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Searching for regularities of slope modelling by extreme events (diversity of rainfall intensity-duration and physical properties of the substrate)

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Abstract: In the last decades, research into slope transformation, especially transformation caused by debris flows and shallow landslides has set great store by the establishment of thresholds based on the relation of mean rainfall intensity to its duration. The present author is no exception. In the 1970s, after examining that relationship he distinguished three main types of extreme rainfalls (heavy downpours, continuous rains and rainy seasons). In this paper, while noting the great diversity of extreme events in space and time, he stresses the function of extremely high rainfall intensity in triggering off the slope transformation. Taking into account the role of such parameters as the effect of substrate, relief and land use on the distribution of precipitation into overland flow, subsurface runoff, and ground water storage, he proposes several models that connect geomorphic processes with different types of extreme rainfalls. In critical comments to the establishment of thresholds based only on mean daily rainfall and mean rainfall intensity he follow the opinion on limitation of factors to standart climatic and hydrologic and hydrologic data presented earlier by T. Dunne and A. Freeze. This analysis also notes the role of clusterings of events in various climatic zones and stresses the need of continuous monitoring of rainfall intensity and any other aspects of water circulation on slopes. All of those elements are indispensable for the construction of a more diversified pattern of thresholds.

Keywords: thresholds, slope processes, extreme rainfalls, physical properties, substrate, monitoring water circulation

Introduction

In present-day slope transformation two processes appear to be most common and need to be taken into account, slope wash and shallow landslides accompanied by debris flows. Both processes are characterised by great diversity, which has been the object of numerous studies. Their authors usually correlate those phenomena with heavy rains on local or regional scale and try to grade those phenomena by establishing thresholds which usually depend on rainfall duration and intensity and, less frequently, also by taking into consideration the physical properties of the substrate (Douglas 1976, Glade et al. 2005).

The literature dealing with thresholds of debris and earth-flow formation may be exemplified by studies conducted in New Zeeland (Selby 1974, Glade 1998, Crozier 1996 1999), monsoonal South East Asia (Froehlich & Starkel 1987), Italy (Govi & Sorzana 1980, Guzetti 2000), and the United States (Hack & Goodlett 1960, Ellen & Wieczorek 1988). In my paper on extreme rains in Darjeeling Himalaya (Starkel 1972) and a review paper from 1976 I distinguished various effects of heavy downpours and continuous rains. In each case I paid special attention to the superposition of both types of rainfalls in so far as they produced a total transformation of slopes and valley floors.

Caine (1980) published a fundamental paper on the thresholds of rainfall parameters (the relation of mean rainfall intensity to rain duration). On the basis of 73 events registered in various parts of the globe he drew a linear relation curve describing that threshold (Fig. 1). His pioneering study found many followers who worked on developing sets of rainfall parameters that would account for slope failures in various climatic zones (Crosta 1998, Aleotti 2004, Jackobs & Hunger 2005). A complete list of those studies (and the resulting parameters) was presented

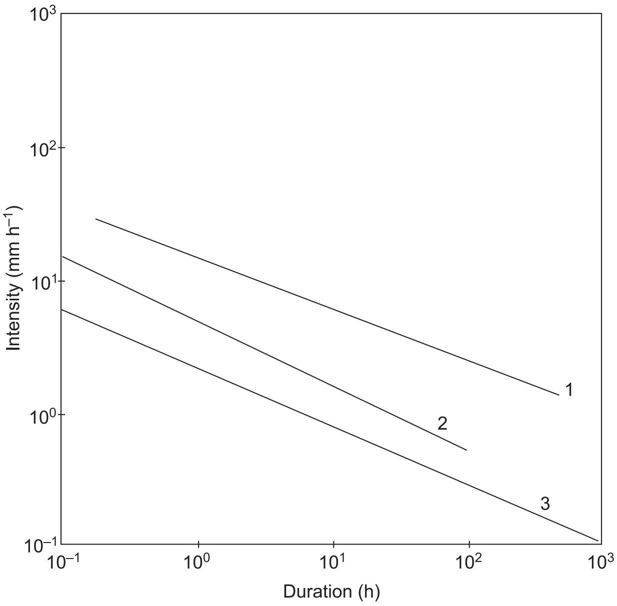

Fig. 1. Global rainfall intensity-duration (ID) thresholds based on a different number of rainfall events published by various authors: 1 – Caine (1980), 2 – Innes (1983) and 3 – Guzetti et al. (2008)

in a paper by Guzetti et al. (2008). It notes, among others, the duration and intensity of the critical rainfall event (eg. daily; length in hours; type, i.e. average or maximum), antecedent rainfall etc. (Fig. 1).

Those authors amassed an extensive literature from all parts of the world covering a total of 2,626 rainfall events which produced shallow landslides or debris flows. The data bank includes information on the location, type and number of landslides, rainfall conditions and, partly, the lithology of the substrate While 83.2% of cases in that collection represent single landslides, only 16.8% represent multiple ones. Moreover, 47.2% of cases have been classified in accordance with various landslide types. The remaining 52.8%, though unidentified, are nevertheless included in the register.

The information on rainfall intensity and duration is usually limited to daily rainfall totals and mean intensity. Records on antecedent rainfalls are on the whole extremely scarce. As we shall see later such records are inadequate both for the task of explaining the mechanism of landsliding as well as and for the marking of slope failure thresholds.

All of the records in that collection were classified with regard to various climatic regions, to which a separate slot for the mountain environment (which can be found in any climatic zone) was added. After pooling all of the 2,626 events the authors proceeded to draw regional and global threshold curves, i.e. a set of linear equations that would present a global picture of the mechanisms of downslope movement. The intriguing thing about that graph is that its lines run well below the contour of rain intensity and duration compiled by Caine (1980). It seems that the discrepancy is due to the fact that Guzetti's chart, while attempting to present a generalised global picture, oversimplifies the existing relations to such an extent that it is difficult to make out the real causes of the great dispersion of events or to identify their types.

Apart from those large-scale studies, the last decades saw also the publication of numerous contributions focusing on individual regions, e.g. the Polish Flysch Carpathians (Starkel 2006, 2011, Ziętara 2002, Gorczyca 2004). The latter are chiefly concerned with demonstrating a connection between the type and number of landslides, on the one hand, and the daily rainfall or, occasionally, the total rainy season precipitation, on the other hand.

Water circulation over slope

The relations between rainfall parameters, substrate and slope relief on the one hand and the thresholds of effective slope processes, on the other hand, are highly complex. To account for the latter one needs to take a close look at the overall water circulation on the slope, i.e. acknowledging the role of overland flow, infiltration, subsurface throughflow, base flow and groundwater storage in the transfer of colluvia over slopes. This procedure of studies on runoff generated mechanisms, depending on soil permeability, slope profile and vegetation cover leading to division of runoff into overland flow and subsurface flow has been presented earlier by Freeze (1972), Dunne (1978) and Dunne et al. (1975). In practice it means monitoring all the factors which contribute to the water circulation on the slope, measuring the geomorphic effects, and registering the time when a threshold of slope wash, debris flow or landsliding is passed.

A proper procedure should begin with the separation of atmospheric precipitation falling on the ground surface into overland flow, which is the main factor in slope wash and linear erosion, and infiltration in the substrate. The levels of infiltration depend on permeability and the water capacity of the soil; the infiltrated water then feeds into the water storage, subsurface flow and base flow (Słupik 1981, Fig. 2). In the process of water circulation we may distinguish several thresholds. They are the onset of overland flow followed by slope wash, the onset of subsurface runoff and piping, the onset of various types of mass movements connected with overloading, liquefaction, the formation of a sliding surface, etc. This pattern can be complicated by changeable hydrologic parameters of particular soil horizons and bedrock, factors that may be activated by continuous rain, as e.g. in Darjeeling Himalaya (Froehlich & Starkel 1987).

Also the character of slope relief should be considered – its length, profile, dismembering of slope surface by gullies and shallow depressions (Fig. 3).

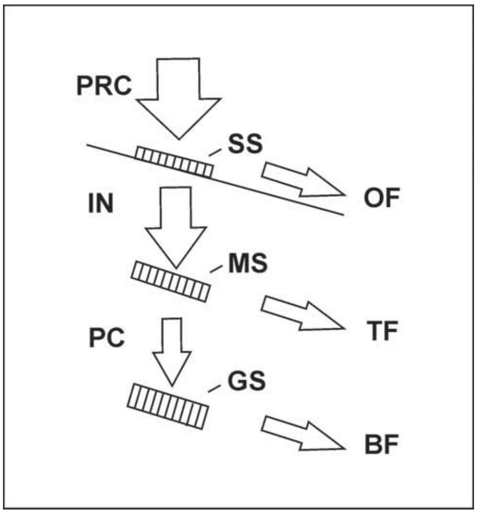

Fig. 2. Scheme of water circulation in the substrate on slope (modified after Slupik 1981)
PRC – precipitation, OF – overland flow, TF – throughflow, BF – base flow, SS – surface storage, MS – soil moisture, GS – ground water, IN – infiltration, PC – percolation

While most of our attention usually concentrates on rainfall totals and the intensity of precipitation falling on the ground surface, we should not ignore the increase of water flowing downslope (both overland and subsurface) or the amount of water gathering in the slope depressions (Fig. 3). During continuous rains the quantity of water passing through shallow depressions in the lower part of the slope may be even twice as large as the amount of rain falling on the ground in its upper part.

The reactivation of debris in chutes that tap water from large niches was described in studies dealing with the Swiss Alps (Rückenmann & Zimmermann 1993) and the Polish Tatra Mts (Kotarba 1999). Also the increased throughflow of subsurface water combined with piping may trigger off the formation of debris flows (Starkel 1972).

These observations allow us to reassess the situation in which unexpectedly intense gully erosion or debris flow formation occurs in conjunction with fairly unremarkable indicators of mean rainfall intensity. It is only with the help of this more nuanced explanation that we can resolve the puzzle of relatively low threshold curves of rainfall initiating the formation of shallow landslides or debris flows (Guzetti et al. 2008).

Three main types of extreme rainfalls

The three principal types of extreme rainfall differ mainly in their mean and highest intensities as well as in rainfall totals and their duration, which, in turn, conditions various types and rates of geomorphic processes (cf. Starkel 1976, 2006). Yet, what is also of crucial importance in any of the three types is the antecedent rainfall (water storage before heavy rains) and the fluctuation of rain intensity during a single event (Fig. 4).

The first type is represented by local heavy downpours reaching 50–200 mm and more in 1–4 hours with intensities exceeding 1–5 mm min. A rain of this kind can set off an overland flow followed by a slope wash on a deforested slope in a matter of minutes (Gil & Słupik 1972a). On steeper slopes it can cause shallow slides and earth flows, while in small valleys the rapid rise of water can result in concentrated debris flows (Gil 1998, Cebulak et al. 2008). The dynamics of the downslope processes may also depend on the permeability of the soil and the density of the vegetation cover (Starkel 1976).

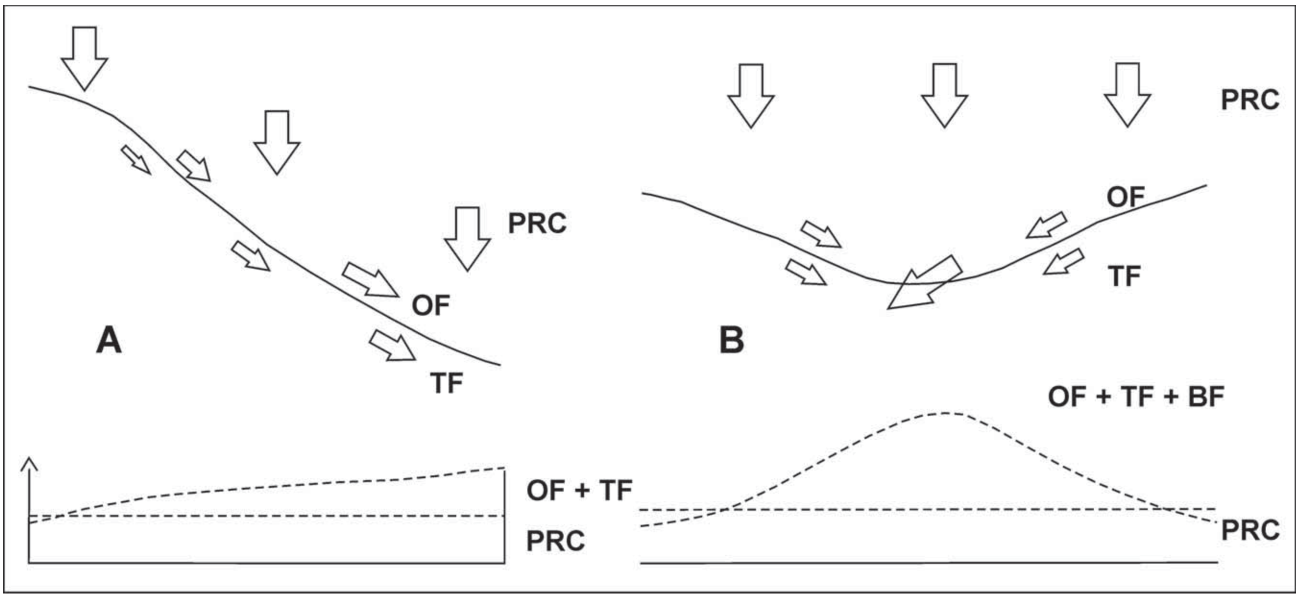

Fig. 3. Changes in water outflow and storage in the: A – longitudinal slope profile and B – transversal section of slope depression showing surplus of water triggering mass movements
Explanation of symbols see Fig. 2

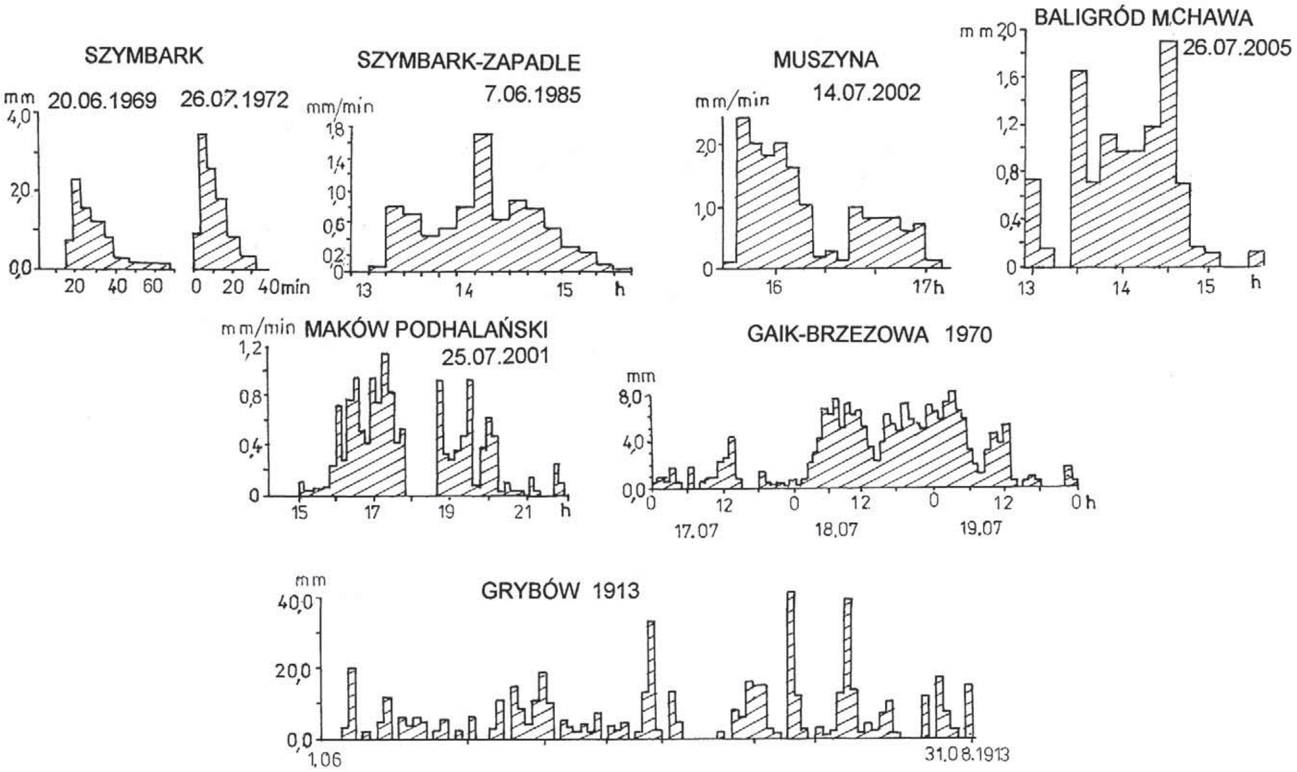

Fig. 4. Examples of extreme rainfalls of various intensity and duration in the Polish Flysch Carpathians (6 heavy downpours, one continuous rain and one rainy season – their effects are described in the text)

The sequence of changes in rainfall intensity is a major factor in producing a wide range of downslope effects. The most conspicuous of them are usually caused by rains mounting to high-intensity surges.

Continuous rains are characterised by their long duration, i.e. one to five days, and broad territorial scope (the area affected may amount to several thousand km^2). The precipitation totals may exceed 500–1000 mm, but the mean intensity is usually below 10 mm hour^{-1}. Such rains are frequent at the edge of mountain ranges which block the replacement of cyclonic systems (Govi & Sorzana 1980, Starkel 2006). There water is infiltrating deeper, and the processes of piping and various types of shallow and deeper landslides prevail. In the monsoon climate the rainfall may reach 1000–2000 mm (Soja & Starkel 2007). However, especially dangerous are downpours at the very end of the rainy season, when the threshold of liquefaction of saturated regolith is passed and debris flows pour out (Starkel 1972). A similar effect was observed after long-lasting antecedent rainfall in the Italian Piedmont (Passuto and Silvano 1998).

The third type of extreme rainfall is represented by rainy seasons of long duration (from several weeks to months). Low intensity rain with totals up to several hundred mm facilitates deep infiltration, subsurface runoff and deep-seated landslides. The landslides are usually triggered off by occasional spells of intense rain which is passing the storage capacity (Gil & Starkel 1979, Gil 1997).

More complex phenomena may be observed during snowmelts over frozen ground (characteristic of the continental type of the temperate climatic zone) when slope wash and earth flows are triggered off by additional rains (Gil & Słupik 1972b, Starkel 1976, Grin 1970).

The total geomorphic effect of present-day extreme rainfalls depends on their frequency, which varies in different climatic regions. However, no factor is as important as clusters of heavy rain, which make the return to previous parameters impossible (cf. Starkel & Sarkar 2002).

In July 1997, a few days of heavy downpours in the Polish Carpathians caused flash floods which, in turn, brought about a gradual reactivation of sliding masses and the formation of debris flows (Froehlich 1998, Gorczyca 2004). A unic character in the Carpathians had summer 2010, when between May and early September four or even fife heavy rains (downpours or continuous rains) were recorded. Each of them was reflected in flash flood and the whole cluster in formation or reactivation of hundreds of landslides (Starkel 2011).

In small catchments of the Meghalaya Upland (near Cherrapunji), the thresholds may be passed several times during one monsoon season (Soja & Starkel 2007). At the edge of the Bhutanese Himalaya, where such events recurred every 2–3 years (in the last two decades), the changes are irreversible and the new features soon become entrenched (Starkel & Sarkar 2002). Similar clusters of three wet summers were observed in the Flysch Carpathians (e.g. in 1958–1960, Ziętara 1968). In the Darjeeling Himalaya, where such catastrophic events were recorded only three times over the last 110 years, the long periods of relatively normal conditions made recovery and revegetation possible (Starkel & Basu 2000).

Other factors involved in slope evolution and some modifications of the models

Rainfall is the decisive, but by no means the only factor responsible for events resulting in the passing of thresholds of slope wash and various gravitational processes. A comprehensive account of the mechanism of downslope movement would have to include at least three more elements, namely, the physical properties of the substrate, the existing relief and land use (vegetation). All these factors have been discussed in detail by Freeze (1972) and Dunne (1978). Their presence determines how much of the rain (or melt) water will run off in overland flow and how much will infiltrate into the ground. Moreover, they influence the process of denudation and the rate of slope transformation. A list of the physical properties of the substrate that have a role in the passing of thresholds includes infiltration rate, water capacity and storage, rate of subsurface runoff, limits of plasticity and liquefaction for various soil and bedrock horizons (cf. Douglas 1976 and others). The values of those parameters in a slope profile vary with the type and density of vegetation cover. These variations are so great that it is hardly possible to construct a single model for the three main types of rainfalls passing various thresholds (de Ploy 1972, Starkel 1976). Nor is it possible to adopt a single threshold line (Guzetti et al. 2008). Taking into account all those constraints I have developed several simplified schemes (two of them presented on Fig. 5) which characterise various types of substrate and relief and may be exemplified by some well-known geographical locations.

The upper parts of the models present the distribution of water falling on the ground during three different types of extreme rainfalls. The lower ones present the main types of geomorphic processes connected with various types of rainfall, intensity and duration of rain (as well as with rainfall totals).

Type A (Fig. 5A) is characteristic of mountains and foothills built of flysch or other rocks with permeable regolith. The slope wash and linear erosion

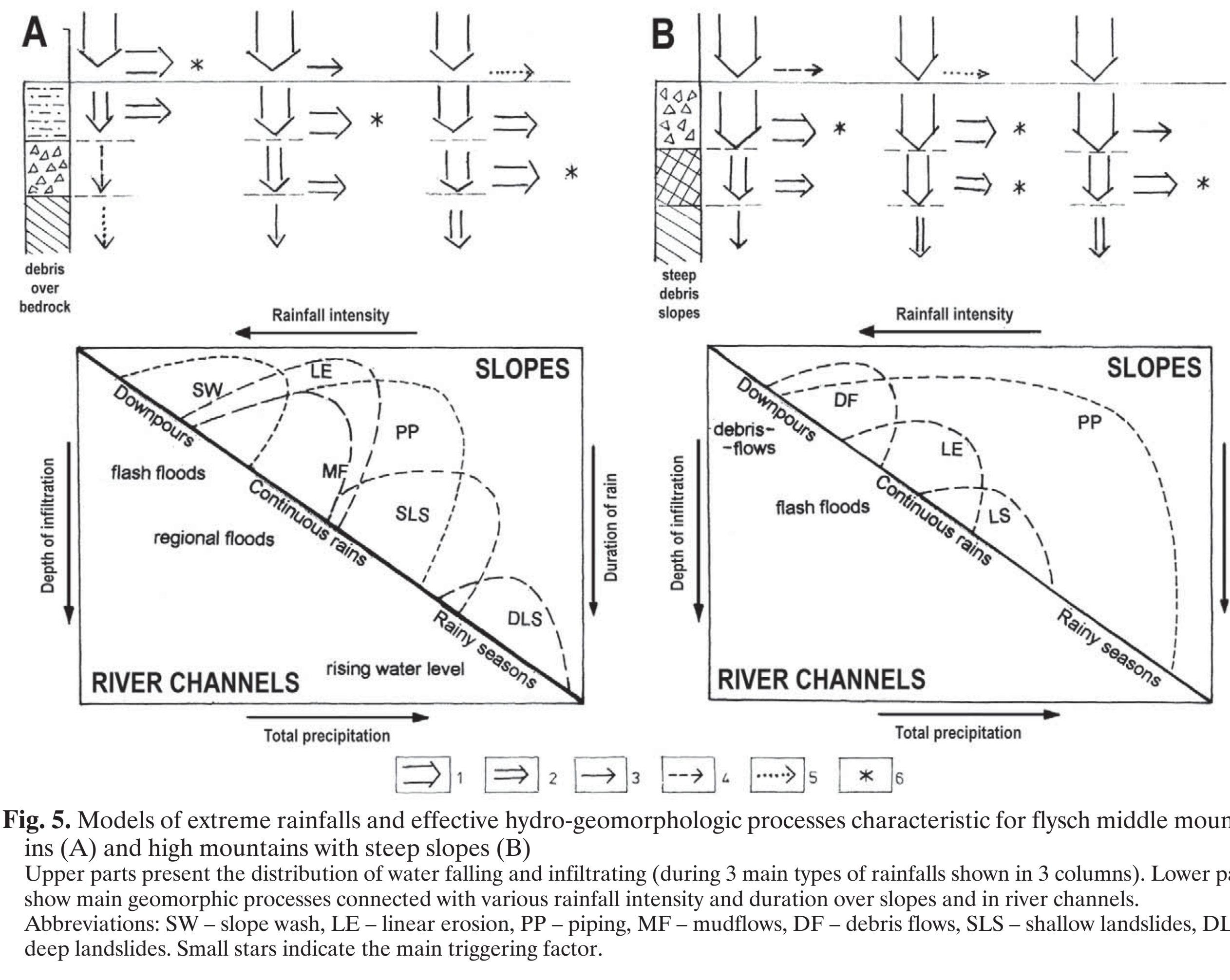

Fig. 5. Models of extreme rainfalls and effective hydro-geomorphologic processes characteristic for flysch middle mountains (A) and high mountains with steep slopes (B)

Upper parts present the distribution of water falling and infiltrating (during 3 main types of rainfalls shown in 3 columns). Lower parts show main geomorphic processes connected with various rainfall intensity and duration over slopes and in river channels.

Abbreviations: SW – slope wash, LE – linear erosion, PP – piping, MF – mudflows, DF – debris flows, SLS – shallow landslides, DLS – deep landslides. Small stars indicate the main triggering factor.

are characteristic of heavy downpours. During continuous rains piping, mudflows and shallow landslides over deforested slopes are frequent. Deep-seated landslides are typical of rainy seasons (Gil & Starkel 1979, Starkel 1976, 2006 and others). All three types are exemplified by events monitored at the Szymbark field station in the Polish Flysch Carpathians. During downpours of 40 mm with highest intensity of 2 mm min^{-1}, the overland flow may reach 20% of rainfall totals combined with the washing of several mm of soil on cultivated fields (Gil & Słupik 1972a, Słupik 1981). During continuous rain, above 150 mm in four days and highest intensity below 0.5 mm min^{-1}, the overland flow takes no more than 10% of rainfall totals (Słupik 1981). The rainy season may be exemplified by the autumn of 1974, when at the close of the vegetation season, 285 mm of rain was reached in 44 days, infiltration down to118 mm, overland flow 85 mm, subsurface runoff 32 mm, the soil profile was saturated and several landslides were formed (Gil & Starkel 1979, Gil 1997).

Similar conditions are observed on the loess plateaux of Southern Poland, where heavy downpours produce characteristic overland flow and slope wash (Rodzik et al. 1998). During continuous rains with deeper water percolation, the role of linear erosion and piping is still high. Also, after full saturation of the soil, mudflows and shallow landslides are in more frequent.

Type B (Fig. 5B) is characteristic of high mountains, earlier glaciated, rising above the timberline with steep rocky slopes, unconsolidated debris and talus at their base. In that terrain most of the rain water infiltrates and subsurface runoff with piping is most typical. Only during high intensity storms the oversaturated debris produces debris flows concentrated in chutes and extending over talus cones at their base (Kotarba 1992, Ballantyne 2002). The examples of such downpours and debris flows are recorded at Hala Gąsienicowa field station in the Tatra Mountains, located close to glacial cirques in the alpine belt (Kotarba 1992). Continuous rains with rainfall totals passing 500 mm provoke formation of chutes, shallow slides and flash floods (Kotarba 1999).

Discussion and conclusions

In the course of individual weather events the mechanism of changes and the scale of transformation are widely diversified both in space and time, which is well illustrated by the diagrams compiled by Guzetti et al. (2008). In some cases an important role is played by antecedent rain as its occurrence affects water storage in the soil (regolith) profile. During downpour or continuous rain the sequence of changes in rainfall intensity may be critical for the resulting denudation. This point may be illustrated by the striking contrast between the effect of a downpour that starts with the intensity of 2–5 mm min^{-1} (Słupik 1981) and the effect of a high intensity rain on a soil saturated by a preceding temperate rain. When an event of that kind occurred in October 1968 in Darjeeling Himalaya, it was followed by hundreds of debris flows (Starkel 1972). Also fairly insignificant showers may trigger off landslides during a long rainy season when weathered flysch rocks have been saturated by groundwater (Gil & Starkel 1979, Gil 1997, Rączkowski & Mrozek 2002) and the surplus water flows out as subsurface runoff.

One of the distinctive features of the new trends in slope transformation studies is the acknowledgement of the role of clusters of extreme events (Soja & Starkel 2007, Starkel et al. 2008) and the feedback mechanisms between the slope and the fluvial processes (Starkel 1976, 2006, Harvey 2002).

Meanwhile, the construction of universal models and the search for broad regularities and thresholds valid on a global or zonal scale appears to oversimplify the role of quite disparate factors (or parameters) and to pass over the great diversity of the events in question.

To arrive at a better understanding of the irreducible diversity of the extreme weather and landforming processes we need to collect more detailed records. Daily rainfall data or even hourly checks of rainfall intensity are not sufficient, if we know that the effective threshold under some types of substrate or relief depends on rain intensity minute by minute. We should work, in fact, on the assumption that every landslide may well have some individual features.

Similarly, the records of one meteorological station may not be sufficient to explain the debris flows and landslides that occur over vast tracts of land. Already several detailed studies show that rainfall gradients in places one kilometer apart may differ by a few centimeters (Gil 1998, Starkel & Singh 2004, Cebulak et al. 2008); consequently, the conclusions about the threshold values may be totally wrong!

Therefore, the setting up of modern monitoring stations – as in Japan, USA, New Zealand, Poland and in other countries – is of paramount importance. It is necessary to extend the network of stations that are measuring and correlating not only rainfall and its ultimate geomorphic effects, but also to monitor the process of water circulation over slopes in all its forms and aspects following the methods presented by Dunne (1978) as well as by Słupik (1981), and in this way to provide a solid basis for a thorough understanding of such slope processes as overland flow, subsurface runoff, and variations in groundwater storage.

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