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An application of different summary statistics for modelling piping collapses and gully headcuts to evaluate their geomorphological interactions in Golestan Province, Iran

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ABSTRACT

The quantitative characterizations of piping collapses (PCs) and gully headcuts (GH_S) are an important part of the study of geomorphological processes under different types of climate such as arid, semiarid, and temperate and non-climatic conditions like land use changes and agricultural machinery. The present study aimed to evaluate summary statistics to characterize PCs and/or GH_S structure by using numerical functions as well as understanding the interaction of gully head features and collapse pipes by applying univariate and bivariate summary statistics. To this end, a 703.36 ha area was first selected in the loess-covered hilly region of Golestan Province, eastern-north of Iran. Then, the maps of 345 PCs and 133 GH_S were obtained by a detailed reconnaissance surveys in the field by using an unmanned aerial vehicle (UAV) photography. Finally, the univariate (L, g, and O-ring functions) and bivariate (L_{12}, g_{12}, O_{12}, $g_{22}(r)$ - $g_{11}(r)$, $g_{12}(r)$ - $g_{11}(r)$, and $g_{1,1+2}$ - $g_{2,1+2}$ functions) summary statistics were used to investigate the statistical analyses of PCs and GH_S, separately. Based on the results of the univariate summary statistics, the PCs had a clustered distribution and the pattern of GHs was aggregate. Based on bivariate summary statistics, gully headcuts were positively related to collapse pipes. In addition, PCs had more aggregation compared to the GH_S. The neighborhood density of PCs was relatively less frequent around GHs than PCs. The PCs were spatially located in more dense parts of the study area. It means that PCs are positively correlated with each other and generally multi PCs should be put together to form one gully headcut. In general, the proposed summary statistics lead to a better understanding of the studied soil erosion processes in the study area.

1. Introduction

In arid and semi-arid environments around the world with sparse vegetation cover, piping and gully headcut retreat (GHR) represent some of the most severe land degradation processes (Faulkner 2013; Vanmaercke et al. 2016). Soil piping erosion, as a critically important soil erosion process 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 the soil surface to collapse and discontinuous gullies to form and develop (Bernatek-Jakiel et al. 2017; Bryan and Jones 1997; Faulkner 2013; Jones 2004; Verachtert et al. 2011a; Wilson et al. 2015; Zhu 2003). In addition, it plays an important geomorphic and hydrologic role in many parts of the world (Bryan and Jones 1997). Gullies as a major driver of land degradation on the global scale are often characterized by actively retreating headcuts (Vanmaercke et al. 2016). Gully headcut retreat is a natural, nearly vertical drop in gully channel-bed elevation and gully headcut retreat is recognized as one of the major process of gully expansion in sediment production and land degradation in different environments (e.g., Bouchnak et al. 2009; Faulkner 2013; Higgins 1990; Poesen et al. 2003; Poesen, 2011; Vanmaercke et al. 2016; Zhu 2012).

Although considerable researches have been carried out on the role of piping in gully development (e.g., Faulkner 2006, 2013; Frankl et al. 2012; Nichols et al. 2016; Vandekerckhove et al. 2003; Wilson et al. 2015; Zhu 2003, 2012), less effort has been applied in terms of their spatial locations particularly in loess derived soils (Hosseinalizadeh et al. 2018). Higgins (1990) reported that piping is a source of many gullies in the Sacramento Valley, California, with a Mediterranean climate. The signs of piping erosion in > 60% of badlands in Europe were identified by Bocco (1991). The data from aerial photos in southern Italy indicated that over 900 pipes were collapsed which occurred mostly along the drainage network (Farifteh and Soeters 1999).

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Vandekerckhove et al. (2000) observed 17 piping among 55 surveyed gullies in semi-arid Mediterranean environments in Spain. According to Zhu et al. (2002), tunnel systems deliver 53% of the runoff and 57% of the sediments in the sub-catchment in the Loess Plateau, North China. The effect of piping erosion on gully formation and development was introduced as a novel approach for investigation of this subsurface flow erosion by Valentin et al. (2005). Gully growth which has been resulted from pipe origins was also confirmed by Faulkner (2006). Samani et al. (2009) investigated threshold conditions and gullying processes in the arid rangelands of Iran based on the slope area relationship. High rates of soil loss resulting from piping on collapsible loess on Luvisols have been reported by Verachtert et al. (2011a). Verachtert et al. (2011b) found that soil loss by piping is 4 times greater than soil loss by wash processes. In various European study areas, soil loss rates due to piping erosion range between 1.5 and 287 t/ha/yr. These rates reach between 1.3 and 15 t/ha/yr under grassland (Bernatek-Jakiel et al. 2017; Verachtert et al. 2011a).

In parallel with the above mentioned studies, Zhu (2012) examined the interactions between tunnel erosion and gully development in the hilly Loess Plateau region of northern China. Verachtert et al. (2013) investigated the spatial interaction between piping collapses and landslides in hilly regions with loess-derived soils. Frankl et al. (2016) proposed a subsurface geomembrane dam to decrease flow in subsurface pipes which are near gullies. Bergonse and Reis (2016) addressed the controls over development of gully systems using two supplementary regression techniques. In a recent article, Zabihi et al. (2018) considered the spatial distribution and susceptibility zonation of gully erosion using bivariate statistical models in Mazandaran Province, northern Iran. Although the impact of piping on gully initiation and development was analysed using dendrogeomorphology very recently (Bernatek-Jakiel and Wrońska-Wałach 2018), the spatial pattern and the land factors associated to piping erosion are not well studied in a semiarid climate (Hosseinalizadeh et al. 2018).

Summary statistics include the methods used for understanding the ecosystem structure and point patterns (Genet et al. 2014). Although point pattern analysis based on the univariate and bivariate second-order summary statistics has been commonly used in ecological studies (Dale 2000; Diggle 2003; Illian et al. 2008; Svatek and Matula 2015; Tonini et al. 2012; Wiegand et al., 2013; Yu et al. 2009; Yuan et al. 2018), it has been less emphasized in geomorphological fields (Dutilleul et al. 2009; Ghosh et al. 2011; Tonini et al. 2012; Hosseinalizadeh et al. 2018). Moreover, the quantitative characterization of spatial structures of PCs and GH_S based on their locations is useful in predicting natural and human-induced events, especially in the Northeast part of Iran, which is influenced by the recent changes in the amount of these kinds of erosive mechanisms. There is a need to greater understand the spatial pattern and association between piping collapses and gully head features to reduce their devastating effects and improve environmental conditions worldwide. Therefore, the present study aimed to obtain a model to explain the spatial distribution of PCs and GH_S and their spatial association via statistical analyses based on point processing theory in the Northeast part of Iran. However, it is recognized that the hydraulic connectivity of the system is not being represented by this choice of exploratory approach.

2. The study area

The Golestan Province is located in the Northeast of Iran and on the south-eastern shore of the Caspian Sea. Iky Aghzly sub-catchment, as a part of the Gorganrood Catchment, in Golestan Province, located between 55° 38′ to 55° 40′ eastern longitude and 37° 37′ to 37° 39′ northern latitude, includes a region of approximately 703 ha with an altitude between 336.374 and 548.01 m (Fig. 1). The map was created by using a digital elevation model (DEM) with 50 cm resolution obtained from an UAV images. Based on Iranian Meteorological Organization, the average annual rainfall and temperature in the region are

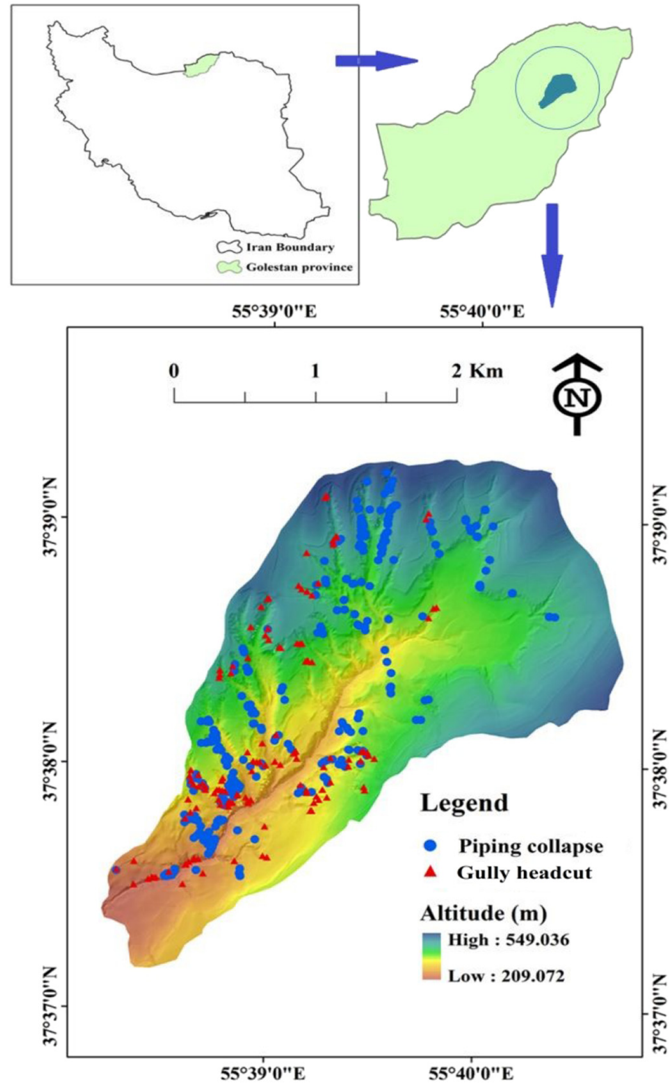

Fig. 1. The study area in Golestan Province, Iran.

385 mm and 18.2 °C, respectively. Planimetric form of collapsed pipe features in the area can be classified into star, circle, ellipsoid, diamond, triangle, and rectangle. Fig. 2 illustrates some examples of piping and headcut landforms. Based on the USDA system, the area includes "silt loam" and "silty clay loam" soil textures (Fig. 3a). In addition, the Iky Aghzly sub-catchment, as a part of the Gorganrood Catchment, includes agricultural use which is cultivated with *Triticum* and rangeland use which is more covered with *grasses*, *Paliurus spina-christi, Phragmites australis*, *Punica granatum*, and *Ficus carica*. As shown in Fig. 3b, 42 (~12%) PCs and GHs are located in agricultural lands and 303 (~88%) PCs and GHs are distributed in rangelands. Moreover, as shown in Fig. 3c, the map of plan curvature presented that the study area has convex, concave and flat topography suggesting some link between collapsed pipe locations and topographic settings where convex topography changes to concave topography. The study area reported in this paper has also been documented using an UAV that provides *an overview* of the key visual landscapes (Video 1).

3. Methods

We specifically focused our studies on the spatial distribution of PCs and GHs and their spatial association via statistical analyses based on point processing theory. Fig. 4 illustrates a flowchart for the method used in the present study.