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Links between episodic groundwater recharge rates and rainfall events classified according to stratiform-convective storm scoring: A plot-scale study in eastern Nebraska

Paolo Nasta[a,b,*], Zablon Adane[a,c], Noah Lock[a], Adam Houston[a], John B. Gates[a]

[a] Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE, USA
[b] Department of Agricultural Sciences, AFBE Division, University of Napoli Federico II, Portici (Napoli), Italy
[c] World Resources Institute, Washington D.C., USA

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ABSTRACT

Groundwater recharge rates emerge from complex interactions within the soil-vegetation-atmosphere system. While it is widely recognized that numerical models are able to properly simulate soil water dynamics depending on boundary forcing data, in-depth information on episodic recharge generation needs to be gained. In this study, the water balance of a heterogeneous 300 cm-deep soil profile beneath a rainfed maize agro-ecosystem in eastern Nebraska was numerically simulated in HYDRUS-1D for 12 years (2001–2012) on daily time steps. We estimated potential groundwater recharge as the downward flux simulated below maximum maize root depth (150 cm). This model was calibrated in a previous study by using direct field measurements. Simulated results indicated that annual rainfall scarcely controls the amount of annual recharge. The impact of individual storm event on recharge episodicity was assessed through iterative scenario modeling. We investigated the importance of rainfall events classified according to convective-stratiform scoring, spanning from 0 and 1, designating extremely stratiform and convective, respectively. The inequality of frequency distribution of rainfall and recharge was assessed by using the Gini coefficient. We detected relatively few significant recharge responses clustering near the 1:1 rainfall/recharge line in late winter (38% of events) and spring (only 13% of events). Generally, the recharge events are triggered by stratiform (28% of total sum) and convective (44% of total sum) precipitation events. Nonetheless, the most efficient recharge events are generated by stratiform rainfall when soil saturation increases without runoff generation. The intense convective storm events often cause saturation excess with runoff generation and mostly occur when evapotranspiration demand is high. For these two main reasons, convective storms lead to inefficient recharge rates characterized by extreme episodicity.

1. Introduction

Understanding the potential impacts of meteorological regimes on subsurface soil hydrology can lead not only to improved management of water resources but also to better forecast groundwater recharge processes under future climate change scenarios (Bovolo et al., 2009; Green et al., 2011; Crosbie et al., 2013). Particular concern is given to precipitation regimes that will alter rainfall intensity and seasonal variability, which increase sensitivity to climatic extremes over continental United States (Groisman et al., 2004; Zhao et al., 2017). The role of the climatic fluctuations on the generation of episodic groundwater recharge is difficult to assess over different time-scales but holds critical importance in the management of groundwater resources that are increasingly more stressed by industrial and agricultural demands (Warner, 2007; Ng et al., 2010; Zhang et al., 2016).

In view of climate change scenarios, it is important to gain a better insight on the impact of the meteorological regime on groundwater recharge rates by adopting robust model-based approaches (Keese et al., 2005; Smerdon et al., 2008; Wang et al., 2009; Chen et al., 2012; Nasta et al., 2016). Previous field and modeling studies have illustrated that temporal patterns (both intra-annual and inter-annual) of moisture drainage below the root zone are often irregularly distributed (Tashie et al., 2015). Deep drainage can be highly episodic, whereby large percentages of cumulative drainage rates are attributable to a relatively small number of wetting events (Zhang et al., 1999; Nimmo et al., 2015).

Abbreviations: SC, storm classification; P, precipitation; ET, evapotranspiration; R, recharge; Q_r, runoff; WS, water storage; G, Gini coefficient

* Corresponding author at: Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE, USA.
E-mail address: paolo.nasta@unina.it (P. Nasta).

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Links between storm-scale rainfall patterns and their influence on recharge have been studied particularly in semi-arid and arid regions including Australia (Lewis and Walker, 2002; Barron et al., 2012; Crosbie et al., 2012), Tanzania (Taylor et al., 2013), Nigeria (Eilers et al., 2007), Italy (Allocca et al., 2015), USA (Thomas et al., 2016), to mention a few. Under non-arid conditions, it is important to explore the role of regular and sporadic events in determining the amount of annual recharge. This study investigates the role of storm classification in explaining episodic recharge generation patterns under sub-humid conditions. Individual storm events are classified on a stratiform/convective scale through radar-based measurements (Fabry et al., 2017). In USA, these ground-based devices are densely distributed in space and provide km grid geographic footprint with volumetric datasets instead of the 2D images offered by satellite platforms (Houston et al., 2015). The water balance of a soil profile under an agro-system (rainfed maize) was numerically simulated for 12 years (2001–2012) by exploiting rainfall daily records retrieved from weather radar data in eastern Nebraska. A calibrated unsaturated zone flow model (HYDRUS-1D) was used to assess individual groundwater recharge rates through an iterative scenario modeling approach. The target of this study is to evaluate the importance of daily rainfall events classified according to stratiform-convective storm scoring in generating episodic groundwater recharge dynamics.

2. Materials and methods

2.1. Description of the experimental plot

The study site is located on a gentle-slope rainfed (non-irrigated) maize field in eastern Nebraska's glaciated region, near the town of Oakland, Burt County (96.53°E, 41.83°N; 415 m a.s.l.) (Gates et al., 2014; Naylor et al., 2015). The soil profile is characterized by four soil horizons classified as silty clay loam texture (Nasta and Gates, 2013).

Weather Surveillance Radar-1988 Doppler (WSR-88D) provided reflectivity-based hourly rainfall ($cm\,h^{-1}$), P forcing data and storm classification (SC) that was set on a scale from 0 (extremely stratiform) to 1 (extremely convective) according to the Thunderstorm Observation by Radar (ThOR) algorithm (Roberts and Rutledge, 2003; Houston et al., 2015; Lock and Houston, 2015). Fig. 1 shows three maps as illustrative examples of reflectivity, storm classification, and rainfall intensity of a storm event recorded in eastern Nebraska. Reflectivity represents the weather radar's measurement and is used to retrieve rainfall and storm classification (Fabry et al., 2017). Convective rainfall events are associated to squall lines (lines of thunderstorm that can form along or ahead of a cold front by producing cumulonimbus clouds). Stratiform rainfall is generated by the collision of a tropical air front from the south along with a cooler front from the north, which generates nimbostratus clouds. For modeling purposes, hourly rainfall data were aggregated to daily data.

An automated weather station in close proximity to the study location recorded snowfall, air temperature, air relative humidity, wind speed, and net solar radiation (NOAA-NWS, 2007). The reference potential evapotranspiration ET_0 ($cm\,d^{-1}$) was computed with the Penman-Monteith equation from the meteorological data, whereas the potential crop (maize) evapotranspiration ET_p ($cm\,d^{-1}$) and its partition between potential evaporation E_p ($cm\,d^{-1}$) and potential transpiration T_p ($cm\,d^{-1}$) were computed by following the protocol summarized in Nasta and Gates (2013).

2.2. Set up of the numerical model

The numerical HYDRUS-1D model (Šimůnek et al., 2008; Šimůnek et al., 2012) was used to simulate one-dimensional vertical movement of water in the unsaturated zone and root water uptake (RWU). HYDRUS-1D numerically solves the Richards equation given by:

$$\frac{\partial\theta}{\partial t} = \frac{1}{\partial z}\partial\left[K(\psi)\left(\frac{\partial\psi}{\partial z}+1\right)\right] - \xi(\psi) \tag{1}$$

where t (T) is time, z (L) is soil depth, ψ is the soil matric potential (L), θ ($L^3\,L^{-3}$) is the soil volumetric water content, and $\xi(\psi)$ is the RWU sink term (T^{-1}). The units of time (T) will be expressed either in day (d) or hour (h) while length (L) is measured in centimeters (cm) in the remainder of this paper. The soil water retention function $\theta(\psi)$ is described by van Genuchten's equation (van Genuchten, 1980):

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha\psi)^n]^m} \tag{2a}$$

with Mualem's condition (Mualem, 1976):

$$m = 1 - \frac{1}{n} \tag{2b}$$

where α (cm^{-1}), m (−) and n (−) are water retention shape parameters, θ_r ($cm^3\,cm^{-3}$) and θ_s ($cm^3\,cm^{-3}$) are residual and saturated water contents, respectively. Considering the degree of saturation, $S_e = (\theta-\theta_r)/(\theta_s-\theta_r)$, which varies from 0 ($\theta = \theta_r$) to 1 ($\theta = \theta_s$), an expression for the unsaturated hydraulic conductivity function $K(S_e)$ is

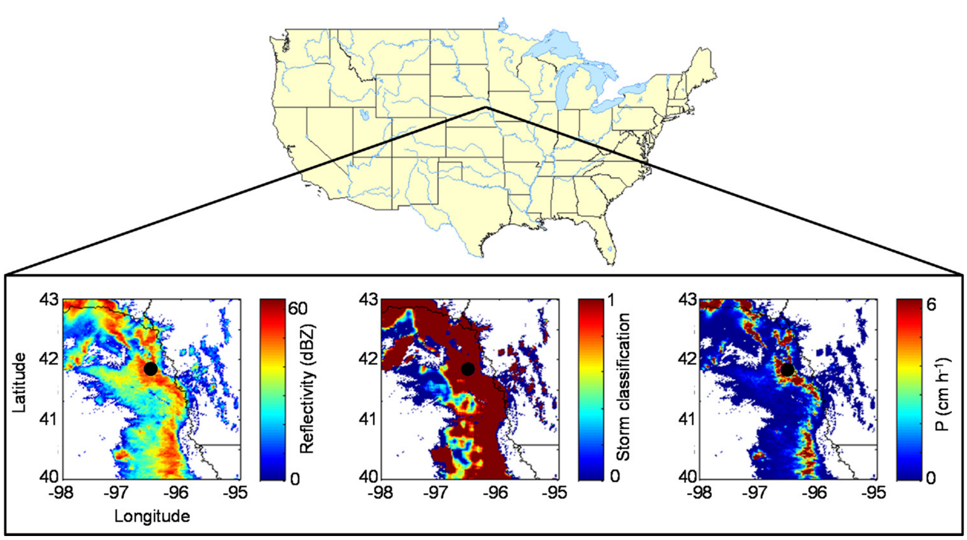

Fig. 1. Geographic position of the study site (black circle) and maps (from left to right) of reflectivity (dBZ), storm classification and rainfall intensity, P ($cm\,h^{-1}$) of a storm event recorded in eastern Nebraska through Weather Surveillance Radar-1988 Doppler.