Journal of Hydrology 527 (2015) 494–504

Contents lists available at ScienceDirect

Journal of Hydrology

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

Analysis and simulation of large erosion events at central Texas unit source watersheds

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ARTICLE INFO

Article history:
Received 4 June 2014
Received in revised form 29 April 2015
Accepted 11 May 2015
Available online 16 May 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ehab A. Meselhe, Associate Editor

Keywords:
Daily erosion
Long-term erosion
SWAT model
Agriculture erosion
Empirical erosion
Unit source watershed

SUMMARY

This study uses long-term daily sediment records (12–51 years) from 5 unit-source watersheds in central Texas to examine the role of large infrequent erosion events in the makeup of the overall soil loss record. Additionally, multi-decadal daily erosion simulations with the Soil and Water Assessment Tool (SWAT) using both the Modified Universal Soil Loss Equation (MUSLE) and physics based erosion routines are conducted to assess the routine's ability to predict extreme events and long-term budgets. The empirical record indicates the upper 10% of erosion events (in terms of mass) comprise roughly half of the long-term soil loss sum. These upper end events are characterized by large unit flow erosion values and not necessarily associated with precipitation or runoff extremes. The two SWAT routines showed little differences in total soil loss masses; however, the distribution of soil loss events from the physics based simulation, including upper end events, more closely resembled the empirical record than the MUSLE prediction.

1. Introduction

Conducting accurate long-term (decadal plus) simulations of watershed erosion are problematic in part due to the inherent difficulties in developing mathematical descriptions of dynamic soil supply-transport-deposition cycles over space and time (Boardman, 2006; White, 2005; Nearing, 2013). Spatially distributed and continuous catchment models that simulate runoff and erosion have been developed and enhanced over the past few decades with the development in computing processors and geographical information systems. These models allow estimation of soil erosion from complex hydrologic systems characterized by heterogeneous soils, vegetation, and topography over a long period (Merritt et al., 2003). For surface erosion processes, a large portion of the literature has been dedicated to different versions of the empirically developed Universal Soil Loss Equation (USLE). The USLE was originally developed during the 1950s and 60s from greater than 10,000 plot years of data at approximately 50 research stations across the United States (Wischmeier and Smith, 1978). While the USLE has proven successful in many applications, its derivatives, the Revised USLE and Modified USLE (Williams, 1975; Renard et al., 1997), are presently the most commonly used empirical models. Nevertheless, recent efforts have focused more on developing process based models using physically based equations to describe surface processes and sediment routing. Models such as KINEROS (Smith, 1981), EUROSEM (Morgan et al., 1998), and WEPP (Nearing et al., 1989) estimate soil detachment from raindrop energy, sheet flow, and rilling using physical descriptions of detachment theory. The models also benefit from sophisticated descriptions of climate, hydrology, plant growth, and land management. Despite their complexity, physics-based models have shown similar ability to empirical models in predicting long-term soil losses (Bhuyan et al., 2002; Tiwari et al., 2000; Aksoy and Kavvas, 2005).

Model choice aside, there are practical limits placed on modeled predictions related to the natural variability of erosion and errors in field measurements. Few studies exist examining the variability in erosion data, but fairly large coefficients of variation (3–173%) have been reported among replicated plots (Wendt et al., 1986; Ruttimann et al., 1995; Nearing, 2000). The relative difference between replicates tends to decrease as erosion magnitude increases, but the non-unique erosional response from a given storm presents problems for model calibration and assessment of model results.

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http://dx.doi.org/10.1016/j.jhydrol.2015.05.014
0022-1694/

Erosion measurements are needed to develop, calibrate, and validate models, but this type of data is woefully inadequate for most parts of the world (Boardman, 2006). Where data are available, they are largely concentrated in the form of standard erosion plots. Analysis of plot data is constructive and necessary; however we should not expect standard plots to provide an accurate depiction of landscape level processes. Plot data are often based on short, relatively linear slopes not representative of the landscape as a whole, and tend to show larger amounts of erosion than may be expected at the field level. This may in part be due to sampling devices at the end of these confined areas increasing flow across the plot driving the erosion rate higher (Evans, 1995).

Lack of long-term empirical data from unit-source watersheds and larger has limited our understanding of decadal plus processes and the role large infrequent meteorological events have on long-term erosion budgets. From the standard plot perspective, Risse et al. (1993) suggests at least 22 years of monitoring are needed to arrive at representative annual values and characterize large infrequent meteorological events. Similarly, Lane and Kidwell (2003) recommend 16 years or greater. Gonzalez-Hidalgo et al. (2009) show a minimum of 100 measured events should be sufficient to capture long-term plot dynamics. These plot studies along with others provide considerable evidence that individual storms can have a large impact on long-term erosion budgets. From the unit-source perspective, Nearing et al. (2007) reported 6–10 storm events produced 50% of the total sediment yield at six rangeland unit-source watersheds (southern Arizona) over an 11 year period. In the seventh watershed studied, two storms produced 66% of the total sediment yield. At nine small cultivated watersheds within the North Appalachian Agriculture Research Station, 5 events produced at least 66% of total soil loss for each of the unit-source watersheds over 28 year timespan (Edwards and Owens, 1991). Watershed sizes in these unit-source studies ranged from 0.2 to 5.4 ha.

Recognition of the importance of extreme erosion events is easy to identify in the field and through the analysis of adequate empirical records; however, relatively little attention has been given to the subject from the modeling community. The USLE was designed and has mainly been used to find average rates over long periods of time ignoring the individual events contributing to the rate (Boardman, 2006). If large scale erosion events are in fact the dominant force behind erosion budgets at the catchment level, their recognition in erosion models is necessary to arrive at reasonable conclusions. Watersheds in arid-semiarid regions subject to infrequent high intensity events would have the most to gain from analysis of individual rainfall/runoff events in the construction of long-term records.

In the present study, we analyze daily soil erosion records at 5 unit-source watersheds from the Grassland, Soil, and Water Research Laboratory located near Riesel, Texas (herein "Riesel watersheds"). Three land use types are examined including row crops, hay production, and native prairie. The length of the erosion records range from 12 to 51 years and are among the longest continuous records in the world for unit-source sized watersheds. Objectives of the study are to (1) discern the impact of large erosion events on long-term sediment budgets and describe their temporal and land use characteristics and (2) assess the ability of empirical and physics based routines to predict long-term budgets and large erosion events.

2. Methods

2.1. Site information

The Riesel watersheds were established by the United States Department of Agriculture – Soil Conservation Service (USDA-SCS) to examine soil and hydrology responses to various agricultural land management practices (Fig. 1). The station began collecting data in the late 1930s and is the only original USDA experimental watershed still in operation today. Presently, the Riesel and other experimental watersheds around the US are managed by the USDA Agricultural Research Service (ARS). Research at the Riesel watersheds has been used in the development of several hydrologic and erosion models (EPIC/ALMANAC, APEX, SWAT) and has been instrumental in shaping modern agricultural practices across the central Texas region (Williams et al., 2008). There are numerous published reports using data from the watersheds including works on precipitation and weather (Harmel et al., 2003), runoff processes (Allen et al., 2005; Arnold et al., 2005; Harmel et al., 2006), soil erosion (Allen et al., 2011; Harmel et al., 2006; Wang et al., 2006), and the sampling network (Harmel et al., 2007). Previous analyses of soil erosion have focused attention on monthly or annual data. A brief description of the watersheds pertinent to the current study is described below. Readers requiring additional detail on specific aspects of the network are asked to refer to works cited above.

Five watersheds were selected for analysis based on continuity of a daily erosion record, size (1–10 ha), and land use type (Fig. 2; Table 1). Each of the watersheds contains a single land use and represents edge of field erosion processes. Watersheds Y6, Y8, and Y10, have remained cultivated under conservational methods with contoured rows, terraces, and grassed waterways over the length of the erosion record (Allen et al., 2011). These watersheds have primarily been used to produce corn/sorghum during the warm season and wheat/oats for overwinter crops. Watershed W10 has been used for grazing and/or haying, while SW12 has been maintained as a remnant native prairie. Management records are available for a subset of the erosion record.

2.2. Environmental characteristics

Long hot summers and short mild winters are typical across the central Texas region with a warm annual growing season from mid-March to mid-November. Mean annual rainfall over the period of record is between 880 and 900 mm. Spring (April, May, June) and Fall (October, November, December) are the wettest seasons followed by Winter (January, February, March) and Summer (July, August, September) (Harmel et al., 2003). The majority of rainfall can be attributed to passage of continental fronts, while convective events during warmer months contribute short-duration high intensity events. Occasionally, tropical disturbances protrude far enough inland resulting in major precipitation events (Asquith and Slade, 1995).

Houston Black (Vertisol) soils containing an approximate size distribution of 17% sand, 28% silt, and 55% clay dominate the watershed. The soil erodibility factor (K) for this clay rich soil is 0.32 (0.013 metric ton $*$ m^2 $*$ h)/(m^3 $*$ metric ton $*$ cm). Sheet and occasional rill erosion are the dominant soil detachment and transport mechanisms observed at the site. The soil series consists of moderately well drained, deep soils formed of weakly consolidated calcareous clays and marls. The soils have a high shrink swell capacity allowing for high infiltration rates when dry due to preferential flow through surface cracks and very low hydraulic conductivity when saturated (hydraulic conductivity $\approx$ 1.5 mm h^{-1}). Allen et al. (2005) describe distinct seasonal soil phases affecting flow in the clay terrain. Soils are (1) extensively cracked mid-summer to fall (2) at field capacity late fall to winter (3) experiencing crack closure and lateral groundwater flow from late winter to late spring and (4) below field capacity beginning to crack from early spring to summer. The majority of surface runoff occurs from December–June when the soils are holding more water and cracks are closed. During the summer and fall months there is