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Subsurface erosion by soil piping: significance and research needs

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ABSTRACT

Soil erosion is not only a geomorphological, but also a land degradation process that may cause environmental damage affecting people's lives. This process is caused both by overland and subsurface flow. Over the last decades, most studies on soil erosion by water have focused on surface processes, such as sheet (interrill), rill and gully erosion, although subsurface erosion by soil piping has been reported to be a significant and widespread process. This paper presents a state of art regarding research on soil piping and addresses the main research gaps. Recent studies indicate that this process (1) occurs in almost all climatic zones and in the majority of soil types, (2) impacts landscape evolution by changing slope hydrology, slope stability and slope-channel coupling, (3) is controlled by various factors including climate and weather, soil properties, topography, land use and land management. These issues are illustrated with various case studies from around the world. However, the majority of the reviewed studies used surface methods for soil pipe detection, although soil piping is a subsurface process. Surface methods, such as geomorphological mapping, may underestimate the piping-affected area by 50%. Moreover, most studies are limited to few case studies without presenting thresholds for soil pipe development in different environments. Subsurface erosion by soil piping is not represented in currently used soil erosion models. Therefore more research is needed to better understand the morphology and connectivity of soil pipes, their subsurface catchments, as well as soil erosion rates by piping in different environments. Knowledge of thresholds that induce erosion in pipes and subsequent initiation of gullies may help to improve models of hillslope hydrology and soil erosion that include pipeflow and piping erosion. The investigation of soil piping also requires improved methods that allow to better predict pipe development and collapses, and thus to detect piping-affected areas. Studies dealing with effective prevention and control measures of soil piping are scarce. Addressing these research gaps will help to improve our insights into subsurface erosion by soil piping, and thus help to better understand landscape evolution and hillslope hydrology, as well as to develop and improve effective piping erosion control techniques and strategies.

1. Introduction

Soil erosion by water represents a key environmental issue worldwide (e.g. García-Ruiz et al., 2017; Lal, 2001; Morgan, 2005; Poesen, 2018). It may be caused both by overland and subsurface flow. However, over the last decades, most research dealing with soil erosion by water has mainly focused on surface processes caused by rainfall and overland flow, such as sheet (interrill), rill erosion and gully erosion (e.g. Castillo and Gómez, 2016; Cerdan et al., 2010; Maetens et al., 2012; Poesen, 2018; Poesen et al., 2003; Valentin et al., 2005). Moreover, there is hardly any information on subsurface erosion, such as soil piping, in recent review papers on soil erosion by water (García-Ruiz et al., 2017; Li and Fang, 2016). Runoff plot studies mainly focus on surface soil erosion processes (Boix-Fayos et al., 2006; Cerdan et al., 2010; Maetens et al., 2012), and erosion rates are calculated without considering subsurface erosion (Verheijen et al., 2009). Subsurface erosion by soil piping is not considered in any water erosion model such as e.g. the USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1997), WEPP (Flanagan and Livingston, 1995), EUROSEM (Morgan et al., 1998) or SIDASS (De La Rosa et al., 2005).

The disproportion in the number of studies on surface erosion compared to those on subsurface soil erosion is striking, although soil piping has been reported to be significant and widespread process (Poesen, 2018). Figure 1 indicates that soil piping has been reported in almost all climatic zones of the world, i.e. from arid and semi-arid (Faulkner, 2013; Sirvent et al., 1997; Zhu, 2012), through tropical (Sayer et al., 2006; Uchida et al., 2005), temperate (Bernatek, 2015; Bernatek-Jakiel et al., 2017a; Botschek et al., 2002b; Rodzik et al.,

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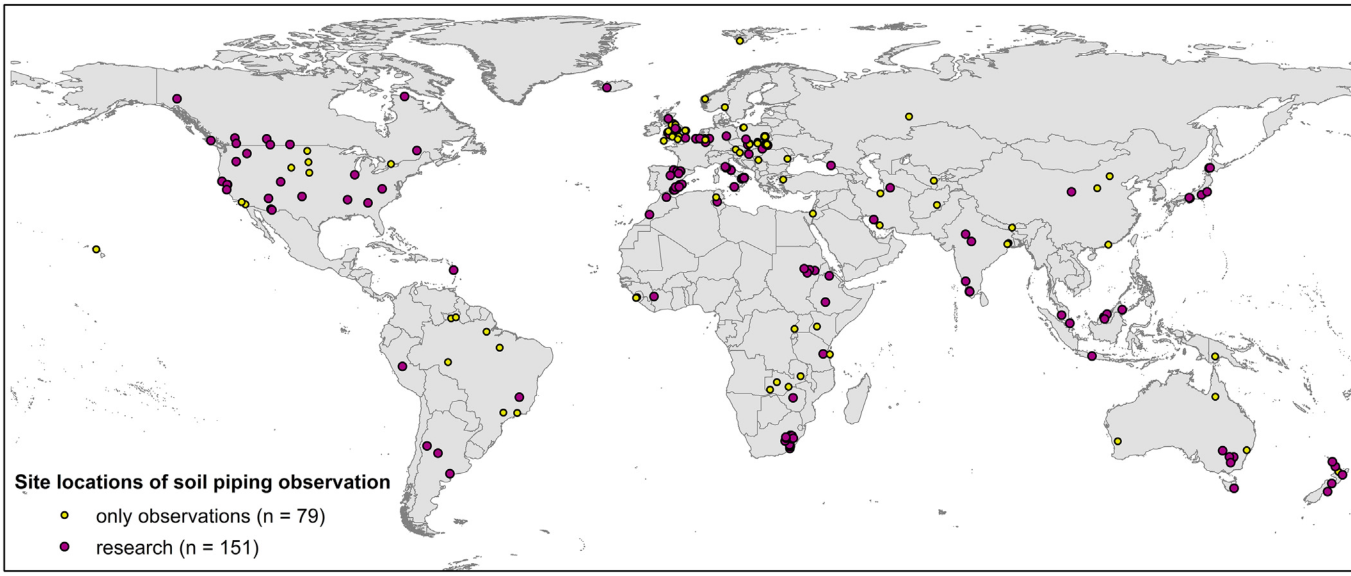


Fig. 1. Overview of sites where soil piping has been reported: "only observations" means that soil piping was observed in the field and reported in literature, but without studying this process, whereas "research" means that soil piping studies were conducted at the site. n is the number of sites.

2009; Verachtert et al., 2012; Wilson et al., 2015) and periglacial areas (Carey and Woo, 2000, 2002; Seppälä, 1997). Piping erosion occurs in natural landforms, such as alluvial plains and fans (Gutiérrez et al., 1988; Higgins and Schoner, 1997; Masannat, 1980; Ternan et al., 1998; Zhang and Wilson, 2013), hillslopes (Bernatek, 2015; Govers, 1987; Verachtert et al., 2012), peatlands (Holden and Burt, 2002), gullies (i.e. in gully walls and heads; Bocco, 1991; Frankl et al., 2012; Nichols et al., 2016; Poesen et al., 2011; Stocking, 1980; Vandekerckhove et al., 2003, as well as in gully channel bottoms; Bernatek, 2015; Rodzik et al., 2009), as well as in earth banks (Fox and Wilson, 2010; Heede, 1971; Midgley et al., 2013; Poesen, 1993, 2018; Poesen et al., 1996, 2003; Vandekerckhove et al., 2000). However, soil piping also occurs in anthropogenic environments, for instance near broken field drains, road drainage systems, earth dams, levees along rivers (Erikstad, 1992; Fell et al., 2003; Foster et al., 2000a, 2000b; Hanson et al., 2010; Lopez de la Cruz et al., 2011; Richards and Reddy, 2007; Schweckendiek et al., 2014; van Beek et al., 2012), agricultural terraces (Romero Díaz et al., 2007; Solé-Benet et al., 2010; Tarolli et al., 2014; Watts, 1991), sunken lane banks and lynchets (Poesen, 1989; Poesen et al., 1996), and in cities (Khomenko, 2006).

Soil piping occurs in different soil types (Tab. 1). Faulkner (2006) distinguished three piping-prone soil types in Europe, i.e. Xerosols (Calcisols), Luvisols and Histosols. However, piping is also active in other soil types, such as Gleysols and Cambisols (Bernatek-Jakiel et al., 2016; Farres et al., 1990) or in Vertisols (Frankl et al., 2012; Somasundaram et al., 2014). Considering the global areal distribution of soil types, ca. 70% of the continents may be potentially affected by soil piping (Tab. 1). Moreover, piping may be intense at several depths within a soil profile and at different positions, i.e. at the soil–bedrock interface (Bernatek-Jakiel et al., 2016; Jones et al., 1997; McDonnell, 1990a; Uchida et al., 2001) and at the interface of different soil horizons (Jones, 1994). This illustrates the large variability of soil characteristics that affect the presence and intensity of piping.

Compared to other water erosion processes, the number of studies on soil piping is small, and research on mechanisms, factors, models and prevention techniques remain scarce, mainly because of the difficulty to study this process (Poesen, 2018). Due to the subsurface nature of this process, pipes cannot be easily detected and controlled for both technical and economic reasons. Soil pipes are only visible at the soil surface when a pipe roof collapses (Bernatek, 2015; Verachtert et al., 2011), so they remain (apparently) inactive during a relatively long period before the surface evidences appear. Piping is affected by numerous factors including topography, lithology and soils, climate, vegetation and land management, resulting in this process to be very variable across landscapes.

In the 1960s and 1970s, the complexity of runoff generation and the impact of subsurface flow on storm hydrographs have been observed

Table 1
Global areal distribution of soil types with indication if the soil type has been reported to be affected by soil piping. n.a. is not available.

Soil type	Reports on soil piping	Area (10^6 km^2)[a]
Acrisols	yes	10.0
Albeluvisols	yes	3.2
Alisols	yes	1.0
Andosols	yes	1.1
Anthrosols	yes	0.0
Arenosols	no	13.0
Calcisols	yes	10.0
Cambisols	yes	15.0
Chernozems	yes	2.3
Cryosols	yes	18.0
Durisols	no	n.a.
Ferralsols	no	7.5
Fluvisols	yes	3.5
Gleysols	yes	7.2
Gypsisols	no	1.0
Histosols	yes	3.5
Kastanozems	no	4.7
Leptosols	no	16.6
Lixisols	yes	4.4
Luvisols	yes	5.5
Nitisols	yes	2.0
Phaeozems	yes	1.9
Planosols	no	1.3
Plinthosols	no	0.6
Podzols	yes	4.9
Regosols	yes	2.6
Solonchaks	yes	2.6
Solonetz	yes	1.4
Stagnosols	no	1.8
Technosols	yes	n.a.
Umbrisols	no	1.0
Vertisols	yes	3.4
Reports on soil piping (%)		*69*
No reports on soil piping (%)		*31*

[a] Source: IUSS Working Group (2007).

together with an increasing number of reports on subsurface erosion features in different soil materials and climatic zones (Bryan and Jones, 1997). This situation resulted in the first extensive reviews of research on the hydrologic (Gilman and Newson, 1980), geomorphic (Jones, 1981) and hydrogeomorphic (Boucher, 1990; Jones, 1994) significance of subsurface flows. Boucher (1990) was the first to summarize reclamation techniques in piping-affected lands, whereas other authors focused on the overview of soil piping in badlands and drylands (Bryan and Yair, 1982; Parker and Higgins, 1990; Torri and Bryan, 1997). The last comprehensive reviews on soil piping date from the late 1990s (Bryan and Jones, 1997; Jones, 1997b). More recent papers represent regional overviews on soil piping, i.e. in Europe (Faulkner, 2006) or in the humid tropics (Chappell, 2010), or they are focussing on some specific topics, such as piping in earth dams (Richards and Reddy, 2007) or on the hydrological functioning of pipeflow (Jones, 2010). Uchida et al. (2001) reviewed the effects of pipeflow on hillslope hydrology and its relation to landslides in forested areas, whereas Fox and Wilson (2010) summarized the role of subsurface flow in hillslope and stream bank erosion. Also experimental and numerical analysis of pipeflow has been reviewed (Wilson et al., 2013). Recently, Wilson et al. (2017b) underlined several research needs in the sediment detachment and transport processes in soil pipes, as these processes have not been well studied or documented compared to much more extensive and detailed studies conducted on streams and industrial pipes.

So far, soil piping has been mainly investigated in hydrological studies, whereas the wider environmental implications of soil piping are only just beginning to be recognized (Jones, 2010). Soil piping is a complex process occurring under various climatic, lithological, pedological and land use conditions. Thus, it is not strange that the process has engendered a variety of different names and questions regarding its genesis, development, and role in soil erosion (Parker and Higgins, 1990), and this has not changed over the last decades. Various research questions can still be identified, among them the most important are:

1. What is soil piping? How is soil piping related to other subsurface processes?
2. How can we identify the intensity of soil piping as it is a subsurface process? Are there any specific soil piping forms? How persistent are they in a given landscape?
3. How does soil piping interact with other geomorphic processes? How does soil piping impact landscapes?
4. What is the contribution of soil piping and pipeflow to overall runoff, soil loss and sediment production at various temporal and spatial scales in different environments?
5. How can soil pipes be non-destructively identified and mapped? What are appropriate techniques and methods for studying and monitoring soil pipes, for assessing their connectivity and for measuring soil susceptibility and erosion rates due to soil piping?
6. Which factors control soil piping? Can we identify critical thresholds for the initiation and development of pipes in different environments in terms of rain, soils, topography and land use? How to predict soil piping?
7. What are efficient soil piping prevention and pipe control measures?

These questions need to be answered if we want to advance our insights into subsurface erosion by soil piping. This paper highlights some of these issues by reviewing recent examples taken from various environments around the world. A better understanding of soil piping mechanisms, its controlling factors and role in soil erosion and landscape development are fundamental for the identification of potential solutions to environmental problems associated with this erosion process.

2. Background of soil piping studies

Soil piping is a widespread subsurface process (Fig. 1) reported in many studies, but it is described using different terms. In this section we address the following questions. How can we define soil piping and its relation to other subsurface processes? How can we identify the intensity of soil piping as it is a subsurface process? Are there any specific soil piping forms? How persistent are they in a given landscape?

2.1. Terminology

Piping was first described by Richthofen in China in 1877 (von Richthofen, 1877; Zachar, 1982). Later this process and its effects have been described under a variety of names: suffosion (Czeppe, 1960; Galarowski, 1976; Pavlov, 1898), subterranean erosion (Fuller, 1922), sub-cutaneous erosion (Guthrie-Smith, 1926), sinking of the ground (Buckham and Cockfield, 1950; Rubey, 1928), sink-hole erosion (Cockfield and Buckham, 1946; Thorp, 1936), tunnel erosion (Bennett, 1939), rodentless rodent erosion (Bond, 1941), pothole gullying (Cole et al., 1943), tunnel-gully erosion (Gibbs, 1945; Laffan, 1973), tunneling erosion (Downes, 1946); pothole erosion (Kingsbury, 1952), piping (Fletcher et al., 1954; Fletcher and Carroll, 1948) and soil piping (Carroll, 1949). As piping forms resemble karstic features, a landscape modelled by piping is sometimes called pseudokarst (Halliday, 2007; Parker, 1963; Zachar, 1982).

There is no single meaning of the term "piping", which is in detail reviewed by Richards and Reddy (2007) and Wilson et al. (2013). In earth sciences, it most often refers to the formation of linear voids (pipes) by concentrated flowing water in soils or in unconsolidated or poorly consolidated sediments (Jones, 2004b). A critical feature of a pipe is its water-sculpted form in contrast to "macropore" (Jones, 2010). Soil pipes act as conduits for water, solutes, dissolved gases and sediments. The mechanism of pipe formation is complex and it covers a variety of related processes, such as seepage erosion, sapping, heave, internal erosion and backwards erosion (Bryan and Jones, 1997; Dunne, 1990; Richards and Reddy, 2007; Wilson et al., 2013). It has to be added that piping is not a pure water erosion process (i.e. not only pure particle detachment by excess shear forces), and similar to gully erosion it also interacts with mass movement processes (wall and roof collapses driven by gravity; Fig. 2). Wilson et al. (2017b) recently presented the state of art regarding the sediment detachment and transport processes associated with internal erosion of soil pipes. Both processes require more research.

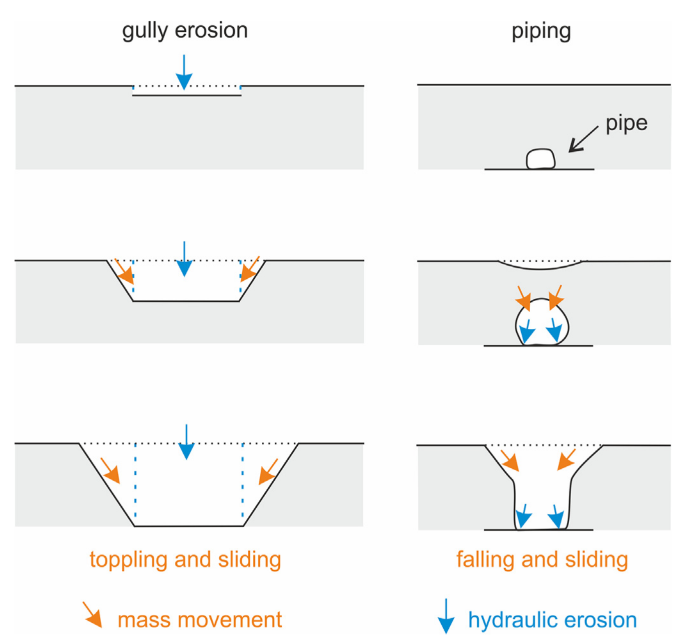


Fig. 2. Gully erosion and soil piping as complex geomorphic processes resulting from hydraulic erosion and mass movement processes.

Recently, some authors proposed to restrict "true piping" to erosion by concentrated flow through a discrete soil pipe and to call it internal erosion (Richards and Reddy, 2007; Wilson et al., 2013, 2017b). However, the piping inducing processes interact and it is often virtually impossible to separate these processes (Bryan and Jones, 1997; Dunne, 1990). Therefore, in the light of this practical difficulty, the term "piping" as a process of linear voids (pipes) formation in soils or in unconsolidated or poorly consolidated sediments continues to be used. This paper focuses on soil piping by describing various aspects of piping occurring only in soils.

2.2. Identification of soil piping at the soil surface

The subsurface nature of soil piping makes this process generally difficult to observe. Most often one identifies the occurrence of soil piping based on surface indicators, i.e. pipe collapses (PCs), which form when the pipe roof collapsed, or when one observes pipe inlets and outlets (Fig. 3). The following features indicating pipe collapses (Fig. 3) may be distinguished:

1) closed depressions that developed when the soil surface smoothly lowered above a pipe, but where no break in the vegetation cover occurred; these can evolve into sinkholes;
2) sinkholes that developed when the soil surface was clearly interrupted and the soil collapse has vertical or nearly vertical walls; the bottom of these forms is also the bottom of the pipe, and the soil material which has collapsed may sometimes still rest on the bottom of the sinkholes;
3) blind (discontinuous) gullies that developed when within the same pipe several sinkholes develop and there are successive collapses of the soil between sinkholes or when one sinkhole is enlarged by the collapse of a roof pipe.

Figure 4 illustrates some contrasting examples of pipe collapses in temperate humid, temperate continental, Mediterranean and semi-arid environments, where soil piping was reported. Piping forms may occur both in temperate (Fig. 4A–D) and warm dry climates (Fig. 4E–H), in different landscape positions: on hillslopes (Fig. 4A, C), on gully banks (Fig. 4B, D), on agricultural terraces (Fig. 4E, F) or at gully heads (Fig. 4G, H), and in different soil types, e.g. Luvisols (Fig. 4A, B), Cambisols (Fig. 4C, D), Calcisols (Fig. 4E, F) or Vertisols (Fig. 4G, H).

Soil piping not only results in erosional forms (i.e. PCs), but may also lead to the formation of depositional forms (Figs. 3 and 5). This aspect of soil piping has been rarely reported (Jones, 1981), and different terms have been used to describe these features, such as fan mound and cone mound (Jones, 1981), mound and clay fan (Boucher, 1990), outwash fan (Faulkner, 2007), colluvial fan or 'spew' hole (Hardie et al., 2007), deposition fan (Rodzik et al., 2009) or sediment mound (Wilson et al., 2015). It seems that these forms result from at least two processes, therefore two types of forms may be distinguished:

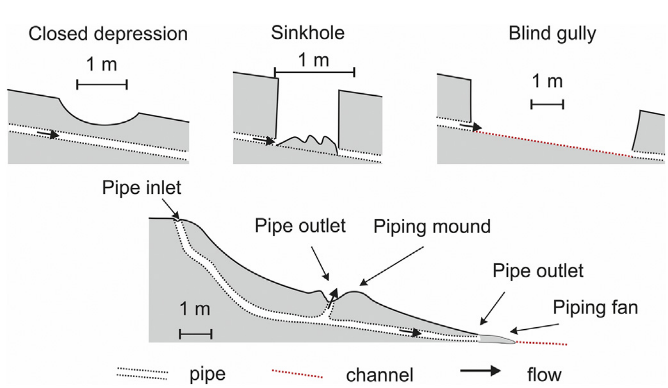


Fig. 3. Piping forms and piping-related features based on Verachtert et al. (2010) and Bernatek (2015), modified.

1) piping fans: these develop and look similar to colluvial or alluvial fans; after exfiltrating from the pipe outlet, flowing water transporting sediments is no longer limited by the pipe walls, so the flow rate and transporting capacity decreases and the transported sediment is deposited as a fan (Fig. 5A, B);
2) sediment mounds: these mounds typically develop on gently sloping foothill sections when pipeflow exfiltrates and the sediments are deposited (e.g. on grass-covered soil surfaces) around the pipe outlet forming a small mound (Fig. 5C, D).

The depositional aspect of soil piping, its mechanisms and controlling factors require more detailed studies.

All reported pipe collapses and depositional forms indicate zones, where pipes develop underground. Sometimes several piping-related features indicate the presence of a pipe. Such a complex of piping forms, which is associated with one or more combined pipes, constitutes a piping system (Fig. 6).

Some soil pipes seems to have an erratic and even stochastic nature (Bernatek-Jakiel et al., 2017a; Botschek et al., 2000; Pickard, 1999; Vandekerckhove et al., 2003; Verachtert et al., 2011). Therefore, it is hard to estimate the age of pipes and piping forms. The oldest documented (and still active) pipes were found in the Bieszczady Mts., Poland. They are at least 45 years old, as they were first mapped in the 1970s (Galarowski, 1976) and resurveyed recently (Bernatek-Jakiel et al., 2017a). A resurvey of pipes was also conducted in the Burbage Brook of the English Peak District after 35 years (Jones and Cottrell, 2007). In Spain and in Hungary it was assumed that pipes are 30–40 years old (Romero Díaz et al., 2011) and 25 years old (Kerenyi, 1994) respectively as they started to develop, when agricultural terraces were abandoned. In the loess-belt of Belgium Verachtert et al. (2011) assumed a period of 5 to 10 years for pipe collapses to occur based on interviews with farmers and field surveys. Based on the analysis of aerial photos Wilson et al. (2015) revealed that the first signs of gullies initiated by pipe collapses in Goodwin Creek watershed, Mississippi, USA, date from 1978. The persistence of piping forms within a landscape depends on the land use and land management. However, pipes may be also preserved from past geological periods. Bell (1968) found traces of 'paleopiping' in an Eocene formation in North Dakota, USA. Nevertheless, the age of pipes and piping forms as well as their persistence in the landscape require further study. Dating methods, such as dendrochronology may be used in such situation, and first attempts have been recently reported in the Bieszczady Mts., Poland (Bernatek-Jakiel and Wrońska-Wałach, 2018). For instance, in areas where pipes develop in grassland, and shrubs and trees begin to grow in the bottom of piping forms, it can be assumed that pipe collapses are at least as old as trees growing in their bottom.

3. Importance of soil piping in hydrological and geomorphological processes

Previous research reveals that soil piping is an important hydrological and geomorphological process that may impact on landscape evolution (Fig. 7). A key question is: what is the contribution of soil piping and pipeflow to overall runoff, soil loss and sediment production at various temporal and spatial scales in different environments?

3.1. Hydrological aspects of soil piping

The importance of soil piping as a hydrological process is underlined by the contribution of pipeflow (e.g. Video 1) to overall catchment runoff, which can be as high as 70% (Tab. 2). This indicates that pipeflow may have a large impact on hillslope and catchment hydrology. It may influence stream water chemistry, runoff temperature, fluvial carbon fluxes, and local hydrochemical cycling (Smart et al., 2013;

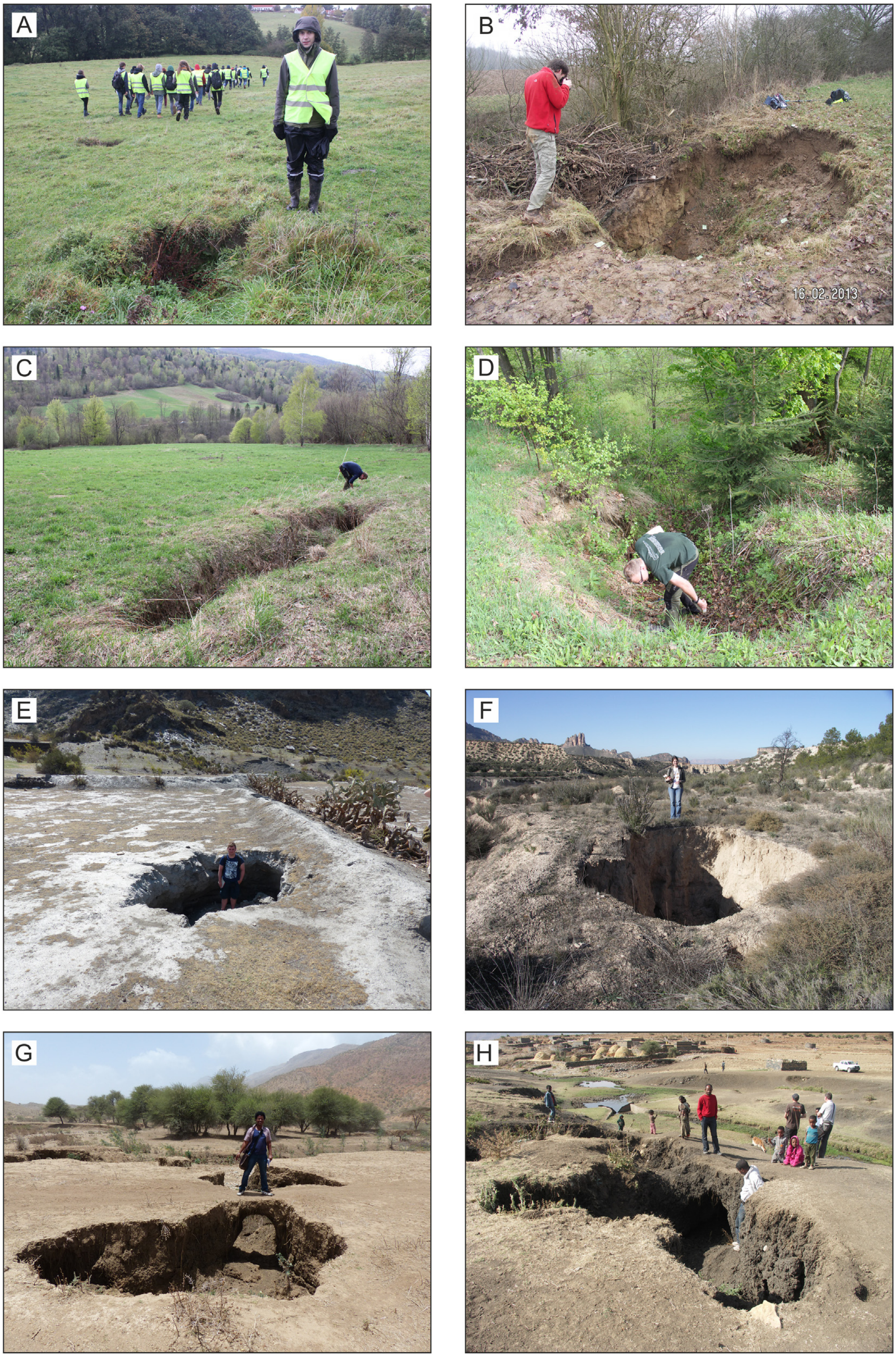


Fig. 4. Examples of soil pipe collapses from contrasting pedo-climatic environments: A – Flemish Ardennes, Belgium, Luvisol, temperate humid (photo: A. Bernatek-Jakiel et al., 2016); B – Loess belt, Huldenberg, Belgium, Luvisol, temperate humid (photo: J. Poesen, February 2013); C – Tyskowa catchment, Bieszczady Mts., Carpathians, Poland, Cambisol, temperate continental (photo: A. Bernatek-Jakiel, April 2013); D – Bereźnica Wyżna catchment, Bieszczady Mts., Carpathians, Poland, Cambisol, temperate continental (photo: A. Bernatek-Jakiel, May 2013); E – Rambla Honda, Almería Province, Spain, Calcisol, Mediterranean (photo: J. Poesen, May 2016); F – Carcavo, Spain, Calcisol, Mediterranean (photo: J. Poesen, January 2007); G – Aba Ala, Tigray, Ethiopia, Vertisol, semi-arid (photo: J. Poesen, April 2015); H – Chelekot, Tigray, Ethiopia, Vertisol, semi-arid (photo: J. Poesen, January 2010).

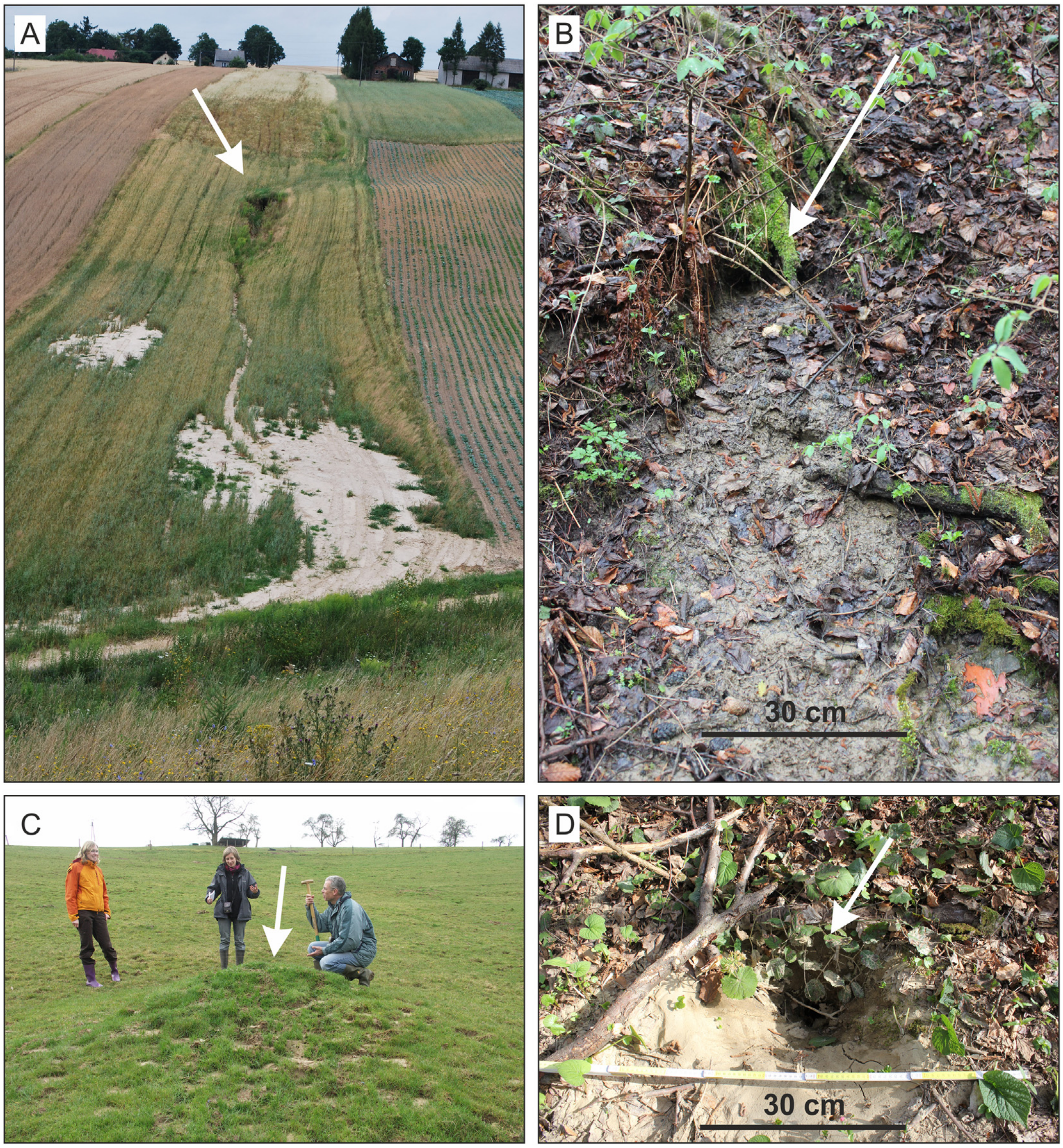


Fig. 5. Depositional soil piping forms: A – pipe outlet and piping fan in the Miechowska Upland, Poland (photo: S. Chmielowiec, July 2013); B – pipe outlet and piping fan in the Bieszczady Mts., Carpathians, Poland (photo: A. Bernatek-Jakiel, April 2013); C – piping mound in the Bergisches Land, Germany (photo: J. Poesen, February 2008); D – pipe outlet and piping mound in the Bieszczady Mts., Carpathians, Poland (photo: A. Bernatek-Jakiel, April 2013). Arrows indicate pipe outlets.

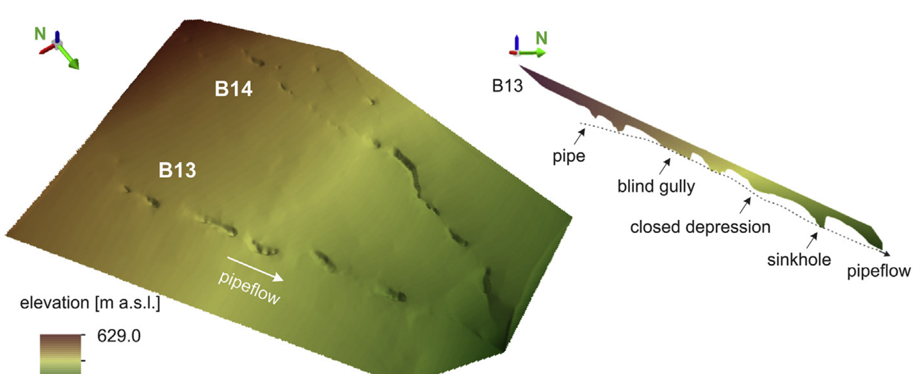


Fig. 6. Example of a piping system in the Bieszczady Mts., Poland: left – the overview of the hillslope with two piping systems; right – hillslope profile of a piping system with various piping-related features (based on Bernatek-Jakiel and Kondracka, 2016).

Vannoppen et al., 2017). For instance, recently, the role of pipeflow in maintaining of interstorm flow has been stressed (Smart et al., 2013), as well as its role in carbon flux (Dinsmore et al., 2011; Holden et al., 2012b) and catchment-scale greenhouse gas losses (CO_2,CH_4, and N_2O) (Dinsmore et al., 2011). These studies were conducted in peatlands, which are characterized by specific hydrological conditions. However,

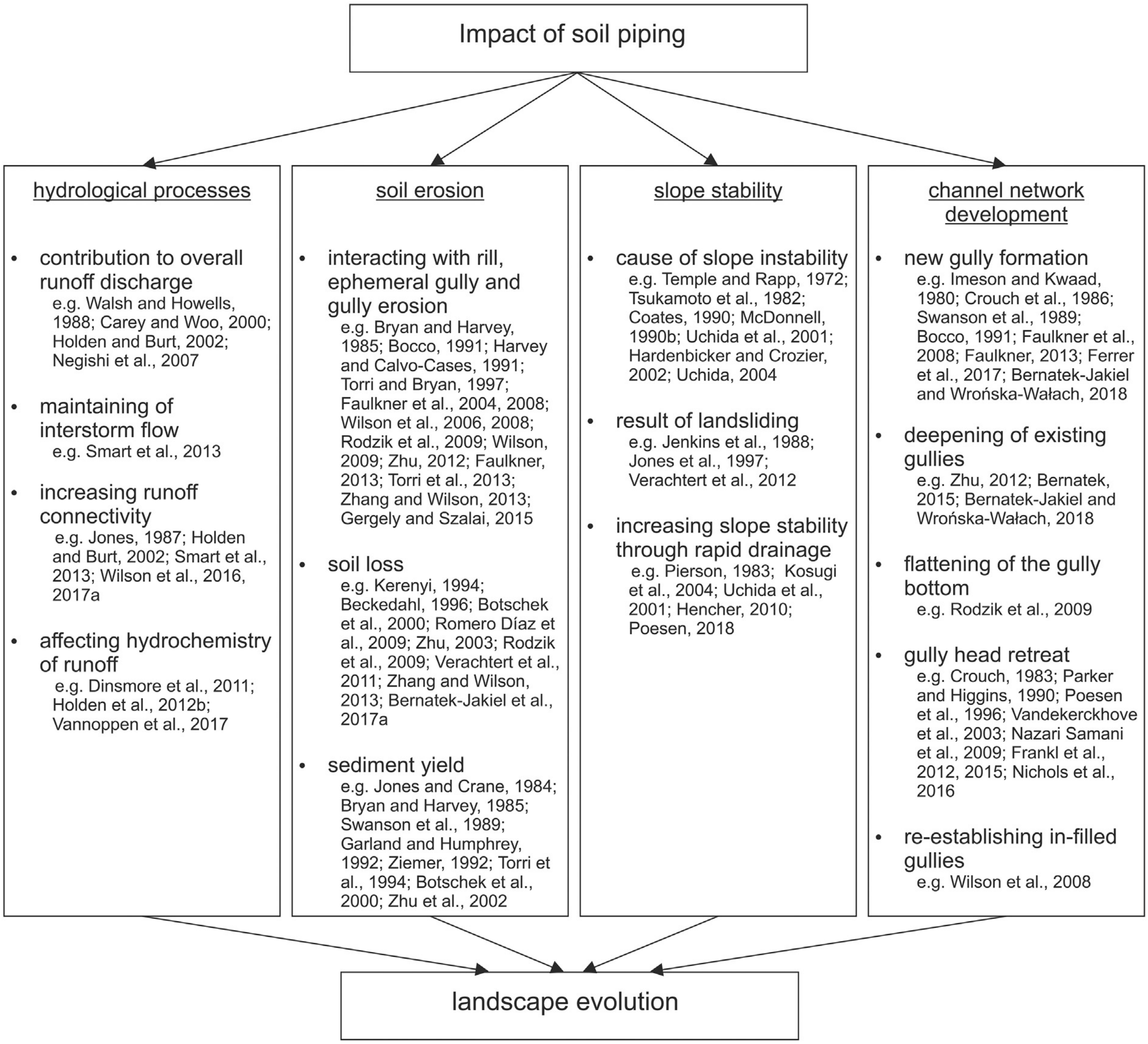


Fig. 7. Impact of soil piping on hydrology, soil erosion, channel network development and slope stability.

all these effects should also be studied in other piping-prone areas around the world (Fig. 1), which may shed new light on hillslope and catchment hydrology. Simultaneously, a basic problem should be considered, i.e. defining the pipeflow networks and pipeflow catchments (Bryan and Jones, 1997), as surface catchments may not always correspond to subsurface catchments (Beckedahl, 1996).

3.2. Soil piping as a soil erosion process

Soil piping is one of the soil degradation processes. Its interaction with surface soil erosion processes (i.e., sheet, rill, ephemeral gully erosion and gully erosion) has been noted by several authors (Fig. 7). Pipe collapses on hillslopes can act as depressions, in which overland flow is diverted into subsurface pipeflow pathways, which then can reduce sheet and rill erosion (Zhang and Wilson, 2013). However, rill erosion may also be enhanced by piping as rill channels may be formed due to pipe roof collapses, which was reported for sodic soils in badlands (e.g. Benito et al., 1993; Faulkner, 2013; Faulkner et al., 2004; Torri et al., 2013). On the other hand, swelling of such materials may result in rill closure and formation of horizontal pipes, and closure of vertical pipe inlets (Harvey and Calvo-Cases, 1991). Soil piping (besides seepage erosion) often plays an important role in the initiation of bank gully erosion. Overland flow crossing an earth bank in the landscape often infiltrates near the bank into macropores (such as tension cracks or biopores) where intense subsurface erosion (piping) may occur. Upon collapse of the pipe roof a bank gully is formed (Poesen, 1989; Poesen et al., 1996). Piping on gully channel walls also contributes to channel widening. As all these reports suggest that soil piping is an important contributor to other soil erosion processes by water, this process cannot be neglected in soil erosion models, which is still the case for all plot and catchment-scale models predicting soil erosion rates by water (see Introduction).

Soil piping leads to soil loss, which can be expressed by the soil mass lost (Fig. 8) or by the sediment concentration in pipeflow (Tab. 3). Soil loss rates vary significantly, i.e. between less than 1 up to almost 120 t ha^{-1} y^{-1} (with a maximum of 550 t ha^{-1} y^{-1} in Spain; Romero Díaz and Ruiz-Sinoga, 2015). Likewise, the contribution of pipeflow erosion to total catchment sediment yield ranges from 15 up to 90% (Tab. 3). However, these data are limited to a few case studies mainly from study areas with loess-derived soils and from badlands formed in marls. Moreover, soil piping is a spatially and temporally varying process (Bernatek-Jakiel et al., 2017a) similar to sheet and rill erosion processes (Cerdan et al., 2010; Maetens et al., 2012). This complicates the interpretation and comparison of piping erosion rates in different environments (Bernatek-Jakiel et al., 2017a).

Difficulties in observing soil pipe development may suggest that PCs

Table 2
Contribution of pipeflow to overall catchment runoff in different parts of the world.

Location	Soils/lithology	Land use	Climate	Pipeflow contribution [%]	Source
Wolf Creek basin, Yukon, Canada	peat overlying glacial clay with permafrost	peat	subarctic continental	21[a] < 3[b] > 15[c]	Carey and Woo, 2000
Alberta Badlands, Canada	clay rich shales and sandstones	bare soils	semi-arid	10	Bryan and Harvey, 1985
Little Dodgen Pot Sike catchment on the Moor House National Nature Reserve, North Pennines, UK	Interbedded limestone, sandstone and shale covered by glacial till (clay)	peat	sub-arctic oceanic	10	Holden and Burt, 2002
Cottage Hill Sike on the Moor House National Nature Reserve, Northern England, UK	Interbedded limestone, sandstone and shale covered by glacial till (clay)	peat	sub-arctic oceanic	13.7	Smart et al., 2013
the Maesnant catchment, mid-Wales, UK	Histic Podzols	peat	oceanic	49	Jones and Crane, 1984
Mean Bull Gully Basin, San Mateo County, California, USA	Vertisols	grasslands	Mediterranean	70	Swanson et al., 1989
Bukit Tarek Experimental Catchment, 80 km NW of Kuala Lumpur, Peninsular Malaysia	metamorphic sedimentary rocks	forest	humid tropical	50 (zero-order basin)	Negishi et al., 2007
NE of Dominica	volcanic clay soils	banana plantations and coconuts	humid tropical	14–16	Walsh and Howells, 1988

[a] During snowmelt; [b] during summer rainfall; [c] during large rainfalls.

appear stochastically in the landscape (Bernatek-Jakiel et al., 2017a; Pickard, 1999; Vandekerckhove et al., 2003; Verachtert et al., 2011). However, some trends in the formation and degradation of pipes have been observed. In the Ebro Basin in Spain (García-Ruiz et al., 1997) and in Natal Drakensberg in South Africa (Garland and Humphrey, 1992) it was observed that the largest sediment yield from pipeflow occurred at the beginning of flow and during flow events following dry periods or a prolonged dry period. The latter may be explained by slaking effects following the sudden wetting of dry soils, enhancing their dispersion. Also, seasonal trends were observed in the Bieszczady Mts. (Poland) under a temperate climate. Snowmelt and thawing at the beginning of spring caused the detachment of soil particles in soil pipes, whereas the detached sediments were transported during summer rainfalls (Bernatek-Jakiel et al., 2015). Moreover, pipeflow erosion in forest occurred during high precipitation events, whereas on grassland soil detachment in soil pipes was observed with a delay, i.e. 1–2 years following the years with high precipitation. This suggests that the presence of grassland may delay pipe collapses, because the fibrous root system of grasses stabilizes the topsoil (through root cohesion and tensile strength; De Baets et al., 2006, 2008) while in the subsoil soil particles are easily washed out (Bernatek-Jakiel and Wrońska-Wałach, 2018). In the Loess Plateau of China no seasonal trends in pipeflow erosion were observed (Zhu et al., 2002).

3.3. Impact of piping on slope stability

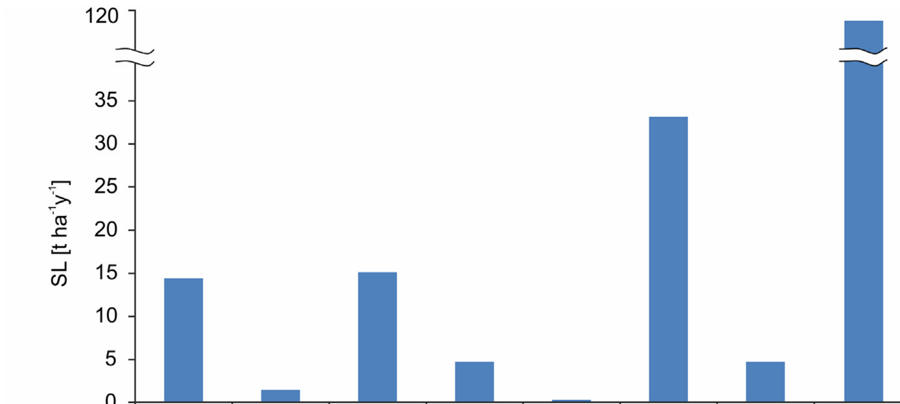
Soil piping may contribute to slope stability by increasing the rate of soil drainage and limiting the development of perched groundwater conditions (Hardenbicker and Crozier, 2002; Hencher, 2010; Kosugi et al., 2004; Pierson, 1983; Uchida et al., 2001), similar to drainage pipes that facilitate drainage of agricultural land (Uchida et al., 2001). However, this drainage effect depends on the soil characteristics. For instance, in low permeable soils, soil pipes may be ineffective in reducing pore water pressure build-up, since the opportunity to feed water to the piping system is small (McDonnell and Taratoot, 1995). Uchida et al. (2001) stated that soil pipes contribute to the effective soil drainage system only when two hydrological effects of soil pipes are well combined: (1) the concentration of water into the soil pipe network, and (2) the rapid drainage of water downslope. Otherwise, if the rate of water concentration to the soil pipe network is in excess of the pipeflow transmission capacity, the soil pipe could be readily filled with water during a rain event, increasing pore water pressure in the surrounding matrix, which may induce slope instability (Uchida et al., 2001). The same will happen, when pipes become blocked (Wilson and Fox, 2013). Coates (1990) reported a decrease of slope stability, when the fine-grained sediments are selectively eroded from stratified materials and hillslopes become unsupported. These statements are mainly based on research conducted in forested headwater catchments, i.e. in Japan (Tsukamoto et al., 1982; Uchida et al., 2001), and in Tanzania (Temple and Rapp, 1972). There is a need to verify these processes in other piping-prone areas, as soil piping is widespread under different land use types (see Section 5.4).

Moreover, there are some reports stating that piping might be a result of landsliding. For instance, tension cracks formed due to landsliding may develop into pipes (Jenkins et al., 1988; Jones et al., 1997). Landslides may also result in subsurface flow obstruction by tilting less permeable clay-rich substrates, which induce pipe formation (Verachtert et al., 2012).

It appears that the relationship between soil piping and slope stability are more complex and ambiguous. This requires further studies, especially in the field, as piping occurs under various land use and soil types.

3.4. Significance of piping in channel network development

Already in the 1970s piping was described as an unstable and



	Hungary	Poland	Germany	Belgium	USA	China	South Africa	Spain
SL [t ha^{-1}y^{-1}]	14.3	1.3	15.0	4.6	0.2	33.0	4.6	119.7
SP [y]	25	45	0.25	5–10	1	12	15	40
SA [ha]	2.0	0.42	1.0	0.3	14.6–19.6	20.6	18–25	0.000198
land use	vineyards	grassland	grassland	grassland	cropland	pasture	grassland	farmland

Fig. 8. Mean soil loss rates (SL) due to piping measured in several countries, based on Verachtert et al. (2011) and Bernatek-Jakiel et al. (2017a). SP indicates length of study period and SA is size of study area.

transient stage in the erosional development of gullies (Barendregt and Ongley, 1977). Soil piping may lead to new gully formation after total pipe collapse as well as it may deepen or widen the existing gully channels or contribute to the formation of a flat sediment accumulation bottom in a gully (Fig. 7). Piping may also lead to the re-establishment of ephemeral gullies that were filled in (Wilson et al., 2008). The significance of soil piping in gully development can be expressed by its impact on gully head retreat rate (Tab. 4), which may reach up to 10.50 m in one single storm (Parker and Higgins, 1990). Therefore, gullies should be considered as complex geomorphic systems which are induced and transformed not only by overland flow, but also by subsurface processes (such as soil piping) and mass movements (De Ploey and Poesen, 1987; Poesen, 1993; Starkel, 2011). However, it is difficult to determine which and how many gullies have been initiated or affected by soil piping. Development of gullies removes the evidence of their origin, and the failed material covers up the evidence of piping (Hagerty, 1991; Wilson et al., 2013). Dendrogeomorphological analysis in forested areas seems to be promising for such research, as it enables the reconstruction of gully development (Bernatek-Jakiel and Wrońska-Wałach, 2018; Vandekerckhove et al., 2001). Piping erosion affects

Table 3
Contribution of pipeflow to catchment sediment yield. n.a. is not available.

Location	Soils/lithology	Land use	Climate	Sediment concentration (g/l) in pipeflow	Pipeflow contribution (%) to total sediment yield	Source
Alberta Badlands, Canada	clay rich shales and sandstones	bare soils	semi-arid	97.1	n.a.	Bryan and Harvey, 1985
Yangdaogou, Loess Plateau, China	loess	bare soils	semi-arid continental	34 to 671 (mean)	57 (from 0 to 80)	Zhu et al., 2002
Mean Bull Gully Basin, San Mateo County, California, USA	Vertisols	grasslands	Mediterranean	17.8	90	Swanson et al., 1989
California, USA	clayey, vermiculitic soils derived from sedimentary rocks	forest	Mediterranean	< 0.02 (forest) 46.5 (after deforestation)	n.a.	Ziemer, 1992
Podere Beccanello, Italy	marine clays	bare soils	Mediterranean	0.00011–0.00016	n.a.	Torri et al., 1994
Logroño, La Rioja, Ebro Basin	marine clays	bare soils	Mediterranean	33–4738 (pipe A) 68–5618 (pipe B)	n.a.	García-Ruiz et al., 1997
Bergisches Land, Germany	Luvisols and Cambisols	grasslands	humid temperate	0.3–25.6	n.a.	Botschek et al., 2000
Maesnant catchment, Wales, UK	Histosols	peats	humid temperate	n.a.	15	Jones and Crane, 1984
Danum Valley Conservation Area, Sabah, Malaysian Borneo	silt- loam Ultisols	rainforest	humid tropical	0.0462	21.6–29	Sayer et al., 2006

Table 4
Gully headcut retreat rates due to soil piping.

Continent	Country	Study area	Headcut retreat (m y^{-1})	Source
N America	USA	Arizona	5.00	Jones, 1968
		New Mexico	10.50[a]	Parker and Higgins, 1990
			1.45 (7.40[a])	Nichols et al., 2016
Africa	Ethiopia	Hagere Selam	1.93	Frankl et al., 2012
Europe	Poland	Parsęta catchment, Polish Plain	1.00	Mazurek, 2010
Oceania	Australia	New South Wales	2.50	Crouch, 1983

[a] During a single storm.

roots by exposing them starting from the bottom side of a root (in the pipe roof) in contrast with surface soil erosion, where root exposure starts from the soil surface. The signs of root exposure are expressed in wood anatomy changes, e.g. vessel lumen area changes (Bernatek-Jakiel and Wrońska-Wałach, 2018).

3.5. Role of soil piping in landscape changes

Soil piping, as described above, leads to the formation of different landforms (see Section 2.2 and Figs. 3, 4 and 5), interacting with other geomorphological and hydrological processes (see Section 3.1–3.4), and therefore leading to landscape changes. However, soil piping has never been included in catchment sediment budgets (Poesen, 2018) and rarely in models of landscape evolution, except for studies on badlands evolution (Faulkner et al., 2008; Harvey and Calvo-Cases, 1991; Torri and Bryan, 1997).

Figure 9 illustrates changes of a hillslope when soil piping occurs. Soil pipes may form on hillslopes above and in the bottom of gully channels and independently of them, mainly in earth banks. Their development leads to a change in local slope gradient and a transition towards concave hillslope profiles (Bernatek-Jakiel et al., 2017a; Jones, 1987). Soil piping is thus partly responsible for producing more dissected hillslopes (Fig. 9), and even entire landscapes (Kirkby and Bull, 2000; Löffler, 1974). All these morphological changes have an impact on both surface and subsurface hillslope hydrology.

Soil pipes behave as transmitters. They are conduits for water, solutes, dissolved gases and sediments (Smart et al., 2013; Vannoppen et al., 2017; Wilson et al., 2017a). Until now, their importance in biogeochemical cycles has been underlined mainly in blanket peats. For instance, pipes take part in carbon transfer (Holden et al., 2012b) and greenhouses gases, such as CO_2, N_2O and CH_4 (Dinsmore et al., 2011). García-Ruiz et al. (1997) also suggested that pipes may transfer water pollutants in irrigated fields. When soil pipes develop on slopes, they increase slope–channel coupling which increases sediment, hydrological and ecological connectivity. Soil piping as a sediment source for fluvial systems has been rarely recognized, even if piping has been reported as an important, or even the main sediment source (Bernatek-Jakiel et al., 2017a; Verachtert et al., 2011). All these aspects of soil piping require more detailed studies in different environments, especially in the context of climate and land use change (Poesen, 2018).

4. Techniques and methods for studying soil piping

How can soil pipes be non-destructively identified and mapped? What are appropriate techniques and methods for studying and monitoring soil pipes, for assessing their runoff and sediment connectivity and for measuring soil susceptibility and erosion rates due to soil piping? Here, we present a brief overview of recent field and laboratory-based techniques used to study soil piping.

4.1. Detection of soil pipes

Pipe detection is a methodological challenge (Grellier et al., 2012). The most frequently used method to detect and study soil pipes is geomorphological mapping, which is based on the location of pipe roof collapses, pipe inlets and outlets (Figs. 3 and 4). This method is applied in a wide range of environments: in loess-mantled areas (e.g. Zhu, 2012; Zhu et al., 2002; Verachtert et al., 2010, 2013; Zhang and Wilson, 2013; Wilson et al., 2015), in badlands (e.g. Torri and Bryan, 1997; Farifteh and Soeters, 1999; Romero Díaz et al., 2007; Faulkner et al., 2008), in peatlands (e.g. Holden and Burt, 2002) and in mountainous areas (e.g. Bernatek, 2015; Bernatek-Jakiel et al., 2016).

Soil pipes can be also detected using aerial photographs in areas without forest cover (Fig. 10), such as badlands (Farifteh and Soeters, 1999) or grasslands and pastures (Grellier et al., 2012; Smart and Wilson, 1984; Verachtert et al., 2010; Wilson et al., 2015). However, a subsequent verification in the field is required, as some PCs may be obscured by infilled material, shadow of trees, bushes or other

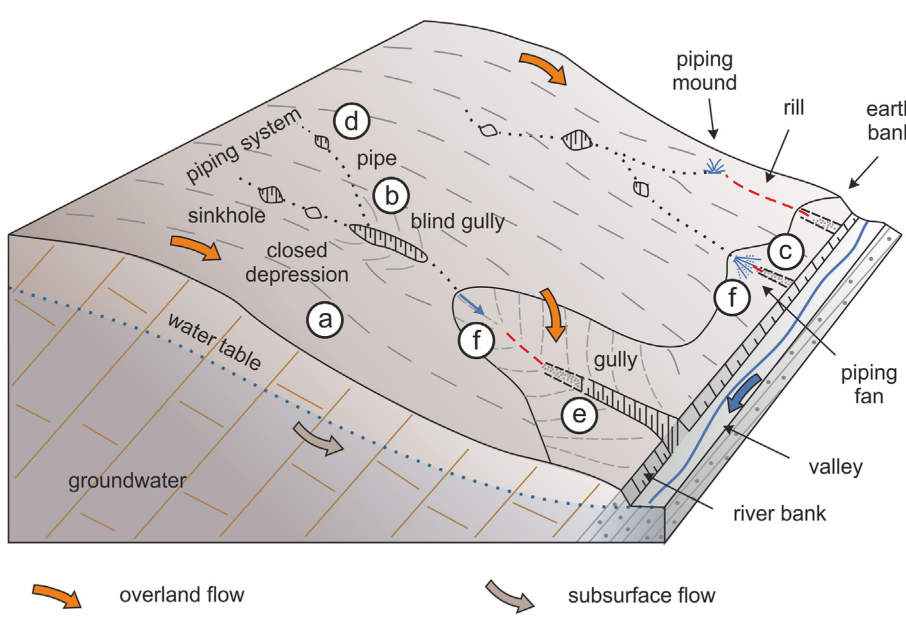


Fig. 9. Sketch illustrating changes of a hillslope when piping occurs: a – retreat of convex slope sections with corresponding local changes in slope gradient; b – local changes in runoff circulation on the slope; c – formation of a pipe in an earth bank (independently of the actual gully network); d – formation of pipes above gully head; e – formation of pipes in the bottom of a gully channel; f – slope–channel coupling due to piping.

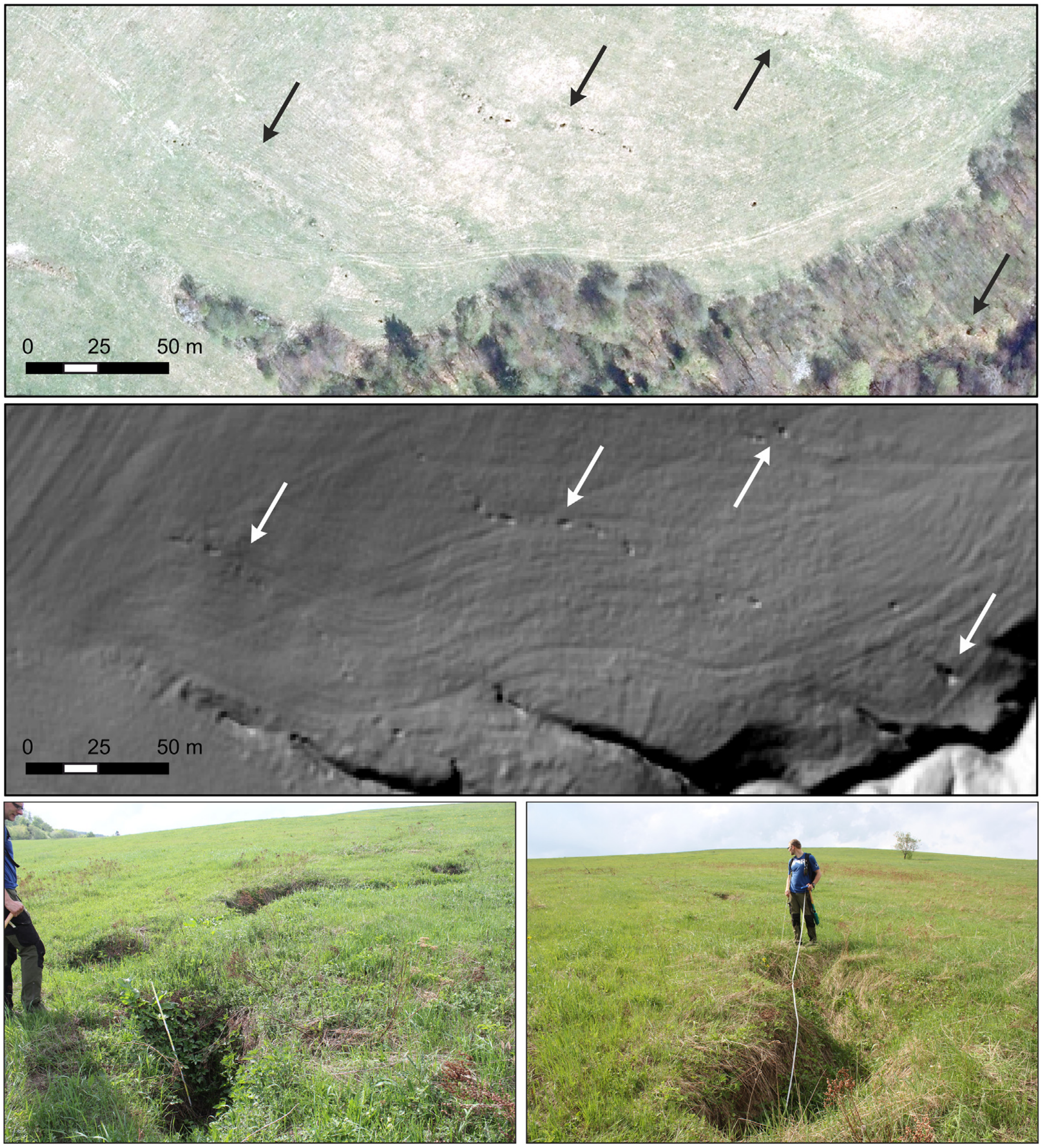


Fig. 10. Signs of pipe collapses visible on an aerial photo (2009) and on a digital elevation model derived from LIDAR data (2012) in Tyskowa catchment, Bieszczady Mts., Poland (arrows indicate the sites with pipe collapses). This model is based on the airborne laser scanning (LIDAR), with an accuracy of 4 points per 1 m^2. The aerial photo and LIDAR data were obtained from the Geodetic and Cartographic Documentation Centre in Poland (CODGiK). The terrestrial photos (author: A. Bernatek-Jakiel, May 2013) show the hillslope with pipe collapses as indicated on the aerial photo and the LIDAR-derived model.

obstacles. This method has also another limitation as some PCs cannot be detected because of their small sizes.

The analysis of very high spatial resolution digital elevation models (DEM) seems to be a promising technique to detect PCs, as it can be applied in areas with different vegetation types. This approach should include the combination of various data types (Fig. 10) and field validation is recommended. Recently, LIDAR and Structure from Motion (SfM) photogrammetry (terrestrial and aerial images using an unmanned aerial vehicle – UAV) have been applied in a study of soil piping in badlands (Ferrer et al., 2017). The challenges in PC detection are associated with the possibility of digital mapping of forms (e.g. using LIDAR data) and the use of new technologies (e.g. UAV).

Surface mapping enables the detection of PCs, but does not allow to identify and characterize a complete underground pipe network (Cappadonia et al., 2016). It seems that soil pipes are characterized by vertical and horizontal sinuosity. Thus, in the case of pipe length surface mapping of PCs may lead to an underestimation of network density, which may achieve up to 50% (Bernatek-Jakiel and Kondracka, 2016; Holden et al., 2002). Therefore, geophysical methods are used in piping studies, such as ground penetrating radar (GPR) (Bernatek-Jakiel and Kondracka, 2016; Botschek et al., 2000; Got et al., 2014; Holden, 2004, 2006; Holden et al., 2002), electrical resistivity tomography (ERT) (Ahmed and Carpenter, 2003; Bernatek-Jakiel and Kondracka, 2016; Giampaolo et al., 2016; Leslie and Heinse, 2013), seismic refraction tomography (SRT) and self potential (SP) (Cardarelli et al., 2014). Some geophysical methods have been used to detect pipes in earth dams and levees, such as passive seismic interferometry (Planès et al., 2016), which may be also tested for soil pipe detection in natural environments. Also, active and passive acoustic techniques were tested in a laboratory study to detect and monitor soil pipeflow and the resulting internal erosion (Lu and Wilson, 2012). Each of these methods should be always evaluated in terms of their suitability and limitations for use in different topographical, lithological, pedological, land use and hydrological conditions.

A promising technique to study soil pipes is the endoscope or fibrescope, which has already been used in soil science to assess soil texture (Breul and Gourvès, 2006), and soil bioporosity (Pagenkemper et al., 2015), including root growth in biopores (Athmann et al., 2013; Kautz and Köpke, 2010). To the best of our knowledge, fiberscope was used only by Terajima et al. (2000) to study soil pipes, its morphology and structure. It seems that the use of an endoscope or fibrescope in piping research can also detect blockage of pipes, sediment deposition on pipe bottoms, interconnection of pipes and internal shape of pipes and its spatial changes.

There is a SmartBall technology used in industry for pipeline leak detection (e.g. Fletcher and Chandrasekaran, 2008), which could be used for soil pipe detection. The limitation is that one can track the signal as the ball moves through a pipe, so the pipe has to be located on a slope and the ball can be only introduced at the uppermost PC (Glenn Wilson, personal communication).

4.2. Assessment of soil pipe connectivity

The connectivity of soil pipes can be assessed in the field using dye tracer tests (Anderson et al., 2008; Bernatek-Jakiel and Kondracka, 2016; Bíl and Kubeček, 2012; Cappadonia et al., 2016; Crouch et al., 1986; Wilson et al., 2016), smoke bombs (Bíl and Kubeček, 2012; Zhu, 2003; Zhu et al., 2002), flexible tubing (Leslie et al., 2014) and geophysical methods, such as GPR (Bernatek-Jakiel and Kondracka, 2016; Holden, 2004). Knowledge of the soil pipe network is crucial for a better understanding of hillslope hydrology, slope–channel coupling, runoff and sediment connectivity and soil erosion by piping.

Recently, computed tomography (CT) technology was used to scan pores and pipes in a loess sample of the Loess Plateau in China in order to characterize the network, including connectivity (Li et al., 2018). This study revealed that the pores showed good connectivity in vertical direction and formed vertically aligned pipes in contrast to weak connectivity in horizontal directions. However, this method is limited to the microscale characterization of pipes as the studied samples were $60 \times 60 \times 60$ mm in size.

An alternative, but expensive and destructive method studying soil pipes is the production of casts of pipe network, similar to subterranean ant nests (e.g. Tschinkel, 2010). Several casting materials have been tested to make such casts of the underground nests of ants: dental plaster, paraffin wax, aluminium, zinc or even cement (Moreira et al., 2004; Tschinkel, 2010). After injection, the liquid becomes solid, and after that the entire piping system can be excavated. The selection of casting substances depends on the size of soil pipes and the extent of their network. It seems that dental plaster and paraffin wax may be too fragile for pipes, whereas zinc too heavy for bigger features. Moreover, in dense, non-porous soils, the casting material might not easily displace air from the pipes into the surrounding soil, entrapping air and causing voids and incomplete casts. Despite these limitations this method may be promising.

4.3. Monitoring of soil pipes and pipe collapse development

So far, the dynamics of soil piping has been mainly studied based on surface indicators, i.e. PCs and pipe outlets using geomorphological mapping (Holden et al., 2012a; Verachtert et al., 2011; Zhu, 2003) and geodetic measurements (Bernatek-Jakiel et al., 2015, 2017a). However, these methods do not allow the measuring of complex morphologies such as soil pipe inlets and overhanging pipe walls. These issues may be solved using 3D photo-reconstruction methods (e.g. Frankl et al., 2015), terrestrial and aerial SfM photogrammetry and Terrestrial Laser Scanning (TLS) with different scanner positions (Ferrer et al., 2017). It seems that image-based modelling, which was used to produce accurate models of gullies (Castillo et al., 2012; Gómez-Gutiérrez et al., 2014; Kaiser et al., 2014), could be also used to study PCs. Repeated models can then be compared to analyse the dynamics of PCs development.

If we still do not know how to map pipe network, the question on how to monitor the development of subsurface tunnels (i.e. pipes), is still open (see Section 4.1 and 4.2). Geophysical methods have a lot of potential, but these are still in experimental phases.

4.4. Assessment of soil susceptibility to soil piping

One of the first methods used to assess soil susceptibility to soil piping was the pinhole test proposed by Sherard et al. (1976), and modified by Nadal-Romero et al. (2011) to achieve quantitative data by measuring the pipeflow discharge ($cm^3\ s^{-1}$) and the sediment discharge ($g\ s^{-1}$). This test uses flow of water passing through a small hole in a soil specimen, under varying hydraulic heads. The pinhole test has been used to study soil piping in undisturbed soils (Botschek et al., 2002b; García-Ruiz et al., 1997; Goldsmith and Smith, 1985; Ismail et al., 2008; Nadal-Romero et al., 2011; Wilson et al., 2015).

Other methods are based on measurements of soil aggregate stability to check their resistance to dispersion and slaking, as both processes impact soil piping. The slaking test is based on a visual observation of the disintegration of air-dry soil aggregates completely immersed in distilled water (Bruthans et al., 2014; Laffan, 1973). Among dispersion tests one can distinguish Emerson crumb test (Emerson, 1967), double hydrometer test (dispersion index, dispersal index test) (Jermy and Walker, 1999) and the determination of the Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) based on the cation analysis of the pore water. The first one is a subjective test used to identify dispersive clay soils, and it was rarely used in piping studies (Fox et al., 2013). The second one is based on the natural tendency of clay to go into suspension (based on a standard hydrometer test), and it was also used in piping research (Benito et al., 1992, 1993; Fox et al., 2013; Gutiérrez et al., 1997). The most widely used method in piping studies is the cation analysis in order to determine SAR and ESP (Benito et al., 1992; Calvo-Cases et al., 2011; Faulkner et al., 2000, 2003, 2004; Gutiérrez et al., 1997; Nazari Samani et al., 2009; Romero Díaz et al., 2007; Torri and Bryan, 1997). Faulkner et al. (2000) proposed the functional relationship between electrical conductivity (EC) and SAR as a useful tool in characterising badland sites for their susceptibility to piping.

Analysis of clay mineralogy is also useful to assess the soils' susceptibility to piping, especially in order to identify the presence of swelling clays (Faulkner, 2006). Their role in controlling soil piping is discussed below (see Sections 5.1 and 5.2).

Silt content may also help to identify soils prone to piping as silt-rich materials are generally susceptible to piping. However, it seems to be of less importance to identify sites with piping (Bernatek-Jakiel et al., 2016; Jones, 1971; Verachtert et al., 2010) as this process may also occur in different soil texture as illustrated in Figure 12.

4.5. Assessment of erosion rates due to soil piping

Erosion rates due to soil piping are mainly based on volumetric measurements, i.e. volumes of PCs and soil pipes (Bernatek-Jakiel et al., 2017a; Botschek et al., 2000; Kerenyi, 1994; Romero Díaz et al., 2009; Verachtert et al., 2011; Zhu, 2003). However, there is still no standardization in this method, i.e. until now the measurements were conducted over variable study periods (from 3 months to 45 years) and within study areas of different size (i.e. various plot sizes), which hinder comparison (Bernatek-Jakiel et al., 2017a). Also, the erosion rates may be under- or overestimated, because we do not know the exact length of soil pipe below the soil surface as well as its geometry along the entire pipe length.

Soil erosion due to piping can be also assessed by measuring sediment export at pipe outlets (in pipeflow) which are transferred from pipe drainage areas (Jones, 1997c; Sayer et al., 2006; Uchida et al., 1999; Zhu et al., 2002).

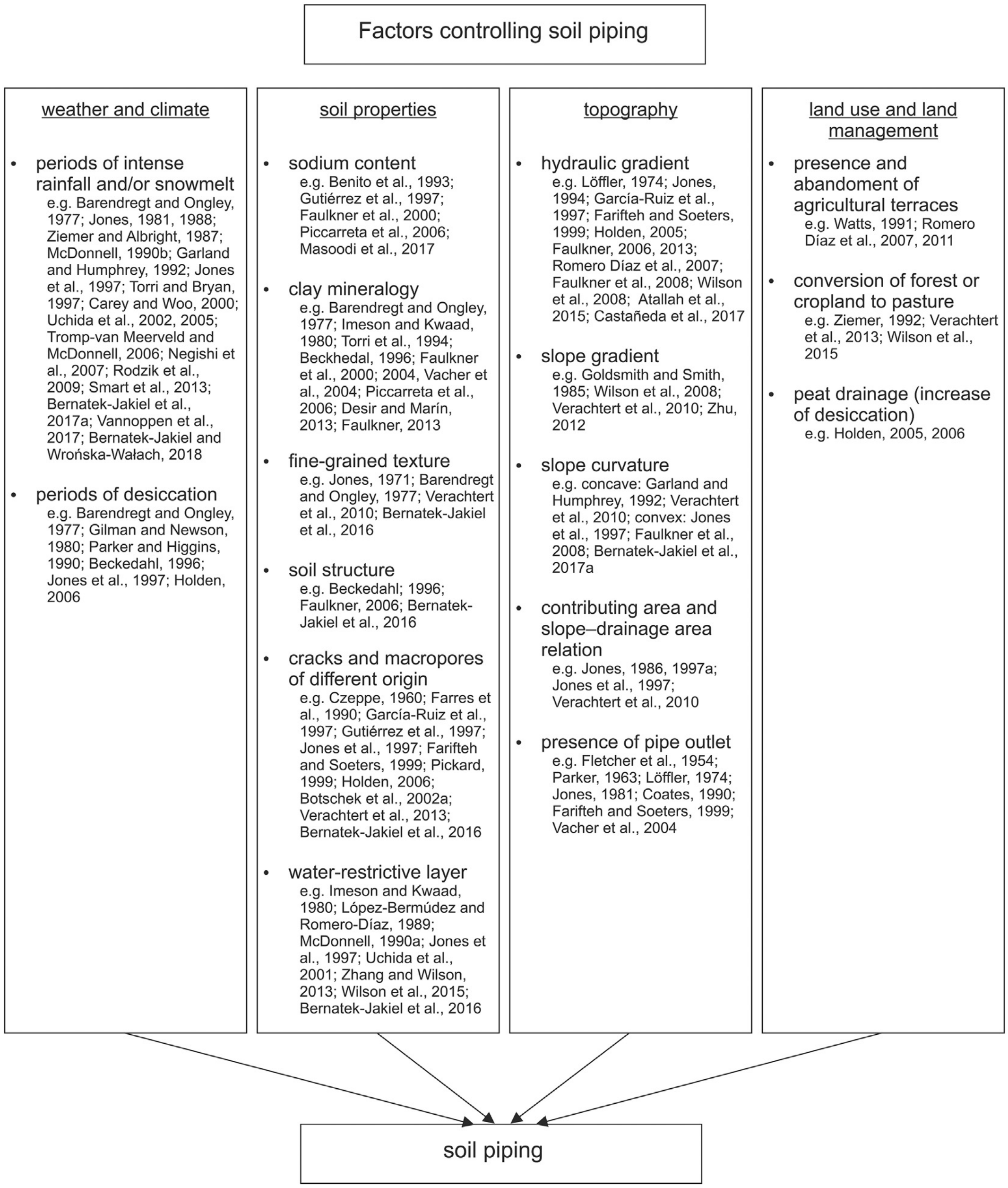


Fig. 11. Factors controlling soil piping.

5. Factors controlling soil piping

Given the variety of environments where pipes have been observed (Figs. 1 and 4), no single factor can be held responsible for pipe development (Fig. 11). Knowing these factors, can we predict soil piping? Can we identify critical thresholds for the initiation and development of pipes in different environments in terms of rain, soils, topography and land use?

5.1. Weather and climate

Soil piping occurs in almost every climate zone of the world (Fig. 1). As it is a water erosion process, there is a need for runoff concentration that can be produced during rainfall (Barendregt and Ongley, 1977; Bernatek-Jakiel et al., 2017a; Bernatek-Jakiel and Wrońska-Wałach, 2018; Jones, 1988; Jones et al., 1997; Uchida et al., 2002; Vannoppen et al., 2017; Ziemer and Albright, 1987) or snowmelt (Bernatek-Jakiel et al., 2015; Carey and Woo, 2000; Heede, 1971; Rodzik et al., 2009).

In Britain, Jones et al. (1997) observed that in piped catchments annual rainfall was higher than in unpiped catchment. However, others reported that annual rainfall has a minor role in the initiation of new PCs, both under a temperate climate in Poland (Bernatek-Jakiel et al., 2017a) and under a semi-arid climate in the Loess Plateau of China (Zhu, 2003). Also, the significance of cumulative rainfall depth and rainfall intensity as triggers for piping erosion is different in various regions. Under a semi-arid climate, piping systems in badlands develop most rapidly under prolonged low-intensity rainfall, while in short, high-intensity storms surface erosion becomes more dominant (Torri and Bryan, 1997). Also in South Africa (Drakensberg Mts.) peak flow discharge in soil pipes was correlated with total storm rainfall, but not with rainfall intensity (Garland and Humphrey, 1992). On the contrary, in the tropics, it is suggested that pipeflow is often related to rainfall intensity, once the total depth of rain becomes large enough for pipeflow to occur (Elsenbeer and Lack, 1996; Uchida et al., 2001, 2005).

This raises the question of rainfall thresholds that are needed to initiate pipeflow. Table 5 summarises some thresholds rainfall depths,

Table 5
Rainfall threshold depths needed to initiate pipeflow.

Location	Soils/lithology	Land use	Climate	Event rainfall depth (mm)	Source
Flemish Ardennes, Belgium	loess	pasture	humid temperate	9 (summer); 4 (winter)	Vannoppen et al., 2017
Panola, Georgia, USA	sandy loam	forest	humid subtropical	55	Tromp-Van Meerveld and McDonnell, 2006; Uchida et al., 2005
Toinotani (Kyoto),	clay loam soils, brown forest soils	forest	humid continental	40	Uchida et al., 2005
Jozankei (Hokkaido), Japan	clay loam soils, brown forest soils	forest	humid continental	10–20	Uchida et al., 2005
Kamberg Nature Reserve, Drakensberg Mts., South Africa	Histic Gleysols	grasslands	humid subtropical	32	Garland and Humphrey, 1992

which are rather scarce compared to the many reports on soil piping (Fig. 1). These data as well as previous reports suggest that different rainfall thresholds are controlled by the effects of climate and soil characteristics on pipeflow response (Uchida et al., 2001, 2005; Vannoppen et al., 2017). Pipeflow response is also strongly associated with the drainage area and soil pipe geometry, density, and depth (Uchida et al., 2001, 2005). Several authors also underlined the importance of pre-storm wetness in the catchment, i.e. pipeflow is more pronounced when pre-storm wetness increases (Jones, 2010; Tromp-Van Meerveld and McDonnell, 2006; Uchida et al., 2005; Vannoppen et al., 2017; Wilson et al., 2017a). Wilson et al. (2017a) suggested that rainfall thresholds for pipeflow initiation are seasonal and hence they cannot be relevant during seasons in which the pre-storm wetness is above a threshold. In such situations any precipitation will result in pipeflow. Rainfall thresholds should be established for all conditions characterized by the above-mentioned factors.

The significance of snowmelt in soil piping has been reported by several authors (Bernatek-Jakiel et al., 2015, 2017a; Carey and Woo, 2000; Heede, 1971; Rodzik et al., 2009). Rodzik et al. (2009) observed that piping and sediment accumulation processes at pipe outlets took place primarily during snowmelt events in loess deposits under a temperate climate, whereas gully erosion was caused by rainfall-induced runoff events. Carey and Woo (2000) observed that during snowmelt in an area with permafrost under a subarctic climate pipeflow discharge closely followed the daily snowmelt cycles and responded earlier than surface runoff on the slopes.

The initiation and occurrence of soil piping are also correlated with periods of desiccation that lead to soil cracking (Barendregt and Ongley, 1977; Bull and Kirkby, 1997; Gilman and Newson, 1980; Holden, 2006; Jones, 2004a; Jones et al., 1997; Parker and Higgins, 1990). Cracks open up new routes for bypass flow, thus also for pipeflow and piping. Therefore, soils with swelling clays, especially in semi-arid regions are particularly prone to this process.

However, any environmental change that induces soil desiccation, may also initiate soil pipe development, provided that enough runoff is still supplied to the preferential flow paths that enlarges them. In the light of increasing global mean air temperature, there is a need for further studies of this piping mechanism. Moreover, Holden (2006) reported that even desiccation induced by artificial drainage in peat catchments can be followed by a rapid pipe network expansion. This means that not only climate change, but also land management may induce an environmental change that encourages soil pipe development.

5.2. Soil properties

The importance of both physical and chemical soil properties in soil piping has been discussed by several authors (Bernatek-Jakiel et al., 2016; Botschek et al., 2002b; Faulkner, 2006; Faulkner et al., 2003; Gutiérrez et al., 1997; Masoodi et al., 2017; Nadal-Romero et al., 2011; Piccarreta et al., 2006; Verachtert et al., 2013; Wilson et al., 2015). A high susceptibility of soils to piping has been correlated with high contents of soluble salts, i.e. with dispersive soils (e.g. Desir and Marín, 2013; Faulkner, 2006; Faulkner et al., 2000; Imeson and Kwaad, 1980; Vacher et al., 2004), expressed by high values of SAR and ESP. Also, the presence of swelling clays enhances pipe development. Some double-layer clay minerals (e.g. smectite) with sodium present on the exchange complex, swell and disperse upon wetting, rendering them very erodible (Faulkner, 2013; Faulkner et al., 2000; López Bermúdez and Romero Díaz, 1989). However, it seems that chemical soil properties are more important in arid and semi-arid environments, especially in badlands. Furthermore, in temperate regions the geochemistry of the soil is assumed to be less relevant to pipe initiation (Bernatek-Jakiel et al., 2016; Botschek et al., 2002b; Verachtert et al., 2013; Wilson et al., 2015).

Physical soil properties that control soil erodibility, and thus soil piping are texture, structure, consistency, porosity, and bulk density (Bernatek-Jakiel et al., 2016; Nadal-Romero et al., 2011). Soil piping has been reported in almost every soil texture (Fig. 12), even in sands and loamy sands (e.g. Gallardo et al., 2017; Bhagyalekshmi et al., 2015) characterized by high pH, significant Na^+ content and high biological activity (Gallardo et al., 2017). It is most often reported in fine- and

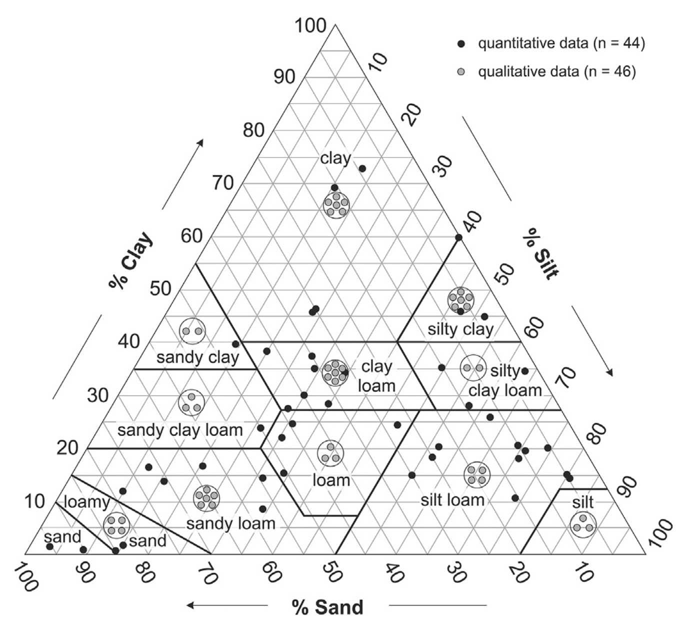


Fig. 12. Texture of soils for which piping has been reported in the literature. One dot represents one site where soil piping was reported and soil texture was given. Quantitative data means that the contents of sand, silt and clay were reported, whereas qualitative data means that only the name of the soil textural class was given (all these qualitative data is plotted in the centre of the textural class within the textural triangle). n is the number of sites for which soil piping has been reported.

Table 6
Macropores of different origin affecting soil pipe development.

Origin of macropores	Source
desiccation cracks	Bryan, 2000; Farifteh and Soeters, 1999; Frankl et al., 2012; Gilman and Newson, 1980; Heede, 1971; Higgins and Schoner, 1997; Holden, 2006; Huddart and Bennett, 2000; Jones et al., 1997; Lazzari et al., 2006
tectonic joints and cracks	Farifteh and Soeters, 1999; Lazzari et al., 2006; Torri and Bryan, 1997
tension cracks	Alexander, 1982; Calvo-Cases and Harvey, 1996; Harvey, 1982; Poesen, 1989
animal burrows and roots	Bernatek-Jakiel et al., 2016; Bernatek-Jakiel and Wrońska-Wałach, 2018; Botschek et al., 2002a; Czeppe, 1960; Farres et al., 1990; García-Ruiz et al., 1997; Leslie et al., 2014; Pickard, 1999; Poesen et al., 1996; Torri et al., 2013; Verachtert et al., 2013

medium-grained textures, especially in silt-rich soils (Bernatek-Jakiel et al., 2016; Bíl and Kubeček, 2012; Botschek et al., 2002a, 2002b; Gergely and Szalai, 2015; Laffan and Cutler, 1977; Nadal-Romero et al., 2011; Verachtert et al., 2010, 2013; Zhu, 2012), which mainly develop in loess sediment. Such soils are also the most erodible for sheet and rill erosion, provided that their organic matter content remains below 2% (Poesen, 1993). Although soil texture is an important property controlling the susceptibility of soils to piping, it seems to be of lesser importance for identifying sites with piping erosion (Bernatek-Jakiel et al., 2016; Jones, 1971; Verachtert et al., 2010).

Soil structure may enhance soil piping, because a well-developed structure may facilitate water infiltration and percolation into deeper soil horizons, as reported in silt loams in the Bieszczady Mts. (Bernatek-Jakiel et al., 2016). In contrast, Faulkner (2006) underlined that the structureless nature of loess makes it more erodible and collapsible. Failure planes occurring in loess concentrate throughflow causing piping. Porosity may also facilitate water infiltration. It has been shown that macropores of different origin contribute to the formation and development of soil pipes (Tab. 6). However, it is not always easy to distinguish what was the initial factor, as for instance interactions between biological activity and pipe formation may work in both ways (Verachtert et al., 2013). On the one hand, macropores enhance pipeflow and, thus, initiate piping. On the other hand, a pipe can act as a drain for water, which encourages the presence of earthworms (Nuutinen and Butt, 2003).

Soil profile development, with the presence of different horizons, may also affect soil piping. Several studies report that soil piping occurs above a water-restrictive (boundary) layer, which induces a lateral subsurface flow. Such a boundary layer may be formed at the organic–mineral horizon interface (Carey and Woo, 2000, 2002), above argic and fragipan horizons (Faulkner, 2006; Jones, 1971; Wilson et al., 2006, 2015; Zhang and Wilson, 2013), at the soil–bedrock interface (Ahmed and Carpenter, 2003; Bernatek-Jakiel and Kondracka, 2016; Bernatek-Jakiel et al., 2016; Hardie et al., 2012; McDonnell, 1990b; Uchida et al., 2001; Walsh and Howells, 1988), and at the interface between the buried paleosols and the contemporary soil (Hardenbicker, 1997).

5.3. Topography

Field (Atallah et al., 2015; Castañeda et al., 2017; Farifteh and Soeters, 1999; Faulkner, 2013; Faulkner et al., 2004; García-Ruiz et al., 1997) and laboratory studies (Bernatek-Jakiel et al., 2017b; Nadal-Romero et al., 2009; Wilson, 2009; Wilson et al., 2008) pointed to the hydraulic gradient as a critical factor determining soil pipe development. Soil piping associated with a steep hydraulic gradient is mainly observed in earth banks, such as agricultural terraces (Romero Díaz et al., 2007; Tarolli et al., 2014), lynchets and sunken lane banks (Poesen, 1989; Poesen et al., 1996). Also on hillslopes affected by soil piping, hydraulic gradient is important, although pipe formation is additionally controlled by other factors such as groundwater table fluctuations (Vannoppen et al., 2017) or subsurface flow obstruction due to landslides (Verachtert et al., 2012). Some authors reported that a sufficient slope gradient is needed to produce critical hydraulic gradients, and thus to drive the preferential flow (Wilson et al., 2008). However, surface topography may not always reflect the subsurface one (Jones, 1981). Additionally, pipes may also develop in rather flat areas, such as alluvial plains (Zhang and Wilson, 2013).

The role of slope curvature in pipe development is ambiguous. On the one hand, convex slope profiles induce larger hydraulic gradients (Faulkner, 2006), whereas concave profiles provide convergent flow paths (Garland and Humphrey, 1992; Verachtert et al., 2010). Jones et al. (1997) suggested that pipes often start on convex hillslope sections of areas where soil desiccation and crack development is more important than the flow concentration for pipe initiation. Also under temperate climate conditions convex hillslopes may be favoured for soil piping (Bernatek-Jakiel et al., 2017a).

Verachtert et al. (2010) established topographical thresholds for pipe initiation using soil surface slope and contributing drainage area (i.e. S–A relation). These threshold conditions for piping are similar to the conditions needed for shallow ephemeral gully initiation in cropland of the Belgian loess belt. The establishment of such thresholds is questioned as the surface area does not always correspond to the subsurface drainage area (Jones, 1986, 1997a; Wilson et al., 2015). Jones (1997c) and Holden and Burt (2002) proposed a maximum dynamic contributing area (DCA, m^2) defined as the ratio between the total storm discharge in the pipe (m^3) to the total storm rainfall (mm). Topographical thresholds for pipe development under various environmental condition require more research efforts.

Some authors underlined the need of a pipe outlet (Fig. 11) as a place where mobilized sediment and water can be evacuated. This can be located at a gully head, on gully and river banks, on road cuts, and at footslopes (see Fig. 5). However, there are some reports of closed pipes, i.e. dead-ends or blocked pipes, which may lead to high pore water pressures and thus to slope instability (Hardenbicker and Crozier, 2002; Pierson, 1983), to sediment mound formation (Wilson et al., 2017a), or to the occurrence of new pipes and pipe collapses (Midgley et al., 2013; Verachtert et al., 2012).

5.4. Land use changes and land management

Soil piping occurs under different land use types (Fig. 13). However, the relationship between soil pipes and land use changes is scarcely investigated (Jones and Cottrell, 2007; Romero Díaz et al., 2007; Wilson et al., 2015). Some studies in blanket peats show that land management is the most important control of hillslope pipe frequency (Holden, 2005), and that afforestation leads to a significant reduction in size and number of soil pipes (Jones and Cottrell, 2007). Wilson et al. (2015) reported that the transition from cropland, through forest to pasture with the filling-in of old gullies increased soil pipe activity in a loess pasture in the USA.

In the loess belt of central Belgium, Verachtert et al. (2013) also reported that soil pipes mainly occur in pasture which they attributed to intense biological activity (especially by earthworms and moles) in combination with a high winter groundwater table position in the soil profile. However, soil pipes may also form in agricultural land (Fig. 13C; Govers, 1987), though their persistence in such landscapes is short due to annual tillage operations, which reduce their size. In the

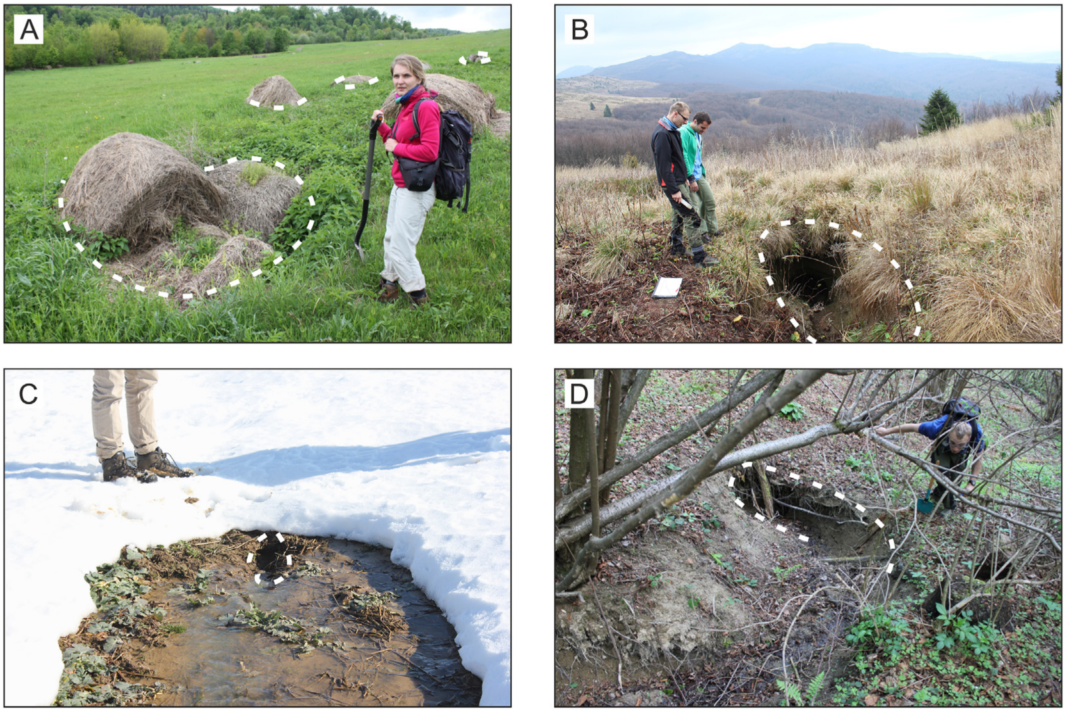


Fig. 13. Examples of pipe collapses in different land use types: A – grassland with collapsed pipes filled with hay bales, Tyskowa village, Bieszczady Mts., Carpathians, Poland (photo: M. Jakiel, May 2015); B – subalpine/alpine meadows, Kińczyk Bukowski Mt., Bieszczady Mts., Carpathians, Poland (photo: A. Bernatek-Jakiel, October 2013); C – cropland, Halenkovice village, Chrziby, Carpathians, Czech Republic (photo: A. Bernatek-Jakiel, February 2015); D – forest, Tyskowa village, Bieszczady Mts., Carpathians, Poland (photo: A. Bernatek-Jakiel, May 2013).

Bieszczady Mts., pipes develop both in grassland (Fig. 13A) and in forest (Fig. 13D), so these land use types do not prevent soil piping (Bernatek, 2015; Bernatek-Jakiel and Wrońska-Wałach, 2018). However, more research is required to analyse the impact of past land use on pipe development.

This section highlighted some important factors controlling soil piping intensity. At present, however, no factorial model to predict soil piping intensity exists to predict soil piping at different spatial and temporal scales and for a range of environmental conditions in natural landscapes. More research is needed if we want to predict impacts of soil type, topography, land use, land management and climate change on soil piping intensity.

6. Prevention and control of soil piping

Preventing soil piping is one of the most overlooked issue in piping research as well as in the field of soil erosion control. There is a lack of detailed studies on effective measures to prevent soil piping in different climatic regions and with different soil types. As shown above, soil piping may lead to significant soil losses (including gully erosion), slope instability and may also contribute to stormflow in catchments. Therefore one should consider control measures that reduce pipeflow discharge, hydraulic subsurface erosion and mass movements caused by soil piping. However, at present there are very few studies dealing with piping control measures, some of them only suggesting possible techniques without detailed testing (Tab. 7). Such techniques mainly focus on reducing soil erosion by piping rather than stabilizing entire hillslopes against piping.

In humid climates lowering of the groundwater table and draining the areas affected by soil piping might be tested, whereas in dry climates raising the water table height and irrigating the soil might limit piping erosion (Frankl et al., 2016). In humid regions one should avoid water supply to macropores, and in the piped zones excess water should be evacuated. In contrast, water supply to piping-susceptible soils in dry regions may decrease the formation of desiccation cracks and hence pipe formation (Frankl et al., 2016). At the end, it has to be underlined that all control measures should be always adjusted to the individual sites, as different processes are involved in soil pipe initiation (Crouch et al., 1986).

7. Conclusions and research needs

Over the last decades, soil piping research has contributed to a better understanding of its geomorphological and hydrological role around the world. However, several aspects of soil piping still remain under-researched. The following major research gaps can be identified:

a) lack of detailed, quantitative information on the morphological characteristics of pipes and pipe networks, e.g. pipe size which changes laterally and vertically along the pipe, the extension of pipe networks, the length of pipes, the tortuosity of pipes and pipe connectivity;
b) need for non-destructive detection and mapping of soil pipes and pipe networks;
c) lack of models of hillslope hydrology and soil erosion including pipeflow and piping erosion;
d) lack of subsurface catchment models when soil piping occurs, as the surface catchment might be different from the subsurface catchment;
e) lack of environmental thresholds to determine when soil piping initiates gullies;
f) lack of rainfall depth thresholds that induce soil detachment in pipes as well as sediment transport (flushing) in pipes;
g) limited availability of representative data on total soil loss and soil loss rates due to piping in different environments, as well as lack of standardization in data collection (different study periods and plot sizes);
h) lack of models to predict pipe development and collapse, and thus

Table 7
Piping erosion control measures (A) tested in the field and laboratory, (B) not-tested, but presented as a potential measure.

(A) Type of measure	Examples of measures	Aims	Soils/lithology	Region	Source
Mechanical	1) Procedure: - destruction of pipes - filling the eroded spots and compact the filling soil - building-up the humus content of the topsoil - restriction of introducing too deep tap roots 2) maintenance of sufficient irrigation in semi-arid areas	prevent piping by farmers	alluvial deposits	SE Arizona, USA	Carroll, 1949
Mechanical and chemical	1) Procedure: - excavation of the entire length of the tunnel system - chemical amelioration with gypsum - compaction of repacked fill to reduce internal porosity - installation of sand blocks with porous geotextile to capture and remove water moving along the reinstalled cable	prevent tunnel erosion along an optical fibre cable	sodic soils	Tasmania, Australia	Hardie et al., 2007
Mechanical	1) application of coir fibers in soil (derived from coconut)	increase the piping resistance	various types of soils (sand, red soil and mixture of sand and red soil)	*based on laboratory experiments*	Babu and Vasudevan, 2008
Mechanical	1) growth of grass roots	increase the soil cohesion	sandy soils	*based on laboratory experiments (pinhole test)*	Bernatek-Jakiel et al., 2017b
Mechanical	1) installation of vertical subsurface geomembrane dams perpendicular to gully channels	reduce soil cracking by increasing the local soil moisture content and blocking bypass flow in soil pipes near check dams	Vertisols	Hagere Selam, Ethiopia	Frankl et al., 2016
Mechanical and vegetative	1) contour furrows 2) residue (wheat straw) incorporation	investigate potholes when formed under different conservation measures	Vertisols	Chambal region, southeastern Rajasthan, India	Somasundaram et al., 2011
(B) Type of measure	**Examples of measures**	**Aims**	**Soils/lithology**	**Region**	**Source**
Mechanical, vegetative and chemical	1) gully filling or significantly reducing gully side slope 2) raising the gully floor with check dams 3) use of gypsum or deep-rooted plants to penetrate and improve the soil structure	1) prevent piping induced by gully development 2) reduce both the hydraulic gradient and the exposure of the permeable zone in which the tunnels initiate 3) prevent piping wher e tunnels forming at the natural groundslope with dispersive B horizon	sodic soils	New South Wales, Australia	Crouch et al., 1986
Mechanical	1) site drainage and reduction of hydraulic gradient 2) place material over the exfiltration face, lengthen the seepage path, and reduce the exit gradient (material balance) 3) bank protection by filter	1) prevent piping which is caused by seepage from a localized source of water 2) prevent piping caused by precipitation infiltration 3) protect streambank	river- and streambank	USA	Hagerty, 1992
Vegetative and mechanical	1) increase of vegetation cover 2) digging deep trenches perpendicular to the contour	1) prevent pipe initiation by intercepting rainfall and reducing the possibility of infiltration–excess overland flow 2) improve the drainage of soil water during the monsoon/heavy downpour	forest soil (Alluvial soil) and laterite soils	southern Western Ghats, India	Bhagyalekshmi et al., 2015
Mechanical and vegetative	1) drainage 2) deep rooted vegetation	1) prevent soil erosion (laboratory studies)	loess soil	USA	Wilson et al., 2008

allowing to detect piping-affected areas, i.e. sites with collapse hazard and the development of discontinuous gullies;

i) lack of research on piping control measures under various factors controlling soil piping rates in different environments.

Addressing these research gaps will not only help to better understand hillslope hydrology and evolution of landscapes prone to soil piping, but will also allow to prevent and control this soil degradation process.

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