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RATES OF FROST EROSION IN RIVER BANKS WITH DIFFERENT PARTICLE SIZE (WEST CARPATHIANS, POLAND)

Abstract: Augustowski K. & Kukulak J., *Rates of frost erosion in river banks with different particle size (West Carpathians, Poland). (IT ISSN 0391-9839, 2017).*

An important process of river bank erosion is multigelation - alternating freezing and thawing of the banks caused by cyclical oscillation of ground temperature around 0 °C. This paper presents the results of studies on the influence of multigelation on stability of river banks in the Beskid Niski and at Podhale. Repeated measurements of scarp retreat on river banks (those composed of alluvium and those cut in bedrock) were conducted using erosion pins and sediment catchers for gravity-transported debris. The progress of erosion in time and amounts of eroded material were correlated with the record of temperature changes above ground. Multigelation resulted in significant modification of the studied river banks. Amount of erosion depended mainly on lithology and grainsize of the rocks composing the banks. The banks composed of fine sediments retreated in a uniform way and at a uniform rate over the whole surface. Progress of erosion of the banks composed of medium granels was selective. Finest sediment was loosened first. Then coarser clasts that lost suport, became detached and fell down. On the banks composed of flysch rocks, densely fractured shales were eroded first, followed by bigger fragments of sandstone layers. Frost erosion was the most intense on the banks built of fine gravels with clay matrix and the least intense on the medium-sized sandy gravels. Layers of alluvial clay were more resistant to frost erosion than fine and coarse gravels embedded in clay or sand.

Key Words: multigelation, frost phenomena, river banks, Beskid Niski, Podhale, Poland.

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Cofanie się brzegów rzek jest skutkiem działania głównie procesów naturalnych. Jednym z takich procesów są cykliczne wahania temperatury gruntu wokół 0 ^{0}C (multigelacja). W tym artykule przedstawiono wpływ działania multigelacji na stabilność brzegów rzek w Beskidzie Niskim i na przedpolu polskich Tatr. W badaniach zastosowano metodę ciągłych pomiarów ruchu powierzchni brzegów (aluwialnych stoków teras rzecznych i podcięć ścian skalnych) przy pomocy zamontowanych prętów erozyjnych i łapaczy materiału osypiskowego. Przebieg czasowy i rozmiary erozji brzegów skorelowano z zapisem wahań temperatury powietrza nad gruntem i w gruncie. Wyniki badań wykazały, że multigelacja spowodowała duże przekształcania powierzchni badanych brzegów. Rozmiary erozji brzegów były zależne głównie od litologii i uziarnienia materiału skalnego budującego brzegi. Brzegi zbudowane z materiału drobnego cofały się na całej wysokości ich odsłonięcia w podobny sposób, a ubytki były jednakowe. Przebieg procesów mrozowych na brzegach zbudowanych ze średnich żwirów był bardziej selektywny. Najdrobniejszy materiał ulegał odspojeniu jako pierwszy. W konsekwencji grubsze żwiry traciły stabilność i przy zsuwaniu się po powierzchni brzegu naruszały spójność niżej położonych okruchów. Na brzegach zbudowanych z warstw fliszu w pierwszej kolejności odspojeniu ulegały silnie spękane łupki, a następnie duże okruchy piaskowców. Cofanie się brzegów rzecznych przebiegało najintensywniej na brzegach zbudowanych z gliny i drobnych żwirów, najwolniej zaś na brzegach zbudowanych ze średnich żwirów.

Słowa kluczowe: multigelacja, procesy mrozowe, brzegi rzeczne, Beskid Niski, Podhale.

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INTRODUCTION

Retreat of river banks results from many processes, mostly undercutting by stream erosion and gravitational downfall. Frost phenomena are also involved and according to Wolman (1959), Thorne (1990) and Couper (2003), they prepare soil for actual erosion. Frost processes can also directly control retreat of river banks (Walker & Arnborg, 1966; Jahn, 1970; Teisseyre, 1979; Yumoto & *alii,* 2006). Intensity and results of these processes may differ, as they depend on various climatic factors and local conditions of the banks. The progress of frost phenomena depends also on: grain size of the bank material (eg. Wolman, 1959; Walker & *alii*, 1987), moisture conditions in bank material (Lautridou, 1982; Thorne & Osman, 1988; Chen & *alii*, 2004) and the physical state of this moisture (ice or water; Thorne 1990). Also important are: ground porosity, density and its content of organic matter (Grissinger, 1982; Knapen & *alii,* 2007), bank angle (Allen & *alii,* 1999; Wynn, 2004; Kozielska-Sroka & *alii,* 2010), the number of freeze-thaw cycles (Martini, 1967; Potts, 1970; Miller, 1980), cohesion of bank material (Mitchell & *alii,* 2003), depth of ground freezing (Webb & *alii,* 1983), the presence of vegetation (Thorne, 1982; Przedwojski, 1998; Abernethy & Rutherfurd, 1998, 2000; Hubble & *alii,* 2010) or snow cover (eg. Gatto, 1995).

Important role is played by various susceptibility of sediments to frost heave. According to Taber (1929) sandy grounds are less susceptible than clays. The size of "pore spaces controls the rate of capillary draw during freezing" (Taber, 1929). Kaplar (1974) and Berg and Johnson (1983) contend that the most prone to frost heave are clays and muds, especially when wet. According to Beskow (1935), medium-grained sediments (muds, fine sands) are exceptionally susceptible to frost-related processes. Frost heave does not occur in loose gravels and sands devoid of mud or clay, even when they are saturated with water (Glinicki, 1983; Wiłun, 1987; Szymański, 2007). Among solid sedimentary rocks, frost heave occurs in shales because these are the least resistant in the presence of water (Keil, 1951; Rolla, 1961; Glinicki, 1983). Water freezing in shales and sandstones results mainly in their fracturing (Koniszew, 1973; Martini, 1976; Dione, 1983), especially when they have argillaceous matrix (Flageollet & Helluin, 1986). Results of laboratory tests of susceptibility to frost heave of fluvial sediments and soils show that not only granulometric characteristics of sediments are important but also their moisture conditions (Potts, 1970; Glinicki, 1983; Chen & *alii*, 2004). No category of sediments could be identified in which frost heave will always occur (Henry, 1990).

Previous studies on frost erosion of river banks concerned mainly banks composed of homogenous fine-grained alluvium. Reid (1985) found, in his study of the shores of Orwell Lake, that frost phenomena were responsible for 20-80% of the lake shore erosion. Lawler (1993) estimated the general share of frost phenomena in bank erosion at 32-43%. Also Teisseyre (1984) identified multigelation as one of the main factors influencing retreat of river banks. The dependence of ground swelling and shrinking on its grain size has been hitherto described only for the banks in homogenous materials (Beskow, 1935; Wolman, 1959; Gatto & *alii* 2001; Coffman, 2009). However, erosion of heterogeneous banks is a more complex process, as the layers differing in grain size differ also in moisture conditions, consolidation and the course of frost processes (Jahn, 1971; Teisseyre, 1979; Augustowski & Kukulak, 2013).

The course and intensity of frost processes on river banks composed of texturally heterogenous sediment layers have not been studied yet. This study is an attempt to evaluate morphological results of freeze-thaw phenomena (multigelation) on layered river banks built of texturally contrasting sediments. We studied the results of frost phenomena on coarse, medium and fine gravels, on alluvial clays present in the studied, actively eroded river banks. We accepted that heterogeneity of the sediments in the banks may result in uneven intensity of frost processes and as a consequence, uneven rates of bank recession. Previous studies on the course of frost phenomena in sediment indicate that freezing and thawing are slower in cohesive (clayey) sediments than in granular ones (Popow, 1962; Walker & Arnborg, 1963; Jahn, 1970; Teisseyre, 1979; Couper & *alii,* 2002). This does not mean, however, that sandy and gravelly banks are more intensively eroded by multigelation. It has been stressed also that the frost processes do not alter markedly banks built of sand and gravel, because such grounds do not tend to become water-logged (Teisseyre, 1979). Nevertheless, erosion on such banks may be greater than on clayey alluvia because of the greater dimensions of intergranular pores (Szymański, 2007). It seems thus that granulation of sediments in individual layers is of crucial importance.

The results of previous studies have shown that mobility of sediments due to freeze-thaw depends on the percentage of three grain-size fractions: clay (<0.02 mm), silt (<0.05 mm) and fine sand (<0.1 mm) in the sediments (Schaible, 1954; Schenk, 1955; Orlov, 1978; Glinicki, 1983; Wiłun, 1987). The higher is the percentage of the finest fraction (up to 10-15%), the greater is the frost heave effect and deformation after thawing. Argillaceous sediments, muds and clays with up to 20% of the fraction finer than 0.02 mm and sandy clays that contain up to 15% of this fraction are considered as the most susceptible (Kaplar, 1974; Berg & Johnson, 1983). Frost processes are initiated in homogenous sediments already when the content of grains smaller than 0.02 mm exceeds 10%, while in heterogeneous sediments when it exceeds 3% (Dücker, 1937; Glinicki, 1983). The high content of fine grains facilitates capillary forces of water in sediments and their swelling (frost heave) upon freezing (Beskow, 1935; Chamberlein, 1981; Glinicki, 1983; Muench, 2006; Szymański 2007).

Individual layers of sediments in the studied river banks differ strongly in their grain-size characteristics. We can thus observe the kind and measure the rate of changes caused by freezing and thawing for each of the layers in a river bank surface. By measuring the amounts of bank erosion during the winter season we wanted to find which types of sediments are eroded faster under the influence of frost phenomena. By comparison with literature data we can check if resistance of clays to frost phenomena is really low.

STUDY AREA

The studied river banks lie in the drainage basins of the Czarny Dunajec (region of Podhale) (fig. 1A) and the Ropa (Beskid Niski) (fig. 1B) in the Polish part of the West Carpathians. The values of near-ground air temperature in this region often oscillate around 0 °C in the winter season. The river bank sections selected for this study are erosional scarps cut into fluvial terraces and into bedrock of the valley slopes. They were selected because of well visible and rapid progress of bank erosion. The study sites were located on the scarps, where internal structure of the banks was exposed beneath turf. The bases of the bank scarps are in direct contact with flowing water or are within the

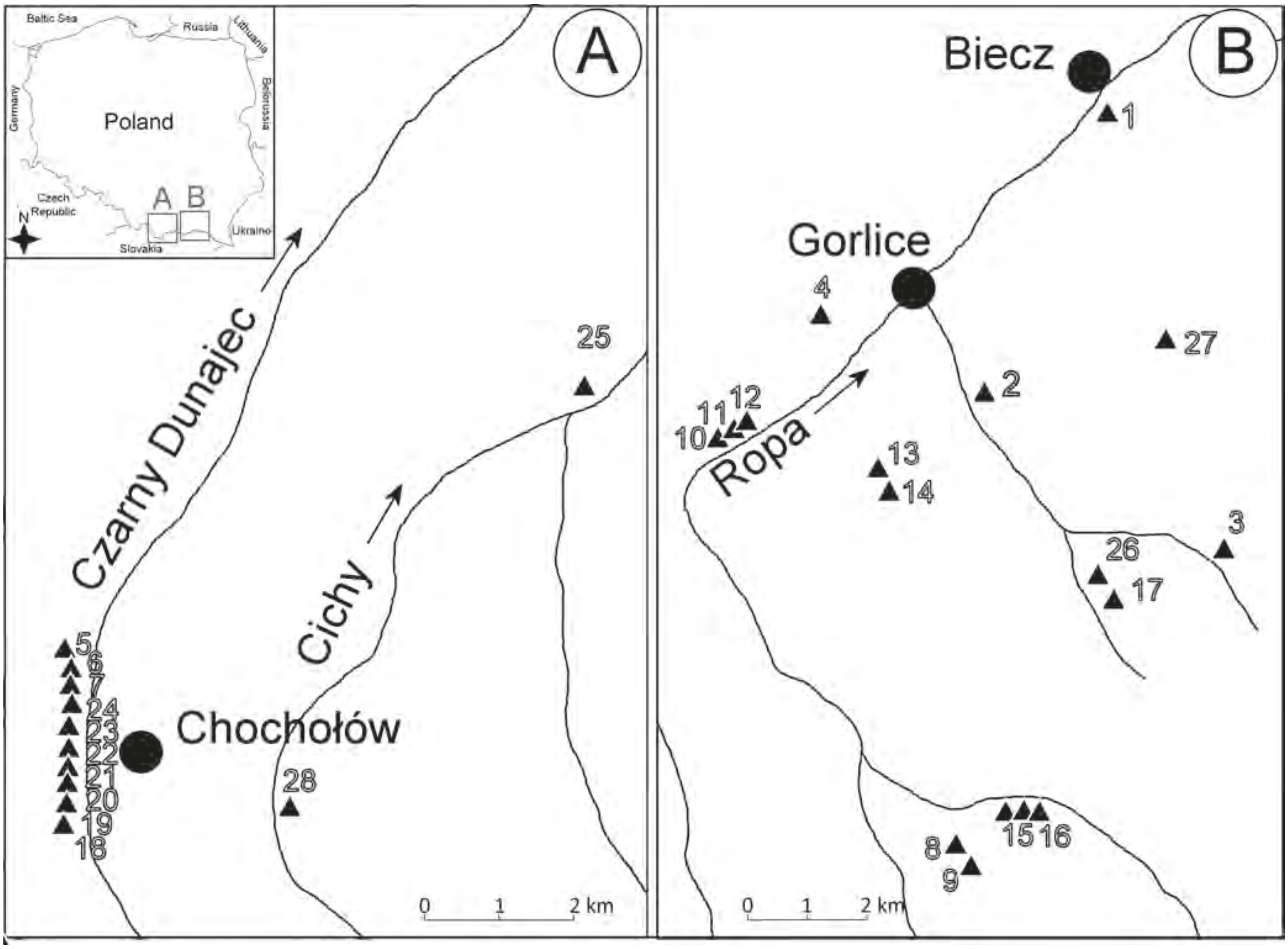

FIG. 1 - Distribution of the studied sites (triangles) within the watersheds of the Czarny Dunajec (A) and Ropa (B). Names of study sites are described in the text.

reach of water during high water stages. Changes in water stage during the winter season are relatively small and they do not contribute to increased fluvial erosion of the banks. Twenty eight sites were selected for detailed measurements, on banks composed of hard rocks and those composed of alluvium, so that grain-size profiles were different at each site. (fig. 1). The progress and amount of erosion on sandy-clayey banks were studied at two sites (1 and 2), on banks composed of fine gravel and sand at ten sites (3-12), on those composed of medium gravels at five sites (13-17), on coarse gravels at eight sites (18-25), and on banks of solid bedrock at three sites (26-28).

The study sites in the Ropa watershed are located on scarps of three young (Holocene) terraces, 1.5 m, 2.5-3.5 m and 7.0 m high. Each of the terraces is underlain by a layer of alluvium 1.5 to 5 m thick and lying on a low (0.5 - 2 m) strath carved in bedrock. The alluvial layer under the lowest terrace is composed mostly of mud and sand (fig. 2A), while in the higher terraces it is composed of medium gravel and sand with a clay layer on top (fig. 2B). All these sediment types are arranged in layers, so that susceptibility to erosion may be determined for each layer separately. All sediments are friable, only the top clays are more cohesive.

The studied terrace scarps in the Czarny Dunajec watershed belong to Holocene terraces 4 and 6 m high and a Pleistocene terrace 11 m high. The lowest, 4 m terrace is composed entirely of coarse and medium gravel with sand matrix (fig. 2C). The sequence of layers in sections of the higher terraces comprised (from bottom to top): Neogene clays in terrace basements, coarse and medium gravelrich in sand, topped with a layer of clay (Augustowski & *alii*, 2012). The gravel is feebly cemented, slightly stronger in the upper part (fig. 2D).

Also studied were: a stream-cut exposure of the Podhale Flysch in the Cichy stream (tributary of the Czarny Dunajec; site 28; fig. 2E) and an exposure of strongly cemented Neogene gravel (Stare Bystre; site 25) (Kukulak & Augustowski, 2016). These studies were done during the period November 2011 to April 2012 and no high water stages occurred in this time. As for the exposition to the sunlight, the studied banks are variously oriented: to SW, S and SE.

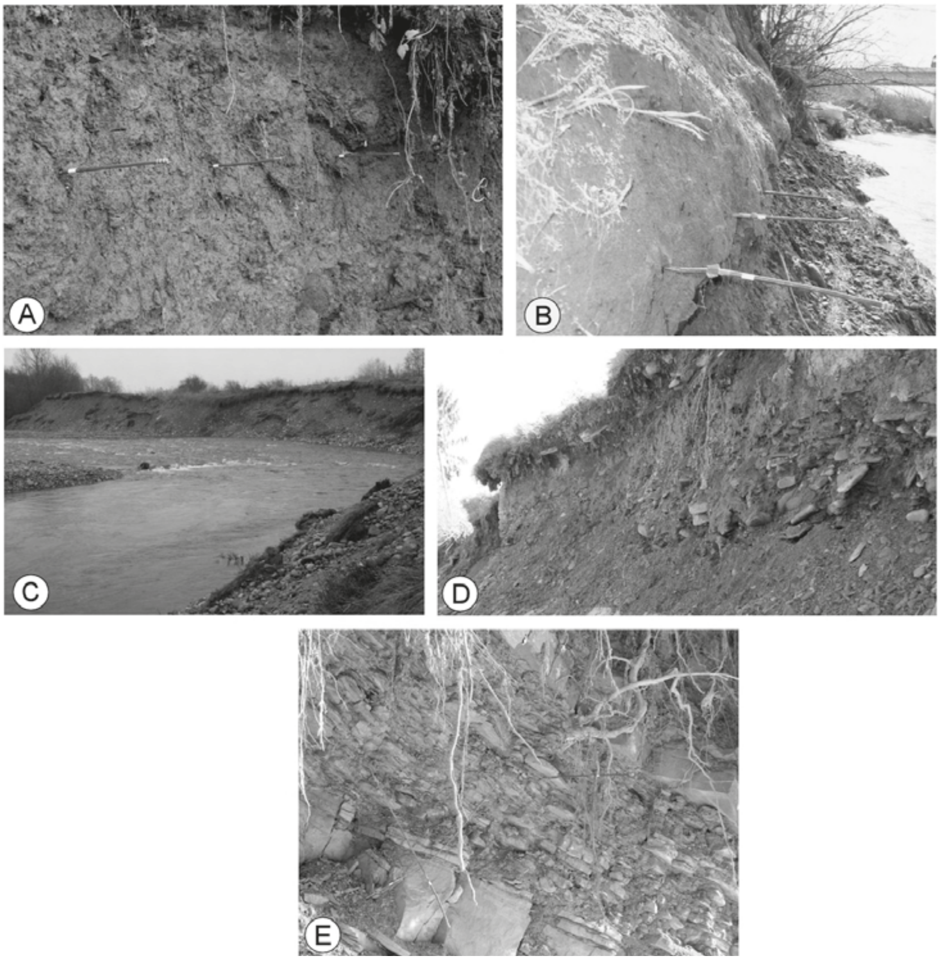

FIG. 2 - Various geological structures of the studied river banks (A – site 1; B – site 8; C – site 15; D – sites 22 and 23; E – site 28).

METHODS

The rate of river bank erosion at the studied sites was measured using erosion pins (fig. 3A). Changing exposure of each pin was accepted as a proof of frost swelling – when the exposed length of a erosion pin decreased – or as a proof of removal of sediment and recession of the bank surface – when the exposed length of the pin increased.

Erosion pins have been used in studies of slope and river bank stability since 1950s (Wolman, 1959; Hooke, 1980; Thorne, 1981; Lawler, 1986; Stott, 1997). This method was used in Australia for measuring the rate of bank recession on the rivers: Ngaradj (Saynor & *alii,* 2003), Daintree (Bartley & *alii,* 2006) and the Gowrie stream (Howard & *alii,* 1998). In Italy erosion pins were used to study erosion by the Cecina river (Luppi & *alii,* 2008), in Denmark on the Odense shores (Kronvang & *alii,* 2012), while in the USA on the shores of the Michigan Lake (Vallejo, 1977, 1990). Sirvent & *alii* (1997) used them in their studies on slope stability in NE Spain and Shi & *alii* (2011) in the Hubei province and near Chongqing in China. Arens & *alii* (2004) used this method for measuring the rate of dune movement at Kennemerland in the Netherlands. Stott (1997, 1999) and Couper & *alii* (2002) used a caliper with precision 0.17 to 0.33 mm. We used a ruler precise to 1 mm.

The erosion pins used in the study of bank erosion along the Czarny Dunajec and Ropa were 100 cm long and 6 mm in diameter. They were hammered into bank scarps and rock walls to the depth of 80 cm. The pins were pointed in order to reduce mechanical disturbance in ground structure. This depth of anchoring was accepted because oscillations of ground temperature around 0 °C very seldom reach deeper than 80 cm in Podhale and Beskid Niski regions. The erosion pins were marked with tapes in four colours to facilitate recognition of amount of erosion. The pins were inserted in horizontal rows so as to maintain them within the same type of the mostly horizontally stratified sediment. The pins were inserted in the higher parts of the banks with the aim of reducing the impact of sediment falling down from the scarp above them (fig. 3A). Two to five erosion pins were installed at every study site, at distances of 0.5-1.0 m. Their number depended on the degree of homogeneity of the studied sediments. The erosion pins were monitored after every

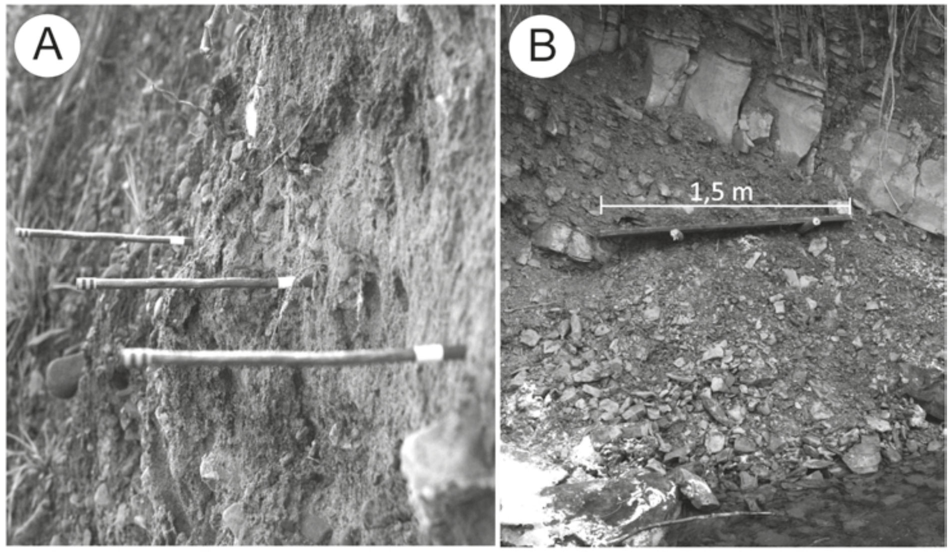

FIG. 3 - Erosion pins (A) and scree catchers (B).

period of multigelation when the transformations of the banks ceased. The pins were re-set after reading if there occurred a scarp retreat, that is they were inserted again to the marked depth. They were not re-set when ground swelling was registered. The values of erosion/swelling presented below are cumulative, summed up since the beginning of the study. The volume of scree was determined using wooden catchers (fig. 3B) planks 1.5-2 m long and 15-25 cm wide, attached perpendicular to the bank surface. The volume of material accumulated on them, fallen from the fragment of the bank above the planks (including the zone with the erosion pins), was measured after every registered period of multigelation. In this way the magnitude of bank erosion above the catcher could be assessed and compared with the results obtained using the erosion pins.

Measurements and observations within clay layers included the amount of swelling upon freezing and of shrinking upon thawing, registration of the appearance and widening of cracks, their pattern and density, registration of the sites of detachment of clay lumps.

Observations of the gravel layers consisted in determination of the degree of their consolidation, grain-size characterization of the groundmass and its share on the exposed surface. The mechanism of erosion was observed for banks in fine, medium and coarse gravels upon thawing; positions and dimensions of debris cones were registered on photographs. The volumes of the cones were measured after every phase of multigelation.

Observations on the rocky banks consisted in registration of attitude of strata, density of joints in sandstone layers and translation of slabs over the bank surface.

For brevity, the periods identified when air temperatures oscillated around 0 °C are referred below as active phases (fig. 4). Four such periods occurred in the Beskid Niski (1^{st} - 10^{th} January, 10^{th} - 20^{th} February, 1^{st} - 10^{th} March and 25^{th} March - 5^{th} April), and five at Podhale (1^{st} - 10^{th} January, 10^{th} - 20^{th} February, 1^{st} - 10^{th} March, 25^{th} March - 5^{th} April and 10^{th} - 20^{th} April). Water levels were registered at three state survey (IMGW) stations at Koniówka (on the Czarny Dunajec), Ropa and Klęczany (both on the Ropa) in order to eliminate interference of fluvial erosion in the readings on the erosion pins (fig. 5). The water stages on both rivers were within the zone of lower and medium stages so they had no influence on the course of the frost and gravity processes on the studied sites. Thus, we assume that multigelation was responsible for the bulk of the processes of bank destruction.

RESULTS

The banks of composite structure were unevenly affected by frost phenomena. The loss of material was greatest on the banks composed of fine gravel and clay (mean value of bank retreat was 33.8 cm) and on the bedrock banks (31.0 cm). Bank retreat was several times slower on the banks composed of medium gravel (4.8 cm). The mean value of bank retreat on the clay banks was 8.4 cm, and on the banks built of coarse gravel it was 23.1 cm (fig. 6).

The effects of frost phenomena were apparent first on densely jointed exposures of shales and sandstones. At the bank of the Cichy stream (site 28), significant loss was registered as early as the second active phase. On the banks composed of gravel and clay, the effects of frost phenomena became clearly perceptible only during the third or even fourth active phase. The banks were then already heavily soaked with water from thaw; their moisture condition was as high as 60-90%. Ground moisture appeared to be important for efficiency of frost phenomena. When ground porosity allows for capillary rise of water or for growth of needle ice and ice lenses, the water content becomes decisive for the dynamics of frost phenomena (Thorne & Osman, 1988; Thorne, 1990; Przedwojski, 1998). The value of temperature near the ground appeared less important than the number of temperature oscillations around the value of 0 °C.

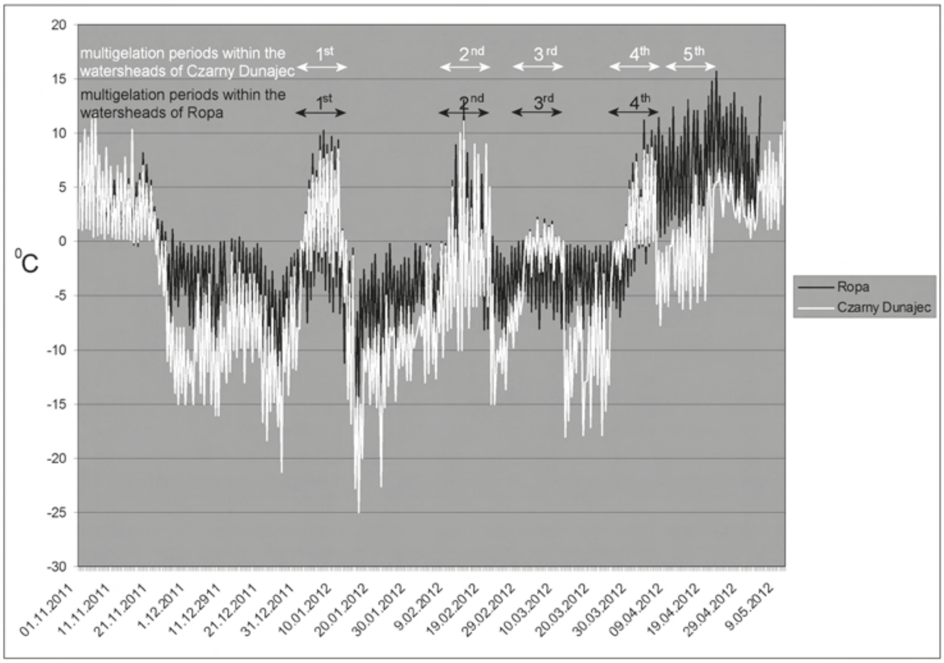

FIG. 4 - Temperature distribution and multigelation periods within the watersheds of the Czarny Dunajec and Ropa.

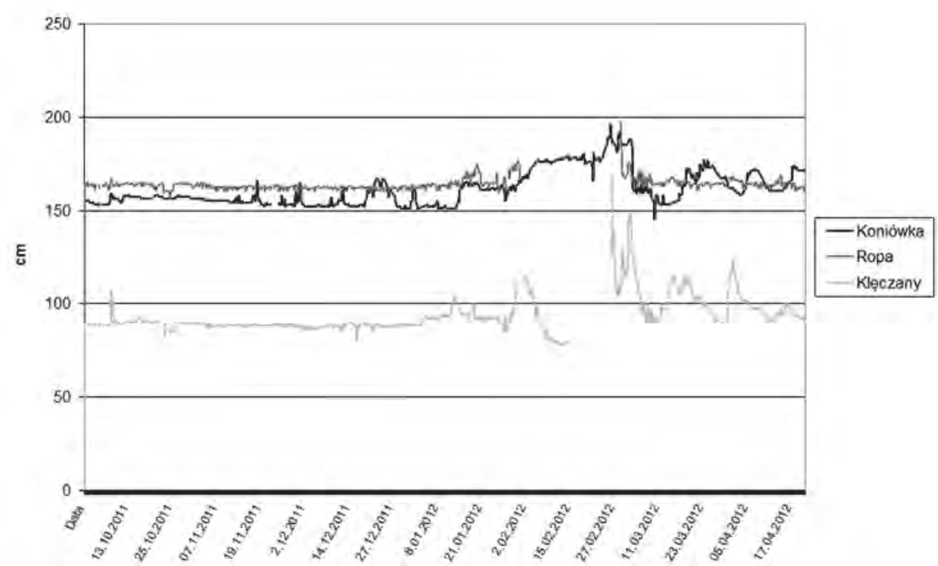

FIG. 5 - Water levels on the Czarny Dunajec (IMGW station Koniówka) and Ropa (IMGW stations Ropa and Klęczany) - (for Koniówka: the lowest recorded value multi-annual flow (LRV) = 148; mean recorded value multi-annual flow (MRV) = 173; the highest recorded value multi-annual flow (HRV) = 320; for Klęczany: LRV = 50; MRV = 101; HRV = 665). Interruptions in records of water level were caused by damage to a sensor. The water stage was then monitored by direct monitoring of changes, without numeric data. Changes in water level were then minimal.

The volume of scree during the first active phase was similar on the surfaces of the studied river banks and amounted only to ca. 0.002 m^3/m^2, regardless of the rock type in the bank scarp (fig. 7). Greater diversity in the volume of material laid down at the base of bank scarps was noted during the second active phase. Increase in volume of scree was greatest at the banks composed of medium gravels, with values of 0.013 m^3/m^2. The volumes of scree laid down at the base of slopes composed of coarse gravel and flysch were slightly smaller – ca. 0.008 m^3/m^2. The smallest debris fans (relative to the surface area of scarp fronts) were recorded on the banks composed of clay. During the third active phase, the greatest scree fans formed on the banks composed of medium gravel (0.094 m^3/m^2) and of fine gravel (0.074 m^3/m^2). Volume of scree on banks with scarps in flysch and on banks composed of coarse gravel attained ca. 0.04 m^3/m^2. Similarly as during the earlier active phases, volume of scree at the feet of clay banks was the least and equaled 0.02 m^3/m^2. Volume of scree accumulated after the fourth active phase varied on the banks composed of fine and medium gravel between 0.11 and 0.15 m^3/m^2, on the banks composed of coarse gravel and exposed flysch between 0.057 and 0.069 m^3/m^2, and on clay alluvium it was 0.0215 m^3/m^2.

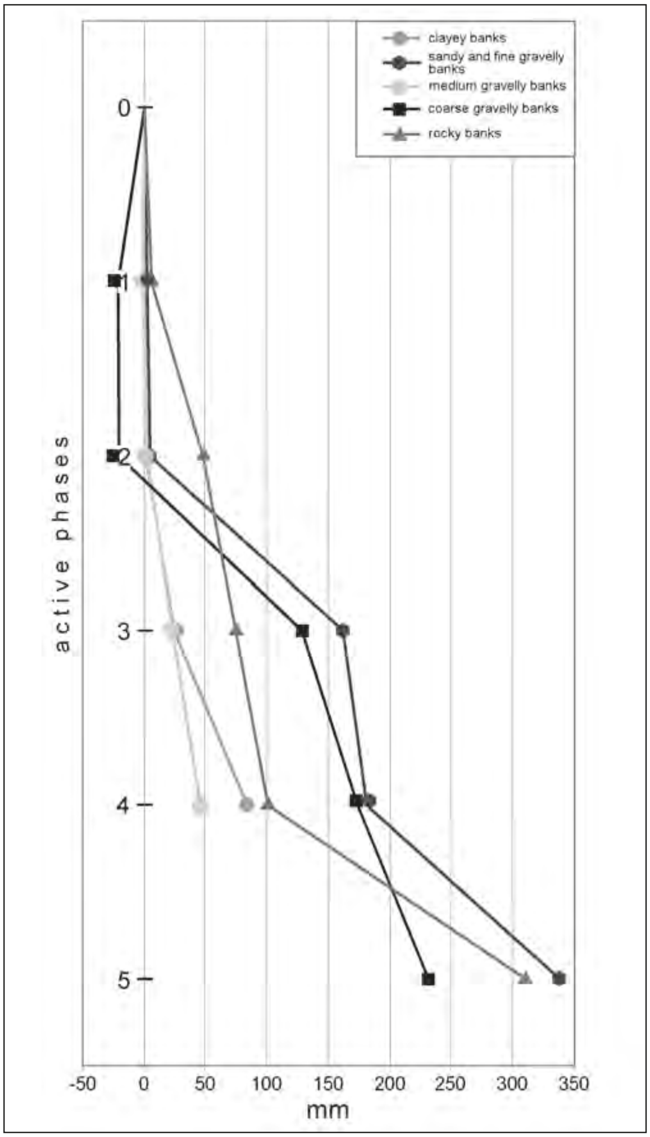

FIG. 6 - Average values of erosion pin exposure during successive active phases on river banks of various structure.

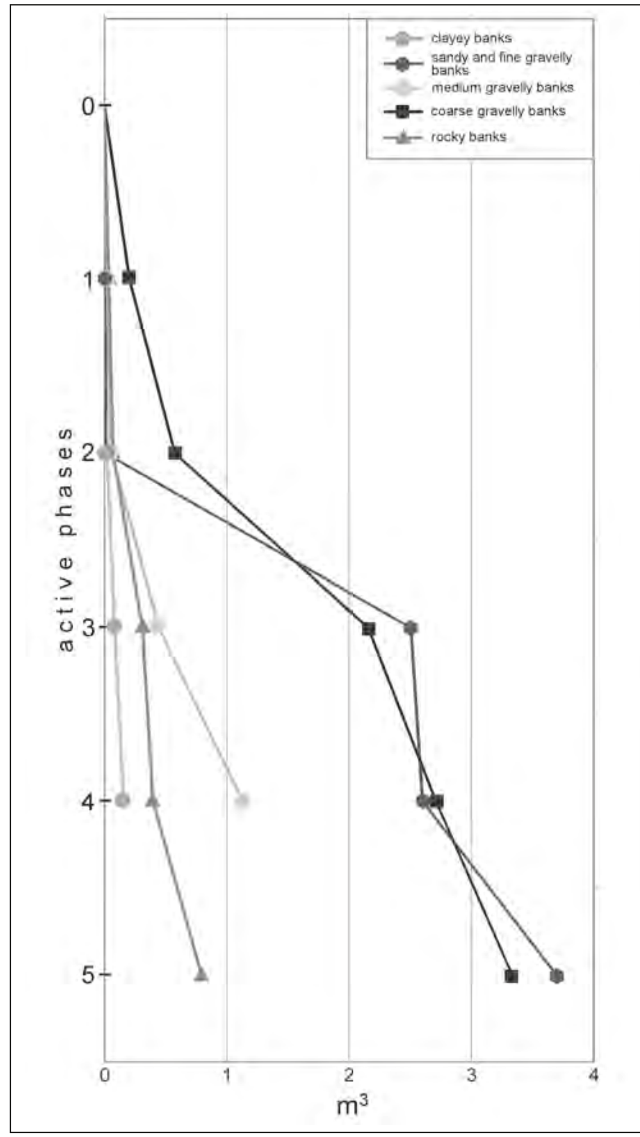

FIG. 7 - Average increase in volume of frost-related scree on banks of various structure.

Frost phenomena on river banks composed of clayey sediments

The studied river banks (sites 1 and 2) are scarps of terraces 2.5 m high, undercut by stream erosion. A layer of clay and muddy-sandy deposits, nearly 2 m thick, predominates in the section. The clay is friable, penetrated by contraction cracks and millimetric biogenic channels. The clay layer is underlain by a thin layer of gravel and sand (up to 0.5 m thick). The gravel is poorly sorted and it is more consolidated than the overlying clay.

At site 1, destruction of the fine-grained layer by frost phenomena became well marked only during the third and fourth active phases. Average amount of bank recession calculated from all erosion pins for the third active phase was 38.7 mm and for the fourth phase – 89.2 mm (fig. 8A). During the third active phase, erosion of the bank at site 1 progressed unevenly.

At site 2, the bank surface was more stable and the small losses at some spots were compensated by frost swelling of the same surface. The growth of needle ice in the ground resulted in apparent sinking of the erosion pins so that their exposed length became shorter than at start. The volumes of eroded material were twice larger during the fourth active phase, relative to the third active phase. The amounts of eroded material were many times greater at site 1 than at site 2.

The mean value of bank retreat on all the clayey banks was 0.7 mm after the first active phase, 0.8 mm after the second, 23.1 mm after the third, and 59.8 mm after the fourth.

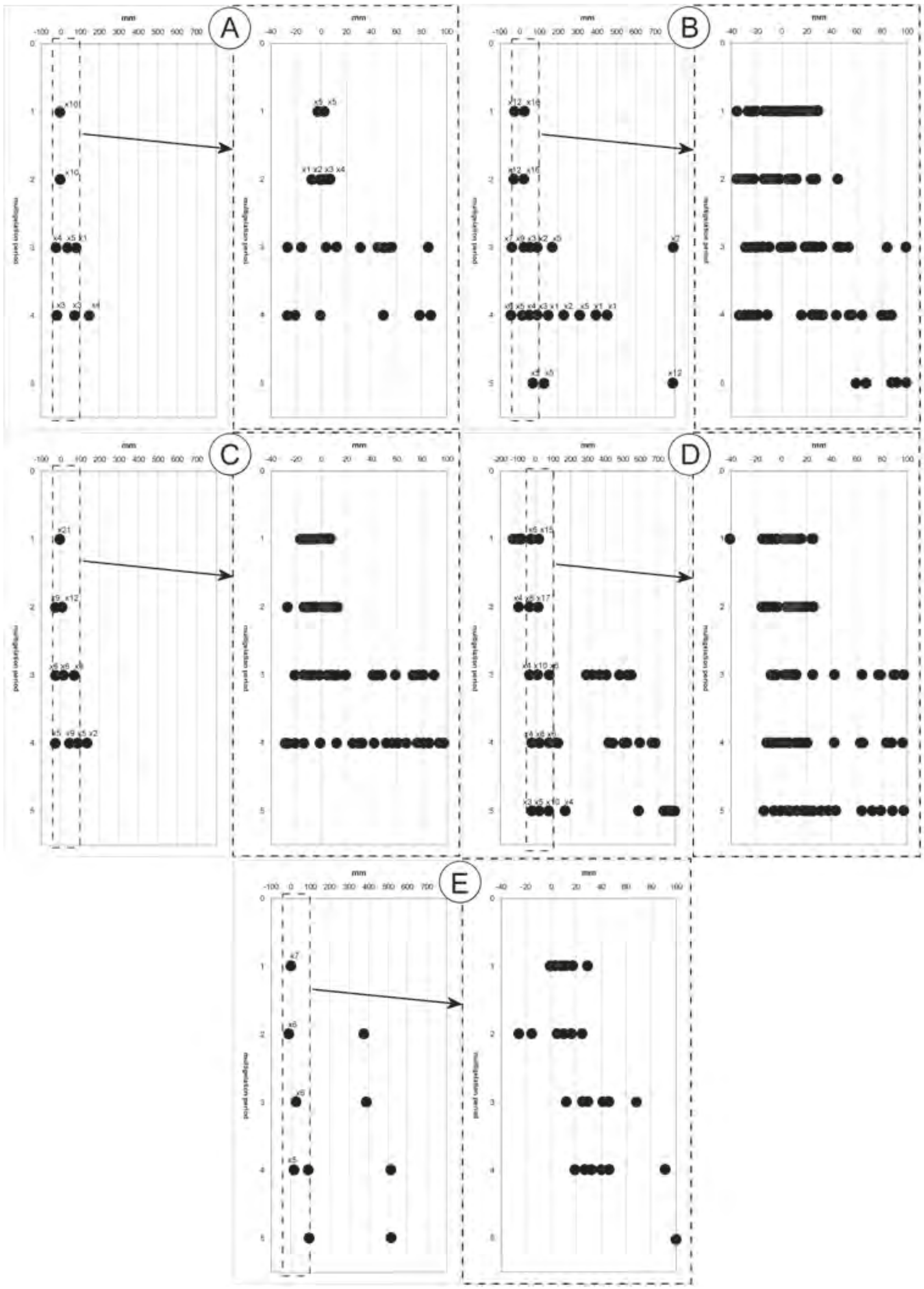

FIG. 8 - Record of bank retreat on all erosion pins during successive periods of multigelation; clay banks (A); fine-gravel banks (B); medium-gravel banks (C); coarse-gravel banks (D); rock banks (E). Each point denotes a single erosion pin.

Frost phenomena at banks composed of fine gravel and sand

Fine gravel and sand compose the thickest layers (1-2 m) at ten of the studied sites on the low terraces (2-3.5 m). Frost phenomena on such banks acted selectively, depending on the compactness of sediments involved. Transformation of the banks by frost phenomena was strongest at sites 4 and 6, where the banks retreated by 80 cm on average during the whole period of study (fig. 8B). Intensity of frost erosion differed between individual active phases. Transformation of the bank surfaces was relatively small during the first two active phases. Erosion was intensified only during the third and fourth active phases. Volume loss by multigelation was especially large during the third phase, resulting in similar amounts of bank retreat at all the studied sites. The mean value of bank retreat for all the studied banks built of fine gravel and sand was 2.2 mm after the first active phase, 2.8 after the second, 156.9 after the third, 19.1 mm after the fourth and 156.9 after the fifth. The mean value of total bank retreat after the study period was 337.7 mm.

Frost phenomena on river banks composed of medium gravel

Medium gravels, embedded in coarse sand, predominate in the structure of the studied river banks in this group. They include single coarse clasts and small lenses of finer sand, which facilitated emplacement of the erosion pins. Frost phenomena on these banks resulted in significant erosion only during the third and the last active phase, similar to the banks composed of fine gravel and clay. However, the volume of scree was small on the banks composed of medium gravels. The progress of bank erosion strongly depended on the structure of eroded sediment. Erosion of poorly sorted sediment began with mobilization of finer components, and the coarser components fell out later. Detachment and collapse of the finer grains reduced stability of the coarser ones, so the latter became gradually incorporated into scree. Moreover, the coarse clasts sliding down over the thawing bank surface contributed to loosening of the underlying gravel and mobilization of its clasts. The bank surfaces retreated by 4.8 cm on average (compared to 10-30 cm in finer sediments) during the whole period of study (fig. 8C). At every site one active phase – the third or the fourth one – was clearly pronounced as the most effective , producing greater bank retreat than other phases.

The mean value of bank retreat on all the studied banks built of medium gravels was 0.7 mm after the first active phase (swelling predominated), 3.2 mm after the second , 20.5 mm after the third and 24.3 mm after the fourth. The mean value of total bank retreat after the study period was 48 mm.

Frost phenomena on river banks composed of coarse gravel

The studied banks are composed of pebbles 5-10 cm, maximum 35 cm, in size, packed in sand or clayey sand. The gravels on the banks of the Czarny Dunajec were less consolidated than those on the banks of the Cichy. The amount of bank retreat was not related to the degree of consolidation. The loss by erosion on the Czarny Dunajec was greater in those places where the coarse pebbles were set in sand devoid of clay. Frost phenomena became manifest during each of the active phases. The mean value of bank retreat for all the studied banks built of coarse gravels was 20.7 mm after the first active phase (swelling predominated), 0.3 mm after the second, 148.4 mm after the third, 45.8 mm after the fourth and 57.2 mm after the fourth. The mean value of total bank retreat after the study period was 231 mm.

Frost phenomena on rocky river banks

Sandstone and shale exposures in the studied banks of the Ropa (sites 26 and 27) were less eroded than those in the banks of the Cichy stream (site 28). The difference was even more than tenfold and it was most likely caused by uneven density of joints in the exposed rocks at the studied sites. Intense erosion of this bank was especially significant during two such phases (fig. 8E). The bank retreated by 18.8 cm during the second phase and by another 4.2 cm during the fourth phase. Erosion of sandstone layers was uneven in space, controlled, among others, by layer thickness and by nature of joints as well as by the occurrence of the sandstone layers as single layers or groups of layers among the accompanying shales. The shale layers, thinner and densely fractured, were more susceptible to erosion. The volume of scree from shales was smaller than the volume of sandstone grus. The mean value of bank retreat for all the studied banks cut in bedrock was 6.8 mm after the first active phase, 41.6 mm after the second, 25.7 mm after the third, 26.8 mm after the fourth and 209.1 mm after the fifth. The mean value of total bank retreat after the study period was 310.0 mm.

DISCUSSION

Frost phenomena destroyed the studied banks unevenly. The banks composed of alluvial clays retreated at a similar rate over the whole height of the scarp (fig. 9A). The high content of fine grains (especially those smaller than 0.02 mm) facilitated capillary forces of ground water (Kaplar, 1974; Glinicki, 1983; Berg & Johnson, 1983; Chen & *alii*, 2004; Szymański, 2007), so that the bank surface swelled upon bank freezing. Ice destroyed fabric of the clay with a network of ice needles, resulting also in exfoliation of surface layers (Teisseyre, 1979). Freezing of water within clayey-silty sediments occurs only at air temperatures below -5 °C (Grabowska-Olszewska & Siergiejew, 1977; Teisseyre, 1979; Migoń, 2006); it is delayed relative to sands and gravels where it starts at temperatures -0.1 to -1.5 °C. This is why frost action was more pronounced in sandy clays (site 1, Fig. 2), which also contained more free water which was converted to needle ice upon freezing. The more silty and argillaceous clays became covered with a dense and irregular network of fractures, widening toward the surface. Upon thawing, brittle multifaceted lumps of clays were falling from the steep surface of the bank and accumulated in debris fans at its base. It should be noted, however, that susceptibility of sediments to fracturing under the action of multigelation is variable, a largely depending on initial moisture conditions of the ground (Thorne & Osman, 1988; Thorne, 1990; Przedwojski, 1998). Othman & Benson (1993) recorded large increase in water conductivity and formation of a fracture network already after the first freezing-thawing cycle.

Erosion proceeded selectively on the banks composed of poorly sorted gravels. Sand grains and fine clasts in the matrix between the bigger pebbles were loosened first. The bigger pebbles were mobilized only after them. The large clasts sliding or rolling down the slope destabilized by direct collisions other clasts on their way down. The other clasts were thus detached and all of them gathered in debris cones at the base of the banks (fig. 9B). Differences in the rate of erosion within fine, medium and coarse gravels are probably caused by the differences in amounts and in granulometric composition of the matrix between the pebbles. Gravels rich in fine-grained components in the matrix swelled on the bank surface upon freezing. Upon thawing individual pebbles and detached gravel packets slid down to the base of slope. These processes were intense and they

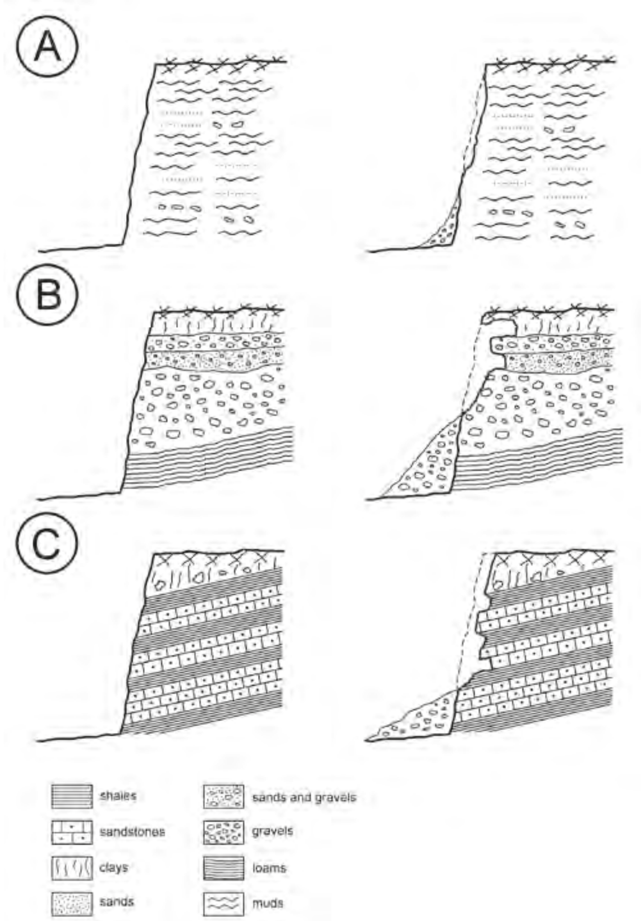

FIG. 9 - Schematic diagram showing retreat of banks of various structure.

probably are responsible for the fastest erosion of the banks composed of fine, clay-rich gravels. In sandy gravels, where adhesion water freezes easier than in clays (Glazer, 1985; Szymański, 2007), cohesion of sediment weakened faster, resulting in pebbles being pushed away toward the surface. Downfall of individually detached pebbles and sand grains toward the bank base was the predominant process in such gravels. Upon thawing, large slabs of gravels slid down locally, detached along vertical surfaces from the still frozen gravel. Frost action on flysch exposures was also selective. Densely fractured shales, fell first. During the first active phases no sandstone grus was present in the scree fans. Only after the shales had fallen apart did the overlying sandstone slabs loose support and fall down to the bank base (fig. 9C). The reason for the variation in the scale of bank erosion at individual sites is likely the uneven density of fractures in flysch rocks at the studied sites (Dione, 1983; Lautridou, 1988).

The banks with heterogeneous structure were destroyed most efficiently near their upper edges (fig. 10). This was the effect of freezing proceeding from two directions: from the scarp front and to a lesser degree from the upper surface, covered with snow. The ground in this zone was frozen to the greatest depth. Moreover, these parts of banks are usually composed of finer-grained material. The only protection against falling apart was provided by root systems of plants, but it usually was not enough to protect the margin efficiently during the warmer season (Thorne, 1982; Abernethy & Rutherfurd, 1998; Hubble & *alii*, 2010). The frost processes in the lower parts of the banks proceed in a more complex way, depending also on other factors than the granulometric characteristics of sediment. Literature data point to the role of sediment wetness. In porous sediments where capillary forces and the growth of needle ice may easily occur, the amount of water in void spaces is decisive for the rate of the frost processes (Lawler, 1986; Thorne & Osman, 1988; Thorne, 1990; Krantz & Adams, 1996; Przedwojski, 1998; Prosser & *alii*, 2000; Matsuoka, 2001; Chen & *alii*, 2004; Vlahou & Worster, 2010). Also important are the number of the freeze/thaw cycles during a cold season (Martini, 1967; Potts, 1970; Teisseyre, 1979), the presence of snow cover (Jahn, 1970; Teisseyre, 1979) and the value of temperature drop near the ground surface. According to Walder & Hallet (1985) frost weathering is the most intense at temperatures between -4 °C and -15 °C. The effects of the frost processes may markedly differ even over small distances of the bank surface. The number of temperature oscillations across the 0 °C value is usually similar, hence the differences in the effects of frost processes are more likely due to uneven cementation of the substrate. Poorly cemented gravels or densely jointed solid rocks are eroded more intensely. The rate of erosion is greatest during thaw when augmented by weakening of the sediment fabric and by the flow of melt water (Yumoto & *alii*, 2006).

CONCLUSIONS

Erosion of alluvial banks due to frost processes proceeded mainly when the bank surfaces thawed.

The amount of erosion is clearly dependent on the granulometric composition of the sediments. The most affected by erosion related to frost processes are banks built of fine clayey gravels, and the least affected are the banks composed of medium sandy gravels.

A layer of alluvial clays appeared more resistant to frost phenomena than fine and coarse gravels embedded in a sand layer, which contradicts our initial expectation.

Alluvial clays swelled and fractured upon freezing, then intensely disintegrated into lumps that fell down by gravity.

No frost heave was observed on the surfaces of sandy gravels. Measurements on erosion pins revealed erosion of the banks only during their thawing and drying up. Frost heave was present on clayey gravels.

Uneven erosion of sediment layers built of various size fractions resulted in uneven profiles of the banks.

Clayey matrix reduces the rate of frost erosion of river banks.

Determination of the effectiveness of frost phenomena in erosion of river banks requires farther studies. Studies should be extended to the entire hydrological year to de-

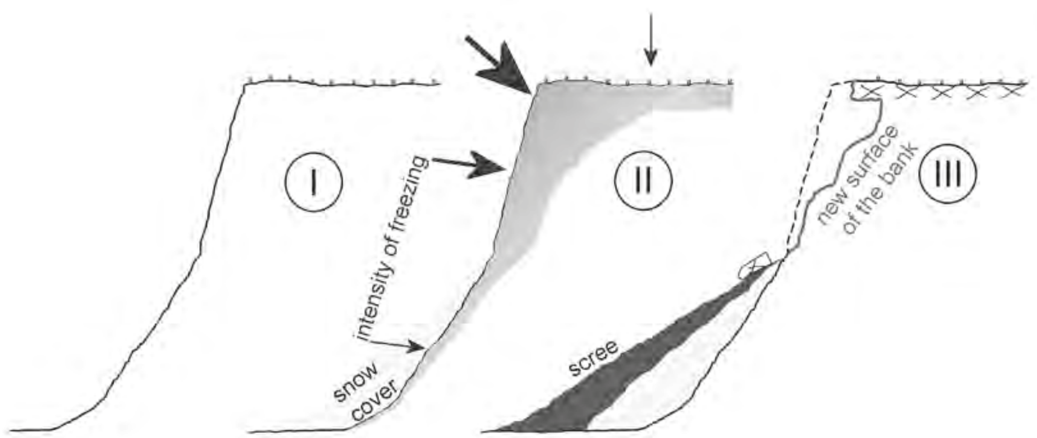

FIG. 10 - Schematic diagram of fluvial terrace scarp evolution under the action of frost phenomena.

termine the share of frost processes in the general balance of river bank erosion. Especially useful would be studies in the years lacking in high water stages and in the years with high water stages. How large should be share of frost processes in those years?

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