Journal of Hydrology 534 (2016) 440–450

Contents lists available at ScienceDirect

Journal of Hydrology

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

Rainfall erosivity–intensity relationships for normal rainfall events and a tropical cyclone on the US southeast coast

Kazuki Nanko [a,*], Susanne M. Moskalski [b,1], Raymond Torres [b]

[a] Department of Meteorological Environment, Forestry and Forest Products Research Institute, Tsukuba, Ibaraki 305-8687, Japan
[b] Department of Earth and Ocean Sciences, University of South Carolina, Columbia, SC 29208, USA

ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form 25 November 2015
Accepted 9 January 2016
Available online 15 January 2016
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Emmanouil N. Anagnostou, Associate Editor

Keywords:
Disdrometer
Kinetic energy
Raindrop size distribution
Winyah Bay
South Carolina

SUMMARY

The work done on the intertidal landscape by low tide rainfall events has been shown to augment the cycling of dissolved and particulate nutrients, but low tide rainfall events are not a well-documented component of coastal ecosystem models. Here we develop the relationships between rainfall intensity (I), and median volume raindrop diameter, and three rainfall erosivity indices (kinetic energy, momentum, and momentum multiplied by the drop diameter) using an optical disdrometer deployed in the intertidal zone during summer and fall of 2010 and 2011. These data include the local effects of Hurricane Irene in 2011. Raindrop data measured for 27 days of late summer were analyzed. The best fit between median volume raindrop diameter and I was a combination of the power-law and logarithm equations, and the best fits of three erosivity indices and I were obtained with power-law equations. Kinetic energy was slightly higher than the world average. Observed raindrop velocity was typically lower and more widely distributed than the theoretical raindrop terminal velocity. Hence, erosivity indices based on observed velocity were lower than those based on terminal velocity. The hurricane provided larger raindrops and more widely distributed raindrop velocity than normal events. Overall, results indicate that it is not suitable to assume that background erosivity–I relationships apply to cyclonic events. We derived new erosivity–I relationships to help characterize soil erosion processes in salt marsh areas for normal events. These results will help predict material and nutrient fluxes between intertidal and subtidal landscapes.

1. Introduction

Intertidal landscapes, the areas between high and low tide, are susceptible to rainfall-driven material transport in response low tide rain events (e.g., Anderson, 1972). Hence, intertidal rainfall–runoff processes may arrest the incipient long-term estuarine sediment storage (Chalmers et al., 1985), and in the process facilitate the cycling of highly nutritious particulate matter (Torres et al., 2004). For instance, Chen et al. (2015) showed that low tide rainfall events give rise to a narrow range of particulate organic carbon fluxes, regardless of location. Taken together these studies show that low tide rainfall events enhance material cycling at the terrestrial – marine transition, and they augment coastal zone biogeochemical cycling (Chen et al., 2015).

As with terrestrial systems, coastal rainfall events cause erosion through the detachment of soil particles and the subsequent transport of the detached material. Rainfall kinetic energy (KE) is one of the most widely used indicators of rainfall erosivity (e.g., Al-Durrah and Bradford, 1982; Ekern, 1954; Ellison, 1944, 1947; Lal, 1994; Morgan et al., 1998; Morgan, 2009; Nanko et al., 2008; van Dijk et al., 2002). On the other hand, Rose (1960) recognized momentum (M) as a better indicator, and Ghadiri and Payne (1988) showed that KE is not a reliable indicator at all. Later, Salles and Poesen (2000) found that the product of momentum and drop diameter (MD) was more appropriate for describing splash erosion. Regardless of the approach, in order to calculate estimates of these erosivity indices raindrop mass and fall velocity are necessary.

Direct measurements of raindrop impact are rare (Mikoš et al., 2006) because they require inordinate and costly instrumentation (Fornis et al., 2005). Therefore, erosivity is often derived from widely available rainfall intensity (I) data through the implementation of empirical erosivity–I relationships. A number of studies have proposed various expressions for erosivity–I for certain locations with specific climate conditions. The use of any specific erosivity–I relationship in a climatically different environment should be justified prior to implementation.

Recent studies provided erosivity–I relationships based on raindrop measurements with optical disdrometers (e.g., Salles et al.,

---

* Corresponding author. Tel.: +81 29 829 8240; fax: +81 29 874 3720.
E-mail address: knanko@affrc.go.jp (K. Nanko).

[1] Present address: Stockton University, 101 Vera King Farris Dr., Galloway, NJ 08205, USA.

http://dx.doi.org/10.1016/j.jhydrol.2016.01.022
0022-1694/© 2016 Elsevier B.V. All rights reserved.

2002; Nanko et al., 2008; Petan et al., 2010; Sanchez-Moreno et al., 2012). One of the advantages of optical disdrometers is the independent measurement of raindrop diameter and fall velocity. However, previous studies typically calculated erosivity using observed raindrop size distribution (DSD) with estimated raindrop terminal velocity through well established associations (e.g., Laws, 1941; Gunn and Kinzer, 1949; Atlas et al., 1973; Atlas and Ulbrich, 1977). Stagnant or still wind conditions would give rise to the theoretical terminal velocity; however, actual situations do not always create raindrop terminal velocity, and for windy conditions in particular. In fact, some noise in the velocity distribution relations was reported with the Gunn and Kinzer (1949) curve even under relatively still wind conditions (Krajewski et al., 2006). Moreover, Montero-Martínez et al. (2009) showed all raindrops did not fall at terminal velocity. Although there is uncertainty associated with estimating raindrop velocity with optical disdrometers (Friedrich et al., 2013), estimates of the erosivity–I relationship from such data remain valuable (Nanko et al., 2008 and Petan et al., 2010).

In temperate coastal landscapes of eastern North American, Chen et al. (2015) hypothesized that low tide rainfall events give rise to a characteristic response of carbon and nutrient transport in expansive salt marsh areas. The summer-fall convective storms that they observed have a short duration with high intensity (Torres et al., 2004). Moreover, their particular study location is susceptible to the impacts of tropical cyclone-driven rainfall. Hence, the intertidal landscape is susceptible to sediment redistribution by both high intensity rainfall conditions from summer thunderstorms and from hurricanes.

Tropical cyclones have distinct rainstorm characteristics and they occur with relatively strong winds. Previous studies showed various DSD characteristics in cyclonic events. For example, Merceret (1974) reported that the DSD from Hurricane Ginger in 1971 was well represented by the widely-used exponential relation of Marshall and Palmer (1948). Tokay et al. (2008) highlighted a high concentration of small to midsize drops with both the presence and absence of large drops during seven storms. Also, Kumari et al. (2014) showed that DSDs between two cyclones differed in that the precipitation induced by a more stratiform cyclone contained a higher concentration of small drops compared to a more convective cyclone. On the other hand, Friedrich et al. (2013) highlighted the misclassification of particles by an OTT Parsivel disdrometer deployed during Hurricane Ike in 2008 that was characterized by a large concentration of raindrops with large diameters (>5 mm), and unrealistically low fall velocities (<1–2 m^{-1}). This misclassification was caused by winds in excess of 10 m s^{-1}. Overall, DSD varied with each cyclonic event and the corresponding data were insufficient to determine the corresponding DSD characteristics. Furthermore, the objectives of these previous studies included evaluation of DSDs, but rainfall erosivity in response to these cyclonic events have gone largely unexplored.

The objective of this study is to estimate the three major rainfall erosivity indices (KE, M, and MD) and provide these erosivity–I relationships for the US southeast coast as taken from the OTT Parsivel optical disdrometer measurements. We evaluated the difference between two kinds of erosivity calculated using observed raindrop velocity and estimated raindrop terminal velocity. A second objective is to verify the ability to apply the erosivity–I relationships developed in normal events to hurricane event.

2. Materials and methods

2.1. Site description and measuring equipment

Field measurements were taken in the intertidal area of North Inlet estuary, near Georgetown, SC, an area that is part of the US National Estuarine Research Reserve (Fig. 1). The study site is located in a 32 km^2 bar-built estuary and is dominated by the smooth cordgrass *Spartina alterniflora*. South Carolina has a humid subtropical climate, with average temperatures ranging between 9 and 27 °C and an average of 1330 mm of rainfall per year (National Climate Data Center http://www.ncdc.noaa.gov/cdo-web/search, station GHCND: USC00383470). Mwamba and Torres (2002) report that the low lying coastal plain region of South Carolina extends up to 200 km inland and this landscape typically experiences frequent high intensity and low duration convective summer time rainfall events (thunderstorms). For example, for the months of June–August they report regional 30-min duration storms of 1-yr, 2-yr, 5-yr and 10-yr recurrence intervals have rainfall totals of 35, 42, 52 and 61 mm, respectively.

Rainfall occurs throughout the year but has a distinct seasonal peak for July – September. Late summer and early autumn rainstorms, the focus of this study, are associated with small convective thunderstorms with heavy precipitation over a limited surface area, on the order of 5–10 km^2. The National Weather Service Hydrometeorological Design Center (http://www.nws.noaa.gov) reports that the area can experience 5-min rainfall intensities of 146–171 mm h^{-1} with a 1-year recurrence interval (Chen et al., 2012).

A weather station was deployed during late summer and early autumn of 2010 and 2011. The weather station consisted of a barometer, a Texas Electronics 525 tipping bucket rain gauge (0.2 mm per tip), a Met One wind sensor set, and an OTT Parsivel disdrometer (Löffler-Mang and Joss, 2000); all run by a Campbell Scientific CR1000 data logger/controller. The station was deployed on a salt marsh island adjacent to the mouth of a tidal creek (Fig. 1) and on a wooden platform about 2 m above the marsh surface and 1 m above high tide. The Parsivel measures the size and velocity of rain drops passing through a laser beam of 5400 mm^2 (180 mm length × 30 mm width) and it assigns them to one of 32 logarithmically distributed size and velocity bins (Löffler-Mang and Joss, 2000). Measurements by the barometer, the rain gauge, and the wind sensor were recorded every one minute. To conserve battery power, the Parsivel was turned on for 14 s and these measurements were recorded when the rain gauge tipped one or more times (=>12 mm h^{-1}) in the previous minute.

2.2. Data filtering and calculation of raindrop data

We used 1-min time unit data with the Parsivel measurements for the analyses. Some data from the Parsivel were removed because they were taken to be unrealistic. For instance, here we assume rain drops have a diameter less than 8 mm, and velocity less than 16 m s^{-1}; measurements with higher diameter and velocity were believed to be erroneous artifacts of the instrumentation. Also, for drop data with diameter greater than 0.5 mm, the corresponding velocities that were less than 1 m s^{-1} were removed because they were deemed too slow for gravity-fall raindrops, and they could not be distinguished from Parsivel housing splash effects. Further, the data with fewer than 50 drops per time unit were not used. The data on August 26, 2011 was extracted as the data from Hurricane Irene. Subsequent "hurricane" analyses were based on 879 time units of normal events, and 144 time units of a cyclone event.

Rainfall intensity, I (mm h^{-1}), was calculated as the sum of raindrop volumes in all drop classes c, assuming spherical drops had passed through the detection area A (=5400 mm^2) of the monitoring duration Δt (=14 s):

$$V_i = \frac{\pi}{6} D_i^3 \tag{1}$$

$$I = \frac{3600}{A\Delta t} \sum_{i}^{c} n_i V_i \tag{2}$$