Lee et al., 2009). Thus, both urbanization and extraordinary weather conditions in South Korea are accelerating the risk of soil erosion.

A few foreign researchers have estimated soil loss in Korea. Walling (1983), for example, estimated soil loss of 500–750 ton/km^2/year, while Lvoivich et al. (1991) proposed a range of 1000–5000 ton/km^2/year. However, observational data were lacking. Additionally, domestic researchers, such as Park (2003), Kim et al. (2007), Oh and Jung (2005), Lee et al. (2006), and Lee and Hwang (2006) calculated the amount of soil loss using GIS and RUSLE and analyzed the distribution characteristics by rating each category according to the risk of soil erosion. Most studies have targeted a specific watershed because of spatial and temporal limitations of data collection and analysis. Recently, thanks to Kim et al.'s (2009) research, maps showing the distribution and risk class of soil loss have been completed. However, time-series analyses of soil loss and future forecasting have not yet been completed.

Thus, this study quantitatively analyzed time-series changes in soil loss over the last 20 years in Korea. Compared with natural soil erosion, soil loss due to human activities, such as agricultural, urban, and road development, may be increased by a few to a few million times, even under the same rainfall conditions (Goldman et al., 1986). This study analyzed the amount of urban growth and forecasted the amount of 2020 soil loss, due to changes in rainfall. As primary data, this study used digital elevation model (30-m DEM) data from the Korea National Geographic Information Institute, 1:25,000 detailed soil maps from the Korea National Institute of Agricultural Science and Technology, and 1:25,000 land cover maps from the Korea Ministry of Environment. These detailed data, combined with the use of GIS and remote sensing (RS) analysis techniques, allowed for an accurate analysis.

For the analysis of urban growth, a 1:25,000 land suitability index (LSI) map was completed, considering the Environmental Conservation Value Assessment Map (EVCAM) for Korea by modeling the relationship between drivers and urban growth, using the frequency ratio (FR), logistic regression (LR), and analytic hierarchy process (AHP) methods. The ECVAM shows the environmental and legislative regions of the country, ranked by grades of 1–5. An LSI map is a probability map that analyzes urban growth that preserves the environment as well as urban growth that focuses on development, rather than the environment. An LSI map is a cover-management factor in RUSLE. Rainfall frequencies for 10, 50, and 100 years were applied for the rainfall–runoff erosivity factor. On the basis of these factors, the amount of soil loss was predicted and the differences with and without considering the ECVAM were analyzed.

This quantitative analysis and forecast of soil loss will contribute to efforts to minimize the environmental impacts of development and prevent natural disaster due to soil loss. Moreover, the results can serve as primary data for planning short- and long-term policies and in developing methods to preserve and manage soil resources.

2. Methodology

2.1. Study area

The study area was all land areas of South Korea (hereafter, Korea), except some smaller islands, such as Jeju Island, Ulleung Island, and Dokdo. The target area lies between 34°18′42″N and 37°22′43″N and 124°19′30″E and 130°52′31″E, covering 100560.87 km^2 (Fig. 1). The research period focused on 1985 and 2005.

Korea has a continental monsoon climate. Within Korea's relatively small land area, climate conditions vary widely from north to south and from east to west. Seasonal variations are also distinct. Summer is hot and humid with severe rain storms, and winter is cold and very dry. The annual average temperature (based on the average temperature between 1971 and 2000) ranges from approximately 10 to 16 °C except in the central mountainous areas. The hottest month, August, has an average temperature of 27 °C, while in the coldest month, January, temperatures can fall to −7 °C. In addition, the annual average precipitation (based on the average precipitation between 1971 and 2000) is 1000–1400 mm in the central region, 1000–1800 mm in the southern