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# CONTENTS

# GEODETIC MONITORING METHODS OF LANDSLIDE-PRONE REGIONS – APPLICATION TO RABENOV

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**ABSTRACT**

The article focuses on the geodetic monitoring of the Rabenov landslide territory. The monitored slope is situated in the landscape deteriorated by mining activity in North Bohemia, West of Ústí nad Labem, in Chabařovice, a reclaimed brown coal pit. The article presents a general description of the application and accuracy of geodetic methods used to measure on the movement of material in landslides. Also, the history, the problems and the plans for reclamation of the monitored territory are briefly mentioned. The text concentrates on the description of the network of three observed points which are formed by geotechnical instrumentations and on the description of a terrestrial and GNSS measurement in the network of monitored points. The assessment methods and the results from the eight-year phased monitoring process are also discussed. Different methods were tested during the phases. For terrestrial measurements, standard deviations of about 2 mm in position were made and for GNSS standard deviations of about 14 mm. Surveys in a local grid showed that there were continuous movements of observed station points of about 10 mm per year. The paper also discusses the use and assessment of digital terrain models in zones with on-going artificial as well as natural changes. Models indicate elevation changes of about 2–6 m and movement of about 10,000–100,000 m$^3$ of material.

**Keywords:** digital terrain model (DTM), geodetic monitoring, global navigation satellite systems (GNSS), Rabenov landslide territory, terrestrial measurements

## 1. Introduction

The monitoring of landslide territories is a multi-disciplinary branch which, based on systematic phase measurements, observations and analyses of the current state, leads to the estimations of the slope development, the designs of safety measures and potentially the documentation of past landslides. The monitoring is implemented in areas where the occurrence of shifts and deformations is probable or has already been manifested. Landslides cause natural disasters or limit the territorial development in many countries worldwide being the subject of great research interest (Pesci et al. 2004; Burda et al. 2013).

In monitoring landslides, geodetic methods are applied together with geotechnical methods using, among others, inclinometers, declinators, extensometers and hydrostatic levelling instruments to measure deformations, stresses and forces. Geotechnical measurements are costly requiring the digging of deep trial holes for measurements; the results are data on spatial deformations in individual layers of soils representing, however, local relationships. In the case of insufficient coverage of the monitored territory by geotechnical probes, additional methods must be used such as surveying, which contributes to the prediction of the depth and extent of movements. Geodetic methods may provide data on the overall deformations of the monitored area of interest and, apart from measurements (cubatures, longitudinal profiles, mapping of soil shifts within the whole territory, monitoring of stabilised survey marks), they also focus on the coordinate description of positions of geotechnical facilities.

The expansion of new technologies has allowed the development of novel measurement techniques as well as innovations of long-term proven methods applied in failure zones. The text below presents geodetic methods that are generally applicable for the monitoring of landslides and specific applications for the long-term monitored Rabenov landslide territory in North Bohemia.

## 2. Geodetic monitoring methods

Geodetic monitoring methods of slope movements may be subdivided into "point" and "area".

In point methods, specific points (marks) are monitored which are usually formed by geotechnical probes with mounted reflective targets or otherwise suitably stabilised points. If the spatial position of monitored points changes between individual measurement phases, the vectors of coordinate changes are non-zero being greater than the identified difference limit value expressing the measurement inaccuracy, and the change is called a shift. A shift may be "relative", if it is related to other observed points, or "absolute", if related to the grid reference system. Depending on the comparison with the other points, conclusions and assumptions about the slope behaviour must be formulated. Point methods may have little conclusive evidence if the coverage of the whole territory is incomplete, covering only certain parts of it is guaranteed. These methods include classical terrestrial measurement using total stations or levels and methods using global navigation satellite systems (GNSS).

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Research terrestrial measurements are usually used in geodetic networks where the accuracy of the spatial coordinates ranges in millimetres (local network Rabenov). Classical terrestrial measurements from one standpoint are used e.g. in ČSA Pit where 45 permanently stabilised points are monitored at regular hourly intervals (Stanislav, Blín 2007) with the accuracy rate of the spatial coordinates identification of 20–30 mm (Hampacher et al. 2008).

The measurements with GNSS are easier than terrestrial methods, but the accuracy of position mainly depends on the observation time, atmosphere conditions, unobstructed view of the sky, number of satellites and transformation of coordinates into reference system (Raška, Pospíšil 2011; Urban et al. 2013). The position of observed points with permanent stations may be determined with millimetre accuracy (Manetti et al. 2002). The expected accuracy of the coordinates of points with rover stations and with the observation time of ca. 20 minutes (static method) may be ca 5–10 mm and in mapping the real time kinematic (RTK) method (measurement of 5 s), the expected accuracy is of ca 25–50 mm.

In "area" methods, as their name suggests, the entire monitored territory is surveyed where guided by the principles of mapping the measured points are selected on prominent terrain landmarks, on the very faults and within a regular grid or the points are obtained by an automated survey technology. Such measurements usually allow plotting a digital terrain model (DTM), which represents the measured surface with its morphological features and enables the observer to make a complex overview of the monitored area of interest and changes occurring in it. DTM may subsequently serve for making various analyses (changes in volumes, shifts of soil, changes in slopes), or for exporting longitudinal profiles and contour plans. An extensive number of measured points may be obtained by using classical measurement methods with total stations (the polar method), RTK GNSS technologies where points are selected by the operator, or automated methods using laser scanners or photogrammetry.

Laser scanning is an automated method where the instrument measures separately in a certain preset steps (ca 10 cm onto 100 m). The result of such measurement is a point cloud with the accuracy of coordinates of ca 20–30 mm (Pospíšil et al. 2006). It is a developing method where the measurement conditions and the accuracy of shifts are studied in many theses (Barbarella et al. 2013; Abellán et al. 2009).

Photogrammetry is based on the identification of coordinates from photographs. The accuracy of the resulting points is ca 10 cm, and the method is comparable to laser scanning. The advantage of this method is the speed of taking the image (capturing) of a monitored object with minimum regards to its shape complexity and inaccessibility. Apart from terrestrial photogrammetry, aerial photogrammetry may expediently be used for extensive landslide bodies; the results are orthophotos of the territory and DTM (Pesci et al. 2004).

Apart from the classification by the data collection methods, geodetic monitoring may also be classified according to the measurement interval and assessment into "active" and "passive".

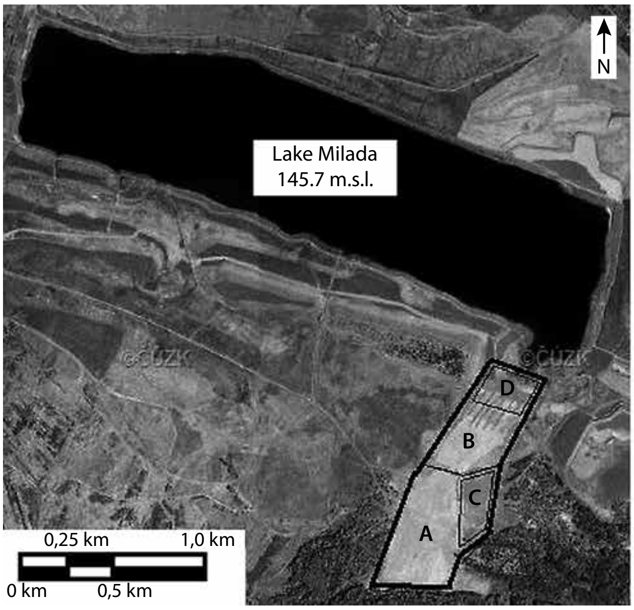
In active monitoring, automated total stations performing automated measurements according to the preset programme or permanently installed GNSS receivers may be applied. These instruments make measurements in short time intervals and immediately send the results into the monitoring centre connected to the hazard reporting system. Such measurements are only made in high risk zones. An example may be the ČSA Pit and the monitoring of South East slopes of the Krušné Mountains (Burda et al. 2010).

In passive monitoring, the interval between individual measurement phases depends on the hazard factor and the client's requirements ranging from days to years. The results of measurements are only known after they are assessed in the office by a surveyor, and the outputs are usually extensive reports including the assessment of observed points and summary maps of the monitored territory. Passive monitoring is carried out on the described Rabenov locality or elsewhere in the world (Bitelli et al. 2004; Barbarella et al. 2013).

## 3. Rabenov landslide territory

The monitored Rabenov landslide territory is a part of outer dumps of the former Chabařovice opencast brown coal mine situated 5 km to the southwest of the town of Ústí nad Labem (Figure 1). The slope is situated to the southeast of the extracted pit space, below the peak of Rovný Hill (376 m.s.l.). The upper South part, so-called top site, was not directly affected by overburden, but has impaired stability thanks to the reduction of load and the removal of the foot of the slope. The lower North part, the bottom site, is formed by an unstable outer dump. The monitored area covering about 40 ha is situated between elevations 145 and 275 m.s.l. The dimensions of the territory are 1.15 km × 0.37 km (0.30 km at the foot of the slope).

In Figure 1, the whole monitored territory is marked with a subdivision into subterritories. The upper South (A) and the lower North (B) part cover the entire monitored zone, and the border between them is the road running across the centre of the territory at an altitude of ca 190 m.s.l. The other two parts have recently become the focus of interest due to extensive changes. Landslides continuously occur in the surface soil layer in the southeast part (C), while extensive material transfers (130,000 m$^3$ of stone material) were performed at the foot of the slope (D) (former spoil tip of titanium clays (PKÚ website, 2013)) to ensure the slope's stability.



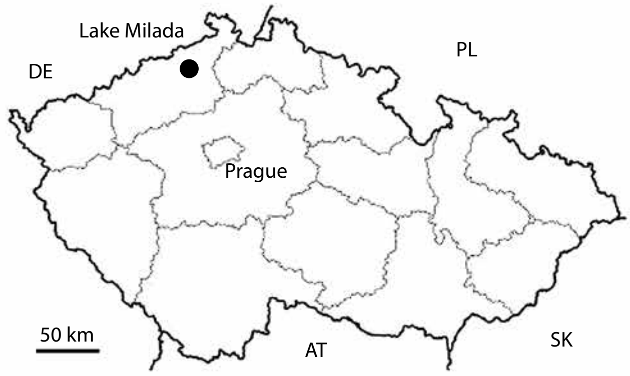




**Fig. 1** An orthophoto with a marked monitored territory.
Source: Braun 2011

### 3.1 History of the territory

Chabařovice Pit was one of the last opencast mines in the North Bohemian brown coal basin. The new pit was situated in a flat valley of the Modlanský Stream where outer dumps were established on southern slopes and mining was carried out northwards along less steep slopes. Mining began in 1977 and it was presumed that the open pit operation would be terminated after the extraction of all coal deposits in the easternmost part of the basin. In 1991, the Government Decree of the Czechoslovak Federal republic decided to stop mining in Chabařovice Pit, and a strict mining policy was set up. This decision was caused by an attempt to preserve the town of Chabařovice and adjacent steelworks. The actual shutdown began in 1994, and all mining, processing and sales of coal ended in April 1997. In March 2000, the last technological unit, ensuring the backfilling of the bottom of the residual pit with soil according to the approved shutdown plan, was stopped.

The total of 61.5 million tons of high-quality low-sulphur brown coal, 9.3 million $m^3$ of spoiled material and 256.1 million $m^3$ of overburden were extracted during the mining activity in Chabařovice Pit. After mining was stopped, additional 128 million tons of coal, which were supposed to be extracted according to original plans, were left in the deposit (Šípek, Němec 2008).

At the time of extraction, the monitored Rabenov slope was used as an outer dump for storing overburden soil. Local landslides of uncovered layers of clay were

**Fig. 2** Landslide in the southeast part of Rabenov (April 2009).
Source: Braun 2011

manifested on the Rabenov slope territory as early as the 1990's. Stability problems were partly caused by deposits of non-cohesive soils (loess, soils with high contents of boulders), but mainly by wetting of the area originating from former small water supply structures. As the stability design using a mining method (supporting by layers of an interior dump) was technically not feasible due to the limitation of mining, a decision was made in 1994 to carry out remedial works using a construction method. In 1994–1999, the state-owned Palivový kombinát Ústí (PKÚ) took measures to secure the slope, including, in particular, the construction of drainage structures and the foundation of supporting stabilization ribs. Despite the efforts to stabilize the territory, slope movements, that are even now apparent in the southeast (C) part of the slope, developed over time (Figure 2).

### 3.2 Restoration and planned use of the territory

In April 1999, the Ministry of the Environment of the Czech Republic approved the "General Plan of Land Reclamation until the Completion of Complex Revitalization of the Territory Affected by Mining Activity by the State-Owned Palivový kombinát Ústí". Based on this plan, reclamation works are currently in progress in the area performed by the Palivový kombinát. Planned completion date of the work is after 2015.

The surface area of the territory disturbed by mining and by founding outer dumps is nearly 1500 ha. The basic concept of remediation and reclamation activities, which are aiming to restore the landscape function in the area disturbed by mining, is the hydric reclamation method of the residual mining pit, i.e. its filling with water. The creation of the total of eight lakes in residual mining pits is planned in the North Bohemian brown coal basin. The hydric reclamation process was first used in Chabařovice Pit, which became a prime model site in terms of a potential future application of the knowledge gained during reclamation activities in the other 7 residual pits.

The filling of the newly created Milada Lake (formerly known as Chabařovice Lake) with water from streams in the Krušné Mountains and water from the residual pit's watershed started on the 15th of June 2001. The estimated filling time was 5–6 years. On the 8th of August 2010, the filling was terminated by reaching the final operating water level at an elevation of 145.7 m.s.l. After reaching this level, the lake covers an area of 252.2 hectares, retains 35.601 million $m^3$ of water with the maximum depth of 24.7 m and an average depth of 15.5 m (PKÚ website, 2013).

The southern part, which accommodates the monitored area and consists mainly of outer dumps, is planned to fulfill primarily ecological functions. Forest reclamation will be complemented by new grassed areas. In the southeast part of the lake adjacent to the slope, a bay was formed to be used as a jetty for boats (sailboats, barges, sports boats).

Remediation work on the monitored Rabenov slope began in 2006. Its main objective is to secure the geomechanical stability of the slope. This is done by 7 anchored pile walls (Figure 3) installed in the southern part at an elevation of 240 m.s.l. in 2007, by building drainage structures, by the removal of unstable soil layers along with the modification of the gradients of parts of the slope and by the building of stabilization benches at the foot of the slope.

## 4. Geodetic monitoring of Rabenov landslide territory

Guided by the above described reasons, the monitoring of the Rabenov landslide territory was performed by the Department of Geotechnics and the Department of Special Geodesy of the Faculty of Civil Engineering, CTU in Prague working for the state-owned Palivový kombinát Ústí, which is in charge of land reclamation. Three instrumented inclinometric boreholes for geotechnical measurements, which were assumed to extend into stable underlying rock, were bored. They were fitted with combined casing to a depth of 24 m, and hydrological probes for the monitoring of the water table were installed. Geodetic monitoring running in a mutual coordination with

**Fig. 3** Distribution of retaining walls in the upper South part of the slope (April 2010).
Source: Braun 2011

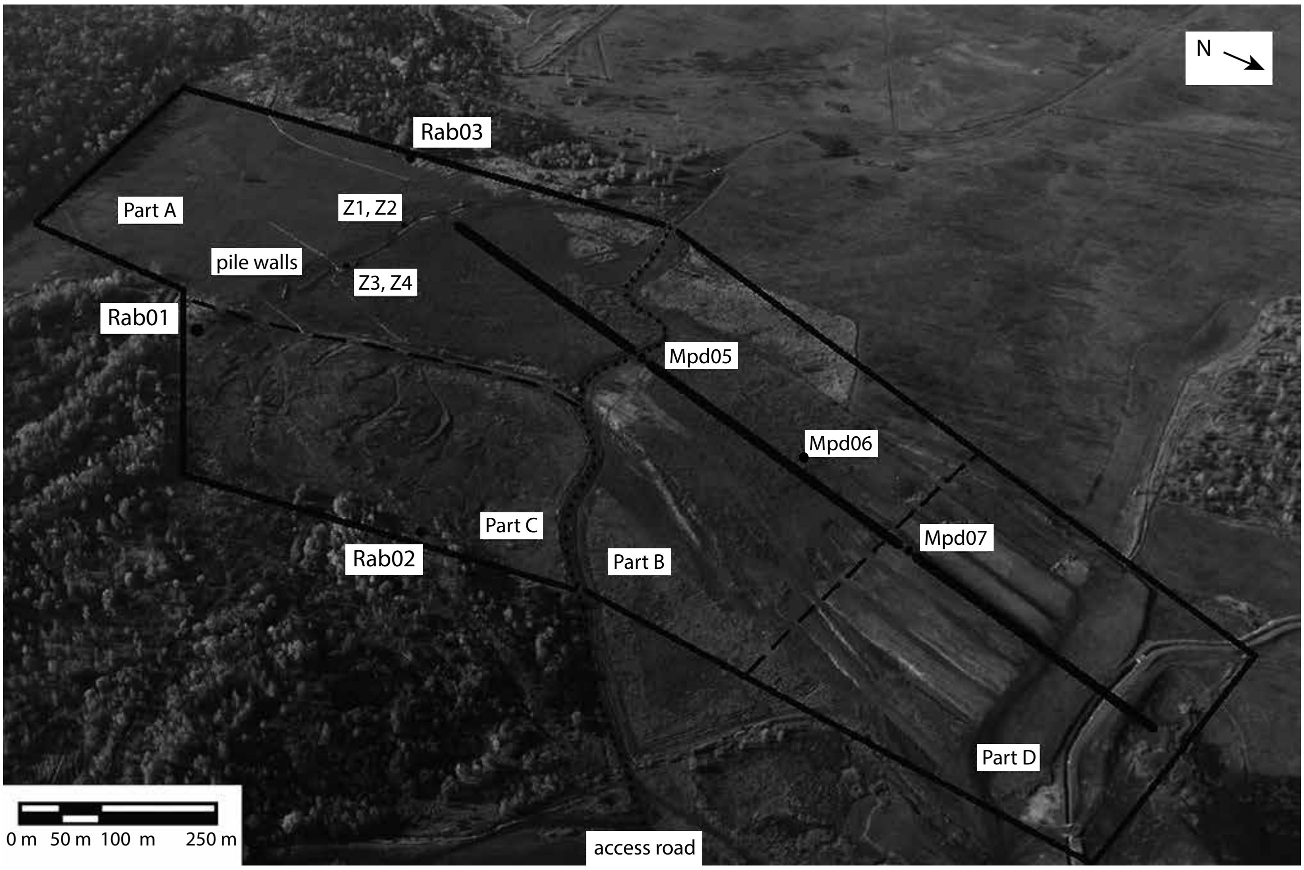



**Fig. 4** Aerial view of Rabenov slope with marked points and the profile route (October 2008).
Source: Braun 2011

geotechnical monitoring was performed since 2003 to 2011, including 19 measurement phases in all. In 2003 and 2004, the measurements were done three times a year (in April, June and October). From 2005, the measurements were performed twice a year (in April, July). Various monitoring and assessment methods for the identification of changes of points and the slope were tested during individual phases.

Individual phases involved the survey of a local spatial grid and the monitoring of detailed survey points using terrestrial methods (in 17 phases) and the GNSS technology (in 12 phases). Another element of the monitoring survey was the establishment of monitoring longitudinal profiles (in the last 7 phases) and the survey of background data for the generation of digital terrain models (in the last 5 phases). All of the results were presented in final diploma theses at the Department of Special Geodesy, e.g. (Braun 2011; Rytíř 2012; Riegerová 2012). Figure 4 displays the main observed points and the route of the monitored longitudinal profile.

### 4.1 Terrestrial measurement – local spatial grid

The establishment of the Rabenov local grid in the southern part of the slope in 2002 was part of the GA ČR grant project No. 103/02/116 "Research and verification of slope movement monitoring methods".

The Rabenov spatial survey grid was originally composed of four points. Points labelled Rab01, Rab02, Rab03 are formed by instrumented inclinometric boreholes. Spatial deformations of the earth body in the borehole are measured with a modified inclinometer (horizontal changes) and the sliding deformeter (vertical changes). The borehole head is modified to use a special centering fixture which serves for an unambiguous final centering of surveying instruments on the tripod. The borehole head also houses a bench mark to which the point's elevation is referred. The fourth station point labelled Rab04 was a chaining arrow located on a concrete base of an old unused power line pole in the upper part of the slope. 23 discrete characteristic points of the terrain were observed from the points of this grid. These points were stabilised by a steel rod with a diameter of 0.06 m and a length of 1.25 m with an internal thread at its upper end into which a special fixture with two all direction reflective prisms had been mounted (Hánek 2007). Point Rab04 is presently no longer used for a measurement (since 2007), and the original detailed survey points are no longer surveyed either for the reason of their destruction during earthworks or their disappearance due to the effect of growing natural self-seeding vegetation (since 2008). Starting from the 12th phase (April 2008), points Z1–Z4, which are formed by geomechanical instrumentations on two pile walls, have been surveyed from the points of the grid. The instrumentations were installed for the measurement of relative deformations of the reverse and the face of the bent pile by means of a sliding micrometer and for the identification of the wall activation pattern due to the pressure of the stabilised slope (Záleský et al. 2013a). These points are used for the identification of the centre of the protective lid with the main emphasis on the points' elevation. 7 pile walls were built for the slope stabilisation in 2007 based on the results of on-going monitoring.

The starting point of the local grid is Rab01, which is considered stable for calculations. The Rab01–Rab03 connecting line, 419 m in length, lies approximately on the horizontal, on a convex fault of the terrain, and the +X axis of a local coordinate system is laid onto it. The height difference of Rab02–Rab03 points reaches ca 54 m for a length of 664 m, and the height difference of Rab02–Rab01 points reaches ca 52 m for a length of 364 m. The grid has a shape approximating an isosceles triangle. The distribution of points is displayed in Figure 5.

To ensure a highly accurate survey of the standpoints of the grid and the detailed survey points, Leica TC1700 (TC1800) total stations, which have the manufacturer declared accuracy of 0.5 mgon (0.3 mgon) in angles and 2 mm + 2 ppm in lengths (ISO 17123-3 2001 and ISO 17123-4 2001), were used in measurement phases 0–15. In phases 16–18, more up-to-date Topcon GPT7501 instruments with the manufacturer declared accuracy of 0.3 mgon in angles and 2 mm + 2 ppm in lengths (ISO 17123-3 2001 and ISO 17123-4 2001) were used. The measurements were performed with targeted prisms matching the used instruments and also with all direction Leica prisms, which accelerated the targeting from different standpoints during the measurement onto detailed survey points. The grid survey always followed the procedure in which tripods were centered and levelled over the standpoints, and then horizontal angles, zenith angles and slope distances were measured from each standpoint onto other standpoints and visible detailed survey points. All measurements were performed minimally in two rounds.

As a redundant number of variables were always measured in the grid, the least squares adjustment method was used for the calculation of individual spatial coordinates.

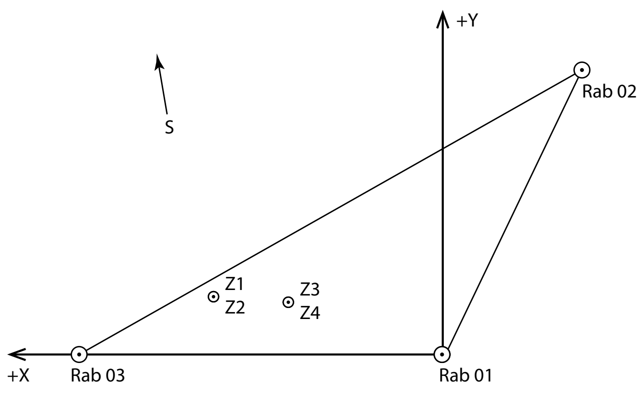



**Fig. 5** A sketch of the Rabenov local grid.
Source: Braun 2011

The method of free net was chosen with one defined point (Rab01) and direction of X-axis. The resultant accuracy of the coordinates ranges around 2 mm thanks to accurate instruments and the selected measurement procedure. The detailed measurement and calculation procedure is presented e.g. in (Braun 2011).

Based on the resulting coordinates, phase changes between individual points may be compared, in particular a change in horizontal length and in height difference. As the grid only contains of 3 points of which point Rab01 was assigned fixed coordinates, the assessment of changes cannot be made using solely the differences in coordinates between phases.

Despite this drawback, a shift of 0.04 m in the slope direction and of −0.01 m in height was manifested in the standpoints from the measurement in 2003–2008. Over the years, the slide slowed down and only the slope settlement continued.

Because of the unsuitable grid configuration and the minimum number of points, potential unstable standpoints were identified using the method of comparing horizontal lengths and height differences between individual points. This procedure is based on the assumption that one of the points reaches greater changes in position than the other two points, and the length (height difference) does not contain this point, changes least of all between phases during the comparison of three lengths (height differences).

The difference limit value between phases was identified using a general law on the accumulation of standard deviations, and based on the results of grid adjustment (standard deviations of coordinates) in phase 16 and 17. The difference limit value in horizontal length between phases was identified as 5 mm, and the difference limit value in height difference between phases as 3 mm.

The horizontal lengths (D) between standpoints in the last seven phases are presented in Table 1, together with differences against phase 0 ($\Delta D_{0,i}$) and differences between individual phases ($\Delta D_{i,i+1}$). Based on the assumptions above, horizontal shifts are still likely to continue, particularly on point Rab02.

The height differences (dH) between station points from the last seven phases are presented also in Table 1, together with differences against phase 0 ($\Delta dH_{0,i}$) and differences between individual phases ($\Delta dH_{i,i+1}$). Based on the assumptions above, shifts in elevation are likely to occur on point Rab03.

The changes in length and height difference are also displayed in charts (Figure 6–11). The table and charts also imply that changes between phases grew smaller and, therefore, the slope stability improved after the installation of piled retaining walls in 2007. At the same time, some periodicity in height changes (ca 30 mm per season) of point Rab03 may be observed, which probably relies on the season (water saturation of the soil).

Detailed survey points Z1–Z4 on retaining walls were verified in the same way as standpoints. The main

**Tab. 1** Lengths and Height differences between standpoints and their changes.

| Phase | Points | D | $\Delta D_{0,i}$ | $\Delta D_{i,i+1}$ | dH | $\Delta dH_{0,i}$ | $\Delta dH_{i,i+1}$ |
|---|---|---|---|---|---|---|---|
| | | [m] | [mm] | [mm] | [m] | [mm] | [mm] |
| **0 (04/2003)** | Rab01–Rab02 | 364.162 | – | – | 52.279 | – | – |
| | Rab01–Rab03 | 419.043 | – | – | 1.854 | – | – |
| | Rab02–Rab03 | 664.196 | – | – | 54.133 | – | – |
| **12 (04/2007)** | Rab01–Rab02 | 364.200 | −38 | 8 | 52.276 | 3 | −8 |
| | Rab01–Rab03 | 419.055 | −12 | 7 | 1.787 | 67 | −24 |
| | Rab02–Rab03 | 664.255 | −59 | 13 | 54.063 | 70 | −32 |
| **13 (08/2008)** | Rab01–Rab02 | 364.204 | −43 | −5 | 52.261 | 18 | 15 |
| | Rab01–Rab03 | 419.056 | −13 | −1 | 1.753 | 101 | 34 |
| | Rab02–Rab03 | 664.265 | −70 | −10 | 54.014 | 119 | 49 |
| **14 (04/2009)** | Rab01–Rab02 | 364.211 | −49 | −6 | 52.274 | 5 | −13 |
| | Rab01–Rab03 | 419.079 | −36 | −23 | 1.771 | 83 | −18 |
| | Rab02–Rab03 | 664.291 | −95 | −26 | 54.045 | 88 | −31 |
| **15 (07/2009)** | Rab01–Rab02 | 364.219 | −57 | −8 | 52.275 | 4 | −1 |
| | Rab01–Rab03 | 419.083 | −40 | −4 | 1.751 | 103 | 20 |
| | Rab02–Rab03 | 664.312 | −116 | −20 | 54.026 | 107 | 19 |
| **16 (04/2010)** | Rab01–Rab02 | 364.203 | −41 | 16 | 52.267 | 12 | 8 |
| | Rab01–Rab03 | 419.057 | −14 | 26 | 1.771 | 83 | −20 |
| | Rab02–Rab03 | 664.270 | −74 | 41 | 54.038 | 95 | −12 |
| **17 (07/2010)** | Rab01–Rab02 | 364.197 | −36 | 5 | 52.266 | 13 | 1 |
| | Rab01–Rab03 | 419.054 | −11 | 3 | 1.745 | 109 | 26 |
| | Rab02–Rab03 | 664.272 | −76 | −2 | 54.011 | 122 | 27 |
| **18 (07/2011)** | Rab01–Rab02 | 364.197 | −35 | 0 | 52.264 | 15 | 2 |
| | Rab01–Rab03 | 419.050 | −7 | 4 | 1.776 | 78 | −31 |
| | Rab02–Rab03 | 664.264 | −68 | 8 | 54.040 | 93 | −29 |

Source: Braun 2011, Rytíř 2012

monitored parameter was the height difference between points, where the difference limit value in height differences between two phases is identified at a value of 30 mm (based on adjustment results and experience with measurement). The higher value of the difference limit value was accepted as the measured points are represented by a screwed-in lid and no control was done whether the lid has always been identically screwed in between phases, plus there is some inaccuracy in the identification of the prism height on the detail pole. Nearly all differences between phases presented in Table 2 are smaller than the identified difference limit value, except for the difference between phase 14 and 15 on points Z2, Z4. The value exceeds the difference limit value by only 3 mm, besides, a change due to the screwing of the lid may be suspected there. Based on the results, no changes between piled retaining walls were manifested, which also confirms the functionality of these measures for enhancing the slope stability.

## 4.2 Terrestrial measurements – assessment of detailed survey points

The accuracy in the determination of the spatial position of observed points of the terrain and the centres of probes is described in the formula for the standard deviation of the 3D polar method, considering the point survey method using a fixture with a mounted pair of all direction prisms. During the measurement of a detailed survey point, the fixture is screwed in the detailed survey point's stabilisation and it may be said, that the axis of the fixture is the extension of the point stabilisation axis. Knowing these axes (vectors) the angle formed by them between individual phases may be calculated using analytic geometry. The changes identified in the inclinations of survey marks may subsequently be used to draw conclusions about the pressures acting in the surface layers of rock. In stabilised detailed survey points, therefore, not only changes (shifts) in coordinates, but also changes in the inclination of the stabilisation may be monitored. The issues of determining the inclination of survey marks are treated in more detail in (Bubeník et al. 2006).

Stabilised detailed survey points in the locality were surveyed from 2003 to 2006. The average monthly shift of observed points measured on the Y axis was +10 mm to +49 mm, on the X axis −7 mm to +4 mm, and on the Z axis −11 mm to −36 mm. It is obvious that the greatest shift in position occurred on the Y axis, while it is almost zero on the X axis. This may be explained by the

**Tab. 2** Height differences between detailed survey points and their changes.

| Height differences between detailed survey points | | | Differences against phase 12 | Differences against previous phase |
|---|---|---|---|---|
| **Phase** | **Points** | **dH [m]** | **$\Delta dH_{12,i}$ [mm]** | **$\Delta dH_{i,i+1}$ [mm]** |
| **12 (04/2007)** | Z1–Z3 | 2.948 | – | – |
| | Z2–Z4 | 2.964 | – | – |
| **13 (08/2008)** | Z1–Z3 | 2.964 | −16 | −16 |
| | Z2–Z4 | 2.966 | −2 | −2 |
| **14 (04/2009)** | Z1–Z3 | 2.952 | −4 | 12 |
| | Z2–Z4 | 2.936 | 28 | 30 |
| **15 (07/2009)** | Z1–Z3 | 2.959 | −11 | −7 |
| | Z2–Z4 | 2.969 | −5 | −33 |
| **16 (04/2010)** | Z1–Z3 | 2.953 | −5 | 6 |
| | Z2–Z4 | 2.967 | −3 | 2 |
| **17 (07/2010)** | Z1–Z3 | 2.967 | −19 | −14 |
| | Z2–Z4 | 2.975 | −11 | −8 |
| **18 (07/2011)** | Z1–Z3 | 2.959 | −11 | 8 |
| | Z2–Z4 | 2.969 | −5 | 6 |

Source: Braun 2011, Rytíř 2012

orientation of the axes where the +Y axis is almost identical to the terrain fall line, and the +X axis lies horizontally.

The VZ MSM 6840770001 research plan – "Reliability, optimisation and durability of building materials and structures" involved the construction of a mathematical model allowing the assessment of deformations of detailed survey points. The mathematical model is based on the application of fuzzy logic which is presently used in numerous branches for intelligent control systems. The advantage of the model applying fuzzy logic is the possibility of including also data that cannot be considered in the classical concept in the decision making process of the point's shift. For, fuzzy logic allows us to include, apart from objective, unambiguously measurable views, also subjective views in a statement on deformations. Then, the representatives of objective views in the generated model are the spatial standard deviation of an identified point in individual phases of measurement, the point stabilisation method, the relevance of the observed point, the error of automated targeting of the instrument or the operator's personal error and climatic conditions during the measurement. Subjective views are represented by the impressions of the participants in the measurement – visual control of the terrain in close proximity to the point and its assessment, the operator's feeling during focusing on the target (Note: targeting may be made more difficult by climatic or vegetation conditions). Based on input parameters defined in this way, the decision making mechanism may be set up containing several fuzzy rules, after its defuzzification the observed points may be divided into several categories expressing their stability. The advantage of the model is a possibility of generating scales of point categories of different fineness meeting the needs of the recipients of geodetic monitoring results against the commonly used two degree scale. A finer categorisation may bring advantages during the interpretation and, in particular, the application of survey results as input data for the generation of prediction or assessment models of phenomena in monitored localities. The whole set-up of an experimental model is described in (Hánek, 2009) and its brief summary can be found in (Hánek, 2010).

### 4.3 GNSS measurements

Starting from phase 3 of April 2008, the measurement of standpoints using the fast-static GNSS method began with the objective of enabling the grid connection to the national reference systems (connection by the terrestrial method would be less feasible) and thus identifying which points move and in which direction. The Czech reference systems are S-JTSK (map coordinate reference system) and Bpv (Baltic vertical datum – after adjustment).

The GPS Trimble 5700 apparatus was used between phase 3 and 17, and the fast-static method with the observation time of 8 minutes onto minimally 6 satellites of the NAVSTAR-GPS system and double measurement on identified points was selected. In phase 18, three Topcon HiPer Plus receivers and one Topcon PG-A1 receiver were used, and experimental measurement on multiple stations was simultaneously performed with different observation times. The results of this experiment are presented in (Riegerová 2012).

Until phase 17, the value of 14 mm was considered the standard deviation in position $\sigma_{p17}$ and in height $\sigma_{H17}$ (based on the results of the calculations), and the difference limit value in position and height of a point between phases of 49 mm (a general law of the accumulation of standard deviations). The standard deviation in position $\sigma_{p18}$ for phase 18 was determined from the resulting coordinates in the value of 13 mm, and the standard deviation

**Tab. 3** Comparison of coordinates – Differences in coordinates against phase 3.

| Point | Rab01 | | | Rab02 | | | Rab03 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Phase** | $\Delta Y_{3,i}$ [mm] | $\Delta X_{3,i}$ [mm] | $\Delta H_{3,i}$ [mm] | $\Delta Y_{3,i}$ [mm] | $\Delta X_{3,i}$ [mm] | $\Delta H_{3,i}$ [mm] | $\Delta Y_{3,i}$ [mm] | $\Delta X_{3,i}$ [mm] | $\Delta H_{3,i}$ [mm] |
| **3 (04/2004)** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4 (07/2004)** | 15 | 0 | 25 | 55 | −20 | 91 | −14 | −47 | 17 |
| **5 (10/2004)** | −23 | −1 | −38 | 70 | −34 | 25 | 9 | −67 | −11 |
| **6 (07/2005)** | 24 | −2 | −36 | 68 | −50 | 55 | −4 | −65 | −24 |
| **7 (11/2005)** | 37 | −27 | −44 | 80 | −31 | 25 | 7 | −79 | −27 |
| **8 (04/2006)** | 34 | −14 | −23 | 75 | −47 | 31 | 13 | −84 | −28 |
| **9 (07/2006)** | 31 | −8 | −54 | 74 | −40 | 8 | 12 | −81 | 3 |
| **10 (04/2007)** | 31 | −18 | −43 | 72 | −52 | 20 | 18 | −97 | −27 |
| **12 (04/2008)** | 30 | −19 | −12 | 76 | −44 | 19 | 19 | −100 | −3 |
| **13 (08/2008)** | 19 | −27 | −39 | 63 | −39 | −76 | 20 | −89 | −22 |
| **15 (07/2009)** | 22 | −4 | −59 | 54 | −48 | 35 | −4 | −108 | 51 |
| **17 (07/2010)** | −27 | −29 | −11 | 21 | −76 | 12 | −46 | −155 | 22 |
| **18 (07/2011)** | 12 | 30 | 2 | 50 | −7 | 77 | 0 | −77 | 29 |

Source: Braun 2011, Riegerová 2012

**Tab. 4** Coordinates of points in S-JTSK and Bpv (the first and last phase).

| Phase | 3 (04/2004) | | | 18 (07/2011) | | |
|---|---|---|---|---|---|---|
| **Point** | **Y [m]** | **X [m]** | **Z [m]** | **Y [m]** | **X [m]** | **Z [m]** |
| **Rab01** | 766400.858 | 977584.680 | 253.251 | 766400.846 | 977584.650 | 253.249 |
| **Rab02** | 766195.735 | 977553.771 | 201.035 | 766195.685 | 977553.778 | 200.958 |
| **Rab03** | 766815.303 | 977792.946 | 255.047 | 766815.303 | 977793.023 | 255.018 |

Source: Braun 2011, Riegerová 2012

in height $\sigma_{H18}$ was identified in the value of 30 mm, while the difference limit value between phases is 48 mm for position and 83 mm for height.

Table 3 presents differences in coordinates against the initial phase, based on them we may conclude that the difference limit value for both position and height was not exceeded in the majority of cases. If, however, it was exceeded, it might have been due to a gross error during the measurement or processing, or the cause may be in one of the explanations below. A significant difference in position and height was first discovered between phases 3–4, which may be the consequence of building activity in the vicinity of the 000906080130 trigonometric point, which served as a reference station at that time. Another significant change occurred between phase 15–17 and phase 17–18. The most likely reason may be the use of another reference station in the calculation of coordinates. For phases 3–15, the reference station was the 000906080130 trigonometric point, while for phase 17 the reference point was a virtual station provided by the CZEPOS service. The considerable exceeding of the difference limit value $\Delta metp18$ between the last two phases may again be caused by the use of another reference station during the calculation. The reference station for the last phase, phase 18, was the permanent station of the CZEPOS network – Litoměřice (CLIT). Despite this, however, unstable points in the grid cannot be identified with due reliability (Riegerová 2012).

In analogy to terrestrial measurement, horizontal lengths and height differences between standpoints are compared in the GNSS measurement, too. The difference limit value in length applied until phase 17 was 70 mm, and for phase 18 it was 68 mm. The height difference limit value applied until phase 17 was 70 mm, and for phase 18 it was 117 mm. The difference limit value magnitudes imply that the GNSS measurement in the selected configuration is less accurate and comparing the phases the difference limit value was mostly not exceeded, thus the shift of any point was not confirmed. Figures. 6 to 11 present changes in lengths and height differences together with the results of terrestrial measurement. It is apparent that comparing lengths, the terrestrial measurement corresponds to the GNSS measurement, but comparing height differences the results between the methods are significantly different (which may also be expected due to a greater standard deviation in the height determination in the GNSS measurement).

### 4.4 Monitoring longitudinal profile

The route of the longitudinal profile runs along the axis of points Mpd05 and Mpd07 (Figure 4), and it was

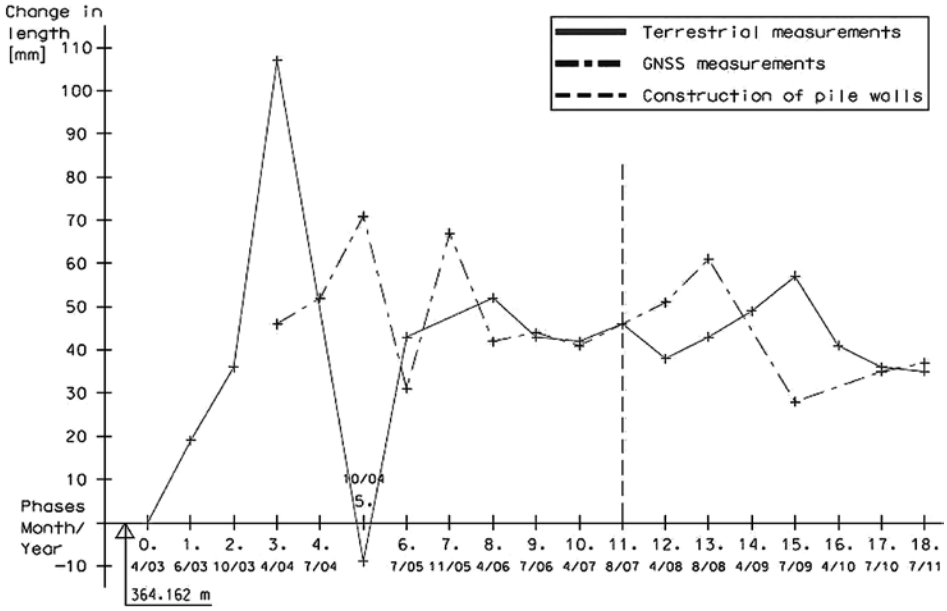



**Fig. 6** Changes in length between Rab01–Rab02 points. Source: Rytíř 2012, Riegerová 2012

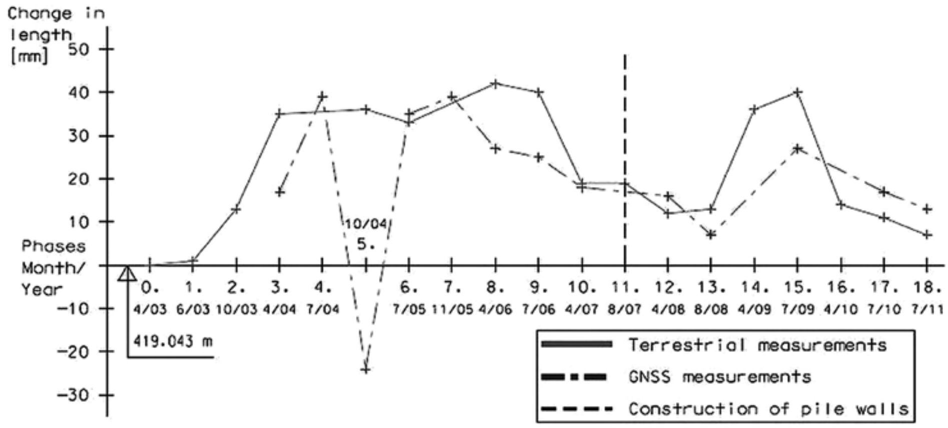



**Fig. 7** Changes in length between Rab01–Rab03 points. Source: Rytíř 2012, Riegerová 2012

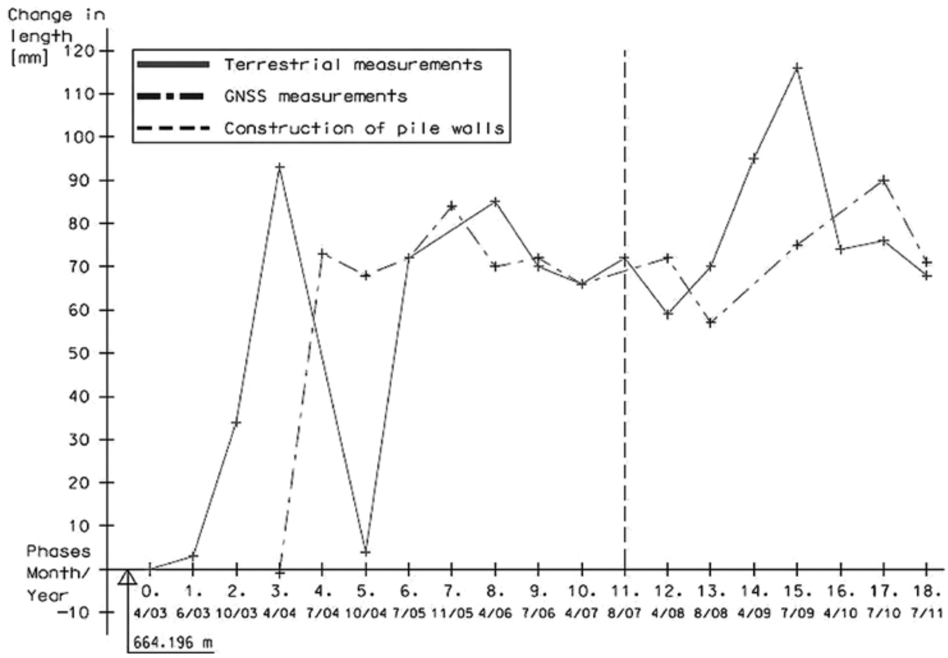



**Fig. 8** Changes in length between Rab03–Rab02 points. Source: Rytíř 2012, Riegerová 2012

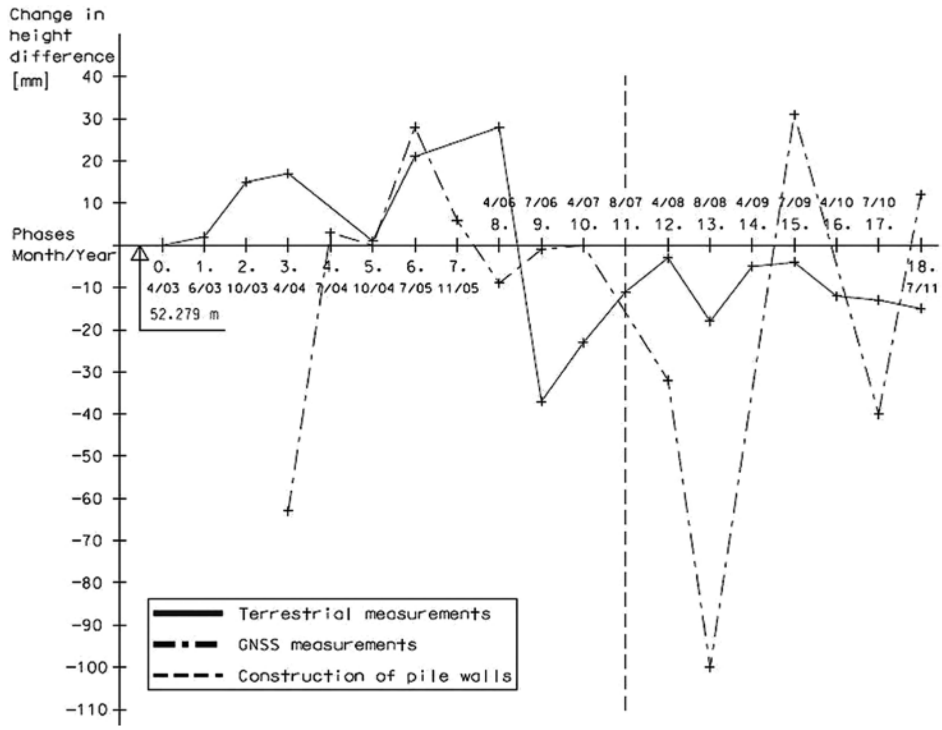



**Fig. 9** Changes in height difference between Rab01–Rab02 points. Source: Rytíř 2012, Riegerová 2012

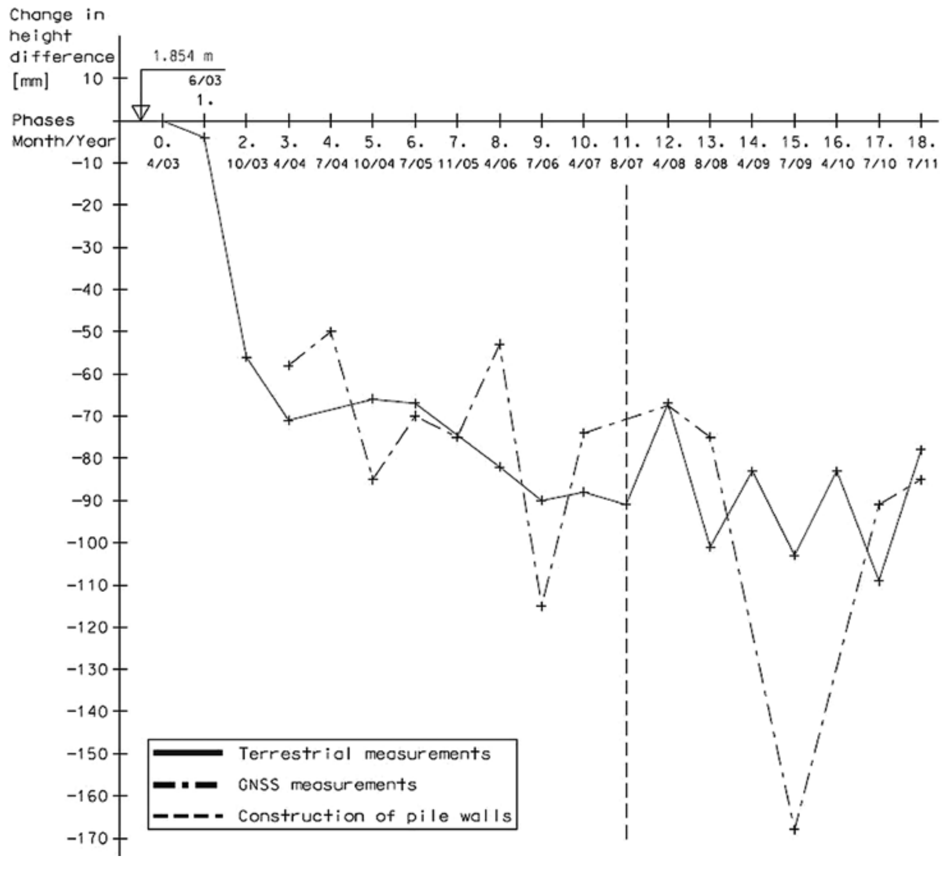



**Fig. 10** Changes in height difference between Rab01–Rab03 points. Source: Rytíř 2012, Riegerová 2012

determined as the requirement of the Department of Geotechnics. Points Mpd05–07 are geotechnical monitoring boreholes instrumented with combined casing for the measurement of spatial deformations in the outer dump body and for the determination of the shear plane area and the shear strength of the outer dump (Záleský et al. 2013b). The profile starts at the foot of the slope by the lake surface and ends in the upper part under pile walls (length 830 m, elevation 86 m). The longitudinal profile was measured for each phase after the construction of retaining walls (the last 7 phases) and its objective was to check whether significant spontaneous changes in

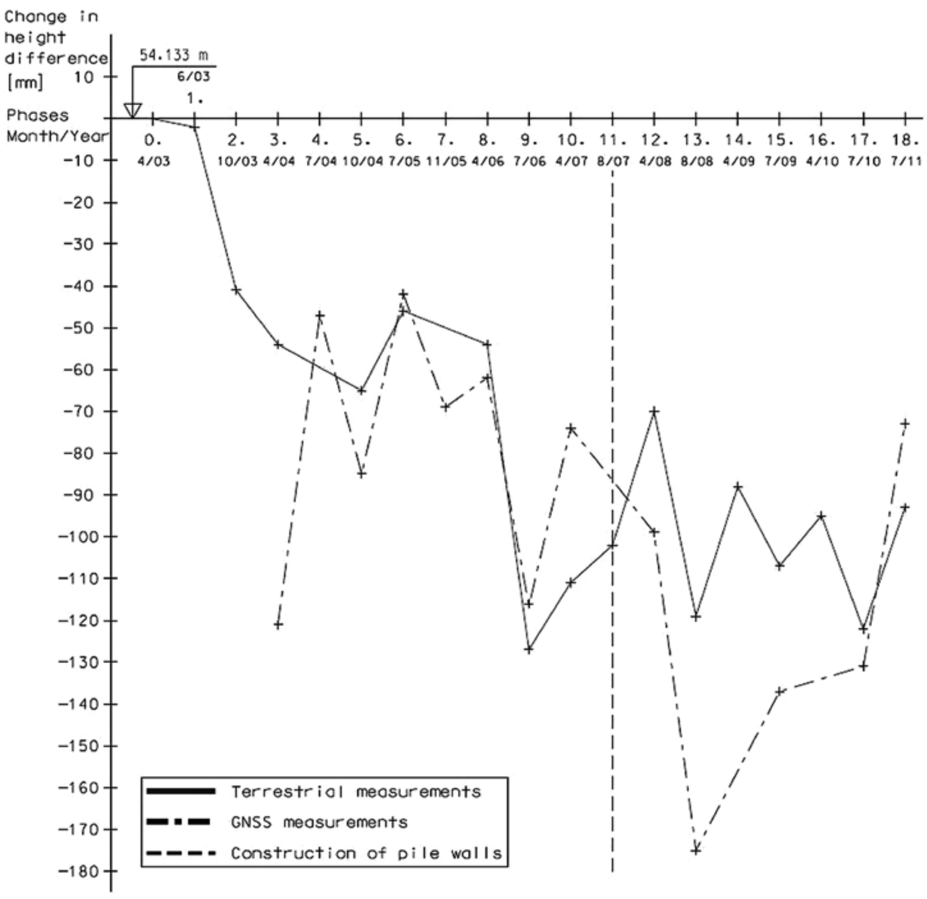



**Fig. 11** Changes in height difference between Rab03–Rab02 points. Source: Rytíř 2012, Riegerová 2012

height occur in some parts of the slope (shear plane area determination).

The profile was always surveyed using the standard polar method where the measurement standpoint was selected on the profile axis near point Mpd06. Connecting coordinates in the S-JTSK and Bpv system were taken over from the nearest phases of measurement using the GNSS method. The measured points of the profile were selected on terrain faults (edges of slopes, roads, drainage ditches) and in non-dissected terrain roughly in 25 metre spacing.

The geodetic assessment of individual phases did not reveal any natural changes, only a terrain rise in height by up to 6 m at the foot of the slope during the building of stabilisation benches.

### 4.5 Digital terrain model

The background data for DTM were obtained by classical terrestrial polar method. Considering the application of laser scanning, the principal negative arguments were the impossibility of placing the scanner on the opposite slope and also the spread of self-seeding vegetation which would dramatically distort the results.

The models are generated in the S-JTSK and Bpv system. Tacheometric measurements were performed in the initial grid of Rab01, Rab02, Rab03 points whose coordinates were determined by the GNSS method in the respective phase (or the nearest previous phase). Detailed survey points in non-dissected terrain were measured in a square grid with sides of 20–40 metres. The main measured elements were artificial embankments and landslides which had to be identified in such a way that they would form closed shapes for the resulting 3D model. Among planimetric elements, paved and unpaved drainage ditches, access roads, a creek bed, concrete culverts, pile walls and geotechnical probes were measured. For the appropriate choice of points, the maximum effort was made to observe the principle of measuring against the slope.

In 2009, the entire territory with the area of 41 ha was surveyed (in phase 14 the southern (A) part and in phase 15 the northern (B) part), and 1366 points were measured for its description (Figure 12). In the following phases, only localities where surface changes occurred were surveyed. In phase 17, the area at the foot of the slope (D) was surveyed, where 3 terrain levels of rockfill had been made between July 2009 and July 2010. Individual places of the terrain had been raised by up to 6 metres and 130,000 m$^3$ of stone material had been backfilled there. In phase 16 and 18, the southeast (C) part, where continuous landslides and land deformations occurred, was surveyed. Between April 2009 and April 2010, the landslides were levelled, the terrain level was lowered by up to 2 metres in the upper part and 10,000 m$^3$ of soil were

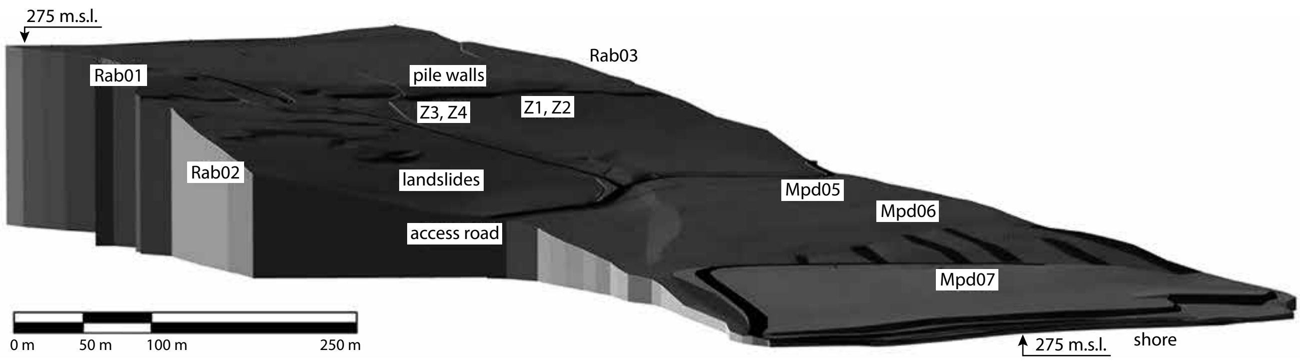



**Fig. 12** The slope seen from the northeast (2009).
Source: Braun 2011

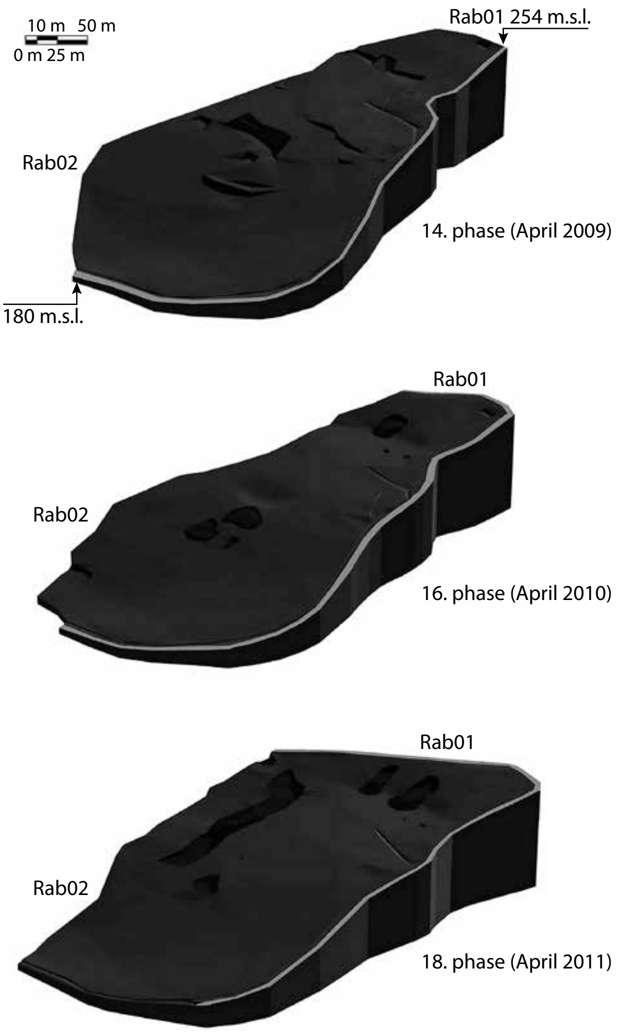



**Fig. 13** Comparison of the southwest part – seen from the northwest (04/2009, 04/2010, 07/2011).
Source: Braun 2011, Rytíř 2012

removed. Between April 2010 and July 2011, new landslides appeared on the slope again (Figure 13).

Apart from digital elevation models, contour plans in 1 : 1000 scale were developed for each phase, and the data from DMT are further used by the Department of Geotechnics for the automated generation of longitudinal profiles for research needs.

## 5. Conclusion

Three basic monitoring and assessment methods were used during the geodetic monitoring of the Rabenov landslide slope, in particular terrestrial measurement in a local surveying grid, GNSS measurement using the fast-static method for the grid connection into the S-JTSK and Bpv national reference systems and detailed measurement using the terrestrial polar method to generate digital terrain models which capture complex changes.

Inclinometric boreholes, 24 meters in depth to ensure the grid stability were used during the local grid establishment; nevertheless, accurate measurements (with the standard deviation of coordinates of ca 2 mm) confirmed the instability of these points, which affected the possibilities of assessing the measurement onto detailed survey points. Based on this experience, potential establishment of larger combined grids with more points stabilised also outside the landslide zone should be considered during the design of detailed survey grids.

The same reference points were not always used during the measurement by GNSS methods, which may have a significant effect on the accuracy of coordinates (the standard deviation in position of ca 14 mm) and the possibility of assessing the shifts of individual points. Because of higher standard deviations in position and in height, this method failed to reliably confirm the stability of the points in the grid. During the construction of new grids, it would be desirable to stabilise more points and to select points outside the monitored zone, but relatively close to it and well protected, as reference points. This would shorten the vectors between reference and rover stations and enhance the accuracy of the assessed coordinates.

The application of detailed tacheometric measurement on small localities of up to 10 ha proved highly efficient in terms of time and a possibility of capturing the major terrain changes which are displayed in a complex digital terrain model. If contact measurement on landslide zones does not pose any risks, this method may be applied arbitrarily, mainly if there are not suitable conditions (vegetation, unsuitable positioning of instruments) for the use of the laser scanner.

Surveys in a local grid manifested that there were continuous movements of observed station points, but the magnitude of changes in position was small depending apparently on the season. On the basis of length changes, persistent positional instability of point Rab02 was presumed (shifts ca 10 mm per year) and by comparing height differences there is an expressed assumption of height instability of point Rab03 (height changes ca 30 mm per season). The comparison of digital models of the southwest part leads to the conclusion that this part was still not fully stable in 2011, and there are mainly hazards of landslides which may destroy the reclamation elements installed there (drainage ditches and roads).

The additional geodetic monitoring would be useful on Rabenov slope. Measurements in grid are unfortunately no longer possible, because point Rab02 was destroyed by reclamation works. Many changes have been on the southwest part and new landslides have appeared on the west side of the pile walls. These facts lead to new DTM, which will be measured in autumn 2013 and spring 2014.

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**RÉSUMÉ**

**Geodetické metody sledování sesuvných území – aplikace na lokalitě Rabenov**

Při geodetickém monitoringu sesuvného svahu Rabenov byly použity tři hlavní metody sledování a vyhodnocení, konkrétně terestrické měření v místní geodetické síti, GNSS měření metodou fast-static pro připojení sítě do státních referenčních systémů S-JTSK a Bpv a podrobné měření terestrickou polární metodou pro vytvoření digitálních modelů terénu, které zachycují komplexní změny.

Při zakládání místní sítě byly použity 24 m hluboké inklinometrické vrty, které měly zaručit stabilitu sítě, ovšem přesným měřením (směrodatná odchylka souřadnic cca 2 mm) byla potvrzena nestálost těchto bodů, což ovlivnilo možnosti vyhodnocení měření na podrobné pozorované body.

Při měření metodami GNSS nebyly vždy použity stejné referenční body, což může mít významný vliv na přesnost souřadnic (směrodatná odchylka v poloze cca 14 mm) a možnost vyhodnocení posunů jednotlivých bodů. Kvůli vyšším směrodatným odchylkám v poloze a ve výšce nebyla touto metodou spolehlivě potvrzena stálost bodů sítě.

Při budování nových sítí by bylo vhodné stabilizovat více bodů a vytvořit tak komplexnější síť i s body mimo sledované oblasti, které by sloužily jako referenční pro GNSS i terestrické měření.

Použití etapového podrobného tachymetrického měření na malých lokalitách do 10 ha se ukázalo velmi efektivní z hlediska času i možnosti zachytit nejdůležitější změny terénu, které se zobrazují v komplexním digitálním modelu terénu.

Geodetické měření v místní síti prokázalo, že stále dochází k pohybům stanoviskových pozorovaných bodů, ale velikost změn polohy je malá a zřejmě závislá i na ročním období (posun bodu Rab02 v poloze o 10 mm za rok, výškové změny o velikosti až 30 mm bodu Rab03 za roční období). Z porovnání digitálních modelů jihozápadní části lze usoudit, že tato část v roce 2011 ještě nebyla plně stabilní a hrozí v ní zejména svahové zátrhy, které mohou zničit vybudované rekultivační prvky (odvodňovací příkopy a cesty).

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# ESTIMATION OF BEDLOAD TRANSPORT IN HEADWATER STREAMS USING A NUMERICAL MODEL (MORAVSKOSLEZKÉ BESKYDY MTS, CZECH REPUBLIC)

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**ABSTRACT**

The TOMSED numerical model, originally developed for Alpine torrents, was successfully applied on the May, 2010 flood event in headwater streams of the Czech part of the Western Flysch Carpathians. The Manning equation was used together with application of a reduced energy gradient and potential erosion limits. Contributions of form resistance and grain resistance to Manning's roughness parameter were considered separately. The absence of bedload discharge measurement made it difficult to validate the model for local headwater channels, although channel reaches with recent erosional and depositional trends were recognized fairly well by the simulations. Bedload transport was calculated in the range from 480–1240 $m^3$ for the richly-supplied headwater stream and 380–860 $m^3$ for the stream with limited sediment-supply conditions. It turns out that the channel reaches with higher sediment supply have less developed bedforms (e.g. steps) and thus lower flow resistance resulting in a higher intensity of bedload transport.

**Keywords:** headwater stream, hydrological modelling, bedload transport, TOMSED, Moravskoslezské Beskydy Mts

## 1. Introduction

Steep headwater streams can generally be characterized by high channel gradients (>2–4%), wide grain-size distributions, channel-spanning bedforms (step-pool systems), shallow flows, common presence of large woody debris and variable channel widths (e.g. Chiari et al. 2010; Nitsche et al. 2011; Zimmermann et al. 2010). These parts of drainage network show extremely rapid rainfall-runoff response (Rickenmann 1997) and present a major flood hazard in a mountainous terrain (Chiari et al. 2010). Nevertheless, bedload transport and hydraulics of steep mountainous streams are poorly understood relative to those of lowland streams (Rickenmann 1997; Aberle & Smart 2003). Supply-limited character together with increased flow resistance are the main reasons for the fact that observed bedload transport in steep torrents may be considerably smaller than that predicted by conventional bedload transport equations (Yager et al. 2007; Chiari & Rickenmann 2011). The introduction of grain and form resistance in order to lower energy gradient helps to correct bedload estimation in high-gradient streams (Rickenmann 2005; Chiari et al. 2010; Chiari & Rickenmann 2011). Some uncertainty in estimation of critical conditions for the beginning of bedload transport in gravel bed streams can also arise due to the significant occurrence of interstitial flows and thus, decrease in potential stream power for sediment transport processes (Carling et al. 2006).

The SETRAC numerical model (Rickenmann et al. 2006), a predecessor of the TOMSED model, was successfully applied in the reconstruction of bedload transport during high-magnitude floods in Alpine catchments (Chiari et al. 2010; Chiari & Rickenmann 2011). TOMSED represents a one-dimensional bedload transport model used to simulate bedload transport at steep slopes developed by Friedl and Chiari (2011) at the University of Natural Resources and Applied Life Sciences, Vienna. Several flow resistance and bedload transport equations have been implanted into the model that enables the use of a specific combination of approaches for particular conditions. Since simple flow resistance and bedload transport equations usually overestimate bedload discharges due to limited sediment-supply conditions and energy loss connected with bed deviations (e.g. steps, pools, and large grains), approaches of form roughness losses need to be taken into account and armouring effects help to calibrate the intensity of bedload transport with field observations. Channel network is defined by nodes, cross-sections and sections. In the TOMSED model, it is also possible to simulate potential erosion or deposition in a stream channel during a flood event and it is possible to set spatial limits of bed elevation changes for individual sections. As stream widths remain constant during the simulation, lateral erosion is not taken into consideration. Input hydrographs can be related to cross-sections as time series in the same way as sediment inputs. For more details about the TOMSED model see Friedl and Chiari (2011), the model is free for download at www.bedload.at.

As we indicated previously, bedload transport estimations in small steep streams represent a challenge for both geomorphologists and water resource engineers due to lack of direct bedload measurements in high-gradient channels. Thus, the main aim of the study was to evaluate the application of the TOMSED v0.1 numerical model in midmountain relief of the Czech landscape. The model was tested on two selected headwater basins of the Western Flysch Carpathians affected by 5/2010 flood. Previously, Galia and Hradecký (2012a, 2012b) investigated critical conditions of the incipient motion of individual boulders moved during range of discharges including

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5/2010 event in the study area. Bedload transport was also considered in local gravel-bed rivers with respect to their geomorphic transitions caused by human disturbances (Galia et al. 2012). This time, the authors attempted to evaluate total bedload transport connected with changes in the longitudinal profile, whereas TOMSED simulations were compared to field observations. The authors sincerely hope that the research results will bring a new insight into the knowledge of the behaviour of local headwater streams and improve the management of these forested watersheds.

## 2. Studied streams

Simulations of bedload transport were conducted in two headwater streams of the Radhošťská hornatina Mts (Moravskoslezské Beskydy Mts), namely Malá Ráztoka and the upper part of Velký Škaredý potok (Table 1, Figure 1, and Figure 2). Lengths of simulated channels were 2100 m of Malá Ráztoka Stream and 1900 m of Velký Škaredý potok respectively, both with 50 m discretisation between individual measured cross-sections.

The streams significantly differ in sediment supply and transport regime (Figure 3). Bedrock outcrops often occur in Malá Ráztoka channel (up to 1/2 of the total length of the longitudinal stream profile) and the stream is recognized as sediment-supply limited. Sediment sources are infrequent bank failures and gullies; non-resistant claystone members of the Godula Formation (lower Cretaceous period) also contribute to sediment delivery in the downstream part of the basin. On the contrary, Velký Škaredý potok lacks bedrock outcrops in the channel bed except for the steepest part of the longitudinal profile consisting in resistant sandstone layers of the middle-part of the Godula Formation. Between 0.0–1.3 km, the stream is located in less-resistant claystones of the Lhoty Member, Veřovice Member and Těšín-Hradiště Formation with a frequent occurrence of bank failures and shallow landslides richly supplying the stream with material. At the bottom of the V-shaped valley of Velký Škaredý potok at 0.0–1.0 km, there is an 8–20 m wide cover of sediments that have been transported there by fluvial processes and also by older debris-flows with related 'fire hose' effect (see Šilhán & Pánek 2010). These facts imply that Velký Škaredý potok is rather transport-limited, characterized by relatively unlimited supply conditions, although accelerated vertical erosion was observed in some locations at the bottom of the valley (up to 1 m). Both the basins are also influenced by deep-seated slope deformations in the culmination parts of ridges (e.g. Hradecký & Pánek 2008). Moreover, the relief of the Moravskoslezské Beskydy Mts can be described as polygenetic (Pánek et al. 2009). Spruce and beech forests cover nearly 100% of area

**Tab. 1** Characteristics of the studied streams. Symbol "*" indicates different values of sediment parameters for channel-reaches based in generally claystone layers (0.0–1.3 km) with lower values of $d_{30}$, $d_{50}$ and $d_{90}$.

| | Malá Ráztoka | Velký Škaredý potok |
|---|---|---|
| **Basin area (km²)** | 2.20 | 1.06 |
| **Altitude (m)** | 570–1084 | 510–1129 |
| **Channel gradient (m/m)** | 0.02–0.27 | 0.03–0.53 |
| **Bankfull channel width (m)** | 3.2–5.1 | 2.6–4.1 |
| **Bankfull hydraulic radius (m)** | 0.23–0.33 | 0.22–0.41 |
| **$d_{30}$ (mm)** | 30 | 30 |
| **$d_{50}$ (mm)** | 55 | 45*, 55 |
| **$d_{90}$ (mm)** | 220 | 140*, 180 |

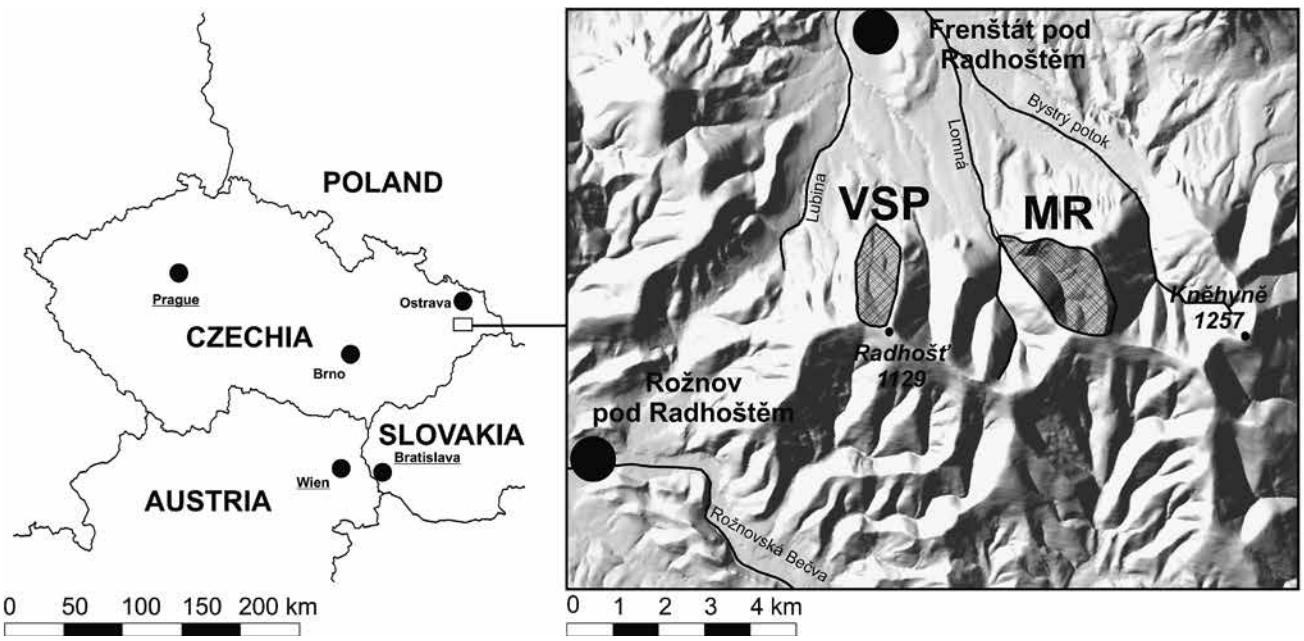



**Fig. 1** Location of studied streams: Malá Ráztoka (MR) and Velký Škaredý potok (VSP).

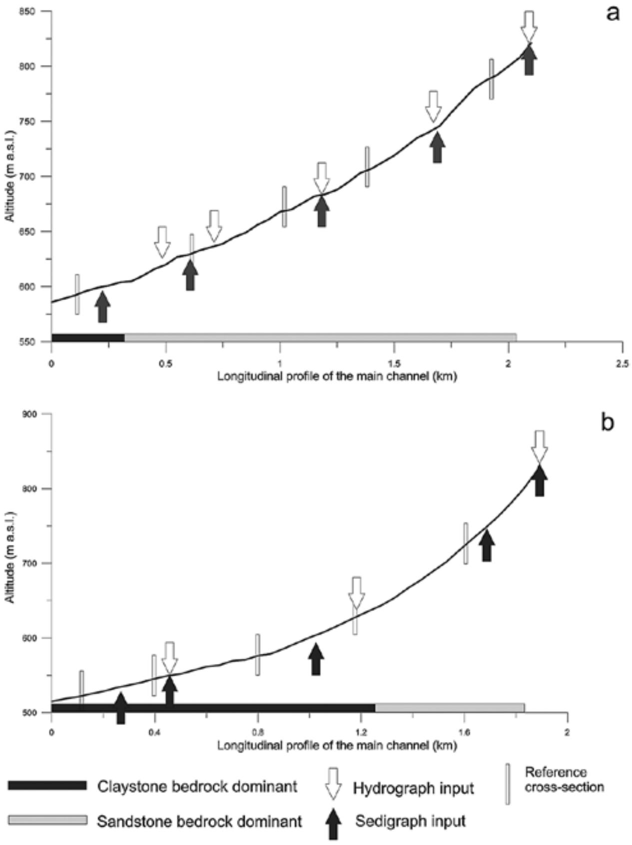



**Fig. 2** Schematic longitudinal profiles of Malá Ráztoka (a) and Velký Škaredý potok (b) used in simulations with indicated locations of inputs of water and sediments during a flood event.

of the studied basins. Large woody debris are systematically removed from the local channels by forest management except the uppermost parts of the Velký Škaredý potok basin, where the nature reserve "Radhošť" has been established.

Discharge data from the gauging station in Malá Ráztoka stream, which cover 2.01 km$^2$ of the basin, were used to reconstruct bedload transport. Local 2-year discharge corresponds to 0.95 m$^3$ s$^{-1}$, 10-year discharge to 2.71 m$^3$ s$^{-1}$, 25-year discharge to 4.38 m$^3$ s$^{-1}$ and, finally, 100-year discharge is equal to 8.5 m$^3$ s$^{-1}$, as it was derived from the 1954–1993 specific discharge data series (Chlebek & Jařabáč 1995). In addition, mean annual discharge corresponds to 0.061 m$^3$ s$^{-1}$, as measured at the gauging station on the stream.

After 5/2010 flood event, erosion and deposition of material was observed in both studied headwater channels. There were some noticeable signs of accelerated vertical erosion in Malá Ráztoka stream at 0.10–0.15, 0.40, 0.50, 0.65–0.75 and 1.9 km from the mouth to Lomná stream. By contrast, depositional processes were evident at 0.05 km, 0.45 km (due to the lowering of bed gradient by one of the check-dams), 1.60–1.65 km and 1.8 km. Velký Škaredý potok indicated some erosional trends at 0.00–0.05 km, 0.90–0.95 km, 1.20–1.25 km (due to the action of a sluice as a barrier) and 1.65 km upstream from the ford and the reservoir near the first building of Trojanovice village, which is the end of the studied channel. As it was mentioned above, almost the whole profile of the longitudinal profile of the stream is characterized by a sufficient amount of sediments, whereas most of the deposits were reactivated and transported during 5/2010 flood. In both headwater streams, large woody debris also contributed to create alluvial accumulations in active channels. Three check dams and a measuring flume have been constructed in the bottom part of Malá Ráztoka longitudinal profile between 0.25 and 0.45 km during the second half of 20th century. They naturally affect the transport dynamics during flood events. Similarly, a sluice built across the road at 1.25 km of Velký Škaredý potok stream has recently been acting as a barrier since sediments clogged up inside. For bedload material, we use a bulk density value of 2550 kg m$^{-3}$, which is valid for sandstones of the Godula Member.

## 3. Methods

During the summer season of 2011, channel cross-sections were measured using tape in 50-m-long intervals. Laser rangefinder including a clinometer was used to obtain individual vertical distances between

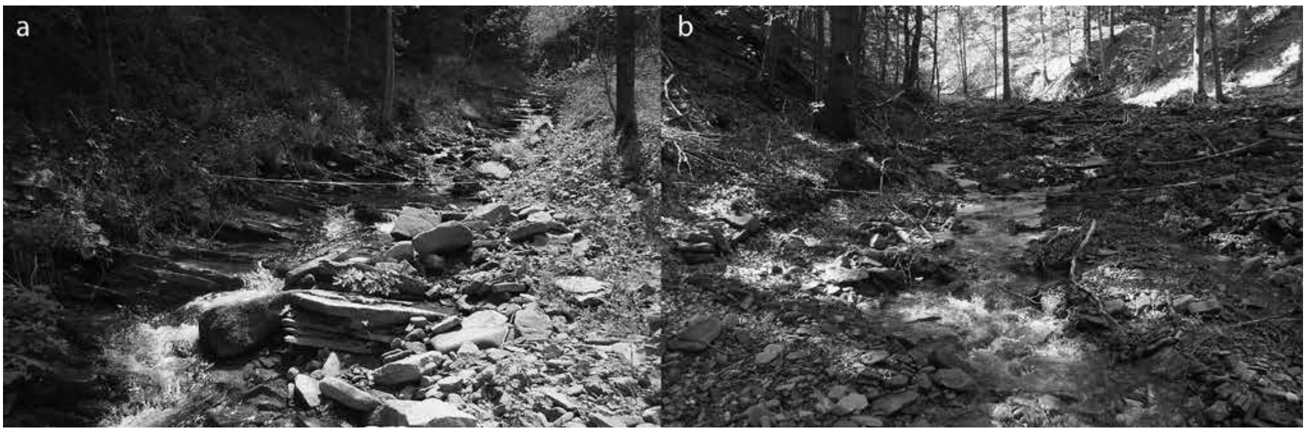



**Fig. 3** Supply-limited reach with frequent bedrock outcrops in Malá Ráztoka stream (a) and well sediment-supplied (transport-limited) reach of Velký Škaredý potok stream (b).

individual cross-sections. One type of sediment-size distribution was applied into the Malá Ráztoka modelled profile due to relatively uniform lithology of channel-bed material (sandstone layers of the Godula Member), whereas in the case of Velký Škaredý potok, two diverse types of sediment-size distribution were applied for cross-sections based in sandstone layers and claystone-prevailing formations. Measurement of the sediment size was conducted by the Bevenger-King sampling method (1995), which had been derived from the Wolman method (1954).

Based on the data series measured at Malá Ráztoka gauging station, a 6-hour interval of time steps between 16 May 2010 0:00 and 20 May 2010 0:00 was used to simulate bedload transport during an event using the TOMSED v0.1 model. The flood culminated on 17 May 2010 at 12:00 with 3.96 $m^3 s^{-1}$ discharge, which corresponds to a 20–25y flood, as based on published specific discharge data series (1954–1993) from the basin (Chlebek & Jařabáč 1995). Then approximate inputs of hydrographs were added to the stream profile (Figure 2). These inputs were dependent on their sources and sub-basin areas and their total sum was equivalent to the final observed discharge at the gauging station. Discharges for Velký Škaredý potok stream were derived from Malá Ráztoka gauging station using a simple specific discharge method. Consequently, individual inputs for the stream profile were developed. This showed that the flood culmination in the modelled outlet of Velký Škaredý potok (1.06 $km^2$, 2.0 km length) reached values of 2 $m^3 s^{-1}$. Some inputs of sediments ('sedigraphs') were also assigned to locations in both stream profiles where the delivery of material is expected during a flood event (large active bank failures, outfalls of gullies). However, no exact measuring was conducted of material delivery to the fluvial system of the study area; therefore, quantitative values of inputs were rather adjusted to modelled bedload discharges and geomorphic evidence in the field.

In order to make an exact comparison of results, identical flow resistance and bedload equations were used as those presented in the paper of Chiari and Rickenmann (2011). Flow velocity v was computed by well-established Manning equation including hydraulic radius of channel ($R$), energy gradient ($S$) and total flow resistance represented by Manning coefficient $n_{tot}$

$$v = R^{0.67}S^{0.5}/n_{tot}, \quad (1)$$

although some authors (e.g. Ferguson 2010) suggest the application of more appropriate flow-resistance approaches for shallow flows and steep gradients. TOMSED also allows the use of logarithmic and power approaches, but we only investigated very small differences comparing the results obtained by Manning equation without reduced energy gradient, logarithmic law after Smart and Jäggi (1983) and power law after Rickenmann et al. (2006). To obtain total flow resistance during a known discharge $Q$ in steep channels >0.008 m/m, Rickenmann (1996) derived the equation:

$$1/n_{tot} = (0.97g^{0.41}Q^{0.19})/(S^{0.19}d_{90}{}^{0.64}), \quad (2)$$

where $g$ is the acceleration of gravity and $d_{90}$ is the 90th percentile of grain-size cumulative curve. Due to the importance of bedforms in steep channels, Rickenmann (2005) proposed a general empirical function of increased form resistance which is based on dividing total resistance into grain and form resistance and subsequent determination of reduced energy gradient $S_{red}$ related to grain resistance $n_r$ only. The equations take forms:

$$n_r/n_{tot} = 0.092S^{-0.35}(D/d_{90})^{0.33} \quad (3)$$

and

$$S_{red} = S(n_r/n_{tot})^a, \quad (4)$$

where $D$ means flow depth and $a$ is an exponent occupying the range $1 \leq a \leq 2$. Chiari and Rickenmann (2011) used $a$ equal to 1.0 and 1.5 to correct bedload estimations according to field observations in Alpine streams. In order to compute unit bedload transport $q_b$, Rickenmann's (2001) equation was used:

$$q_b = 3.1(d_{90}/d_{30})^{0.2}(q - q_c)S^{1.5}(s - 1)^{-1.5}, \quad (5)$$

where $d_{30}$ is the 30th percentile of a grain-size cumulative curve, $q$ is unit discharge, $q_c$ means critical unit discharge for the incipient motion of bed material and $s$ is a ratio of sediment density and fluid density ($\varsigma_s/\varsigma$). Finally, critical unit discharge $q_c$ necessary to initiate bedload transport may be obtained by the equation originally proposed by Bathurst et al. (1987):

$$q_c = 0.045(s - 1)^{1.67}g^{0.5}d_{50}{}^{1.5}S^{-1.12}, \quad (6)$$

where $d_{50}$ represents median grain size of the bed surface layer. Later Rickenmann (1990) modified the value 0.045 in Eq. (6) to the value 0.065, which can be understood as the substitution of dimensionless critical shear stress. Dimensionless shear stress occurs commonly in sediment transport equations. TOMSED does not allow including specific values of dimensionless critical shear stress for individual cross-sections or channel reaches. This fact affects the intensity of bedload transport particularly in steeper reaches (further in the text) via some other approaches (e.g. logarithmic flow resistance) implanted in the model. Although the simulation of an armour layer is possible in the TOMSED model, no such layer was supposed in Velký Škaredý potok stream due to high sediment delivery into headwater segments. At the same time, frequent occurrence of bedrock in Malá Ráztoka stream prevents the formation of a continuous armour layer, therefore this criterion was neglected the in simulation of both streams.

## 4. Results

### 4.1 Malá Ráztoka stream

The simulation of 5/2010 flood event was performed by means of Eq. (1–6) for four different stages: *i*) no sediment feed, no energy slope reduction and no limit for vertical erosion was introduced (10 m limit was set for all cross-sections), *ii*) rough limits were defined for erosion depth in accordance with field observations: 0.2 m for bedrock-cascade reaches, 1.0 m for all the other reaches), *iii*) sediment feed was introduced in locations with supposed delivery of material during the flood, and finally *iv*) slope reduction was established for the simulated stream, while parameter *a* was set to 1.5 in Eq. (4). As Figure 4 illustrates, stage *i*) shows unrealistically large erosion (up to 10 m limit) in the upper part of the basin. After introducing incision limits (stage *ii*), erosive trends prevailed in the whole longitudinal profile, except the downstream part near the junction with Lomná stream. This roughly corresponds with field observations according to which the channel of Malá Ráztoka is generally considered as a sediment supply limited system. The supply of sediment feed (*iii*) only created small positive peaks in places of supposed sediment supply due to installed sedigraphs. The overall character remained to be erosional. Reducing the slope (stage *iv*), several positive peaks were computed where deposition might occur, although the trend of erosional processes was preserved along the majority of the stream length. Depositions simulated at 0.4 km, 1.7 km and 1.9 km roughly correspond to after-flood field observations. In the most downstream part, by the junction with Lomná stream, material accumulation occurs both in the model and in the field. On the contrary, the TOMSED model predicts depositional processes for the zones at 0.6–0.75 km, 1.05 km and 1.45–1.55 km, but most of the reaches are recently eroded bedrock-cascades with no signs of aggradation.

Figure 5 displays the potential intensity of bedload transport at five selected cross-sections if considering stage *iv*) (limits in erosion depth, introduced sediment feed and slope reduction with $a = 1.5$). The simulation supposed the highest bedload transport at 0.1 km, 0.6 km and 1.4 km cross-sections, where the values of up to 40 $m^3$/h (100t/h) of transported material were reached during the peak discharge. On the contrary, the smallest intensity was predicted in the uppermost investigated reach (1.8 km), which could correspond to the real situation during the 5/2010 flood event, according to smaller field observed dynamics of erosional or depositional processes after that event. Flood situation and damages of the afternoon of 18th May (about 24 hours after flood culmination) were evaluated in the downstream part of the basin (0.0–0.5 km). Bank erosion as well as some fresh material deposits, mainly upstream of the check-dams, were noticed with a higher frequency and of a greater size than those observed in the uppermost reaches. This implies that the TOMSED model can predict well the intensity of bedload transport, which facilitates the comparison of individual cross-sections and reaches. Absolute values of computed transported material sound realistic, but no exact measuring of bedload transport intensity has been carried out in local high-gradient streams to calibrate modelled calculations.

Total bedload transport during the 5/2010 flood event was estimated in a range of 380–860 $m^3$ (970–2200 t) of transported coarse material in selected cross-sections at 0.1 km, 0.6 km, 1.0 km, 1.4 km and 1.8 km (Figure 6).

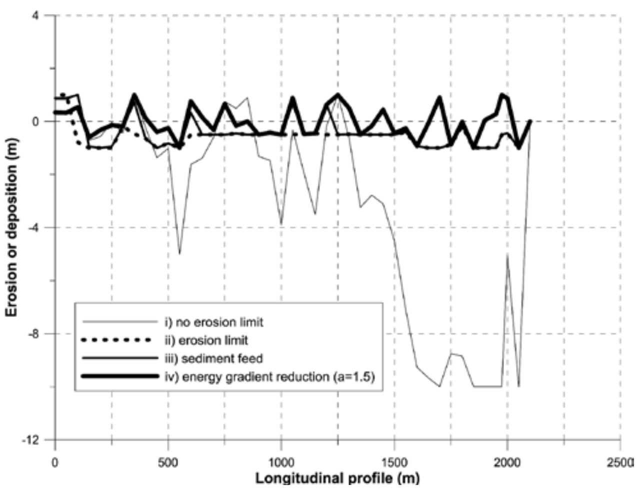



**Fig. 4** Modelled changes in the longitudinal profile due to erosion or deposition during the 5/2010 flood in Malá Ráztoka stream.

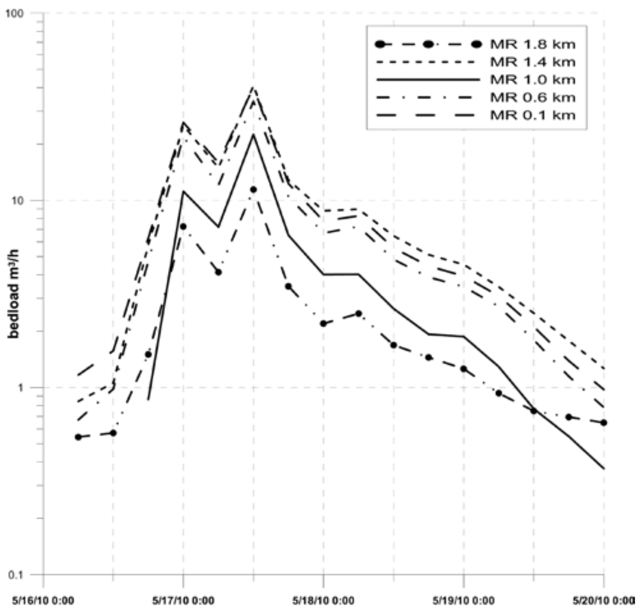
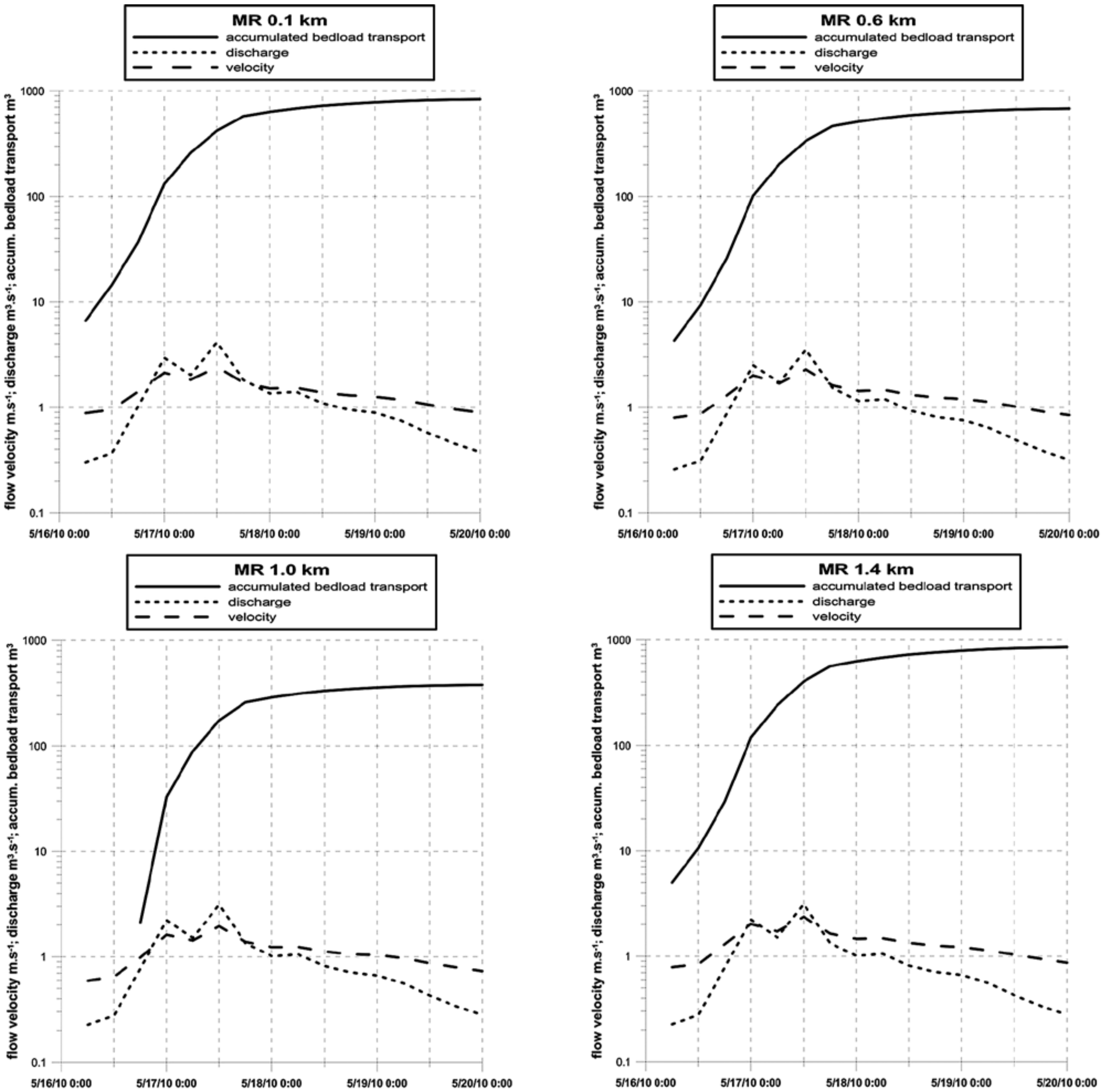



**Fig. 5** Intensity of bedload transport during the 5/2010 flood at 0.1 km, 0.6 km, 1.0 km, 1.4 km and 1.8 km of the longitudinal profile of Malá Ráztoka.



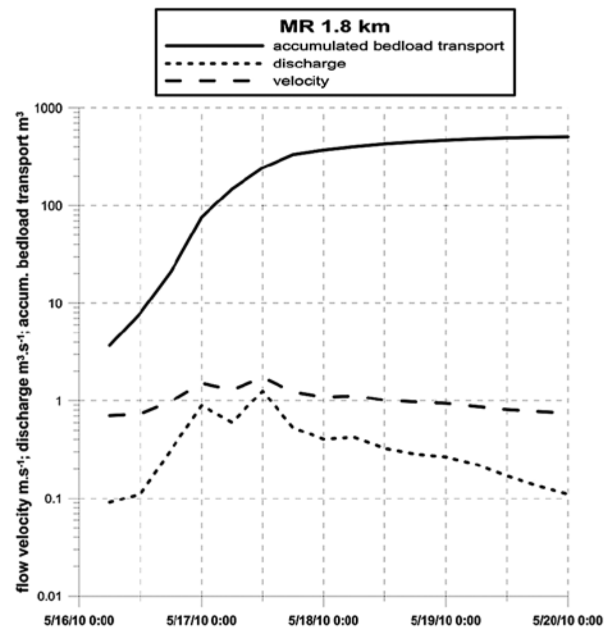




**Fig. 6** Flow velocity, discharge and cumulative bedload transport simulated at the reference cross-sections of Malá Ráztoka stream during the 5/2010 flood.

The cross-sections at 0.1 km together with 1.4 km indicated the highest amounts of transported material with values exceeding 800 m³ (2000 t). It is notable that suspended transport is not considered in the reported total volumes of transported sediment. Mean modelled flow velocities were equal to 1.7–2.4 $m\ s^{-1}$ during the flood peak when the highest values were rather observed in the downstream reaches (0.1 km and 0.6 km) and 1.4 km cross-section.

### 4.2 Velký Škaredý potok stream

Flood event discharge data were computed using a simple specific discharge method for the modelled outlet of Velký Škaredý potok stream. Consequently, individual inputs of hydrographs and sedigraphs were made for particular reaches based on local assumptions. Similarly to simulations in Malá Ráztoka, four different stages were used for bedload modelling. In relation to high amounts of potentially mobilized material at the bottom of the stream valley, fairly high dynamics of erosional and accumulation processes was observed in the lower parts (0.0–1.0 km) after 5/2010 flood. Resulting intensity of bedload transport in lower parts (0.1, 0.4 and 0.8 km) at the stage *iv*) was lower than the intensity calculated for the 0.1, 0.6 and 1.4 km of Malá Ráztoka stream and even lower than the intensity obtained in the uppermost cross-sections of Velký Škaredý potok (e.g. 1.6 km). This did not correspond to the real situation, especially to total sediment availability for bedload transport and observed erosion and accumulation forms after the flood in both the streams. To increase simulated bedload discharge in lower parts of Velký Škaredý potok, the exponent $a$ in Eq. (4) was optimized to value 1.0 and included in the stage *v*).

Stage *i*) simulation showed as huge incision in the uppermost part of the longitudinal profile during the flood as in Malá Ráztoka, but some deposition was also observed in the lowest parts (Figure 7). The stages void of slope reduction and erosion limits (stage *ii*) and stage *iii*)) resulted in a similar model of the longitudinal profile, although some positive peaks occurred due to inputs of sediment in stage *iii*). Both *ii*) and *iii*) stages indicated the erosional trend along almost the whole length of the simulated channel even though little aggradation was found within stage *iii*) at 0.15–0.40 km. Stage *v*) ($a$ = 1.0) simulation showed higher amplitudes in erosional/depositional trends than stage *iv*) ($a$ = 1.5), but the courses of the trends were similar. Highly fluctuating trends with noticeable peaks of erosion and deposition were observed in the upper parts of the stream, whereas a relative equilibrium between incision and aggradation was observed further downstream. Compared to the real situation, no larger erosional or depositional forms were observed in the upper part of the profile, except at the 1.6 km, which was recognized well by the simulation. Therefore, the use of $a$ = 1.5 in Eq. (4) would be appropriate for upstream reaches. On the contrary, as it was mentioned above, higher intensity of bedload transport had been assumed in the lower parts (0.0–1.0 km) and thus $a$ exponent equal to 1.0 in Eq. (4) led to better agreement with the real situation in the downstream parts. Also, trends of incision at 0.00–0.05 km and 0.90–0.95 km and downstream the jammed sluice at 1.20–1.25 km were exposed well by the simulations within *iv*) and *v*) stages. Deposition of material up the sluice (1.25 km) was indicated in the modelled profiles as well.

Reference cross-sections of 0.1 and 0.4 km showed higher bedload discharges during the flood event (Figure 8) with peak values of about 50 m³/h (125 t/h) for $a$ = 1.0 at Eq. (4). Bedload transport was of a higher intensity in these lower parts due to large potential sediment delivery to the stream. The main channel of the stream

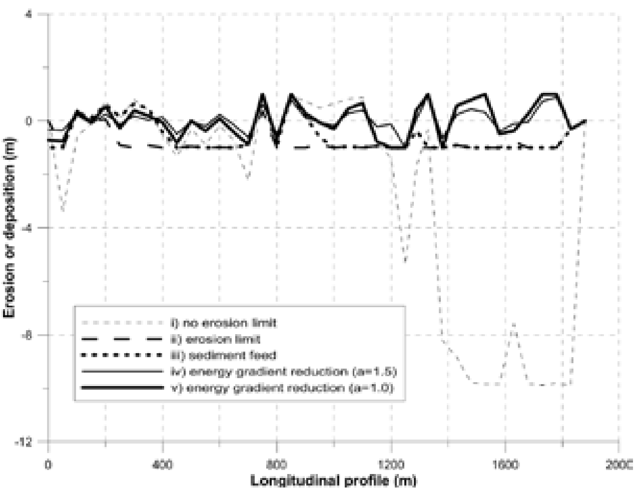



**Fig. 7** Modelled changes in the longitudinal profile due to erosion or deposition during the 5/2010 flood in Velký Škaredý potok stream.

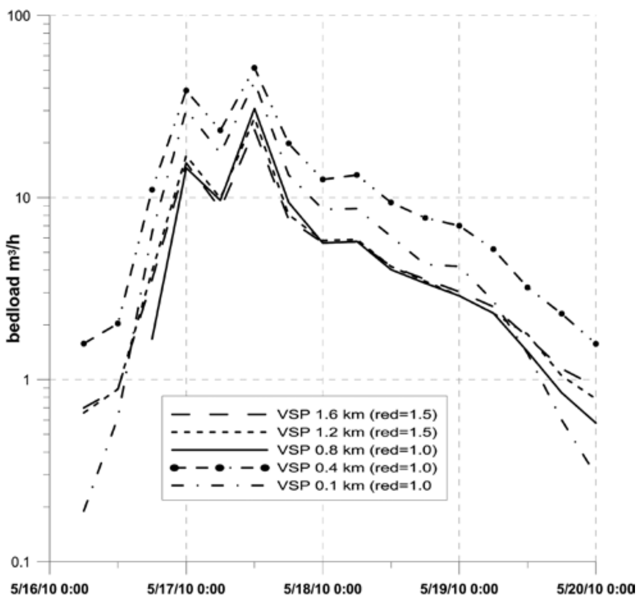
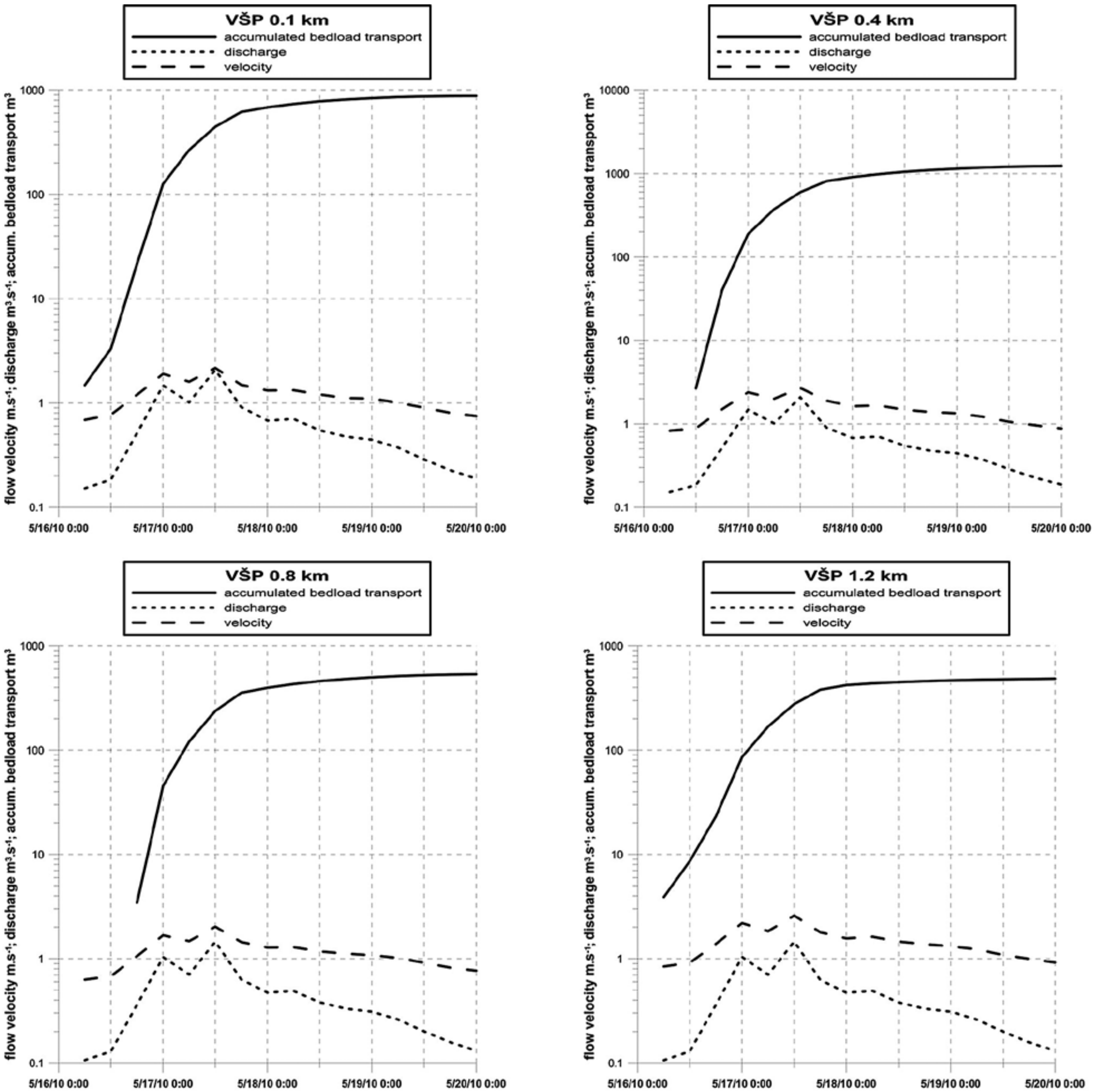



**Fig. 8** Intensity of bedload transport during the 5/2010 flood at 0.1, 0.4, 0.8, 1.2 and 1.6 km of the longitudinal profile of Velký Škaredý potok.



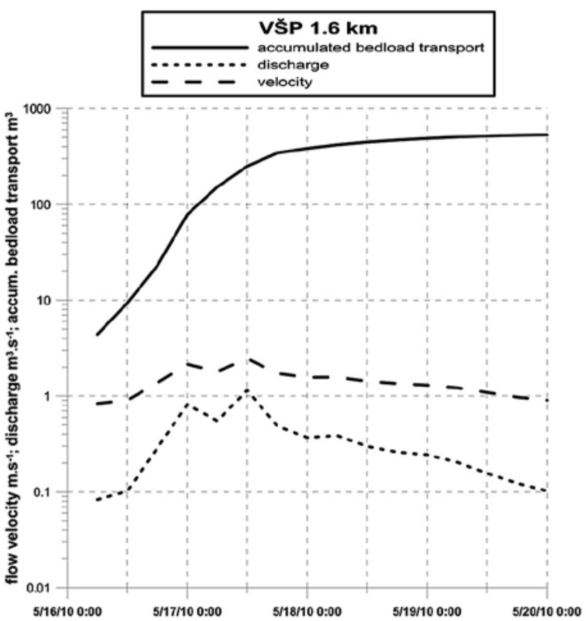




**Fig. 9** Flow velocity, discharge and cumulative bedload transport computed for the reference cross-sections of Velký Škaredý potok stream during the 5/2010 flood.

changed its course in the relatively wide valley bottom (up to 20 m) during the flood event as transported material was stored or eroded by the stream flow. Bedload transport reached values of up to 25–30 $m^3$/h (75 t/h) for *a* = 1.5 at Eq. (4) in the upper part of the stream during the flood culmination. With respect to local channel gradients of 0.20 m/m, some movement of the type of smaller debris flows might have been reactivated in the channel.

Total volumes of transported bedload are a bit higher than those simulated for Malá Ráztoka. Values were computed in a range of 480–1240 $m^3$ (1220–3170 t) for 0.1, 0.4, 0.8, 1.2 and 1.6 km channel cross-section (Figure 9). Smaller moved amounts were assumed in connection with the upper part of the stream (0.8, 1.2 and 1.6 km) with transport rates of 480–540 $m^3$, whereas the downstream part (0.1 and 0.4 km) indicated much higher intensity with values of 880 $m^3$ and 1240 $m^3$ during the flood event. It was in agreement with the real situation, when a higher activity of depositional and erosional processes was recognized in the lower part of the basin after the flood event. The highest mean flow velocity during the peak discharge was simulated in the uppermost part of the longitudinal profile (2.5 m $s^{-1}$) in accordance with the highest channel gradient (up to 0.5 m/m) at 0.4 km (2.7 m $s^{-1}$). On the other hand, the lowest velocities of about 2.0 m $s^{-1}$ were only computed for 0.1 and 0.8 km cross-sections.

## 5. Discussion

This study makes use of the same approaches of bedload transport simulation that were originally applied in the reconstruction of bedload transport in Alpine streams with larger basin areas (6–180 $km^2$) and much higher peak discharges (24–140 $m^3$ $s^{-1}$) by Chiari and Rickenmann (2011). They regarded the application of macro-roughness (Eq. 3 and Eq. 4) with the calibrated parameter *a* in Eq. (4) in a range of 1.0–1.5 as the best-fitting predictor of bedload transport in such high-gradient streams, although they admitted that the quantification of macro-roughness remained difficult. According to our investigations, *a* exponent equal to 1.5 may fit to reaches with a limited supply of sediments for further transport and occurrence of well-developed bedforms (interlocked structures of individual steps). On the other hand, a lower value (1.0) most likely corresponds to parts of the longitudinal profile with almost unlimited delivery of material and thus less developed or infrequent step structures or other flow resistance bedforms. The degree of stability of steps and individual large grains affect potential bedload transport due to kinetic energy losses. Moreover, frequent bedrock outcrops in Malá Ráztoka stream substitute alluvial steps in flow energy dissipation and as a result they permanently act as resistance forms until they are buried by sediments during rather rare aggradation.

Another problem arises in connection with the incipient motion of grain or bedload layer according to Eq. (6). Chiari and Rickenmann (2011) used a single value 0.065 after Rickenmann (1991), whereas Bathurst (1987) originally recommended the value 0.045. This value can simply be understood as an expression of dimensionless shear stress or the so-called 'Shields parameter'. The TOMSED v0.1 model only allows the application of a single value of Shields parameter for a simulated stream, but it is possible the application of various values in the newest 0.2 version. Lamb et al. (2008) and later also Parker et al. (2011) demonstrated the dependence of dimensionless shear stress and at the same time the stability of individual grain on the channel gradient, pointing on a positive trend between increasing channel gradient and dimensionless shear stress. The specification of dimensionless shear stress values for various ranges of channel gradients will possibly make the resulting intensity of bedload transport more accurate for one-grain size models, especially in case of steeper gradients. Lenzi et al. (2006) also assumed different values of dimensionless shear stress, this time for different sizes of bed particles. His method is based on the comparison of a certain grain diameter with bed surface $d_{50}$ or $d_{90}$. Applying this approach on Malá Ráztoka stream, the calculated values of dimensionless shear stresses were from 0.02 for the 0.5 m boulders to low values of about 0.400 for 0.01 m grain diameters (Galia & Hradecký, 2011). This is further applicable to the calculations of fractional bedload transport, which the TOMSED model allows as well.

Exact values of real bedload transport discharges are not known for the Beskydian basins for any flood event, which makes the validating of the TOMSED model complicated for local mid-mountain conditions. Alpine torrents investigated by Chiari and Rickenmann (2011) indicated much higher intensity of bedload transport with total volumes of transported sediments commonly exceeding 10,000 $m^3$ during flood events due to larger basin areas and peak discharges than those simulated in this paper (maximum 1240 $m^3$ at the 0.4 km cross-section in Velký Škaredý potok). Kabina and Halaj (2004) reported storage of 3310 $m^3$ of bedload material during an extraordinary 100y flood event in Slovakian mid-mountain stream Hrondín (basin area 7.25 $km^2$, peak 100y discharge 27.8 $m^3$ $s^{-1}$). By contrast, Lenzi et al. (1999) observed peak bedload discharges of about 250 $m^3$ $h^{-1}$ only resulting in 900 $m^3$ of accumulated bedload transport in the sediment supply limited Alpine basin of Rio Cordon (5 $km^2$) during a 30–50y discharge. As for smaller events (1–5y discharge), the bedload rate did not exceed the values of 6 $m^3$ $h^{-1}$ in Rio Cordon. On the other hand, TOMSED relatively well estimated particular reaches with prevailing erosional or depositional processes, mainly in Velký Škaredý potok headwater stream, although the simulations were conducted on after-flood measured cross-sections.

## 6. Conclusions

The TOMSED model, originally developed for Alpine torrents, was applied first time in the conditions of the Czech midmountains. The Beskydian headwater streams of Malá Ráztoka and Velký Škaredý potok were selected in order to simulate the 5/2010 flood (20–25y discharge). Maximum intensity of bedload transport in a range of 10–50 $m^3/h$ (25–125 t/h) was computed during the flood event peak discharge and reaches with potential erosion and deposition were estimated. Although the inexistence of field measurement in the studied locality made it impossible to validate simulated values of bedload sediment transport, the TOMSED model indicated the reaches with recent incision or aggradation acceptably well. The approach of reducing the energy gradient for bedload transport was considered to be reliable for the estimations of coarse sediment transport and for the determination of the intensity of incision or aggradation in accordance with the resulting simulated longitudinal profiles. Decrease in flow resistance partitioning was suggested for high sediment supply related with less developed bedforms. The paper also discussed possibilities related to accuracy estimations of bedload transport by introducing individual values of dimensionless critical shear stress for different channel gradients or size fractions of transported material.

Moreover, obtained calculations may improve the management of local high-gradient streams (stream restorations, protections against flood damages etc.) due to bringing relatively exact values of the maximal intensity of bedload transport and volumes of totally transported material during high-magnitude flood event. Our results indicate that the TOMSED model is applicable in high-gradient streams of the Czech landscape, nevertheless the further improvement of simulated bedload transport is naturally related to some exact measurement in any of small mountain stream.

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## RESUMÉ

### Použití numerického modelu pro odhad dnového transport sedimentů v pramenných tocích (Moravskoslezské Beskydy, Česká republika)

Numerický model TOMSED, původně vyvinutý pro alpské bystřiny, byl úspěšně aplikován na povodňovou událost 5/2010 v pramenných tocích české části flyšových Západních Karpat. Ve výpočtech byl použit Manningův vztah s rozděleným drsnostním koeficientem na drsnost forem a drsnost zrn společně s redukovaným energetickým gradientem a limitní hloubkou potenciální eroze. Chybějící přímé měření transportu dnových sedimentů komplikovalo validaci modelu pro místní pramenné toky, nicméně korytové úseky se současnými erozními či akumulačními trendy model určil poměrně přesně. V toku bohatě dotovaném sedimenty byly vypočteny hodnoty dnového transportu sedimentů v rozmezí 480–1240 $m^3$, tok s limitovanou donáškou sedimentů vykázal hodnoty tohoto parametru v rozmezí 380–860 $m^3$. Bylo zjištěno, že korytové úseky s vyšší dodávkou sedimentů mají méně vyvinuty dnové formace (např. stupně) a tak u takových úseků vede nižší celková korytová drsnost k vyšší intenzitě dnového transportu sedimentů.

# VARIABILITY OF THE MORPHOMETRIC CHARACTERISTICS OF VALLEY NETWORKS CAUSED BY VARIATIONS IN A SCALE

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**ABSTRACT**

According to their shape, the valley networks are divided into six basic types (Howard 1967; Fairbridge 1968; Demek 1987; Babar 2005; Hugget 2007). Relevance to the given shape tends to be determined only based on the visual similarity to the pattern of the given network shape. The valley networks have a fractal character (Turcotte 1997, 2007a, 2007b; Baas 2002; Mandelbrot 2003) and their analysis is influenced by the scale selection (sensu Bendix 1994). This article indicates the quantitative tools, with assistance of which it is possible to characterize the morphology (shape) of the valley network and determine their variability caused by the scale change. The monitored morphometric characteristics (quantitative tools) are: 1) "number of various order valleys" according to the Gravelius order system; 2) "valley networks' density"; 3) "bifurcation ratio of various order valleys"; 4) "total lengths of various order valleys"; 5) "total length-order ratio of various order valleys"; 6) "average lengths of various order valleys"; 7) "average length-order ratio of various order valleys"; 8) "fractal dimension of various order valleys"; 9) "relative fractal dimension of various order valleys"; 10) "valley junction angles"; 11) "homogeneity of various order valleys". These characteristics have been applied to the paradigmatic examples of the schematic valley networks and have been analyzed in three scales.

In order to analyze the valley networks, the most suitable are "valley junction angles" and "homogeneity of various order valleys", i.e. morphometric characteristics resistant to any increase in the scale, "number of various order valleys" and "total lengths of various order valleys", where the relevant values dropped while increasing the scale, but the normal (Gauss) distribution of values was preserved.

**Keywords:** valley network, morphometry, fractal dimension, hierarchical scale

## 1. Introduction

The system of interconnected valleys forms the valley network, i.e. the system of linear depressions that are interconnected. The basic units of the valley networks are individual valleys. Not only valleys are connected into networks, which may be observed with other landscape elements, e.g. the patterned ground (Washburn 1979), drainage patterns (Horton 1945), leaf venation (Zalenski 1904 in Uhl and Mosbrugger 1999), transport routes (Kansky 1963), etc. The shape of the valley network and its density is the result of geomorphological development of the whole area and reflects the influence of the lithological-tectonical base and erosion (Stoddart 1997).

Six basic shapes of the valley networks are distinguished (colour appendix Figure I, Howard 1967; Fairbridge 1968; Horník et al. 1986; Demek 1987; Gerrand 1988; Babar 2005; Huggett 2007): 1) dendritic networks (often formed in the areas with a low vertical division); 2) parallel networks (often formed in the areas with a considerable inclination of slopes; 3) trellis networks and 4) rectangular networks (both of them are formed in the areas with a frequent presence of tectonics); 5) radial networks, and 6) annular networks (both of them are formed, for example, on volcanic cones or on other convex or concave curved landscape parts). For a long time, determination of the valley network shape was solely based on visual estimation without considering the importance of the scale, within which the valley network is evaluated (Howard 1967; Huggett 2007).

The valley networks shape could be characterized by the morphometric parameters describing the topologic and geometric properties of valley networks, which are given by the landscape characteristics. The studied morphometric characteristics are (sensu Horton 1945; Netopil et al. 1984; Babar 2005; Hugget 2007): 1) "number of various order valleys" according to the Gravelius order system (it indicates the number of valleys within the given network and the number of valleys belonging to the given order); 2) "bifurcation ratio of various order valleys" (indicates the rate of the valley networks branching); 3) "average length-order ratio of various order valleys" (allows mutual comparison of the average lengths of valleys); 4) "valley networks' density" (expresses the number of valleys in a certain area). It generally applies that greater "number of various order valleys", greater "bifurcation ratio of various order valleys" and greater "valley networks' density" are in the areas: A) with low inclination of landscape; B) with alternating resistant and less resistant rocks; C) with occurrence of faults and cracks; D) with impermeable rocks; and E) with a higher rainfall (Huggett 2007).

The valley networks are specific fractals (from Lat. *Fractus* = disintegrate) (Stuwe 2007) and are featured by a hierarchical scale (Bendix 1994) that expresses their self-affinity (Mandelbrot 1967; Stuwe 2007) and self-similarity (Mandelbrot 1982; Voss 1988). Determination of the valley network's shape by means of morphometric parameters is not, with respect to its fractal substance (so called scale independence), quite trivial. It is known that

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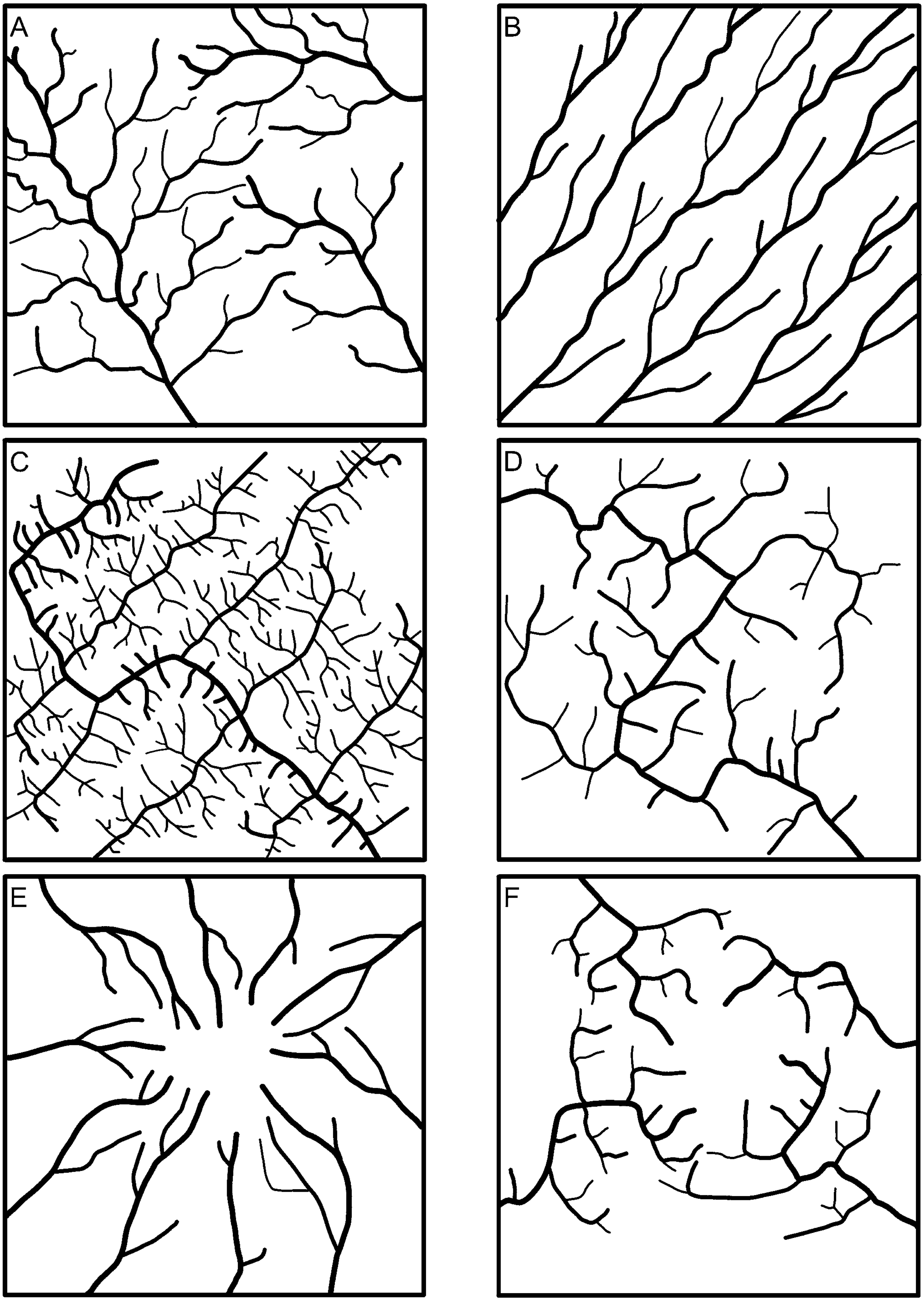


**Fig. 1** Howard's schematic valley networks (1967). Note: A – dendritic valley network, B – parallel valley network, C – trellis valley network, D – rectangular valley network, E – radial valley network, F – annular valley network.

the "fractal dimension of various order valleys" and the values of the other morphometric characteristics vary due to different conditions of the investigated territories, but also due to the scale change (sensu Burrough 1981; Tarboton 1996; Sung et al. 1998; Baas 2002; Mandelbrot 2003; Sung and Chen 2004; Turcotte 1997, 2007a, 2007b; Bi et al. 2012). But the real value changes of the "fractal dimension of various order valleys" and other morphometric characteristics within individual shapes of valley networks have not been known so far.

The main goal of this article is to define quantificators, with support of which it is possible to characterize the shape (i.e. morphology type) of the valley network and to determine variability of these quantificators caused by increasing of scale.

## 2. Methods

### 2.1 Schematic networks and scale selection

In order to analyse the valley networks, schematic valley networks have been selected (samples of valley networks) (Howard 1967; Fairbridge 1968; Horník et al. 1986; Demek 1987; Gerrand 1988; Babar 2005; Huggett 2007) that have been used for visual classification (Figure 1). Each shape of the valley network (dendritic, parallel, trellis, rectangular, radial, annular) has been represented by one example.

Schematic valley networks have been analyzed in various scales (sensu Bi et al. 2012). The original analyzed territory of the given (primary) scale corresponded to the patterns of valley networks taken from the literature (e.g. Howard 1967). Furthermore, a secondary square as an inscribed square has been formed from the original image, where its corners are placed in the middle of the original square sides. The newly formed square is half of the area as compared with the original (primary) square and the ratio of side lengths of the original (primary) and secondary square is approximately 1 : 0.7. The territory with the area of 1/4 of the original (primary) square has been derived by analogy from the secondary square – thus the tertiary square has been formed, where the ratio of the side lengths of the original (primary) and tertiary square is 1 : 0.5. The scale increase has been simulated by ascribing the same side lengths of the inscribed squares as are the side lengths of the original (primary) square (Figure 2).

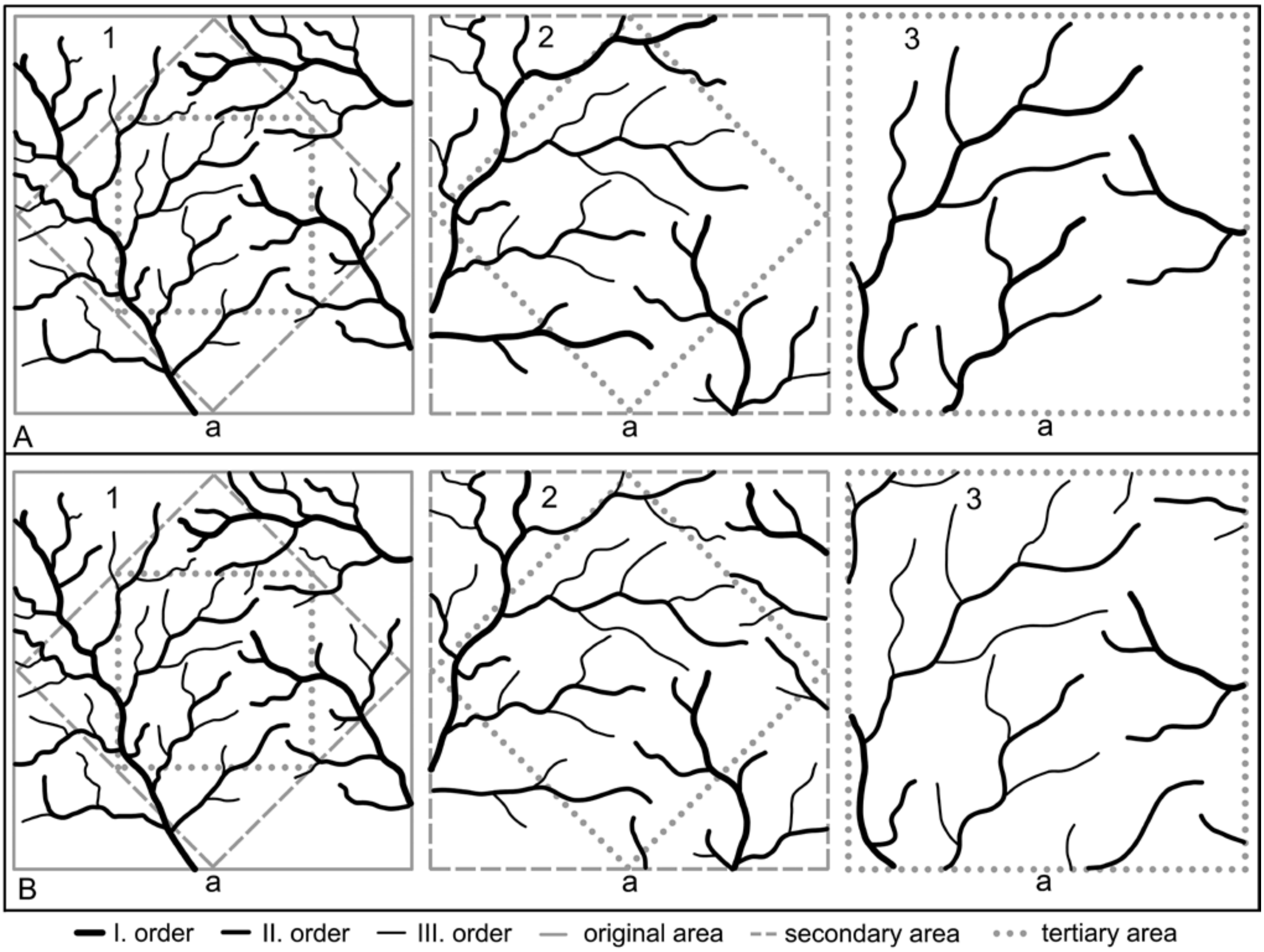


**Fig. 2** The valley order during the scale change. Note: A – variant A with main valley defined by length of a valley source; B – variant B with main valley defined by valley junction angle between a valley source and blended valley; 1. – original area (primary scale); 2. – secondary area; 3. – tertiary (cutout) area; a – side length of squares.

As the original schematic images of valley networks do not have same scales, it has been necessary to reflect that fact in the relevant analyses. Therefore variability of morphometric characteristics asociated with changes of scale were monitored and analyzed and/or new characteristics (non-dependant on scale changes such as indices) were defined.

## 2.2 Determination of the valley networks' order

The valley networks' order has been determined based on the Gravelius order system that defines the valley networks' order in the direction from the outfall towards the valley head. The valley network is formed by the main/primary (i.e. the I. order) valley, into which outfalls the subsidiary/secondary (i.e. the II. order) valley, and into these valleys later outfalls the tertiary (i.e. the III. order) valley, etc. (Gravelius 1914 in Zăvoianu et al. 2009).

The analysis of the valley network is dependent on the mode of determination of the main valley that influences the valley order calculation. The main valley has been determined either by comparing the lengths of blending valleys (variant A) or based on the valley junction angle with respect to the common (joined) valley (variant B) (Figure 2) (sensu Horton 1945). As far as the variant (A) is concerned, the longer valley has been designated as the main valley (and it has been assigned order X). The shorter valley has been identified as a secondary one and has been assigned order X + 1. As far as the variant (B) is concerned, the valley with a smaller angle towards the common valley axis (axis of the valley formed by blending of compared valley sources) has been identified as the main valley and has been assigned the same order as the common valley, i.e. order X. The valley with a greater angle towards the axis of order X valley has been designated as a secondary one and has been assigned order X + 1. As for variant (A), while considering either the secondary or the tertiary square (simulating the scale increase), the order was again re-determined for the specific square (Figure 2), because the ratio of lenghts of valleys was changed by trimming. If new I. order valleys arose by this trimming (from the remainders of the original valleys), such new valleys were not therefore considered (Figure 2). As for variant (B), no order changes occurred from the point of view of formation of the secondary and tertiary squares (Figure 2), because the angle of valleys did not changed by trimming.

## 2.3 Morphometric characteristics of valley networks

On studied schematic networks (patterns), following morphometric characteristics have been determined: 1) "number of various order valleys" according to the Gravelius order system; 2) "valley networks' density"; 3) "bifurcation ratio of various order valleys"; 4) "total lengths of various order valleys"; 5) "total length-order ratio of various order valleys"; 6) "average lengths of various order valleys"; 7) "average length-order ratio of various order valleys"; 8) "fractal dimension of various order valleys"; 9) "relative fractal dimension of various order valleys"; 10) "valley junction angles"; and 11) "homogeneity of various order valleys".

The "number of order X valleys" $n_X$ has been determined as the number of all order X valleys in the valley network.

Calculation of the "valley networks' density" $D$ has been determined as the ratio of the total lengths of thalwegs $L$ to the valley network area $P$ (Horton 1945), i.e.:

$$D = L / P.$$

The valley network area is understood as the area of a minimum square, in which the valley network has been intercepted.

The "bifurcation ratio of valleys" indicates the rate of valey network's branching (Horton 1945):

$$Rb = n_X / n_{X+1},$$

where $n_X$ is the "number of valleys of the given order" according to the Gravelius order system (Gravelius 1914 in Zăvoianu et al. 2009) and $n_{X+1}$ is the "number of valleys of one degree higher order" in the given valley network.

The "total lengths of order X valley" $t_X$ has been defined as the sum of lengths of all order X valleys in the valley network.

The "total length-order ratio of valleys" $T$ has been defined by the relation (Horton 1945):

$$T = t_{X+1} / t_X,$$

where $t_X$ is the "total lengths of valleys of the given order" according to the Gravelius order system (Gravelius 1914 in Zăvoianu et al. 2009) and $t_{X+1}$ is "the total lengths of valleys of one degree higher order" in the given valley network.

The "average lengths of order X valleys" $l_X$ has been defined by the relation (Horton 1945):

$$l_X = t_X / n_X,$$

where $t_X$ is the "total lengths of valleys of the given order" according to the Gravelius order system (Gravelius 1914 in Zăvoianu et al. 2009) and $n_X$ is the "number of valleys of the given order" in the given valley network.

The "average length-order ratio of valleys" $Rr$ has been defined by the relation (Horton 1945):

$$Rr = l_X / l_{X+1},$$

where $l_X$ is the "average lengths of valleys of the given order" according to the Gravelius order system (Gravelius 1914 in Zăvoianu et al. 2009) and $l_{X+1}$ is the "average valley length of one degree higher order" in the same network.

The "fractal dimension of valleys" $D$ used in this study has been based on the "bifurcation ratio of valleys order X and X + 1" $Rb$ and the "average length-order ratio of valleys order X and X + 1" $Rr$ and has been defined by the relation (Turcotte 1997):

$$D = ln\ (Rb)\ /\ ln\ (Rr).$$

The value of the fractal dimension shows to what extent is the territory covered by valleys

of the given order. Increase in the value of "fractal dimension of valley orders X and X + 1" means that the "number of valleys of the X + 1 order" has increased or the "average lengths of valleys of the X + 1 order" has risen.

The "relative fractal dimension of valleys" $Dr$ has been defined by the relation (Turcotte 1997):

$$Dr = ln\ (Rb)\ /\ ln\ (T),$$

where $Rb$ is the "bifurcation ratio of valleys order X and X+1" according to the Gravelius order system (Gravelius 1914 in Zăvoianu et al. 2009) and $T$ is the "total length-order ratio of valleys order X and X + 1" in the given valley network.

The "valley junction angles" express the angles at which the subsidiary (order X + 1) valleys run into the main (order X) valleys projected on a horizontal plane (Horton 1945).

"Homogeneity of order X valleys" has been defined by comparing the lengths of the longest and the shortest valleys of the given order. This characteristic is based on the analogy of homogeneity of the polygon lengths of the patterned ground (Mangold 2005). The valleys of a given order are homogeneous if the lengths of the longest order valley does not exceed three times the lengths of the shortest valley of the same order. If the valley network is not "homogeneous", it is designated as "variable".

## 3. Results and discussion

### 3.1 Changes in the values of morphometric characteristics while increasing the scale

While increasing the scale, the "valley junction angles" and "homogeneity of various order valleys" have been preserved in all types of network (Table 1; Table 2). With respect to the fractal substance that has been described with the valley networks by e.g. Mandelbrot (1967, 1982, 2003), Voss (1988), Tarboton (1996) and Turcotte (1997, 2007a, 2007b), while describing them, the constancy of their characteristics is necessary with regard to the scale change.

Independently from the shape of the valley network and the method of determining the main valley (according to the lengths of source valleys – variant A and according to the angle error of the source valley from the blended valley – variant B), while increasing the scale 1.43 times from the original to the secondary square, or while increasing the scale 2 times from the original to tertial square (Table 1; Table 2), there occurred:

1) drop in the "number of valleys of the II. order" by 2.3% (for the trellis network) up to 50% (for the parallel network) (while increasing the scale 1.43 times), or by 22.7% (for the trellis network) up to 80% (for the radial network) (while increasing the scale two times);

2) drop in the "number of valleys of the III. orders" by 20% (for the paralel network) up to 100% (for the radial network) (while increasing the scale 1.43 times), or by 40% (for the parallel network) up to 100% (for the dendritic and radial network) (while increasing the scale two times);

3) shortening of the "total lengths of valleys of the II. orders" by 4.2% (for the annular network) up to 44.4% (for the dendritic network) (while increasing the scale 1.43 times), or by 18.1% (for the trellis network) up to 72.2% (for the radial network) (while increasing the scale two times);

4) shortening of the "total lengths of valleys of the III. order" by 6.3% (for the annular network) up to 61.6% (for the rectangular network) (while increasing the scale 1.43 times), or by 1.4% (for the parallel network) up to 76.8% (for the rectangular network (while increaing the scale 2 times).

While increasing the scale, a drop in the "number of various order valleys" and shortening of the "total lengths of various order valleys" takes place. However, while increasing the scale, both of these characteristics have preserved the normal (Gauss) distribution of values (Table 1; Table 2). Preservation of the normal (Gauss) distribution shows that the reduction in the "number of various order valleys" and shortening of the "total lengths of various order valleys" was similar for all valley orders.

5) increase in the "average lengths of the II. order valleys" by 8.9% (for the dendritic network) up to 57.3% (for the annular network) (while increasing the scale 1.43 times), or by 2.8% (for the trellis network) up to 82.4% (for the annular network) (while increasing the scale two times);

6) increase in the "average lengths of the III. order valleys" by 19.0% (for the parallel network) up to 84.9% (for the rectangular network) (while increasing the scale 1.43 times), or by 15.6% (for the radial network) up to 182.5% (for the rectangular network) (while increasing the scale 2 times).

In order to describe the shapes of valley networks, the most appropriate characteristics are those that are resistant while changing the scale (sensu Burrough 1981; Bi et al. 2012). From the definition of the "average lengths of various order valleys" it results that this characteristic is based on the "number of various order valleys" and on the "total lengths of various order valleys". Since the scale increase resulted in the increasein the "average lengths

**Tab. 1** Variability of the morphometric characteristics of valley networks caused by variations in a scale by variant A. Note: 1 – original (primary) square; 2 – secondary square; 3 – tertiary square; f – from.

| Method | Change of scale (order) | Shapes of the valley networks | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dendritic | | Parallel | | Trellis | | Rectangular | | Radial | | Annular | |
| | | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. |
| Change of numbers of valleys [%] | I. | 0.0 | 0.0 | −16.7 | −16.7 | 0 | 0 | 0 | 0.0 | +40.0 | +20.0 | 0.0 | −25.0 |
| | II. | −42.3 | −57.7 | −47.8 | −73.9 | −2.3 | −22.7 | −28 | −64.0 | −40.0 | −80.0 | −39.0 | −73.8 |
| | III. | −55.6 | −100.0 | −40.0 | −80.0 | −53.8 | −83.4 | −70 | −87.0 | −100.0 | −100.0 | −40.0 | −85.0 |
| Change of bifurcation ratio [%] | I. and II. | −42.3 | −57.7 | −37.4 | −68.7 | −2.3 | −22.7 | −28.0 | −64.0 | −57.2 | −83.4 | −39.0 | −71.0 |
| | II. and III. | −23.1 | −100.0 | +15.2 | −23.0 | −52.7 | −78.6 | −57.7 | −63.8 | −100.0 | −100.0 | +0.6 | −31.0 |
| Change of average length of valleys [%] | I. | +4.8 | +11.2 | +2.5 | −14.4 | +15.8 | −39.5 | +7.5 | −3.0 | −20.8 | −31.7 | −17.7 | −14.3 |
| | II. | +8.9 | +15.2 | +33.8 | +19.1 | −7.2 | +2.8 | +19.5 | +38.7 | +26 | +38.6 | +57.3 | +82.4 |
| | III. | +45.8 | – | +17.8 | +83.6 | +43.7 | +71.1 | +84.9 | +157.7 | – | – | +57.3 | +63.5 |
| Change of avcerage length-order ratio [%] | I. and II. | −4.0 | −3.4 | −23.5 | −28.1 | +24.8 | −41.4 | −10.0 | −30.0 | −36.9 | −50.9 | −47.5 | −53.0 |
| | II. and III. | −25.5 | – | +13.6 | −34.3 | −34.0 | −38.5 | −36.3 | −46.2 | – | – | 0.0 | +11.7 |
| Change of fractal dimension of I. and II. order [%] | | −23.1 | −37.9 | −20.0 | −82.1 | −8.7 | +18.0 | −6.4 | −19.3 | – | – | +34.1 | −35.7 |
| Change of total length of valleys [%] | I. | +4.6 | +11.5 | −14.8 | −11.8 | +15.9 | +21.0 | +7.3 | −2.8 | +10.9 | −18.8 | −17.9 | −35.9 |
| | II. | −35.9 | −50.4 | −30.3 | −71.1 | −8.0 | −18.1 | −13.6 | −49.8 | −24.4 | −72.2 | −4.2 | −60.3 |
| | III. | −35.3 | – | −32.4 | −64.8 | −38.7 | −70.5 | −61.6 | −76.8 | – | – | −6.3 | −75.7 |
| Change of total length-order ratio [%] | I. and II. | −38.6 | −55.6 | −18.3 | −59.1 | −20.7 | −32.2 | −19.4 | −48.4 | −32.4 | −66.2 | +16.8 | −39.8 |
| | II. and III. | +2.0 | – | −4.1 | +22.6 | −33.5 | −64.0 | −55.8 | −53.9 | – | – | −3.2 | −38.7 |
| Change of relative fractal dimension of I. and II. order [%] | | +52.9 | +309.7 | – | – | +22.1 | +6.6 | +17.8 | +151.4 | – | +294.7 | −50.1 | – |
| Change of valley networks´ density [%] | | +2.08 | −6.25 | +9.38 | +3.12 | +1.92 | +1.92 | +30.43 | −4.35 | +36.36 | +22.73 | +21.74 | −13.04 |

| **Scale** | | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Valley junction angles [°] | | 60 | 60 | 60 | 30 | 30 | 30 | 90 | 90 | 90 | 90 | 90 | 90 | 30 | 30 | 30 | 90 | 90 | 90 |
| Homogeneity of various order valleys | I. order | yes | yes | no | no | yes | no | – | – | yes | – | – | – | yes | yes | yes | yes | yes | yes |
| | II. order | no | no | no | no | no | no | no | no | no | no | no | no | no | no | yes | no | no | yes |
| | III. order | no | no | – | yes | yes | yes | no | no | no | yes | yes | yes | – | – | – | yes | yes | yes |
| | IV. order | – | – | – | – | – | – | no | no | no | yes | – | – | – | – | – | yes | – | – |
| | V. order | – | – | – | – | – | – | yes | yes | yes | – | – | – | – | – | – | – | – | – |

of various order valleys", it means that shortening of the "total lengths of various order valleys" was not so noticeable as the decrease in the "number of various order valleys" (Table 1; Table 2). Consequently, the "total lengths of various order valleys" is more suitable characteristic for describing the valley network than the "number of various order valleys".

### 3.2 Suitability of morphometric characteristics for the analysis of valley networks

The characteristic that best describes the shape of the studied valley network was the "valley junction angles" (Table 1; Table 2), as the networks shape is determined by the angles between interconnecting sections forming the network (Horák et al. 2007). The characteristic of the "valley junction angles" may include an information on the tectonic influence upon the studied territory or the inclination of slopes. The "valley junction angles" were similar for the trellis, rectangular and annular networks (ca 90°; Table 1; Table 2). As the tectonic disturbances are largely parallel or orthogonal to each other (Howard 1967; Fairbridge 1968; Demek 1987), it is possible to assume that the intersecting valleys, whose "valley junction angles" are about 90°, are bound to tectonic failures. The most frequent value of "valley junction angles" of the radial and parallel networks reached about 30° and those of the dendritic networks reached about 60° (Table 1; Table 2). Similar angle values corresponding to the individual types of valley networks were traced at the real valley networks by the remote sensing methods, by Burr et al. (2013); trellis and rectangular networks reached 80–90°, dendritic networks reached 40–80°, radial and parallel networks less than 40°.

For the complete differentiation of valley network groups, the characteristic of the "valley junction angles"

**Tab. 2** Variability of the morphometric characteristics of valley networks caused by variations in a scale by variant B. Note: 1 – original (primary) square; 2 – secondary square; 3 – tertiary square; f – from.

| Method | Change of scale (order) | Shapes of the valley networks | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Dendritic | | Parallel | | Trellis | | Rectangular | | Radial | | Annular | |
| | | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. | f 1. to 2. | f 1. to 3. |
| Change of numbers of valleys [%] | I. | 0.0 | −33.3 | −33.3 | −50.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | II. | −34.6 | −65.4 | −43.5 | −65.2 | −50.0 | −63.6 | −4.0 | −44.0 | −15.0 | −45.0 | −21.7 | −52.2 |
| | III. | −30.8 | −53.8 | −20.0 | −40.0 | −46.2 | −71.0 | −34.7 | −69.9 | 0.0 | 0.0 | −30.0 | −70.0 |
| Change of bifurcation r atio [%] | I. and II. | −34.6 | −48.1 | −15.2 | −30.3 | −50.0 | −63.6 | −4.0 | −44.0 | −15.0 | −45.0 | −21.7 | −52.2 |
| | II. and III. | +6.0 | +33.3 | +41.9 | +72.8 | +7.0 | −20.3 | −57.7 | −45.7 | +18.0 | +82.0 | −10.6 | −37.4 |
| Change of average length of valleys [%] | I. | −23.1 | −41.7 | +13.1 | −1.8 | −29.0 | −41.5 | +7.3 | −16.3 | −10.5 | −35.3 | −17.1 | −31.4 |
| | II. | +23.4 | +73.9 | +35.9 | +58.5 | +33.3 | +47.5 | +16.9 | +42.7 | +18.7 | +31.3 | +36.9 | +24.2 |
| | III. | +48.6 | +105.7 | +19.0 | +69.3 | +58.0 | +108.7 | +82.5 | +182.5 | +49.8 | +15.6 | +54.5 | +87.3 |
| Change of average length-order ratio [%] | I. and II. | −37.6 | −69.1 | −16.8 | −38.0 | −46.7 | −60.3 | −8.2 | −41.3 | −24.6 | −50.9 | −39.3 | −44.6 |
| | II. and III. | −14.7 | −15.1 | +14.6 | −6.3 | −15.7 | −29.4 | −35.9 | −49.4 | −20.5 | +13.7 | −11.2 | −33.7 |
| Change of fractal dimension of I. and II. order [%] | | +33.5 | +767.0 | +1.0 | +11.3 | +8.7 | +15.3 | +2.1 | +6.4 | +4.7 | −59.4 | +34.9 | +1.6 |
| Change of total length of valleys [%] | I. | −48.2 | −61.0 | −24.7 | −51.0 | −29.0 | −77.8 | +7.9 | −15.73 | −10.3 | −35.3 | −17.1 | −32.3 |
| | II. | −44.4 | −38.2 | −20.8 | −43.3 | −37.5 | −46.0 | +2.5 | −19.23 | +1.3 | −27.4 | +7.8 | −40.6 |
| | III. | −33.2 | −7.8 | −8.5 | −1.4 | −14.5 | −40.0 | −17.4 | −40.5 | +55.0 | +15.0 | +7.2 | −44.1 |
| Change of total length-order ratio [%] | I. and II. | +7.3 | +58.3 | +5.4 | +15.1 | −12.1 | +143.7 | −4.8 | −4.0 | +13.2 | +11.8 | +30.8 | −11.9 |
| | II. and III. | +20.0 | +50.0 | +16.4 | +13.7 | +36.6 | +10.9 | −18.6 | −25.5 | −85.1 | −83.6 | 0.0 | −6.5 |
| Change of relative fractal dimension of I. and II. order [%] | | −25.1 | −52.9 | – | – | −8.91 | −57.4 | +4.5 | −14.1 | – | – | −50.9 | −10.4 |
| Change of valley networks´ density [%] | | +19.6 | +30.0 | +9.4 | +12.5 | +15.4 | +19.2 | +30.4 | +39.1 | +36.3 | +45.5 | +30.4 | +17.4 |

| **Scale** | | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Valley junction angles [°] | | 60 | 60 | 60 | 30 | 30 | 30 | 90 | 90 | 90 | 90 | 90 | 90 | 30 | 30 | 30 | 90 | 90 | 90 |
| Homogeneity of various order valleys | I. order | yes | yes | yes | no | yes | yes | – | – | yes | – | – | – | yes | yes | yes | yes | yes | yes |
| | II. order | no | no | no | no | no | no | no | no | no | no | no | no | no | no | yes | no | no | no |
| | III. order | no | no | no | yes | yes | yes | no | no | no | yes | no | yes | – | – | – | yes | yes | yes |
| | IV. order | – | – | – | – | – | – | no | no | yes | yes | – | – | – | – | – | yes | – | – |
| | V. order | – | – | – | – | – | – | yes | yes | yes | – | – | – | – | – | – | – | – | – |

must be completed by the characteristics “number of various order valleys” and the “total lengths of various order valleys”. From the definitions of characteristics of the valley networks it results that the “bifurcation ratio of various order valleys”, “total length-order ratio of various order valleys”, “average lengths of various order valleys”, “average length-order ratio of various order valleys”, “fractal dimension of various order valleys”, “relative fractal dimension of various order valleys”, are based on the “number of various order valleys” and the “total lengths of various order valleys”, and therefore they correlate with these characteristics (Figure 3).

“Valley networks’ density”, which Slaymaker (2004) and Huggett (2007) consider to be the basic characteristic of the valley network description, also contains information about landscape in which the valley network developed. The largest “valley networks’ density” at the trellis and dendritic networks (Table 1; Table 2) may be caused by their occurrence in the areas: A) with a low inclination of landscape; B) with alternating resistant and less resistant rocks; C) with occurrence of faults and cracks; D) with impermeable rocks; or E) with a higher rainfall (sensu Demek 1987; Tarbotton 1996; Huggett 2007). In contrast with that, the lowest “valley networks’ density” with the parallel and radial networks (Table 1; Table 2) may be caused by their occurrence: A) in the areas with a considerable inclination of slopes; B) in the areas with permeable subsoil or in the karst areas; or C) in the arid areas (sensu Demek 1987; Tarbotton 1996; Huggett 2007). Although the “valley networks’ density” is mentioned in the literature as one of the most frequently referred to characteristic describing all types of networks (e.g. Davis 1913 in Goudie et al. 2004; Zalenski 1904 in Uhl and Mosbrugger 1999; Horton 1945; Kansky 1963; Howard 1967; Fairbridge 1968; Demek 1987; Babar 2005; Huggett 2007), the comparison of the mutual relation of the

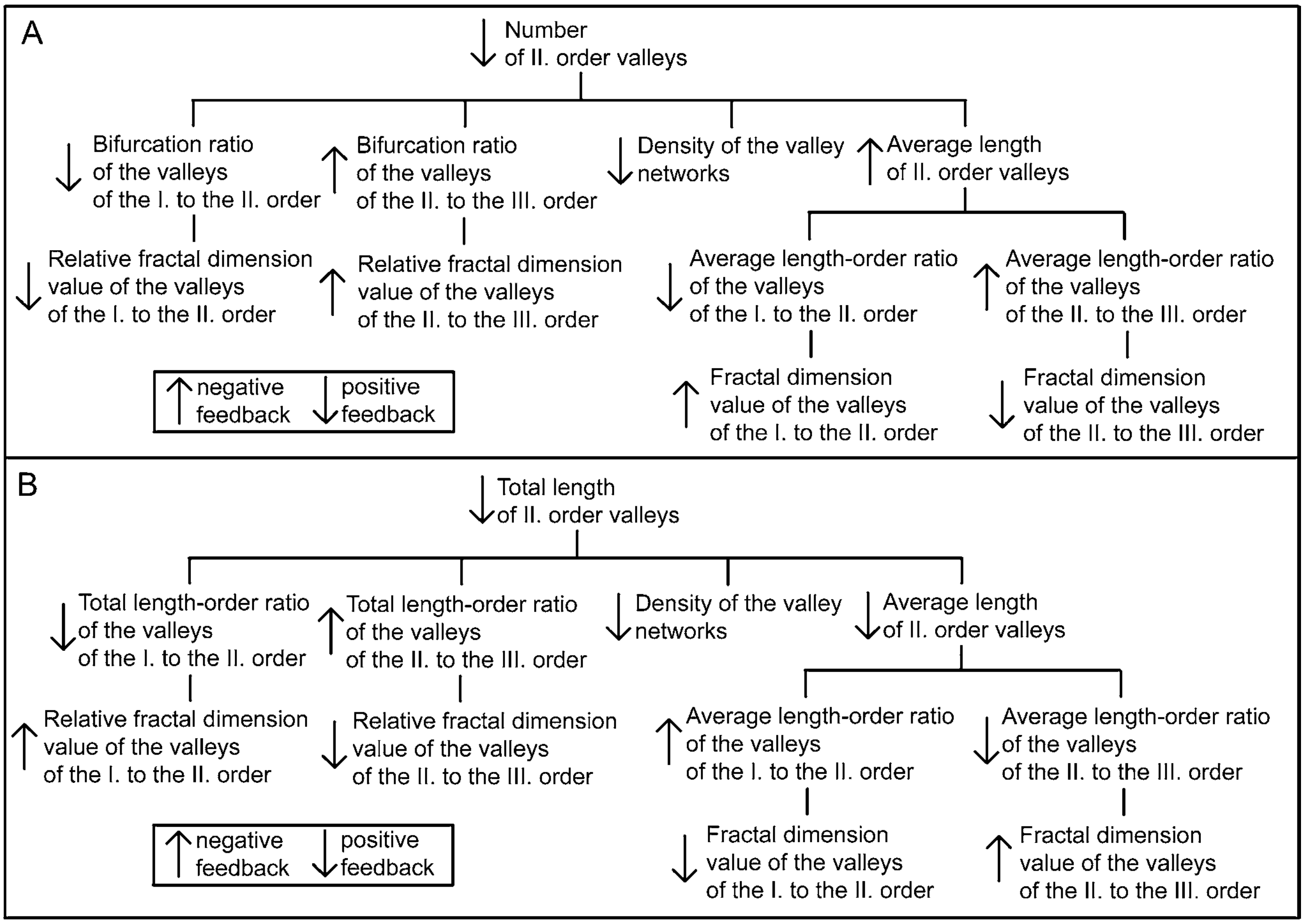


**Fig. 3** Relation of morphometric characteristics to: A) "number of valleys of the II. orders"; B) "total length of valleys of the II. orders".

characteristics (Figure 3) indicates it as being correlated with the "number of various order valleys" and the "total lengths of various order valleys", and therefore already expressed in these characteristics.

A suitable additional characteristic of the "valley junction angles", "number of various order valleys" and the "total lengths of various order valleys" may be the "homogeneity of various order valleys" that remained preserved while increasing the scale. When comparing the "homogeneity of various order valleys" among various authors it is necessary to expect that various authors use various and incompatible order systems of valleys (e.g. Gravelius 1914 in Zăvoianu et al. 2009; Horton 1945; Strahler 1957; Shreve 1966; etc.).

As no short valleys have been considered with variant A that arose by trimming the remainders of the original valleys while magnifying the scale, as compared with variant B (always considered all of the valleys), in variant A a greater drop in the "number of valleys of the II. to the III. order" occurred. If the valley order was re-determined again while increasing the scale (variant A), then shortening of the "total lengths of valleys" was greater with the growing number of the valleys order (Table 1). If the valley order was preserved when changing the scale (variant B), the shortening of the "total lengths of valleys" was smaller with the growing order of valleys (Table 2).The results of chapters 3.1. and 3.2. imply that the values of the "number of various order valleys", "total lengths of various order valleys" and the characteristics influenced by them (Figure 3) depend on the scale, in which the valley networks have been analyzed and on the mode of determining the main valley, or the order system of valley networks.

## 4. Conclusion

In order to analyze the valley networks, the most suitable characteristics are "valley juncion angles" and "homogeneity of various order valleys" that are resistant against any changes (increase or decrease) in the scale, and the "number of various order valleys" and "total lengths of various order valleys" that are influenced by the choice of scale, however, the normal (Gauss) distribution of their values is retained.

Any changes in the values of characteristics like the "number of various order valleys" and the "total lengths of various order valleys" influence the values of the characteristics "bifurcation ratio of various order valleys", "total length-order ratio of various order valleys", "average lengths of various order valleys", "average length-order ratio of various order valleys", "fractal dimension of various order valleys", "relative fractal dimension of various order valleys" and the "valley networks' density".

Increase in the "average lengths of various order valleys" while increasing the scale shows that the "total lengths of various order valleys" is a more suitable for analysis of the valley networks than the "number of various order valleys" because a smaller change (i.e. decrease) in its values took place there.

In order to compare the "number of various order valleys", "total lengths of various order valleys" as well as morphometric characteristics influenced by them, the same scale and the same method of selecting the main valley (variant A or B) have to be selected. While analysing the schematic or real valley networks of different shapes, it is more suitable to determine the main valley by the size of angular deviation of the source valley from the blended valley (variant B) for conservation of valley order of valleys while increasing the scale.

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**RESUMÉ**

**Proměnlivost morfometrických charakteristik údolních sítí způsobená změnami měřítka**

Údolní sítě se dle tvaru rozlišují na šest základních typů (Howard 1967; Fairbridge 1968; Demek 1987; Babar 2005; Hugget 2007). Příslušnost k danému tvaru bývá určována jen na základě vizuální podobnosti se vzorem daného tvaru sítě. Údolní sítě mají fraktálový charakter (Turcotte 1997, 2007a, 2007b; Baas 2002; Mandelbrot 2003) a jejich analýza je ovlivněna volbou měřítka (sensu Bendix 1994).

Tento článek ukazuje kvantitativní nástroje, s jejichž pomocí lze charakterizovat morfologii (tvar) údolní sítě a určit jejich proměnlivost způsobenou změnou měřítka. Sledovanými morfometrickými charakteristikami (kvantitativními nástroji) jsou 1) „četnost údolí různých řádů“ dle Graveliova systému řádovosti; 2) „hustota údolních sítí“; 3) „bifurkační poměr údolí různých řádů“; 4) „celková délka údolí různých řádů“; 5) „poměr celkové délky údolí různých řádů“; 6) „průměrná délka údolí různých řádů“; 7) „poměr průměrných délek údolí různých řádů“; 8) „fraktálová dimenze údolí různých řádů“; 9) „relativní fraktálová dimenze údolí různých řádů“; 10) „velikosti úhlů mezi údolími“; a 11) „homogenita údolí různých řádů“. Tyto charakteristiky byly aplikovány na vzorové příklady schématických údolních sítí dle Howarda (1967) a byly analyzovány ve třech měřítkách.

Pro analýzu údolních sítí jsou nejvhodnější „velikosti úhlů mezi údolími“ a „homogenita údolí různých řádů“, tj. morfometrické charakteristiky rezistentní vůči zvětšení měřítka, a „četnost údolí různých řádů“ a „celková délka údolí různých řádů“, u kterých došlo při zvětšení měřítka k poklesu hodnot, ale bylo zachováno normální (Gaussovo) rozdělení hodnot.

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# COLOUR APPENDIX

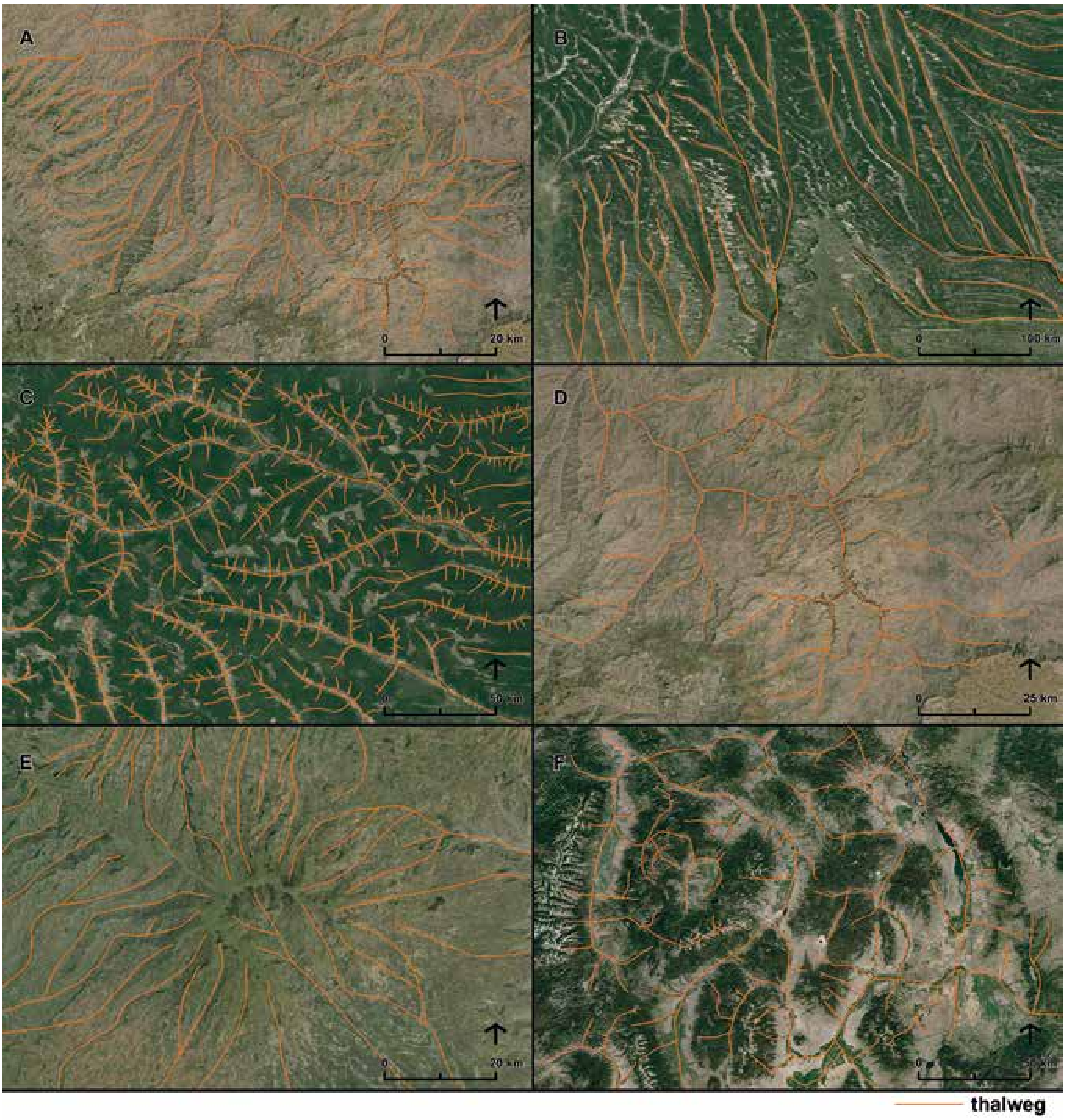


**Fig. I** Valley networks (on aerial photo from Google Earth 2014): A – dendritic valley network (Tekeze Wenz, Ethiopia; left corner coordinates: N12°19′, E38°06′), B – parallel valley network (Bié Plateau, Angola; left corner coordinates: S12°52′, E18°56′), C – trellis valley network (Bié Plateau, Angola; left corner coordinates: S12°05′, E18°30′), D – rectangular valley network (Tekeze Wenz, Ethiopia; left corner coordinates: N12°12′, E38°27′), E – radial valley network (Mt. Choke, Ethiopia; left corner coordinates: N10°57′, S37°32′), F – annular valley network (southern Montana, U.S.A.; left corner coordinates: N46°47′, W114°19′).

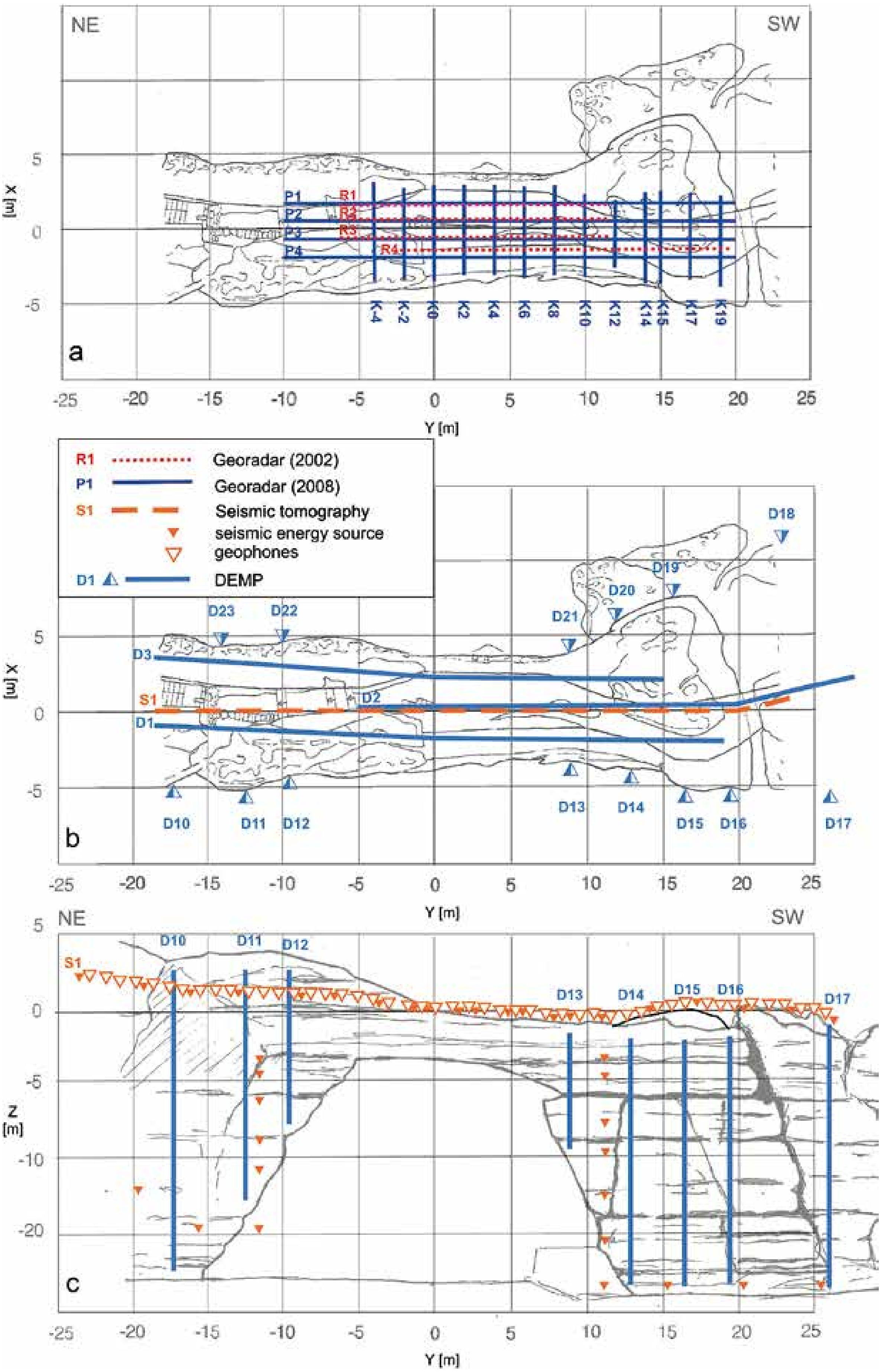


**Fig. II** Schematic layout indicating all of the measured profiles from 2002 to 2009 (a, b – ground plan and c – profile).

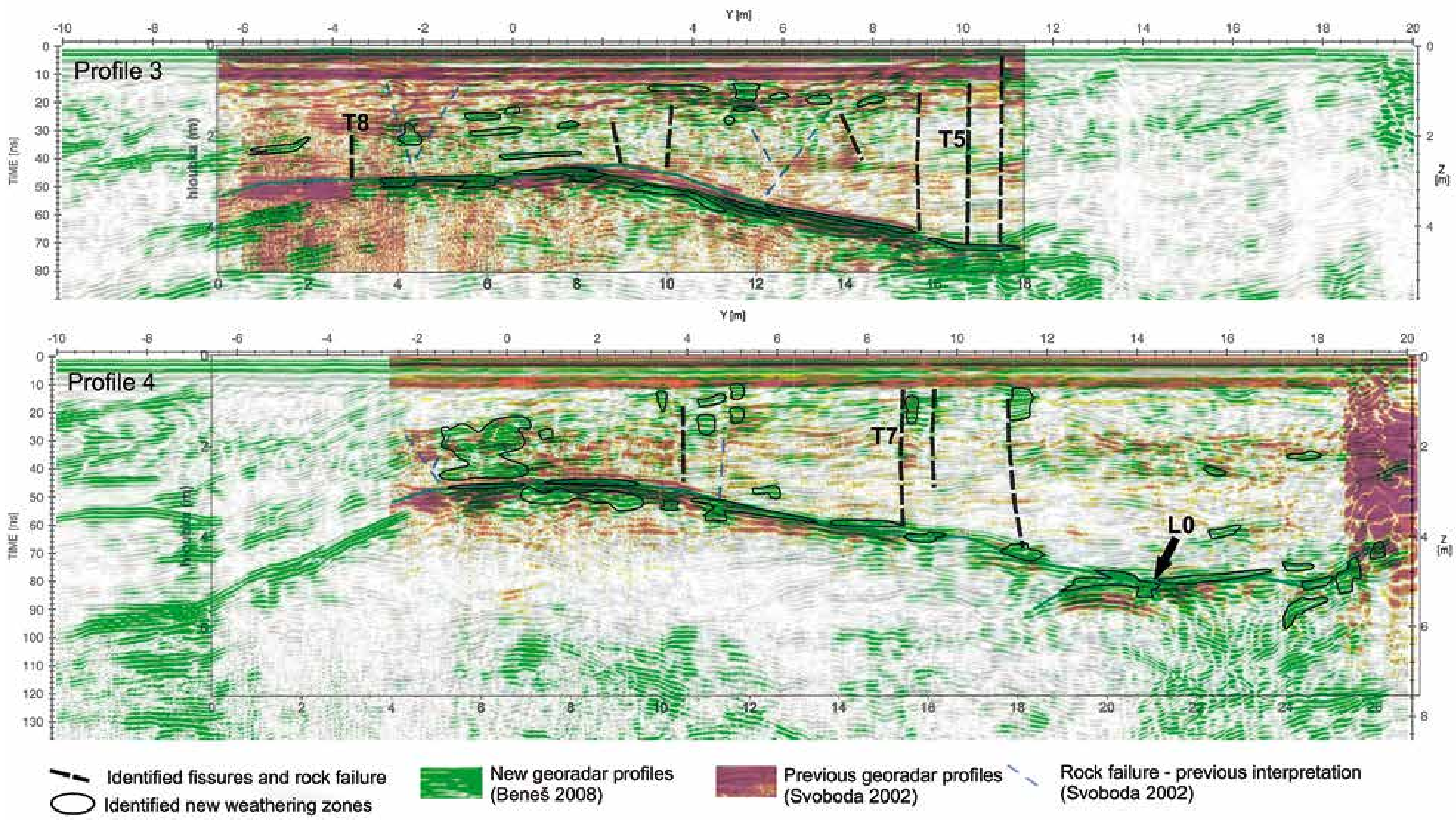


**Fig. III** Comparison of georadar measurements from 2002 and 2008 (view from the west), indicating changes (especially the identified higher intensities of weathering of parts of the rock massif) and newly identified fissures (in profiles 3 and 4, the most distinctive vertical fissure T5 is marked there).

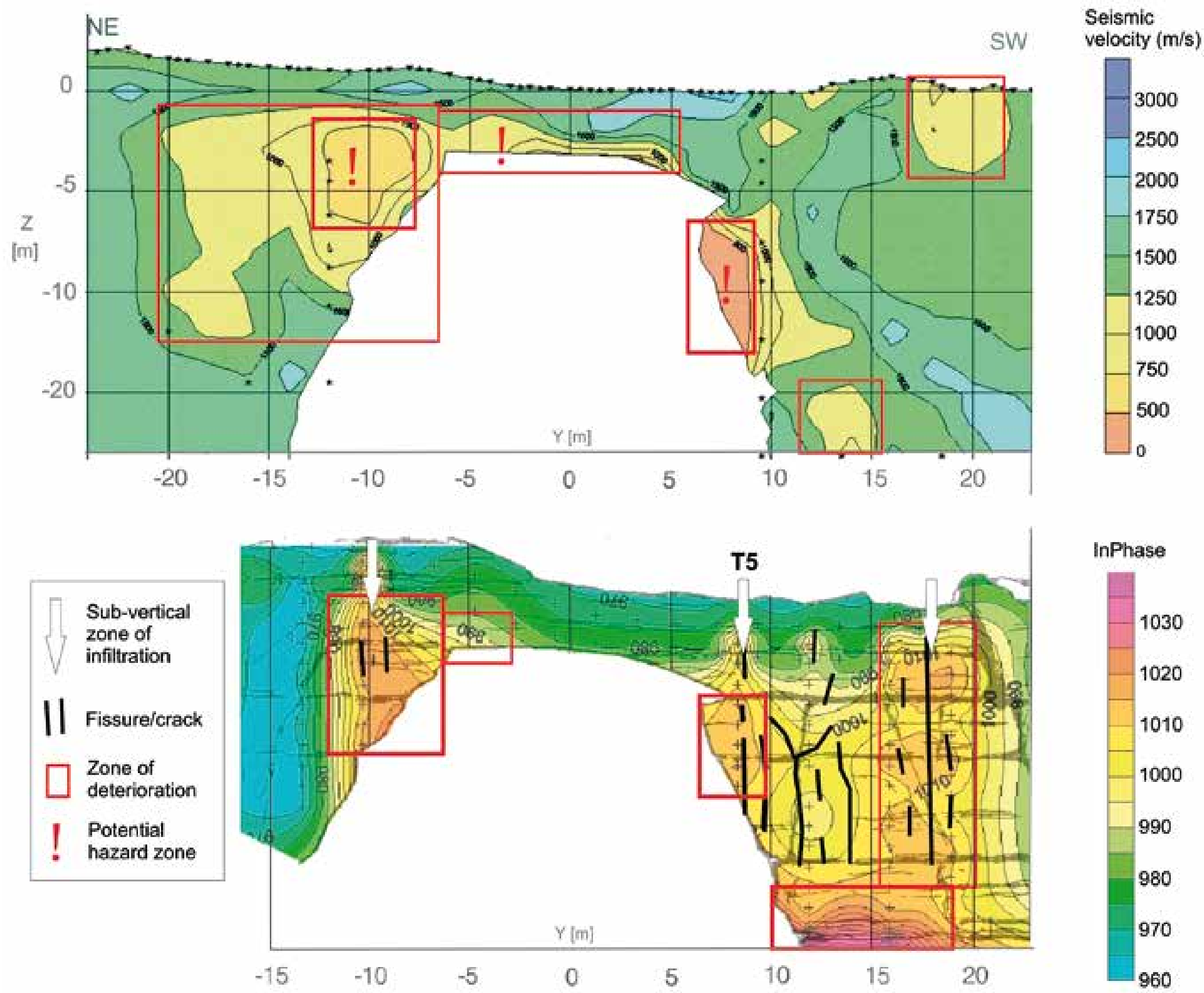


**Fig. IV** Map of seismic velocities in the western wall of the rock arch, identified by the method of seismic tomography (above), where red to yellow zones indicate the most weakened parts of the rock arch, correspond with Inphase profile (at depths of 3–4 m depth behind the rock wall) as a results of dipole electromagnetic profiling/DEMP (below) from which material changes in the rock (represented by violet/orange colour) can be inferred.

# THE APPLICATION OF NON-DESTRUCTIVE METHODS TO ASSESS THE STABILITY OF THE NATIONAL NATURE MONUMENT OF THE PRAVČICKÁ BRÁNA ROCK ARCH, CZECH REPUBLIC

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**ABSTRACT**

The study contains the results of non-destructive research of the Pravčická Brána Rock Arch which focuses on the structure and natural dynamics of this rock formation and its current level of stability. The main results include a description of the block fabric of the rock body and the nature of the contact zone between the arch beam and the southern pillar, discovery of relatively fresh secondary fissures and identification of zones with weakened strength within the sandstone massif. Also the local hydrodynamic regime was determined by a combination of geophysical methods. Long-term monitoring has demonstrated slow and irreversible body movements and reversible quasi-cyclical movements associated with changes in temperature on a scale of days up to years. The collected information was used to develop a structural deformation model of the arch body, including a description of the nature of the disintegration. The work was designed to fully respect the protective conditions of the site, to facilitate future follow-up activities and to monitor any possible negative changes in the rock massif.

**Keywords:** cretaceous sandstones, rock arch, stability, geophysical methods, displacement monitoring

## 1. Introduction

The current form of the rugged sandstone relief of the Bohemian Switzerland National Park (BSNP – location on Figure 1) has resulted from long-term dynamic development (Vařilová and Zvelebil 2007) which has taken place within the full range of spatial and time scales and has affected the massive block sandstones of the Late Cretaceous age, which are part of the Bohemian Cretaceous Basin (BCB). The study site, i.e. the Pravčická Brána Rock Arch (PBRA), is found at the top of a ridge in the area of rocks called Křídelní stěny. Reaching a height of 16 m and length of 26.5 m, the formation represents a mature form of sandstone arches and a natural monument of European significance (Vařilová and Belisová 2010). Due to its geometry and exposure it is currently threatened not only by the stress posed by its own weight but also by extreme microclimatic factors, which act not only in the form of dynamic effects of volumetric changes but also as a driving force of physical and chemical weathering (see Vařilová et al. 2011a, 2011b; Navrátil et al. 2013). The geological and tectonic patterns of the rock body together with the effects of the microclimate are fully manifested in a gradual degradation of the sandstone material and a deterioration of physico-mechanical parameters of the rock. The key parts include the rock arch itself and its contact with both supporting pillars.

Consequently, the formation has been a subject of professional interest since the early 1990s, mainly in terms of determining the most suitable protective conditions and evaluating its lifespan. The initial evaluation of the stability of the rock body, however, was based only on a short-term data series of monitoring and a low level of knowledge of the exact geometry and structure of the formation (Zvelebil et al. 2002). In addition, the threat to the local rock massif from salt weathering processes, which have either been indirectly caused or their action intensified by anthropogenic effects, has been an issue examined over recent decades (Soukupová et al. 2002; Schweigstillová et al. 2009; Vařilová et al. 2011b).

Knowledge of the rock fabric and the weakness level of the actual rock massif form a basis for the assessment of the current condition and a plan for the optimal management and protection of this natural monument. Due to legal protective restrictions, geological and geotechnical investigation using common deep boreholes or standard rock sampling for laboratory testing cannot be conducted. Therefore, non-destructive methods of investigation had to be applied to document the condition of the rock arch, in particular to identify areas of discontinuity and inhomogeneity in the rock massif and to study the level of sandstone weathering. Regular monitoring and geophysical measurement are rigorous and non-invasive methods of describing the basic structure of the rock massif and

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AUC Geographica, 49, No. 1, pp. 49–59

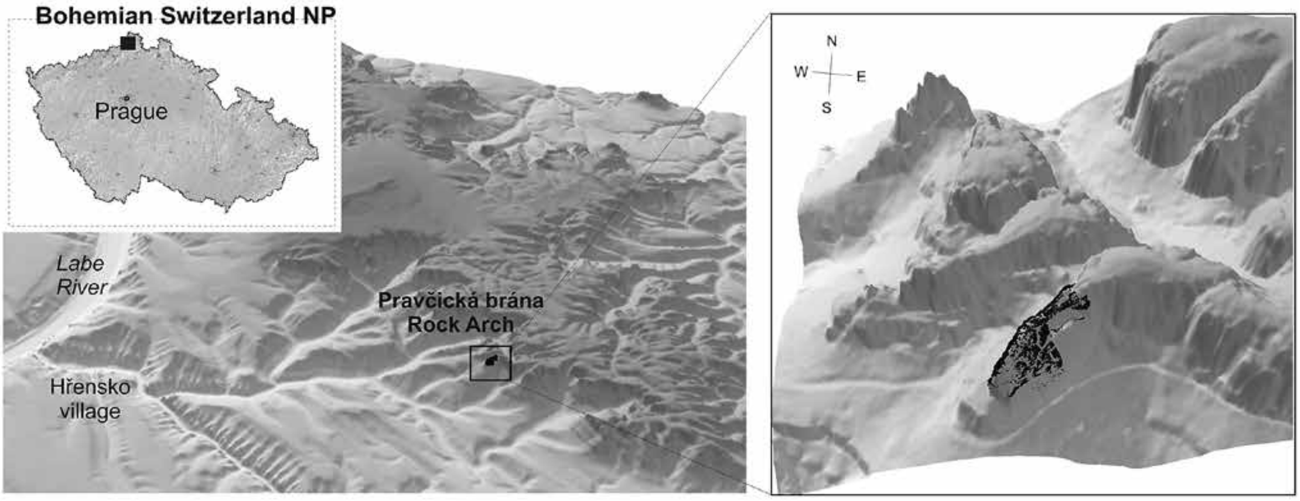


**Fig. 1** Location of the Bohemian Switzerland National Park within the Czech Republic, digital model of the PBRA terrain and its surroundings (Technical University of Dresden; NASA (SRTM) – provided by the BSNP Administration).

its stability and can also be used to perform long-term monitoring of its alterations.

## 2. Description of the studied locality

The Pravčická Brána Rock Arch (PBRA) along with the rock towers in its surroundings are built up of Mesozoic sediments (forming part of the Bohemian Cretaceous Basin – the Jizera Formation, Middle to Upper Turonian age – e.g. Čech et al. 1980; Härtel et al. 2007). Relatively massive quartzose sandstones with fracturing in distant spacings along with the formation of basal planes show typical rectangular jointing. The rocks show subhorizontal bedding with quasi-cyclical variable granularity (from fine-grained sandstones at the base of the cycle passing into medium-grained and then coarse-grained sandstones to conglomerates – e.g. Uličný et al. 2009).

The PBRA is formed from the base of the original rock wall by gradual deepening of a double-faced overhang at the base of the present-day rock arch. The rock opening was then probably extended by blocks and flakes falling out along bow-shaped exfoliation fissures, supported by concurrent erosion and weathering processes to reach its present-day appearance. The ceiling of the PBRA is presently relatively thin (its width at the narrowest point is 7.5 m and the thickness of the cross-beam is a mere 2.5 m), its axis is NE–SW oriented and it is formed by a slab of fine-grained to medium-grained sandstone with conglomerate layers. The selective weathering of less solid layers has given rise to the characteristic horizontal structure (accentuated by gradual deepening of ledges – Figure 2). The most distinctive structure is the horizontal layer (L0), at a height of 17.5 m, which is built from a weaker conglomerate layer and forms a visual boundary between the cross-beam and the southern pillar.

The diagonal structure of the rock ridge is represented by sub-vertical joints following a predominantly NW–SE (locally also NNW– SSE) trend, which not only separate the narrow rock cliff into the individual sub-parts, but also influence the circulation of seepage water (sandstone percolates) in the rock body. The most distinct open joint

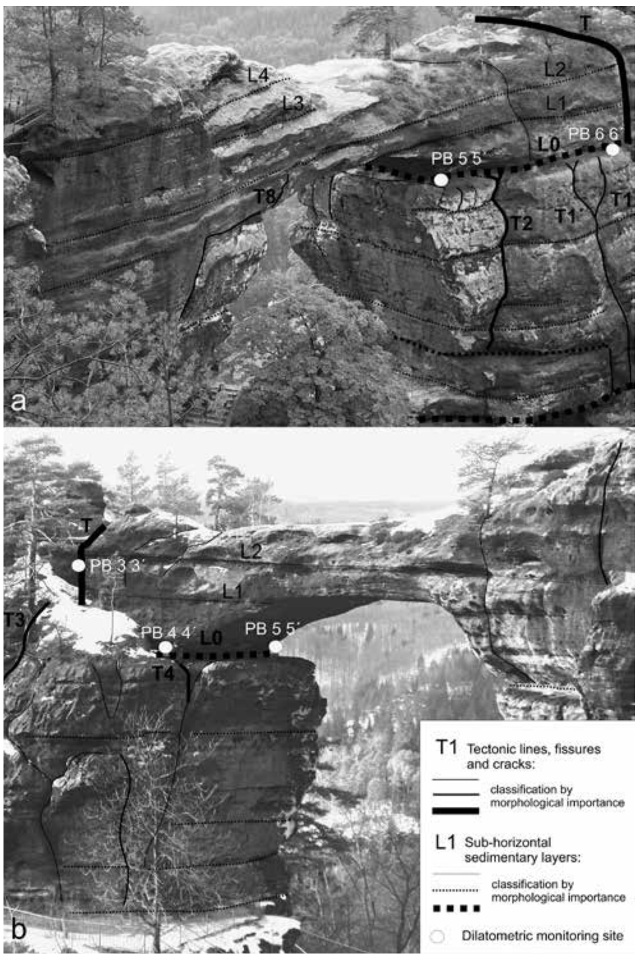


**Fig. 2** View of the Pravčická Brána Rock Arch from the north (upper photo) and view from the east (lower photo) showing the positions of the morphology. The marked height levels correspond with the lithology of the arch body (L0, L1–L4), the main tectonic structures (T, T1–T4) and the dilatometric monitoring sites.

passing the body at the point of termination of the southern end of the rock arch cross-beam is also the formal end point of the investigation activities (marked T in Figure 2).

## 3. Methodology of data measurement and processing

### 3.1 Geophysical investigation

The status and the fabric of the rock massif as a whole were characterised by several independent geophysical parameters that complement each other. The geophysical investigation focused on the potentially hazardous parts and points of instability, with attention given to the arch block structure to verify lines of the main joints and identify new failures and any inhomogeneity within the rock massif, and to the southern pillar exhibiting a worn surface with special regard to the method of drainage and any intense salt weathering displayed. Combined geophysical methods, i.e. repeated georadar and seismic measurements, resistivity tomography profiling (ERT) and dipole electromagnetic profiling (DEMP) were selected for the investigation (Table 1).

The first georadar profiling conducted at the end of 2002 (Svoboda 2002) is considered the zero point of the geophysical monitoring of the rock body. In the second, main phase of the investigation in 2008 (conducted by G IMPULS Praha, Beneš 2008), the georadar measurements were repeated and refined, and also seismic methods were applied; in 2009 the methods applied so far were complemented by DEMP measurements (conducted by KOLEJ CONSULT & servis, Frolka et al. 2009).

**Tab. 1** List of the geophysical methods applied during the non-destructive investigation of the Pravčická Brána Rock Arch.

| Geophysical method | Purpose of application at the Pravčická Brána Rock Arch |
|---|---|
| Ground penetrating radar (GPR) | Identifications (orientation and character) of the course of the main bedding planes, open joints and fissures. |
| Seismic tomography (ERT) | Description of the state of stress and geomechanical state of the rock massif. |
| Dipole electromagnetic profiling (DEMP) | To indicate changes in lithology of the rocks, distribution and changes in moisture or the level of rock failure. |

The condition of the entire PBRA body was assessed on the basis of measurements conducted on profiles running across the cross-beam and both pillars (the complete profile grid of the cross-beam is shown in colour appendix Figure II). The basic profile of the cross-beam used for all of the methods applied is situated in the longitudinal axis of the rock arch.

Georadar (ground penetrating radar/GPR) measurements using a SIR 20 radar manufactured by GSSI (USA) were conducted on the profiles at the top of the rock arch cross-beam. Conversion of the radar signal arrival time to the depth of the reflection boundary was done using the estimated value of dielectric constant $\varepsilon = 6$ (relative permittivity was determined by calculating the zones of known beam thickness). The error in the determination of depths caused by using estimated dielectric constant values should not exceed ±15% (more in Beneš 2008). The radar measurements were conducted using a 400 MHz antenna, penetration depth was approx. 10 m. The measurement was performed in both longitudinal (4 vertical profiles, P1 through P4) and transverse directions (13 vertical profiles, K4 through K19 – colour appendix Figure II) with a measurement density of approx. 40 scans per 1 m of the profile. During detailed processing of the georadar data, direct conversion of the time record to depth record was made according to the 2D velocity model, by which the error in determining depths of the individual boundaries was substantially reduced to less than 5% (more in Hubatka 2009).

Seismic measurements (tomography) were conducted using ABEM Terraloc Mk 6 (Sweden) apparatus. The seismic sensors (geophones) were placed on the profile along the cross-beam in regular spacings of 1 m. The seismic impulses were excited using a seismic hammer. The blow points were placed on the cross-beam between the geophones, on the fall line profile on the margin of the rock pillars and along the base of the pillars. The layout plan of the geophones and excitement points is shown in colour appendix Figure II.

Dipole electromagnetic profiling (DEMP) using CM-031 apparatus was conducted on 3 lateral profiles on the top of the rock arch cross-beam (spacings of 2 m between the profiles and measuring pitch of 2 m), 8 vertical profiles from the western part of the rock body (profiles D10–D17) and 6 vertical profiles from the eastern part of the rock arch (profiles D18–D23) with a measuring pitch of 1 m (colour appendix Figure II). Two measurements with a maximal and a 50% depth of penetration were performed at one point (reduction of the reach was achieved by turning the apparatus 90°). The measurements on the D1 and D2 profiles were conducted at the time of variable saturation of the rock body and were repeated under different microclimatic conditions (i.e. after a very dry summer, during 3 successive days with different rainfall intensities).

### 3.2 Monitoring of deformation behaviour

Long-term monitoring of the relative displacement of the PBRA was carried out using a combination of all of the methods applied throughout the BSNP as part of rock collapse prevention schemes (e.g. Zvelebil et al. 2005). Monitoring in the form of manual measurements (using a portable rod dilatometer) has been conducted since 1993 on 6 key sites along selected rock fractures in the PBRA body (i.e. 10 measuring points – Figure 7). An automatic remote monitoring system with online data transfer, containing 12 metering sensors with dilatation and temperature readings being carried out every 5 minutes, was also between 2006 and the middle of 2010. In addition to displacement, changes in air temperature were also measured at the study site.

The data were statistically analysed to identify not only long-term trends of irreversible movement of rock blocks but also to describe the daily and seasonal behaviour of the sandstone massif in detail which is represented by irregular reversible cycles. The time series of movements and temperatures were not only evaluated using time-tested standard qualitatively-empirical methods (e.g. Zvelebil 1995) but new procedures were used, as well. Based on the theory of complex systems these were successfully used until very recently in the field for monitoring sandstone blocks in the Děčín region (more in Zvelebil et al. 2005; Vařilová et al. 2011c).

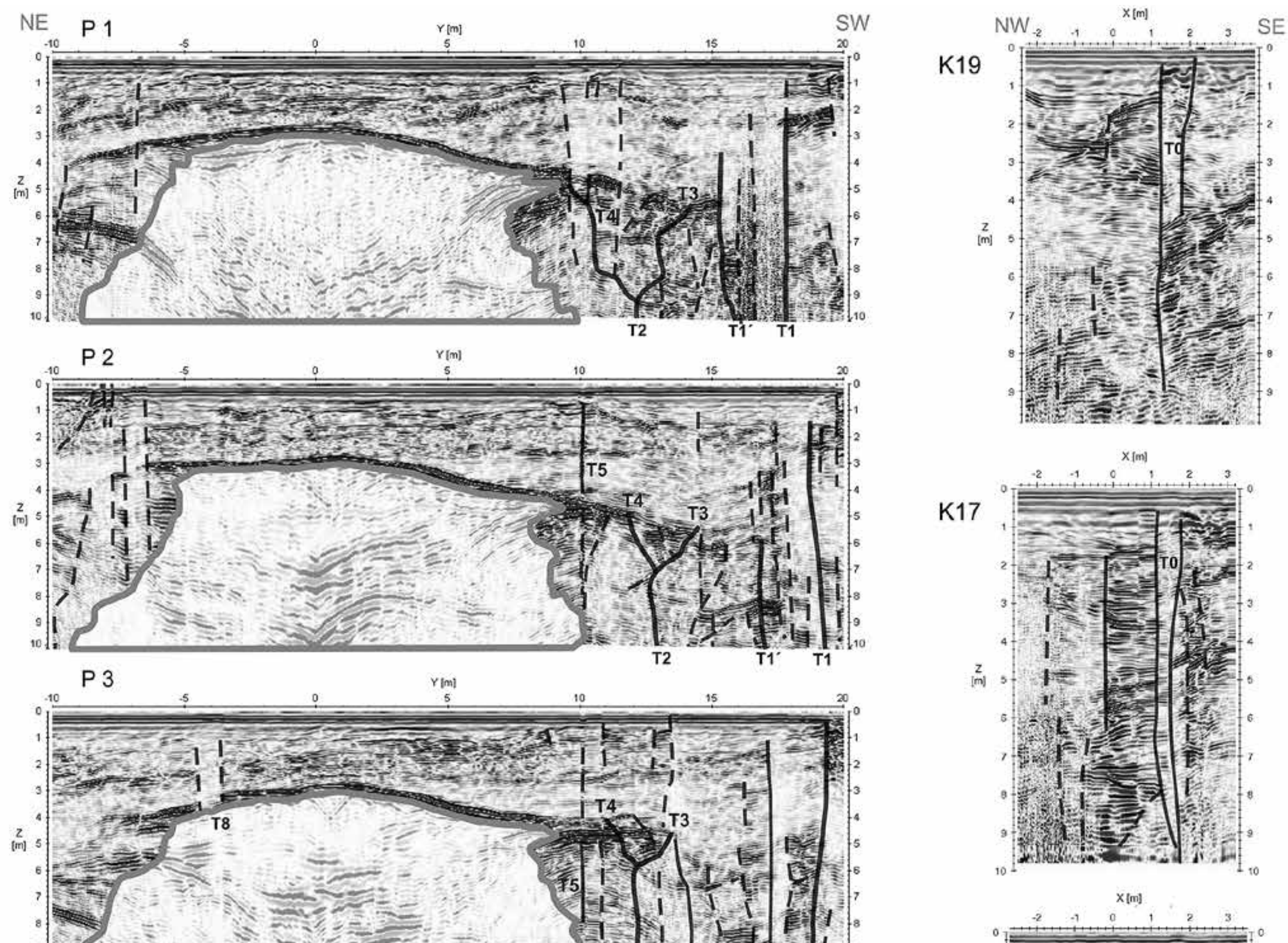


**Fig. 3** Interpretation of the tectonic lines and fissures in a) lengthwise GPR sections (P1–P4), b) diagonal GPR sections (K19, K17, K15). The course of the horizontal reflection boundary (corresponding with the lithological structure) is deformed by not respecting the relief shape (topographic correction of the real terrain is not applied). The major joints were situated in places of interruption or termination of the reflexion boundaries (marked with a solid line), secondary assumed joints are interpreted in places of frequency changes (marked with a dashed line).

## 4. The results and interpretation

### 4.1 Massif fabric and strength distribution

Distribution of joints define the inner block structure of the sandstone massif and present the basic predisposition affecting the instability of local rocks (Vařilová and Zvelebil 2007). From the horizontal georadar cross-sections it is evident that the extent of failures of the rock massif differs at different depth levels. The sandstone gets substantially homogenized with increasing depth (downwards the joints close up and the rocks are less disturbed). Detected joints in the southern pillar can be considered open. No direct interconnection of the visible joints on the eastern and western walls is noticeable. Nevertheless, it is possible to delimitate three major (T0, T2, T4) and several minor joints in the individual vertical cross-sections, which mutually correlate in the area and delimitate the individual rock blocks (Figure 4). We consider the occurrence of the joint separating the triangular block in the southern pillar to be crucial (T2 in Figure 3a, Figure 4, observed from depths of 5 m, bifurcating into joints T3 and T4). Using a georadar, zones of secondary disintegration were found within the PBRA in areas where they had not been expected, with the most intense disruption and severe loosening of the rock identified in the area of the southern pillar, at a depth corresponding to the zone of contact with the arch beam (represented by a less-resistant conglomerate layer L0 – Figure 2). From the longitudinal radar cross-sections it is evident that L0 is not continuous within the entire face as originally hypothesized (Zvelebil et al. 2002). The disintegration of horizontal layer L0 is noticeable especially in the western part of the rock arch (on profile P4 in Figure 3a); in further cross-sections (P3, P2, P1) the subhorizontal face terminates near joint T3, failing to continue further southwards.

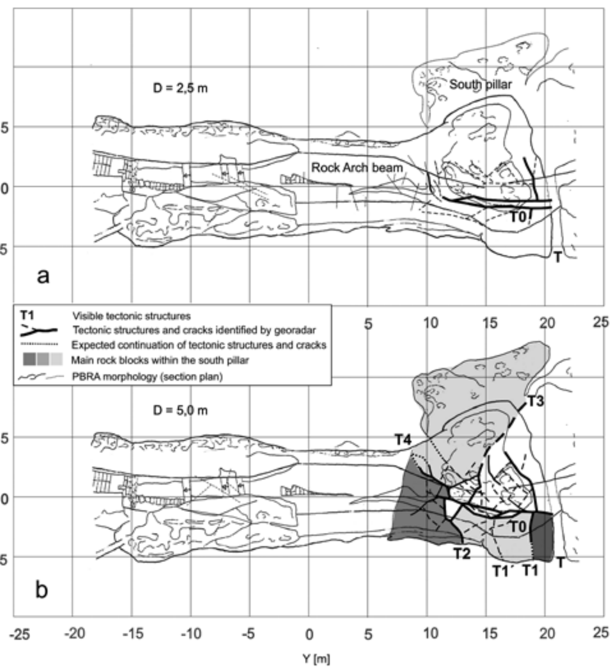


**Fig. 4** Areal correlation of the course of the joint system in horizontal (ground plan) cross-sections in two depth levels from the cross-beam surface (2.5 metres/A – 5.0 metres/B) with the introduced visualization of real joints and with an indication of the main rock blocks of the pillar at the level of the horizontally trending layer.

The discovery of sub-vertical fissures in the southern pillar as well as in the arch beam itself is of essential importance. The open lengthwise joint running throughout the beam in its southern half (marked T0 in Figure 3b, observed within the depth range from 1 to 9 m) and the entirely fresh sub-vertical fissure (6 years old at most) in the beam, that presents an additional rainfall infiltration zone, were assessed to be of the highest significance (in colour appendix Figure III the most distinctive disturbance is marked T5). Another newly identified lengthwise fissure passes through almost the whole of the rock beam (marked T7 in colour appendix Figure III) and follows the direct course of the T0 continuation (and could become continued disturbing at the axial joint). The fissure on the ceiling of the arch beam first observed in 1992 is a subsurface rupture and takes up a third of its whole thickness (marked T8 in Figure 2 and colour appendix Figure III). Due to the fact that the rock arch cross-beam zone is very thin in places, even minor fissures could play a crucial role in the future development of the PBRA.

The geophysical data demonstrate also the curved interfaces at the contact of the cross-beam with both pillars. This may indicate the preparation of the next phase of the rock arch development through gradual falling away along arch exfoliation (this development is partly indicated only in the seismic tomographic cross-section – see red zone on colour appendix Figure IV).

The seismic method also verified the zones of rock massif weakening at the places where intensive weathering processes on the rock surface were already earlier visually documented (Zvelebil et al. 2002; Vařilová et al. 2011b), with the most marked ones being on the northern side of the southern pillar and also in the topmost layer of the northern pillar. Seismic measurements demonstrated areas of significant weakening in the interior of the rock mass along the arch vault (seismic velocities decreased to a value of 500 m/s, representing sand and clay based on the standards). The triangular part of the southern pillar presents not only a separate block bounded by continuous fissures but also the place of the deepest material weakening. The body of the arch also generally exhibits a relatively low seismic velocity that does not exceed 2500 m/s, which points to the sandstone being affected by weathering, as is further suggested by very low strength values (according to the classification of Deere and Miller 1966) found by sporadic laboratory testing: average uniaxial compression strength reached only 0.9 MPa in a samples of intensive weathered sandstone, 2.78 MPa in a sample of typical sandstone and 6.6 MPa for relatively fresh rock. Moreover, a comparison of the georadar measurement results from 2002 and 2008 shows that physical alterations have occurred in the cross-beam body indicating the advanced weathering of the subsurface part of the PBRA. The most significant alterations can be observed at the bottom part of the arch and along the contact zone of arch beam with the southern pillar (colour appendix Figure III).

Inside the arch body there is a redistribution of stress due to progressive disintegration and weakening of individual portions of the rock massif through weathering, which is an important finding from the perspective of stability compared with the processes of near-surface weathering that take place mostly in the form of flaking, spalling and granular disintegration.

The distribution of moisture identified using DEMP is a result of intensive infiltration and local drainage of the entire rock body. The measured specific conductivity values range between 7 and 9.8 mS/m. The data show that specific conductivity values increase towards the centre of the rock massif, the highest saturation was identified directly at the base of the southern pillar (above the less permeable layer of fine-grained sandstone). The repeated measurements on the D1 and D2 profiles (colour appendix Figure II) document a high water absorption capacity shown by porous sandstones and also indicate very rapidly changing rock saturation with percolating solutions (i.e. rapid evaporation and drying of the rock due to extreme exposure of the rock arch – more in Vařilová et al. 2011 a, b). At the time of intensive rainfall, the conductivity in the cross-beam increases to reach almost triple the value (i.e. 23 mS/m) compared to 8 mS/m measured on the same profiles the next day. Precipitation solutes firstly infiltrates into the top rock layer and then preferentially "trickles down" the slightly inclined rock arch cross-beam in a southward direction. Here the sandstone percolates sub-vertically infiltrates along several secondary inhomogeneities into the interior of the rock massif. Distribution of moisture within the PBRA is generally influenced by the existence of sub-vertical fissures and micro fissures that serve as preferential pathways of gravitational infiltration of rainfall and melting water under a gradual weakening of the surroundings (Young et al. 2009; Vařilová et al. 2011a).

### 4.2 Structural – deformation model

The identified block structure of the rock body allows long-term trends of the relative movement of the PBRA to be better explained, as demonstrated by the monitoring conducted between 1993 and 2010 (Zvelebil et al. 2002). The results of long-term monitoring have shown that both quasi-cyclic (reversible) movements and slow irreversible deformations were observed (Table 2 and Figure 5).

Reversible movements of the PBRA include a hierarchical system of partial quasi-cycles: 20, 15, and 10–11-year cycles; standard annual cycle; daily, and quarter-daily (8 hourly) and 2.5 daily (60 hourly) cycles. Most cycles can be causally linked to volume reactions of sandstone massif, depending on fluctuations in air temperature (or even tidal variations of gravity), or cycles of solar activity (sunspot cycles). The total irreversible deformation identified by long-term monitoring pertains (in comparison with other hazardous BSNP localities) to minor movements which do not poise a direct danger

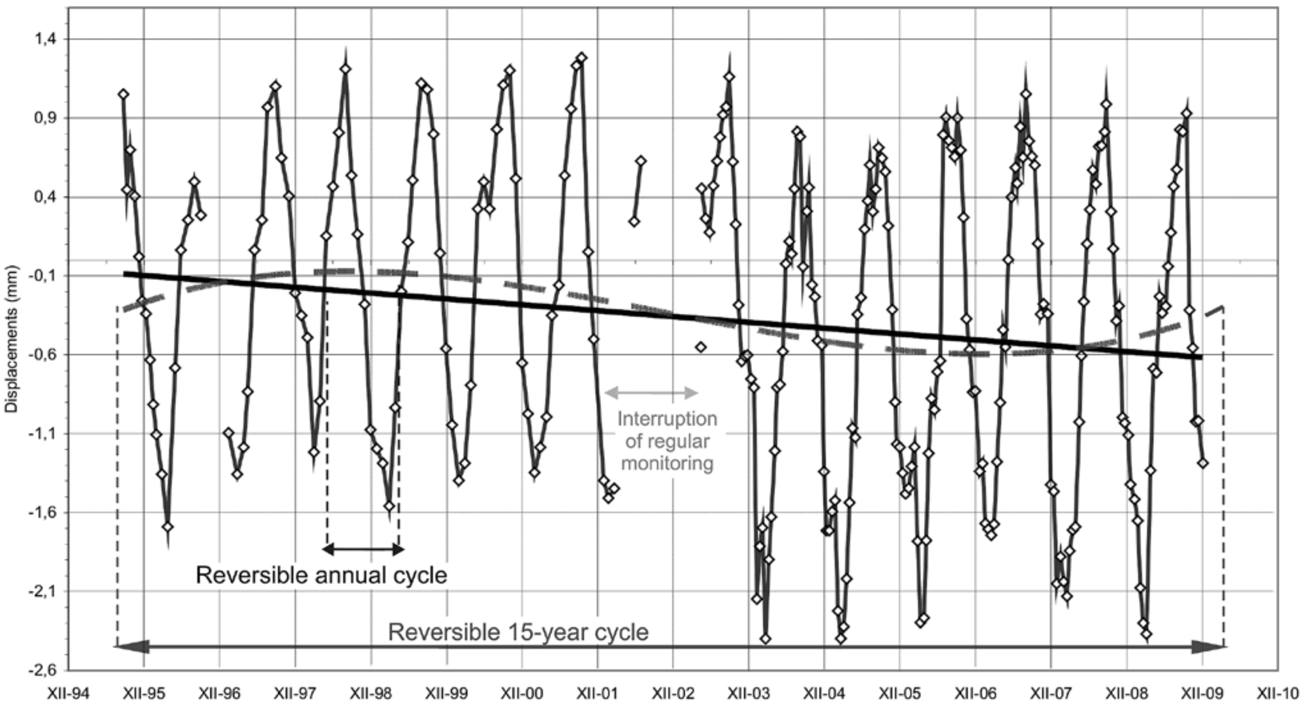


**Fig. 5** Graph of relative movements – data from manual measurements: Displacements at site PB 5 (average amplitude for whole monitored period amounts to 2.81 mm), with the annual and 15 year interspersed reversible cycle. Long-term irreversible trend of deformation is represented by the very slow closing of the measured crack (the black linear connecting line of trend more than 0.5 mm/15 years).

to the PBRA body (Table 2). Nevertheless, the data provide very important information about the kinematics of reversible and irreversible movements (the dependence of these on the exposure and microclimatic conditions was also assessed).

More processes should be added to the initial model of the quasi-cyclic loading of the arch top beam i.e. bending up with parallel longitudinal arching due to the action of changes in volume of rock in a north-south direction (Zvelebil et al. 2002). The eastern and the western parts of the PBRA body behave differently both in terms of reversible and irreversible deformation. The effects of external temperature changes (specifically the influence of insolation) produce not only flexural stress but

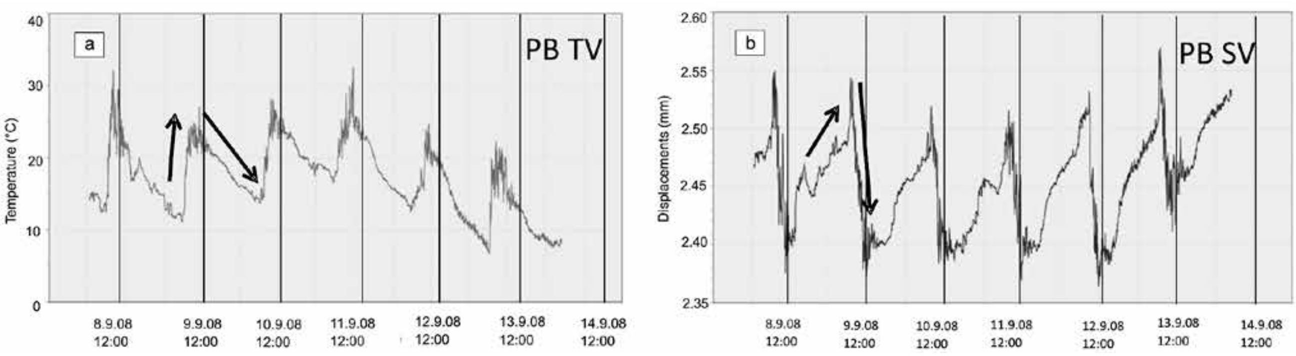


**Fig. 6 a)** Daily changes of temperature (a) and daily quasi-cycles of deformation (b) of the rock arch beam (example of an automatic monitoring data, from the sunny period 2008, site PB V on the east).

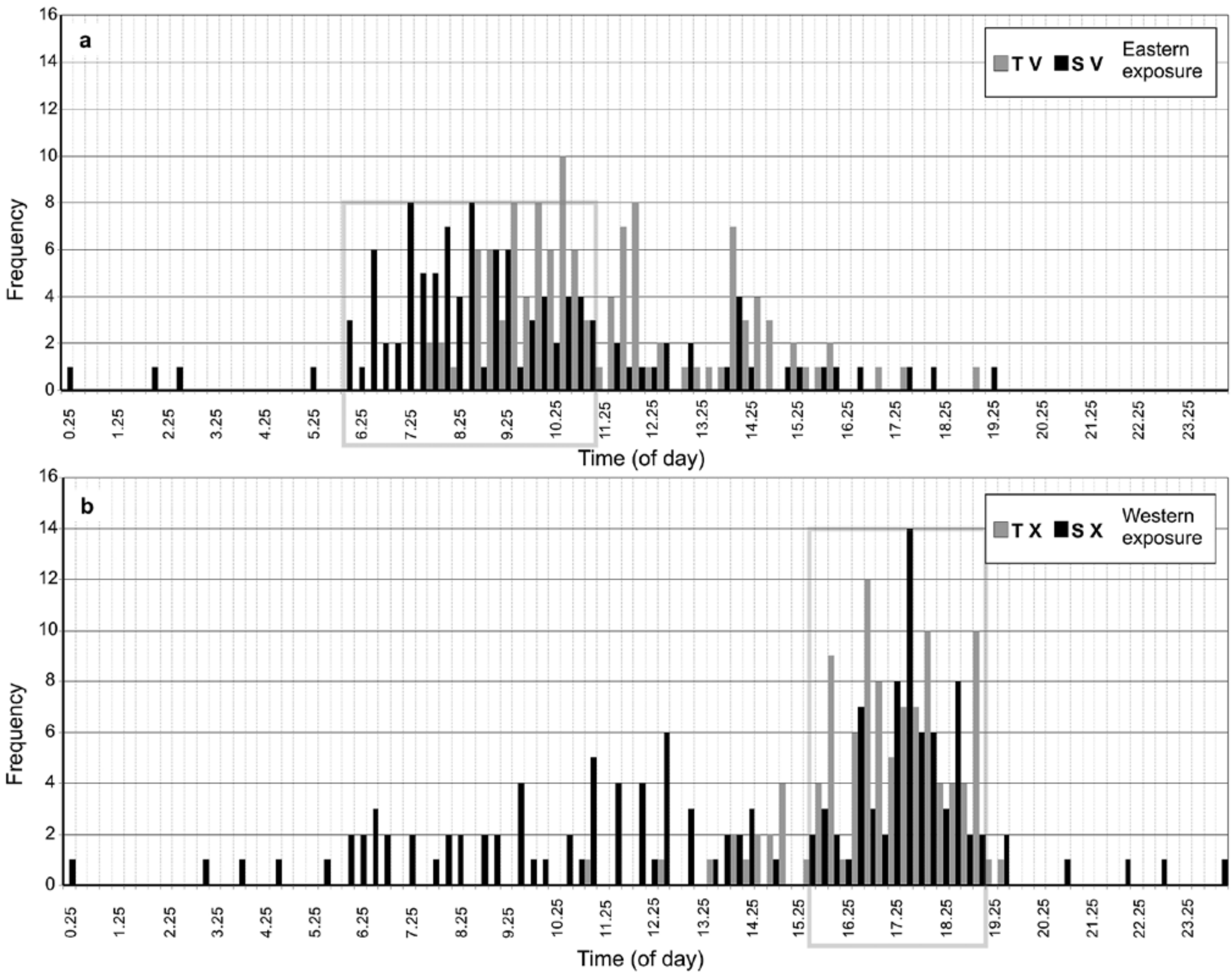


**Fig. 6 b)** Histogram showing the time-distribution of maximum temperature changes (T) and maximum displacement (S) during the daily quasi-cycles at site PB V and PB X (both oblique oriented measurement points). There is a difference between reaching the maximum of displacements on the east and on the west side of the arch beam depending on insolation effect (the maximum was reached between 6.00–11.00 a.m. on the east as distinct from 15.30–19.00 p.m. on the west). Transmission of partial deformation across the rock massive (from east to west and the other way around) was identified also with using automatic monitoring data.

partly also uneven sideways strain and torsion stress on the beam (the behaviour of the arch is displayed on Figure 7, example of daily quasi-cycles is on Figure 6a,b). When repeated many times daily, along with seasonal stress-strain pulses (due to temperature fluctuations), it leads to the gradual reduction of strength in the stressed parts of the sandstone rock mass, as well as to the accumulation of micro-deformations.

Higher seasonal amplitude of the movement was also detected on the western side of the beam compared to the eastern side (Table 2), which corresponds to the interpretation of the georadar data, showing only partial passability of the contact zone, i.e. not involving the entire area, as envisaged under the original interpretation by Zvelebil et al. 2002. The spatial asymmetry, as reflected in macro scales of long-term monitoring has also shown an irreversible long-term collapse of the western side of the arch beam, while a slow sub-horizontal displacement towards the south prevails on the eastern side (site PB 3′, PB 4′ in Table 2 and on Figure 7). To the west, the arch beam has completely separated from the southern pillar, with any unevenness being crushed and broken off the surface due to movement along the contact area. In addition, there is associated intense weathering of the near-surface parts of the massif. As the separation is not yet complete to the east, movement in the zone above L0 is of a mixed, elastic-plastic nature. Therefore there is an obvious and very slow cutting and gradual formation of continuous horizontal bedding of joint L0 throughout the area. This fact increases the importance of the sub-vertical joint T0, which is very probably a secondary crack produced additionally as a linear element, along which there is likely an offset of the stress between the two sides of the beam, each of which acting in a different manner. In terms of the future development of the arch, the direction of this axial joint is of particular importance, as well as its progress in response to changes in stress within the massif.

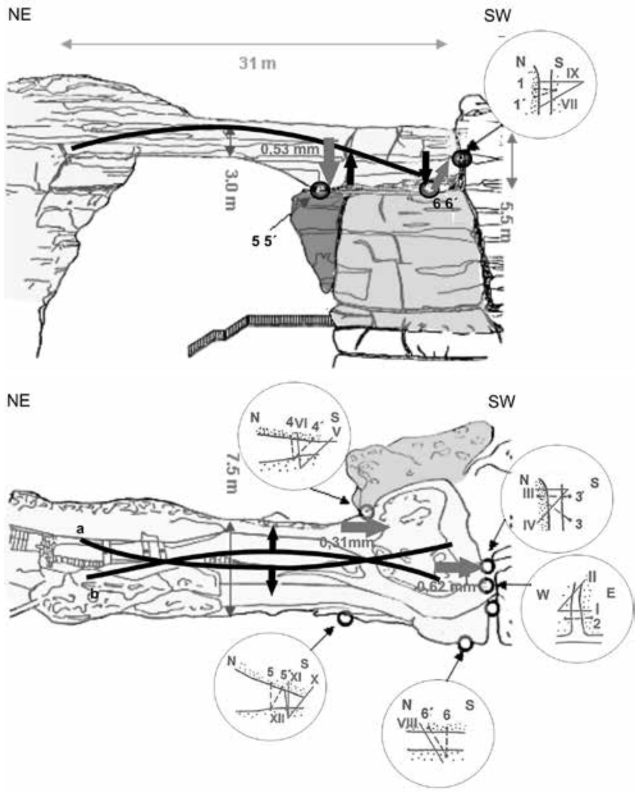


**Fig. 7** Model of kinematics of reversible and irreversible movements of the PBRA: View from the west (above) and a top view of the arch beam (below) with highlighted dimensions of the rock body and locations of each measurement point during automatic (Roman numerals) and manual (Arabic numerals) monitoring. The arrow indicates the direction of observed deformation: irreversible movements are marked with grey colour while reversible thermal dilatations and ways of quasi-cyclic stress of the body are marked with black colour (lines marked a, b represent the torsion during daily quasi-cycles according to insolation).

Irreversible restriction of the passable joint T and especially the decline of the arch at the point of the cliff leads to a very slow flattening, which may cause a reduction in the future efficacy of the vault effect and a higher

**Tab. 2** Irreversible deformation and average season amplitude of PBRA monitored sites (calculated by nonlinear visual analysis of data from dilatometric measurement). The categorization of displacement (as per Zvelebil 1995) includes the ambiguity of the relative trend of movement influenced by several years of reversible cycles.

| Monitoring site | Direction of measurement | Period of measurement (years) | Total deformation (mm) | Categorization of displacement | Average season amplitude of reversible movements / 15 years (mm) | Interspersed reversible mega-cycles (years) |
|---|---|---|---|---|---|---|
| PB 1 | horizontal | 16.5 | −0.08 | standstill | 1.33 | – |
| PB 1′ | oblique | 16.5 | **−0.20** | minor | 0.87 | modest 10 (11) years |
| PB 2 | horizontal | 16.5 | −0.15 | standstill | 0.97 | modest 11 years |
| PB 3 | oblique | 16.5 | −0.20 | standstill – minor | 2.35 | modest 20 years |
| PB 3′ | horizontal | 16.5 | **−0.62** | minor | 2.15 | 15 years |
| PB 4 | vertical | 16.5 | −0.02 | standstill | 1.81 | modest 20 years |
| PB 4′ | oblique | 16.5 | **−0.31** | minor | 1.61 | modest 20 years |
| PB 5 | vertical | 14.5 | **−0.53** | minor | **2.81** | 15 years |
| PB 5′ | oblique | 14.5 | +0.03 | standstill | 1.97 | modest 15 years |
| PB 6 | vertical – oblique | 14.5 | +0.17 | standstill – minor | 0.95 | modest 15 years |

tensile-bending load. Moreover, the daily and seasonal strain-stress pulses (causes by temperature fluctuations) lead to a gradual reduction of strength in strained parts of the rock massif (e.g. Glamheden and Lindblom 2002; Vlčko et al. 2009a, 2009b; Brček et al. 2010) and cumulative folding of micro deformations.

## 5. Discussion

Detailed investigation and long-term monitoring of selected processes were carried out using a set of non-destructive, in-situ methods. A combination of them provides basic information about the PBRA body such as its behaviour, characteristics of the rock massif, intensity and distribution of weathering. The results of the investigation confirmed the appropriateness of selected methods in this non-standard locality (within the study of macro-measures as per Turkington and Paradise 2005). The partially limiting factor of the geophysical methods used is particularly the non-standard morphological structure of the rock body (alternatively surface unevenness at the place of profiling). The highest informative value are the data acquired repeatedly by the georadar, complemented by the results of the methods of seismic tomography. Further monitoring needs to adhere to the defined unchanging conditions, technical parameters and the position of all measured profiles. In the summarized assessment of the acquired data it is also necessary to take into account the season and the period of the conducted measurements due to the fact that the level of applicability of the geophysical methods may be affected by extreme climatic effects (especially rainfall levels).

The local hydrodynamic regime (rapid changes in rock massif saturation with percolate solutions, infiltration and accumulation areas), which is of crucial importance to the correct assessment of the intensity and distribution of salt efflorescence and the associated processes of the chemical weathering of the rock body (Zvelebil et al. 2002; Vařilová et al. 2011a, 2011b), was identified by using the non-standard method of DEMP. Commonly used methods to identify moisture distribution, like resistivity tomography profiling (ERT) (e.g. Matsukura and Takahashi 1999; Beauvais et al. 2004; Sass 2005; Sass and Viles 2006; or Mol and Viles, 2010), unfortunately did not produce exploitable results due to several complications (primarily the impossibility to fix the electrodes using the standard technique, i.e. drilling boreholes, together with the less permeable surface of the rock crust). In order to refine the interpretation of the results of the DEMP method, it would be profitable to perform complementary measurements at the time of the minimal saturation of the rock massif with solutions and, on the contrary, at the time of the maximal saturation with water, in order to acquire limit values for the studied locality.

Data from the automatic monitoring system describe the detailed behaviour of the arch body and help to understand quasi-cyclic reactions of the rock massif However, operation of the system is very expensive and it occasionally malfunction able, in addition it produces a very large volume of data sets which requires their exact processing. This is why it is recommended to continue particularly with the dilatometric monitoring without interruption in order to obtain a database with a time-invariable quantitative shape. Long-lasting quasi-cycles of movement is necessary to take into account when evaluating the data, because their influence can distort long-term reversible trend of deformation, particularly in the case of shorter measurement time (examples are just points PB 2 and PB 3 – compare with Zvelebil et al. 2002). The distinctive response of the rock mass to temperature changes (during season and daily quasi-cycles) have been confirmed at the PBRA body. In this case is not possible to use standard monitoring data evaluation and warning thresholds applied throughout the BSNP. The existing collection of monitoring sites needs to be complemented with additional locations in light of the rock block displacements. The possible decline of the triangular block in the southern pillar together with the shear displacement on the axial joint T0 are important for the development of the arch and potential risk to it. In future it will also be necessary to continue to focus on the general geometry and structure in the inner parts of the arch beam (especially the extension of existing fissures/cracks and progradation of weathering zones), with special attention to the character of the contact zone between the beam and the southern pillar, together with the distribution of strength within the rock massif.

The acquired information on the structure of the PBRA will allow in the future to perform long-term monitoring of the condition of the rock arch and will significantly help to prepare more accurate interpretation of the long-term monitoring of the rock body movements, then produce an updated geomechanical model and prepare a prediction of the future development of the rock arch body. The actual degree of instability of the arch or rather the necessity of potential technical measures, will be determined from planned parametric sensitivity studies (Young et al. 2009), in which the input strength properties will be defined by tensile and compressive stress (Hoek and Brown 1980) with the model of distribution of the axial load (Heyman 1982) determining the overall tension along the opening gate. Nevertheless in the case of the PBRA, other factors such as existing fissures and cracks, weathering along weakened zones, and anticipated shear zones are also crucial for its continued stability. More detailed analysis (considering the combination of several forms of sandstone massif disruption, the non-standard morphology and complicated inner fabric, hydrodynamic conditions and variable strength parameters) will require advanced numerical methods (Stead et al. 2001); the different variation of PBRA stability collapse can be simulated for example by numerical analysis (finite and distinct element methods – e.g. Ohnishi et al. 1993).

## 6. Conclusion

The completed comprehensive research applied basic geophysical exploration together with long-term monitoring of movements in the rock massif. The research results have refined knowledge of the inner structure of the arch body, the kinematics of reversible and irreversible movements (their dependence on exposure and microclimatic conditions was also assessed) and knowledge of the distribution and growth of parts affected by weathering processes. The investigation was designed to fully respect the protective conditions of the given locality and to allow in the future repeated measurements and thus monitor over time any other potential negative alterations in the rock arch massif.

The results of this study helped to understand the complexity of the system of deterioration of the sandstone massif and to better understand the natural dynamics of the specific rock formation. The results also provide valuable information about the actual status of the PBRA. New stability risks were discovered associated with intense tectonic and secondary brittle impairment of the rock massif and involvement of episodic aquifers. By using geophysical methods, it was possible to define the local hydrodynamic regime of the rock arch body and identify sub-vertical sub-zones of infiltration (passing through the bedding). This demonstrated selective weathering in the PBRA body that so far had not been considered, one that not only causes damage to the near-surface parts but also weakens the strength of the internal parts of the massif, significantly influencing the overall stability of the object.

The collected information was used to create a structural deformation model of the arch body, including a description of the patterns of disintegration found. The model is to become an essential basis for subsequent geomechanical modelling of the arch stability and development. The gained knowledge will thus become not only an essential basis for management planning and designing the most suitable stability and security measures in the study area, but it can also be applied to similar small-scale protected areas and used for drafting master plans of field protection of the sandstone relief within the studied region, and hence also in the greater area of the rock formations throughout the BCB.

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## RÉSUMÉ

**Využití nedestruktivních metod k posouzení stability Národní přírodní památky Pravčická brána**

Práce obsahuje výsledky nedestruktivního průzkumu Pravčické brány, který byl zaměřen na poznání vnitřní stavby tohoto skalního útvaru, jeho přirozené dynamiky a zejména pak posouzení současné úrovně stability. Ke studiu bylo použito kombinace geofyzikálních metod (opakovaného měření georadarem, seismiky, odporové tomografie a dipólového elektromagnetické profilování/DEMP) spolu s dlouhodobým kontrolním sledováním deformačního chování brány. Realizovaný průzkum byl koncipován tak, aby plně respektoval ochranné podmínky dané lokality, bylo na něj možné v budoucnu navázat a sledovat případné negativní změny v horninovém masivu. K hlavním výsledkům náleží popis blokové stavby tělesa a charakteru kontaktní zóny mezi trámcem brány a jižním pilířem, objevení relativně čerstvých sekundárních trhlin a identifikace pevnostně oslabených zón uvnitř pískovcového masivu. Popsán byl rovněž režim jeho přirozeného odvodňování. Dlouhodobým sledováním byly prokázány pomalé nevratné pohyby skalní brány a vratné kvazi-cyklické pohyby související s teplotními změnami v měřítkách dnů až let. Bylo zjištěno rozdílné chování východní a západní strany trámce a potvrzeno jeho obloukovité ohýbání, obohacené navíc o nerovnoměrné namáhání torzí a smykem. Ze získaných informací byl vytvořen strukturně-deformační model Pravčické brány (včetně popisu charakteru porušování). Výsledky poskytují cenné informace o současném stavu významného skalního objektu, napomohly k rozpoznání potenciálně rizikových partií a budou využity nejenom pro účely modelace budoucího vývoje, ale také pro případný návrh nejvhodnějších sanačních opatření.

# LOCAL PLACE NAMES AS A PART OF LANDSCAPE MEMORY (CASE STUDY FROM HANÁ REGION, CZECH REPUBLIC)

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**ABSTRACT**

Local place names in the landscape represent an important part of the spiritual component of the landscape memory and form an essential part of the intangible traditional folk culture on the local scale. This paper presents the research results regarding the level of knowledge of the landscape place names in the Haná region (Czech Republic) in children belonging to the age group of primary school pupils. It was revealed by the method of questionnaire survey that the majority of pupils in rural schools in Haná do not currently know the specific local names in the landscape. In the investigated sample of respondents, we found a statistically significant correlation between the knowledge of local names and active use of the Haná dialect. At present, a large share in maintaining the knowledge of landscape local names can be attributed to local and regional social activities aimed at conservation of the traditions of folk culture and at maintaining the relationship of the young generation to the landscape.

**Keywords:** ethnographic region of Haná, landscape memory, place names in the landscape, primary school pupils, questionnaire survey, regional identity

## 1. Introduction

Region Haná (Figure 1) is one of the major ethnographic areas in the Czech Republic (Frolec 1992; Jeřábek 2000). Traditional folk culture in this region is unusually rich (Bečák et al. 1941). The creators and bearers of this folk culture were obviously the Haná farmers observing the order and traditions of peasant life (Petráň, Petráňová 2006). According to letters of Filip Friebeck, a chaplain at St. Maurice Cathedral in Olomouc, dating back to 1778, Haná peasants were serious men, comfortable and pious, who loved their region and never wanted to leave (Zíbrt 1908). Peasantry in Haná disappeared in the fifties of the 20th century during the socialist collectivization of agriculture (Přidal 2009). Earlier widespread deep piety of the Haná people (Klvaňa 1907) is still preserved in the Haná landscape in the form of a large number of historical landscape structures (Machar 2008).These landscape structures are part of the so-called landscape memory (Löw, Míchal 2003). Landscape memory can serve as a suitable concept for determining and quantifying "ordinary" cultural landscape values (Skaloš et al. 2011).

In the wider concept, landscape memory is part of the cultural and historical heritage that includes landscape elements ("landscape heritage") as well as elements of material and spiritual (immaterial) traditional folk culture. Caring for the cultural and historical heritage in the landscape is closely related to sustainable development (Nováček 2010).

Areas of material and spiritual cultural and historical heritage in the landscape cannot be strictly kept apart since both partly overlap each other. Examples are place names in the landscape (Lapka, Gottlieb 2000) that relate to the specific landscape elements (they are an important part of the spiritual component of the landscape memory) and simultaneously (on the local scale) form an essential part of the local spiritual folk culture. Place names also have a significant role in maintaining awareness of the local people about their home countryside in the frame of regional identity (Dejmal 2000).

The aim of the research, the results of which are presented in this paper, was to determine the current level of knowledge of the landscape memory regarding the local names in Haná landscape in children belonging to the age group of primary school pupils.

## 2. Material and methods

### 2.1 Method of data collection and analysis

The research was conducted in April 2012 using standard methods of education research according to Chráska (2007) in two primary schools: Náměšť na Hané and Horka nad Moravou. Both primary schools are located in the ethnographic region of Haná (Kabelík 1907) in the Olomouc Region (Figure 1). The investigated sample of respondents consisted of pupils from the second level of primary school (6th–9th grade) with a total number of 220 respondents. The municipality of Náměšť na Hané has 1993 inhabitants, whereas 107 of them participated in the study as respondents attending the local primary school. The primary school in Náměšť na Hané is attended by pupils from Náměšť and the villages of Drahanovice, Lhota pod Kosířem, Kníničky, Střížov, Luděřov and Olbramice. Horka nad Moravou has 2300 inhabitants, and 113 pupils from its primary school participated in

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the study as respondents. This school is attended by children from Horka nad Moravou and the village of Skrbeň.

Within the pre-research stage and in order to maximize the objectivity of the research, we conducted a check estimate of the minimum number of pupils that would represent a sufficiently representative selection range of respondents surveyed. This estimate was made by the method for investigating nominal data according to Nowak (1965) using the formula

$$n = \frac{t_\alpha^2 \, p(1-p)}{d^2}, \qquad (1)$$

where n is the required sample size, tα is the reliability coefficient for the chosen confidence level α, p is the estimate of relative frequency of the investigated characteristic in the basic set, and d is the desired relative accuracy in the range of 3–4% (i.e. 0.03–0.04). When the value of p = 0.1 (i.e. 10% based on the estimate of preliminary research), the calculation according to the formula leads to the value of 216. To perform the questionnaire survey at 95% confidence level with usual accuracy of 4%, it is necessary to use a basic set containing at least 216 respondents. For the actual research, we used a total of 220 respondents from both primary schools (see above), which meets the requirement for the minimum number of respondents regarding the statistical verifiability of nominal data.

The research was based on questionnaire method with closed questions (Papica 1974). The main advantage of using questionnaires with closed questions is an easy subsequent statistical evaluation of the data because the answers of respondents do not steer away from the scheme of questions prepared. The closeness of questions in the questionnaire was given by a choice of two possible answers ("only one answer is correct" system) in the second and third parts of the questionnaire. The questionnaire was divided into three parts:

Basic information about the respondent (residence, age, name of the attended primary school, year-class of primary school, respondent's gender, education of the respondent's mother and father in the following categories: primary education, secondary education, university education).

Set of ten closed questions focused on the knowledge of Haná dialect in respondents and their parents.

Set of ten closed questions focused on general knowledge of the landscape of Haná, with an emphasis on local geographic names.

The formulation of questions in the questionnaire respected the age level of respondents according to recommendations (Anderson, Arsenault 1998). The final questionnaire score was designed so that the evaluator might draw unambiguous conclusions about the investigated phenomenon (Woods, 1986), in this case about the answer to the question of whether respondents knew the local names in the landscape around their home. Respondents filled out the questionnaire directly at school as part of their classwork with a technical assistance of class teachers and students of the College of Education who applied their observation practice. The teacher's technical assistance greatly facilitated the work of respondents in filling out the questionnaires and proved to be a prerequisite for a hundred percent return of the completed questionnaires.

A detailed evaluation of the results of respondents' answers to the second part of the questionnaire is the subject of a special study which is ready for publication outside of this paper. The third part of the questionnaire was immediately followed by the respondents' work with maps.

To determine the degree of reliability of the questionnaire survey results, we compared the results obtained in two selected sample groups with the same size that originated as a representative selection from the basic set (Chráska 1996). The concordance rate between the answers of respondents in both randomly generated selected sample groups was expressed using Cohen's coefficient (Mareš 1983)

$$\kappa = \frac{p_p - p_0}{1 - p_0}, \qquad (2)$$

where κ is the Cohen's coefficient, pp is the determined concordance rate and po is the expected concordance rate. The test of statistical significance of the resulting coefficient κ was calculated by a standardized normal variable as the criterion according to the formula

$$u = \frac{\kappa}{\sqrt{\dfrac{p_0}{n(1-p_p)}}}, \qquad (3)$$

where u is a value of the standard normal variable and other symbols have the same meaning as in formula (2).

The investigated value "active knowledge of local place names in the landscape in Haná dialect" was defined as the ability of the respondents to independently create a list of at least five specific locations in the landscape within the cadastre of municipalities that are their permanent residences and then correctly identify these locations on a map 1 : 5000. The accuracy of the respondents' answers was verified by the author of this paper and the cooperating teachers of both schools based on local knowledge of all the municipal cadastres addressed.

When comparing the respondents' results of both schools, the data was statistically evaluated by a two-selection t-test for two samples using Minitab version 15.1.1; the set normality was assessed visually in the data distribution diagram (Zvára 2006).

The results of the analysis of research data obtained in the first-degree sorting were used to prepare transparent graphic data representations.

When interpreting the data received from the second-degree sorting, the collected nominal data obtained through questionnaires and used for the pivot table was tested with regard to chi-squared dependence (Peers 1996). Specifically, we tested the relationship between the knowledge of local names in the landscape and the selected phenomena that could affect such knowledge in children: (1) sex of the respondents, (2) education of respondents' parents, and (3) the use of the Haná dialect in children.

Null hypothesis significance testing was carried out at significance level of α = 0.05. Chi-squared criterion was calculated by the formula

$$\chi^2 = \frac{(P - O)^2}{O}, \quad (4)$$

where P is the respective pivot table field and O is the value of expected frequencies. The calculated chi-squared value is an indicator of the extent of the difference between reality and the pronounced null hypothesis. For its assessment, it is necessary to determine the number of degrees of freedom of the table according to the relationship

$$f = (r - 1)(s - 1), \quad (5)$$

where r is the number of rows in the table and s is the number of columns. With regard to the calculated number of degrees of freedom, we compared the test criteria value calculated in statistical tables with its critical value.

### 2.2 Study area – Haná region in the context of ethnographic regions of Central Europe

From early medieval times, the ethnographic region of Haná formed a historical and cultural centre of the Moravian Margraviate. The medieval town of Olomouc – as a natural geographic and administrative centre of the Haná region – was built around the castle of the first Moravian princes of the Premysl dynasty. The name of this ethnographic region is associated with hydronym "Haná" (local river name). For the first time, the region of Haná was depicted in 1627 on the map of Moravia by J. A. Comenius (Semotanová 2001). In prevailing opinion of ethnographers, Hanaci (Hanáci – people living in this region) represented a dominant and most stable component of Moravian inhabitants (Jeřábek 1991). Influenced by relative prosperity due to very fertile agricultural land, Hanaci were never significantly involved in any anti-feudal movement and tenaciously consolidated their language and cultural traditions for a long time (Jančář 2000). Their historical self-confidence was supported by the myth of King Ječmínek whereas a folk model of this good and righteous monarch was probably the Emperor Joseph II (Pisch 1900). Hanaci, as a formed ethnographic group of people, gained awareness of their regional identity in the 19th century at the latest. Haná dialect, costume, dance, music and rituals (e.g. Haná wedding) became widely known at that time and enjoyed a great popularity among intellectuals and artists of the entire Austro-Hungarian Empire (e.g., see paintings by Josef Mánes, etc.). Haná operas with stories of Haná rural life were performed at significant theatrical stages and nobility dressed in Haná costumes had fun during the carnival performances of Haná wedding (Fojtík 1965). A strong regional identity in Haná developed into excessive local patriotism which, along with other personality traits of Haná farmers (indolence, discreetness, …), became the subject of ridicule in other regions where the regional identity was not considered so important (Frolec 1992). Hanaci were farmers strictly observing the order of peasant life based on the seasons and reflected in the course of church holidays during the liturgical year. In this way, the farmers of Haná did not distinguish from peasants throughout Europe (Bláha 1925). In addition to the typical dialect, the main characteristic features of the Haná region include folk costumes. According to specific differences in the male costume, especially in the colour of men's trousers, Hanaci are divided into yellow and red (Paroubek 1905).

The ethnographic region of Haná covers approximately 2634 km$^2$, which represents 11.8% of the total area of the historical land of Morava and 3.3% of the total area of the Czech Republic. Haná extends into six geo-morphological units (Demek et al. 2006): Hornomoravský úval (Upper Morava Vale), Mohelnická brázda (Mohelnice Furrow), Vyškovská brána (Vyškov Gate), eastern parts of the Zábřeh Highlands and Drahany Highlands and the southern edge of the Hanušovice Highlands. The mean elevation of the region is 329.6 m and the highest peak is Velký kosíř (442 m a.s.l.). Haná relief consists predominantly of flat land on Quaternary floodplain sediments of the Morava River and its tributaries (Bečva, Blata, Bystřice, Haná, Oskava). The edges of the region are bordered by low uplands with massive depositions1 of loess loams. The Haná region has a warm temperature climate with sufficient precipitation and spans altitudinal vegetation zones 2 and 3. The entire region is dominated by vast areas of arable land, with narrow strips of floodplain forest lining its rivers.

Urban structure of Haná villages is represented by the type of broad street-like square and, rarely, round-shaped square (Čehovská 1995). Villages were usually built as compact units enclosed along the entire perimeter by a surrounding wall made of clay bricks (adobes). Their street build-up area merged into field paths which were extremely long (hundreds of meters, sometimes up to a kilometre) and also very narrow. Farmhouses had imposing facades often supplemented with porches and faced the square. The porches had an economic function (granary on the floor) as well as important social function (ground floor space to meet and chat with neighbours). Herben (1925) writes: "Haná farmhouses are as special as Haná words. Words are serious, open, staid and considerate. And farms in Haná are ponderable, heavy

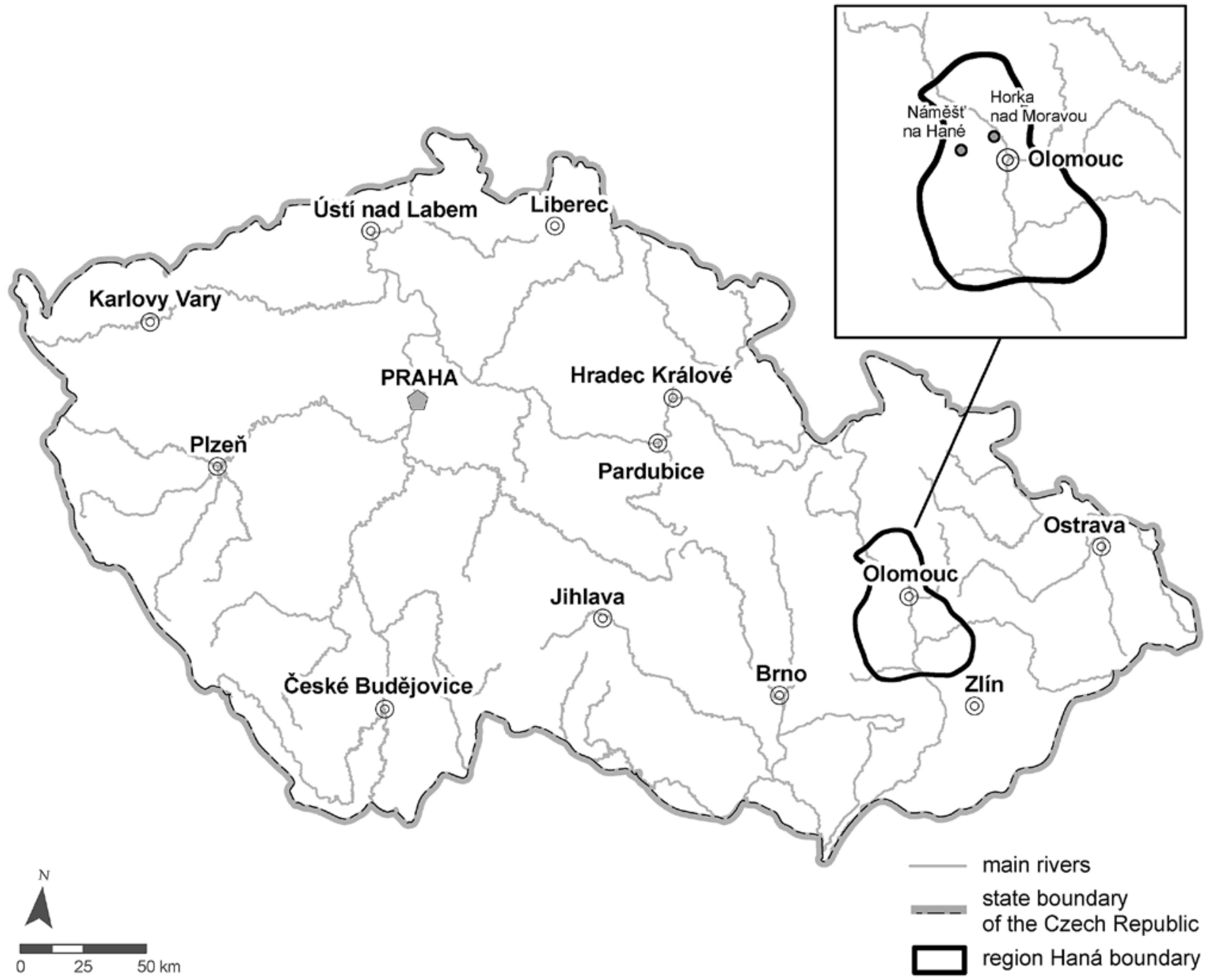


**Fig. 1** Study area: Region Haná in the Czech Republic and location of investigated primary schools.

and thorough as well". Horseshoe-shaped ground plan of the farm living area was closed with cowsheds and stables. Large barns were usually situated at a distance as freestanding buildings due to protection against fire. The farm economic part merged through an ornamental and vegetable garden with an orchard of fruit trees into the fields, i.e. the surrounding landscape. The landscape around villages contained a large number of various small religious buildings (chapels, devotional pillars, crosses, statues of saints).

Folk culture of the Haná region became the subject of interest of collectors and ethnographic specialists already in the 19th century – e.g. folkloric collectors such as Vlasta Havelková, Františka Xavera Běhálková, Ignát Wurm and many others (Václavík 1947).

## 3. Results

As for the concordance between the randomly selected respondents, the calculated value of Cohen's coefficient for the survey results obtained (κ = 0.802) can be considered as satisfactory; this is, therefore, suitable in terms of reliability of the applied research methods. At significance level of 0.01, the value of the standardized normal variable (6.18) is higher than the critical value (2.58) for the two-sided test and we can thus say that the calculated coefficient indicates a statistically significant concordance between the answers of respondents in the questionnaire survey.

The relationship between age categories of the respondents and their knowledge of the local names is evident from the histogram (diagram) describing the frequency of the examined character "active knowledge of place names in the landscape" (Figure 2).

This frequency histogram does not show any development trend. However, the graphical data representation clearly indicates that the current state of knowledge of local names in the young generation of children living in rural areas is at surprisingly low level (in each age category, always only a significant minority of children from the sample group is able to identify the local names in the landscape). In an orientation assessment of variability (i.e. the information value rate) using nominal variance

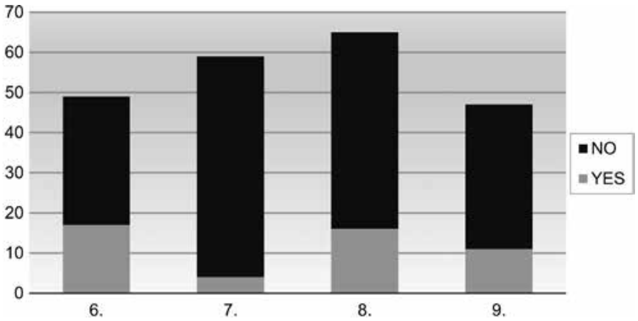


**Fig. 2** Frequency histogram – current level of the knowledge of Haná dialect local names in the landscape by children in primary schools (vertical axis – absolute number of respondents; horizontal axis – grades of elementary school; YES column – respondents who know and actively use the Haná dialect; NO column – respondents who do not know the Haná dialect).

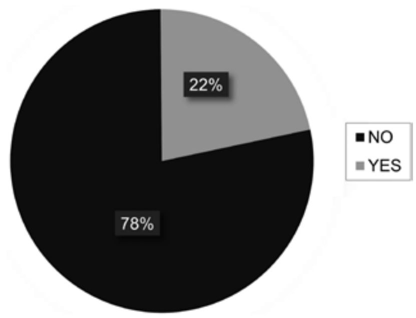


**Fig. 3** Relative proportion of the number of children in the examined group of respondents (n = 492) who actively know local names in landscape in the Haná dialect (YES segment) and who do not know this one (NO segment).

(Průcha 1995), we obtained the value of 0.69 for the possible range in the interval from zero to one which means a relatively high variability, apparently given by the considerable span of age categories within the examined group of respondents.

Evaluation of the data packages obtained from each elementary school through the t-test did not show any statistically significant difference between the schools (calculated value T = 1.22, critical table value P = 2.001, significance level $\alpha = 0.05$). It can be thus summarized that the examined population sample of 220 students of rural schools in Haná contains only 21.8% of children who currently know and are able to actively identify specific local names in the landscape. Most children (78.2%) in the investigated group of respondents do not know them (Figure 3).

The results of the chi-squared test showed that the active knowledge of local landscape names in children is statistically significantly independent of the sex of respondents or the education level of their parents (in the tested categories of primary, secondary and university education). Only when assessing the relationship between the knowledge of landscape place names in children (on the one hand) and active use of the Haná dialect by children (on the other hand), the calculated value of chi-squared test criteria ($\chi 2 = 6.614$) was greater than the critical table value (5.991) which expresses the statistically significant interdependence of both phenomena. It is likely that this finding is partly related to the fact that the majority of local names known by respondents are used in the Haná dialect.

Empirical evidence of completing the questionnaires as well as the work with maps showed that the topic of place-names in the landscape in the vicinity of respondents' domiciles is a theme very distant from their common interests. Generally, respondents consider local names in their home country as something archaic which has absolutely no significance for them. This finding is certainly not surprising in the situation where the most considerable communication space of the respondents' generation is probably represented by the Internet virtual world (Skalková 2007).

## 4. Discussion and Conclusion

Landscape memory is by Sklenička (2003) the ability to retain some landscape attributes and also as the ability to regenerate these attributes. Loss of landscape memory has recently becomes a topical concept (Cílek 2002). The basis of landscape memory is formed by permanent landscape structures (Skaloš, Kašparová 2011), which can be accessed by methods of landscape ecological research (Lipský 2000). A consequence of landscape memory can be also so-called genius loci (Sádlo 1994). The tangible substance of the landscape memory can be identified, e.g. by using comparative analysis of historical maps (Skaloš et al. 2011), where the so-called continuous ecosystems play an important role in this respect (Trpák, Trpáková 2007). Identification of the spiritual (i.e. non-material) nature of the landscape memory (Schama 1995) is more difficult – there can methods such as sociological researches among the rural population (Řehák, Řeháková 1986). This issue is getting into the spotlight through the newly established interdisciplinary fields of ethno ecology (Malý, Viktoriová 1999) and social ecology (Lapka 2008).

This article deals with the part of the non-material nature of the landscape memory in the ethnographic region of Haná (Zíbrt 1907) from the Czech Republic. Geographers generally understand the region as an area in which there is a match of physical space and studied phenomena. Ethnographic region is characterized by awareness of regional identity, i.e. knowledge of the region's inhabitants about own culture and folk traditions which distinguish them from the inhabitants of other regions in the vicinity (Pinchon 1994). The issue of the exact geographic definition of ethnographic regions in Central Europe belongs to the questions addressed by ethnography from its inception as a discipline. At the same time, researchers often have very different opinions on these questions because many phenomena of both material and spiritual folk culture are not tied to clearly definable geographic regions (Aberg 1991). Characters which enable to define a certain ethnographic region are often based on details such as the regionally specific decoration of buildings (Vařeka 1997). Other numerous factors that influence the definition of ethnographic region include dialect, historical boundaries of feudal dominions and church parishes, ethnic and social structure of the inhabitants with their own traditions and generally widespread awareness of the region's name and relationship of the population to this region, etc. According to number of authors (summary in Jančář 2000), the awareness of regional identity and belonging to a particular ethnographic region in Central Europe is particularly significant in the historical region of Moravia which includes several ethnographic regions in the eastern part of the Czech Republic including the study region of Haná.

Ethnographic region need not necessarily be uniform in all its characteristics. It is typical of ethnographic regions of Europe that their signs based on the characteristics of regional folk culture may extend even into neighbouring ethnographic regions. This situation is also characteristic of the studied ethnographic region of Haná. Boundaries of the Haná ethnographic region, subject to the occurrence of typical regional characters, are highly questionable and vague especially on the western edge of Haná being in contact with the ethnographic region of Horácko (Zíbrt 1907).

Already at the beginning of the last century, some authors attempted to define the boundaries of Haná ethnographic region more precisely (Kabelík 1907; Paroubek 1905). Ing. Josef Kšír proposed the Haná boundaries based on geographic expansion of typical elements of Haná folk architecture (Kšír 1956). However, Josef Klvaňa pointed out already in the early 20th century: "A precise and sharp definition of the Haná region is not actually possible – neither according to dialect, nor according to former costumes" (Klvaňa 1907: 144). Jan Herben wrote in a similar way: "Lingual, trait and costume mosaic of Haná is as varied as that of Slovácko" (Herben 1925: 211). Today, ethnologists more or less agree that a clear definition of the Haná ethnographic region is complicated both theoretically and practically (Frolec 1991), also in view of the fact that ethnographic areas are determined and changed by research intentions of ethnology. Most recently, a definition of the Haná ethnographic region was presented by Jeřábek (2004) within the clarification of ethnographic zoning of Bohemia, Moravia and Silesia IV (Woitsch, Bahenský 2004).

Statistical evaluation of the respective presented results showed that most children living in today's Haná village (78.2%) do not know the traditional local names in the landscape. It is certainly interesting that children with knowledge of these local names are actively using the Haná dialect. However, children who actively use this dialect represent a minority group of the respondents in the investigated set (21.8%). These children actively use the Haná dialect mostly for communication in the family environment with their parents and siblings (see the results of the questionnaire survey). It can be, therefore, said that education in the family can be one of the main factors positively affecting the preservation of active knowledge of the folk dialect as well as the knowledge of landscape local names in the examined group of children (Lisická 1993; Schauerová et al. 1999).

The Haná dialect was always seen as an important part of the intangible cultural heritage of Haná (Bartoš 1886). Haná dialectal group belongs to the four (or five) basic dialectal groups of the Czech language (Bělič 1972). Interference between the different dialectal groups often results in the formation of neutralized, so-called, common dialects, the example of which is the today's common Haná dialect. Unification of the Haná dialect, originally locally diversified, into the common Haná dialect and regression of the older local differences within the formerly more colourful Haná dialect is documented in a number of works, e.g. by Matějek (1956).

Of course, a large share of the responsibility of maintaining the regional identity of Haná region currently falls on the local and regional activities aimed at preserving the traditions of folk culture. In this sense, activation educational programs implemented by museums in nature are of great importance (Langer 2005). Round the world, a great attention is therefore devoted to the creation of strategies that should stimulate the society's interest in regional museums and museums in nature (e.g., Bradburne 2001; Falk 1991). Regional museums which can significantly promote regional identity of the local population are often faced with low public interest (Flores, Crawford 2011). Unfortunately, the lack of interest in museums in nature is currently typical of the people in the Czech Republic (Kesner 2003) although the expert discussions on the possibilities and methods to promote the active public interest in such museums are held in our country for decades (Frolec, 1976; Langer, Souček 1986).

Local names in the landscape can undoubtedly be considered as part of the local heritage (Ptáček et al. 2004). In a European context, the strategies of interpreting the local heritage now show a strong shift to an emphasis on the involvement of local communities including their youngest generation (Pierssené 2000; Brochu 2003).

Such activities contribute to maintain awareness of the local names in the local landscape, e.g. by publishing them in the regional natural history publications (e.g. Pospěch, Vaca 2000). One example of activities helping to maintain the Haná regional identity is the Haná Calendar published annually within the framework of editorial activities of the Society of Friends of Villages and

Small Cities. The eleventh volume of the Haná Calendar was specifically devoted to the topic of the local names of landscape in Haná dialect (e.g. Přikryl 2009). Another such activity is keeping the regional bibliographic database HANÁ in the Library of Olomouc (Ševčíková 1993) or the original Haná Dictionary (Pospěch 2012). In recent years, we can even buy books written in the Haná dialect (e.g. Vaca 2010). Despite all these positive events, most regional ethnographic specialists agree in the belief that the knowledge and active use of the Haná dialect is slowly disappearing from Haná villages, especially in the youngest generation (e.g. Olbert 1994; Vaca 1995). Similar trends in gradual extinction of local folk dialects hand in hand with regional identity are described in the other ethnographic regions of Europe (Holtus 1993; Lockwood 1984; Ratter, Gee 2012). These trends can be connected in Europe with problems of immigrations (Bianco 1980) or in the context of economical conditions of regions (Falck et al. 2012; Sliuzinskas 2012).

It is very likely that the situation regarding knowledge of the local names in the landscape is the same. The question is whether such a situation can be really affected by something like school education and training. Generally there is considered, that school education has only a few tools and possibilities to maintaining of regional identity (Núez 2010; Cooper 2011). The fact is that teachers, who offer children activities related to the landscape and traditional folk culture within the school as well as after-school education, are a rare exception (Večerková 1994). It is clear that the period of agrarian countryside from the beginning of the last century is irretrievably gone, not only in the area of Haná (Lipský 1995). A knowledgeable society built on modern technologies requires other schooling priorities than emphasis on the knowledge of local names in the landscape. Nevertheless, the landscape as well as traditional folk culture shaped the lives of the vast majority of our ancestors and affect our lives perhaps more than we are willing to admit. Therefore, the education to knowledge and understanding of the landscape and traditional folk culture should be part of the education of children even for the 21st century (Woitsch 2008).

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## RÉSUMÉ

**Paměť krajiny v pomístních jménech na Hané – jak je to s jejich znalostí u nejmladší generace?**

Pomístní jména v krajině jsou důležitou součástí duchovní složky paměti krajiny a zároveň tvoří podstatnou součást nehmotné tradiční lidové kultury v lokálním měřítku. Obsahem článku je prezentace výsledků výzkumu současné úrovně znalosti pomístních jmen krajiny v etnografickém regionu Hané u dětí patřících do věkové kategorie žáků základní školy. Metodou dotazníkového šetření bylo zjištěno, že většina žáků venkovských škol na Hané v současnosti konkrétní místní názvy v krajině nezná. Statisticky signifikantní souvislost byla zjištěna mezi znalostí místních názvů a aktivním používání hanáckého nářečí ve zkoumaném vzorku respondentů. Velký podíl na udržování znalosti pomístních jmen krajiny v současnosti mají místní a regionální společenské aktivity, zaměřené na udržení tradic lidové kultury. Výsledky prezentovaného šetření jsou diskutovány v kontextu regionální identity místních komunit. V článku jsou rovněž diskutovány geografické a etnografické aspekty vymezení studovaného regionu Hané, který patří mezi nejvýraznější etnografické regiony ve středoevropském prostoru.

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# SWEEPING ETHNO-DEMOGRAPHIC CHANGES IN KAZAKHSTAN DURING THE 20TH CENTURY: A DRAMATIC STORY OF MASS MIGRATION WAVES PART I: FROM THE TURN OF THE 19TH CENTURY TO THE END OF THE SOVIET ERA

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**ABSTRACT**

For quite some time, the population dynamics in Kazakhstan have largely depended on migration processes. At the end of the 19th century, the territory of the country became the main migration space for a large part of Eurasia which was under the governance of the Russian Empire, and later of the Soviet Union. The large scale resettlement of Russian and Ukrainian peasants following the integration of the Kazakh Khanate (name of the Kazakh state in the territory of present-day Kazakhstan and neighbouring countries in 1465–1847) into the Russian Empire, as well as different forms and types of voluntary and involuntary mass movements of populations during the Soviet period, completely changed the demographic picture of Kazakhstan. At the same time, the economic and political conditions established after the end of the Russian Civil War (1917–1920), along with new economic policies implemented in Soviet Central Asia in the 1920s and 1930s and their tragic consequences, resulted in massive outflows of population, namely Kazakhs. All these movements had a significant direct impact on population development within the territory, and on the size, ethno-demographic and other social characteristics of the population.

The aim of the paper is to trace the changes in the total population and its ethno-demographic structure in Kazakhstan from the end of the 19th century to the very end of the 1980s, and to determine the role of migration in these changes. Systematization of migration policies is presented, and the effect of past migration processes in Kazakhstan is discussed. The presented research is based on census data.

**Keywords:** Kazakhstan, population, migration, ethnic structure, Russian Empire, Soviet Union

## 1. Introduction

At the end of the 19th century, ethnic Kazakhs formed a crucial part of the population living within the territory of today's Republic of Kazakhstan. However, at approximately the same time, this territory became the main migration space of the Russian Empire. And it remained in this position throughout virtually the entire period of communism, for about a hundred years all together.

During this long period, millions of people from the European as well as other parts of the country came to the Kazakh steppe. Many immigrants came forever. Many of them or their descendants eventually left the territory in question. Ethnic Kazakhs lost their quantitative dominance within several decades because their natural frontiers opened for the waves of a larger scale migration. There were, however, two main factors supporting this radical change: in addition to migration also cataclysmal phenomena – wars and famines. The change would have been even more pronounced if there had not been some significant differences in reproductive behaviour developments and population statistics.

As a result, at the time of the first post-war census held in 1959, the Kazakhs were a minority in their own country, representing only 30 percent of its population. At the end of the Soviet era they were the largest ethnic group, with 40 percent of the total population, though still in a minority position relative to members of the European nations. No other indigenous nation was in a similar situation when the former Soviet republics were gaining their independence.

The aim of the paper is to trace the changes in the total population and its ethno-demographic structure in Kazakhstan from the end of the 19th century to the very end of the 1980s, and to determine the role of migration in these changes. Systematization of migration policies is presented, and the effect of past migration processes in Kazakhstan is discussed.

## 2. Data

The presented research is based on data from censuses which took place in the territory of Kazakhstan between the years 1897 and 1989. In total, nine full-scale population censuses were held during this period: 1897, 1920, 1926, 1937, 1939, 1959, 1970, 1979 and 1989. However, only the results of seven of them were used in this study. The results of the 1920 census were not included because they were obtained under very specific historical conditions in the period marked by the end of the Civil War and the total collapse of the country and its economy. The 1937 Census was held successfully but afterwards *de facto* annulled. Its results were published for the first time in 2007 (Zhiromskaya, Polyakov 2007). Due to their informal nature, they are only compared with the results of the "corrective" 1939 Census, and the results obtained are briefly discussed in the text.

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There is no doubt that the censuses were of varying quality, and thus the credibility of their outputs differs to some extent. On the other hand, they are the only comprehensive sources of information one can employ to fulfil the objectives of this work. But it has to be done with full awareness and an appropriate degree of caution.

Despite the selection, the resulting set of censuses cannot be regarded as homogeneous in terms of data reliability. This necessarily affects our conclusions about the development of the total size and ethnic structure of the population in the territory of contemporary Kazakhstan between censuses, as well as within the entire study period. For example, in the case of the First General Census of the population of the Russian Empire (1897), ethnicity was judged on the basis not of ethnic but of linguistic features. The mother tongue was the main criterion for inclusion into an ethnic group (Krasnobayeva 2004). Moreover, the term *mother tongue* was not yet clearly defined for the purpose of the census. For instance, the majority of indigenous people noted the Turkic language as their mother tongue. This led to the mixing of different ethnic groups belonging to the Turkic language group (Tatars, Kyrgyzs, Uzbeks and Turkmens) with Kazakhs (Alexeyenko 1999). At the same time, many members of the European nations (Ukrainians, Belarusians, Jews and others) reported Russian as their mother tongue (Krasnobayeva 2004). In addition, it has been documented that the original nomadic population made many efforts to hide for various reasons before the census (op. cit.). The most frequent reasons were related to equity and fiscal motifs.

Similar criticisms also apply to the 1926 Census, when the central statisticians decided to again use the concept of mother tongue in determining the ethnic structure of the population, regardless of the opinion and recommendations of experts. In addition, various historians and demographers have estimated that the census did not count between 4 and 7 percent of Kazakhstan's population, especially young women (Alexeyenko, Alexeyenko 1999). This was associated with both religious constraints and the Soviet campaign against polygamy.

In the case of the 1939 Census, it is difficult to find any assessment of its quality. This can be interpreted as an expression of silent but sound doubts about the credibility of the data. The 1939 Census has to be understood as a "corrective" to the 1937 Census. The latter was successfully completed but the results did not satisfy the ruling elite, who did not approve of the ideological thesis of rapid population growth under socialism. The fact that there was a significant reduction in the list of nations for which it was possible to classify inhabitants, or with which they could identify themselves, may also have had an impact on the comparability of the results. In 1926 there were 160 ethnic groups on the list, whereas in 1939 there were only 62 (Alexeyenko 1999).

The first post-war census of 1959 methodically followed the 1939 Census. Ethnicity obtained a proclamative character, and the list was extended to include 93 ethnic groups. The 1959 Census itself was well elaborated and preceded by a pilot census carried out on a small sample of the population only. Its results are generally considered representative and reliable.

The subsequent censuses of 1970, 1979 and 1989 were carried out according to a similar methodology as the 1959 Census. The basic control mechanisms were also preserved. The observed changes in methodology and content had no significant impact on the size and ethnic structure of the population. In fact, all post-war censuses in the territory of Kazakhstan can be regarded as relatively reliable and comparable, in terms of the obtained results.

## 3. Historical overview of the impact of migration processes in Kazakhstan before 1991

For quite a long time following its inclusion in the Russian Empire (1847), Kazakhstan was a region of active migratory movements. The intensification of migratory flows during this period was mostly a consequence of the decisions of governmental bodies. Most often state regulatory measures encompassed the authorization of already established flows, such as migration of Russian and Ukrainian peasants, as well as different forms of voluntary and involuntary movement. Migration, in turn, also affected the development of the state as a result of changes, mainly caused by migration, in the ethno-demographic composition of the population.

### 3.1 The period of Russian colonization of Kazakhstan

Before entering the Russian Empire, which took place during the period from the 1730s to the middle of the 1860s, the territory of Kazakhstan was inhabited by Karakalpaks, Uzbeks, Kalmyks and Tadjiks, among other non-Kazakh ethnicities. According to Asylbekov (1991), the process of consolidating ethnic territory started after entering the Russian Empire and was accompanied by rapid population growth at the end of the 18th and beginning of the 19th centuries. The eastward migration of Russians from the European part of the empire to Siberia, Kazakhstan and Central Asia involved nearly 6.5 million people (Demko 1969). Approximately a third of these people migrated to Kazakhstan. Among the forces pushing this eastward migration were an oppressive political situation, the socio-economic condition of peasants who were considered to be slaves, rural over-population and the rapid rate of population growth, economic hardship, and a low level of agricultural productivity. Conversely, the existence of vast areas of unused land and an agriculturally suitable territory beyond the Urals was one of the main factors which attracted migration.

As stated by Treadgold (1957), there were two primary causes of peasant migration: land and liberty. Initially, the Russian government did not encourage, and even prohibited peasant resettlement. The ban was later lifted, and with the abolition of serfdom in the Russian Empire in 1861 the number of those resettled in the northern regions of Kazakhstan increased significantly. The first legislation dealing with the migration of peasants was a law concerning temporary rules for resettlement, adopted in 1881. Although the law removed previously existing barriers such as the need to receive permission to settle, it had little effect on migratory flows. Another piece of legislation called the Resettlement Act of 1889 could be considered an important policy measure; it still required that permission be granted to migrate, but offered a number of inducements such as land allotments, loans ranging from 30 to 100 rubles, waiving of taxes for up to 3 years, etc. Akmolinsk, Semipalatinsk and Semireche, Turgay and Uralsk, along with some regions of Western Siberia, were designated for settlement. This resulted in an increase in the share of Kazakhstan's Slavic population, which accounted for about 8% of the total population by the 1870s.

Newcomers, mostly of Slavic ethnicity, settled in the entire territory of Kazakhstan at the turn of the 19th and 20th centuries. Russian and Ukrainian villages formed a Slavic area in the north-western, northern and north-eastern regions of Kazakhstan. After the conclusion of the Treaty of St. Petersburg concerning demarcation of the border between the Russian and Qing Empires in 1881, 45 thousand Uyghurs and 4 thousand Dungans resettled from the Kulja region to the south-eastern territories of Kazakhstan (Sadovskaya 2001). Masanov et al. (2001) stated that by 1897, the population of Kazakhstan consisted of 3,101 thousand Kazakhs, which was 78.4% of the total population, 502 thousand Russians (12.7%), 75 thousand Uzbeks (1.9%), and other ethnicities.

The ethnic structure of the population during the period from 1897 to 1916 showed that the number of Russians, including Belorussians and Ukrainians, increased by more than 1,250 thousand, or by more than three times (Demko 1969). The growth in the Russian population was particularly marked in the northern regions of Kazakhstan, namely the Akmolinsk and Turgay oblasts. By contrast, the indigenous population grew by only 350 thousand persons, or only 14% during the same period. The disparity between Russian and native population growth in Kazakhstan can be explained by the immigration of Russian settlers as well as differences in natural increase – the crude birth rate for the Russian population was nearly two times higher than that of the natives as of 1926, mostly due to the younger age structure of the settler population (op. cit.).

The population growth at the beginning of the 20th century was due to an increase in the size of the indigenous population, as well as migratory flows. The most significant period in terms of settlement was 1906–1914, when more than 1 million migrants moved into Kazakhstan and accounted for 80% of total immigration for the period 1896–1916 (Demko 1969). It is necessary to mention that new legislation enacted in 1904 removed all restrictions on internal movement, and was followed by important changes resulting from the Stolypin reforms of 1906–1910, which dissolved the restrictive commune system and allowed peasants to move freely and enclose their lands.

The migration inflows observed in Kazakhstan from 1896 to 1916 can be divided into three periods, taking into account the intensity of flows. The first period, from 1896 to 1900, is characterized by relatively large inflows. This occurred due to the adoption of favourable legislation by the Siberian Railroad Committee and the completion of a railroad to Lake Baikal. However, the volume of migration decreased in subsequent years, especially 1901 and 1902, due to famine in Siberia and Kazakhstan. The second wave of intensive inflows of peasants is observable for the period 1906–1911, with its peak in 1908 (Demko 1969). This can be explained by the elimination of restrictions on resettlement and massive peasant colonization of Kazakhstan and Siberia. A decrease in migratory flows is seen for the years 1911 and 1912. The land reforms that had taken place in previous years led to alleviation of the intensity of the agricultural crisis and to excellent crop yields in European Russia, and so weakened the main reasons for rural outmigration. Migration began to decrease following the involvement of the Russian Empire in World War I, and continued to do so in the years of the Revolution and Civil War. The eastward Russian migration had obviously affected the size of Kazakhstan's population, which increased during the period 1896–1916 by more than 2 million people, or 2.3% annually, while the same indicator for European Russia was 1.3% (Demko 1969). In Kazakhstan most of the increase – of 43% – occurred by 1911. As far as regional distribution is concerned, the largest absolute increase in population was observed in Akmolinsk oblast, followed by Turgay oblast.

The consequences of World War I and the Civil War were generally disastrous for the population of Kazakhstan, as well as the population of the Empire as a whole. The socio-economic situation caused by a crisis in the economy and agriculture was aggravated by the famine of 1919–1922. This famine resulted in a population decrease of 19.1% (Assylbekov 1991). Olcott (1987) points out that the population declined during this period by well over 1 million people. This number included several hundred thousand emigrants, mostly Russians, some of whom tried to return to their native territory (Olcott 1987) while others moved to the south – Turkestan or other more prosperous regions of Kazakhstan. During the years of Soviet power a decree of the Russian Central Executive Committee and the Council of People's Commissars on planned resettlement for 1925–1926 dated 17 August 1925 increased the population, as the number of in-migrants exceeded the number of out-migrants by the end of the 1920s. However, spontaneous migratory flows dominated organized ones. The number of migrants was

1.5 million, while the population size was approximately 6.2 million in 1926 (Sadovskaya 2001).

The First All-Union Population Census, held on 17 December 1926, showed that since the latest census of the Russian Empire in 1897 the population of Kazakhstan had increased 1.5 times, or by more than 2 million persons (Tab. 1). The ethnic structure of the population of Kazakhstan consisted mainly of Kazakhs, Russians and Ukrainians by the end of the 19th century. However, the 1926 Census revealed that the proportion of Kazakhs in the total population had decreased sharply, from 81.8% in 1897 to 58.5% in 1926. As a consequence, the proportion of Russians and other ethnicities increased to approximately 21%, which represented a three- and four-fold increase in the numbers of Russians and other ethnicities, respectively. The 1926 Census recorded 1,601 thousand persons (Galiyev 1979) who at the time of the census stated that their current place of residence was other than that of their birth. Thus, most of them were settlers who came from Ukraine, the Volga area, the northern, western and central part of the Russian Soviet Federative Socialist Republic and a small number from Siberia, the Urals, Central Asia and the Far East.

**Tab. 1** The size and ethnic structure of the population in the current territory of Kazakhstan according to the 1897 and 1926 censuses.

| Ethnicity | Population size (in thou.) | | Index | |
|---|---|---|---|---|
| | 1897 | 1926 | 1926/1897 (in thou.) | 1926/1897 (in %) |
| All ethnicities | 4,148 | 6,196 | 2,049 | 149.4 |
| Kazakhs | 3,393 | 3,628 | 235 | 106.9 |
| Russians | 454 | 1,275 | 821 | 280.6 |
| Others | 301 | 1,294 | 903 | 430.4 |

**Source:** Department of Statistics of the South-Kazakhstan Oblast. (undated). [Electronic res.]. Accessed in 2012 at http://www.ontustik.stat.kz/rus/perepis_nas/index.php.

The migration processes of the first decade of the Soviet regime in Kazakhstan had a clearly industrial character (Sadovskaya 2001). Indeed, the economic policy of the USSR from 1926 was directed towards industrialization, and the territory of Kazakhstan was considered one of the main regions for accelerated industrial development. However, the initial phase of industrialization faced a labour shortage, and it was decided to transfer unemployed people from the western and central part of the Soviet Union to these areas. Thus, the main population flows were directed towards the industrial and mining areas of Kazakhstan and consisted mainly of peasants.

As a result of the collectivization campaign which began in the second half of the 1920s, the new population flows were mostly involuntary and forced in character. This program was adopted at the Fifth Party Congress in December 1927 and included a formal decision to move toward a collectivized economy. Collectivization aimed to establish socialist production in rural areas by associating individual peasant farms into collective ones. It is difficult to know the percentage of the rural population which was collectivized; however, 60% seems to be a reliable estimate according to Olcott (1987). Moreover, the pace of collectivization was uneven across individual regions of Kazakhstan. Approximately 70% of the populations in the Akmolinsk, Syr Darya, and Pavlodar regions were collectivized, whereas only 20% of Kazakhs in the nomadic areas were collectivized. During the Seventeenth Party Conference in 1932, the government of the Kazakh Soviet Socialist Republic (Kazakh SSR) therefore reported the failure of the collectivization campaign. In addition, 25% of the population left their collective farms due to livestock shortages (Olcott 1987). The Central Committee of the Kazakh SSR resolved that any attempt to forcibly collectivize Kazakhs was wrong, but it nevertheless succeeded in settling them. The forced settling of nomads and the mass collectivization and socialization of land acreage resulted in a shortage of feed and a massive loss of cattle, which led in turn to a shortage of basic products in most households and finally resulted in famine. In the history of Kazakhstan, the famine of 1931–1933 is considered to be the main cost of collectivization. The number of victims in the Kazakh SSR during these years was one of the most discussed issues among historians, and varied between 1,750 thousand and 2,020 thousand (Abylkhozhin et al. 1989; Alexeynko 2000). Some authors believe about 1.5 million Kazakhs died in the 1930s, though the actual losses could be even greater (Olcott 1987).

Collectivization was accompanied by the elimination of kulaks (prosperous peasants who used hired labour) as a social class. These actions were accompanied by confiscation of the means of production from kulak farms, including livestock, food and seed stocks. The dispossessed kulaks fell into three categories: the first category received imprisonment in concentration camps or death; the second category were exiled to the most remote areas of the USSR (so-called "kulak exile" or "labour exile"); and the third category were settled within the district of residence, but outside the farm arrays (PBCC 1930). The Urals, Siberia and the territory of Kazakhstan were selected as places of "kulak exile" for peasants from different part of the country. The mass deportation of kulak households formally ended in 1931, in accordance with a decree of the Political Bureau of the Communist Party of the Soviet Union (Bolsheviks) Central Committee, dated 20 July 1931. However, resettlements in the following years were implemented individually. According to Zemskov (1991), 18,092 families from Lower Volga, 11,477 families from Middle Volga, 10,544 families from the Central Chernozem region, and 2,972 families from the Moscow oblast were exiled to Kazakhstan in 1930–1931. The total number of families residing in the Kazakh SSR as a result of labour settlement was 33,852 on 1 January 1939 and 36,484 families on 1 January 1940 (Zemskov 1991). According to data from the Department on Special

Settlements of the GULag (Chief Administration of Corrective Labour Camps and Colonies), 6,765 peasants were sent from Kazakhstan.

In addition, Kazakhstan lost a considerable part of its population due to the emigration of 616 thousand Kazakhs. This is also proven by the fact that the number of Kazakhs residing in neighbouring countries increased between two censuses (1926 and 1939). Approximately 200 thousand Kazakhs emigrated to China, Mongolia, Afghanistan, Iran and Turkey (Abylkhozhin et al. 1989). The loss of the non-Kazakh population was also difficult to measure due to their intensive migration. Taking into account changes in the resident population, it is possible to estimate indirectly the effect of migration. For instance, the number of Ukrainians residing in the territory of the Kazakh SSR decreased from 859 thousand in 1931 to 658 thousand in 1933, Uzbeks from 228 thousand to 104 thousand, and Uyghurs from 62 thousand to 37 thousand (Abylkhozhin et al. 1989). This is also the result of high mortality during the famine of 1932–1933. The collectivization campaign and its consequences therefore had a significant impact on population during the 1920s and 1930s.

The arrival of dispossessed kulaks partially counterbalanced the loss of population during these years; however, this mostly affected the ethnic composition of the population. In addition, there was the so-called kulak economic factor, which refers to their contribution to the development of the agriculture and economy of the Kazakh SSR. The settlers' labour was used to irrigate the arid regions of Kazakhstan as well as Uzbekistan, Kyrgyzstan and Tajikistan, uproot the land and clear it for agricultural use, pave dirt roads in roadless areas, etc. (Zemskov 1994).

### 3.2 Deportation of nations and forced migration in the 1930s and 1940s

The second half of the 1930s was marked by the intensification of migratory flows, not only stimulated by the totalitarian regime but also directly organized as the deportation of entire nations to Kazakhstan. The first deportations started in the 1920s when Kuban Cossacks (Kazaks) were evicted from their villages and most Russian intellectuals were sent abroad (Sadovskaya 2001). With the consolidation of Stalin's regime in the 1930s, the extent of repression increased and the territory of Kazakhstan, along with Siberia and the northern part of the USSR, were defined as places for exile. According to geographer and historian P. Polian (2001), who researched the issue of forced migration in the USSR, the deportation (forced migration) could be considered a specific form of political repression. The main features of deportations were its administrative or non-judicial character, and both direct and indirect coercion.

Generally, the 1930s was a period which saw the strengthening of the Soviet Union's international self-isolation and the formation of the "iron curtain". This process also affected the deportation policy of the regime. Mass deportations began with the so-called "cleansing of the borders", which refers to a whole campaign aimed at ensuring the safety of cities, state borders and border areas through the class and ethnic "cleansing" of socially dangerous elements (Polian 2001). The campaign started with the cleansing of western borders in 1935–1936. According to a decree of the Council of People's Commissars, dated 28 April 1936, 35,739 Poles out of 35,820 in total were deported from border areas of the Ukrainian SSR to Kazakhstan (Masanov et al. 2001). The social status of deportees was defined as "politically unreliable elements" who resided in the border regions of the Zhitomir, Kiev, Vinnitsa and Kirovograd oblasts of Ukraine.

The cleansing of the eastern borders, which began in 1937 with the mass deportation of Koreans from the Far East to Kazakhstan (mainly South Kazakhstan, the Aral Sea and Balkhash regions) and Uzbekistan, was the primary focus of deportation policy. As a result of the inclusion of the Far East Republic (currently Far East Kray) into the Russian Soviet Federative Socialist Republic in 1922, the population of the country increased by thousands of Korean, Japanese and Chinese settlers. On the other hand, with the growth of militarism in Japan, the occupation of Manchuria and formation of Manchukuo close to the Soviet border was considered a favourable condition for Japanese espionage and intervention (Polian 2001). These deportations were implemented in two stages. The first stage began in fall 1937 and continued till the spring of 1938, when approximately 200 thousand Koreans were resettled from the Far East to Kazakhstan (Alekseyenko 2000). The second stage covered the period from spring 1938, when 60% of Koreans were resettled internally in Kazakhstan. According to the 1926 Census, there were only 42 Koreans residing in Kazakhstan, whereas the 1939 Census showed that this number had increased to 96 thousand (Tab. 2). The cleansing of the southern borders was implemented in 1938–1939. Deportation in this third direction was not as intense as previous ones, and comprised mostly Iranians who resided in the border regions of Turkmenistan, Azerbaijan, Armenia and Georgia.

The results of the Second All-Union Census, held in January 1939, showed that the population of the Kazakh SSR had increased by only 2.6% in comparison with the previous census, held in 1926 (Tab. 2). The Second Census was initially held in 1937 and showed a population loss of 1,072 thousand compared to the 1926 Census results. Obviously, the main reason for the decrease in population was collectivization and the famine of 1932–1933. However, the result of the 1937 Census was declared to be defective given the policy and ideology of the regime. Nevertheless, the decrease in population during these years was considered to be counterbalanced by migration. The population decrease appeared to be due mainly to a decrease in the number of Kazakhs. According to the

1926 Census, Kazakhs formed a majority (58.5%) within the ethnic structure of the population (DSSKO – Department of Statistics of the South Kazakhstan Region – n.d.). However, the share of Kazakhs decreased to 38.0% in 1939 and ranked second behind Russians, who were the major ethnicity with 40% of the total population of Kazakhstan (Tab. 2). The proportion of Ukrainians also decreased from 13.9% in 1926 to 10.8% in 1939. The share of Germans and Tatars increased slightly compared to 1926. However, according to the recently published results of the 1937 Census, the decreases mentioned here were significantly deeper, and the increases significantly more moderate. Statisticians have found about 976 thousand (18.9%) more inhabitants in the territory of Kazakhstan in 1939 than their colleagues found in 1937. Of this difference, there were 132 thousand (i.e., more by 6.0% in 1939 than in the 1937 Census) Kazakhs, 531 thousand (27.7%) Russians and 107 thousand (19.5%) Ukrainians (DSSKO, Zhiromskaya and Polyakov 2007). It is therefore quite likely that the proportion of Russians among the population of the Kazakh SSR was deliberately overrated by the 1939 Census, and that Kazakhs lost their size dominance only after 1939.

The ethnic structure of other Soviet countries showed an increase in the number of Kazakhs, proving the out-migration of Kazakhs during the years of collectivization. In 1939, the number of Kazakhs in the RSFSR increased by 2.3 times, in Uzbekistan 1.7 times, in Karakalpakstan 2.5 times, and in Kyrgyzstan 10 times compared with the previous census (Galiyev 1979). Overall, the share of Kazakhs residing in neighbouring countries increased from 8% to 20% during the intercensal period.

A new wave of deportations was implemented during World War II (the Great Patriotic War). Most migration in this period resulted from preventive deportations of "punished nations". Such a punishment was implemented not for a particular crime or betrayal, but rather for "belonging to a nationality with which the country might be in a state of war" (Polian 2001: 103). In addition, Polian (2001) points out that there was the concept of "geography of unreliability" which derived from the geography of "trustworthy" and "unreliable" nations as well as their relation to certain locations. The first group included a mostly Slavic population whereas the second group included Jews, Germans, Poles and other nations of Caucasus, Central Asia and other territories. Regions where Russians comprised less than 50% of the population were considered "unreliable", hence the level of reliability decreased from the centre of the Empire to its periphery. After the occupation of the eastern regions of Poland in September 1939 and their inclusion into the Ukraine and Belorussia, the Soviet government began deporting Polish nationalists. These special settlers were called *osadniki* (*osadnik* means settler in the Polish language) and were former soldiers in the Polish army. Most of them were sent to the northern regions, the Urals, Siberia and Kazakhstan.

Among the main targets of deportation policy during the war were Soviet Germans, viewed as potential "collaborators" solely because of their ethnic identification with a nation whose titular state was in a state of war with the Soviet Union and could cooperate with them. According to a decree of the Council of People's Commissars and the Central Committee of the All-Union Communist Party (Bolsheviks), dated 26 August 1941, Germans from the Volga Germans ASSR, Saratov and Stalingrad oblasts were sent to Siberia and Kazakhstan, 366 thousand and 67 thousand, respectively. Overall, there were 1,427 thousand Germans in the USSR, and 93 thousand of them resided in Kazakhstan according to the 1939 Census (Polian 2001). In addition, 1,209 thousand Germans were resettled in the USSR during the period 1941–1942, and 444 thousand of them were sent to Kazakhstan (Polian 2001).

The subsequent wave of mass deportations that began in 1943 included nations of the North Caucasus and

**Tab. 2** The size and ethnic structure of the population in the current territory of Kazakhstan according to the 1926 and 1939 censuses.

| Ethnicity | Population size (in thou.) | | Share (in %) | | Index 1939/1926 (in %) |
|---|---|---|---|---|---|
| | 1926 | 1939 | 1926 | 1939 | |
| Entire population | 6,199 | 6,094 | 100.0 | 100.0 | 98.3 |
| Kazakhs | 3,628 | 2,314 | 58.5 | 38.0 | 63.8 |
| Russians | 1,275 | 2,449 | 20.6 | 40.2 | 192.1 |
| Ukrainians | 860 | 657 | 13.9 | 10.8 | 76.3 |
| Germans | 51 | 92 | 0.8 | 1.5 | 180.8 |
| Uzbeks | 129 | 103 | 2.1 | 1.7 | 79.8 |
| Tatars | 80 | 107 | 1.3 | 1.8 | 134.1 |
| Uyghurs | 63 | 35 | 1.0 | 0.6 | 55.7 |
| Koreans | 0 | 96 | 0.0 | 1.6 | x |
| Others | 112 | 240 | 1.8 | 3.9 | 214.7 |

**Source**: Department of Statistics of the South-Kazakhstan Oblast. (undated). [Electronic res.]. Accessed in 2012 at http://www.ontustik.stat.kz/rus/perepis_nas/index.php.

Crimea. A new feature of these deportations was the mass displacement of entire nations, accompanied by the loss of their national autonomy. The liquidation of the Karachay Autonomous Region in October 1943, Kalmyk Autonomous Soviet Socialist Republic (ASSR) in December 1943, and Chechen-Ingush ASSR in March 1944 led to the deportation of 366 thousand Karachays, Kalmyks, Ingush and Chechens to the Kazakh SSR (Polian 2001). They settled mostly in southern regions of Kazakhstan. As a result of reorganization of the Kabardian-Balkarian ASSR into the Kabardian ASSR in March 1944, 37 thousand Balkars were sent to Kazakhstan and especially Kyrgyzstan (Polian 2001). A decree of the State Committee on Defense, dated May 1944, obliged Crimean Tatars to be resettled from the territory of the Crimean peninsula. This decision was motivated by cooperation on the part of the region's population with the Nazi occupiers. Most Tatars were relocated to the Uzbek SSR and some to the Kazakh SSR. Kazakhstan received 4,501 Tatars out of 191,044 in total. According to a decree of the State Committee on Defense, dated 31 July 1944, Meskhetian Turks, Kurds and Khemshils (Muslim Armenians), totalling 92,300 persons, were deported from Georgia to Central Asia. Kazakhstan thereby received 28,600 deported people of the mentioned ethnicities (Polian 2001).

Along with the deportation of "punished nations" and cleansing of the borderlands, the Soviet government implemented the deportation of so-called "anti-Soviet" and "hostile" elements (Polian 2001) from different parts of the USSR, mostly to Siberia, Kazakhstan and Central Asia. Thus the deportation of *ounovtsy* – former members of the OUN (Organization of Ukrainian Nationalists) – from West Ukraine began in 1944 after the liberation of these territories by the Red Army (Polian 2001). The total number of deported Ukrainian nationalists was approximately 100 thousand persons. These deportations also included nationalists from the Baltic States and West Belorussia.

**Tab. 3** The ethnic structure of the evacuated population, as of 30 November 1941.

| Ethnicity | Evacuated population (in thou.) | Share (in %) |
|---|---|---|
| Russians | 51.8 | 32.1 |
| Ukrainians | 26.6 | 16.5 |
| Belorussians | 4.0 | 2.5 |
| Jews | 75.0 | 46.5 |
| Poles | 1.0 | 0.6 |
| Germans | 0.4 | 0.3 |
| Latvians | 0.3 | 0.2 |
| Estonians | 0.2 | 0.2 |
| Lithuanians | 0.1 | 0.1 |
| Others | 1.9 | 1.2 |

**Source:** Bazanova, N. F. (1987).

In addition to migration under the deportation policy of the Soviet government, migratory flows included those who were evacuated from the western part of the USSR to the east. For the first five months of the Great Patriotic War, the majority of industrial regions with 38% of land previously used for crop production and holding approximately 40% of the population were occupied (Olcott 1987). It was therefore decided to evacuate the productive forces of the country to the eastern regions. During the second half of 1941, more than 140 factories and various industrial units were placed in Kazakhstan (Amanzholuly and Kuzembayuly 1999). Given its remote location and mineral resources, Kazakhstan had become a powerful industrial arsenal for the front. The evacuation of plants and factories was accompanied by the inflow of specialists in different spheres of industry.

According to the authorized bodies responsible for registration of the evacuated population, approximately 161,400 persons had been evacuated to Kazakhstan as of 30 November 1941 (Tab. 3). Olcott (1987) points out that nearly 400 thousand evacuees were sent to Kazakhstan. Jews, Russians and Ukrainians were prevalent in the ethnic composition of the evacuated population, comprising 46.5%, 32.1% and 16.5% of the total, respectively.

The population of the Kazakh SSR began to increase after 1945. However, the size of the population was difficult to determine due to the fact that the first post-war census was conducted in 1959 – twenty years after the last pre-war census. Bazanova (1987) stated that the population of the Kazakh SSR was 5,807 thousand by 1945.

Generally speaking, the movement of populations within the Soviet Union in the pre-war period and during World War II was affected by the situation in the international arena and the external affairs of the Soviet Union. The western enlargement of Soviet territory in 1939–1940, achieved through occupation of the eastern territories of Poland and Finland and inclusion of the Baltic States into the USSR, was followed by the forced movement of the population of those areas to the east and central regions of the country. As mentioned before, the main reasons for those actions were to prevent the collaboration of nationalists from the occupied territories with Germany, and to suppress the attempts of some autonomous territories to return or gain independence, etc. The main results of these deportations, for Kazakhstan as well as other regions in the Asiatic part of the Soviet Union, were an increase in population size and a diversification of the ethnic composition of the receiving population.

### 3.3 Labour migration and population movement in the post-war period

The significant inflows into Kazakhstan in the post-war period were related to the industrial development of the country. The increase in the labour force occurred mainly due to resettlements from other republics of the USSR. These flows can be divided into two main streams. The first inflow stream – *orgnabor* (organized recruitment) – aimed to attract mostly skilled workers to industrial enterprises. In general, the resettlement plan for the period 1954–1960 considered 84,360 families. In fact, more than 300 thousand persons were settled in the Kazakh SSR (Amanzholuly and Kuzembayuly 1999). In addition, 39,441 repatriates immigrated to Kazakhstan from the People's Republic of China in 1955 (Ablazhei 2003). They were former Soviet citizens and were considered to be repatriates.

The second inflow stream included workers that were attracted to develop fallow and virgin lands during the Tselina campaign. According to a decree of the February-March 1954 Plenum of the Central Committee of the Communist Party "On increasing grain production in 1954–1955 through the development of virgin and fallow lands", 13 million hectares of virgin lands in Kazakhstan, Siberia, the Urals and the Volga region were designated for cultivation during the indicated years. The main Tselina areas in the Kazakh SSR were the Kustanay, Tselinograd, Kokchetau, North-Kazakhstan and Pavlodar oblasts. Prior to the development of virgin lands, the rural population of Kazakhstan was less than in the pre-war period, even though both the rural and urban population had been increasing gradually since 1945. This increase in population took place due to migratory flows to Tselina. In the first stage of the campaign (1954–1956), 640 thousand workers, or 45.3% of the rural population residing in the Tselina areas, came to Kazakhstan (Masanov et al. 2001). According to the available data, the population increase in Kazakhstan between 1954 and 1958 was 24%, and a similar indicator for the Tselina regions was 40–50%. Most of the migrants who arrived during this period were highly skilled workers.

Migratory flows in the 1950s generally had an effect on population formation in the Kazakh SSR. This era is characterized by significant population growth – approximately 3 million people – and can be conditionally divided into the period before the development of virgin lands and the period during the years of the Tselina campaign. The size of the population at the beginning of the first period in 1954 was 7,555 thousand, which represented an increase of 1,200 thousand people compared to 1949 (Central Statistical Office of the Kazakh SSR, 1971). Although population growth occurred in all economic regions, there was a difference among them – the highest increase was observed in the central region and the lowest in the northern regions. The most significant population growth was observed in the second period, from 1954 to 1959. This can be explained by intensive migratory flows into Kazakhstan, beginning with the development of Tselina. The population of Kazakhstan thereby increased by approximately 2 million people. With regard to regional distribution, the most significant population growth was observed in the central and northern regions of Kazakhstan, while the smallest growth occurred in the southern regions.

The first post-war census, conducted on 15 January 1959, showed a 1.5-fold increase in the population compared to 1939. The high rate of population growth ranked the Kazakh SSR in first place among Soviet republics. According to Table 4, the number of Kazakhs increased by 16.5%, whereas the Russian population increased by 38% and exhibited a growth rate 2.3 times higher compared to the Kazakhs. In addition, the number of other ethnicities as well as their share in the total population of Kazakhstan also increased. However, despite the increase in size among Kazakhs, Ukrainians and Uzbeks, their share in the total population decreased. The share of Kazakhs decreased to 30% and the share of Ukrainians and Uzbeks to 8.2% and 1.5%, respectively, in comparison with the 1939 Census. The reduction in the share of Ukrainians can be explained by the assimilation process, as most Ukrainians and Belorussians considered themselves to be Russian. With regard to regional distribution, Kazakhs became a minority in the northern, central and eastern regions, while remaining the major ethnicity in the western and southern economic regions.

**Tab. 4** The size and ethnic structure of the population in the current territory of Kazakhstan according to the 1959 and 1970 censuses.

| Ethnicity | Population size (in thou.) | | Share (in %) | | Index (in %) | |
|---|---|---|---|---|---|---|
| | 1959 | 1970 | 1959 | 1970 | 1959/1939 | 1970/1959 |
| Entire population | 9,310 | 13,009 | 100.0 | 100.0 | 152.8 | 139.7 |
| Kazakhs | 2,795 | 4,234 | 30.0 | 32.5 | 120.8 | 151.5 |
| Russians | 3,974 | 5,522 | 42.7 | 42.4 | 162.3 | 138.9 |
| Ukrainians | 762 | 934 | 8.2 | 7.2 | 116.1 | 122.5 |
| Germans | 660 | 858 | 7.1 | 6.6 | 714.2 | 130.1 |
| Tatars | 192 | 288 | 2.1 | 2.2 | 179.5 | 149.9 |
| Uzbeks | 137 | 216 | 1.5 | 1.7 | 132.3 | 158.4 |
| Belorussians | 74 | 198 | 0.8 | 1.5 | 236.4 | 267.9 |
| Others | 790 | 759 | 8.5 | 5.8 | 232.3 | 96.0 |

**Source**: Department of Statistics of the South-Kazakhstan Oblast. (undated). [Electronic res.]. Accessed in 2012 at http://www.ontustik.stat.kz/rus/perepis_nas/index.php.

Summarizing the virgin land campaign in Kazakhstan, Olcott (2002) points out that the goal of the Soviet government of developing a modern agrarian economy in Kazakhstan was neither wholly successful nor a total failure. The cultivation of land in the northern regions of Kazakhstan allowed for a transformation of the country's economy. As a result, 20 million hectares of virgin lands were cultivated during the period 1954–1960. Kazakhstan produced 597.5 million tons of grain during these years, which was a significant contribution to the all-union economy. These results were probably achieved due to the importation of labour from other parts of the Soviet Union. In addition, with the development of heavy industry in Pavlodar-Yekibastuz and Rudnyi, the intensity of migration in the northern and central regions of Kazakhstan was high compared to other regions. Approximately 2 million people came to Tselina during the period 1954–1962 (Smailova 2005; Kozina 2007) and about 500 thousand people were attracted as *orgnabor* from Ukraine, Belorussia and Lithuania during the period from 1961 to 1965 (Amanzholuly, Kuzembayuly 1999). In addition, about 200 thousand people who had emigrated during the Civil War and collectivization campaign in the 1930s returned from China in 1959–1963. The ethnic structure of returnees included Kazakhs, Uyghurs, Dungans, Russians, Uzbeks, Tatars and Kyrgyz. However, complicated relations between China and the Soviet Union as well as border conflict in the middle of the 1960s halted this process, and approximately 1 million Kazakhs remained there. The migratory flows of the 1960s are characterized by a gradual decrease by the end of the decade. In 1960–1964, net migration did not change significantly and showed a positive value of 61 thousand people (Smailova 2005). It did start to decrease, however, and turned negative in 1968.

According to the results of the 1970 Census (Tab. 4), the population of Kazakhstan numbered more than 13 million, representing an increase of 40% compared to the previous 1959 Census results. Taking into account the increase in size, the ethnic composition of the population showed that the share of some ethnicities in the total population had also increased compared to 1959. In particular, the proportion of Kazakhs increased to 32.5%, the share of Belorussians to 1.5%, of Uzbeks to 1.7% and of Uyghurs to 1%. Although a slight decline could be observed in the proportions of Ukrainians, Germans and other ethnicities in Kazakhstan, their numbers increased during this decade. An increase in the population size of the western regions of Kazakhstan took place mainly due to migration inflows. Mangystau oblast ranked first as a destination region for migrants, surpassing the previous main destination regions in the central, northern and eastern parts of Kazakhstan. This can be explained by the development of oil fields in the region.

By the mid-1970s, the intensity of migratory flows to Kazakhstan continued to decline. This trend can be explained by the general demographic situation in the USSR, which was faced with a sharp decline in the working age population, decreasing fertility and increasing mortality. Along with the influx of population to Kazakhstan at the beginning of the 1970s, people had begun to return to Russia and other western republics of the Soviet Union. This affected the share of Europeans in the total population, and it started to decrease. The number of returnees was 35 thousand in 1970 and increased gradually during the following years (Asylbekov, Kozina 1995). The number of immigrants from other regions of the Soviet Union decreased by 60% in the period 1966–1979. The main sending countries were Russia – 16.3%, Azerbaijan – 4.0%, Tajikistan – 2.2%, Uzbekistan – 1.6% and Turkmenistan – 5.5%. The 1979 Census results (Tab. 5) showed a population increase in Kazakhstan of 1,680 thousand people compared to 1970. In addition, during the period between the two censuses the share of Kazakhs increased by 1,059 thousand people, namely by 6%, whereas the share of the Slavic population decreased, especially that of Belorussians and Ukrainians, to 1.2% and 6.1%, respectively.

A decline in economic development by the mid-1980s, along with ethnic conflicts in some parts of the USSR, resulted in a crisis of the whole system that affected Kazakhstan as well. The outflow of population which was

**Tab. 5** The size and ethnic structure of the population in the current territory of Kazakhstan according to the 1979 and 1989 censuses.

| Ethnicity | Population size (in thou.) | | Share (in %) | | Index 1989/1979 (in %) |
|---|---|---|---|---|---|
| | 1979 | 1989 | 1979 | 1989 | |
| Entire population | 14,688 | 16,199 | 100.0 | 100.0 | 110.3 |
| Kazakhs | 5,293 | 6,497 | 36.0 | 40.1 | 122.7 |
| Russians | 5,991 | 6,062 | 40.8 | 37.4 | 101.2 |
| Ukrainians | 898 | 876 | 6.1 | 5.4 | 97.5 |
| Germans | 900 | 947 | 6.1 | 5.8 | 105.2 |
| Tatars | 313 | 321 | 2.1 | 2.0 | 102.6 |
| Uzbeks | 263 | 331 | 1.8 | 2.0 | 125.7 |
| Belorussians | 182 | 178 | 1.2 | 1.1 | 98.0 |
| Others | 700 | 807 | 4.8 | 5.0 | 115.2 |

**Source**: Alexeyenko, A. (2001).

observed in previous decades increased by the end of the 1980s, as the number of emigrants exceeded the number of immigrants. The destination countries for emigrants from Kazakhstan were mainly Russia, Ukraine and other western republics of the Soviet Union. The ethnic structure of migrants showed that Russians, Ukrainians and Belorussians were among the emigrants and Uzbeks, Kyrgyzs and Turkmens among the immigrants. However, emigration of population was not significant in 1983–1987 due to restrictive policy regarding exit from the USSR to go abroad. This administrative restriction was lifted in 1988, resulting in the emigration of 23,500 people from Kazakhstan. This number increased to as much as 92,300 in 1990 (Smailova 2005). The largest share of emigrants comprised Germans, Jews and Greeks returning to their historical homelands.

According to the 1989 Census results (Tab. 5), the size of the population in Kazakhstan was 16,199 thousand, representing an increase of 1,511 thousand compared to the previous census. The number of Kazakhs increased by 1,204 thousand, and their share by 4.1 percentage points. Although the number of Russians, Germans and Tatars increased slightly, their share decreased due to an increase in the share of Kazakhs. However, the share of Belorussians and Ukrainians continued to decrease along with a decrease in absolute numbers. With regard to the regional distribution of major ethnic groups, only two regions of the Kazak SSR, out of 19 in total, had less than one-quarter of the population who were non-Kazakh, namely Kyzylorda – 17.3% and South Kazakhstan – 23.5%. The share of the same population in Kokshetau, Pavlodar, East Kazakhstan, Tselinograd (Akmola), Kustanay, Karaganda and North Kazakhstan varied from two-thirds to four-fifths. In the other two regions this proportion ranged from 27.5% in Guryev (Atyrau) to 47.1% in Semipalatinsk.

## 4. Conclusion

For quite a long time, the dynamics of population in Kazakhstan have largely depended on migration processes. At the end of the 19th century, the country's territory became the main migration space for a large part of Eurasia which was under the governance of the Russian Empire and later of the Soviet Union. The large scale resettlement of Russian and Ukrainian peasants following the integration of the Kazakh Khanate into the Russian Empire, as well as different forms and types of voluntary and involuntary mass movements of populations during the Soviet period, completely changed the demographic picture of Kazakhstan. At the same time, the economic and political conditions established after the end of the Russian Civil War (1917–1920), along with new economic policies implemented in Soviet Central Asia in the 1920s and 1930s and their tragic consequences, resulted in massive outflows of population, namely Kazakhs. All these movements had a significant direct impact on population development within the territory, and on the size, ethno-demographic and other social characteristics of the population.

At the same time, the observed migration waves established conditions for potential follow-up migration, both out of and into the territory. Through these consequent movements and also the natural reproduction of immigrants, the original migratory movements have demonstrated their significant secondary impacts on population development. As a result, the consequences of migration observed in this article are clearly traceable up to the present day. They have principally determined the direction, size and structure of new migration waves crossing the borders of an independent Kazakhstan during more than the past 20 years. All these prior movements will then affect the population development of the country, for at least several decades to come.

This article presents only a part of the entire exciting but also often tragic story of migrations into and out of Kazakhstan. Our follow-up article is going to present a detailed insight into the recent history of large-scale migration movements which have affected the population developments of Kazakhstan, as well as their policy background and consequences for the ethno-demographic development of the country, from the time of independence in 1990 till the beginning of the 2010s.

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## RÉSUMÉ

**Rozsáhlé etnicko-demografické změny v Kazachstánu v průběhu 20. století: dramatický příběh masivních migračních vln**

Populační dynamika na území dnešního Kazachstánu byla po celé 20. století zásadním způsobem ovlivňována migračními procesy. Kromě migrace se do vývoje početního stavu obyvatelstva v území a jeho struktur promítaly válečné konflikty, hladomory i politické represe. Vývoj etno-demografické struktury je v celém období pozorování popsán s pomocí dat ze sčítání a analyzován v kontextu opatření vnitřní migrační politiky uplatňované mocenskými strukturami carského Ruska i Sovětského svazu. Podle výsledků sčítání z roku 1897 tvořili Kazaši čtyři pětiny z přibližně čtyř miliónů obyvatel žijících na sledovaném území. Při posledním sovětském sčítání o 92 let později zde žilo na 16 miliónů obyvatel, přičemž podíl kazašského etnika činil dvě pětiny. Území Kazachstánu se během 20. století stalo důležitým imigračním cílem pro početné skupiny obyvatel z různých části Eurasie, která byla nejprve pod nadvládou Ruska a posléze Sovětského svazu. Etničtí Kazaši ztráceli svou početní převahu postupně od druhé poloviny 19. do třicátých let 20. století. Vedle řady různě motivovaných imigračních proudů ke ztrátě této převahy významně přispěl hladomor z let 1932–1933. Ten byl přímým důsledkem uplatňování sovětské ekonomické politiky, zejména politiky kolektivizace a usazování kočovného obyvatelstva. V období před vypuknutím a v průběhu druhé světové války představovalo území Kazachstánu jeden z hlavních cílů procesu násilného přesídlování celých etnických skupin obyvatelstva z různých částí Sovětského svazu. Další výrazná migrační vlna souvisela s industrializací Kazachstánu po druhé světové válce a chruščovskou zemědělskou politikou, rozoráním stepí v severní částí centrálního Kazachstánu. Podle prvního poválečného sčítání v roce 1959 tak Kazaši ve výsledku tvořili již jen 30 % obyvatel Kazachstánu, nehledě na jejich intenzivnější přirozenou reprodukci, zatímco podíl samotného ruského etnika dosahoval v té době více než 40 %. Neúspěch zemědělské politiky z druhé poloviny 50. let a postupné uvolňování vnitřních politických poměrů v následujících třiceti letech vedly k migračnímu odlivu vybraných skupin obyvatelstva a spolu s pokračující intenzivní demografickou reprodukcí kazašského etnika znamenaly zvýšení jeho podílu na obyvatelstvu o deset procentních bodů, na uvedených 40 % v roce 1989. Přesto však až do rozpadu Sovětského svazu v Kazachstánu početně převládali příslušníci evropských etnik, zejména Rusové, Ukrajinci, Němci a Bělorusové.

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# RESIDENTIAL LOCATION CHOICE MODELLING: A MICRO-SIMULATION APPROACH

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**ABSTRACT**

Micro-simulation models have been increasingly used for studying various urban and regional processes. Here, two experimental micro-simulation models are applied to the study of residential location choices of inhabitants of the Tábor micro-region. A wide range of environmental and socio-economic characteristics are analysed for their potential impact on individual residential location choices. The micro-simulation approach proves to be useful for analysing not only housing, neighbourhood, and accessibility characteristics, but also of the interactions between the characteristics of the present and potential new residential locations of individual inhabitants and the role of their personal characteristics in their choice of a new residential location. The ability of the micro-simulation models to replicate the observed residential choices is evaluated by several quantitative indicators with special attention given to the stochasticity of the model behaviour, which is a typical feature of micro-simulation models. The limited availability of sufficiently disaggregated data describing the demographics of households, their socio-economic characteristics, and real estate market dynamics needs to be resolved in order to exploit the full potential of micro-simulation modelling in the future.

**Keywords:** residential location choice, micro-simulation modelling, discrete choice models, multi-nominal logit, micro-data

## 1. Introduction

This paper presents an experimental application of a residential location choice micro-simulation model for the Czech Republic. The two main goals of the experimental application were: a) to provide new insights into residential mobility, which is an essential urban process with a strong impact on changes in land use, b) to test the conditions for the applicability of micro-simulation models in the specific context of the Czech Republic, where there is no tradition of micro-simulation modelling and there is limited availability of suitable data.

Micro-simulation modelling is an alternative to the first generation of urban simulation models. The first generation models were considered to be too aggregated to represent the local variability of social and environmental characteristics, and consequently not able to properly represent the human-environment interaction. They were also considered too mechanical, as they ignored the complexity of human decision making, mainly the diversity of factors and constraints influencing the behaviour of individuals (Lee 1975).

Unlike the first generation models, micro-simulation models and related agent-based models are highly disaggregated. The decision making of individual agents – human actors, households and companies – is explicitly represented, and this makes it possible to explain the influences of a broad range of personal characteristics of agents, and also a broad range of characteristics of the environment related to individual agents. This ability makes micro-simulation and agent-based modelling an exceptionally suitable tool for studying the human-environment interaction on an individual level.

Several comprehensive micro-simulation models have been implemented so far: the UrbanSim model in Oregon, USA (Waddell, Wang, Charlton, & Olsen 2010; Waddell 2002), the San Francisco Bay area model, California, USA (Waddell 2013a), the Île-de-France model, France (IAURIF, THEMA 2004, 2005, 2007), the SimDELTA model in the United Kingdom (Simmonds & Feldmann 2007; Simmonds, Christodoulou, Feldman, & McDonald 2011; Simmonds 2010), the ILLUMASS model in Dortmund, Germany (Strauch et al. 2005; Wegener & Spiekermann 2011), and the ILUTE model in Toronto, Canada (Salvini & Miller 2005, 2005). These models are comprehensive enough to capture the interdependence of essential urban processes, especially population demographics, residential mobility, the evolution of individual companies and their mobility, transportation, the real estate and job markets, and the development of the urban structure and infrastructure. A typical comprehensive model consists of several autonomous sub-models, each addressing particular urban processes in a specific way.

The experimental micro-simulation models described here focus on residential mobility, and specifically on residential location choice. They are intended to supplement an already existing land use change model by the demand side of residential land use changes (Vorel & Grill 2013).

The experimental residential location choice models replicate the residential moves of individual inhabitants in the Tábor micro-region in the southern part of the Czech Republic. The Tábor micro-region consists of 79 municipalities with a total population of 80,641 and a population density of 80.5 inhabitants/km$^2$ in year 2011. The Tábor micro-region has an area of 1002 km$^2$ and approximates the catchment area (Local Labour System Area) of the town of Tábor, which is the main employment and administrative centre for the micro-region.

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The Tábor micro-region features a relatively large proportion of small municipalities: 44 out of 79 municipalities have less than 200 inhabitants in total and contain only 6.35% of the population of the micro-region. Only 10 municipalities have a population greater than 1000 inhabitants. These 10 more populous municipalities contain 78.93% of the population of the micro-region. The highest percentage (43.52%) of the population is concentrated in Tábor, which is the biggest municipality (34,430 inhabitants). Tábor is the only municipality in the micro-region with a population greater than 10,000 (2011 Population and Housing Census 2013).

The average age of the population of the micro-region is higher than the national and regional average. In 2011, the age index (the number of inhabitants older than 64 years per one inhabitant younger than 15 years) was 1.2 for the Tábor micro-region, as against 1.1 for the South Bohemia region and for the whole Czech Republic (2011 Population and Housing Census 2013).

The micro-region shows considerable differences in socio-economic characteristics between the highly-urbanized municipalities that form the central Tábor agglomeration (Tábor, Sezimovo Ústí and Planá nad Lužnicí) and the rural and less populated municipalities on the periphery, especially in terms of age structure, education status and employment structure. The age index is below 0.8 in the Tábor agglomeration municipalities, while it exceeds a value of 2 in the peripheral municipalities. The university-educated population is concentrated in Tábor and neighbouring municipalities, representing more than 8% of the population, while it represents only about 1% of the population in the peripheral municipalities. While the municipalities in the Tábor agglomeration have the biggest share of employment in industry and services, the peripheral municipalities have a share of up to 25% of employment in the primary sector (2011 Population and Housing Census 2013).

The spatial distribution of economic activities in the micro-region is also uneven. Most of the workplaces are concentrated in the Tábor agglomeration. The number of workplaces exceeds the number of economically-active inhabitants in only 10 municipalities (2011 Population and Housing Census 2013).

As will be documented in following text, the heterogeneity of the municipality characteristics, especially the population size, is a challenge for residential location choice modelling. Micro-simulation models are usually implemented as discrete choice models. The sections that follow will first present the theoretical background of discrete choice models and their most frequent operationalization in the form of multi-nominal logit models. Then the concept of residential mobility and an analysis of residential mobility factors will be presented. Two residential location choice models were assembled and evaluated for this purpose. Their usability, validity and the limits to their application in the context of the Czech Republic will be presented.

## 2. The concept of discrete choice micro-simulation models

### 2.1 Formal definition of discrete choice models

Discrete choice models operationalize the decision-making of individuals so that each individual makes choices over a finite number of choice alternatives. For example, an inhabitant planning to relocate chooses a place of residence among the municipalities in a micro-region. The choice of the individual is influenced by the characteristics of the choice alternatives, and also by her or his own personal characteristics. Discrete choice models quantify the effects of the characteristics on the choice process, and then use this knowledge to replicate the choices that an individual would make in various hypothetical situations.

Formally, discrete choice models are implemented as generalized linear models, most often as multi-nominal logit (MNL) models.[1] Logit models link the linear combination of $k \in K$ independent variables $\chi_k$ and their associated coefficients $\beta_k$ to the dependent categorical variable $J$. Variable $J$ represents the set of choice alternatives $j$, here represented by the individual municipalities. The independent variables $\chi_k$ represent the characteristics $k \in K$ of the individual choice alternatives as well as the personal characteristics of the individual making the choice. The coefficients $\beta_k$ related to independent variables $\chi_k$ represent the effect of the characteristics on the choice of alternative $j \in J$.

Unlike in linear regression models, the independent variables $\chi_k$ in MNL models are related to the dependent variable $J$ only indirectly via the link function called logit. Logit is defined as the log odds of the choice probabilities of the examined alternative $j$ and the choice probabilities of one of alternatives selected to be the reference alternative $j_r$:

$$logit(j) = \ln\left(\frac{P(choice = j)}{P(choice = j_r)}\right) = \sum_{k=1}^{K} \beta_k \chi_k \qquad (1)$$

The model parameters can be interpreted more easily by exponentiating both sides of the equation:

$$odds(j) = \ln\left(\frac{P(choice = j)}{P(choice = j_r)}\right) = \prod_{k=1}^{K} e^{\beta_k \chi_k} = e^{\sum_{k=1}^{K} \beta_k \chi_k} \qquad (2)$$

After transformation the individual $e^{\beta_k}$ (odds ratios) are directly related to the odds of the choice probabilities $odds(j)$ of alternative $j$. A unit change of independent variable $\chi_k$ causes an $e^{\beta_k}$ change of the choice probability of alternative choice $j$ relative to the probability of reference alternative choice $j_r$.

[1] Extensive information on the use of logit models for discrete choice modelling can be found in (Ben-Akiva & Lerman 1985; Liao 1994; Train 2009)

As the odds ratios $e^{\beta_k}$ indicate the change in the odds of the probabilities, and not the probability itself, another formal expression of a logit model must be used for directly predicting the probability of the choices:

$$P(j) = P(choice = j) = \frac{e^{\sum_{k=1}^{K}\beta_k x_k}}{\sum_{j=1}^{J} e^{\sum_{k=1}^{K}\beta_k x_k}} \quad (3)$$

As demonstrated, the logits, odds and probabilities are convertible to each other. The use of one or another form of logit model depends on the context of the use: the odds ratios *odds*(*j*) are the most suitable for interpreting the factor influencing the choice, while the probabilities *P*(*j*) are more often used for predicting the choices, utilizing Monte Carlo methods.

### 2.2 Estimating the parameter values

Each combination of parameter values $\beta_k$, $k \in K$ leads to a specific likelihood value, which is equal to the probability of the dependent variable being precisely predicted given the parameter values $\beta_k$. The goal is to set the values of parameters $\beta_k$ to maximize the likelihood of the model. Because the likelihood is usually too small for computational purposes, the log likelihood (*LL*) is used instead. The value of *LL* is in the range from negative infinity to zero; the closer to zero, the better the fit of the model to the observed data (Ben-Akiva & Lerman 1985; Liao 1994; Train 2009).

The parameters $\beta_k$ are themselves random variables, and the probability that they are equal to zero (null hypotheses) should be tested. The log likelihood ratio test, which is the ratio of the log likelihoods of two models – one with the tested variable and the other without the tested variable – is used as the test statistics:

$$-2(LL_{base\ model} - LL_{estimated\ model}) \quad (4)$$

This statistics follows the chi-square distribution with the degrees of freedom equal to the difference between the numbers of parameters used in the models.

Alternatively, we can use the Wald statistic, which tests the significance of individual parameters of the model:

$$Wald = \beta_i \,/\, standard\ error\ of\ \beta_i \quad (5)$$

## 3. Experimental micro-simulation models of residential location choice

Residential mobility is the output of two distinct decisions made by individual households: the decision to relocate, and the choice of a new residence (Coulombel 2011; Pacione 2009). Households decide to relocate when they reach a certain level of stress due to discordance between their housing needs, aspirations and expectations, on the one hand, and their actual living conditions, on the other.

Only the residential location choice is addressed by the experimental models presented here. The models are limited to a single catchment area, therefore replicating only short-distance mobility inside a micro-region. Long-distance mobility, which involves relocation from one housing and labour market to another, is exogenous to the simulation models. The available data on relocations is aggregated to the municipalities, which predetermines them to be choice alternatives.

Residential location choice can be influenced by a number of residence and neighbourhood characteristics, and also by the characteristics of individual households making the choice. Micro-simulation discrete choice models are suitable for studying the interdependences between the choices made by individuals and their personal characteristics. The explicit representation of the choice process enables one to experiment with choice constraints in various phases of the decision process (Ben-Akiva & Lerman 1985; Train 2009; Waddell 2002).

Residential location choice is the outcome of collective decision making by the members of a household. This is an extremely complex matter, as the interdependence of the activities of individual household members and their different interests leads to conflicts that have to be resolved during the decision making process (Axhausen 2005). To cope with the complexity, most of the reviewed residential location choice models assume that households, rather than individual persons, are the decision making entities. The decision-making processes are therefore usually modelled on the basis of the characteristics of households rather than on the characteristics of individuals. Demographic changes on the level of households, changes in economic status and in the working place of economically active household members, and the number of cars used by households, are characteristics that usually enter the decision process.

Unfortunately, no data on residential mobility of households is available at the moment in the Czech Republic. There is only data on the mobility of individual actors.[2] It was not possible to aggregate the individuals to households on the basis of their temporal and spatial coincidence of relocation, and by matching the personal characteristics of individuals, because significant numbers of individuals relocate in order to join each other in new households, and household formation would therefore need to be controlled on an individual level. Instead, the age of the individual was used to indicate her or his role in the collective decision making of the households. Young individuals were assumed to follow the decisions of their parents, and therefore to have a similar propensity to relocate and the same choice preferences as their parents.

Two approaches were adopted for an examination of the impact of personal characteristics on the decision

[2] Data on the movement of individual households will be available for research purposes in the new population census, when it is made available.

making process: a) a comparison of several models, each representing the decision making of individual population strata, b) measuring the interaction effects between personal and choice alternative characteristics in a single model that includes the whole population. The first approach leads to a stratified model, while the second approach leads to a general population model.

### 3.1 The stratified model

The stratified model stratifies the population into five age groups. Three sub-models bring together age groups of individuals that are expected to be joined by common households and therefore by similar residential choice behaviour.

– sub-model 1 for young-age group: 0–9 year-old and 25–34 year-old individuals,
– sub-model 2 for middle-age group: 10–24 year-old and 35–54 year-old individuals,
– sub-model 3 for old-age group: 55 year-old and older individuals.

With one exception, which is discussed below, all three sub-models use the same set of characteristics. The aim is to compare how their effects on the decision making differ between particular age groups. This approach was adopted although the effects of several characteristics were not significant in all three sub-models.

### 3.2 The general population model

The general population model does not stratify the population on the basis of personal characteristics, but it includes observed relocations of all members of the population in a single discrete choice model. To measure

**Tab. 1** The odds ratios $e^{\beta}$ of the stratified model with their statistical significance levels indicated: * 0.05 (t-value 1.95), **0.001 (t-value 3.29).

| **Personal characteristics and characteristics of a municipality** | **Name of variable** | **Odds ratios $e^{\beta}$ of sub-models** | | |
|---|---|---|---|---|
| | | **1** | **2** | **3** |
| The proportion of young age population (0–19 years old) | *YOUNG* | 12.29718** | 9.956643** | 1.38227 |
| Log of number of jobs | *JOBS* | 1.40641** | 1.31367 | 1.08789 |
| Average distance from municipality to railway station less than 3500 m | $I_{DR}(1)$ | 1.417592** | 1.68804** | 1.35744** |
| The proportion of apartment houses in municipalities having a population less than 1600 | $BD{*}I_{PC}(1)$ | 0.33425* | 0.56185 | 0.04773** |
| The proportion of apartment houses in municipalities having a population larger than 1600 | $BD{*}I_{PC}(0)$ | 1.75439** | 2.35679** | 1.47815** |
| The proportion of forest area | *FOREST* | 3.21694** | 4.11031** | 2.92046* |
| The percentage of municipality area designated as developable land | *DEVLAND* | 1.00398 | 1.02373* | 1.00042 |
| Log of number of public services | *PUBS* | 1.27027** | 1.27227** | 1.63406** |
| Minimum one basic school | $I_{BS}(1)$ | 1.54169** | 1.36665** | 3.29649** |
| Bechyňsko from outside | $I^e_{BE}(0) \wedge I^a_{BE}(1)$ | 0.22375** | 0.24837** | |
| Bechyňsko from inside | $I^e_{BE}(1) \wedge I^a_{BE}(1)$ | 5.85455** | 8.26806** | |
| Choustecko from outside | $I^e_{CO}(0) \wedge I^a_{CO}(1)$ | 0.38052** | 0.42309** | |
| Choustecko from inside | $I^e_{CO}(1) \wedge I^a_{CO}(1)$ | 4.282984** | 4.186688** | |
| Chýnovsko from outside | $I^e_{CY}(0) \wedge I^a_{CY}(1)$ | 0.92207 | 1.05846 | |
| Chýnovsko from inside | $I^e_{CY}(1) \wedge I^a_{CY}(1)$ | 2.45532** | 2.20266** | |
| Jistebnicko from outside | $I^e_{JI}(0) \wedge I^a_{JI}(1)$ | 0.73666** | 1.10580 | |
| Jistebnicko from inside | $I^e_{JI}(1) \wedge I^a_{JI}(1)$ | 0.83305 | 1.75303 | |
| Malšicko from outside | $I^e_{MA}(0) \wedge I^a_{MA}(1)$ | 0.88445 | 1.07926 | |
| Malšicko from inside | $I^e_{MA}(1) \wedge I^a_{MA}(1)$ | 1.01569 | 3.18381** | |
| Vožicko, from outside | $I^e_{VO}(0) \wedge I^a_{VO}(1)$ | 0.52209** | 0.59904** | |
| Vožicko from inside | $I^e_{VO}(1) \wedge I^a_{VO}(1)$ | 5.53449** | 11.21913** | |
| Bechyňsko | $I^e_{BE}(1)$ | | | 0.65437* |
| Choustecko | $I^e_{CO}(1)$ | | | 0.35921* |
| Chýnovsko | $I^e_{CY}(1)$ | | | 2.41013** |
| Jistebnicko | $I^e_{JI}(1)$ | | | 0.77554 |
| Malšicko | $I^e_{MA}(1)$ | | | 0.70229* |
| Vožicko | $I^e_{VO}(1)$ | | | 0.92920 |

how much the personal characteristics influence decision making, they must be linked by the interaction term with the characteristics of the choice alternatives. The interaction term indicates how much the personal characteristic modifies the effect that the municipality characteristic has on the choice probability of the municipality. The number of municipality characteristics was tested for their potential interactions with the age, education and family status of individual actors.

### 3.3 Interpreting the model parameters

Due to the non-linear relationship between the dependent and independent variables, the model parameters are not straightforward to interpret. The interpretation of three types of independent variables: continuous variables, categorical variables and variables entering into interaction with other variables will be demonstrated.

In the case of continuous variables, the $\beta_k$ parameters represent the change of the *logit*(*j*) caused by a unit change of a continuous variable *k*. For example, a unit change of the *DEVLAND* variable that represents the percentage of the area of the municipality designated for development will have the following effect on *logit*(*j*) in a single population model:

$$logit(j) = \beta_{DELAND} \times DEVLAND = 0.0368722 \times DEVLAND$$

To interpret the effect of the variable meaningfully, the parameter $\beta_{DEVLAND}$ has to be transformed to the odds ratio $e^{\beta_{DEVLAND}}$ The odds ratio indicates the increase of the choice probability of the municipality by $e^{0.0368722} = 1.03756$ times when *DEVLAND* increases by one per cent.

To evaluate the effects of categorical independent variables, their discrete values have first to be transformed to indicator variables, here referred to as dummy variables. An individual dummy variable is created for each category of original variable, with the exception of one implicit reference category. For example, the dichotomous variable *BS* is represented by single indicator variable $I_{BS}(1)$ indicates municipalities with at least one basic school, while $I_{BS}(0)$ indicates municipalities without a basic school. The value of parameter $\beta_{BS}$ of this dummy variable indicates the change in *logit*(*j*) caused by the presence of a basic school in the municipality, in this case for the choices made by the young population:

$$logit(j) = \beta_{BS} I_{BS}(1) = 0.432887 \times 1 = 0.432887$$

The probability that an individual member of the young population will choose a municipality with at least one basic school is $e^{0.432887} = 1.541702$ times higher than the probability that she/he will choose a municipality without a basic school.

Some continuous variables did not prove to be significant unless they were dichotomized. This is the case for several continuous variables: average distance from municipality to railway station shorter/greater than 3500 m, the municipality having more/less than 0.8 jobs per one economically-active inhabitant, and municipalities in which the housing stock expanded by more/less

**Tab. 2** The odds ratios $e^{\beta}$ of the general population model with their statistical significance levels indicated: * 0.05 (t-value 1.95), **0.001 (t-value 3.29).

| **The personal characteristics and characteristics of a municipality** | **Name of variable** | **Odds ratios $e^{\beta}$** |
|---|---|---|
| Average distance from municipality to railway station less than 3500m | *D_RAIL* | 1.17509** |
| Log of average road distance from the municipality to Tábor municipality (m) | *D_CENTRE* | 0.99994** |
| Job centre (more than 0.8 jobs per one economically active inhabitant) for old population | $I_{JC}(1)*I_{OA}(1)$ | 0.75261** |
| Job centre for young population | $I_{JC}(1)*I_{YA}(1)$ | 1.21213** |
| Job centre for middle-age population | $I_{JC}(1)*I_{MA}(1)$ | 1.1857** |
| Number of public services | *PUBS* | 1.01671** |
| Impact of the population size of the municipality on the effect of additional public services | *PUBS*PSIZE* | 0.9999995** |
| Presence of at least one basic school, if the relative increase in the number of flats between 1999 and 2006 is less than 4% | $I_{BS}(1)*I_{FG}(0)$ | 1.287709** |
| Presence of at least one basic school, if the relative increase in the number of flats between 1999 and 2006 is more than 4% | $I_{BS}(1)*I_{FG}(1)$ | 1.017397** |
| The proportion of flats in apartment houses in municipalities having a population less than 1600 | $BD*I_{PC}(0)$ | 0.92676 |
| The proportion of flats in apartment houses in municipalities having a population higher than 1600 | $BD*I_{PC}(1)$ | 2.63611* |
| The proportion of the population older than 65 years | *OLDPOP* | 0.97772** |
| The proportion of forest area | *FOREST* | 2.85211** |
| The percentage of the municipality area that is designated for development | *DEVLAND* | 1.03756** |
| Log of municipality area ($m^2$) | *ASIZE* | 1.69561** |
| Log of number of flats built between 1999 and 2006 | *NFLATS* | 1.27702** |
| The proportion of vacant family houses | *VACANCY* | 0.41312** |

than 4% between 1999 and 2006. The thresholds used to dichotomize the variables were empirically established in such a way that the statistical significance of the dichotomized variables was maximized. The municipality population characteristics were dichotomized on the basis of the municipality having the status of a town (the seven biggest municipalities with a population size more than 1600: Tábor, Sezimovo Ústí, Bechyně, Planá nad Lužnicí, Mladá Vožice, Chýnov and Jistebnice).

The parameters related to interaction terms are the most difficult to interpret. The interaction term indicates how one independent variable influences the effect that another independent variable has on the choice probability. Two types of interactions can be tested. The first type is an interaction between two or more characteristics of choice alternatives, here municipalities. For example, residential choices are influenced by the proportion of apartment houses in the municipality. The direction and the magnitude of the influence of this characteristic is moderated by the municipality population size.

The second type is the interaction between personal characteristics and the characteristics of the choice alternatives. The following example demonstrates how the job concentration in municipalities is evaluated differently by each age group. The age is represented by categorical variables transformed to dummy variables:

$I_{YA}(1)$ indicates the age of an individual 0–9 or 25–34, otherwise $I_{YA}(0)$;

$I_{MA}(1)$ indicates the age of an individual 10–24 or 35–54 years, otherwise $I_{MA}(0)$.

The dummy variable $I_{MA}$ for the age group 55 and higher is a reference category and is therefore not expressed explicitly in the model.

Job concentration is represented by dummy variable $I_{JC}$: a municipality is considered as a job centre $I_{JC}(1)$ if the number of jobs located in the municipality covers at least 80% of its economically active inhabitants (16 out of 79 municipalities), otherwise $I_{JC}(0)$.

Having both categorical variables transformed to dummy variables, the interaction term can be expressed as:

$$logit(j) = \beta_{OA}I_{JC} + \beta_{YA}I_{JC}I_{YA} + \beta_{MA}I_{JC}I_{MA} = -0.284205I_{JC} + 0.476586I_{JC}I_{YA} + 0.454538I_{JC}I_{MA},$$

where $\beta_{OA}$ indicates how the choices of the old age groups are influenced by the municipality being a job centre, $\beta_{YA}$ indicates how this influence differs when the choice is made by a member of the young age group, and $\beta_{MA}$ indicates how this influence differs when the choice is made by a member of the middle age group.

The resulting effects on the residential choice of a municipality being a job centre is:

$$logit(j) = -0.284205 + 0.476586 \times 1 + 0.454538 \times 0 = 0.192381$$

for an individual belonging to the young age group,

$$logit(j) = -0.284205 + 0.476586 \times 0 + 0.454538 \times 1 = 0.170333$$

for an individual belonging to the middle age group, and

$$logit(j) = -0.284205 + 0.476586 \times 0 + 0.454538 \times 0 = -0.284205$$

for an individual belonging to the old age group.

The β coefficients are related to the *logit*(*j*). However, they can be easily transformed to $e^{\beta}$ to represent the odds of choice probabilities. The municipality being a job centre changes the probability that it will be chosen by an individual belonging to the young age group $e^{0.192381} = 1.212132$ times and $e^{-0.284205} = 0.7526123$ times if the individual belongs to the old age group. This result indicates a significant impact of a personal characteristic on the choices.

## 4. Residential location choices analysed

The reviewed applications of residential location choice models provided an initial list of characteristics related to choice alternatives and individuals making the choice (IAURIF, THEMA 2004, 2005, 2007; Patterson, Kryvobokov, Marchal, & Bierlaire 2010; Vorel & Franke 2012, 2012; Waddell & Borning 2008). The listed characteristics supported by suitable data were analysed for their potential impact on the observed choices of individuals by means of discrete choice models.

The analyses were performed by experimental residential location choice models that were coded in Python programming language. The Open Platform for Urban Simulation (OPUS) open source libraries, together with the Biogeme open source libraries for estimating discrete choice models were used for the estimation and simulation runs of the experimental models ("Biogeme" 2013; Waddell 2013b). The data was stored in the PostGIS database and visualized by QGIS (PostGIS 2013, QGIS 2013).

### 4.1 The interaction between characteristics of present and future residential locations

The characteristics of the present residence, its neighbourhood and its proximity to the potential new residence are assumed to be significant for residential choices (Coulombel 2011; IAURIF, THEMA 2007). As the combination of characteristics is unique for each individual making a decision, their effect on decision making must be evaluated on an individual level. The interaction terms combine the characteristics of present and potential new residential locations. Out of all tested interactions between the characteristics of present and future residential location, only their proximity proved to be significant.

To operationalize the proximity term, the municipalities were sorted into seven sub-regions: Bechyňsko, Malšicko-Opařansko, Choustnicko, Mladovožicko, Chýnovsko, Táborsko, Jistebnicko. The seven sub-regions were delimited by the Planning Analytical Documents


**Fig. 1** Division of the Tábor microregion into seven sub-regions (MÚ Tábor, 2012).

2010 of ORP Tábor on the basis of micro-catchment areas and similarities of the social and natural characteristics of the municipalities (MÚ Tábor 2012). Delimitation of the sub-regions was aimed at aggregating the neighbouring municipalities into groups with distinctive characteristics. Municipalities that are located in the same sub-region are considered to be proximal municipalities, in the sense that their characteristics are more similar than the characteristics of non-proximal municipalities. It is assumed that the adjacency as well as the similarities of the municipalities in the same sub-region leads to social and emotional attachment of their inhabitants and to the higher proportion of relocations that take place inside sub-regions (Coulombel 2011; Pacione 2009).

Two indicator variables $I^e_s$ and $I^a_s$ were created for each sub-region, where index $s$ is replaced by a concrete sub-region identification (see table 1), where:

$I^e_s$ is equal to one $I^e_s(1)$ when the present residential location of the individual is inside the sub-region, otherwise $I^e_s(0)$ and

$I^a_s$ is equal to one $I^a_s(1)$ when the potential alternative residential location of the individual is inside the sub-region, otherwise $I^a_s(0)$.

If both indicator variables $I^e_s(1)$ and $I^a_s(1)$ are equal to one, then the residential move is realized within sub-region $s$, if $I^e_s(0)$ and $I^a_s(1)$, then the residential move to sub-region $s$ is realized from another sub-region.

The interaction term $logit(j) = \beta_S I^a_s + \beta^*_s I^e_s I^a_s$ was then tested, where:

$\beta_S$ represents the change of logit if sub-region $S$ is selected by an individual;

$\beta^*_s$ indicates the change of logit if the individual is living in the same sub-region.

The logit coefficients can be easily transformed to $e^{\beta_S}$ and $e^{\beta^*_s}$ to represent the odds of choice probabilities.

Proximity is not evaluated in the general population model, because the use of higher level interaction terms, including age, sub-region and the characteristics of the choice alternatives could not be evaluated with the limited number of available observations.

In the stratified model, only the young age group and the middle age group sub-models evaluated the impact of proximity. The number of 962 observed residential choices made by individuals of the old age group (individuals older than 54 years) did not allow the interaction between the present and the potential new residential location $\beta^*_s I^e_s I^a_s$ to be evaluated, and only the main effect

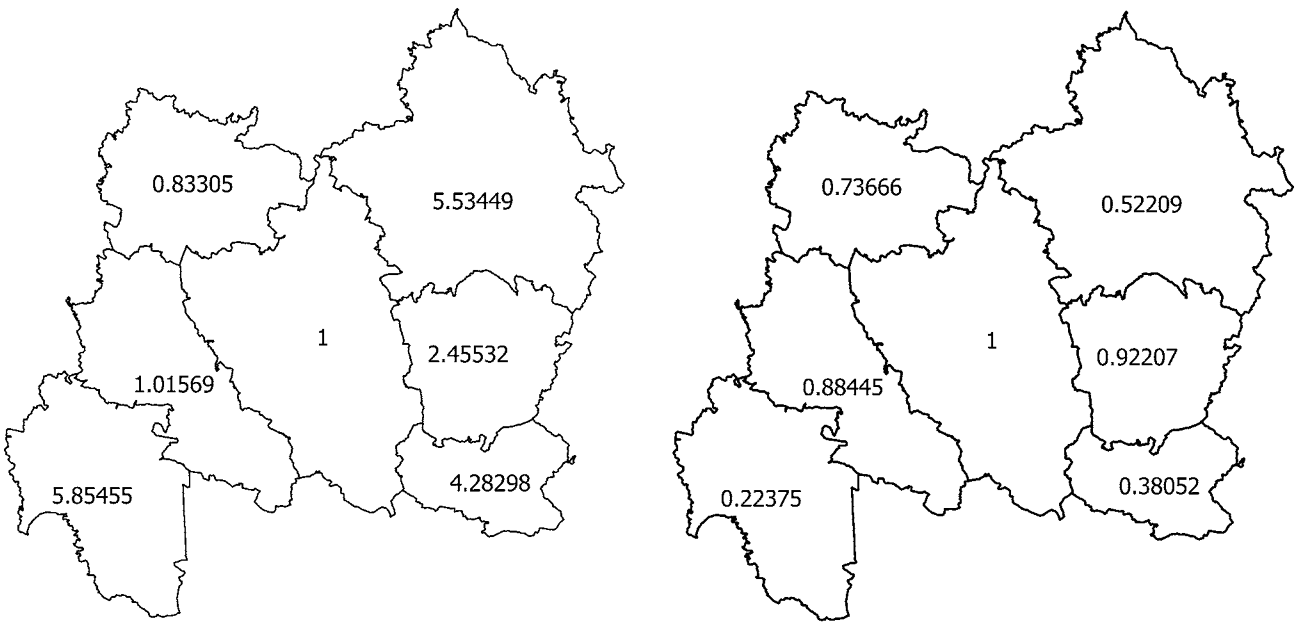



**Fig. 2** The relative probability of a sub-region being chosen (Táborsko sub-region is reference choice) for individuals in the young age groups. On the left are individuals living in the sub-region, on the right individuals living outside the sub-region.

– attractiveness of new residential location $\beta_S I^a_s$ – was evaluated.

The relative probability (chance) of a sub-region being chosen by an individual compared to the reference Táborsko sub-region was evaluated. The impact of proximity proved significant for the choices of the Bechyňsko, Choustecko and Vožicko sub-regions. The effect of proximity is strong enough even to reverse the evaluation of the municipalities in those sub-regions: the evaluation changes from negative, when it is made by residents of other sub-regions, to positive, when it is made by residents living in the evaluated sub-regions.

For example, given that an individual is a member of the young population living in the Bechyňsko sub-region, the probability that she or he will relocate inside this sub-region is exp(1.767) = 5.855 higher than the probability that she or he will relocate to the reference Táborsko sub-region. For another individual living outside the Bechyňsko sub-region, the choice probability of the Bechyňsko sub-region is only exp(−1.497) = 0.224 of the Táborsko sub-region choice probability. The Bechyňsko sub-region therefore has 5.855/0.224 = 26.14 higher probability of being chosen by an individual already living in this sub-region than by an individual living in another sub-region.

The choices of municipalities in other sub-regions – Malšicko, Chýnovsko, Jistebnicko – are less dependent on the present location of the individual. This indicates that their self-containment is lower than the self-containment in the other three sub-regions.

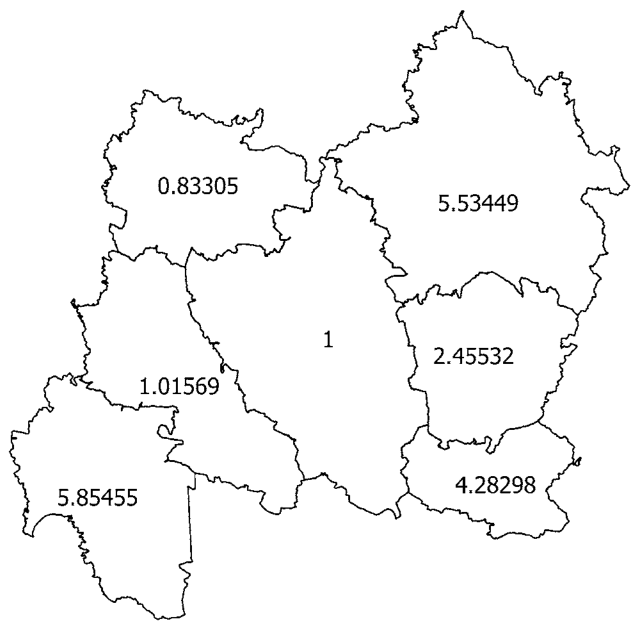
All sub-regions have the highest relative probability of being chosen by their own inhabitants, with the exception of Jistebnicko for the young population. Attachment to sub-regions is weaker in the case of the young age groups. The reviewed literature suggests that the weaker attachment of young age groups could be due to their search for a new job, usually a first job, and due to the formation of a new household. This usually leads to more distant relocation (migration) than with other age groups. However, the relocation of middle age population is usually caused by changing housing needs only, and there are much less strong incentives for more distant relocation (Coulombel 2011; Pacione 2009).

For example, the probability that a middle age individual living in the Bechyňsko sub-region will relocate inside the sub-region is exp(2.1124) = 8.26806 times higher than the probability that the individual will relocate to the reference Táborsko sub-region. However, the probability is only 5.855 in the case of the young age group. An individual from the middle age group therefore has a 8.268/5.855 = 1.41 higher probability of relocating inside the Bechyňsko sub-region than an individual from the young age group.

For the young groups, the Táborsko sub-region, which contains the biggest urban municipalities – Tábor, Sezimovo Ústí and Planá nad Lužnicí – is the second most attractive choice, while for the middle age groups the sub-regions adjacent to the Táborsko sub-region – the Malšicko, Chýnovsko, Jistebnicko sub-regions – are the second best choice. The relatively high employment and socializing opportunities in the Tábor agglomeration could explain the attractiveness of the Táborsko sub-region for the young age groups. Different factors, namely disposable land for development in municipalities adjacent to the Tábor sub-region, influence the residential choice of the middle age population.

### 4.2 Housing characteristics

The proportion of flats in apartment houses *BD* significantly influences the residential location choice in both



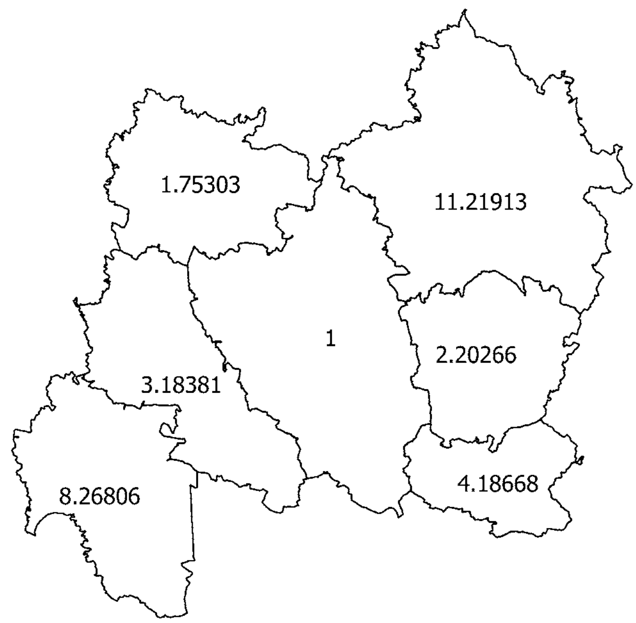




**Fig. 3** The relative choice probability of a sub-region, in which the individual is already living (Táborsko sub-region is reference choice). On the left is young age group, on the right the middle age group.

models. In addition, the population size of a municipality significantly modifies the effect of this characteristic, so that the proportion of flats in apartment houses increases the choice probability of municipalities that are population centres $I_{PC}(1)$ and reduces the choice probability of municipalities that are not population centres $I_{PC}(0)$. Population centres are municipalities with the status of a town. In the Tábor micro-region, the population centres have a minimum population of 1600. Increasing the proportion of flats in apartment houses *BD* by 10% increases the probability of population centre choice 1.101 times, but decreases the choice probability 0.992 times if the municipality is not a population centre. This conclusion corresponds to the observed higher vacancy rate and lower price of flats in apartment houses in small, rural municipalities than in population centres.

The single population model revealed the significance of two additional housing characteristics. The number of flats built between 1999 and 2006 *NFLATS* has a positive influence on the choice of a municipality. 10 new flats built between 1999 and 2006 increased the probability of municipality choice 1.756 times, but 100 new flats increased the probability only 3.083 times. This demonstrates that the effect of a unit increase of an independent variable is not necessarily always constant for all values of the variable.

A high proportion of vacant family houses *VACANCY* has a negative influence on the residential location choice. An increase in the vacancy rate by 10% decreases the probability of municipality choice 0.915 times.

The quality of the flats, indicated by the proportion of the highest quality class (first class) did not prove to be significant in either of the two experimental models. The age structure of the housing stock[3] was only partially significant, as only the periods of construction between 1920 and 1945, and between 1981 and 1990 proved to have a statistically significant, though rather weak, effect on the attractiveness of a municipality. The absence of the price of flats as a trade-off characteristic compensating for differences in the quality of flats could be a reason for the non-significance of the quality and age of flats. The prices of flats were not included due to unavailability, and consequently neither quality characteristics nor age characteristics were included in the experimental models.

In reality, it is an individual house or flat – and not a municipality – that is being chosen by the inhabitants. Aggregating housing characteristics on the level of a municipality leads to a loss of information about the local variability of the housing stock characteristics. The aggregated housing characteristics can then potentially correlate with the neighbourhood characteristics, causing multicollinearity and statistical insignificance of some housing characteristics. In order to model residential choices on the level of individual houses and flats, it would be necessary to observe the characteristics and also the choices on the level of individual dwellings, as was demonstrated in applying the UrbanSim micro-simulation model in the San Francisco Bay area (Waddell 2013a). In the Czech Republic, there is no data available on choices of individual houses and flats, so it is not at present possible to model the choices on the level of individual houses and flats.

### 4.3 Neighbourhood characteristics

The evaluation of the natural, social and economic characteristics of a neighbourhood, as well as the public amenities, the land use and the percentage of the area of the municipality designated for development was made in terms of their effects on individual choices.

With regard to natural characteristics, the proportion of the area of the municipality covered by forest had a significant positive effect on choice probability. A one per cent increase in forest cover increases the choice probability of the municipality 1.011 times for the young population and 1.014 times for the middle age population. Other natural characteristics: proximity to water flows, average slope of the terrain, proportion of arable land, and proportion of areas of nature protection were not significant. This conclusion does not correspond to our expectation, or to the evidence presented in the reviewed literature (IAURIF, THEMA 2004, 2005, 2007; Patterson, Kryvobokov, Marchal, & Bierlaire 2010; Vorel & Franke 2012, 2012; Waddell & Borning 2008). Averaging the characteristics on the level of municipalities with average size 12.6 $km^2$ makes the model ignore the important part played by intra-municipality variation in natural characteristics.

With regard to social and economic characteristics: ethnic composition, income and household size were significant in most of the reviewed residential location choice models that have been applied in metropolitan regions (Coulombel 2011; IAURIF 2007; IAURIF, THEMA 2005; Waddell & Borning 2008). Unfortunately, data on income and ethnicity is not available with a sufficient level of detail in the Czech Republic. Data on household sizes is regularly provided by the general population census, but only in ten-year intervals. The 2011 census data was not available for the experimental models presented in this paper. Because of lack of data, the effect of income, ethnicity and household size characteristics on residential location choice could not be evaluated.

The level of economic activity is indicated by the number of jobs located in a municipality. In correspondence with the reviewed location choice models, both models indicate that higher economic activity in a municipality makes the municipality more attractive for residential use (IAURIF, THEMA 2004; Waddell & Borning 2008; Wegener 2011). An increase in the number of jobs in a municipality from 100 to 200 increases the choice probability

[3] The age structure of the housing stock was indicated by the percentage of flats built in the periods: before 1919, 1920–1945, 1946–1960, 1961–1970, 1971–1980, 1981–1990 and 1991–2001.

1.266 times for the young population and 1.06 times for the old population. An increase from 900 to 1000 jobs increases the choice probability only 1.037 times for the young population and 1.009 times for the old population. This shows that the effect of a marginal change in the number of jobs is not constant.

The interaction between the economic activity in a municipality and the age of the individual making the choice proved to be significant in the single population model. A municipality that is a job centre $I_{JC}(1)$ (a municipality having more than 0.8 jobs per one economically active resident, i.e. 20% of all municipalities in the micro-region) has a 1.212 times higher probability of being chosen by the young population, 1.1857 times higher for the middle age population and 0.756 times lower for the old population than a municipality that is not a job centre $I_{JC}(0)$.

The natural logarithm of the number of all public services (nursery schools, basic and secondary schools, health-care facilities, cultural facilities, social facilities) in municipalities *PUBS* proved to have a statistically significant effect on the choice of a residential location. The stratified model indicates that the presence of public services in a municipality has a positive influence on its attractiveness for all age groups, especially for the old population. For example, an increase from 10 to 11 in the number of public services in a municipality increases the choice probability 1.023 times for the young population and 1.048 times for the old population. However, an increase in public services from 100 to 101 increases the choice probability only 1.002 times for the young population and 1.004 times for the old population. The effect of a marginal change in the number of public services is not constant, but is generally expected to follow the law of diminishing marginal return.

The $PUBS \times PSIZE$ interaction term of the general population model indicates that the positive effect of public services is slightly reduced with increasing population size of the municipality causing an increased number of inhabitants per public service.

Out of specific public services, only the presence of a basic school proved to have a significant effect. The presence of at least one basic school $I_{BS}(1)$ significantly increases the attractiveness of a municipality. The interaction term $I_{BS} \times I_{FG}$ in the single population model indicates that the importance of the characteristic for the choice paradoxically decreases in the case of fast-growing municipalities $I_{FG}(1)$ with a bigger than 4% growth in the housing stock between 1999–2006. The presence of a basic school in these municipalities increases the choice probability only 1.017 times, while the choice probability increases 1.288 times for a municipality with a slowly growing housing stock $I_{FG}(0)$. The inhabitants choosing the fast growing municipalities probably anticipate the location of a basic school in the future, or make use of the relatively good accessibility to basic schools in the nearby Tábor municipality.

Concerning access to public transportation, spatial proximity to a railway station $I_{DR}$ has a positive effect on all age groups, the highest positive effect being on the middle-age population. For the young age group, a municipality with an average distance to a railway station less than 3.5 km $I_{DR}(1)$ has a 1.42 times higher probability of being chosen than a municipality with a longer average distance to a railway station $I_{DR}(0)$. The proximity of a railway station increases the probability of the choice 1.69 times for the middle-age population, and only 1.36 times for the old age population in stratified model. In the general population model, the choice probability is 1.18 times higher for all age groups together.

Unlike proximity to a railway station, the number of bus stops in a municipality did not prove to be significant. The most probable reason is the relatively even spatial distribution of bus stops and the resulting low variance across municipalities.

The supply of land designated by the land use plan for urban development *DEVLAND* was confirmed by both models to be a significant factor for residential choice. A one per cent increase in the area of the municipality designated for development increases the choice probability of the municipality 1.004 times for the young age group, 1.024 times for the middle age group, but only 1.00042 times for the old population in stratified model. These effects are statistically insignificant for the young population and for the old population. The land use mix, although generally considered to have a significant impact on residential choice, did not prove to be significant at municipality level. The variability of the land use composition probably needs to be captured on a much finer scale than on the level of municipalities with an average area of 12.6 km$^2$.

#### 4.4 Overall accessibility

Access to regular work, education and shopping facilities are generally considered to have a significant influence on residential location choice. In an ideal case, the access should be evaluated by a transportation model in terms of transportation time or transportation cost. As no such transportation model has been implemented in the Tábor micro-region, the accessibilities were measured only in terms of road distance.

In reality, each individual has a unique action space, resulting from the location of her or his individual activities in the territory. The decision making of each individual should therefore be analysed with regard to her or his individual action space. Because data on the co-location of activities on an individual level is not usually available, general accessibility to activities is used instead. The ILUTE and ILLUMASS micro-simulation models are the only exceptions, being based on purpose-made surveys (activity logs) of the daily activities of the residents (Salvini & Miller 2005; Wegener 2005). In the case of the experimental models presented here, single general accessibility to work and services activities was tested.

To cope with the high collinearity between work, services and housing characteristics, services were selected as the type of activity that best represents the importance of a municipality for the inhabitants in the Tábor micro-region. The municipalities were ranked according to the number of public services: the town of Tábor as the primary urban centre in the micro-region had 285 public services, while Bechyně, Opařany, Chotoviny, Mladá Vožice, Chýnov, Sezimovo Ústí and Planá nad Lužnicí, as secondary urban centres, had more than 13 but fewer than 49 public services. The effect of the distance by road to both the primary urban centre and the secondary urban centres was tested. Only the average road distance to the town of Tábor $D_{CENTRE}$ in the general population model had a significant effect on residential choice. An increase of ten kilometres in road distance from Tábor decreases the probability of municipality choice 0.51 times, everything else being equal. The fact that this characteristic is not significant in the stratified model implies that accessibility measured by road distance is somewhat weaker predictor for residential choice than other characteristics, such as the distance of the residential move and neighbourhood characteristics.

Distance thresholds to important roads (highways, motorways and first-class roads) as another accessibility measure did not prove to be significant for most of the tested models, and when they were significant they had only a small impact on the choice. These characteristics were therefore not included in the final models.

The weak effects of global accessibility factors correspond to the generally accepted thesis that when access to regular activities in the territory is reasonably good, accessibility as a location factor is not decisive for residential choice.

## 5. An evaluation of the experimental models

Various indicators can be applied to judge the quality of simulation models. Here, four indicators: McFadden $R^2$, mean absolute percentage errors (*MAPE*), relative errors (*RE*) and the individual choice success rate (*ICSR*) were applied.

### 5.1 McFadden $R^2$

McFadden $R^2$ represents the proportion of variance explained by the model. It is equivalent to the coefficient of determination used in linear regression. McFadden $R^2$ is defined as the ratio between the log likelihood (*LL*) of the estimated model and the *LL* of the base model (Ben-Akiva & Lerman 1985; Liao 1994; Train 2009):

$$R^2 = 1 - (LL_{estimated\ model} / LL_{base\ model}) \tag{6}$$

The base model assumes that no characteristics of the alternatives have an impact on the choice process, and that all alternatives therefore have an equal probability of being chosen.

The values for McFadden $R^2$ in the general population model and in all three sub-models of the stratified model are in the range from 0.30 to 0.33 (see table 3), and they are comparable to values from 0.20 to 0.32 of the reviewed location choice models (IAURIF, THEMA 2004 2005, 2007; Patterson et al. 2010; Vorel & Franke 2012, 2012; Waddell & Borning 2008).

### 5.2 Mean absolute percentage error (*MAPE*)

The other three indicators of model quality focus on differences between the simulated choices and the observed choices. The simulated choices are realized by Monte Carlo simulation based on the probabilities calculated by the MNL models. The number of simulated choices of each municipality is therefore stochastic variable. To analyse its variance, it is necessary to run the simulation a number of times. Here, 100 simulation runs were performed and the standard deviations of the relative errors between the number of observed and simulated choices of individual municipalities were evaluated. The average number of choices was used to evaluate the *MAPE* and *RE* indicators.

**Tab. 3** Indicators of the quality of the experimental simulation models.

| Characteristics of municipality | The sub-models of stratified model | | | General population model |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| Number of observations | 4586 | 4555 | 962 | 10103 |
| Log-likelihood | −13364 | −13487 | −2837 | −30587 |
| Null Log-likelihood | −20038 | −19902 | −4203 | −44144 |
| McFadden $R^2$ | 0.33198 | 0.32127 | 0.32131 | 0.30672300000 |
| Suggested \|t-value\| | 2.90357 | 2.90240 | 2.62088 | 3.03654206103 |
| Akaike's Information Criterion (AIC) | 26771 | 27017 | 5705 | 61208 |
| ACE (sub-models) | 0.55200 | 0.56400 | 0.90300 | 0.10200000000 |
| ACE | 0.16600 | | | |

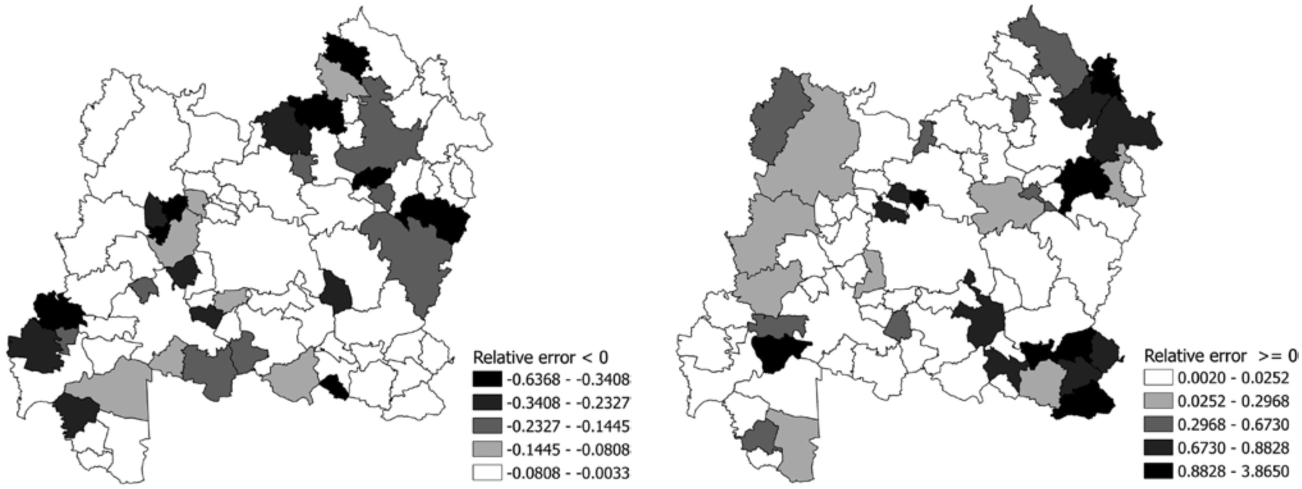



**Figure 4**. The relative error *RE* of the simulated choices for each municipality in the Tábor micro-region: on the left are negative errors indication overestimated municipalities, on the right are positive errors indicating underestimated municipalities.

The mean absolute percentage error (*MAPE*) averages the relative differences between the number of observed $O_n$ and simulated $S_n$ choices of individual municipalities $n$ over all municipalities in the choice set $n \in N$ (IAURIF, THEMA 2004):

$$MAPE = \frac{1}{N}\sum_{n=0}^{N} \frac{|O_n - S_n|}{O_n} \quad (7)$$

The *MAPE* of the general population and stratified model is equal to 0.102 for the general population model and 0.166 for the stratified model. Both values are similar to *MAPE* 0.12 of the UrbanSim household location choice model applied in the Puget Sound region in Washington, USA[4] (Waddell & Borning 2008).

### 5.3 Relative errors (*RE*)

Unlike *MAPE*, *RE* represents the relative difference between the number of simulated $S_n$ and observed $O_n$ choices of individual municipalities $n \in N$:

$$\mathrm{RE} = (O_n - S_n) / O_n \quad (8)$$

In 67% of the municipalities, the maximum relative error ranged from −29.9% to 74.4% for the general population model and from −25.9% to 68.8% for the stratified model.

The *RE* of both models can be compared to the *RE* of the reviewed residential location choice models: the *RE* in the Puget Sound application was in the range from −22% to 124%, with 9 alternative choices. The *RE* in the Lyon application, with 777 Transportation Analysis Zones as choice alternatives, was in the range from −2% to +2% in 11% of the choices, from −5% to +5% in 29% of the choices, and from −10% to +10% in 67% of the choices. In the Paris application, the absolute *RE* was smaller than 15% in 67% of the choices (IAURIF 2007).

The relatively high *RE* of the experimental models presented here is due to a) the overall small number of observed choices compared to the reviewed applications typically applied on the scale of metropolitan regions, b) the uneven distribution of the number of choices across the municipalities. For example, the residential location choice model in Paris was based on 5.893 million observed relocations of individuals between 1991 and 2001 (IAURIF, THEMA 2007), in comparison with 10,103 observed residential choices made between 2001 and 2011 in the Tábor micro-region. In addition, the number of choices is unevenly distributed among the municipalities in the Tábor micro-region: 11 out of 79 municipalities were selected less than 10 times during the 10-year observation period. As is indicated in following scatterplot in figure 5, municipalities with a number of observed choices lower than 100 are associated with high *RE* values. This will lead to the aggregation of least frequent choice alternatives in future versions of the models.

### 5.4 Individual choice success rate (ICSR)

The age characteristic entering the choices in the general population model and the stratified model is expected to improve the prediction of choices on the level of individual actors. To test the improvement, the proportion of individuals having the simulated choice identical with the observed choice is measured by the individual choice success rate (*ICSR*). The two models were compared with the random model, which does not include the age characteristic. The *ICSR* for the single population model was 0.112, while for the stratified model the value was 0.118, but it was only 0.0126 for the random model. This simple demonstration shows that the inclusion of

[4] The comparison of the models has to take into consideration differences in the number of alternatives in the choice set: 9 alternatives for the Puget Sound application, and 79 alternatives for the experimental models presented here.

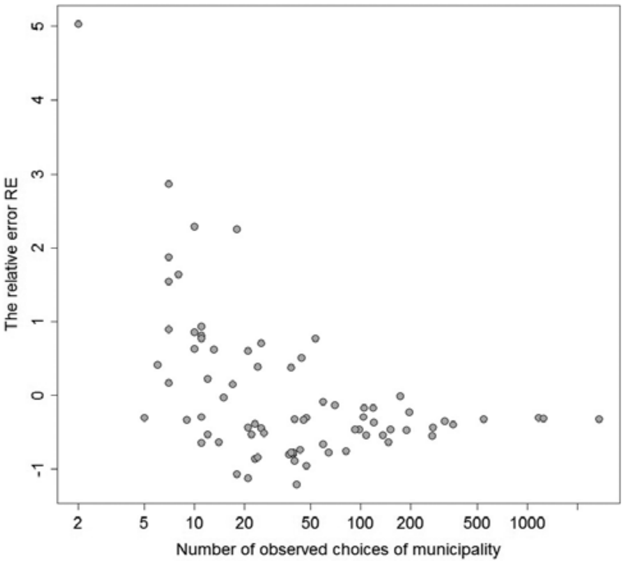



**Fig. 5** The relation between the number of observed choices of a municipality and the relative errors *RE* of simulated choices of the municipality.

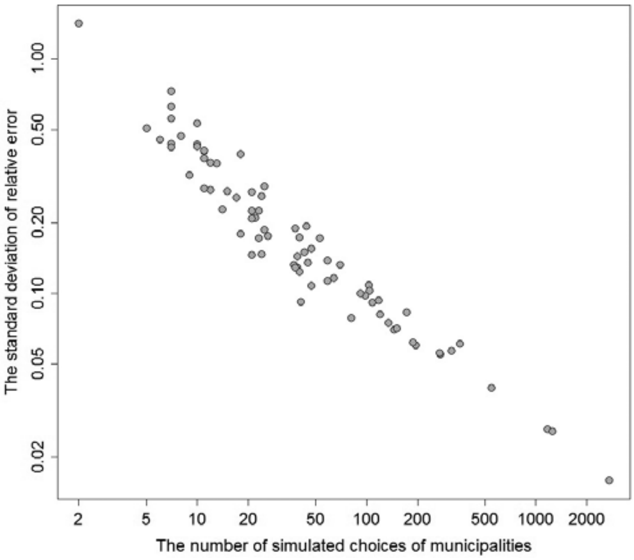



**Fig. 6** The relation between stochastic variation and number of simulated choices.

just a single personal characteristic in the micro-simulation model leads to a significant improvement in the predictions of individual choices.

### 5.5 Stochasticity of the model

The micro-simulation models presented in this paper are principally stochastic. Stochastic variation is measured by the standard deviation of relative errors *RE* on a sample of 100 simulation runs. The scatterplot below in figure 6 indicates that the stochastic variation is indirectly proportional to the number of simulated choices.

The stochastic variation depends not only on the number of simulated choices, but also on the number of alternatives in the choice set. The greater the number of alternatives, the greater the stochastic variation, everything else being equal (Wegener & Spiekermann 2011). The solution to the problem of stochastic variation is presented in the following section.

## 6. Conclusion

The experimental models presented here demonstrate the applicability of the micro-simulation approach where limited data is available. Two major application areas demonstrated in the paper are in analysing the factors influencing residential choice, and in simulating residential choices.

The models proved to be useful for analysing the factors that influence observed residential location choice. To study the residential choices, first a list of factors that are assumed to influence residential location choice was compiled on the basis of a review of applications of the UrbanSim model, and then available data on the factors was searched for. Extensive statistical testing proved the significant effect of several factors. Apart from the main effects of the factors, more complex interdependences were also identified, namely: an interaction between the characteristics of present and potential new residence, an interaction between the characteristics of the municipality and the impact of personal characteristics on the decision making.

The experimental applications of both stratified and general population models did not provide a clear judgement on the superiority of either of the models. The models offer two comparable approaches for analysing how personal characteristics influence decision making: a) a comparison of the sub-models that represent the choices made by selected population strata or b) by building a single model encompassing all the population and then testing the interdependence between the characteristics of particular choices and the personal characteristics of the individuals making the choices.

While the micro-simulation approach proved to be useful in analysing residential location choice factors, the influences have to be interpreted with care as several important factors were not applied due to a lack of suitable data.

The socio-economic and demographic factors influencing decision making are not well covered by suitable disaggregated data. Households are considered to be the decision-making entity in most reviewed residential choice models. In the Czech Republic, however, there is a lack of data on household characteristics that is disaggregated to the level of individual households. There is a lack of data on the household level for simulating residential mobility, and also a lack of data on household relocations, income, mobility, car ownership, as well as household demographic characteristics and their transitions (marriage, divorce, birth of children, children leaving the household). In addition, there is a lack of statistics in a form that would enable synthetic populations of households to be created. Therefore, only relocation of individuals can be simulated at present.

The price and the availability of houses and flats on the housing market are other important factors influencing residential choice that are not covered by disaggregated data. In addition, data on occupancy of the housing stock and household tenure are not available at the moment.

Data on residential choices is aggregated to municipalities. This might raise concern about the proper representation of residence and neighbourhood characteristics. Aggregation of individual residence characteristics to municipality level may hide large inter-locality variances, and may make them interfere with the neighbourhood characteristics in multi-nominal logit models. This could be one of the reasons for the weak significance of some of residence characteristics. Unfortunately, no data on residential choices related to individual houses and flats is currently available in the Czech Republic.

The second area of applying models that has been demonstrated is the simulation of residential location choices. Predictions of decision making on the level of individual actors can in principle be only probabilistic, which causes high stochastic variation in the model results. The choices are simulated using the Monte Carlo techniques on the basis of choice probabilities predicted by multi-nominal models. The stochastic variation could easily be mitigated by making the choices in direct proportion to these probabilities instead of employing probabilistic choice process, but then the unknown factors that influence the decision making of individuals would remain hidden. However, if stochasticity is admitted, the reliability of the model results can be assessed.

A pragmatic and theoretically sound approach to stochastic variation is to scale it according to the purposes for which the model was built. This approach follows the trade-off between the stochastic variation of the model outcomes, on the one hand, and the number of choice alternatives and the number of simulated choices, on the other. This trade-off implies that stochastic variation can be decreased to an acceptable level by spatial aggregation of alternative choices, or by increasing the number of simulated choices.

Based on these conclusions, several recommendations for further research can be made:

- households and not individuals should be represented as decision making entities; for this purpose, synthetic populations of households could be derived from the general population census data, from existing surveys (EU-SILC), and from ad-hoc household surveys;
- market prices and data on the occupancy of buildings should be collected to increase the validity of residential choice models;
- the number of observations should be increased by expanding the area of analysis, or by selecting areas with a dynamic residential mobility pattern.

As most data on individuals is not made public due to privacy issues, these objectives can only be achieved with the involvement of institutions that provide data, i.e. the Czech Statistical Office, the Czech Office for Surveying, Mapping and Cadastre, the tax offices, and the Czech Social Security Administration.

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## RESUMÉ

### Modely výběru místa bydliště: mikrosimulační přístup

Mikrosimulační modely popisují rozhodovací procesy na úrovni jedinců a umožňují tak hodnotit vliv celé řady vnějších faktorů a osobních charakteristik jedinců na jejich rozhodování. Tento příspěvek ověřuje použití mikrosimulačních multinominálních logitových modelů na zkoumání faktorů stěhování obyvatel v územním obvodu obce s rozšířenou působností Tábor. Na základě pozorovaných stěhování obyvatel v letech 2001–2011 byl ověřován potenciální vliv velkého množství faktorů a pro každou kombinaci obce a jedince byla odvozena pravděpodobnost výběru nového místa bydliště.

Experimentální použití mikrosimulačních modelů v této podobě přineslo řadu zjištění: a) statisticky významnou se prokázala být interakce věku jedince s některými charakteristikami místa bydliště; vliv řady dalších významných osobních charakteristik jedinců, zejména vzdělání a příjmu, nemohly být testovány z důvodu nedostupnosti vhodných dat; b) nebyla prokázána významná interakce mezi charakteristikami místa současného a nového bydliště s výjimkou jejich vzájemné polohy: obyvatelé výrazně preferují stěhování v rámci sousedních obcí a tyto preference jsou ovlivněny jejich věkem; c) mikrodata o stěhování obyvatel nezachycují příslušnost jedinců k domácnostem a nebylo proto možné testovat vliv charakteristik domácností na výběr lokality bydliště; předpokládaná vzájemná podmíněnost rozhodování členů domácností byla ověřena vytvořením modelů pro specifické věkové skupiny dle jejich předpokládané příslušnosti k domácnostem; d) hodnoty ukazatelů průměrné absolutní procentuální chyby (MAPE) a procentuální chyby za jednotlivé obce jsou srovnatelné s obdobnými aplikacemi mikrosimulačních modelů v zahraničí; e) procentuální odchylky simulovaných a pozorovaných hodnot vztažené k jednotlivým obcím jsou dle očekávání nepřímo úměrné počtu pozorovaných stěhování obyvatel těchto obcí; příliš nízký počet pozorování v některých obcích výrazně snižuje spolehlivost predikce; f) využití osobních charakteristik jedinců v modelu významně zvýšilo míru shody pozorovaných a simulovaných výběrů na úrovni jedinců; g) spolehlivost predikovaného počtu stěhujících se obyvatel na úrovni obcí je ovlivněna vysokou mírou stochasticity, zejména u obcí s populací menší než sto obyvatel; h) úplné využití potenciálu mikrosimulačních modelů je omezené nedostupností podrobných a spolehlivých dat, zejména sociodemografických údajů o domácnostech a údajů o nemovitostech a jejich blízkém okolí.

## MARTIN OUŘEDNÍČEK, JANA TEMELOVÁ, LUCIE POSPÍŠILOVÁ (EDS): ATLAS SOCIÁLNĚ PROSTOROVÉ DIFERENCIACE ČESKÉ REPUBLIKY – ATLAS OF SOCIO-SPATIAL DIFFERENTIATION OF THE CZECH REPUBLIC

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The atlas aims to depict transformational processes of the last 20 years in the Czech Republic. The described phenomena document a modernisation shock after the collapse of Communism in 1989 and especially the changes affecting the quality of life, housing, labour market, education, health care, etc. in Czech urban as well as rural areas. The atlas consists of 13 interconnected chapters and 37 large, folded maps depicting in the detail of individual municipalities. Each map is accompanied by an analytical text, graphs and tables, all in Czech and English.

The authors from the Faculty of Science of Charles University in Prague collected the data in a long-term project, the information represents one of the first detailed data collection of the transformation of the post-communist Central and East European countries.

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