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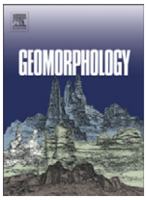

# Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: A case study from central Belgium

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ABSTRACT

Collapsible loess-derived soils are prone to soil piping erosion, where enlargement of macropores may lead to a subsurface pipe network and eventually to soil collapse and gully development. This study aims at understanding the main factors controlling spatial patterns of piping in loess-derived soils under a temperate climate. To map the spatial distribution of piping and identify the environmental controls on its distribution, a regional survey was carried out in a 236 km$^2$ study area in the Flemish Ardennes (Belgium). Orthophotos taken at optimal field conditions (winter) were analyzed to detect piping in open landscapes and ground thruthing was systematically done through field surveys. In total, 137 parcels having 560 collapsed pipes were mapped. Dimensions of the sinkholes and local slope gradient were measured in the field and topographical variables were derived from LiDAR data. Land use plays an important role as 97% of the sites with piping are found under pasture. The probability of piping increases rapidly on hillslopes with gradients exceeding 8% and with a concave profile and plan curvature, enhancing subsurface flow concentration. The zones with soil profiles on shallow loess over a relatively thin layer of homogeneous blue massive clays (Aalbeke Member) are most prone to piping. Soil characteristics are of less importance to explain piping occurrence. Furthermore, the topographical threshold line indicating the critical slope gradient for a given contributing drainage area was determined. This threshold line (negative power relation) is similar to the threshold line for shallow gully initiation.

## 1. Introduction

Subsurface erosion (piping and tunnel erosion) in non-karstic landscapes has for a long time been considered of little importance compared to sheet and gully erosion. In the case of soil piping erosion (further named piping) linear voids are formed by concentrated flowing water in soils or unconsolidated deposits, which can cause collapse of the soil surface and formation of discontinuous gullies (Jones, 2004). The terminology of the different processes causing subsurface erosion features has been discussed more extensively by Dunne (1990) and Bryan and Jones (1997).

Piping has been observed in both natural and anthropogenic landscapes, in a wide range of climatological, geomorphological and pedological settings (Bryan and Jones, 1997). In Europe, Faulkner (2006) distinguished three piping-prone contexts: (i) organic peats (Histosols) and Gleysols, (ii) dispersive sodic marls (Xerosols), and (iii) collapsible loess-derived soils (Luvisols). Most research on piping in Europe was performed on organic-rich soils in the United Kingdom (e.g. Jones et al., 1997; Holden and Burt, 2002) and dispersive material in the Mediterranean area (e.g. García Ruiz et al., 1986; Torri and Bryan, 1997; Farifteh and Soeters, 1999), while limited information exists about piping in loess-derived soils in temperate climate. However, observations made in Belgium (Poesen, 1989), Germany (Hardenbicker, 1998; Botschek et al., 2002a,b) and Hungary (Kerényi, 1994) reveal the importance of piping in this context. Early literature reports about piping in loess-derived soils in Poland (e.g. Malicki, 1935; Czeppe, 1960; Malinowski, 1963). In semi-arid climate, however, the susceptibility of loess for piping is well known in northern China (e.g. Zhu et al., 2002; Zhu, 2003) and New Zealand (e.g. Hughes, 1972). For loess in Germany, Botschek et al. (2002a) reported that there was no relationship between the chemical soil properties and the vulnerability to piping. This is in clear contrast to piping in the Xerosols of the Mediterranean area, where clay dispersion plays a significant role (Faulkner, 2006). Unlike extensive knowledge on sheet and rill erosion and gullying in loess (e.g. Poesen, 1993; Nachtergaele et al., 2001; Vanwalleghem et al., 2005), less is known about the topographical and soil properties triggering pipe development in the collapsible soils of the Northern European Belt under a temperate climate. Therefore, this research aims at a better understanding of the main factors controlling piping in the loess-derived soils in Belgium. More specific objectives for the selected study area in the Flemish Ardennes are: (1) to map the spatial

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distribution of collapsed pipes, (2) to link the occurrence of collapsed pipes to the environmental characteristics, and (3) to compare the topographical thresholds controlling the occurrence of piping to gullies and landslides. To obtain these insights, an extensive regional inventory of collapsed pipes was carried out, unique in loess-derived soils in temperate climate.

## 2. Study area

The study area (236 km$^2$, Fig. 1) consists of five municipalities in the Flemish Ardennes (Belgium). Ecologically, it corresponds to a maritime temperate humid climate with mild winters and an average annual rainfall of about 800 mm well distributed over the year. It is a hilly region with altitudes ranging from 10 m a.s.l. in the valley of the river Scheldt to 150 m a.s.l. on the Tertiary hills, located east of the river. The greater part of the area (99.5%) has slope gradients less than 20%. The topography is characterized by a systematic valley-asymmetry, as the slopes oriented south to northwest are steeper (Vanmaercke-Gottigny, 1995). The Tertiary lithology consists of an alternation of sands and less permeable smectite-rich clays and is covered by Quaternary eolian loess (Jacobs et al., 1999). Many springs and a high drainage density (1.46 km km$^{-2}$) characterize the hydrology of the region. Cropland is located on the loess-covered plateaus of the lower hills, and pastures dominate the hillslopes. The highest loess-free Tertiary hills and the steepest hillslopes are forested (I.W.O.N.L. 1987).

## 3. Material and methods

Aerial photographs (orthophotos 1:12,000, taken in March; AGIV, 2006) were analyzed and the sites with indications of collapsed roofs of pipes (recognized as ‘black spots’ on the orthophoto) were selected for an intensive field check (Fig. 2). Furthermore, farmers and personnel of local technical services of the municipalities were interviewed. The field survey focused on pasture but during the enquiries farmers were also asked for piping phenomena under cropland. The forests within the study area were already checked for piping during recent research on landslides (Van Den Eeckhaut et al., 2005), but only one site with collapsed pipes was observed under forest. In total, 137 parcels having 560 collapsed pipes were mapped with GPS (Trimble 2005 GeoXT; accuracy <1 m). The depth and diameter of the collapsed pipes were measured using a folding rule. The local slope gradient of the soil surface was measured with a clinometer at the most upslope and most downslope collapsed pipe locations within every parcel.

Topographical variables such as hillslope gradient, aspect, distance to the thalweg, profile and plan curvature were derived from LiDAR data (Light Detection And Ranging; DEM of Flanders, 2004) using routines available in IDRISI Andes and ArcGIS™. More information about the LiDAR data used can be found in Van Den Eeckhaut et al. (2007a). Information on lithology and soil was derived from the Tertiary geological map (1:50,000; AGIV, 2001a) and the soil map (1:20,000; AGIV, 2001b) respectively, both converted to raster data with a 10 × 10 m resolution. The upslope contributing area was calculated using routines from the spatially distributed soil erosion and sediment delivery model, WaTEM/SEDEM. Detailed descriptions of the model are provided in Verstraeten et al. (2002). The parcels in the study area with pasture were determined from a land use map (AGIV, 2004).

The relationship between slope gradient ($S$, m m$^{-1}$) at a collapsed pipe site and corresponding drainage area ($A$, ha) was investigated using the negative power relationship earlier derived for gully initiation (e.g. Abrahams, 1980; Moore et al., 1988; Montgomery

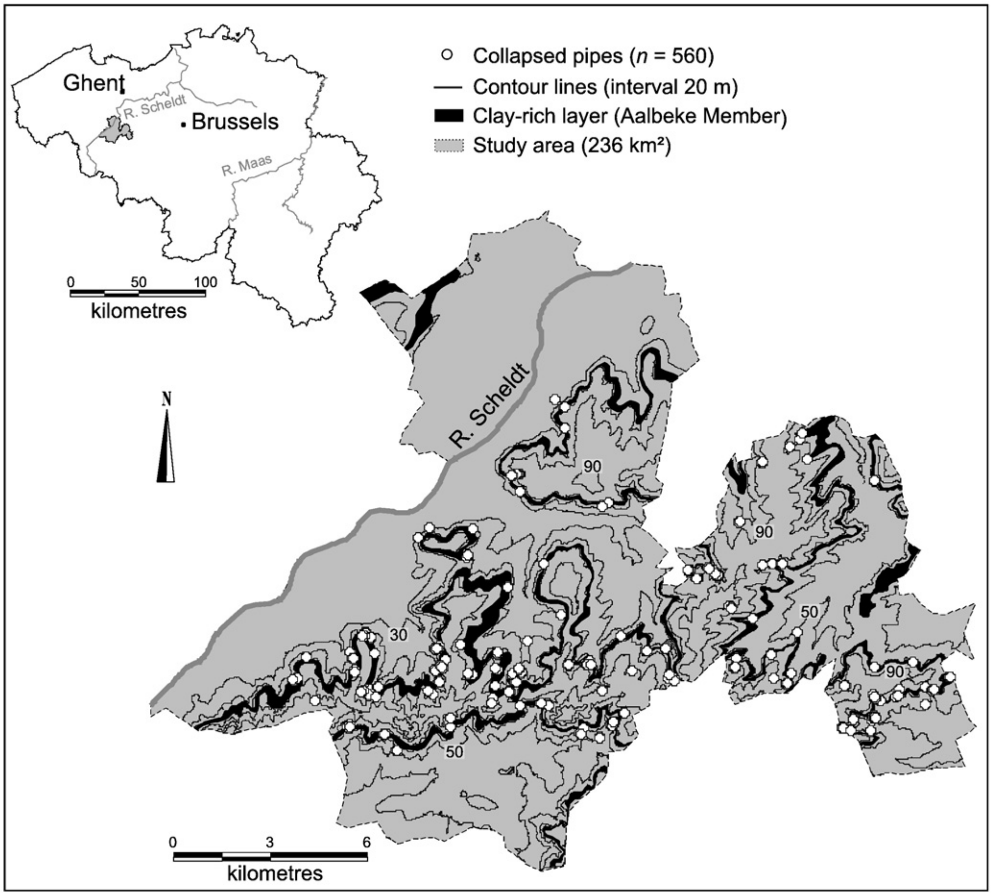

**Fig. 1.** Location of the study area in Belgium and inventory of the collapsed pipes ($n = 560$) projected on a map with indication of the clay-rich Aalbeke Member (Tertiary lithology).

**Fig. 2.** Photographs of the study area. (a) Aerial orthophoto with indications of possible collapsed pipes. (b and c) Terrestrial photos of the sites with collapsed pipes (Kluisbergen, December 2007; see (a) for location).

and Dietrich, 1994; Vandekerckhove et al., 2000; Poesen et al., 2003; Vanwalleghem et al., 2005):

$$S = aA^{-b} \tag{1}$$

with $a$ and $b$ coefficients. This relationship was determined by ordinary least squares regression on double logarithmic scale. In order to obtain the topographical threshold line, a straight line was fitted through the lowermost of the data points, with a slope equal to the slope of the regression line.

## 4. Results

### 4.1. Detection and morphological characteristics

The number of parcels with collapsed pipes observed by analyzing the aerial photographs ($n = 42$) corresponds to one third of all parcels found during the field survey ($n = 137$). Many sites with collapsed pipes were not visible on the orthophotos, due to their small size, because they were obscured by filling material when aerial photos were taken or because they were obscured by shadow of trees or other obstacles. A classification of piping features was made based on their morphological characteristics (Fig. 3). In total, 560 collapsed pipes were mapped (Fig. 1), of which 300 were classified as sinkholes (type 1), 195 as closed depressions (type 2) and 65 as collapsed pipes that were filled up (type 3) by farmers with, for example, stones and soil. Besides the 560 collapsed pipes, three features were mapped, i.e. the pipe inlet (type 4, $n = 7$), pipe outlet (type 5, $n = 21$) and piping on earth and river banks (type 6, $n = 7$). Collapsed pipes were mapped as sinkholes when the surface (mostly grass-covered) was clearly interrupted by more or less vertical walls, while in the case of a closed depression the soil surface smoothly lowered without any break in the vegetation cover. In some cases, soil between single sinkholes collapses too, forming discontinuous gullies (type 1B, multiple sinkholes). The original morphology of filled-up sinkholes and closed depressions (type 3) is unknown, but it could be assumed that farmers mainly fill up type 1 sinkholes. The mapping of pipe inlet and outlet was based on field observations. A spot upslope of collapsed pipes where water (e.g. from a spring) infiltrated into a macropore in the soil was considered as an inlet. The outlets were defined as spots where water flowing through the pipes was exfiltrating downslope of the collapsed pipes. In most cases, the outlet was recognized as a wet spot, often close to a drainage ditch or a river channel, where the water table intersects with the topography resulting in saturated overland flow.

The morphological characteristics of the mapped collapsed pipes are shown in Table 1. Sinkholes and closed depressions have an average depth of 0.6 m and 0.3 m respectively and an average diameter of 1.1 m and 1.3 m respectively, but there is a large variation in the measured data. Where the pipe was visible, it was situated around 0.9 m below the soil surface and had a mean diameter of 0.2 m. Based on the measured pipe dimensions, volumes of the collapsed pipes could be calculated and a conservative estimate of the soil loss due to piping was made. Mean soil loss was calculated to be 23 t $\text{ha}^{-1}$ for 137 parcels with collapsed pipes. Assuming that the process took place over a period of 5 to 10 years, this loss corresponds to a mean soil erosion rate between 2.3 and 4.6 t $\text{ha}^{-1}$ $\text{year}^{-1}$.

### 4.2. Spatial distribution of collapsed pipes and environmental factors

In terms of spatial distribution, 97% of the parcels with collapsed pipes are located in a pasture, while only 3% and 1% are located in arable land or in forest respectively (Fig. 4). The available land use map was used to classify the land use of the study area and to select

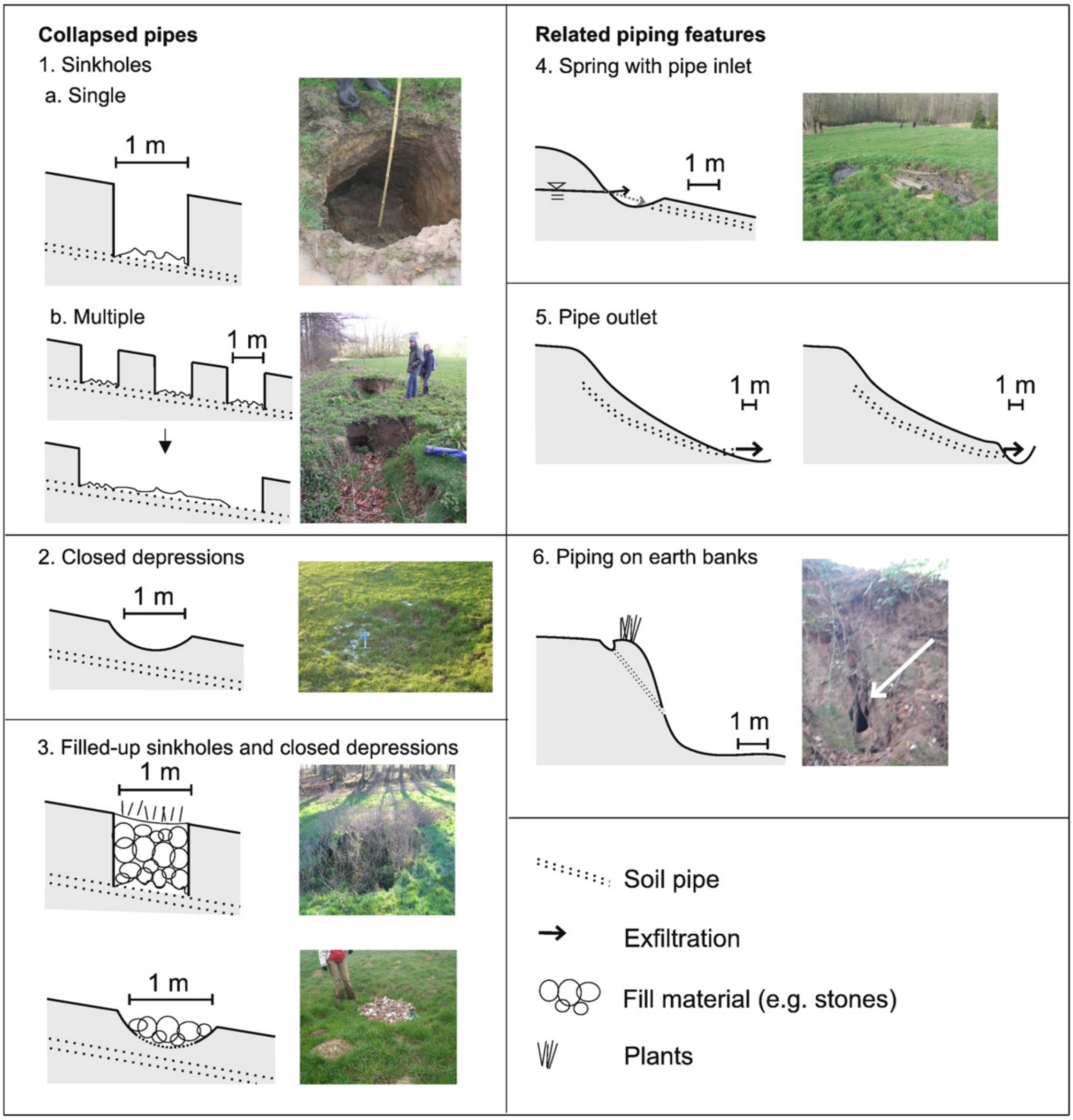

**Fig. 3.** Classification of collapsed pipes and related piping features.

the pastures of the study area, but the land use of the parcels with piping was classified based on field observations because these observations were more accurate. Fig. 5 shows histograms of environmental factors which may influence the spatial occurrence of collapsed pipes in the study area. Due to the grid cell resolution of 10 × 10 m, the analysis was made based on 417 grid cells enclosing 1 or more collapsed pipes ($n = 560$) and $2.3 \times 10^6$ grid cells comprising the entire study area. The collapsed pipes are predominantly located on the hillslopes and less in the valley-bottoms or on the plateaus (Figs. 1 and 5a). In the study area, piping occurs on slopes between 2% and 31%, with a sharp increase in the frequency of piping on slopes with gradients exceeding 8%. Note that the slope gradient in this

**Table 1**
Morphological characteristics of the collapsed pipes.

| | Sinkholes (type 1[a]) | | Closed depressions (type 3 [a]) | | Pipe | |
|---|---|---|---|---|---|---|
| | Depth m | Diameter m | Depth m | Diameter m | Depth[b] m | Diameter m |
| $n$ | 220 | 222 | 131 | 130 | 15 | 24 |
| Mean | 0.6 | 1.1 | 0.3 | 1.3 | 0.9 | 0.2 |
| Median | 0.5 | 1.0 | 0.3 | 1.2 | 0.9 | 0.2 |
| Minimum | 0.2 | 0.1 | 0.0 | 0.2 | 0.7 | 0.1 |
| Maximum | 2.0 | 4.5 | 0.8 | 5.5 | 1.4 | 0.4 |
| Standard deviation | 0.3 | 0.8 | 0.1 | 0.8 | 0.2 | 0.1 |

[a] According to the classification in Fig. 3.
[b] Depth of pipe base.

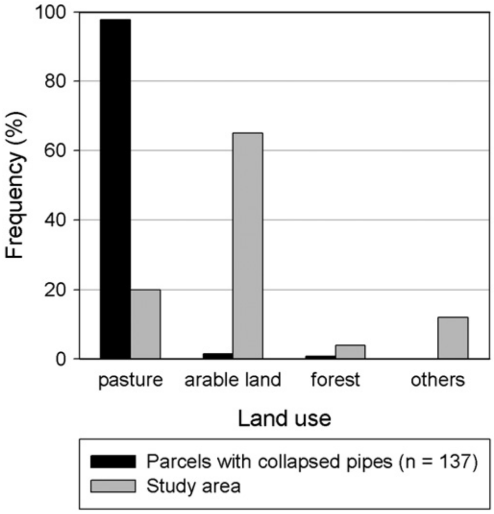

**Fig. 4.** Frequency distribution of land use classes for parcels with piping and that for the whole study area.

figure is calculated from the LiDAR-derived DEM. Slopes facing west, and to a lesser extent east, are most favourable for piping (Fig. 5b). As expected, more piping occurs on hillslopes with plan and profile concavities compared to straight or convex hillslopes (Fig. 5c,d) and 49% of the collapsed pipes are located on a distance less than 15 m from the thalweg. The frequency distribution of slope, aspect and curvature for the pastures in the study area is quite similar to that for the whole study area.

Concerning lithology, most prone to piping are the areas with the Aalbeke Member (>50% smectite clay) under the shallow loess cover. More than 28% of the sites with piping are located on this lithological layer, while this layer covers only 8% of the study area (Fig. 5e). The rest of the collapsed pipes are mainly located on the Tielt Formation and Moen Member. These two lithological layers contain clay as well as silt and sand, and cover a large part of the study area. The pastures of the study area are preferentially located on the Saint-Maur Member (valleys) and Aalbeke Member. Soil texture, soil drainage class and soil profile development seem to be of less importance (Fig. 5f–h). The texture of the soils with piping ranges from silty-clay loam to sandy loam. Moderate wet soils are preferred above very wet or dry soils, and there is a higher frequency of piping on soils with no profile development. In general, the pastures follow a similar soil pattern as the total study area, although there is a slightly higher frequency of pastures on wet soils and soils without profile development.

### 4.3. Topographical threshold for piping

The slope–drainage area relation for piping in the study area (Figs. 6 and 7) shows a significant negative trend of the form of Eq. (1). In order to determine the topographical threshold, a straight line was fitted through the lowermost of the data points, with a slope equal to the slope of the regression line. The points under the threshold line were considered as outliers. The following topographical threshold equations were obtained:

$$S_{\mathrm{DEM}} = 0.017A^{-0.123}(R^2 = 0.16; n = 417) \tag{2}$$

with $S_{\mathrm{DEM}}$ the slope gradient calculated from LiDAR-derived DEM;

$$S_{\mathrm{field}} = 0.019A^{-0.140}(R^2 = 0.15; n = 196) \tag{3}$$

with $S_{\mathrm{field}}$ the slope gradient measured in the field. $S_{\mathrm{field}}$ was measured only for the most upslope and most downslope collapsed pipes of each parcel ($n=196$). The slope gradients of these 196 collapsed pipes were used for calibrating Eq. (3). A significant correlation was found between $S_{\mathrm{DEM}}$ and $S_{\mathrm{field}}$ ($R^2=0.63$; $P<0.05$), justifying the further use of $S_{\mathrm{DEM}}$. A subdivision of the collapsed pipes according to their position along the hillslope (most upslope vs. most downslope) did not result in significantly distinct *S*–*A* threshold equations.

## 5. Discussion

In a wide range of European environments, piping is considered to be a critically important soil erosion process (Faulkner, 2006). In clear contrast to surface erosion, most parcels with piping erosion were found under pasture. For our study area in the Flemish Ardennes, the conservative assessment of soil loss due to piping erosion revealed a value of 2.3–4.6 t $\mathrm{ha}^{-1}$ $\mathrm{year}^{-1}$ for fields with piping. These soil losses exceed by a factor 230 to 460 the mean soil losses by sheet and rill erosion for grassland in Europe, excluding the Mediterranean zone (i.e. 0.01 t $\mathrm{ha}^{-1}$ $\mathrm{year}^{-1}$; Cerdan et al., 2006). In addition, piping is known to play an important role in gullying, inducing high soil losses (Poesen, 1989; Bocco, 1991; Poesen et al., 2003). The dimensions of the pipe can vary widely according to the conditions of formation, specifically the climatic conditions (Bryan and Jones, 1997). A literature review by Bryan and Jones (1997) revealed that average pipe diameters in temperate environments are 0.15 m (midlatitude marine) and 0.25 m (midlatitude humid continental). Botschek et al. (2002a) found pipe diameters ranging from 0.05 to 0.30 m for loess in Germany. Similar dimensions were observed in the present study: i.e. a mean pipe diameter of 0.2 m. In Japanese forests, the diameter of pipe outlets varies widely (0.001–0.50 m) and is sometimes even less than 1 cm (Uchida et al., 2001). In badlands or semi-arid regions, however, the pipe diameter can be several meters (Bryan and Jones, 1997; Uchida et al., 2001; Zhu, 2003). According to Holden and Burt (2002), the pipe shape, size and depth may differ a lot over a small distance.

### 5.1. Environmental factors controlling the spatial distribution of collapsed pipes

Piping occurs on a wide range of slopes in the study area, although slopes steeper than 8% are clearly favoured. In literature as well, the reported slope angles of sites with piping are highly variable. For loess-derived soils, slopes reported range from 10% (New Zealand; Cumberland, 1944) over 11–44% (Germany; Henn and Botschek, 2002) to 30–51% (New Zealand; Gibbs, 1945). An upper-limit value of 12% was reported for the best development of piping in loess covering a clay loam subsoil in New Zealand (Ward, 1966). In this study, 90% of the collapsed pipes have a slope gradient between 8 and 24%. Some authors suggest that a maximum threshold for the slope gradient is established because on very steep slopes, infiltration generally decreases due to an increase of surface runoff (Jones, 1981) or there is a greater probability that mass movements occur, destroying subsurface pipes (Feininger, 1969; Conacher and Dalrymple, 1977; Farifteh and Soeters, 1999). However, contrasting results were found for this study area concerning landslides. The frequency distribution of landslides with slope gradient was similar to that of piping, and no higher probability of landslides on steeper slopes was observed (Van Den Eeckhaut, 2006). We agree with Jones (1981) that the physiographic, hydraulic and pedological context is more important than a specific surface slope.

The requirements for pipe development were summarized by Faulkner (2006) as follows: (a) an infiltrating surface, (b) convergent flow paths and (c) convex profile morphology. The first two are met in our study as the grass cover provides a high infiltration rate and the dominant occurrence of collapsed pipes in plan concavities suggests convergent flow paths. However, the observations revealed no need of a convex profile curvature. Garland and Humphrey (1992) concluded that the conditions necessary for pipe evolution in the Drakensberg

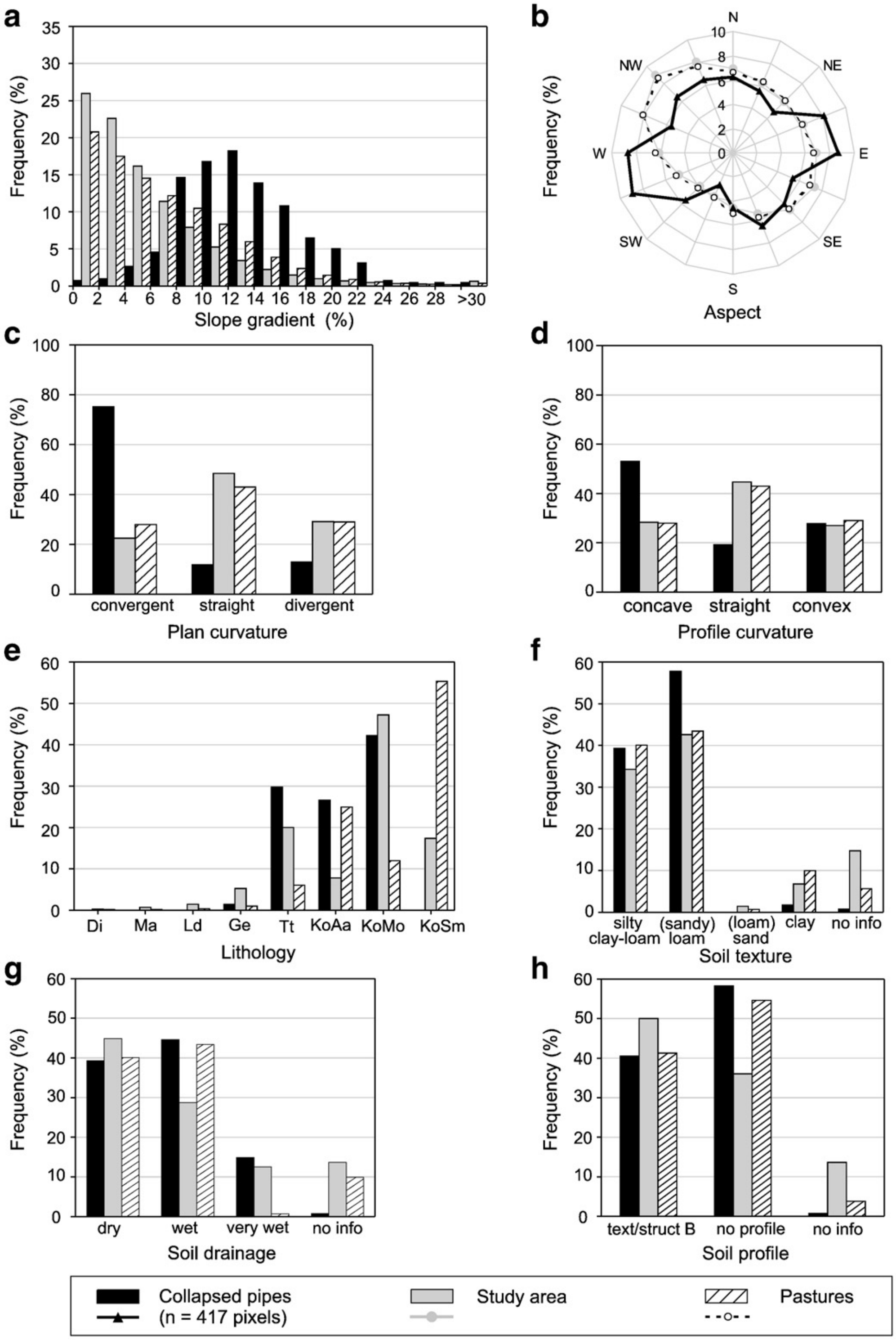

**Fig. 5.** Frequency analysis of environmental parameters for the mapped collapsed pipes, the whole study area and the whole pastures of the study area. (a) Slope gradient. (b) Aspect [N: north, E: east, S: south, W: west]. (c) Plan curvature. (d) Plan curvature. (e) Lithology [Di (Diest): glauconitic sand, Ma (Maldegem): clay and glauconitic sandy clay, Ld (Lede): sand; Ge (Gent): glauconitic sand and clay with sand lenses, Tt (Tielt): glauconitic clayey sand, with clay and lithified sand layers; KoAa (Aalbeke): homogeneous blue massive clay; KoMo (Moen): clayey silt to sand with clay layers; KoSm (Saint-Maur): silty clay]. (f) Soil texture. (g) Soil drainage. (h) Soil profile development [text/struct B: texture or structure B horizon, no profile: without profile development].

(South-Africa) include concave hillslopes. Jones (1981) as well suggested that most collecting areas from which pipes may run are concave, but that the hydraulic gradient is of greater importance than the surface slope. Later he concluded that many pipes begin on convex hillslopes because desiccation was more important than the concentration of water for pipe initiation (Jones et al., 1997). A higher probability of desiccation is also reported to explain the preference of piping occurrence for a certain slope orientation (Hughes, 1972; Jones, 1997; Farifteh and Soeters, 1999). In the studied temperate humid environment, however, desiccation probably plays a minor role, and instead other mechanisms initiate piping. In addition to water convergence, earthworm activity favours rapid vertical

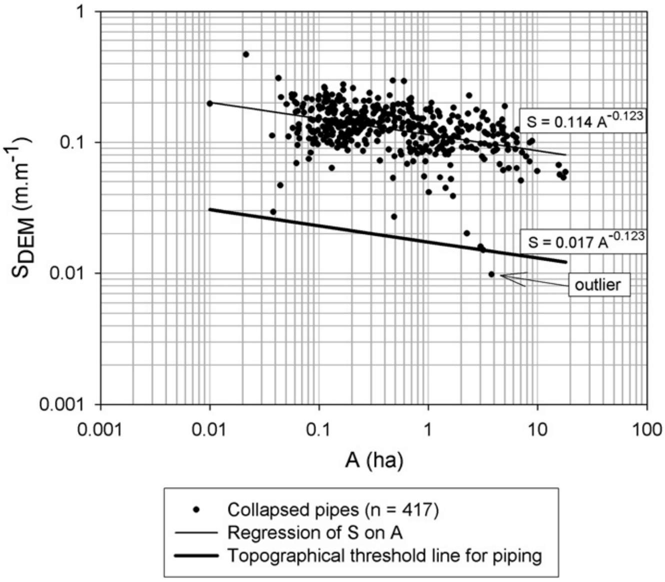

**Fig. 6.** Relation between drainage area ($A$) versus soil surface slope gradient ($S_{\mathrm{DEM}}$), both calculated from the LiDAR-derived DEM, with indication of the topographical threshold for pipe collapse.

infiltration and mole burrows may favour lateral flow in the soil profile leading to piping. Other authors pointed to the role of animal burrows in the formation of pipes as well (e.g. Carroll, 1949; Czeppe, 1960; Botschek et al., 2002b). It can therefore be hypothesized that piping is triggered by high water tables together with important biological activity (earthworms and moles) in pastures. This leads to other conclusions concerning preferred orientation and plan curvature than those made by studies in environments where desiccation is important.

More hillslopes with collapsed pipes are facing west compared to the frequency of these slopes in the study area (Fig. 5b). This observation is similar to findings about the presence of landslides in the area (Van Den Eeckhaut et al., 2007b). Firstly, the west-facing slopes are steeper, because of the abovementioned valley-asymmetry. Secondly, these slopes are probably also wetter, as rains in Belgium predominantly come from the west (Brisson et al., submitted for publication) and generally more rain falls on the windward side (Blocken et al., 2006). Finally, the loess cover on the west-facing slopes is thinner (Goossens, 1997), which may result in a faster subsurface flow response induced by the clayey lithology. On the other hand, the E–NE-facing slopes have a high probability for piping as well. In our study area, a lower evapotranspiration rate might explain wet conditions on these slopes which could favour piping. Neither the distribution of the clay-rich Aalbeke Member, nor the distribution of the pastures in the study could explain the dominance of certain aspects for sites with piping. In similar conditions, Henn and Botschek (2002) reported the aspect of the slope to be of no importance.

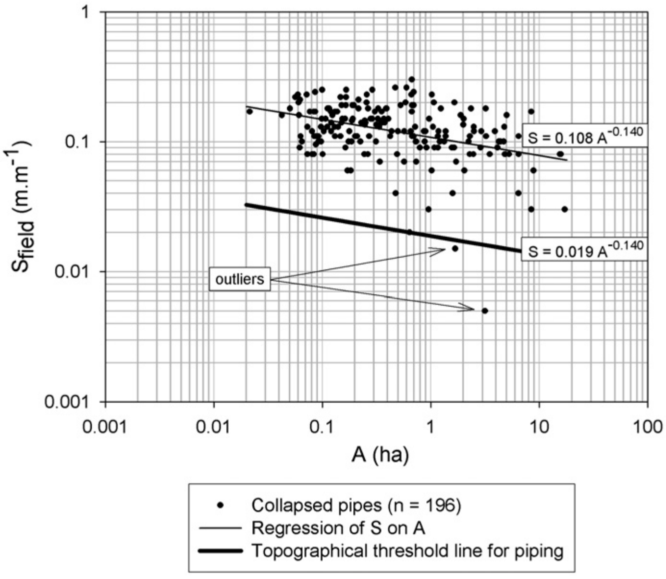

**Fig. 7.** Relation between drainage area ($A$) versus soil surface slope gradient ($S_{\mathrm{field}}$) of collapsed pipes measured in the field, with indication of the topographical threshold for pipe collapse.

Although piping occurs in a wide range of soils, and soil characteristics other than texture (e.g. structure and infiltration capacity) seem to be of greater importance; soils with a moderate to high silt–clay content are favoured (Jones, 1981). Faulkner (2006) recognized Luvisols, including the loess-derived soils of the study area, as one of the three major soil groups in Europe prone to piping. It is often reported that in-profile variations play an important role in pipe development (e.g. Jones, 1981; Faulkner, 2006). The so-called 'duplex' character has mostly been associated with clay relocation down-profile and subsequent differential swelling and shrinkage and/or permeability differences (e.g. Imeson and Kwaad, 1980; Imeson, 1986; Lopez-Bermudez and Romero-Diaz, 1989). This 'duplex' condition infiltrating water to horizontal pathways can be interpreted in a wider context, where argillic horizons in loess-derived soil may have a similar effect. In the present study, however, the presence of an argillic horizon (Bt horizon) does not explain the distribution of collapsed pipes as even more collapsed pipes are located on soils without profile development. Hence, it can be concluded that loamy colluvium or parent material is suitable material for piping to develop, although it is also logical that the distribution of the soils with colluvium in the landscape (in concavities) is responsible for these results. As sites with piping are favoured by high drainage areas and preferentially are located downslope, these areas are also in a suitable topographical situation to receive sediments from upslope. Consequently, the soil profile development is not likely to create a duplex condition in our study area. Instead, the particular sequence of loess on less permeable clay (Aalbeke Member, KoAa) can act as a duplex condition and give rise to a vertical discontinuity. Strikingly more collapsed pipes are located in areas with the Aalbeke Member below the loess cover. This lithological layer contains around 50% smectite clay (Van Den Eeckhaut, 2006), impeding drainage. Apart from this, the clay layer at shallow depth plays an important role in the water supply necessary for the enlargement of macropores to pipes. The alternation of permeable clayey sands and less permeable clays gives rise to perched water tables. Due to the dissected topography, these water tables often intersect the surface, and exfiltrating water is discharged as springs (Closson et al., 1999).

### 5.2. Piping initiation slope and contributing drainage area (S–A relation)

Topographical thresholds are widely used for geomorphological processes, especially for predicting gully initiation (e.g. Desmet et al., 1999; Vandekerckhove et al., 2000; Nachtergaele et al., 2001; Poesen et al., 2003; Vanwalleghem et al., 2005). Some authors pointed to the role that subsurface flow can play in channel initiation and to the influence on the expected $S$–$A$ relation (Abrahams, 1980; Moore et al., 1988; Montgomery and Dietrich, 1994). Abrahams (1980) reported that the inverse relation of $S$ with $A$ no longer applies for channels initiated by subsurface flow. In their theoretical division of the landscape into process regimes in terms of $S$ and $A$, Montgomery and Dietrich (1994) expected a positive $S$–$A$ threshold line for seepage erosion. This is in contrast to the findings of the present study.

The topographical threshold obtained for piping was compared with those of gullies (Vanwalleghem et al., 2005) and landslides (Van

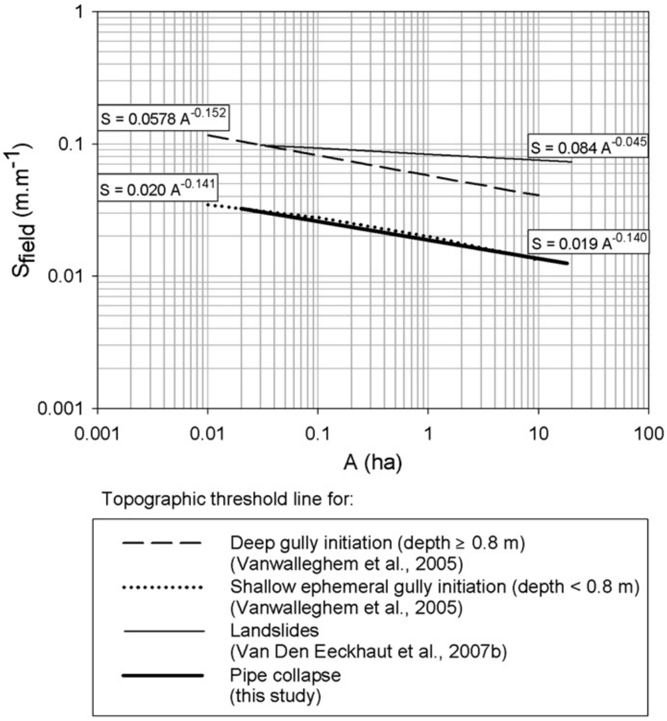

**Fig. 8.** Critical threshold line based on drainage area ($A$) versus slope gradient ($S_{\text{field}}$) for incipient pipe collapse compared to thresholds for landslides in the study area and for shallow and deep gully initiation in loess-derived soils in central Belgium.

Den Eeckhaut et al., 2007b; Fig. 8). The data from Vanwalleghem et al. (2005) were collected for cropland on loamy soils in central Belgium (loess-derived soils) where both $S$ and $A$ were based on field measurements. The landslides were surveyed in the Flemish Ardennes in a 710 km$^2$ study area including the 153 km$^2$ study area of the present study. The average slope gradient for every landslide was calculated by dividing the difference in heights (LiDAR-derived) of the lowest and highest point located within the landslide area by the landslide length (Van Den Eeckhaut, 2006). The drainage areas were calculated with WaTEM/SEDEM similar to those of the collapsed pipes in this study. To allow comparison with the data of gully initiation, also the threshold based on $S_{\text{field}}$ was used for piping. Vanwalleghem et al. (2005) fitted an orthogonal regression ('reduced major axis solution'; Jackson, 1991) to the data for gullies, but for piping and landslides, ordinary least squares regression was more appropriate because the data were asymmetric (Smith, 2009). The slope of the threshold line for landslides is lower compared to that for the other processes (Fig. 8), indicating no important influence of the drainage area. The topographical threshold conditions for piping are similar to the conditions needed for shallow gully initiation. Jones (1981) also reported that piping can occur on gentle slopes when the contributing area is sufficiently large. However, he did not observe a close relation between $A/S$-index and the pipe network initiation points nor the pipe discharges (Jones, 1986, 1997).

Some critical remarks on the $S$–$A$ relation have to be made. The drainage areas used are those derived from the surface topography, assuming that the surface and subsurface drainage areas coincide. It is known, however, that the surface area does not always equal the subsurface area draining to the pipe (Jones, 1986, 1997). For our study area, the use of the surface topography is allowed due to the fact that the lithological stratification is subhorizontal. In other studies, the surface drainage area was replaced by other parameters reflecting subsurface catchment size. Jones (1997) and Holden and Burt (2002) used the maximum dynamic contributing area (DCA) as the best available estimate of the contributing drainage area, with the DCA calculated as the ratio between the total storm discharge in pipe to the total storm rainfall. In this study, however, monitoring pipeflow was nearly impossible in most cases. Most pipes end in feeding the groundwater table which leads to diffuse outlets instead of giving end in a clear bank. Desmet et al. (1999) suggest that unit contributing area, i.e. the upslope contributing area per unit width of contour line (m$^2$ m$^{-1}$), should be used instead of $A$. However, this parameter was not applied in the present study, in order to permit the comparison with the $S$–$A$ relation from Vanwalleghem et al. (2005).

Pipes are water transmitters rather than collectors, making it possible to cross areas where they receive little or no extra discharge (Weyman, 1974; Gilman and Newson, 1980; Jones et al., 1997). This implies that, when the pipes are essentially carrying water collected from the upper slopes, the calculated $A$ of the collapsed pipes on the mid-slopes can be an overestimate of the real situation. On the other hand, there are factors that are not taken into account in the variable $A$ but can increase the water supply to the pipe, such as springs and anthropogenic drainage of roads, buildings and agricultural land. In our database, 30% of the parcels with collapsed pipes are known to be drained artificially, and 5% of the parcels with collapsed pipes are affected by concentrated flow generated by road drainage. Because channel initiation associated with road drainage can occur at smaller contributing areas (Montgomery, 1994; Takken et al., 2008), the same can be expected for piping. For channel initiation at road drain outlets, the road contributing area and slope gradient are the most significant explaining parameters, although no clear $S$–$A$ threshold could be established (Takken et al., 2008).

## 6. Conclusions

The loess-derived soils of the Flemish Ardennes in Belgium are susceptible to piping erosion. This study has resulted in a regional inventory of collapsed pipes, unique for the European loess belt. Although analysis of orthophotos can help to detect collapsed pipes, detailed field surveys remained necessary. Different topographical and environmental factors controlling the development of pipe networks and adjacent pipe collapse are reported for regions with other characteristics. This study has confirmed that in loess-derived soils from temperate regions, a wide range of slopes (i.e. 8–24%) can be affected by piping erosion, and that the surface curvature is more important — concentration of water (plan concavities) favours pipe development. The necessary water supply is also enhanced by the characteristic lithology, consisting of an alternation of sands and less permeable smectite-rich clays and giving rise to numerous springs. The presence of a clay-rich lithological layer seems to be an important factor explaining the spatial distribution of the collapsed pipes in the study area. This may account for the often reported requirement of a vertical discontinuity in infiltration rate in the soil profile. Almost all collapsed pipes were observed under pasture with 25% of the pastures in the study area located on the clay-rich Aalbeke Member. Furthermore, the presence of high biological activity under this land use may also enhance the vertical (earthworms) and lateral (moles) movement of water although more research is needed to confirm it. Soil texture, soil drainage class and soil profile development seem to be of less importance for identifying sites with piping within the study area. Nevertheless, the fact that silt material is susceptible for piping erosion is once more confirmed.

Topographical threshold conditions for the collapse of soil pipes have been established. More than the exact slope gradient, the relationship of the slope gradient with the contributing drainage area is important for explaining the occurrence of collapsed pipes. It can be argued that the surface topography-derived drainage area is not an accurate substitute to the subsurface drainage area of the pipes, due to unknown subsurface topography variations and the influence of anthropogenic drainage changes. Despite this constraint, the $S$–$A$ relation is a suitable first attempt, with the parameters that are rather easy to obtain, to identify topographic controls on piping, and to compare them to other erosion processes such as landslides and gully initiation. In this study, a negative power relation was found, similar to the topographical threshold for shallow gully initiation.

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