PRACE GEOGRAFICZNE, zeszyt 104

Instytut Geografii UJ
Kraków 1999

Kazimierz Krzemień

STRUCTURE AND DYNAMICS OF THE HIGH-MOUNTAIN CHANNEL OF RIVER PLIMA IN THE ORTLER-CEVEDALE MASSIF (SOUTH TIROL)

Abstract: The paper characterises the structure of a proglacial mountain channel system in the Italian Alps. The geomorphologic effects of catastrophic floods and channel management have been presented, based on research conducted between 1987 and 1995.

Key words: proglacial channel system, channel typology, Italian Alps.

1. Introduction

The knowledge about high-mountain channel structures is still limited. So far, the majority of fluvial research has focused on the glacier foreland and dealt with transportation of mainly fine material and the channel development and variability. The entire high-mountain channel systems were researched by J. Tricart and his team (1962). In view of the current state of research, knowledge about the complex structure of the entire fluvial system in a given basin or region must be furthered if these catastrophic events are to be prevented more effectively.

The objective of the research carried out in Val Martello, Italy, were to investigate the River Plima channel structure before and after the flood of 1987, and the effects of the channel engineering in its middle and lower course.

2. Research method

Field research was conducted in the first half of August 1987 and in the first half of August 1995. In 1987 the entire length of the river Plima (Rio Plima) channel, beginning at the Lunga glacier front was mapped and described (Vedretta Lunga). The 26.4 km of the stream length was divided into 24 reaches (Fig. 1). The reaches of the stream were delimited on the basis on the channel pattern and land features within the channel, while the description was based on the notes on the channel characteristics,

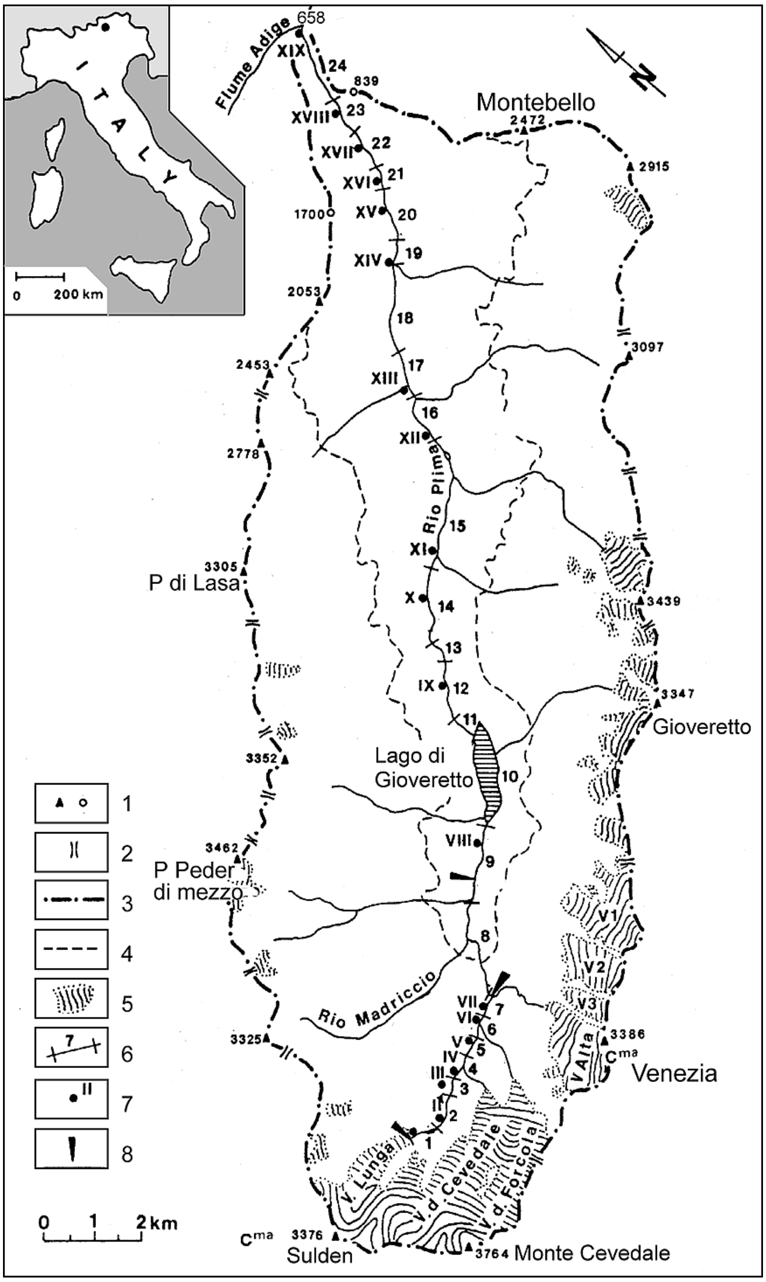


Fig. 1. Plima stream catchment: (1) – major peaks and elevations, (2) – mountain passes, (3) – catchment boundary, (4) – timberline, (5) – glaciers, (6) – reach numbers and boundaries, (7) – bed rubble measurement sites, (8) – discharge measurement sites, V1 – Vedretta di Grámes, V2 – Vedretta Serrana, V3 – Vedretta Ultima.

land features and the channel bed material. This method, developed in the Carpathian Mountains (Kaszowski, Krzemień 1977), had been proven applicable to other areas after its use in the Alps. The same 27 sites were used for the following measurements: bed material grain-size distribution (M.G. Wolman method 1954); water discharge (float method); and the content of the dissolved and suspended material (one-litre water samples).

In August 1995 the supplementary research was carried out. It consisted of mapping the Plima channel reaches changed by the 1987 flood and the subsequent channel engineering (reaches 12-21). The transportation of the dissolved and suspended matter, was periodically measured at the Lunga glacier foreland and along the stream course, in the clear sky condition, i.e. when the glacial ablation was at its most intensive.

Topographical maps 1:25000 and 1:50000, and the C. Adreatta 1:100000 geological map were useful for this study.

3. Research area

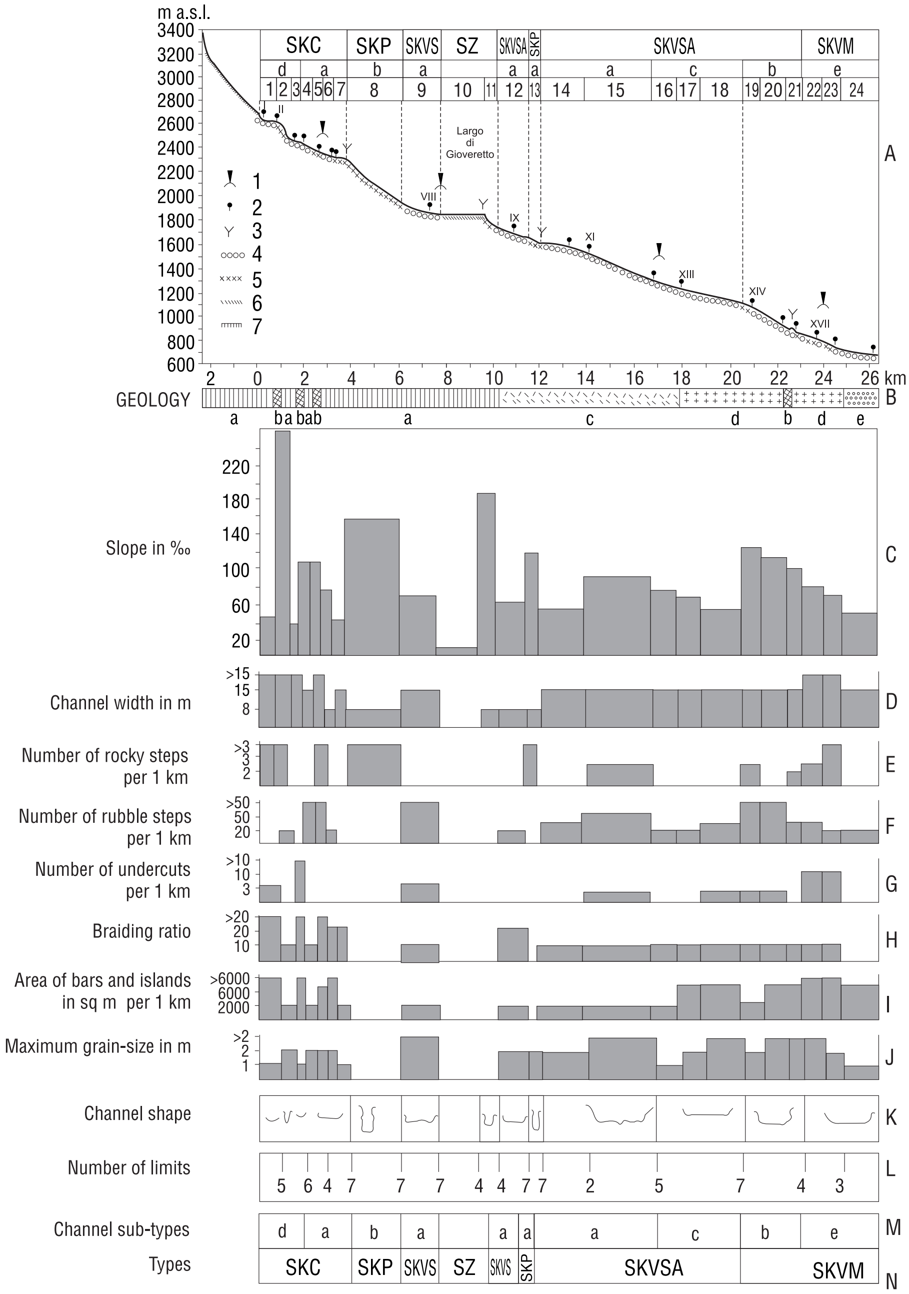
The Ortler-Cevedale Massif, which culminates in the peaks of Ortler (3899 m) and Cevedale (3764 m), and encompasses the dello Stelvio National Park, is part of the Italian Central Alps (Desio 1967). The massif is radially cut-up with several deep valleys including the Martello Valley (Val Martello) in the Northeast.

The Plima stream catchment covers an area of 162.2 km^2 at the altitude of 658-3754 m. The stream's upper course cuts mainly through quartz phyllite and chlorite shale rocks with marble bands. In the middle course, the valley is cut in orthogneisses, granitoides, and granitodiorites. The entire lower section of the valley is cut in paragneisses and chlorite shales with bands of marble (Andreata 1951, see Pozzi 1969; Fig. 2).

The Martello valley is a typical glacial trough with several forms and deposits from the last glaciation period (Rączkowski, Rączkowska 1993). The contemporary glaciers are short, reaching down to an altitude of 2659 m and covering 11% of the valley area (Valentini 1985). The morphology of the Martello valley is strongly related to the geological structure, as well as to the Quaternary deposits. Generally, the valley floor is narrow (100-250 m), with a few wider sections reaching up to 400 m. The entire valley can be divided into a number of reaches marked by distinct steps, as seen on the valley long profile. In its upper section, the Val Martello forms a vast and complex glacial cirque with two distinct, marble interlocking spurs - roche muttonés. At 2300 m, after a steep, 350 metres high, threshold, the cirque turns into a narrow glacial valley with suspended valleys on its sides. The threshold, also muttonéed, consists of metamorphic slates. Further down, the valley long profile reveals three distinct steps: one man-made (at the Lago Gioveretto dam, 1850 m) and two structural (at about 1680 and 1100 m).

The valley long profile shows the presence of recessive moraines, which, however, do not influence the channel structure in any significant way (see Fig. 2).

Both the climate and the vegetation display the characteristic vertical zonality. Forests, which reach up to 2300-2400 m, consist of spruce in the lower tier, and larch



m a.s.l.
SKC
SKP
SKVS
SZ
SKVSA
SKP
SKVSA
SKVM
Largo di Gioveretto
A
GEOLOGY
B
Slope in ‰
C
Channel width in m
D
Number of rocky steps per 1 km
E
Number of rubble steps per 1 km
F
Number of undercuts per 1 km
G
Braiding ratio
H
Area of bars and islands in sq m per 1 km
I
Maximum grain-size in m
J
Channel shape
K
Number of limits
L
Channel sub-types
M
Types
N
km

and stone pine in the upper tier (Pirolla 1960). Above the timberline, forests are superseded by high alpine meadows and, further up, by mosses and lichens. The snow-line varies from 2935 m on the north facing slopes, to 3100 m on the south-western slopes (Valentini 1985). The mean annual temperature crosses the freezing point at 2300 m. In the summer season, below-zero temperatures occur only in the highest parts of the Ortler-Cevedale Massif (Desio 1967). The area belongs to the rather dry part of the Alps (Gabert, Guichannet 1965). With the annual totals rarely exceeding 1000 mm, and sometimes as low as 500 mm, it is characterised by low annual precipitation in comparison to the surrounding areas. The annual precipitation pattern points to August as the wettest month, with June and July trailing close behind.

The Rio Plima has a hydrological regime typical for proglacial streams. Just as in other Alpine regions, mean monthly river flow increases in May-July/August and then decreases until October (Maizels 1978) to reach very low values for the remaining period. The river Plima water discharge values measured during the period of intensive ablation (10 August 1988) were as follows: 3.2 m^3s^{-1} near the front of the Vedretta Lunga, 8.9 m^3s^{-1} below the Vedretta Alta tributary; and 10.8 m^3s^{-1} before the mouth at the Lago Gioveretto. Below the lake, the stream's hydrological regime is disturbed as the result of the water transfer via a system of shafts to the neighbouring valley of Lasa and further down to the Adige valley (Carta Turistica). Additionally, below the dam, water is drawn from the stream at the beginning of reach 14 and in the middle of reach 21, below which the channel becomes dry.

4. Channel characteristic and typology

During the field research the Plima channel was divided into 24 reaches and each of them was described (Fig. 2.). The typology was based on the method of channel reach boundary analysis (Kaszowski, Krzemień 1999) and was conducted in the following stages: First, all 24 reaches were compared for the measured values and geology (Fig. 2.). Next, the number of boundaries in each reach were compared and assessed for significance, with those occurring most frequently adopted as boundaries

Fig. 2. Plima stream typology and structure (A): (1) – recessive moraines, (2) - bed rubble measurement sites, (3) – artificial reservoir dams, (4) fluvioglacial and moraine covers, (5) – rocky outcrops, (6) – lacustrine covers, (7) – glacier (Vedretta Lunga).
Channel types: SKC – glacial cirque type, SKP – glacial thresholds, SKVS – glacial trough – moderately stable, SKVM - glacial trough – mobile;
Channel subtypes (channels displaying a tendency to): (a) – weak deep erosion, (b) – intensive deep erosion, (c) – moderate lateral migration, (d) - intensive lateral migration, (e) – intensive deep and lateral erosion, SZ – the Lago Gioveretto dam system.
Geology (B): (a) – quartz phyllites and chlorine shales, (b) – marbles, (c) – orthogneises, granitoides and granodiorites, (d) – paragneises and chlorine shales, (e) – alluvial fan fluvioglacial drift, (C) – slope in %, (D) – channel width in m, (E) – number of rocky steps per 1 km, (F) – number of rubble thresholds per 1 km, (G) – number of undercuts per kilometre(H) – braiding ratio (number of medial bars and islands per 1 km), (I) – area of middle bars and islands per 1 km, (J) – largest grain-size in m, (K) – channel shape, (L) – number of limits, (M) – channel subtype, (N) – channel type.

of channel types, and those less frequent the boundaries of sub-types (Fig. 2.). The procedure yielded the typology of the Plima fluvial system consisting of four channel types: (1) glacial cirque, (2) glacial threshold, (3) glacial trough - relatively stable, and (4) glacial trough – mobile. The five subtypes were found to display the following tendencies: (a) weak deep erosion, (b) intensive deep erosion, (c) moderate lateral erosion, (d) intensive lateral migration, and (e) intensive deep- and lateral erosion.

4.1. Glacial cirque channels

This type is represented by reaches 1-7 (Phot. 1, 2, 3). The channel shape varies strongly, is generally shallow (0.1 - 0.8 m), and cuts into moraine and fluvioglacial deposits as well as into the solid rock. It comprises alternating straight and braiding stretches, thus revealing a strong relation to the bedrock profile in the valley floor. This type has been subdivided into two subtypes: (a) and (d).

The channel of the subtype (d) (reaches 1-3) is unstable and frequently changes in planform. The braiding reaches 1 and 3 have no equivalents further down the Plima stream, whereas there are similar, if less well developed, channels at the foot of the adjacent glaciers like the Vedretta Alta, Vedretta Forcola and Vedretta del Cevedale (Phot. 1). They are very deep and filled with fluvioglacial material. In 1889, the entire reach no. 3 was occupied by a lake (Lago dei Detrici) right next to the glacier snout (Finsterwalder 1890, see Desio 1967). In 1927, the glacier snout reached to the middle of reach 2 and in 1941 to the bottom of reach 1. The present processes include accumulation of mainly gravel and stone fractions in the foreland of the glacier, along the reach 1, the grain-size quickly decreasing down to dust downstream. At the bottom of reach 1 the finest material undergoes compaction and load casts are formed. The larger grain-size does not reach past this point which is the reason the rocky threshold in reach 2 is not subject to intensive incision as water spreads on the threshold at the width of 25 m and uses natural channels between the roche mutonées.

The (a) type channel is moderately stable, and is not subject to any major pattern changes. Any modelling in this reach is the result of weak deep erosion, the eroded material rarely exceeding the 15-cm size.

4.2. Glacial threshold channel

Channels of this type (reaches 8 and 13) are cut in solid rock down up to 15-25 m. (Phot. 4). The channel of reach 13 is cut in granitoides, and includes rocky thresholds up to 20 m high. The supply of debris is very small and the channel is modelled mainly by weak deep erosion. The channel of reach 8 zigzags following the natural crevices and cracking in the metamorphic slates, which form the bedrock of the entire reach. The stream runs in a deep, 15-25 m, gorge with numerous rocky thresholds and steep, frequently overhanging walls. In this reach the channel receives a supply of fresh, sharp-edged debris which is efficiently broken-up and transported away, particularly during high water.

4.3. Glacial trough channel - moderately stable

This type is represented by reaches 9, 12 and 14-18 where the channel cuts in the moraine and fluvioglacial material. This type has been broken up into two subtypes, (a) and (e), which differ in both their morphology and dynamics (Fig. 2.).

In the subtype (a) there are distinct rubble thresholds based on moraine boulders of 0.5-2.0 m diameter. The largest of these boulders are covered by lichens and even moss, which testifies to their stability. Such thresholds are characteristic for glacial valley channels found elsewhere (Day 1972; Kellerhals 1972; Krzemień 1985, 1991). Along this reach the Plima channel cuts down to 1.2-3.0 m, its banks are strengthened with shrubs and trees, and the occasional sandbars measure 15x3 m on average. The subtype morphology closely resembles that of the channels in the glacial valleys in the Western Tatras (Krzemień 1985; Kotarba et al 1987), particularly in reaches 14 and 15. Weak deep erosion dominates and, as the supply from the banks is limited, the majority of the material transported out (mainly fine fraction) comes from the bed itself; it is deposited partly in the subtype (c) reach below.

The subtype (c), in reaches 16-18, is characterised by the much larger size of the sandbars (25x5 m on average), and the increased proportion of small, 20-30 cm, grain-size, compared to the subtype (a). Reaches 16 and 17 below the recessive moraine in the wide part of the valley had been narrowed and partly stabilised with a stone and concrete embankment and the larger boulders within the channel had been secured to one another. The flood of the 24 and 25 August 1987, however, destroyed this system. The destruction was most severe in reach 16, at the beginning of the valley widening, where the energy of the stream coming out of a narrow gorge was at its highest. The (c) subtype channels normally occur either immediately after the narrow and well-armoured subtype (a) channels, or the above the distinct steps in the valley floor. Their moderate dynamics is connected with in the periodic lateral migration.

4.4. Glacial through channel – mobile

This type occurs in the lower part of the Plima stream, in reaches 19-24. The channel in these reaches cuts down to 3-8 m in moraine and fluvioglacial deposits and partly into solid rock. Many of the rubble thresholds are based on moraine boulders up to 2-2.5 m in diameter. The channel rubble, including boulders, was light-coloured and not covered in algae or lichens. Some of the 0.5-1.0 m boulders were imbricated. There were very few 1-2 m boulders occurring in an unstable position on the 20-30 cm rubble. This type was divided into two subtypes: (b) with a tendency to intensive deep erosion (reaches 19-21); and (e) with a tendency to intensive deep erosion and lateral erosion (reaches 22-24).

4.5. Glacial trough channel, antropogenic - moderately stable

After completion the mapping of the middle and lower part of the Plima stream the typological procedure was repeated (Fig. 4.). As the result, fifth type of channel and two subtypes were determined. The new type was glacial trough channel, antropogenic - moderately stable and the subtypes: (a) with the weak deep erosion tendency, and (f) with the moderate deep erosion tendency. The reaches representing the new channel type are No 12 and 14-21, below the Lago Gioveretto where the channel has been transformed by human activity. The artificially made channel has a tapered shape, depth of 2-5 m and width of 14-21 m. It has been encased in blocks of stone and artificial rubble thresholds (0.5-1.0 m high on average) have been erected in a manner emulating the natural ones (Phot. 5, 6). Reaches 12 and 14-18 belong to subtype (a), and reaches 19-21 to subtype (f).

5. The channel rubble

Rubble along the Plima channel is highly diverse (Fig. 3.). The average maximum grain-size is 0.51-2.27 m and consists mainly of moraine boulders, which may be transported during particularly high water. The grain-size of the rubble is related to the geology the valley floor. In moraine deposits or steep reaches the proportion of large fractions increases and that of smaller ones - decreases (Fig. 3). In the reaches where fluvial transportation occurs more frequently and almost all of the channel material can be carried by water, the proportion of smaller fractions increases downstream replacing the larger fractions (e.g. reaches 3, 7, 17, 18, 23, 24). The falling values of standard deviation in these reaches indicate an increasing degree of material grading.

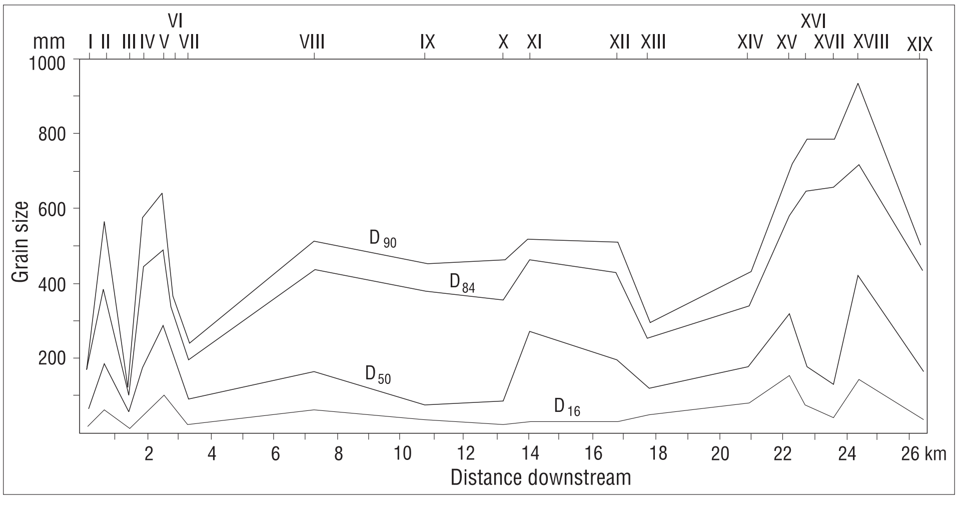


Fig. 3. Rubble in the Plima stream. Mechanical composition in the long-profile.

6. Channel dynamics

During the daytime glacier ablation the dissolved material concentration varies from 38 to 48 mg l^{-1} at the foot of the Vedretta Lunga. Downstream, at Lago Gioveretto these values decrease to 35-43 mg l^{-1} to rise slightly again to 53 mg l^{-1} in the locality of Martello. The concentration decrease in the stream upper course is the result of tributary streams, also of proglacial type, which transport considerably smaller concentrations (22-32 mg l^{-1}). The dissolved matter concentrations are typical for crystalline massifs (Vivian 1970; Caine 1974; Krzemień 1992).

Concentration of suspended material, measured at the same time, reached 1092-1457 mg l^{-1} at the glacier front. Downstream it was gradually falling to 805 mg l^{-1} at the Lago Gioveretto, and 3-5 mg l^{-1} below Martello. This leads to the conclusion that the suspended material is sedimented mainly between large clastsland rubble and in the reservoir. Other proglacial streams carry a much less suspended load (30-695 mg l^{-1}). The amount of suspended load transported by the Plima stream and its tributaries should be regarded as rather small. The suspended matter concentrations in this area are similar to those in the proglacial streams of the Valais Alps, where the values vary between 100 and 3000 mg l^{-1} with the maximum of 14145 mg l^{-1} (Gurnell 1982; Fenn, Gurnell, Beecroft 1985; Gurnell 1987).

During the field research, transport of the bedload material occurred only between the Vedretta Lunga and Lago Gioveretto. The material carried out of the glacier was of fine fraction - gravel and sand. Further downstream the material transported diminished in size to sand and sporadically to gravel (up to 2-cm). Fine, sand/dust material was observed to accumulate between boulders; every day this material was triggered and successively carried downstream. No transportation of bedload material was observed below Lago Gioveretto. However, the existence of fresh rubble bars and the markedly imbricated largest fraction allowed certain conclusions as to the type of material transported during particularly high water. According to measurements the Plima can transport relatively large size material: below 20 cm in reaches 1-7; up to 30 cm in reaches 9-12; up to 50 cm in reaches 12-15; up to 80 cm in reaches 16-18; and above 100 cm in the reaches below. Probably the latter size of material cannot be transported over long distances.

The most significant deep erosion and local lateral erosion-induced transformation of the Plima channel occurs only during catastrophic floods, as a result of glacier ablation or torrential rainfalls. Glacier-triggered floods, referred to in the French literature as „débâcles glaciaires", are related to a blockage and then sudden unblocking of a valley by a glacier or large blocks of ice, as well as blocking and then sudden unblocking of channels within a glacier (Vivian 1974, 1975). Hundreds of thousands, and sometimes millions of cubic metres of rubble is being moved during this type of flood. In the area studied such floods occurred in 1887, 1889, and 1891 (Vivian 1974). They should be considered responsible for the build-up of the vast alluvial fan of the Plima deposited below a recessive moraine ridge in the Little Ice Age (reach 6). It was to protect the

Martello valley against such floods that the water dam was constructed on a bedrock step at 2300 m in 1893. Indeed, it was found no evidence of rubble accumulation below the dam, which suggests that no flood of the mentioned type occurred in the valley after the completion of the dam. In other Alpine areas the „débâcle glaciare" type of flood occurs at various rates, from one in a few hundred years to 40 in 310 years (Vivian 1975).

Since then any catastrophic flooding in the area has been related to the torrential rains. The flood of November 1966 in the upper Adige, well documented in geographical literature, occurred as the result of rainfall which totalled 200 mm between 3 and 6 November; a number that equalled 22% of the annual precipitation value (Castiglioni et al 1974). At the time in the Plima channel, depth and lateral erosion occurred between the Lago Gioveretto and the mouth of the valley and in three right-bank tributaries. Large amounts of material were accumulated on the Plima alluvial fan in the locality of Mortel (reach 24) (Castiglioni et al 1974). Another flood, on 22 May 1983, proved particularly destructive in the lower course of the Plima and in Val Venosta (Chardon, Castiglioni 1984). The last big flood in the Martello Valley was triggered by the torrential rains of the 24-25 August 1987. While there is no precipitation data for the area, 90 mm of rain a day fell in the adjacent Ötztal Alps at the same time (Ganahl 1988). The flood caused a large build-up of alluvial fans by streams running into the Lago Gioveretto and intensive depth- and lateral erosion downstream from the lake. At the end of reach 14 the stream channel was widened. Further down, reach 16 proved to have been the most affected with a road bridge destroyed and a few buildings damaged (Phot. 6). Substantial changes to the channel occurred in reaches 19-24. Being regular feature of floods, the intensive deep erosion could have been expected, but the substantial channel migration in reaches 16 and 17 came as a surprise. Perhaps, the stream engineering had curbed the natural susceptibility to migration in these reaches, which was clearly manifested again during the catastrophic flooding.

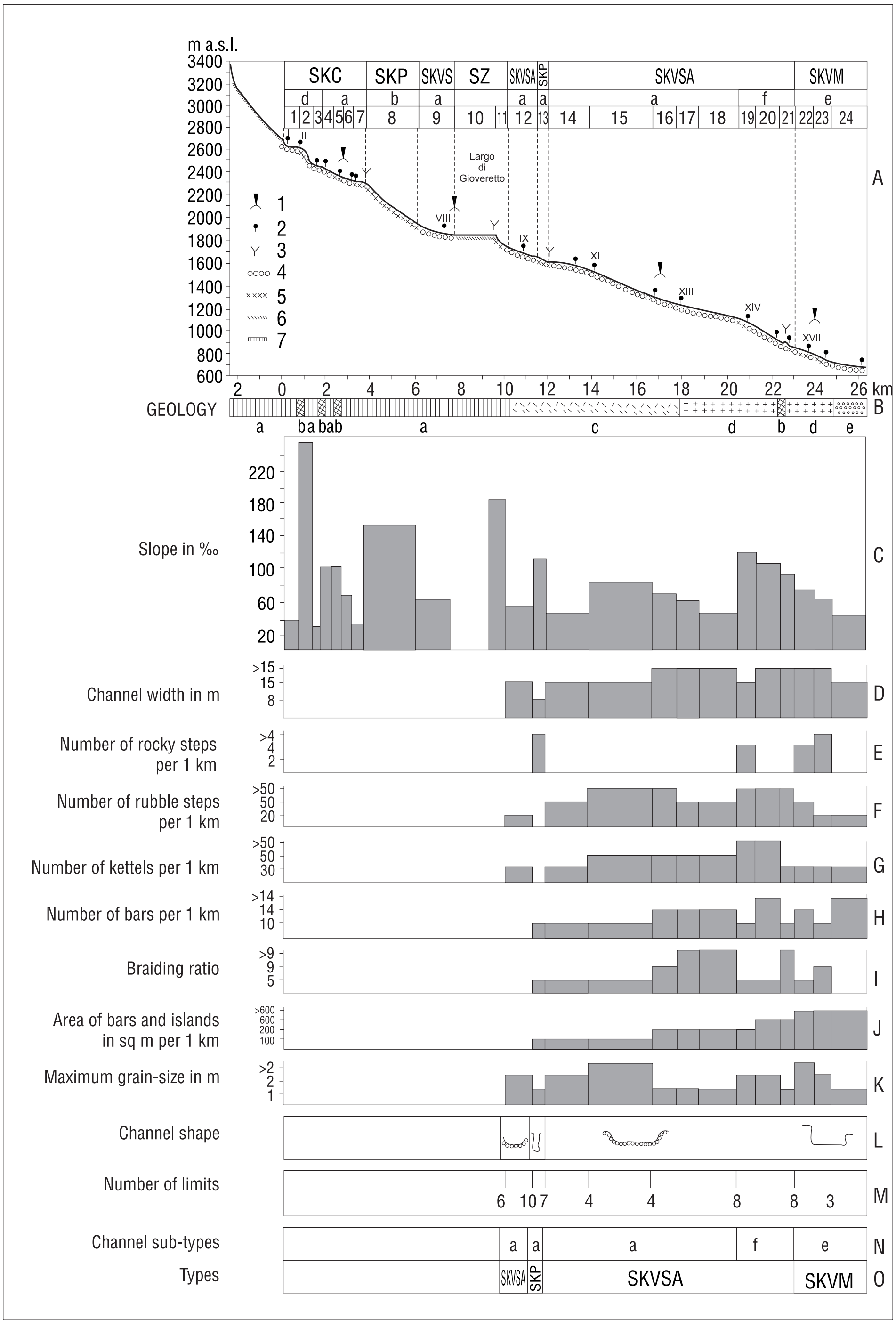
The contemporary modelling processes in the long profile vary considerably (Fig. 2.). Similarly, as in other proglacial streams they consist mainly in the transportation of fine material and armouring of the channel (Fahnestock 1963). The intensity of these processes increases markedly downstream both in the glacial cirque and below the Lago Gioveretto. In the glacial cirque, the rubble removed from the glacier is deposited along the less steep stretches of the channel, within the flatter parts of the valley (Phot. 1.). Fine material from the eroded thresholds is gradually transported downstream, whereas only during catastrophic flooding can the larger fractions be moved, usually up to 200-300 m, and deposited in the form of large alluvial fans (Phot. 3.), which are then subjects to systematic washing-out, lasting for decades. On the rocky thresholds, channels undergo an intensive deepening process. The suspended and bedload material removed from the upper part of the catchment is deposited in the reservoir. The channel below the Lago Gioveretto shows the tendency to armouring. Fines form the channel and the tributaries are successively transported downstream. The sudden increase in competence of the stream in the lower course causes lateral- and intensive deep erosion, while the blocking of the Plima reserve channels increased deep erosion on the alluvial fan and caused transportation of larger fraction, up to 50 cm, into the Adige.

Following the 1987 flood, river engineering works started, beginning form reach 21 up to the Lago Gioveretto: the channel was encased in stone blocks and straightened (Phot. 7-9), and the banks were additionally strengthened with alder trees. The work carried out upwards from the bottom of reach 21, was completed in 1995. The channel cross-section was given a regular trapezoid shape along the entire stretch (Fig. 4, Phot. 9), while in the long-profile artificial rubble thresholds were added in the steeper parts. The new thresholds, which are 0.5-1.0 m high and 5-15 m apart, have been made of boulders and blocks to resemble the natural ones. A single reinforced concrete dam has been placed at the beginning of reach 16 (above the Martello village) to absorb the impact of the water with clasts. The transformations of the Plima channel during the flood and the subsequent engineering have changed the channel structure in the middle and lower part of the stream (Fig. 4.) resulting in an entirely antropogenic glacial trough channel system with two subtypes: (a) – stable, and (f) – unstable. In the lowest part of the regulated stretch, below the artificial thresholds, the deepening of eddy holes and the emergence of numerous gravel bars can already be observed. This is due to the fact that the contemporary Plima channel modelling consists mainly of fine material removal and bed armouring, resulting in the channel migration tendency in the lower part of the stream (Phot. 10). Before the regulation, the Plima channel long-profile maturing process took part in various reaches, depending on the local base-level of erosion. In each of the reaches it consisted of a selective removal of material in the top part of a reach and its deposition in the bottom part, above the valley thresholds. After the regulation this process continues upstream the Lago Gioveretto, whereas below the lake the channel develops in this way along its entire length. Considering the increase in the channel gradient and the inadequate restriction placed on the movement of large fraction rubble, the controlled stream channel can be expected to start braiding again. If the rubble threshold spacing had been better adjusted to the slope gradient the stream management could have been more effective.

7. Conclusions

The channel type boundaries are clearly related to the valley step structure (Fig. 2.). The channel structure is not affected by the frontal moraines, which are in most cases dissected down to the bedrock, with the exception of just one frontal moraine – at 1300 m.

The Val Martello channels develop their long-profile equilibrium in various reaches simultaneously, according to the local erosion base level. The stage achieved and the rate of this process depends on the formation duration, since channels develop gradually as glaciers retreat. Channel reaches achieve their equilibrium through the process of selective material removal from the top sections and deposition in the bottom section, above the valley bedrock thresholds. Another way, in which the local channel development manifests itself, is the process of removing fine material from recessive moraines and depositing it on their foreland. The entire channel long-profile develops


m a.s.l.
SKC
SKP
SKVS
SZ
SKVSA
SKP
SKVSA
SKVM
Largo di Gioveretto
1
2
3
4
5
6
7
km
GEOLOGY
Slope in ‰
Channel width in m
Number of rocky steps per 1 km
Number of rubble steps per 1 km
Number of kettels per 1 km
Number of bars per 1 km
Braiding ratio
Area of bars and islands in sq m per 1 km
Maximum grain-size in m
Channel shape
Number of limits
Channel sub-types
Types
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O

its equilibrium in the process of valley threshold erosion without any significant disturbance of the smoothed-out profile between the local erosion base lines.

At present, the most intensive transformations in the Val Martello channels occur in the lower and upper courses of the Plima stream. However, the transformations in these two parts vary both in quantity and quality: In the former the changes are driven mainly by the large discharge rates during heavy precipitation, high slope gradient and large erosion yield from the bed and banks. In the latter case, the glacier ablation rate and the amount of material carried to the foreground of the glacier are the crucial factors.

The fluvial processes in the Val Martello vary significantly depending on the altitude. The glacier morphodynamic system weathering products are supplied mainly to the Lago Gioveretto, while the debris rate of removal from the entire catchment is rather low, as the result of low slope material supply and the existence of the reservoir. The material carried out of the Martello valley comes mainly from the Plima channel and its immediate vicinity.

After the 1987 flood and the water management work, the Plima stream channel structure has undergone an unprecedented transformation. The effectiveness of these changes will not be verified until the next flood. From the point of view of the dynamics of the morphogenetic processes the regulation efforts have been, by and large, correct because they followed the original channel morphology. Here, the building of artificial rubble thresholds following their natural shape is of particular importance. Although if their spacing had been better adjusted to the channel slope the effectiveness of the regulation would have been even greater.

The field research carried out in the Val Martello and the literature on the region, lead to the conclusion that the channel structure changes may only result from catastrophic floods. Research carried out in the last few decades suggests that such floods may change channel structures below the Lago Gioveretto and in the immediate foreland of the Lunga glacier (reach 1). The remaining part of the channel system shows a high degree of stability which results from the fact that: (1) no „débâcle glaciaire"-type of floods have occurred since the end of the Little Ice Age, and (2) the largest of foods occur in the lower parts of the Ortler-Cevedale Massif, because of a precipitation inversion above the timberline.

The research carried out so far on the northern and southern sides of the Ortler-Cevedale Massif, i.e. in the Val Martello and the Val di Peio (not discussed here) respectively, leads to the conclusion that both the mode and rate of fluvial modelling in the massif valleys are similar.

Fig. 4. Plima stream typology and structure after the 1987 flood. (A): Channel types: SKVSA – glacial trough, anthropogenic – moderately stable. Subtypes (channels with a tendency to): (a) – weak deep erosion, (f) – moderate deep erosion, (B) – geology, (C) – slope, (D) – channel width, (E) – number of rocky steps per 1 km, (F) – number of rubble thresholds per 1 km, (G) – number of eddy holes per 1 km, (H) – number of bars per 1 km, (I) - braiding ratio, (J) – area of middle bars and islands per 1 km, (K) – largest grain-size in m, (L) – channel shape, (M) – number of limits, (N) – channel subtype, (O) – channel type, other elements as in Fig. 2.

Acknowledgements

My heartfelt thanks are first due to Stelvio National Park Authorities for their assistance in arranging my stay at Val Martello and a helpful agreement to my field research in the area. For their assistance in the Cevedale Massif research I want to thank the participants of the trip from the Kraków Branch of the Polish Earth Sciences Society, and specially my colleagues, Jerzy Wala, Henryk Burchard, Piotr Libelt and Marek Angiel. My thanks are due also to Zofia i Wojciech Rączkowscy for the long stimulating discussion about the research area.

References

Andreatta C., 1951, *Foglio "Monte Cevedale" della Carta Geologica delle Tre Venezie*, Scala 1:100000, Magistrato alle Acque di Venezia, Firenze.

Caine N., 1974, *The geomorphic processes of the Alpine Environment, Arctic and Alpine*, Environments, London.

Castiglioni G.B. Ferrari L., Mattana U., Nardin M., Pellegrini G.B., 1974, *Note di commento alla carta dell alluvione del novembre 1966 nel Veneto e nel Trento - Alto Adige: effetii morfologici et allagamenti*, La Calamita' Naturali Nelle Alpi, Novara.

Chardon M., Castiglioni G.B., 1984, *Géomorphologie et risques naturels dans les Alpes occidentales*, Studia Geomph., Carp-Balc., 18.

Day T. J., 1972, *The channel geometry of mountain streams*, Mountain Geomorphology, B.C. Geogr. Ser. 14, Novara.

Desio A., 1967, *I Ghiacciai del Gruppo Ortles - Cevedale (Alpi Centrali), Testo, Tavole*, Consiglio Nazionale delle Ricerche Comitato Glaciologico Italiano, Torino.

Fahnestock R.K., 1963, *Morphology and hydrology of a glacial stream - White River, Mount Rainier*, Washington, U. S. Geol. Survey Prof. Paper, 422-A.

Fenn C. R., Gurnel A. M., Beecroft I., 1985, *An evaluation of the use of suspended sediment rating curves for the prediction of suspended sediment concentration in a proglacial stream*, Geogr., Ann., 67-A, 1-2.

Gabert P., Guichonnet P., 1965, *Les Alpes et les états alpins*, Presses Universitaires de France, Paris.

Ganahl P., 1988, *Rückhalt eines hundertjährlichen Ereignisses durch die Speicher im Zillertal*, Internat. Symp. INTERPRAEVENT 1988, Graz, Tagundspublikation, Band 4.

Gurnell A. M., 1982, *The dynamics of suspended sediment concentration in an Alpine pro-glacial stream network, Hydrological Aspects of Alpine and High Mountain Areas*, IAHS Publ. 138.

Gurnell A. M., 1987, *Fluvial sediment yield from alpine glacierized catchments* [in:] A. M. Gurnell, M. J. Clark (eds), *Glacio-fluvial sediment transfer*, Wiley, Chichester.

Kaszowski L., Krzemień K., 1977, *Structure of mountain channel systems as examplified by chosen Carpathian streams*, Studia Geomorph., Carpatho-Balcan. 11.

Kaszowski L., Krzemień K., 1999, *Classification systems of mountain river channel, River channels – pattern, structure and dynamics* K. Krzemień (red), Prace Geogr., IGUJ, 104.

Kellerhals R., 1972, *Hydraulic performance of steep natural channels*, Mountain Geomorphology, B.C. Geogr. Ser. 14. Vancouver.

Kotarba A., Kaszowski L., Krzemień K., 1987, *High-mountain denudational system of the Polish Tatra Mountains*, Geogr. Studies, Special Issue, 3. Wrocław.

Krzemień K., 1985, *Present-day activity of the high-mountain stream in the Western Tatra Mts.,* Quaest. Geogr., Special Issue, 1. Poznań.

Krzemień K., 1991, *Dynamika wysokogórskiego systemu fluwialnego na przykładzie Tatr Zachodnich*, Rozpr. Hab. UJ, 215.

Krzemień K., 1992, *The high mountain fluvial system the Western Tatra perspective*, Geogr. Polonica, 60.

Maizels J. K., 1978, *Débit des eaux de fonte, charges sédimentaires et taux d'érosion dans le massif du Mont Blanc,* Revue de Géogr. Alpine, 66, 2, 1, Grenoble.

Pirola A., 1969, *Die Vegetation*, Der Stilfser - Joch - Nationalpark, Rovereto.

Pozzi R., 1969, *Geologie*, Der Stilfser - Joch - Nationalpark, Rovereto.

Rączkowski W., Rączkowska Z., 1993, *Rzeźba glacjalna doliny Martello (masyw Ortler-Cevedale, Alpy włoskie),* Folia Geogr., ser. Geogr.-Phys., 24-25.

Tricart J. et al., 1962, *Mécanismes normaux et phénoménes catastrophiques dans l'évolution des versants du basin du Guil (Htes-Alpes, France)* (1), Z. Geomorph., N.F., 5, 4.

Valentini P., 1985, *Il Catasto dei Ghiacciai della Provincia di Bolzano*, Geogr. Fis. Dinam. Quat. 8, 2.

Vivian R., 1970, *Hydrologie et érosion sous-glaciaires,* Rev. Géogr. Alp., 58.

Vivian R., 1974, *Les débâcles glaciaires dans les Alpes occidentales*, Le Calamta' Naturali Nelle Alpi, Novara.

Vivian R., 1975, *Les glaciers des Alpes occidentales,* Grenoble.

Wolman M. G., 1954, *A method of sampling coarse river - bed material* , Am. Geoohys. Union Trans., 35. 35. 6.

Carta turistica 1: 50 000, Ortlergruppe, Martell - Val di Sole, Freytag & Berndt, Wien 1987.

Carta d'Italia alla scala di 1: 25 000, Instituto Geografico Militare, ed. 1972, Roma (Cima Sternai, Martello, Monte Cevedale).