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Stream channel development in the southern parts of the High Atlas Mountains, Morocco

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The aim of this study is to review current knowledge on channels development in mountain basins in arid zones. The research was intended to describe the main triggering factors responsible for the development of ephemeral river channels in such areas. A detailed study was made of the Upper Dades basin located on the southern slopes of the High Atlas Mountains (Morocco). In this paper we analyse the morphometry of channels of different orders in three small basins chosen for a thorough study in order to present the details of channel characteristics.

The results show that the development of stream channels of the same order may vary greatly. This is mainly due to variation between the basins in lithology, vegetation cover, precipitation amounts and hillslope sediment supply. We prove however that the key agents of stream channel development are the energy of water and associated mass gravity movements in the period when water is absent. The morphological component provides strong evidence for this conclusion. The results show that runoff energy generally compensates for the low amount of water in 2nd and 3rd order channels where erosion is dominant. The 4th order channels are therefore better adapted to evacuate significant discharges (weak slope, large channel) which therefore decreases the erosive capacity of their stream flows. In this paper we also discuss whether the impact of the limited hillslope vegetation and the supply of coarse-grained sediment in the channels are important in the development of channels in mountain basins in arid regions. We conclude that intense rainfall-runoff events that lead to short-lived but high-energy flash floods have a more significant impact in contemporary channel development. Channels, especially those of 3rd and higher order, tend to be very unstable during large floods. We show that channels located in small basins in mountains in arid zones are in a state of almost permanent non-equilibrium.

Key words: ephemeral channels, channels morphology, channels development, arid zone, the Upper Dades basin, the High Atlas Mountains, Morocco

INTRODUCTION

Stream channel development in mountainous areas of the arid and semi-arid zone is characterised by specific features resulting from episodic, short-lasting but usually torrential downpours being the sole factors responsible for modelling the channel (Graf, 1988; Bull, Kirkby, 2002). The development of such channels, in particular of the basic channel in the main valleys in the mountains of this zone, is very closely linked to the denudational / fluvial system of the sub-basins. This is mainly caused by the large scale of morphodynamic processes taking place on the slopes and depending mainly of basins hypsometry (Conacher, Sala, 1998; Tooth, Nanson, 2011).

Weathering (notably physical weathering) and hillslope processes influence the development of ephemeral river channels in the sub-basins of the mountains in such zones, including the High Atlas Mountains. The weathering and the above-mentioned morphogenetic processes depend on many interlinked features of the natural environment such as geology, relief features, climatic conditions and vegetation cover (Nanson, Tooth, 1999).

Studies of contemporary relief changes in the land form of the Atlas Mountains include the one carried out by A. Laouina, M. Chaker and R. Nafaa (Laouina et al., 2006) and also that carried out by B. Izmaiłow, K. Krzemień and K. Sobiecki (2003) in the Anti-Atlas. The results of the work carried out on the northern slopes of the Atlas Mountains e. g. by A. Nahid (2001), and preliminary observations on the southern slopes indicate substantial aggradation of material in the river channels. The detailed geomorphological research presented here was carried out in the basin of the Upper Dades River on the southern slopes of the High Atlas Mountains, Morocco. The research was intended to describe the development and factors influencing the ephemeral river channels in the small basins of the southern slopes of the High Atlas Mountains.

MATERIALS AND METHODS

Research methods

In order to attain the goal of the research, three sub-basins representative for the Upper Dades basin were selected for a detailed study. They are located in different parts of the basin, i. e. its lower, middle and upper areas. Furthermore, they differ, among other factors, in size, lithology and relief features. The research was carried out using topographic and geological maps at scales of 1:50 000 and 1:100 000. Four satellite images available on Google Earth at a scale of 1:10 000 were used (29.08.2012, 22.07.2012, 18.08.2010, 08.08.2007). These maps and satellite images were used, together with other materials, to analyse the morphology of the areas covered by the above mentioned detailed studies. The analysis included identifying the channel orders according to A. Strahler's classification system (1952), their length, gradient, sinusoity, channel network density and slope angle. The geology of the basins, especially their lithology and structure, was also studied.

Field studies were carried out in June and October, 2012 and in January, 2013. One element of the work involved determining the channels forms of each order. The channel morphometry, including channel width, gradient and size of channel bedforms were measured along with the size and diversity of the bedload material in the channels of different order. The relationship between the intensity of the ephemeral discharges and the bedload granularity was analysed. The hillslopes were assessed for their potential capability to supply material to the channels, focusing on their lithology, structure, length and inclination. The role of erosion and accumulation in the development on channels of different order was also determined. The patterns and morphometry of the channels and their development in each order was compared between the three studied basins.

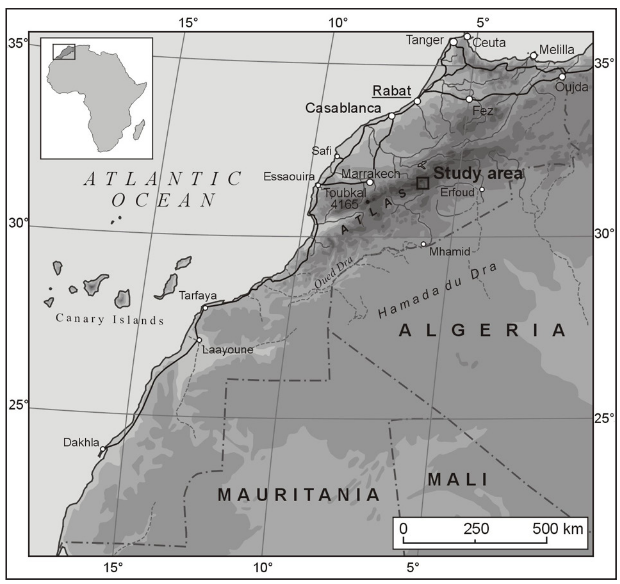

Fig. 1. *Localization of the Upper Dades River study area*

Study area

The altitude of the Upper Dades basin (Fig. 1) in the High Atlas Mountains ranges from above 3 400 m a.s.l. to 1 526 m a.s.l. in the town of Boumalne. The resulting altitude difference is nearly 1 900 m. The basin is characterised by highly differentiated relief.

Hydrological and meteorological features

The Upper Dades basin is in the area of a semi-arid mountain climate. Great fluctuations in the amount of precipitation are typical to the area, as for any other region with a similar climate. The average long-term precipitation (1962–2008) recorded at the Msemrir weather station (2 000 m a.s.l.) was 203 mm · year^{-1}, whereas that at the Boumalne weather station (1 526 m a.s.l.) did not exceed 150 mm · year^{-1}. The difference between the maximum and minimum values of annual precipitation at the Msemrir weather station over the period 1962–2008 was 300 mm · year^{-1}. The maximum annual precipitation recorded for the higher of the stations during the period under study was 392.4 mm · year^{-1} (2006) while the minimum precipitation was only 50 mm · year^{-1} (1964). The precipitation peaks were observed between September and December and between March and May. During other seasons, especially in summer, there is usually no precipitation. In winter the upper courses of the Dades River catchment area may be covered with snow with a thickness of as many as several metres for 2–4 months (Schultz, de Jong, 2004). However, due to low overall air humidity and strong solar radiation, up to 40% of the water contained in the snow is lost through sublimation. On sunny winter days humidity levels amount to a mere 20–30%. In the water balance of the Upper Dades River basin, 49% is accounted for by evapotranspiration and only 28% by discharge, with a surface discharge of merely 3%. A total of 20% is represented by various forms of retention within the basin (de Jong et al., 2005).

The Dades River has several dozen tributaries in the area. The volume of discharge varies greatly. In the upper part of the Dades River it ranges from several m^3 · s^{-1} to several dozen m^3 · s^{-1} during extreme rainfall. At the Aït Moutad hydrometric post (upstream from Boumalne), the long-term average discharge is 33.3 m^3 · s^{-1} (de Jong et al., 2008). Apart from its headwater reach, the discharge in the Dades River channel is, however, even because during dry periods it is supplied by high-yield underground karst sources. The length of most of the tributaries is more than a dozen kilometres. They are active on an intermittent basis, several times a year on average, mainly in September–October and February–April.

Geology and morphometry

Much of the High Atlas relief developed during two phases of the Atlas system formation, i. e. the late Eocene – Oligocene and Upper Pliocene – Lower Quaternary (Frizon de Lamotte et al., 2000). The catchment of the Upper Dades River is fully contained within the structural unit of the Atlas Mountains. It consists of uplifted ranges whose cores of various ages were folded, dislocated and upthrust in the early Tertiary and have since undergone numerous deformation and erosional cycles (Laouina, 2006). The existing drainage system of the Dades River basin probably started to develop during the Pliocene or Pleistocene epochs (about 5 million years ago) (Stokes et al., 2008).

The geology and morphometry of the basins selected for the detailed study are presented in Table 1.

Basin 1 (lower)

The area is mostly made up of continental conglomerates (86%) of Neogenic age (Fig. 2). It mainly consists of well-rounded and very well-rounded rock fragments greater than 10 cm in diameter. At the top of the river basin, at 1950 m a.s.l. (13%

Table 1. **Main characteristics of the studied basins**

Basin	Basin area in [km²]	Length of main valley [km]	Headwater altitude [m a.s.l.]	Height difference [m]	Gradient of main channel [‰]	Sinusoity of the main channel	Lithology
Basin 1	22.73	9.34	2 125	525	56	1.18	Conglomerates, limestones / marls
Basin 2	2.95	3.20	2 455	730	228	1.14	Limestones
Basin 3	7.39	7.36	2 887	812	110	1.23	Oolitic limestones and marls

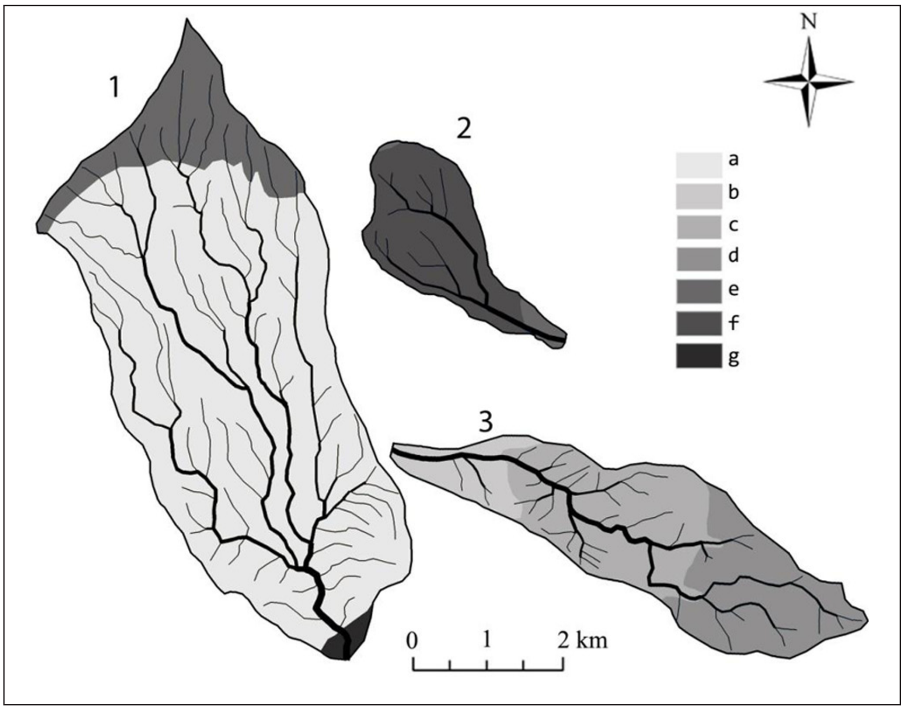

Fig. 2. Geology of the studied catchments (based on Dainelli 2007, Milhi 1997): a – conglomerates, Hamadien, continental Neogene, b – oolitic and oncolitic limestones, sometimes sandstones and marls, the Bin El Ouidane formation 3, Bajoncien, Dogger, Middle Jurassic, c – marls with fossil clusters, the Bin El Ouidane formation 2, Bajoncien, Dogger, Middle Jurassic, d – oolitic limestones and blue fossilised marls, the Bin El Ouidane formation 1b, Bajoncien, Dogger, Middle Jurassic, e – limestones with marl interbedding, Ouchbis formation, Pliensbachien, Liassic, Lower Jurassic, f – undulated black limestones of less than one metre thickness with marl interbedding, Aberdouz formation, Sinemurien / Pliensbachien, Liassic, Lower Jurassic, g – massive limestones and dolomites, Lotharingien, Lower Liassic, Lower Jurassic

of the basin area), Middle Liassic limestone with marl interbedding is also found. The limestone layer, measuring less than one metre in thickness, is much more resistant to physical weathering than the marl, causing the slopes to develop an uneven step-like profile. At the lowest point of the river basin there is a small area (less than 1%) built of massive lithified limestones and dolomites

Table 2. **Population growth and number of households in the Upper Dades basin communes during 1994–2004 (based on: *Monographie de la Province de Ouarzazate* 2009, *Monographie de la Province de Tinghir* 2010)**

Commune	1994		2004		Population growth %
	number of inhabitants	number of households	number of inhabitants	number of households	
BOUMALNE (M)	9 908	1 522	11 176	1 816	1.2
TILMI	9 110	1 456	10 445	1 588	1.4
MSEMRIR	5 992	861	8 107	1 097	3.1
A. S. J. OULIA	3 607	520	4 059	618	1.2
A. S. J. SOUFLA	4 079	583	4 471	650	0.9
AIT YOUL	3 972	482	4 466	616	1.2

of Lower Liassic age that are highly resistant to abrasion.

Basin 2 (middle)

As much as 93% of the middle sub-basin is built of highly folded black limestone (Fig. 2). The limestone comes in layers of several tens of centimetres often with marl interbedding. In the remaining part of the sub-basin there are interbedded limestones and marls of Liassic age (7%). In a similar manner to the upper sub-basin 1, the alternating rock layers of different resistance invite the development of step-like slope profiles.

Basin 3 (upper)

Around 70% of the basin is built of oolitic limestones and marls of the Middle Dogger (Fig. 2), causing the slopes to develop uneven longitudinal slope profiles. The middle area of the basin (16%) is built of marls of the Middle Dogger with numerous fossils. Their lower resistance to erosion results in a more mature valley relief characterised by much longer side slopes and a wider bottom. The lowermost part of the basin (13%) is built of oolitic and oncolitic limestones, and, in places, of Middle Dogger sandstones and marls. The differences between their resistance and the direction and inclination of their layers lead to variations in the angle of slope.

Vegetation cover

The vegetation of the catchment of the Upper Dades River is very modest due to the climatic conditions. It consists of typical xerophytic shrubs, including *Sclerocephalus arabicus* Boiss and *Epherda alata* Decne, growing on average up to 20–30 cm but never more than 50 cm. The prevailing average diameter of each specimen is 30–50 cm. Also, the size and density of the shrub specimens increase with altitude and distance from the main valley (Fig. 3A, B). Despite the intensification of characteristics typical of a high-mountain climate, at higher altitudes precipitation also increases and this is a crucial factor in the development of vegetation cover. The difference in the density and size of the vegetation cover between the higher and lower parts of the basin is also driven by strong human pressure from settlements along the main river. Herding is very strong across the entire catchment area.

Population

The Upper Dades basin is located in the Tinghir Province inhabited by 284 277 people (Monographie de la Province de Tinghir, 2010). The population density is about 21.5 pax/km^2. More than 78% of the population is living in the rural areas. In the Upper Dades basin there are 5 rural communes and only one urban. The Upper Dades is inhabited by almost 43 thousand people. For this area the rate of population growth in period of 10 years was 1.6% on average, with the highest one in Msemrir (3.1%) and the lowest in A. S. J. Soufla (0.9%) (Table 2). This rapid growth causes the necessity of increase of agricultural areas, especially those used for pastoralism and plant collection, primarily herb picking and firewood.

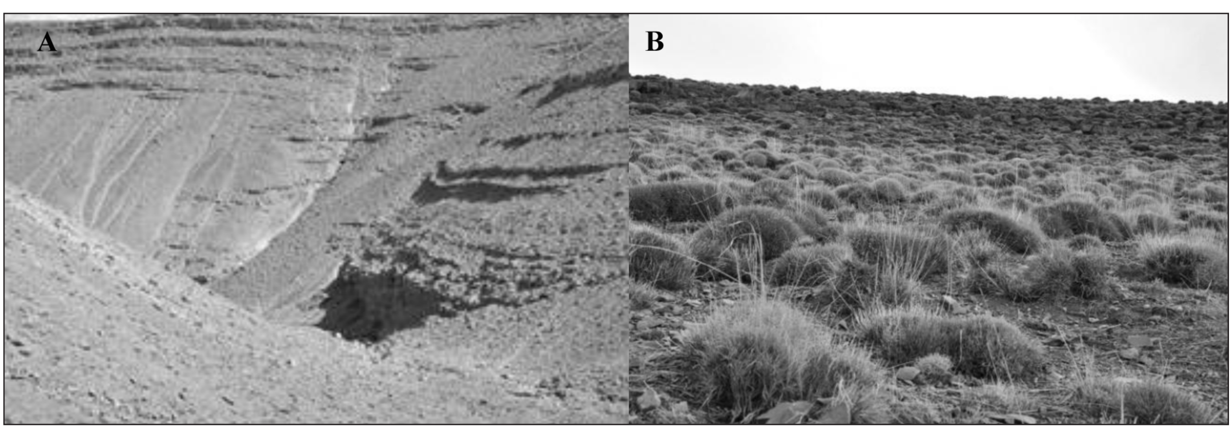

Fig. 3. Vegetation cover in the Upper Dades basin: A – denser vegetation develops in higher altitude where the amount of precipitation is higher, B – sparse vegetation dominates in the lower part of the basin where the amount of precipitation is lower and strong human pressure occurs

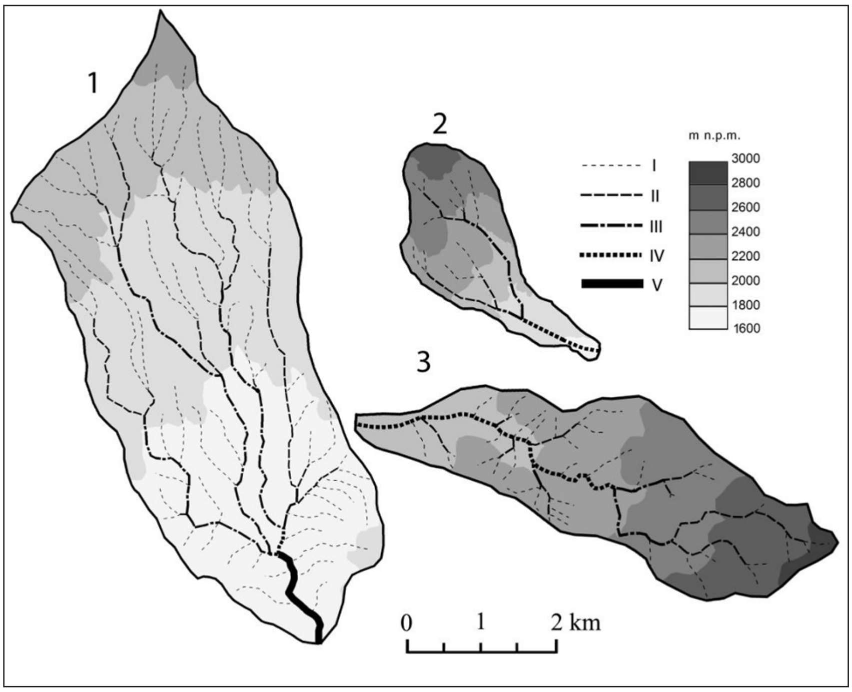

Fig. 4. Ephemeral river channels of various orders (1st–5th) in the catchments studied (based on the topographical maps: Boumalne, 1:100 000, 1968; Tineghir, 1:100 000, 1968)

RESULTS

RIVER CHANNELS DEVELOPMENT IN THE UPPER DADES BASIN

1st order channels

In the catchment area of the Upper Dades River (Fig. 4), 1st order channels have developed in alternating layers of limestone and marl and in conglomerates of the Neogene period in the lowest of the basins analysed (and also partly in the limestones and marls of this basin) (Fig. 2). They are already surprisingly well-developed at a distance of several hundred metres from the mountain ridges and characterised by the presence of clearly visible fluvial forms (Fig. 6A). The gradient of the 1st order channels (Table 3) and of the valley slopes is strictly linked with geology. In areas built of limestone and marl, the angle of the laminae is between 10° and 15°, and often corresponds to the direction of the river flow. The valley bottoms are filled with hillslope sediments (Fig. 5A), the supply of which is linked to the weathering conditions and rare, yet usually

Table 3. **Morphological characteristics of 1st–5th order channels**

Channel order	Channel gradient [‰]	Channel width [m]	Substrata where the channel is formed	Dominant material granularity [cm]	Maximum fraction of rubble [cm]
I	120–300	0.5–3	Limestones, marls, conglomerates	5–12	15–100
II	50–200	1–10	Limestones, marls conglomerates	5–30	25–50
III	50–350	2–70	Limestones, marls, conglomerates	5–20	40–60
IV	50–180	3–30	Limestones, marls, conglomerates	5–30	30–60
V	50	2–6	Limestones, dolomites	7–12	20

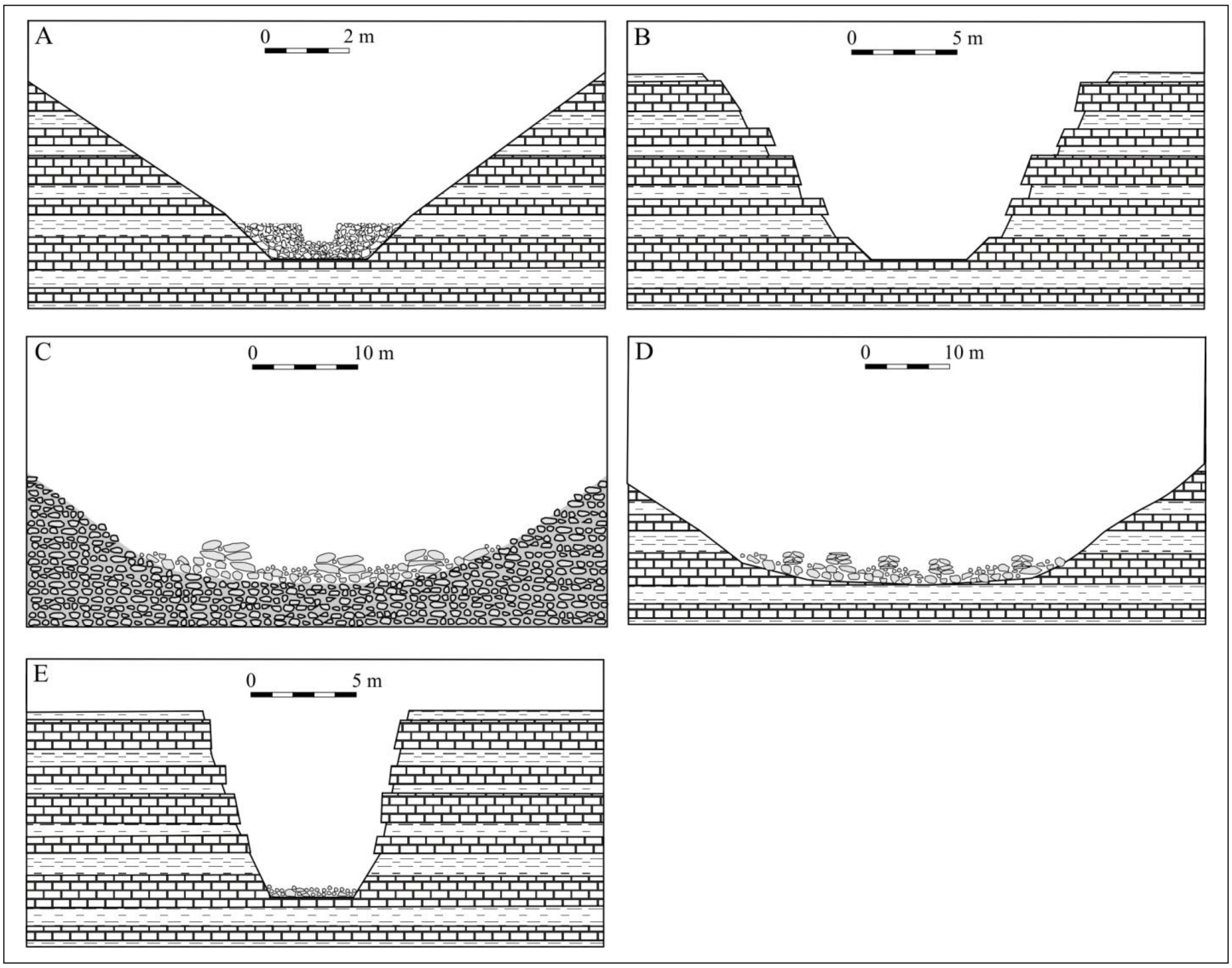

Fig. 5. Cross-section of different valley orders: A – 1st order valleys with channels bottoms filled with hillslope sediments developed in limestones with marl interbedding; B – 2nd order valleys with channel devoid of accumulation material developed in limestones with marl interbedding; C – 3rd order valleys with a typical multi-channel system of braided rivers, developed in conglomerates; D – 4th order with braided channels built mainly of gravel and small pebbles and bars built of much coarser material, developed in limestones with marl interbedding; E – 5th order valleys gap with narrow channels developed in massive limestones and dolomites

strong, downpours. These patterns characterise 1st order channels across the catchments analysed, notably their upper areas. Despite the presence of quite dense vegetation cover (Fig. 3A) there is strong erosion on (not always very steep) slopes. Ephemeral 1st order channels are characterised by weak intensity of flow. Despite this, the intensity is sufficient to form a clearly shaped channel in the erosion material accumulated in the valley bottoms. However, the amount of water is too small for the material to be completely eroded. This causes the channels to be narrow (Table 3). The channels cut into the substrata to various depths, occasionally as many as 1.5 m. Their bedload is very poorly sorted, ranging from sandy-gravel to small pebbles (Table 3). The water flows are insufficient to move the largest boulders. Large-sized boulders found in some places in the 1st order channels contribute to the creation of low ledges (0.3–0.5 m) below which small potholes up to 1 m in diameter develop. In these sections the channels follow stepped longitudinal profiles. Large boulders tend to deflect the water flow causing extensive lateral erosion. Ledges of similar height also develop on the sparse outcrops of limestone layers. Short 1st order channels cut in conglomerates are developed in a similar way as channels cut in marl and limestone. Their bed is filled with hillslope material, which is less varied in terms of fraction but is, however, more rounded. Yet this is not linked to fluvial transport, but rather to the characteristics of the source material, i. e. boulders, making up the Neogene alluvial fans.

2nd order channels

Limestone and marl channels of the second order are very well developed (Fig. 6B). This is caused by the greater flow energy. The erosional strength is often due to the small width of the channels and their height gradient (Table 3) which means that the amount of hillslope material carried downstream to the channels increases. Where the valley floor is intersected by alluvial fans or combined talus-alluvial fans, the channels cut through them to the depth of several metres. The channels gradient is in the same direction as the inclination of limestone and marl layers. Their bed is often filled with sharp-edged alluvial material of various size (Table 3), but may also be devoid of accumulation material (Fig. 5B). As regards rocky channels, there can be numerous ledges of 0.5–0.7 m in height or series of ledges of a maximum height of 1.5 m, depending on the thickness of the rock layers. 2nd order channels are cut more than ten metres into the bedrock and feature steep slopes of approx. 15–40°.

2nd order channels that form in conglomerates develop in very varied ways. Where the channels gradient is more than 180‰, they are often devoid of accumulated material (Fig. 6B). In places the channels narrow down to less than one metre, with vertical rocky banks several metres high and several metres deep. Channels cut in conglomerates differ from limestone channels in featuring numerous potholes 0.5–0.7 m deep, and ledges that are higher (up to 2 m), but scarcer. The channels of 50–70‰ gradient change radically their way of development. They are transformed from an erosive to an accumulative character, with a clear borderline between the morphodynamic courses. They grow significantly in width (Table 3). Conglomerate slopes usually have a steep gradient (up to 40°) which creates favourable conditions for the supply of large volumes of material. As the angle decreases and river channels get wider, the flow energy clearly drops. Such channels consist of well-rounded material originating from the erosion of Neogene alluvial fans (Table 3).

The 2nd order channels have both channel section where accumulation is dominant and channel section where erosion prevails. In tighter sections, with high flow energy, erosion dominates. Where the channel becomes wider, the flow energy decreases, and accumulation greatly increases, with very varied predominant and maximum fractions. This large variation in the shape of 2nd order channels points to their important role in the transport of material downstream.

3rd order channels

3rd order channels also vary greatly in shape. This is attributable both to the lithological diversity of the area and the stages in the development of landform (Stokes et al., 2008).

As a rule, 3rd order limestone and marl channels are relatively narrow with varied gradients (Table 3), usually dependent on the pattern of rock layers. When the gradient of the channel is low, channel floor is filled with coarse-edged material ranging from gravel to pebbles with occasional deposits of larger-sized material (Fig. 6C, Table 3). When the channel gradient has more than 10°, small-fraction material is swept downstream during almost every flow. During the flows channel beds are dominated by fractions of 25 cm and more, which are dislodged exclusively during bankfull flows. Where the channels are significantly steeper (to 250‰, or even 300‰ in certain spots), patches of exposed bedrock appear devoid of any alluvial material. These channels feature numerous ledges or series of ledges on limestone outcrops up to 2.5 m high. Despite the large volume of bedload transported by ephemeral flows, no potholes are found directly beneath these ledges. This proves that the limestone is highly resistant to mechanical abrasion. The 3rd order channels are also very stable in terms of their planforms.

The steep slopes of the deeply-cut valleys, characteristic of 3rd order limestone and marl channels, and the resultant steep (30–40°), and occasionally even vertical, supply large volumes of debris into the channels. Often the channels receive large-sized material (up to several metres in diameter). Water is unable to transport such huge material, which impedes its flow. This causes local lateral erosion that undercuts rock cliffs and widens the channels. In such sections the greatest channel planforms modification occurs.

The 3rd order channels have a typical multi-channel system of braided rivers (Fig. 5C). The channels are much wider than those in limestone and marl. They also have a much gentler gradient (Table 3). The smallest channels are remodelled during each flow. The stronger the flow is, the

Fig. 6. Channels of the Upper Dades basin: A) 1st order channel with a large supply of poorly sorted material from hillslope characterized by relatively dense vegetation cover; B) 2nd order channel with a high gradient and steep slopes, virtually devoid of accumulated material (dominant erosion) cut in conglomerate; C) 3rd order limestone channel with height gradient (180‰) and dominant bedload material of more than 25 cm; D) 4th order channel developed in conglomerate with multi-channel systems typical for braided rivers; E) 5th order channel cut into massive limestone and dolomite with fine-grained material accumulated on the bottom

larger the channels that get remodelled. Bankfull flows release the largest-fraction material that builds up the dividing bars (Table 3). Such channel valleys cut only slightly into the substrata, and as a result the short slopes supply only a very small amount of material to the channels. The numerous lower-order channels constitute the main source of material to channels of this order.

4th order channels

4th order channels have all developed in a similar way across the analysed area. They are predominantly braided channels with alternating accumulation and redeposition, and occasionally erosion (Fig. 6D). Most of them are wide with a low gradient. Only in places where the channel is narrow and the gradient can be slightly greater (Table 3) the erosion intensifies. Occasionally, there are channels with bedrock devoid of any accumulation material. However, the channels are mainly built of alluvial material most of which is supplied by lower-order channels. The nature of the distribution of the material is similar to 3rd order channels cut in conglomerates. The bottoms of the lowest channels are mainly built up of gravel and small pebbles, whilst older channels, in particular the bars they contain, are built of much coarser material (Fig. 5D, Table 3). In general, 4th order channels form sections connecting lower order channels to the main channel of the Dades River.

5th order channels

The 5th order channels within the study area mostly occur in gap (Fig. 6E). The valley studied in the present case transverses massive limestones and dolomites (Fig. 5 E). Despite the high water energy, the width of such channels is not great (Table 3). Such channels are mostly filled with small pebbles because of their gentle gradient (Table 3). The transverse reaches may feature rocky ledges that are as high as several metres. The valley sides are very steep and nearly vertical on the inner sides of the bends.

Vast alluvial fans have developed at the confluence of all the channels with the Dades River. Their size and material mainly depend on the gradient of the channel and the material it transports, and, to a much lesser extent, on the channel length or the catchment area.

THE FLUVIAL PROCESSES IN SMALL CATCHMENTS ON THE SOUTHERN SLOPES OF THE HIGH ATLAS MOUNTAINS

As in other high-mountain areas of the arid and semi-arid climate zone, in the basin of the Upper Dades River, only the main watercourse can be classified as perennial. The others are ephemeral streams. Water flows there only after rainfall, which, given the climate, is usually torrential and short-lasting. The observable frequency of flows during the year varies significantly, ranging from 1–2 to more than 10 annually. As a rule, channel formation occurs during extreme events. In the Upper Dades basin, these are mainly recorded in spring and autumn. It is estimated that flows in the Dades tributaries occur when precipitation exceeds approx. 30 mm/day. Bankfull flows are recorded once every dozen or so years when rainfall intensity is higher than 100 mm/day (the last time this occurred in March, 2010). These values are comparable to other areas of the semi-arid climatic zone (Nanson, Tooth, 1999) but also in northern Europe. For example, in Parisian Basin, >50 mm rainfall in less than 15 h enables to develop a flash-flood which occurs in less than one hour (Douvinet, Delahaye, 2010). Although water retention in the catchment area gradually declines due to the highly degraded nature of the plant cover in the study area, it is hard to definitively conclude how it affects the frequency of the flash-flood and the dynamics of the fluvial processes in the channels.

The dynamics of the fluvial processes across the different orders of channel is very varied. Their intensity is not only determined by the water energy and by the number of lower-order channels supplying it, but also, to a large extent, by the morphometric characteristics of the channel, and notably by its width and gradient. After analysing these characteristics and the channel material, it was concluded that the longest section with erosion dominant is noted in 2nd order channels. Intensive erosion also takes place in large stretches of 3rd order channels cut in limestone and marl. This is evidenced by the existence of numerous rocky floors and steps in the channels. Section rich in alluvial material occurs in such channels when their gradient declines or the rock pattern changes. Erosion and deposition channels mainly occur among 4th order channels and 3rd order channels cut in conglomerates. They are characterised by a low gradient and considerable width. Their bed is built of multi-fractional alluvial material. They feature numerous channels, the location of which changes due to erosion and its subsequent accumulation when flows energy decreases. Also 1st order channels should be ranked among deposition and redeposition channels, and occasionally erosion channels. However, what is of key importance in terms of their development is not only the accumulation of alluvial material but rather of hillslope material. Thus the dynamics and development of 1st order channels depend on the intensity of erosion on the slopes. Here, the size – and in the case of channels developed in Neogene conglomerates, also the shape of the channel material – is not an indicator of the river channel dynamics.

CONCLUSIONS

The results presented in this paper confirm that water energy and associated mass gravity movements in the period where the water is absent are the key agent of stream channel development. The results show however that the development of stream channel of the same order may vary greatly. This is done mainly due to differentiation between the basins in lithology, vegetation cover, precipitation amount and hillslope sediment supply. The erosion in the stream is usually dominant when the channel is narrow and heave height gradient. The accumulation in the channel prevails when the channel becomes larger and / or has lower gradient. The height material supply derived mostly from channels of lower order is also very important in channel development. However, contrary to usually presented results, the role of hillslope sediment supply in channel development is unclear. In all but 1st order channels the water energy is sufficient for transporting this material downstream. Only in the 1st order channels due to low water energy the downstream material transport is slow and the aggradations in the channel prevail.

In the catchments located in the upper parts of the main basin, where the frequency of extreme precipitation is higher, channel remodelling, especially of 1st and 2nd orders takes place more often. In the catchments located in the lower parts of the basin channels remodelling prevails mostly in the higher order (3rd order and up).

The results show that in the mountain basins in the arid region the limited hillslope vegetation and well-developed slope-channel coupling resulting in an abundant supply of coarse-grained sediment in the channels do not necessary have the crucial role in their development. We can conclude that in the contemporary channel development the more significant impact have intense rainfall-runoff events that lead to short-lived but high-energy flash-floods. Low cohesion of channel material and sparse or nonexistent vegetation mean that the channels tend to be very unstable due to large floods. Accordingly, the channels developed on the southern slope of the Atlas Mountains are in a state of almost permanent non-equilibrium.

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VANDENS TĖKMIŲ VAGŲ VYSTYMASIS PIETINĖJE AUKŠTŲJŲ ATLASO KALNŲ DALYJE, MAROKE

Santrauka

Tyrimo tikslas yra patikslinti dabartines žinias apie laikinų vandens tėkmių vagų formavimąsi aridinės zonos kalnuose bei apibūdinti svarbiausius veiksnius, lemiančius šių upių vagų formavimąsi. Tyrimas buvo atliktas Viršutinės Dades baseine, esančiame pietinėje Aukštųjų Atlaso kalnų dalyje, Maroko teritorijoje. Buvo tiriami trijų nedidelių skirtingo rango baseinų upių vagų morfometriniai parametrai.

Tyrimo rezultatai rodo, kad tokio pat rango efemerinių upių vagų formavimasis gali labai skirtis. Labiausiai šiuos skirtumus lemia baseino litologijos, augalijos, kritulių kiekio ir šlaituose sukauptų nuogulų kiekio skirtumai. Nepaisant minėtų skirtumų svarbiausi visų vagų formavimąsi lemiantys veiksniai yra vandens tėkmės energija bei gravitacijos poveikis sausuoju laikotarpiu. Šią išvadą patvirtina atlikti vagų morfometrijos tyrimai. Srovių energija kompensuoja mažą vandens kiekį antrosios ir trečiosios kategorijos upeliuose, kuriuose nuolydžiai yra didžiausi, o erozijos procesai – dominuojantys. Ketvirtosios kategorijos vagos yra prisitaikiusios praleisti didesnį vandens debitą (mažas nuolydis, plati vaga), todėl jose vandens tėkmės vykdoma erozija yra mažesnė. Straipsnyje įvertinta šlaitų augalijos ir stambesnės frakcijos nuogulų, esančių pačioje vagoje, poveikis vagų evoliucijai kalnuotose aridinėse srityse. Didžiausią poveikį vagų morfometrijos kaitai daro intensyvių liūčių sukelti poplūdžiai, kurių metu susiformuoja trumpalaikės, bet daug energijos turinčios tėkmės. Trečiosios ir aukštesnės kategorijos upių vagos per didesnius poplūdžius yra labai nestabilios, todėl mažuose aridinės srities kalnuotuose baseinuose esančios upių vagos yra nuolatinėje kaitos būsenoje.

Raktažodžiai: efimerinių upių vagos, upių vagų morfologija, upių vagų vystymasis, aridinės sritys, Viršutinės Dades baseinas, Aukštieji Atlaso kalnai, Marokas