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Water erosion and supply of material for fluvial transport under episodic surface flow conditions in the semi-arid zone on Boa Vista (Cabo Verde)

Piotr Gierszewski

Polish Academy of Sciences
Institute of Geography and Spatial Organization
Department of Geomorphology
and Hydrology of Lowlands
ul. Kopernika 19, 87-100 Toruń

Jan Rodzik

Maria Curie-Skłodowska University
Institute of Earth Sciences
Roztoczańska Research Station
ul. Akademicka 19, 20-033 Lublin

Abstract: This paper presents the effects of the natural conditions of the semi-arid zone on the temporal and spatial variability of production and supply of material for fluvial transport under conditions of episodic surface flow. Based on measurements of water runoff, concentration of suspension and dissolved material in the course of a one-hour rainfall, it has been determined that the catchments under study have a considerable resistance to the effects of water erosion. Some protection is supplied by the ablation pavement, which reduces rainsplash and slopewash and prevents flow concentration. Considerably more erosion has been noted on unpaved roads concentrating water flow even on plateaux and gently inclined slopes. Obviously the potential for leaching rock material in short-duration flow is limited. Large proportions of the dissolved material carried away from the catchments are salts of marine and aeolian provenance. The high intensity of erosional processes in the early phase of runoff is evidence of the role of physical weathering between rainfalls, which supplies the material for fluvial transport.

Key words: surface flow, water erosion, suspended sediment, dissolved material, semi-arid, Cabo Verde

Introduction

The Cabo Verde Archipelago is a group of 18 volcanic islands, 4033 km^2 in area. They are situated in the Atlantic Ocean, 460 km west of the African coast, at the latitude of the southern extremity of the Sahara (Fig. 1). The eastern, older group of islands, including Boa Vista, probably emerged from the ocean in the Miocene (Mitchell-Thome, 1972). The western islands of the archipelago are younger, a notion supported by the contemporary vulcanicity on the islands of Fogo. The differences in the volcanic relief provide further evidence of the different ages of the islands, and consequently of different lengths of time of action of exogenous factors weathering volcanic rocks. The eastern islands (Sal, Boa Vista, Maio) are nowhere higher than 436 m a.s.l. and have gentle relief whereas the others are higher (from 774 to 2829 m a.s.l.) and much more diversified morphologically.

Boa Vista, like the remaining islands of the archipelago, consists of volcanic rocks, mainly basalts, phonolites and tuffs. Sedimentary rocks, up to several meters thick, represented by limestone, sandstones and conglomerates, occur only on marginal benches, which represent former sea levels (Mitchell-Thome, 1972). The island's relief is dominated by vast flat pediments, glacis and marine terraces with gentle slopes. They are dissected by valleys of temporary rivers. Volcanic necks dominate the island's scenery.

The climate of the Cabo Verde islands is determined by their situation in the Atlantic tropic zone, which is dominated by northeastern trade winds. By contrast, the close vicinity of the African continent causes an influx of dry and warm land air-masses. The average annual rainfall on the eastern flat islands of the archipelago does not usually exceed 150 mm (Klug, 1973). More than 90% of the annual rainfall is concentrated in the period from July to October.

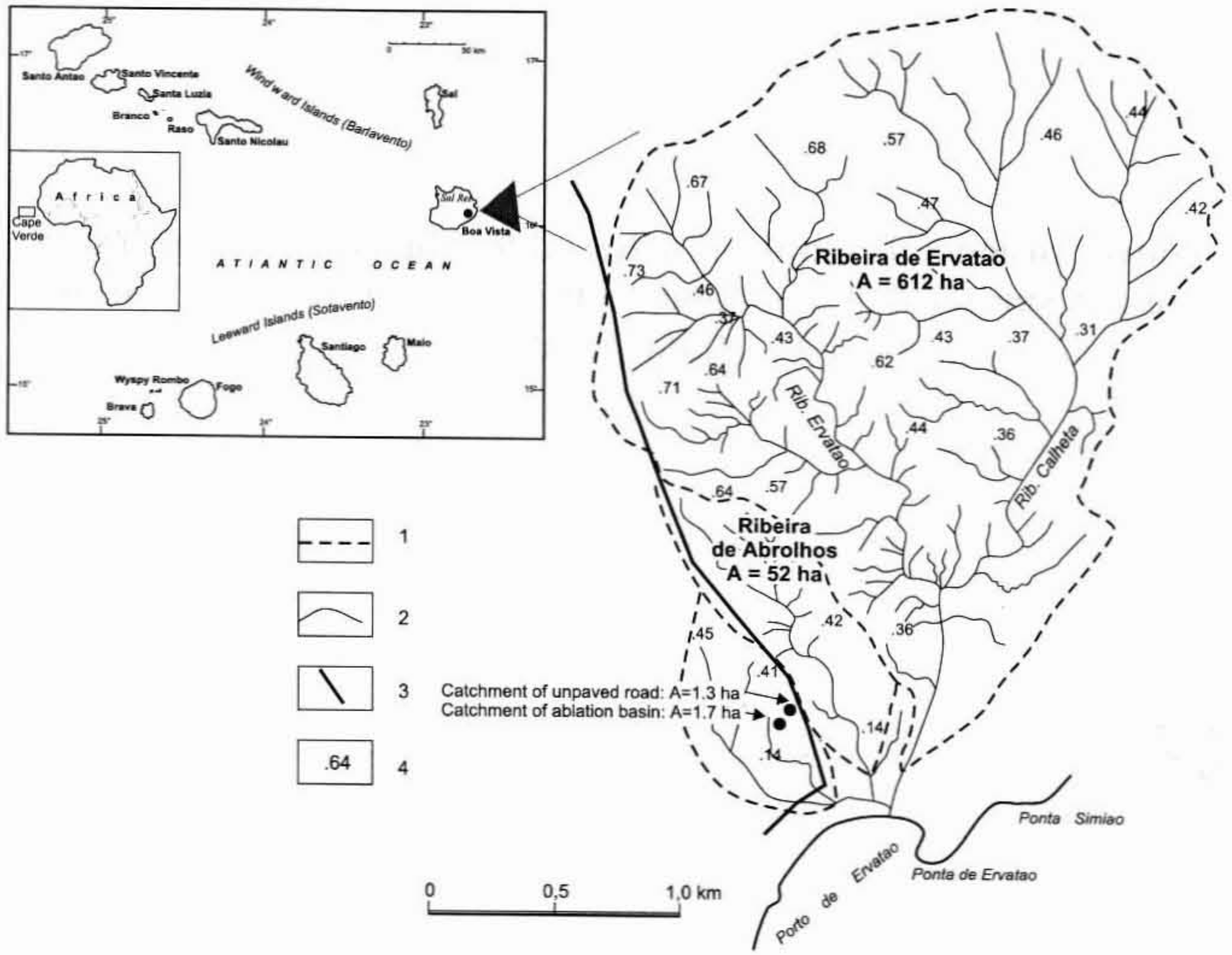

Fig. 1. Localization of study area
1 – boundaries of catchments, 2 – channel of episodic watercourses, 3 – road, 4 – altitudes m a.s.l.

The weakening of the trade winds towards the end of summer accounts for an influx of warm and humid equatorial air masses, the result of which are the prevalent torrential short-duration rains. Data from the area of Praia (Santiago Island) inform about the frequency of rainfall's incidence. In the years 1980–1987 notified 63 rainfall events there. However only 29 times occurred falls above 10 mm which, in these conditions, cause erosion (Mannaerts, Gabriels, 2000). However, since 1968 the rainfall conditions have deteriorated considerably. The rainy season, which before that date characteristically lasted five months, contracted to only two months, and the total annual rainfall decreased by nearly 50%. Subsequently catastrophic droughts, lasting 2–3 years in succession, are not unusual (Ferreira, 1987). The progressive desertification of the islands, together with the torrential rains, cause intensive erosion. This is currently the most important factor in the modeling of the islands' relief (Ferreira, 1996).

Water erosion is considered to be the most important relief transforming factor in the geomorphological landscapes of the semi-arid and arid zones (e.g., Langbein & Schumm, 1958; Saunder & Young, 1983; Woodward, 1995; Detkov, 1998). That the high potential of erosion, due to intensive physical weathering processes and poor vegetation, is due not only to small amount of infrequent rainfall, but also to the characteristics of the surface over which the runoff takes place is not generally appreciated (Nicholson, 1998). However, the low frequency of rainfall is largely compensated by its torrential character. Even a single shower can cause considerable erosion.

Both the considerable surface sealing of desert areas, due to the consolidation of soil aggregates by rain drops, and the occurrence of various kinds of mineral duricrusts obstruct the infiltration of rain water (Römkens *et al.,* 1990). Under such conditions practically the entire runoff becomes overland flow, and the predominant erosive processes are: rainsplash, soil detachment, rilling and gullying (Abrahams *et al.,* 1994).

The shortage of water necessary to remove salts also reduces the rate of chemical denudation. However, chemical weathering can be quite considerable, as evidenced by the presence of mineral duricrusts and the salinity of the upper part of the soil profile, caused by the evaporation of the ascending ground water (Gat, 1980; Crabtree, 1986; Nativ *et al.,* 1997; Weisbrod *et al.,* 2000).

The objective, area and methods of studies

The main objective of the present paper is to assess the effect of certain features of the natural environment of the semi-arid zone on the spatial and temporal variability of production and supply of material for fluvial transport under episodic surface overland flow conditions. In order to do that the effects of a one-hour-long tropical shower of 14 mm were measured and analysed the conditions of water flow down the slopes and runoff in the wadi channels were thereby evaluated. The sources of supply of dissolved material and of suspended sediment for fluvial transport have been determined and the constraints of sediment supply in various flood phases was assessed. The field work was carried out as part of the scientific expedition to Cabo Verde led by Prof. Dr. Elżbieta Mycielska-Dowgiałło (Gierszewski, 2000).

The study area was a declivity in the Cha de Ervatao Plateau, situated on the south-eastern coast of Boa Vista. This plateau situated at 60–70 m a.s.l, inclines gently (2–10°) towards the shoreline (Fig. 2). A series of tuffite sandstones and calcarenites overlain by vulcanites strongly weathered at the top overlies the basalt bedrock. The lateritic weathered material is covered by a basalt ablation pavement. Its relief characteristics, geological structure and altitudes indicate that the area in question is most probably an early-Pleistocene (Sicilian) marine terrace (Mitchell-Thome, 1972). Lower benches are present on the declivity of the plateau at 40–50 and 20–30 m a.s.l. Its relief is diversified by ablation basins and deeply inserted (to 20–40 m), highly-branched valleys which may appropriately be described as wadis. That is a semi-arid area, as evidenced by the poverty of the herbaceous vegetation on the slopes. Only the more fertile fragment of the wadi floors are vegetated by extensive pulse crops and date and coconut palm plantations.

The field research consisted of observation and hydrological and geomorphological measurements of the effects of the heavy shower which occurred on 12th October 1999. They were carried out on a small slope fragment consisting of a semi-natural catchment of an ablation basin, 1,3 ha in area, and the catchment of an unpaved road, 1,7 ha in area. Also included in the studies were the outlets of the much larger neighbouring catchments of the wadis Ribera de Abrolhos (52 ha) and Ribera de Ervatao (612 ha) (Fig. 1). The measurements of discharges, turbidity and electrical conductivity of water were carried out both during the shower and its aftermath. Considering the ephemeral character of the phenomenon, only the simplest of measurement methods were possible. Height and intensity of precipitation marked by using calibrated container which have been stuck out in different rainfall's stages. Discharges in wadis' channels were assessed by the float gauging method and in slope's catchments by the volumetric method. Suspension's concentration was marked by the weight method and its grain size by the laser technique (Fritsch Analyssette).

Results of studies

Characterization of water runoff

The surface water flow down the slopes of the Cha de Ervatao plateau, followed by runoff down the channels of wadis were the result of a one-hour-long shower amounting 14 mm. For the first few minutes the rainfall was of low intensity. After that it was variable, but never exceeded 0,5 mm/min.

Water flow from slope catchment areas started after 15 minutes of rainfall. In the ablation catchment it was overland flow, whereas in the unpaved road catchment it was concentrated. Rainsplash of material on the slope was clearly reduced by the ablation pavement. At the time of increasing amount of flow the discharges, as registered in the profile closing the slope catchments, amounted to 2,1 dm^3s^{-1} in the ablation basin catchment and 3,5 dm^3s^{-1} in the unpaved road catchment. The water flow culmination followed after about 50 minutes. The discharge values measured at the time were 2,5 dm^3s^{-1} and 4,2 dm^3s^{-1} respectively. The moment the shower ended, so did the sheet flow, and the concentrated flow decreased considerably. Ten minutes later, the discharges in the collective channels on the slope amounted to 1,4 dm^3s^{-1} in the ablation basin catchment, and 2,1 dm^3s^{-1} in the dirt road catchment. After another five minutes, the runoff from the slope catchments was terminated.

Water runoff in the upper reaches of the wadis started the moment the shower finished. The flood wave front appeared at the mouth of the Abrolhos wadi channel half an hour after the termination of the shower and in the Ervatao wadi channel five minutes later. The channels, completely dry up till then, rapidly filled with turbid water (Fig. 3). The flood was characterized by a very short, only 5-10 minutes long, phase of water level increase followed by a prolonged fall. The discharge at the time of flood culmination was estimated at ca 100 dm^3s^{-1} in Abrolhos and at 2000 dm^3s^{-1} in Ervatao. Water runoff from the smaller Abrolhos catchment was terminated after 40 minutes, that from the Ervatao catchment stopped after 2 hours and 10 minutes. Thus, the total duration time from the start of water flow from the slopes to the termination of the runoff in the wadi channels was 3,5 hours.

Sheet wash and suspended outflow

The measurements of suspension transport intensity in the catchments of a semi-natural ablation basin and a road ditch were carried out in the falling limb of the flood. The amount of suspension transported in that phase of the flood was already much smaller, although there were essential differences between the catchments under study. The turbidity value of the water flowing down the road ditch was nearly ten times as great (3,12 g dm^{-3}) as that in the ablation basin catchment (0,36 g dm^{-3}) (Fig. 4A). The sediment transported in that flow phase was represented mainly by the clay fraction (Fig. 5). In the measurement section of the ablation basin, that fraction accounted for 99,63% of the transported sediment, and in the catchment of the road ditch, 82,65%. The remaining part of the transported material was silt.

The concentration of the suspended material in the lower segment of the Abrolhos wadi varied with the flow conditions. The highest turbidity occurred in the initial phase of water runoff (0,86 g dm^{-3}), the lowest at the end of the flood (0,37 g dm^{-3}). Suspension transport in the Ervatao wadi proceeded in the same way (Fig. 4A). However, the more morphologically diversified catchment area of that wadi supplied considerably more material for fluvial transport, which was reflected in the much higher concentration of the suspension carried down the wadi channel. The greater energy of the flood waters of the Ervatao was also reflected in the increased percentage of the silt fraction in the total mass of the transported sediment, which at the start of the runoff was as much as 46%. The suspension of the Abrolhos consisted mainly of clay with a subsidiary silt (Fig. 5).

Dissolved material outflow

The role of the particular sources of supply of dissolved material and the variation in the time intensity of its outflow from the catchments under study is elucidated by the measurements carried out at the mouth of the Abrolhos (Fig. 6). The highest specific electrical conductivity of water (SEC) was found there at the start of the outflow.

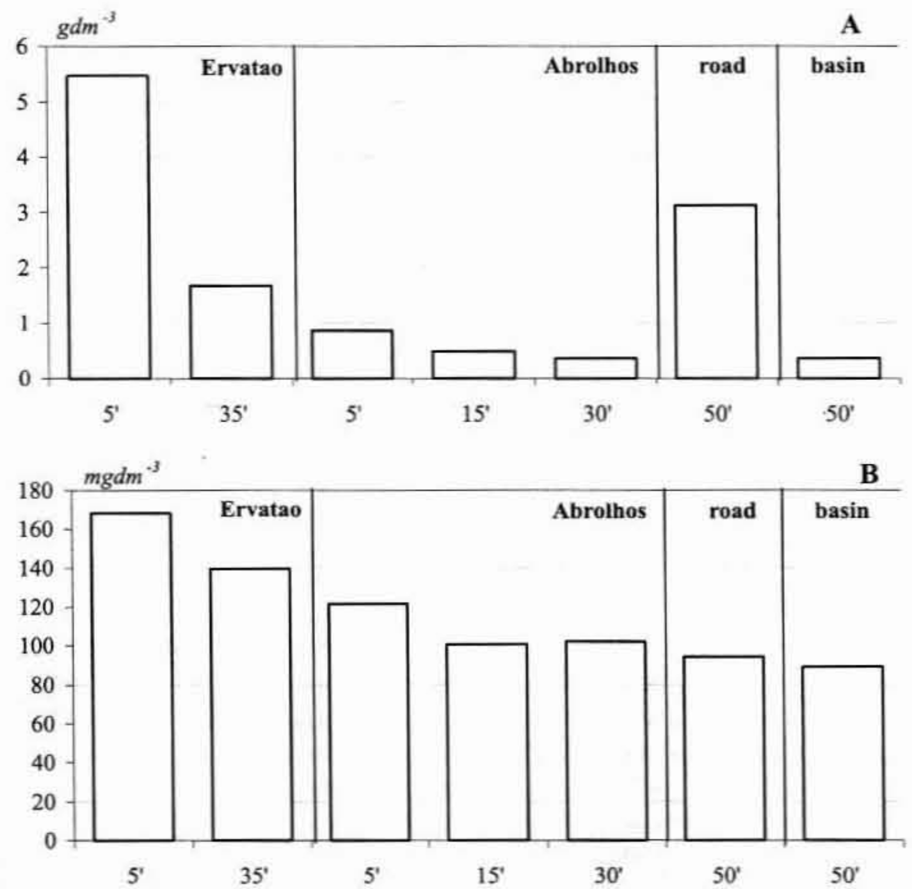

Fig. 4. Concentration of suspension (A) and dissolved material (B) in successive minutes of runoff

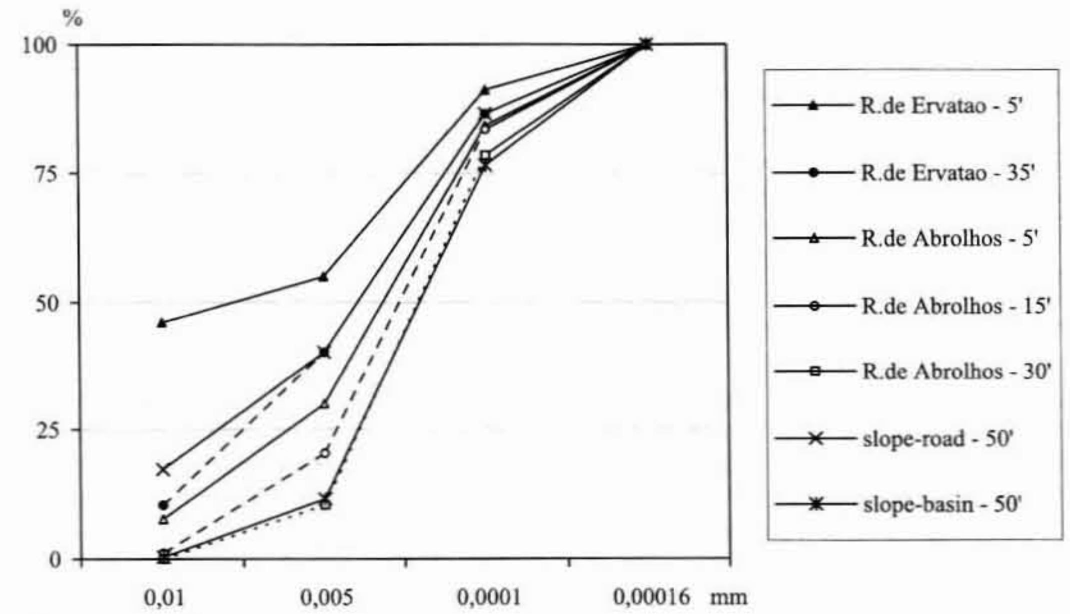

Fig. 5. Cumulation curves of graining of suspension in successive minutes of runoff

It was then 188 $\mu S\ cm^{-1}$, i.e. four times as much as that of the rain water (mean of the total shower 55 $\mu S\ cm^{-1}$). As the water level increased, its conductivity decreased. After 15 minutes, shortly after the flood culmination, it decreased by 50 $\mu S\ cm^{-1}$. In the course of the following 20 minutes, the conductivity of the water did not significantly change, after while it gradually increased through only slightly. In the flow cessation phase, water conductivity increased presumably due to evaporation.

In order to determine water turbidity, measurements of total mineralization were also carried out in the samples taken (Fig. 4B). The limited number of samples analyzed makes it difficult to define the progress of the dissolved material outflow. However, a clear tendency of variability can be seen, as noted in the plot of the conductivity in the Abrolhos catchment.

The mineralization of water outflowing from the slope catchment was similar to that from the Abrolhos catchment. The water of the Ervatao catchment were more highly mineralized (Fig. 4B). Its eastern part, drained by the Calheta, is made up of leached marine sediments containing a large proportion of carbonate rocks.

Discussion of results

Observations have demonstrated that rainfall, even of comparatively low intensity and short duration, initiates water surface flow on the study slopes. The time lag of the flow relative to the beginning of rainfall (c. 15 minutes) was presumable due to the low rainfall intensity in its early stage but it could also be associated with water retention in the covers of weathered material on

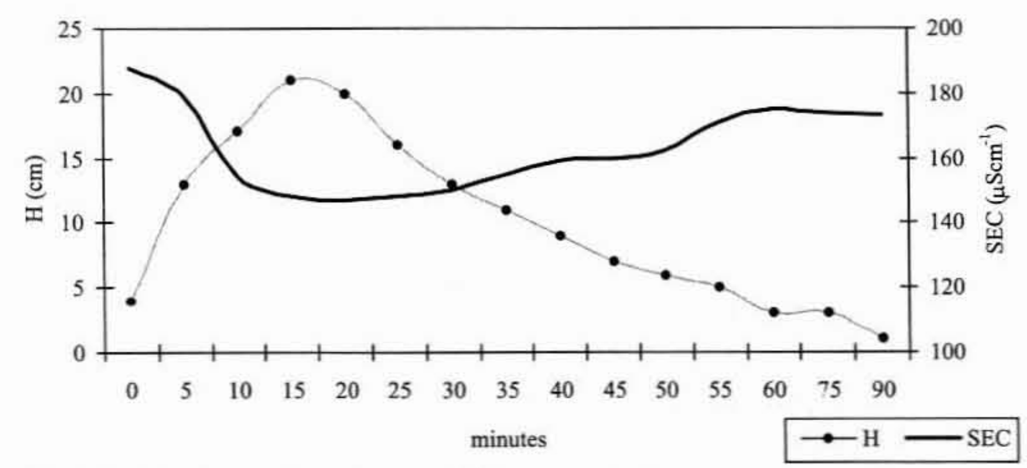

Fig. 6. Variation in specific conductance (SEC) compared with water stage (H) in mouth segment of Ribeira de Abrolhos

slope. Certainly a much higher retention capacity characterized the alluvia filling the wadi channels. The fact that runoff appears there after only one hour's rainfall is evidence of intensive infiltration of water into the alluvia.

The turbidity values and the textural characteristics of the transported suspension point to a diversity of resistance to water erosion of the slope catchments under study. Despite having a smaller catchment area, the road flow showed discharges nearly 70% higher than those of the ablation basin catchment flow. The higher dynamics of the hydrological process in the road catchment is reflected in the characteristics of the suspension load, which was characterized by concentration values ten times at of the other catchment areas and by a higher percentage of coarser-silt fraction in the transported material, the greater amount of material transported from the road catchment must be associated with erosion of the old and the currently used unpaved road. Repeated showers were conductive to the development along the line of the old road; of a gulley this was area 1 m^2 in cross section. This developed from an evorsion hole 8 m^3 in volume at the edge of the plateau (Fig. 7). The considerable role of unpaved roads in supplying weathered material to river channels in other climate zones has been emphasised by a number of authors (e.g. Froehlich, 1995; Fransen *et al.*, 2001; Madej, 2001).

The lesser erosion in the semi-natural ablation basin catchment is, to a large extent, due to the protective function of the ablation pavement which covers the surface of the plateau and the slopes of Cha de Ervatao. Certainly, the stony covers occurring on the terrain surface effectively reduce the water erosion (Poesen *et al.*, 1994). Their presence considerably reduces rainsplash, enhances infiltration and percolation and causes increased frictional coefficients. This eventually leads to both a reduction in the volume and a slowing down of the overland flow, and consequently of erosion. According to Poesen *et al.* (1994), even a 10% cover of the terrain by stones considerably reduces erosion. In the case of the Cha de Ervatao Plateau and declivity, that percentage is much higher – as much as 60%. However, in what seem to be a seemingly homogeneous surface covered with ablation pavement certain places appear to be more liable to erosion than others. Erodibility clearly both on the smaller number of stones accumulated and on their arrangement. According to Posen and Ingelmo-Sanchez (1992), boulders embedded in hardened surfaces no longer constitute such effective protection against erosion. In the case in question, these can be the various types of duricrust, whose considerable development on Boa Vista has been recorded by Mitchell-Thome (1972), and compact deluvial covers occurring on flat slopes where, according to the authors' measurements, the effects of erosion are particularly high, particulary along unpaved roads.

According to Frostick *et al.* (1983) and Lavee *et al.* (1991), a high concentration at the very beginning of the flood is a characteristic feature of suspension outflow down channels of wadis. At that time, the coarser fractions constitute a significant proportion of the transported material. Although the number of samples analysed is small, the results agree with those them to by typical of suspension outflow down channels of episodic water courses have been validated by the results obtained in the Abrolhos and Ervatao wadis.

The size of the transported particles and the fact that the maximum concentration appears at the beginning of the flood, both indicate the slope surfaces as the principal source of material supply. The sediment washed down from the slopes represents similar textural characteristics to that of the suspension load present in the wadi streams. Their channels, in filled-up with gravelly-sandy alluvia can only affect the concentration and the granulometric composition of the transported suspension at the time of floods with lower energy of water flow to a small extent. The provenance of the material transported in the channel illustrates the close relationship of the fluvial and slope systems in the denudation system under study. In the light of the above statement it seems evident that the Ervatao catchment, being morphologically more varied and characterized by a denser valley network, supplied considerably more material for fluvial transport than its neighbours.

The general salinity of the waters, which drained from the catchment areas under study at the time of the rainfall flood studied is high. The source of salt here is not only the basalts but also the easily leached carbonate marine sediments, which occur in the Ervatao catchment area. A considerable proportion of the total mineralization of water is explained by non-denudational components. The largest part is played by marine salt supply, which results from the situation of the catchment area. The oceanic provenance of the rainfall water supplying the islands, as indicated by the high value of the Na^+/Cl^- index, has been demonstrated by Louvat & Allègre (1998). According to these authors, this kind of salt supply into the system cannot be ignored when assessing the denudation balance. Owing to the close in the area under study vicinity of the ocean the marine aerosols deposited on its surface in rainless dry periods are an important source of salt. Also the dryness of Boa Vista's climate and the resulting aeolian salinity of the environment contribute to an increased concentration of the material dissolved in the surface waters. The increase in total mineralization of rain waters flowing down the terrain surface is also related with the dissolving of salts contained in the aeolian dust which to present on the surface of the catchment area (Gierszewski, 1998). The salinity of the upper part of the soil profile resulting from evaporation of soil moisture is clearly of great importance in this case (cf. Gat, 1980; Naiv *et al.*, 1997; Weisbrod *et al.*, 2000). The highest salt concentration in the water outflowing from the catchments under study is therefore to be expected at the beginning of the rain season as a whole and each particular rainfall episode.

The general conditions affecting also in the extent of total mineralization of the surface water in the semi-arid zone in catchments within the influence range of the ocean are fully reflected in the results of studies carried out on Boa Vista. In the initial phase of water outflow, salts of marine and aeolian provenance are dominant in the solution load removed from the catchments. However, their supplies are soon exhausted as is indicated by the pronounced decrease in dissolved material concentration after only a few minutes of flood, and often before its culmination. Thereafter the water mineralization does not change to any significant extent. A similar relationship has been observed in the Judea desert (Levee *et al.*, 1991).

Conclusion

The results of our studies make it possible to identify water erosion as the dominant process in the modeling of the contemporary relief of the study area. The high intensity of erosional processes in the initial runoff phase emphasizes the role of physical weathering in the periods between rainfalls as the factor responsible for the preparation of material for fluvial transport (Abrahams *et al.*, 1994). The torrential showers which occur with varying frequency are evidently quite capable of carrying away most of the weathering products.

It must, however, be pointed out that the comparatively gentle natural slopes on Boa Vista are very stable despite of the sparse vegetation cover there. The protective factor here is the ablation pavement, which reduces rainsplash and sheet wash and minimises flow concentration. Under natural conditions, erosion is limited to a deepening of the upper parts of valleys and a retreat of the wadis heads. In the wadi floors, there are usually channels with a marked prevalence of aggradation. In contrast, the unpaved roads concentrate water flow even on the plateaux and very slightly inclined slopes.

Owing to obstruction of water infiltration which is the present of soil salinity (Lavee *et al.*, 1991), or the occurrence of compact diluvial covers and duricrusts, or the shallow profile of permeable deposits, the potential for leaching of rock material in these short-lasting flows is extremely limited. A considerable portion of the dissolved material carried away from the catchments represents salts of marine and aeolian provenance, and their supplies are concentrated on the terrain surface and in the upper part of the soil profile.

The characteristics of transport of dissolved material and suspension in the wadi channels suggest a close relationship between the fluvial system and the slope system in the denudation system under study. Most of material washed down from the slope is carried away down the wadi channels to the sea.

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Fig. 2. Fragment of slope surface of the Cha de Ervatao plateau

Fig. 3. Mouth segment of the Ribeira de Ervatao wadi

Fig. 7. Eversion hole in the cutting of the unpaved road

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The Czarny Dunajec River, Poland, as an example of human-induced development tendencies in a mountain river channel

Kazimierz Krzemień

Jagiellonian University
Institute of Geography and Spatial Management
ul. Grodzka 64, 31-044 Kraków, Poland

Abstract: The Czarny Dunajec is a typical river originating in high mountains (the Western Tatras). Over the entire Quaternary era the river laboured carrying material away from the Tatras and depositing it in the form of a typical braided channel at their foot. At the end of the 19th century, river management projects and quarrying operations located directly in the very channel set off a rejuvenation process that was further accelerated at the end of 1960s. The activities resulted in the damaged several sections in their natural form and considerably deepened the channel. Measures taken to restrict the amount of material entering the Czorsztyn Dam have largely failed. From the geomorphologic and environmental points of view a continued transformation of the Czarny Dunajec river channel should be regarded as highly adverse.

Key words: mountain river channels, fluvial processes, human pressure, Western Carpathian Mts.

Introduction

The contemporary diversification of river channels is a result of long-term processes covering the entire catchment basins. As active channel sections indicate the current stage of a river channel evolution, a description of the entire river channel system helps understand the principles of how it works (Choeley, Kennedy, 1971). Information on the entire channel systems is mainly supplied by field research, supplemented by maps and aerial photographs (Mosley, 1987; Thorne, 1998; Kamykowska *et al.*, 1999). However, as most of the research has focused only on selected river sections, little is known about river channel systems at the scale of entire mountain ranges or even larger catchment areas.

Similarly, treated as a whole, the upper Vistula-catchment system is unquestionably under-researched. Meanwhile, as several Carpathian rivers are subject to management schemes and their channels dug for building aggregates, their systems have not been properly investigated. The research carried out so far shows that alterations made to one river section can lead to changes, which are difficult to predict in others (Osuch, 1968; Klimek, 1983). In order to determine their current status and to try to predict the development tendencies (Wasson *et al.*, 1993; Chełmicki and Krzemień, 1999), therefore, it is very important to evaluate the entire systems. Channel structures should be evaluated first and only then can changes be made. The Czarny Dunajec river is a very worthy object of such an investigation, as its river channel has been subject to intensive human-induced transformation involving river management and aggregate extraction, especially after the Second World War. These activities are still being carried out despite the official declarations of the relevant authorities that no further river management work is planned and the extraction of the material from the river being legally prohibited.

The research project conducted in the Czarny Dunajec catchment basin was aimed at understanding the structure of the channel system and demonstrating the natural and human-induced causes of its transformation.