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Spatial point pattern analysis of piping erosion in loess-derived soils in Golestan Province, Iran

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ABSTRACT

Point pattern analysis of collapsed pipes as a subsurface erosion in natural and manmade conditions plays an important role to understand their landforms/features, predisposing factors, and for prevention and forecasting purposes. Thus, the present study aimed to evaluate the spatial pattern and the associated land factors of piping erosion in loess-derived soils in a semiarid climate in Golestan Province, Iran by applying numerical summary statistics. To this end, a 105 ha area with homogeneous environmental conditions (gentle slope and loess-derived soil) was selected and the maps related to 101 collapsed pipes and their features were obtained by the aerial photos provided by an unmanned aerial vehicle (UAV) with a 50 cm resolution and field survey. The mean of spatial distances between pipe locations was 309 m, and the frequency of pipes per hectare was 0.97. Moreover, soil samples of the pipe locations were collected and physical-chemical soil properties were measured in laboratory. Approximately 95% simulation envelopes were selected using the 5th-lowest and 5th-highest values of 199 Monte Carlo simulations of the null model of homogeneous complete spatial randomness. Based on the results of univariate pair correlation function, the significant aggregation of 101 collapsed pipes was observed at a scale of 0–50 m in both rangeland and agricultural land use types. The bivariate pair correlation function, which is considered to be the most informative second-order summary characteristic, was used for analyzing the statistical correlations between collapsed pipes and linear phenomena including distance from drainage networks, ridges, and roads. Based on bivariate summary statistics, collapsed pipes had positively been affected by both the distribution of drainage networks and ridges. However, the negative statistical correlations occurred between pipes and roads at the scales of 1–50 m. Also, the correlations of soil characteristics (silt content, *exchangeable sodium percentage* (ESP), the weight of soil in a given volume (bulk density), soil electrical conductivity (EC), and organic matter (O.M.)) of neighboring collapsed pipes were evaluated by mark correlation function. Based on mark correlation function $k_{mm}(r)$, a significantly positive correlation was found between the pipes density and silt content, ESP, and bulk density, when they are more than overall average. In addition, less values of EC and O.M. were positively related to the aggregation of collapsed pipes. Similar to the results of summary statistics, the maps confirmed all statistical correlations. Consequently, the outcome of this study highlights the spatial pattern of collapsed pipes and their associations in the study area.

1. Introduction

In different climate regions and in many differing landscapes, piping causes numerous problems (Frankl et al., 2012). Soil piping, as critically important soil erosion in a wide range of environments, refers to the formation of linear voids by concentrated flowing water in soils or unconsolidated sediments, which can cause collapse of the soil surface and result in formation of discontinuous gullies in natural landscapes (Boucher, 1990; Jones, 2004; Verachtert et al., 2011a, 2011b, 2011c). It is extremely widespread in different regions. The largest diameter of pipes has been found in semi-arid regions (Jones, 1994). Piping dynamics may be monitored in different ways, i.e. by soil volume loss, by changes in the gully development induced by piping, mainly by headcut retreat or by elongation of pipes (Bernatek-Jakiel et al., 2017). Although piping erosion in loess-derived soils cause an important loss of soil and damage to infrastructure (Kerenyi, 1994; Zhu, 2003; Rodzik et al., 2009; Verachtert et al., 2011a, 2011b, 2011c; Bernatek-Jakiel et al., 2017), there is still uncertainty about their properties inducing

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subsurface pipe development and the statistical correlation between pipes in loess-derived soils. It may also be the major cause for the development of badlands and commonly occurs in the vicinity of gullies and is an important factor in the development of gully erosion (Poesen, 1989; Faulkner et al., 2004). Piping is exacerbated by a combination of inappropriate management practices and particular combinations of different natural or/and artificial factors can result in a severe degradation of the environment. So, identifying these factors and their impacts on land degradation processes in different areas is crucial for any sustainable development action plan (Ownegh, 2009; Frankl et al., 2012).

The spatial variability of patterns of every phenomenon and their impacts on soil within the landscape is being considered as a basic criterion for decision making, especially in sustainable development. For instance, spatial pattern of plants is a central concept in ecological theory (Lan et al., 2011), and a data-set consisting of a series of mapped point locations is an important example of a spatial point pattern (e.g. Dale, 2000; Botschek et al., 2002a, 2002b; Diggle, 2003; Wiegand and Moloney, 2004; Illian et al., 2008; Yu et al., 2009; Lopez et al., 2010; Verachtert et al., 2010; Navarro-Cerrillo et al., 2013; Verachtert et al., 2013; Wiegand and Moloney, 2014; Svatek and Matula, 2015). The methods for quantifying these characteristics of point pattern are summary statistics (Genet et al., 2014). From a statistical point of view, the methods are also appropriate for phenomena that represent various types of geomorphologic features (Tonini et al., 2012). Therefore, this is the first time that application of point pattern functions has been investigated in subsurface erosion (pipe and tunnel formation) studies. In addition, a useful part of the study of geomorphological forms/features especially in fertile loess deposits is evaluating the spatial point patterns (i.e. aggregation and dispersion) and the spatial correlations and relationships (i.e. positive and negative) between pipes and the variety of inter-related factors that affect the pipes in different area. According to literature review, field investigation, and interviews with local stakeholder and farmers, seems that pipes are spatially related with linear phenomena such as drainage network, ridges, and roads (Poesen, 1989; Poesen et al., 1996; Romero Díaz et al., 2007). So, to better understand the factors controlling the intensity and occurrence of piping erosion, univariate and bivariate summary statistics have been used. Moreover, a more promising approach in such analyses is to complement point position with quantitative size attributes and use mark point patterns (i.e., one pipe with a quantitative sign such as silt content, ESP, bulk density, EC, and O.M.). In fact, the spatial distribution of piping in an environment can be described and modeled by point pattern processes where the points are given by locations of the piping (Getzin et al., 2008; Goncalves and Pommerening, 2012; Bernatek-Jakiel et al., 2016). Since the properties of soils that are susceptible to piping include silt content (Parker (1963), ESP, bulk density, EC, and organic matter to identify hot spots of piping propensity (Piccarreta et al., 2006; Faulkner, 2013; Verachtert et al., 2013; Wilson et al., 2015). Thus, the three functions (i.e. univariate pair correlation function, bivariate pair correlation function, and mark correlation function) are used to characterize the pipes spatial pattern and their correlations with different factors hypothesized to influence their occurrence.

In general, it is still difficult for scientists to characterize the spatial pattern as they develop in an episodic fashion. The main objectives of this study are to analyze the spatial point pattern of piping erosion and to understand the influence of different soil properties and linear phenomenon their development in the loess-derived soils of the Iky Aghzly sub-watershed, Golestan Province, Iran.

2. Study area

Golestan Province is located in the northeast of Iran and on the south-eastern shore of the Caspian Sea (Fig. 1.). The study area, Iky Aghzly sub-catchment, as part of Gorganrud catchment, lies between 53° 51′ to 56° 21′ eastern longitude and 36° 30′ to 38° 7′ northern latitude. It comprises a region of approximately 105 ha (30 ha rangeland and 75 ha agriculture) with mean slope of 27%. 5 pipes (~5%) in agricultural lands and 96 pipes (~95%) in rangelands are recorded. Based on Iranian Meteorological Organization, average annual rainfall and temperature in the region are 385 mm and 18.2 °C, respectively and it is a semiarid region. The lowest and highest altitudes are 229 m and 566 m, respectively and loess deposits cover the all area. In the study area, piping erosion forms are circular, rectangular, triangular or oval (Fig. 2).

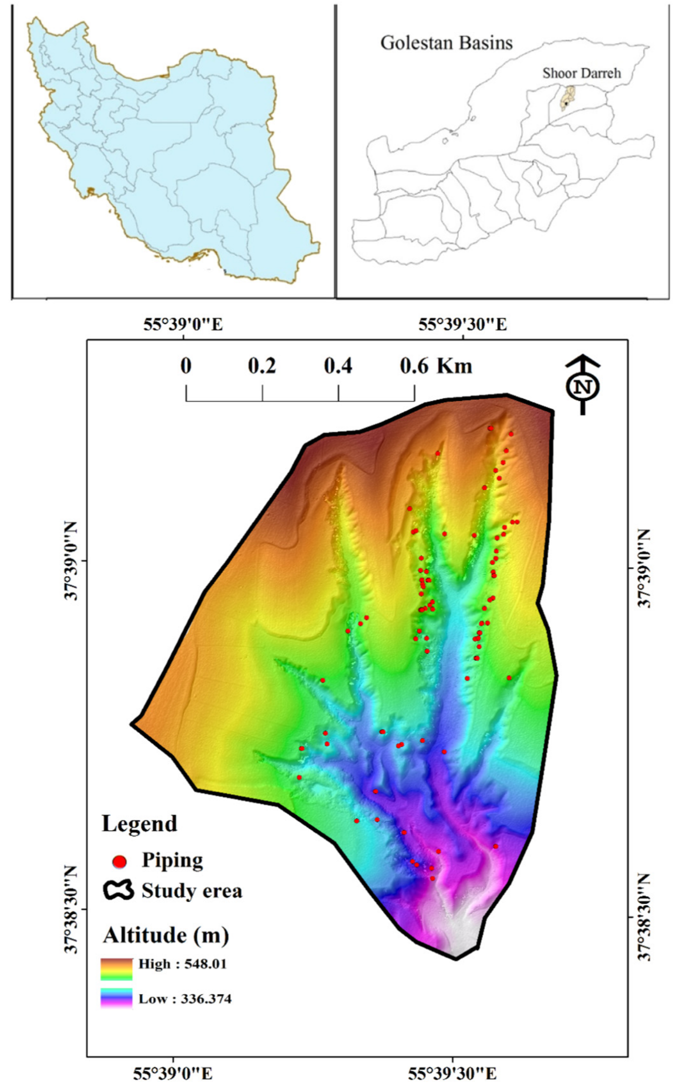

Fig. 1. Location map of the study area.

3. Methods

3.1. Field measurements

To investigate the most important factors associated with the pipes occurrence, a 105 ha area was selected and 101 collapsed pipes were identified through field survey and the aerial photos, obtained using an unmanned aerial vehicle (UAV) with a 50 cm resolution. The UAV applied in this study was DJI Phantom-4 quadcopter equipped with a digital camera with a 1/2.3 in. CMOS sensor and a size of 3000 × 4000 pixels (Fig. 3a). The maximum flight time length was about 30 min. All RGB (Red-Green-Blue) images were acquired in jpeg format with the digital camera set in automatic mode in clear and calm climatic conditions at noon to reduce shadow and wind effects on the