Formation and development of a 1st-order valley network in postglacial areas (the Dębnica catchment)

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Abstract: This article describes the formation and development of the 1st-order valley network in the postglacial catchment of the Dębnica River (NW Poland). Its valley network is an example of a system of polygenetic depressions, and its 1st-order sections are comprised of denudational hollows and valleys, dissections, and erosional-denudational valleys. In the article, both landforms with no permanent flow and those nourished by groundwater and included in the river runoff network are characterised. In the course of their development, dry valleys have continued to grow in width and length, while the gradient of their bottom has decreased due to slope wash processes. In groundwater outflow zones, in turn, the modelling of their slopes indicate retreat as a result of seepage erosion and mass movements, which has led to the preservation of their convex parts and the development of a concave section at the foot, passing into the flat bottom of an alcove. In headwater alcoves, which mark the start of a valley or are inserted into older valley landforms, morphological contrasts are enhanced because of an increase in their width and depth, as well as changes in their cross-profile.

Key words: valley network, erosional-denudational valleys, unchanneled colluvial valley, headwater alcoves, Dębnica catchment

Introduction

The postglacial relief zone in Poland offers an opportunity for tracing the development patterns of a polygenetic valley network (Piasecki 1982), largely determined by the morphogenesis of postglacial depressions modified by fluvial and denudational processes controlled by climate, neotectonics (Florek 1991, Błaszkiewicz 2005, Chybiorz 2008) especially in Holocene (Zwoliński *et al.* 2008), and in the recent centuries, by a rise in multi-dimensional human intervention (Florek 1991, Szpikowski 2010).

A uniform valley system on the northern slope of Pomerania started to form during the recession of inland ice in the Pomeranian Stage of the Vistulian Glaciation. The development of the valley network involved a gradual integration of depressions produced by glacial, fluvioglacial and periglacial processes into a system of river runoff. As a result, within the present-day river valleys located on the northern slope of Pomerania, including the Parsęta River Basin, one can find valley sections of various ages and derivations (Sylwestrzak 1978, Piasecki 1982, Błaszkiewicz 1998, 2005). Predominant among them are marginal valleys (or pradolinas), running mostly latitudinally, as well as longitudinal trough valleys (subglacial troughs) and glaciofluvial valleys linked by erosional sections with a fluvial genesis (Zwoliński 1989).

The process of the river network's integration and development is still in progress, but the main stage took place at the close of the Vistulian (Kozarski *et al.* 1988, Florek 1991, Błaszkiewicz 1998). In that period, an important role in the organisation of the valley network was played by meltwater coming from the melting of blocks of dead ice and hydrogenic ice, as observed by Florek (1991), Andrzejewski (1994) and Błaszkiewicz (2005). The end of subaerial deglaciation also meant the conclusion of the most important stage in the development of the present-day drainage system of Pomerania (Lewandowski, Nita 2008), which now includes higher-order streams.

The further evolution of the valley network which thus formed included the appearance and development of 1st-order landforms (using Horton's hierarchical classification of river networks), such as denudational hollows, erosional dissections and valleys, as well as erosional-denudational valleys. The pattern of this lower-order colluvial valley network (Montgomery, Buffington 1997) is subsequent to the directions of the trunk valleys determined by the structure and relief of the older substratum. Such landform complexes were identified by Marsz (1964, 1995), Churska (1965), Szupryczyński (1967), Gołębiewski (1981), Kostrzewski *et al.* (1997), Florek *et al.* (1999), Smolska (2005), Majewski (2008) and Paluszkiewicz (2008, 2011).

The network of small valleys in Pomerania was initiated in the Late Vistulian by wash and solifluction processes when there was permafrost in the substratum. The amelioration of climatic conditions and gradual degradation of the permafrost, accompanied by an expansion of forest vegetation, limited the significance of overland flow in favour of groundwater flow. The melting of blocks of dead ice and ground ice had morphological consequences that were accompanied by changes in the hydrogeological conditions (see e.g. Nowaczyk 1994, Bajkiewicz-Grabowska

2002, Błaszkiewicz 2005). The increased depth of rainwater infiltration contributed to the gradual development of the local, transitional and regional systems of groundwater flow (Petelski, Sadurski 1987) while limiting overland flow (Rotnicki 1991). Lewandowski and Nita (2008) found that the groundwater level had stabilised at the start of the Atlantic, while the development of a regional system of groundwater flow probably brought about spatial stabilisation of the river network, as was the case in NE Poland (Bajkiewicz-Grabowska 2002). A consequence of
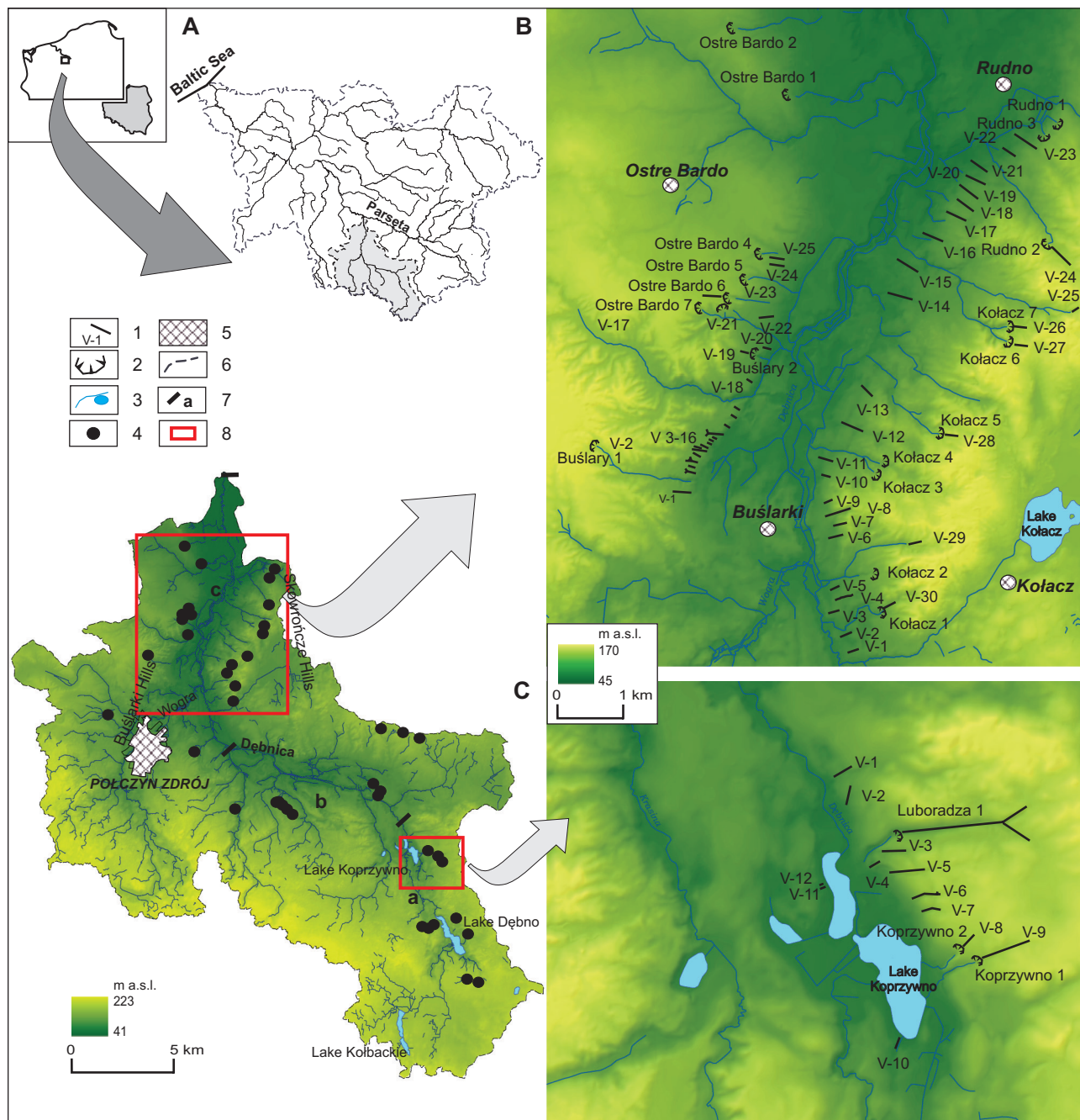
Fig. 1. A. Study area in the Dębnica catchment (NW Poland). River network in the Dębnica catchment against its hypsometry, B. Location of study site: the lower Dębnica River valley, C. Location of study site: the upper Dębnica River valley

Headwater alcoves, erosional-denudational hollows and valleys in which topographic measurements and morphological mapping were carried out have been numbered or named

1 – erosional-denudational hollows and valleys, 2 – headwater alcoves, 3 – river network, lake, 4 – groundwater outflows, 5 – town, 6 – watershed of the Dębnica catchment, 7 – limits of sections of river course: a - upper, b – middle, c – lower, 8 – study areas

these events was a decline in the number and length of streams flowing in small, 1st-order valleys. Some valleys located within the aeration zone dropped out of the drainage network and functioned as intermittent streams only during high groundwater stages.

Slope processes intensified in the neo-Holocene (the sub-Atlantic) as a result of human activity, and then again in the early Middle Ages and the Little Ice Age (Smolska 2005, Majewski 2008). In the scarp zones of uplands and on valley slopes, small, poorly branched erosional valleys developed, while in the upper sections of older denudational and erosional-denudational valleys there appeared badlands and gullies, which grew deeper and more elongated. Not all of these valleys are part of the present-day drainage network; only some are used by 1st-order streams as elements of river runoff.

Some dissections are very young, having developed as a result of deforestation over the last 100–200 years. Today, the formation of new forms of rill erosion, mostly episodic or ephemeral in nature, can be observed on slopes used in agricultural. Their development is facilitated by morphological conditions, the physical properties of the soils, sparse vegetation cover, and farming practices (Kostrzewski *et al.* 1989). The afforestation of zones with a great amplitude of relief has curbed denudation processes (Smolska 2007) and stabilised valley landforms. The significant changes in the morphology of the valleys that are taking place today result from gully erosion triggered by extreme weather events (Jonczak, Kuczyńska 2008).

In some denudational and erosional valleys, the deepening of the bottoms has led to a dissection of aquifers and various forms of groundwater drainage, and this, in turn, has made the valleys part of the network of overland flow (Majewski 2008). Areas of groundwater outflow include not only places where streams rise, but also where seepage erosion leads to the formation of the headwater section of a river-valley network. Further stages of the river network's development thus formed include a rise in the number of 1st-order tributaries, which started to develop towards the water divide through elongation and branching (cf. Schumm 1977, Bajkiewicz-Grabowska 2002).

In the valley network of the post-glacial zone of West Pomerania, which is far from uniform in its development and organisation, research interests have tended to focus on its headwater sections, which determine the development of the relief on the morainic uplands and valley slopes of this region. Headwater areas are highly sensitive to changes in environmental conditions caused by various forms of human activity or catastrophic events. Hence, they can also be regarded as a good geoindicator of threats to the natural environment on a variety of spatial scales (Bull, Kirkby 1997, Zwoliński 1998, 2004, McNamara *et al.* 2006, Wrońska 2006).

The main research aims of this article are to characterise the development of 1st-order valleys in the post-glacial areas of West Pomerania and to describe the stages of their inclusion into the river runoff network via groundwater. The study area is the Dębnica catchment, part of the Parsęta River Basin (Fig. 1), comprising the postglacial geoecosystem of the Drawsko Lakeland situated in a wide and morphogenetically diversified marginal zone of the Pomeranian Stage of the Vistulian Glaciation, with a Late Glacial and Holocene retouch. The valley network in the Dębnica catchment is an example of a system of sections of various ages and glacial, fluvioglacial, fluvial, and erosional-denudational in origin.

Study methods

In the research, use was made of the following source materials: topographic maps at a scale of 1:10,000, geological maps at a scale of 1:50,000, hydrographic maps at a scale of 1:50,000, and a Computer Map of Poland's Hydrographic Division (KMPH 2004). In the Dębnica catchment, a detailed geomorphological and hydrological mapping of selected 1st-order valley sections was conducted. Because of the size of the valleys and headwater alcoves, as well as the insufficient accuracy of the topographic maps, it was necessary to perform direct topographic measurements of these landforms. The measurements were carried out using a GPS receiver and supplemented with topographic measurements. On the basis of digital elevation models, field studies were made of the landforms created by groundwater outflows, mass movements and surface waters, as well as those produced by the impact of plants, animals and humans. A lithological identification was made of surface sediments in the denudational-erosional valleys and headwater alcoves. A total of 55 hand drillings were made, as well as 17 exploration holes and exposures from which sediments were sampled for further analyses.

Laboratory analyses and the accompanying indoor processing of their results included the following stages:
- an analysis of the mechanical composition of the deposits using Casagrande's areometric-sieve method modified by Prószyński (Racinowski 1973),
- determination of the calcium carbonate ($CaCO_3$) content using Scheibler's apparatus.

To process the data collected during fieldwork, use was made of the *ArcGIS, Idrisi Selva,* and *Surfer* programs.

Study area

Natural environment

The study area chosen was the Dębnica catchment, which covers an area of 289.5 km^2 (Fig. 1). The Dębnica is a left-bank tributary of the Parsęta, with a length of 42 km and a mean gradient of 2.8‰. The relief of its catchment has developed as a result of the transgression of Pomeranian Stage inland ice from the Vistulian Glaciation and frontal-areal deglaciation on the northern slope

of the lakeland elevation (Karczewski 1989, Dobracka, Lewandowski 2002). In the study area, a postglacial landscape with three distinct morphogenetic zones is predominant (Karczewski 1998). The diversity of the morphogenetic processes that have shaped the present-day relief in the Dębnica catchment is reflected in lithological differences in its surface deposits (Fig. 2). The various sediment series and their pattern are an effect of direct glacial accumulation and the action of glaciofluvial water and meltwater. The youngest sediment series formed in the course of fluvial, aeolian and organic accumulation. In the south and south-east, this is a zone of marginal landforms from the Pomeranian Stage of the Vistulian. Predominant in the structure of end-morainic hills are sands and gravels with a large proportion of stones. Also located in the southern part of the catchment is a small fragment of the Gwda outwash plain built of glaciofluvial sand-gravel sediments. North of the marginal landforms of the Pomeranian Stage, the morainic upland falls towards the Baltic in seven morainic levels that differ in terms of the development of the stream network (Karczewski 1989, 1998).

Fig. 2. Geology of the Dębnica catchment (based on Detailed Geological Map of Poland, http://ikar2.pgi.gov.pl/index.php/pl/mapy.html, 2013, modified)

1 – alluvia, peats and organic silts, 2 – lake sands, silts, clays and gyttjas, 3 – fluvial sands, gravels and silts, 4 – lake sands and silts, 5 – ice-dam clays, silts and gravels, 6 – outwash sands and gravels, 7 – kame sands and silts, 8 – end-moraine gravels, sands, boulders and tills, 9 – tills, weathered tills, glacial sands and gravels, 10 – river network, lake, 11 – groundwater outflows, 12 – watershed of the Dębnica catchment, 13 – study areas

The Dębnica catchment occupies the two highest levels: VII and VI, built predominantly of sandy or stony morainic tills, sometimes replaced by glacial gravely-silty sands. The levels of the morainic uplands are enriched with hills of accumulation end moraines and dead-ice moraines, kame complexes (e.g. the Skowrończe Hills), and melt-out basins (like Lake Kołacz). In the central and northern parts of the area, there extend valleys and cut-and-built plains left by meltwater, which are filled with glaciofluvial sand-gravel sediments.

Valley network in the Dębnica catchment

The valley network in the Dębnica catchment is an example of a system of depressions of glacial, fluvioglacial, fluvial and erosional-denudational origin. The upper section of the Dębnica Valley lies on an outwash fan (Figs. 1 and 2), the surface of which was dissected by narrow valleys of proglacial waters; one of them is now filled by Lake Kołbackie. The Dębnica flows through Lake Kołbackie, and after crossing a short latitudinal section, changes the direction of its course and flows into a longitudinally oriented gorge section. The deep gorge valley dissects the end-morainic hills near Uradz. This is the fragment of the valley where water, initially flowing south, was shifted north through the gorge section during the period of formation of a uniform river runoff. In the gorge section, the difference in elevation amounts to 40 m, while channel gradients attain up to 23‰.
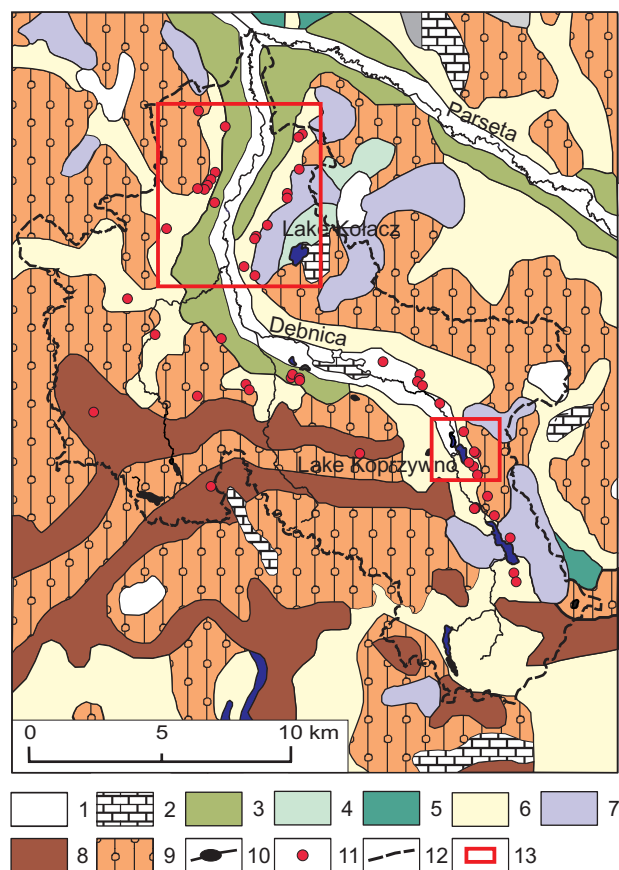
In the further part of its upper course, the river uses a longitudinal subglacial trough which follows the Ciemino fault in the substratum. The trough has two wider segments filled by the Dębno and Koprzywno Lakes (Figs. 1 and 2). The valley was used by fluvioglacial runoff, hence predominant in its geological structure are fluvioglacial sands and gravels with occasional erratics. River gradients in this section range from 6 to 10‰.

In its middle and lower courses, the Dębnica makes use of a marginal valley of fluvioglacial waters. In the lower section, the valley assumes a longitudinal course in accordance with the inclination of the neighbouring upland areas. Here the floodplain is accompanied by higher-lying cut-and-built terraces inserted into a meltwater plain. The river, flowing at a gradient of 0.5‰, meanders over the valley floor, the width of which increases substantially, locally to almost 1,000 metres. In the middle and lower parts of the Dębnica Valley, its floor is filled with sands, muds and peats from the Holocene floodplain (Fig. 2).

An analysis of the distribution of 1st-order valleys in the Dębnica catchment makes it possible to distinguish three zones of occurrence:
1) morainic uplands,
2) meltwater plains, and
3) river valley slopes of various origins.

These landforms, widely differing in hypsometric and lithological terms, and present-day denudation processes (Mazurek 2010, Paluszkiewicz 2011), also differ in the

geological situation of their water-bearing horizons and modes of their surface drainage. A detailed geomorphological identification of the 1st-order valley landforms was made in two test areas, one embracing the scarp zone of the subglacial trough of Lake Koprzywno and a morainic upland (the upper Dębnica River valley), and the other, the scarp zone of a morainic upland and the Buślarki-Ostre Bardo glaciofluvial valley as well as the slopes of the Kołacz-Rudno kame hills (the lower Dębnica River valley).

Morphometric and geomorphological analysis – Research results

The upper Dębnica River valley

Along a distance of some 3 km on the eastern shore of Lake Koprzywno, nine small 1st-order colluvial valleys have developed, while on its western slope three such landforms can be found (their density amounting to 0.87 km km^{-2}). Absolute heights in this area range from 90 to about 140 m a.s.l. (Fig. 1C), and slope gradients reach up to 30° locally. Most of the valleys are single landforms, ranging from dozens to more than 200 m in length. Their depth of incision varies from a few to a few dozen metres. Among them are some where runoff is episodic and three with a permanent flow. In the slopes of the valleys, one can find glaciofluvial sands with gravels covered by sandy till or glacial gravely-silty sands that accompany the till. At the lowest levels, underlying glaciofluvial sands, is morainic till from the Leszno-Poznań Stage of the Vistulian. The deep incisions of the valleys and the high hydraulic gradients create favourable conditions locally for the drainage of groundwater from the inter-morainic level. Groundwater outflows are located at the lithologic contact of varigrained sands with clay silts and glacio-lacustrine clays or morainic till, and give rise to permanent streams.

Most of the valleys on the Koprzywno scarp zone are single landforms a few dozen to more than 200 m long (Figs. 1C and 3A). Their depth of incision varies from a few to just over a dozen metres. Their slopes are steepest among the valleys inventoried in the Dębnica catchment, which indicates a great amplitude of relief (the inclination of the right slope is 47°–71°, with an average of 59°; of the left slope, 44°–55°, with an average of 50°). In addition, the Koprzywno valleys have the greatest maximum gradients of the bottom (71°–43°, or 57° on average). What has certainly helped to give the valleys in this area such a considerable size is land inclination, which can attain a maximum of 20° in the Koprzywno scarp zone (the average being 3°).

In the upper part of the long profile of the 1st-order valleys examined, at a depth of about 1.3 m, there is a stone-gravel erosional pavement marking the old bottom of a valley. Overlying it is a massive layer of poorly sorted medium sand (up to about 0.5 m thick). The top series consists of fine, massive, moderately sorted sands. The homogeneity of the series and its massiveness indicates their gradual accumulation. The content of calcium carbonate is low in the entire profile, ranging from 1.8% in the bottom layers to 1.5% at the top.

In the middle and mouth sections of the valleys similar lithological series were observed, the differences only involving their depth and thickness. In the mouth section there is a boulder-stone series at a depth of about 1.5 m. Overlying it is a massive layer of medium and fine poorly-sorted sand. These sediments are connected with the dissection of the bottom and the transport of material along the valley axis. What differentiates the mouth sections of the valleys from the middle ones is a greater proportion of fine sand at the top of the profiles of the former.

An analysis of the sediments and morphology of the small unchanneled colluvial valleys showed wash and rill erosion to be the basic process modelling their development. As follows from an analysis of the long profiles of the valleys, wash was most extensive in their upper and middle sections. Colluvial material was carried along the valley axis. The lower part of the profile is usually straight or slightly concave, and as a rule, is an accumulation site. In the analysed valleys, alluvial cones do not stand out distinctly in the relief. The material was probably transported farther down and included in the system of fluvial flow. Today most of the slopes in the study area are covered by woodland, which significantly reduces the extent of erosion by water.

The deepening of some of the erosional-denudational landforms at the Koprzywno scarp zone led to the dissection of aquifers and the drainage of groundwater onto the surface, thus initiating permanent flow in formerly unchanneled colluvial valleys. In such valleys such as Koprzywno 1 and 2, and Luboradza 1 (for the location of the sites, see Fig. 1C), the flow is episodic in their upper and middle parts, while there are headwater alcoves cut in their lower sections, where subslope seeps and springs initiate the formation of a stream channel. The high slopes of the headwater alcoves, which attain more than a dozen metres in height (e.g. 21 m at Koprzywno 1, Fig. 4) and incline at angles of up to 50°, surround a flat bottom (its gradient amounting to a few degrees). The area of the bottoms of these headwater landforms is small (267 m^2 in the Koprzywno 1 alcove). The alcoves are narrow, elongated and poorly branched. Such landforms are described as spindle-like alcoves (Mazurek 2010). Their bottoms are separated from the dry part of the valleys by a seepage erosion scarp, which in the Koprzywno 1 valley attains a maximum height of 0.3 m.

In the analysed alcoves, the role of the chief relief-forming factor was assumed by groundwater outflows, which started a set of headwater relief-forming processes. The subslope exfiltration of groundwater triggered seepage erosion, which has led to the undercutting and retreat of the slopes. In locations of outflows, erosional undercuts 0.2-0.3 m high have developed. In some alcoves, the undermining of the stability of the slopes by abundant

subslope outflows has set in motion such gravitational processes as falls, dry ravel events, and slides. The shifted material accumulates temporarily on the alcove bottom in the form of a colluvial cone, which is gradually washed away. Mass movement and seepage erosion bring about a change in the cross-profile of the alcove, which grows ever wider, like at the Koprzywno 1 site, and has now attained a maximum bottom width of 12.7 m, while the bottom of the higher-lying dry valley is narrow, at about 5 m. The intensification of vertical and lateral erosion in the alcove bottom has led to the development of a stream channel with bedforms in the mouth section of the alcove. Seepage erosion in the bottom of the alcove and vertical erosion in the stream contribute to the deepening of the bottom, as indicated by seepage erosion scarps closing the channel heads that stand out from the bottom to heights of dozens of centimetres.

At the Koprzywno scarp zone, headwater alcoves are cut in medium and fine fluvioglacial sands. At the bottoms of the alcoves there are medium sands with a gravel fraction, and in the channel flow zone there are coarse sands, locally with a stone pavement. With the gradient of the alcove bottom attaining up to 8°, water gradually washes out the silt and fine-sand fractions from the colluvial cones, as indicated by the great amount of suspended matter transported by streams. As a result, coarser fractions – medium sands mixed with gravel – are left in the subslope zone.
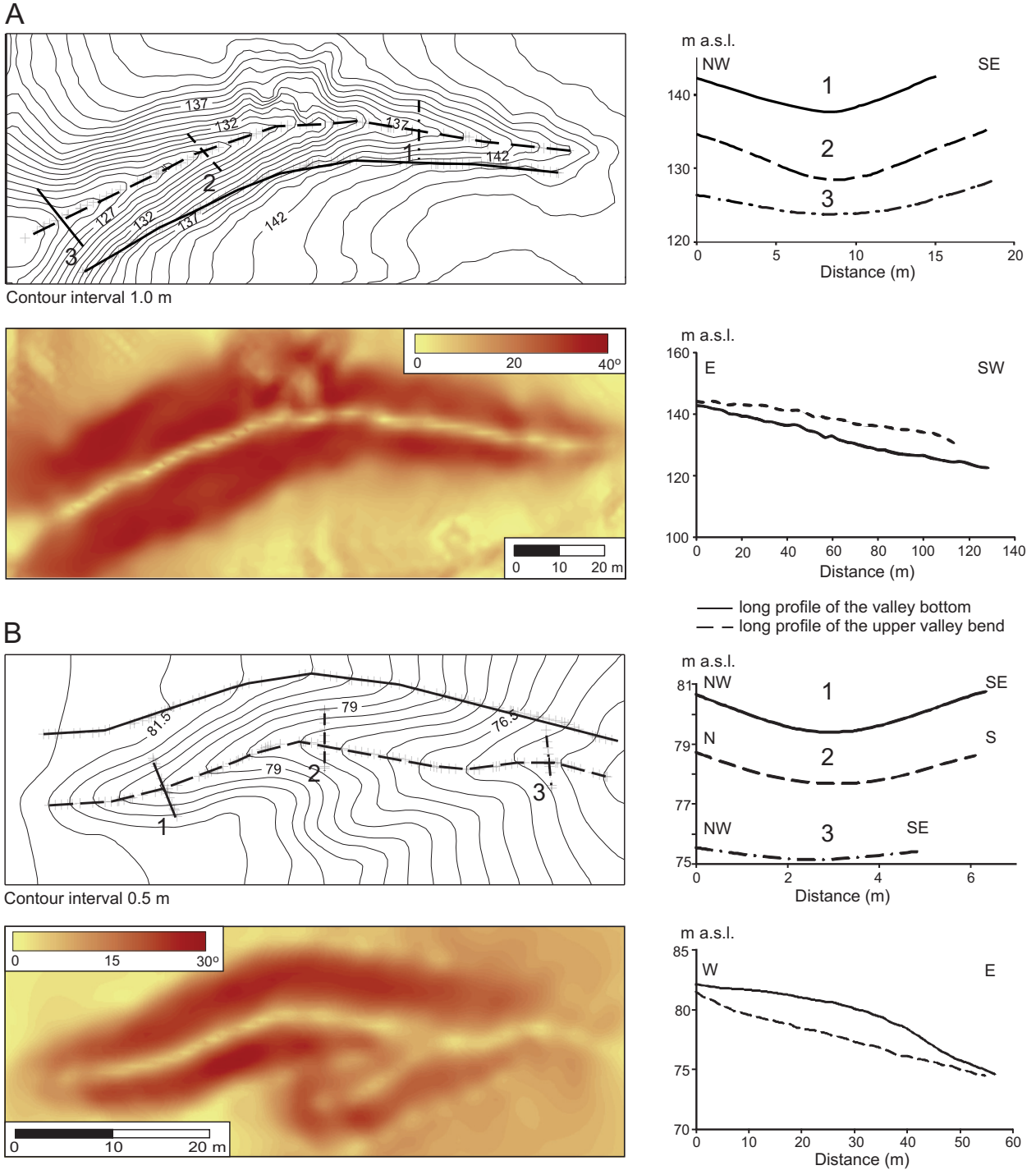
The lower Dębnica River valley

The other study site embraces the eastern slopes of the morainic upland of the Buślarki Hills and the western slope of the kame plateau of the Skowrończe Hills, separated by a section of the Dębnica Valley of fluvioglacial origin (Fig. 1A and B). From the top of the Buślarki Hills situated at an altitude of 150 m a.s.l. the terrain falls towards the Dębnica River Valley in a belt 0.7 to 1.2 km wide to an altitude of 80 m a.s.l. (Fig. 1C). The Buślarki-Ostre Bardo scarp is about 4 km long, and its absolute heights range between 70 and 90 m a.s.l. The difference in gradients between the gently inclined surface of the morainic upland and the outwash plain filling the Dębnica Valley has caused the development of several erosional dissections and small denudational-erosional valleys varying in the length and depth of their incision. Along the entire length of the scarp, 25 1st-order valleys running NW-SE were identified (their density amounting to 0.92 km km^{-2}). Most of these dissections are dry, only in eight of them is the flow permanent or periodic. Exposed in the valleys are colluvial and glaciofluvial sandy sediments underlain by morainic tills (Fig. 2). At the lithologic contact of these deposits of varying permeability, a zone of groundwater contact outflows has developed. The outflows are located in the upper and middle sections of the valleys.

East of the Dębnica Valley (the Kołacz-Rudno zone), in turn, there extends the kame plateau of the Skowrończe Hills, which attain a maximum altitude of 168.9 m a.s.l. The kames are built of varigrained sands with intercalations of gravels and silts. Groundwater outflows in the form of single seeps, springs or their clusters, situated at various heights in the kame slopes, arise at the contact of permeable sands with intercalations of silts, while outflows at the foot of the slopes develop at the contact with the substratum built of morainic till; these springs can be of both of the contact or barrier type. Groundwater outflows are mostly located in the middle sections of the valleys, but also in their head parts, in which case the head of the channel flow coincides with the head of the valley network. On the western slopes of the kame plateau, 30 1st-order valleys were identified, among which 10 are connected with the Dębnica via channel flow.

The erosional-denudational valleys at the lower Dębnica River valley study site are small landforms (Fig. 1C). Most are single forms 30 to 130 m long, but there are also some that consist of a trunk valley joined by one or several lateral valleys. Short lateral valleys (at most a dozen metres long, often measuring just a few metres) hang over the bottom of the trunk valley. Most of the valleys have flat bottoms. The depth of their incision varies greatly along their length, being deepest, at about 3–4 m, in their middle sections and shallowest at the mouth. The long profiles are usually smooth, although in some dissections they are stepped (Fig. 3B). The average gradient of the long profiles of the valleys is about 6°, diminishing towards the mouth. In turn, their cross-profiles (oriented S-N and SW-NE) display the highest inclination in the middle part, up to a maximum of 26°, and at the mouth, from 10° to 23°. When analysing the cross-profiles of the valleys in the study area, it is hard to take a stand on the problem of slope asymmetry, so often raised in the literature on the subject as an effect of climate changes (e.g. Okołowicz 1947; Maruszczak, 1968). It can be noted more readily in the Piaski Pomorskie scarp zone of the Drawsko Lakeland (Paluszkiewicz 2009). The difference in gradients between the E and W slopes of the analysed landforms slightly exceeds 2°.

A similar study to that of the sediments forming the valleys at the Koprzywno scarp zone was made of basic lithological groups of valleys in the Buślarki-Ostre Bardo area. In the head zone of these valleys, the substratum consists of fine and medium fluvioglacial sands, moderately sorted. This series is usually overlain by a stone-gravel layer about 40–20 cm thick. In an earlier paper by Paluszkiewicz (2009), this layer was interpreted as an erosional pavement blocking further dissection of the valley bottom. The sand-gravel level with stones at a depth of 1.4 m below the ground-level derives from the valley bottom being dissected by wash. Overlying this is a thick series (1.4 m) of medium and fine sand, divided by a thin, dozen-centimetre layer of medium and coarse sand. This series displays moderate and poor sorting, while its negative skewness figures indicate its enrichment with coarser fractions. It has the lowest percentage of calcium carbonate in all the series (about 2.5% of $CaCO_3$). The

Fig. 3. Hypsometric and slope maps of erosional-denudational valley together with its long and cross profiles from: A – the upper Dębnica River valley, and B – the lower Dębnica River valley

top part of the profile is a layer of fine and medium sand, about 20 cm thick and poorly sorted.

In the mouth section of the valleys, the substratum of fluvioglacial sands is covered by a stone-gravel series, very poorly sorted. It is certainly a remnant of sediment of the old valley bottom, which was about 80 cm lower than the present one. The entire overlying series is colluvial sediment built of massive medium and fine sands, poorly sorted and with negative skewness indices. An analysis of the sediments and morphology of the valleys showed that

the processes contributing to the development of these landforms were wash and rill erosion.

A type of valley development and modification by groundwater outflows similar to that registered for the upper Dębnica River valley study site was also found in the Buślarki-Ostre Bardo and Kołacz-Rudno areas. Here headwater alcoves are located in shallow erosional-denudational valleys (Buślary 2 and Kołacz 1, 5, 6 and 7 sites; for the location of the sites, see Fig. 1B) or denudation hollows (Ostre Bardo 5 site). The asymmetric de-
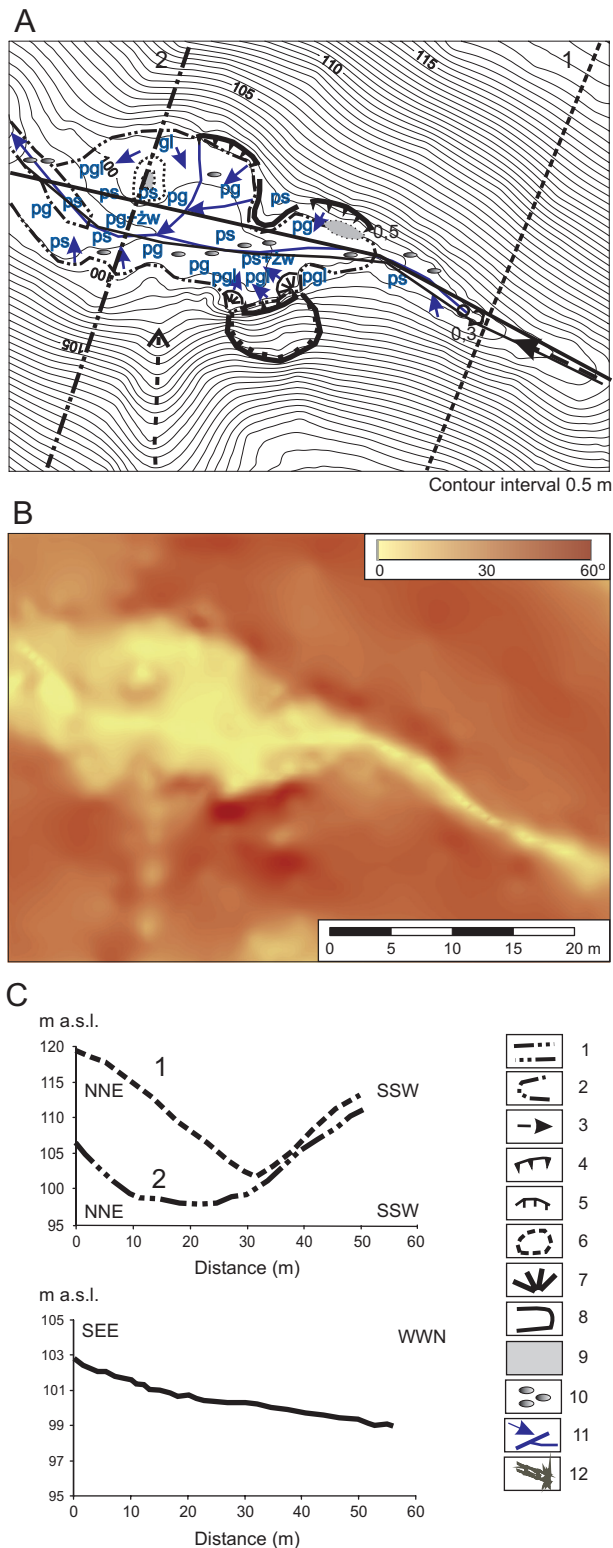
Fig. 4. Koprzywno 1 channel head: A - contour map with locations of selected geomorphic activity and lithology, B – slope gradient map derived from DEM obtained by ground survey, C – cross and long profiles

Geomorphology: 1 – fluvial processes, 2 – seepage erosion zone, 3 – episodic rill wash, 4 – seepage erosion scarp, 5 – landslide scar, 6 – erosional residuals, 7 – sediment fan, 8 – spur, 9 – organic sediment, 10 – erosional pavement, 11 – drainage line, 12 – fallen tree

Lithology: gl – glacial till, pgl – loamy sand, ps – medium sand, pg – coarse sand, ps+żw – medium sand with gravel, pg+żw – coarse sand with gravel

velopment of the alcoves, as in the case of Ostre Bardo 5, is an effect of the diversified geological structure of the slopes surrounding the alcoves and its effect on the discharge volume of groundwater outflows. The rate of development of the alcoves is fastest around abundant outflows, as they favour fragmentation of their slopes and determine the directions of headward erosion. In the zone of active water outflows and in the routes of its flow, there are coarse deposits in the alcove bottom: sand and sand-gravel with a stone pavement. When the runoff in the bottom is stopped by coarse plant detritus in the form of tree trunks, organic material accumulates which decays quickly, thus enriching the mineral deposits in the alcove substratum.

Apart from the alcoves inserted in older denudational landforms as characterised above, there are also some that can be classified as slope types. Such alcoves, which also comprise the heads of 1st-order valleys, develop on the slopes of kames, dead-ice morainic hills, erosional residuals, etc. (e.g. Rudno 1, 2 and 3, Ostre Bardo 1 (Fig. 5) and 2; Mazurek 2010). The heads of the valleys are located on slopes that are straight or convex in shape, with the curvature of their contour lines indicating an unconcentrated water flow. The alcoves are compact landforms with slopes of considerable gradients (17–23° on average, with a maximum of even 53°) along the entire circumference. The slopes, up to 10 m in height and having a convex-concave profile, pass via a distinct break into a flat bottom (inclined at 3–10°). In the outflow zone, the bottom narrows to the width of a stream channel, as in the alcoves Rudno 1, 2 and 3, Ostre Brado 1 (Fig. 5). Such forms have been termed basin-like alcoves (Mazurek 2010).

In the subslope zones of the headwater alcoves studied, seepage erosion leads to the development of erosional undercuts exceeding 0.5 m in height. The exfiltrating water washes the sand-gravel sediments of the bottom, causing it to deepen evenly, as indicated by small differences in its inclination. In the water, which so far runs across the entire surface of the bottom, there develop separate rivulets which combine at the mouth of the alcove to form a channel flow. The flowing water takes with it fine fractions of mineral material, and as a result what is left on the alcove bottom is an erosional pavement (coarse sand with gravel). The accumulation of mineral-organic muds in the alcoves under study is small and limited to zones of low-discharge seepage.

Tendencies in the development of 1st-order valleys – Discussion

In the Dębnica catchment, which represents a post-glacial relief zone, the network of 1st-order valleys can start with shallow wash hollows, solifluction hollows, denudation hollows and valleys, erosional dissections (gullies, badlands), and erosional-denudational valleys (colluvial valleys). Land depressions of this type have the ability
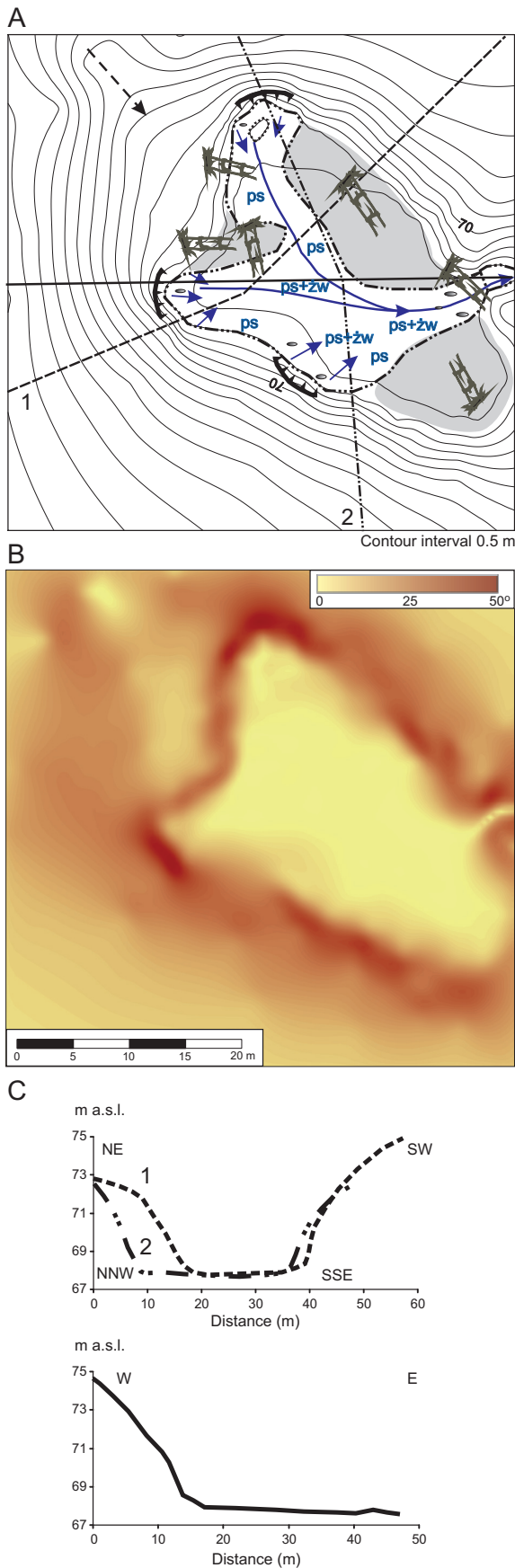
Fig. 5. Ostre Bardo 1 channel head: A – contour map with locations of selected geomorphic activity and lithology (legend as in Fig. 4), B – slope gradient map derived from DEM obtained by ground survey, C – cross and long profiles

to concentrate enough water from overland runoff to initiate the processes of wash and rill erosion. They also determine the direction of water flowing from subsurface levels in the aeration zone. Some of these valleys are now drained only episodically by streams nourished directly by precipitation and local groundwater horizons, and therefore having a variable discharge throughout the year. The deepening of erosional-denudational landforms can lead to the cutting of aquifers and the drainage of groundwater, which allows a steady channel flow to be maintained.

The morphometric features of the small, dry 1st-order valleys are a record of their development stages and indicate processes that dominated in them. In the course of their widening and lengthening, their bottom gradients decreased. The valleys in the Koprzywno area have steep bottom gradients, 21° on average, compared to 12° for the valleys in the Buślarki-Ostre Bardo area. In most of these landforms, the ratio of the length of the valley bottom to its maximum width, L/W, is greater than 1. The valleys are single landforms, but some are composed of a trunk valley joined by several lateral ones. The bottoms of the lateral valleys hang over the bottom of the trunk valley, which indicates that they developed later than the trunk valley. Their cross-profile is V-shaped. They have flat bottoms which are at most a few metres wide. Their long profile is usually even, although a few smaller dissections have a stepped one. In most of the valleys, the width of their bottom in the lower section is greater than that measured in the upper and middle sections, which suggests intensive slope wash processes in their lower parts. This growing width of the bottom towards the mouth of the valleys is determined to some extent by vertical differences in the relief within these landforms and an increase in the intensity of slope wash. There are mass-movement processes occurring on the high slopes.

The catchments of the studied erosional-denudational landforms with no steady runoff can be called a colluvial system, to use Teisseyre's (1994) term. In this system, one can distinguish a nourishment zone with predominant processes of wash and rill erosion that supply the material which is transported down to, and deposited in, the middle or lower part of the valley. In the transport zone, embracing an episodic channel, transport processes predominate over those of erosion and accumulation. Here the chief processes are rill erosion and episodic channel erosion (Rodzik *et al.* 1998, Janicki *et al.* 1999). During heavy rainfalls, episodic runoff occurs in this part of the valley. There is a depositional zone located in the mouth section of the valley which forms a boundary separating the zone of subslope colluvial deposits from the flat bottom of a higher-order valley. Only rarely can one find a colluvial cone here, the material being mostly deposited in the form of colluvial covers. Depending on the vegetation cover, this zone can be described as having a depositional or an erosional-transport character. The distinguished elements of the denudation system indicate that the processes of erosion and accumulation differ in pattern and intensity (Paluszkiewicz 2009).

Some of the valleys at the study sites studied have gained nourishment by groundwater and become part of the contemporary network of river runoff. Geomorphological mapping shows groundwater in the zones of its outflow onto the surface to be a relief-forming factor modifying older erosional-denudational landforms and leading to the development of 1st-order valleys that start in the form of spring-niche valley heads (Ahnert 1998). The zero-discharge catchments of the drained valleys can be regarded, following Teisseyre (1994), as an incomplete colluvial system because their depositional zone has been destroyed or deeply dissected.

Most of the relief-forming processes in small valleys with headwater alcoves are generated by groundwater outflows, and their intensity is regulated by external factors, e.g. the amount of precipitation, an effect of the biosphere, as well as increasing human impact in headwater areas. The morphology of the alcoves has been determined by the efficiency of the relief-forming processes, which partly depends on the susceptibility to erosion of the sediments that build them. The lithology and stratigraphy of Pleistocene and Holocene sediments affect the shape, orientation and size of the alcoves through the development of the bottom of the aquifer and a step-like change in its thickness and transmissivity, thus determining the direction of groundwater flow, whether its outflows are concentrated or run across the land surface, as well as their discharge and location on the slopes.

Seepage erosion (cf. e.g. Baker 1990, Dunne 1990, Nash 1996, Afelt 2012), which manifests itself in slope undercutting and/or bottom deepening, takes place in all the headwater alcoves under study. The modelling of their slopes involves their retreat as a result of repeated episodes of subslope seepage erosion and gravitational mass movements. Degradation caused by falls and landslides embraces the lower and middle parts of the slope and leads to its steepening and parallel movement. The material loosened by erosional-denudational processes is transported by streams rising at the headwater alcoves. This sequence of processes contributes to the preservation of the steep gradients of the convex slopes of an alcove and the formation of a distinct concave section at the foot of the slope that passes into a flat erosional bottom. Seepage erosion also contributes to a gradual widening of the head (closing) part of the alcove.

An analysis of the geomorphological location of the alcoves, their size proportions and spatial relations to their surroundings makes it possible to establish a relative chronology of events connected with the evolution of slope and spindle-like alcoves.

The evolution of slope alcoves leads to the development of a valley network from a local water divide to a higher-order river valley. A good illustration of this development path is headwater areas located in the Rudno and Ostre Bardo region (Rudno 1 and 3 sites, Ostre Bardo 1). The groundwater flowing onto the land surface starts headwater processes that cause headward erosion and the deepening of the initial depression. At first there develops an elongated and shallow alcove which gives rise to a valley. Seepage erosion leads gradually to the widening and deepening of the head (closing) part of the alcove. In turn, in its lower part, the volume of outflowing water grows along with the growing discharge of groundwater drainage, which causes vertical erosion to become more intensive. In the lower part of its long profile, in the place where it opens to its foreland, the alcove attains a considerable depth while preserving its small width. This gradual development – from a small depression of varying origin through a narrow and elongated alcove to a basin-like one – results from the growing intensity of morphogenetic processes (Fig. 6A). This path of development of the headwater alcove conforms to the stages of its development as a result of erosion by groundwater obtained by Smith *et al.* (2008) in a laboratory experiment.

It is not known what creates a depression on the slope that initiates the development of a valley (cf. Churska 1965). Headwater processes have modified such depressions so thoroughly that it is hard to tell their origin with any certainty today. In the case of the Dębnica catchment and post-glacial areas, significant for the location and development of slope alcoves is the lithofacies variability of glacial sediments determining the conditions of groundwater flow. When discussing a similar sequence of the inclusion of the beginning of a channel that starts on a slope into a valley network (down-valley development), Coelho-Netto (1999) emphasises the role of structural conditions in the location of headwater areas resulting from the geological structure.

As to the spindle-like alcoves (Mazurek 2010), two basic stages can be distinguished in their evolution:
1) the appearance and development of a valley- or hollow-like landform of various origins, and then,
2) its modification by groundwater outflows (Fig. 6B). At the Koprzywno study site, one can trace the morphological and lithological effects of these two stages of development of this type of valleys.

The initial valley landforms inherited from earlier morphogenetic cycles, e.g. the periglacial cycle or one of the stages in the development of the Holocene relief, went through successive stages of being dissected and filled with sediments. The cyclicity of their development (Dietrich *et al.* 1986) results from changes in the climatic conditions and/or land use (e.g. deforestation). The deepening of some of the denudational and erosional landforms has led to the dissection of aquifers and the drainage of groundwater onto the surface, thus starting permanent flows in formerly dry valleys. The role of the chief erosion factor was then taken over by groundwater outflows. At first the morphometry of alcoves reflected the elongation and gradient of the bottoms of the initial landforms in which they had formed. As a result of seepage erosion and mass movements, narrow headwater alcoves gradually kept widening and assumed a spindle-like shape. Vertical erosion led to the levelling and deepening of the older landforms, the steepening of their slopes, and in effect, a modification of the inherited cross-profile from
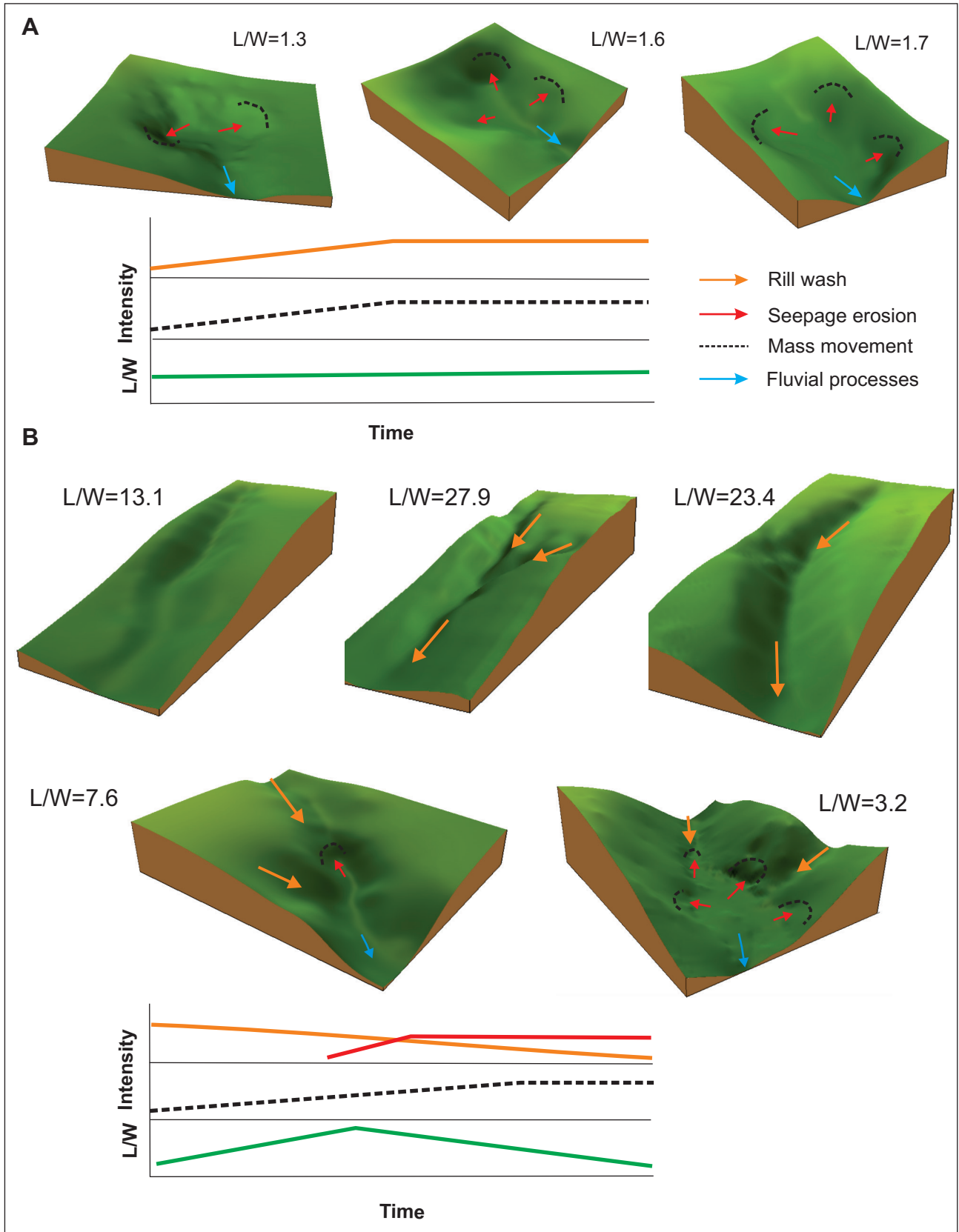
Fig. 6. Development sequences of 1st-order valleys in the Dębnica catchment observed today as an effect of slope wash, seepage erosion, mass movements, and fluvial processes against tendencies of change in the length/width (L/W) ratios of these landforms.
A – basin-like alcoves, B – erosional-denudational hollows, valleys and spindle-like alcoves inserted in inherited landforms

a V-shaped into a flat-bottomed one. Ever more marked in the development of an alcove was the flat bottom and the steep section of the slope as an effect of falls and slides (Figs. 4 and 6B). The morphometry of the group of elongated and narrow alcoves in the Dębnica catchment displays a similarity to landforms from the periglacial area of the Łódz Hills (Central Poland) examined by Maksymiuk and Moniewski (2000) and Moniewski (2004). Their common morphological characteristics result from similarities in their geological structure (glacial sands and tills, fluvioglacial sands), and hence similar conditions of groundwater flow and types of its outflows. A similar pattern of several generations of valley landforms in post-glacial areas was presented by Majewski (2008).

Owing to the morphogenetic impact of groundwater outflows, there was a change in the morphology of the earlier erosional-denudational landforms involving an increase in their width and depth, as well as a change in their cross-profile. Headwater alcoves that give rise to valleys or that modify older landforms stand out in post-glacial areas as places of radical slope transformations and reinforcement of morphological (hypsometric and topographic) contrasts.

Conclusion

In the network of river valleys in the post-glacial zone, which are heterogeneous in terms of their development and organisation, worth noting is the network of 1st-order valleys consisting of landforms initiated by denudational and erosional processes. Valley-like landforms in this area are of various origins and ages. At this stage of the research, it is still impossible to identify the time of initiation of the valleys and headwater alcoves, which may differ for individual landforms. Their development (and partly also of 1st-order streams) was probably not synchronous at the sites studied, due to several factors, such as their location in different geomorphological units (morainic uplands, fluvioglacial plains, river valleys), differences in hydrogeological conditions (nourishment from a local and transitional water-bearing system) as well as hydrological conditions, and in effect their different origin. In addition, owing to the small size of these landforms and great significance of the local conditions, the development of the valleys and possibilities of their inclusion into the stream network can be highly individual, and the result is the co-occurrence of landforms representing various stages of development.

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