# COMPARISON OF THE LONGITUDINAL AND LATERAL PROFILES OF WATERCOURSES USING SONAR-BASED METHODS (ADCP) AND HYDROLOGICAL ANALOGY

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## ABSTRACT

In many cases, a flood wave has a pronounced transforming effect on the channel, and the knowledge of the watercourse longitudinal and lateral profiles is of great importance. To obtain data meeting these requirements with adequate accuracy, we alternated the conventional geodesic methods with sonar-based approaches – ADCP – and with results from the CroSolver software, constructed for obtaining bathymetric information.

We compare results achieved from two approaches for preparing geometric data for hydrodynamic models. The respective approaches are considered as possible replacements for the costly conventional geodesic methods. The proposed methods use either data available from the continual monitoring of surface water courses (i.e., discharge measurements), which can capture precisely the lateral channel profile within the entire longitudinal profile, or a robust sonar-based system.

Results obtained from the conducted studies show that our statement about a possibility to synthesize the ALS data with data from hydrological measurements or ADCP sonar in preparing watercourse computational geometry, is valid. A very good agreement was achieved between lateral profiles (determined inundation areas) prepared by using the CroSolver software or the ADCP sonar with lateral profiles established by geodesic surveying.

**Keywords:** sonar, ADCP, Doppler, discharge, lateral profile, aerial laser scanning

## 1. Introduction

One of the key factors in getting relevant results from hydrodynamic models is the initial data for schematization of the watercourse channel (Coveney et al. 2010). Proper requirements for the initial data also enable quantification of employed hydrodynamic models to be used for simulations. One-dimensional (1D) hydrodynamic models require initial data with the computational pathway consisting of a set of lateral profiles of the watercourse channel; on the other hand, for two-dimensional (2D) hydrodynamic models, a detailed digital model of the area topography has to be provided, i.e. adjoining inundation areas along with the watercourse itself. Thus, the initial data and the employed model may increase the financial costs of the project (Roub et al. 2012a).

LIDAR (Light Detection and Ranging) aerial laser scanning is one of the most common technologies for obtaining spatial data about a territory (Dolanský 2004). The method of aerial laser scanning (ALS) is based on the principle of laser beam reflection interpreting the image of the investigated object to the laser beam (Novák et al. 2011). The beam is emitted to the Earth surface, and measures the travelled distance to the surface of the investigated area or object.

The most lidar systems consist of a LIDAR scanner, a GPS receiver, an inertial measurement unit (IMU) represented by a desk computer and a device for data storage.

This system is mostly applied to generate accurate digital models of terrains and surfaces (DMT x DMP), which are then used in many fields (building industry, architecture (Hofman and Potůčková 2012), transport, forestry, environment science, defence, etc.), including hydrology and river hydraulics (Roub et al. 2012a). Recently, the activities providing such data sources have been performed in collaboration with the Czech Office for Surveying, Mapping and Cadastre (COSMC), Ministry of Agriculture of the Czech Republic (CR) and Ministry of Defence of the Czech Republic. The following application products will be (and for some localities have already been) generated – the Fourth-generation Digital Model of the CR Territory (DMR 4G), the First-generation Digital Model of the Surface of CR Territory (DMP 1G), the Fifth-generation Digital Model of the CR Territory (DMR 5G) (Brázdil 2009).

The expected date for the completion of DMR 5G, i.e. the date until which the DMR 5G should be completed for the entire CR territory is planned for the end of the year 2015. The present state of DMR 5G processing is shown in Figure 1. In his report, Brázdil (2009) described the basic parameters of individual application products. The potential use of ALS data in the fields of hydrology and river hydraulics was described in other reports, e.g. in Uhlířová and Zbořil (2009), Novák et al. (2011), Roub et al. (2012a), Roub et al. (2012b), Roub et al. (2013).

Aerial laser scanning is characteristic by having its own source of radiation, and therefore by not being limited (as is the case of photogrammetry) by insolation. As already mentioned, the information on the Earth surface (surface objects – buildings, vegetation, etc.) is obtained

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AUC Geographica, 49, No. 2, pp. 111–119

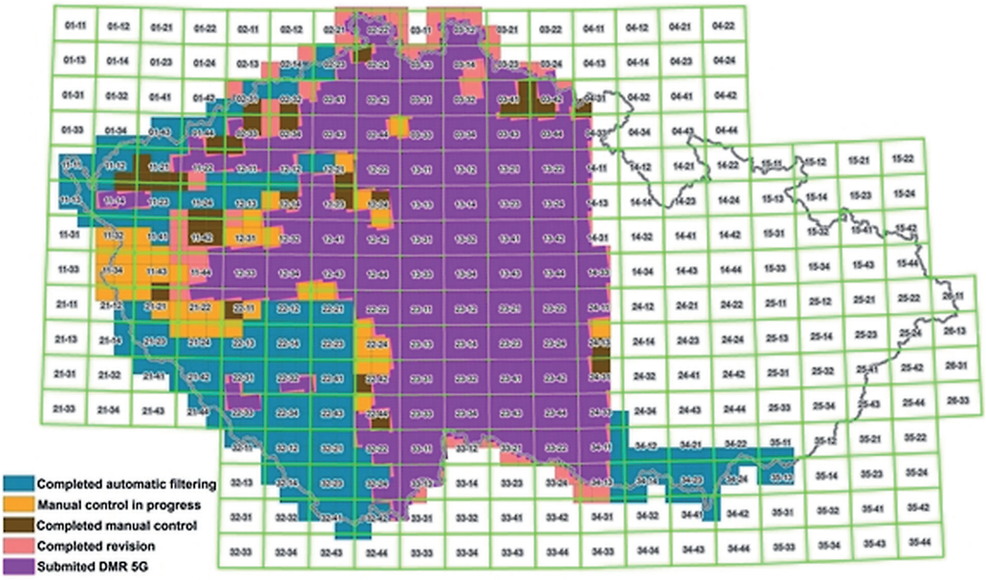

**Fig. 1** Present state of DMR 5G processing.

by using the emission of laser beams in the form of pulses from a scanner placed on the airborne carrier (Šíma 2009).

In the case of beam reflection we can talk about 'laser beam reflection' – single or multiple – occurring in localities with significant differences in altitude, such as forests or building edges (Dušánek 2008).

The principle of laser beam behaviour after reaching the surface (vegetation, terrain, buildings) has essentially been defined; however, the situation is different when the laser beam falls close to watercourses and water surfaces. To acquire data from aerial laser scanning, two basic scanners (lidars of different laser detection wavelengths) are used. The first are scanners employing a proximal infrared spectrum laser (see the COSMC project). In the case of water (water surfaces), however, a typical spectral phenomenon consists in the almost complete absorption of infrared radiation resulting in a 'no data' area, i.e. an area missing the altimetry information. Mapping under water level, we have to use the green or blue-green part of the spectrum, which is not absorbed by water and thus (in ideal conditions) reaches the bottom from where it is reflected back.

The current mapping of the levels of watercourses/watercourse channels is based on the principle of dual-use scanners, i.e. infrared (mapping the surface) in combination with blue-green (mapping the bottom). This system is named DIAL – Differential Absorption Lidar. In very clear waters with a quiet surface, the mapping can be done theoretically to depths reaching 50 m. To apply these systems, the flight level must be significantly lower, within a standard range of 200–400 m (Dolanský 2004).

The aim of this work was to verify longitudinal and lateral watercourse profiles obtained from ALS data, which were to a detail specified by sonar-based methods (ADCP) and hydrological analogy (CroSolver) using longitudinal and lateral profiles obtained by conventional geodesic methods.

Table 1 and Figure 2 show the selected segments of watercourses, including the list of their basic characteristics.

## 2. Selection of the pilot segments of watercourses

Selection of the pilot segments of watercourses was made pursuant to a schedule established by the Czech Office for Surveying, Mapping and Cadastre, as a guarantor of the project 'Preparation of a new altimetry map using the method of aerial laser scanning (ALS)'.

To take into account the specific altitude distribution and variability of the river pattern in the Czech Republic,

**Tab. 1** Selected segments of water courses.

| Stream ID | The name of the stream | Section of the stream | Length (km) | r.km from – to |
|---|---|---|---|---|
| 120020000100 | Otava | Bohuslavec – Písek | 7.049 | 20.343–27.392 |
| 133060000100 | Úslava | Srby – Novotníky | 13.024 | 49.420–62.444 |
| 131080000100 | Radbuza | Bělá nad Radbuzou | 5.948 | 8.890–14.838 |
| 133060000100 | Úslava | Blovice | 7.319 | 34.330–41.649 |
| 132140000100 | Úhlava | Nýrsko | 6.420 | 79.867–86.287 |
| 132140000100 | Úhlava | Dolní Lukavice – Přeštice – Lužany | 9.253 | 26.000–35.253 |

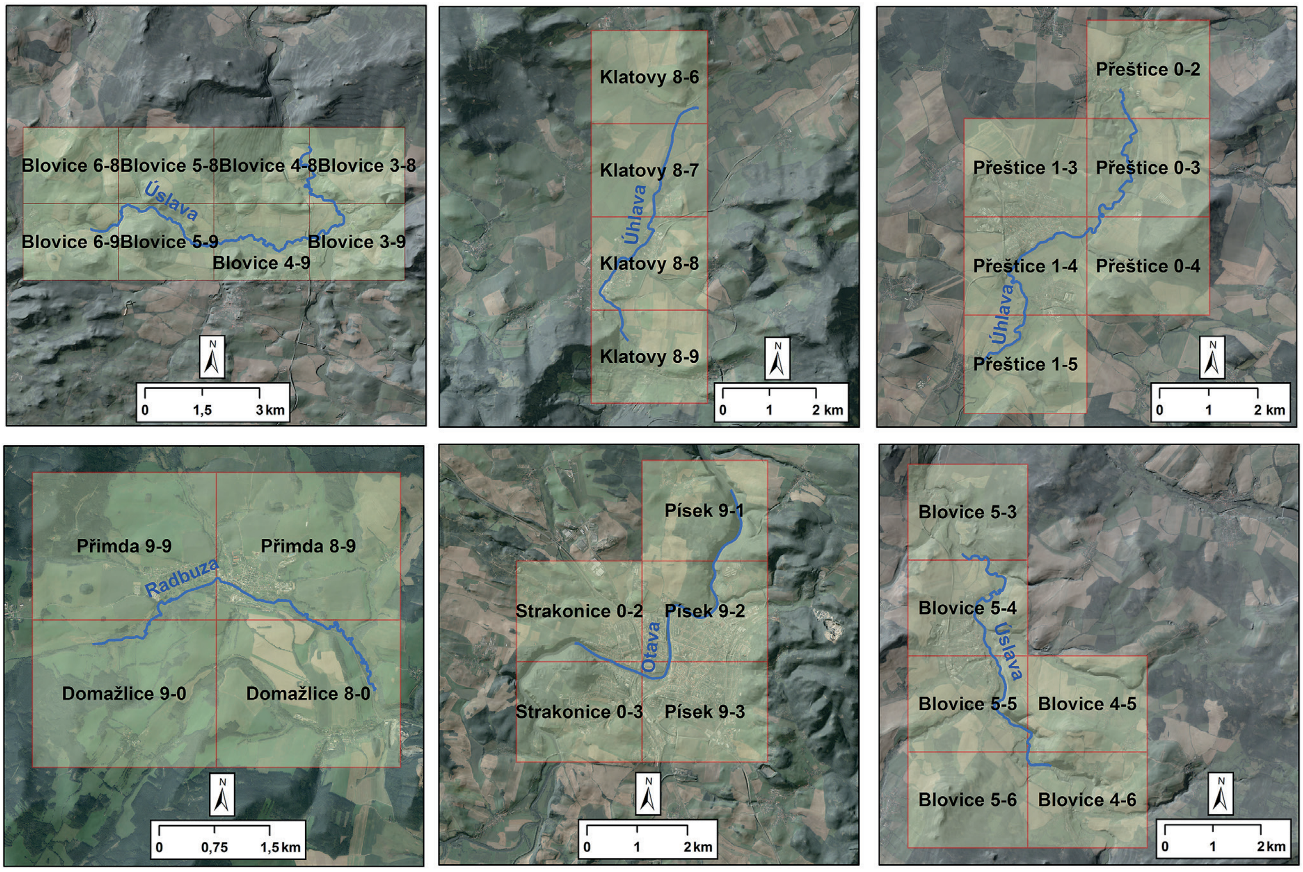

**Fig. 2** Selection of pilot segments of water courses.

we selected watercourse segments characterizing best the altitude specificity, which is one of the main criteria of relief articulation. Beside the spatial and temporal distribution of physio-geographic components and elements such as precipitation type, temperature, air humidity, or flora and fauna representation, the altitude also influences characteristics reflecting the nature and course of inundation events.

The variability of the river pattern was assessed in terms of both hydrological parameters, i.e. discharge characteristics and anthropogenic adaptations of watercourses (Langhammer 2003; Maidment 1993), although in most cases, the direct statistical relationship between the watercourse adaptation and the extreme degree of inundation is difficult to prove.

## 3. Methods

To assess the suitability of employing ALS data for modelling the inundation zones (maps of flood risks/threats), we alternated various approaches to prepare initial altimetry data for setting up a hydrodynamic model. Flood events were modelled in the following variants:

a) As initial data for preparing the watercourse geometry (computational pathway), we used the ALS data, while the model event was reduced by discharge reached at the time of ALS data acquisition (Novák et al. 2011);
b) As initial data for preparing the watercourse geometry (computational pathway), we used the ALS data, while the watercourse channel was recessed by discharge reached at the time of ALS data acquisition using the *CroSolver (Cross section Solver)* software (Roub et al. 2012b);
c) As initial data for preparing the watercourse geometry (computational pathway), we used the ALS data, and the profile of the watercourse channel was adjusted (recessed) based on the data obtained from the ADCP sonar;
d) As initial data for preparing the watercourse geometry (computational pathway), we used the data obtained by the conventional geodesic methods.

### a) Reduction of the model discharge by discharge reached at the time of ALS data acquisition

To prepare the initial – geometric – data for hydrodynamic models, the costly conventional geodesic methods were substituted with data available from the continual monitoring of surface water (discharge measurements), which perfectly reflect the lateral channel profile within the entire longitudinal profile. The methodology of this computing variant consists in the establishment of watercourse discharge at the time of ALS data acquisition. Discharge determined in this way is then subtracted from the model event, while the initial computational geometry

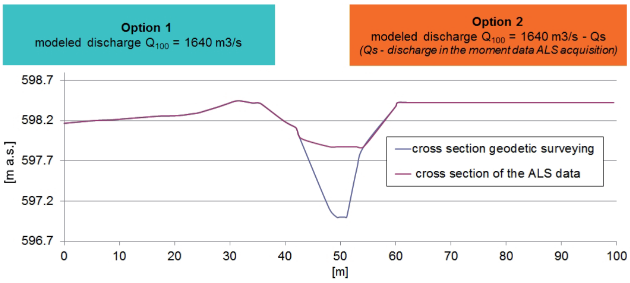

**Fig. 3** Computing algorithm for the variant with reduced model discharge.

of the watercourse (and adjoining inundation zones) is prepared on the basis of the ALS data themselves. This approach is documented in Figure 3.

In this case, one of the key factors in getting relevant data is adequate setting of Manning's roughness coefficient (Forzieri et al. 2012) for the transitional zone (no data zone). To achieve the corresponding rate distribution in the lateral channel profile, we had to set up the initial conditions. These conditions had to respect the basic hydraulic principles during water flow in open channels. To create correct conditions in these hydrodynamic models, we had to take into account the effects of absent viscous sub-layer in the transitional zone of the computational geometry derived from the ALS data only. The most appropriate and simplest variant was to adjust the channel roughness adequately using the roughness coefficient. Using a proper setup, we achieved a shift (augmentation) of rates in the channel lateral profile in the location of the transitional zone (Novák et al. 2011).

### b) Recess of the watercourse channel by discharge reached at the time of ALS data acquisition

The reflection of hydrological measurements during watercourse schematization into a hydrodynamic model consists in deriving the discharge reached at the time of ALS data acquisition and in using thus determined discharges as a basis for recessing the digital relief model prepared from the ALS data. In this way, we can substitute for the remaining part of the channel profile that has not been reflected by the ALS method in the digital relief model. This enables us to obtain the required watercourse channel geometry, with the capacity equal to the discharge value found in the natural channel (Roub et al. 2012b).

To solve the particular computational variant based on specifying the digital terrain model (DMT) with ALS data, we used discharge established at the time of ALS data acquisition (similarly as in a), but without reducing the simulated discharge by discharge reached at the time of ALS data acquisition). The discharge obtained in this manner was then used for recessing the water channel course in DMT obtained from the ALS data. The computing algorithm is shown in Figure 4.

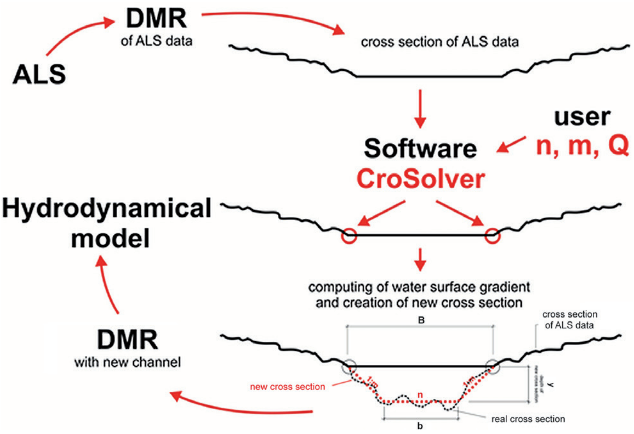

**Fig. 4** Computing algorithm for the variant using the CroSolver software.

To recess the watercourse channel, we used the CroSolver programme particularly developed for this purpose by the research team. The CroSolver software represents an external – independent – programme, which is not dependent on an already existing user platform. Thus, users are not limited by the need to have an ESRI license for ArcGIS products, as is the second case in which we are planning to develop software constructed as an individual ArcGIS extension.

### c) Establishment of longitudinal and lateral profiles using the ADCP sonar (SonTek)

RiverSurveyor SonTek M9 (Figure 5) is represented by a robust and extremely accurate system of Acoustic Doppler Profiler (ADP) designed particularly for measuring watercourse discharge, depth and rates. This new technology is employed to solve a number of current problems, such as the development of sediments, siltation of retention space in water reservoirs, establishment of discharge in watercourses, etc. (Hess et al. 1995; Liebe et al. 2005; Oyebode et al. 2013). High accuracy and simple use make it possible to measure with security, without any need of incessant adjustments to particular river conditions. To determine the situation and altimetry information x, y, z (h) with ±3 cm accuracy, there is an integrated RTK GPS

**Fig. 5** RiverSurveyor SonTek M9.

(real-time kinematic) system allowing a detailed localization of the performed measurements for direct conversion into the S-JTSK system of coordinates. Such accuracy is achieved with the signal available from 8–9 satellites, which in most cases is obtainable. Basic parameters of the employed product SonTek M9 are given in Table 2.

**Tab. 2** RiverSurveyor M9 specification [Anonym 2010].

| **Velocity Measurement** | |
|---|---|
| Profiling Range (Distance) | 0.06 to 40 m |
| Profiling Range (Velocity) | ±20 m/s |
| Accuracy | ±0.25% of measured velocity |
| Resolution | 0.001 m/s |
| Number of Cells | Up to 128 |
| Cell Size | 0.02 to 4 m |
| **Transducer Configuration** | Nine (9) Transducers |
| | Dual 4-beam 3.0 MHz/1.0 MHz |
| | Janus at 25° Slant Angle |
| | 0.5 MHz Vertical Beam |
| **Depth Measurement** | |
| Range | 0.20 to 80 m |
| Accuracy | 1% |
| Resolution | 0.001 m |
| **Discharge Measurement** | |
| Range with Bottom-Track | 0.3 to 40 m |
| Range with RTK GPS | 0.3 to 80 m |
| Computations | Internal |

To prepare initial data for the hydrodynamic model using the SonTek software, we alternated the approach based on the ADCP-determined lateral profiles with the adjustment (recess) of DMT obtained only with the ALS data, generating the final data form.

By using this approach, the watercourse channel profile is recorded to DMR from the ALS data and individual lateral profiles obtained from the sonar location are mutually interpolated. This methodology is illustrated in Figure 6a and Figure 6b, showing the course of the lateral profile and additionally the distribution of point rates in individual vertices of the colour spectrum.

### d) Preparation of initial data by conventional geodetic methods

This method alternates the employment of ALS data with data obtained by the conventional geodetic methods. The method is based on the standard approach currently applied to obtain relevant DMR with regard to river hydraulics.

Additionally located lateral profiles of the watercourse channel are used for the subsequent interpolation of watercourse inter-profile space, similarly as in the variant employing the SonTek product. Watercourse channel bathymetry determined in this way is then combined with the ALS data into final DMR, from which the schematization of the watercourse channel and adjoining inundation is generated.

## 4. Results and Discussion

To assess the relevance of individual approaches, we compared the scenarios with either the reduction of simulated discharge by the discharge level detected at the time of data acquisition using the ALS method, i.e. based on DMR generated from ALS only, or without reducing the simulated discharge, i.e. based on DMR with the adequately included water-course channel (ALS data + geodetic location), prepared in the variants combined with data from hydrological measurements (CroSolver), data obtained by sonar (RiverSurveyor SonTek M9), or data from the geodetic location of lateral profiles.

In the locations with the geodetically determined lateral profiles, we generated new lateral profiles based on DMR prepared by using the individual approaches (ADCP, hydrological analogy), and we then compared them with the geodetically located lateral profiles.

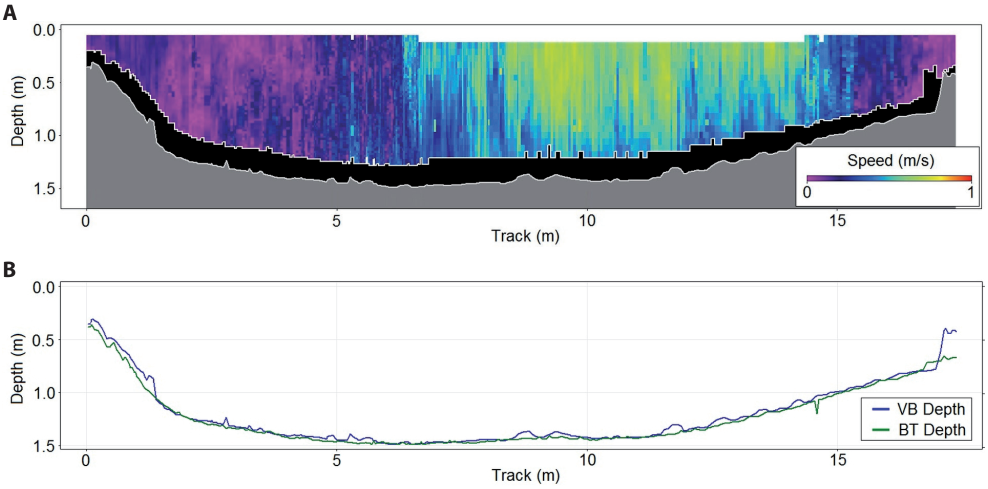

**Fig. 6**
A – Computing algorithm for the variant using the ADCP sonar (SonTek).
B – Computing algorithm for the variant using the ADCP sonar (SonTek).

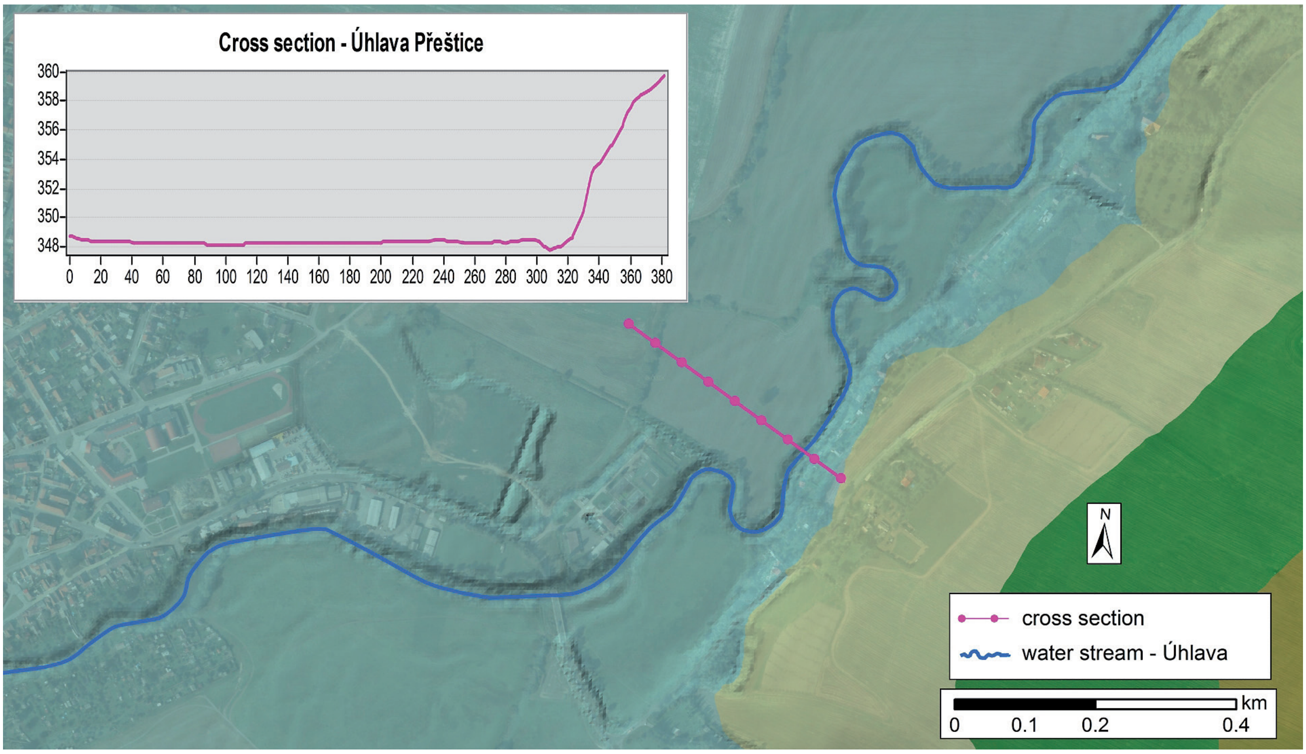

**Fig. 7** Typical cross section.

The following results are presented for the lateral profile of the Úhlava watercourse near the town of Přeštice (Figure 7).

Figures 8–11 show lateral profiles for the individual considered variants. The *x* axis shows the length [m] of the lateral profile (its segment in the watercourse channel). The *y* axis shows the altitude [m above sea level].

The comparison of lateral profiles generated from the final DMT, i.e. after recessing the discharge reached at the time of ALS recording, with the geodetically located lateral profiles and profiles prepared with CroSolver shows good correlation, see Figure 12.

The results are also satisfactory for the modelling of the inundation zones themselves, including the scenario

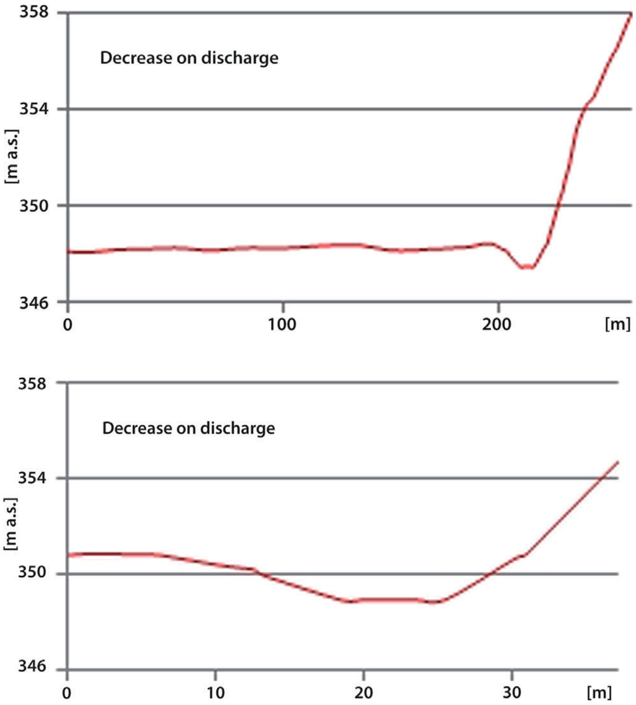

**Fig. 8 a,b** Option 1 – Decreace on discharge.

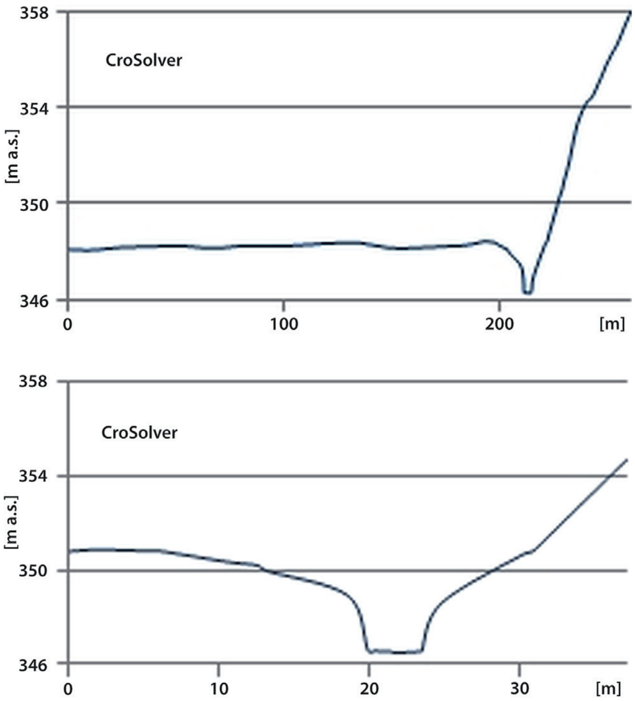

**Fig. 9 a,b** Option 2 – CroSolver.

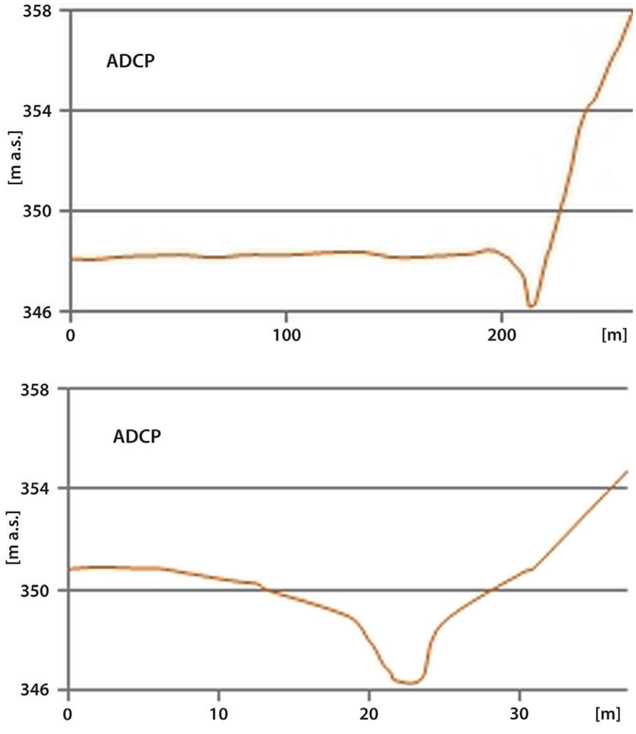

**Fig. 10 a,b** Option 3 – ADCP.

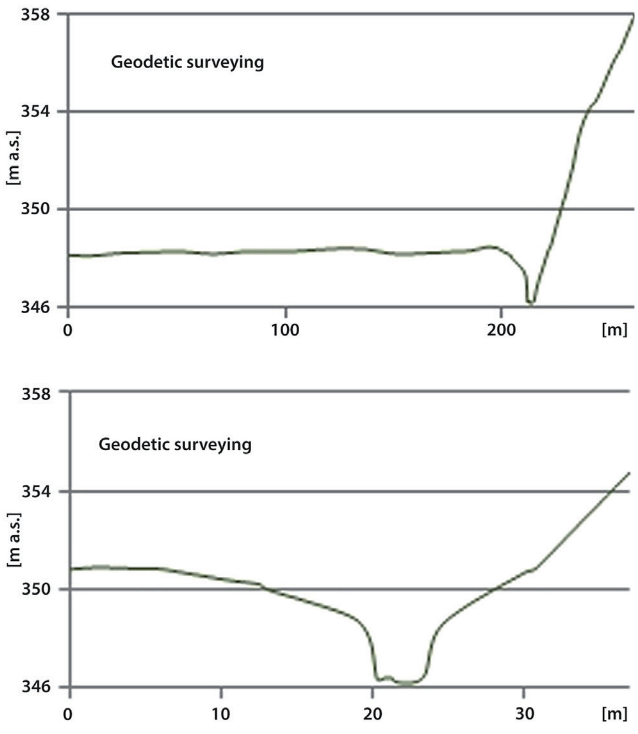

**Fig. 11 a,b** Option 4 – Geodetic surveying.

prepared with DMT without recessing the water channel course, which is simulated with reduced discharge.

Although the depicted lateral profiles do not reach absolute similarity, i.e. are not totally identical, the deviations are rather small and do not have subsequent effects on the results obtained with the hydrodynamic model.

Moreover, the application of the CroSolver software led to significant correlation of results even in the area between the individual lateral profiles within the 'inter-profile' area. These results were obtained by depicting new lateral profiles using DMR prepared by the CroSolver software in the area between the individual geodetically located lateral profiles (at a spacing of ca 90–120 m). These profiles were then compared with the additionally located profiles by conventional geodesy as well as with the lateral profiles from DMR prepared by expert interpolation of the original geodetically located profiles.

The comparison of lateral profiles from the interpolated inter-profile area with the additionally geodetically located lateral profiles shows that the lateral profiles obtained from DMR with the interpolated – manually edited – inter-profile area display high fluctuation as compared with the geodetically located profiles.

Furthermore, the accuracy of the lateral profiles from the manually edited inter-profile areas decreases with the increasing distance from the reference (geodetically located) lateral profile, resulting in channel profile over-sizing or under-sizing (Roub et al. 2012b).

An advantage in using ADCP methods in the preparation of watercourse geometry is also the acquisition of relevant data about the discharge profile of the watercourse within its entire longitudinal profile. However, time consumption and financial costs for obtaining the data are considerably higher as compared with methods based on the quantitative monitoring. With using the sonar, the lateral profile is recorded in detail and with high accuracy since it consists of a great amount of points. This situation, however, leads to inaccurate up to chaotic generation of watercourse channel in the inter-profile areas (at interpolation of lateral profiles). This particularly applies to segments with the pronounced watercourse meandering. A partial solution of this problem is the reduction of points in the respective lateral profiles. A more detailed specification of the inter-profile parts of watercourses is a subject of further development. In more or less straight segments, the generated course of watercourse channel is

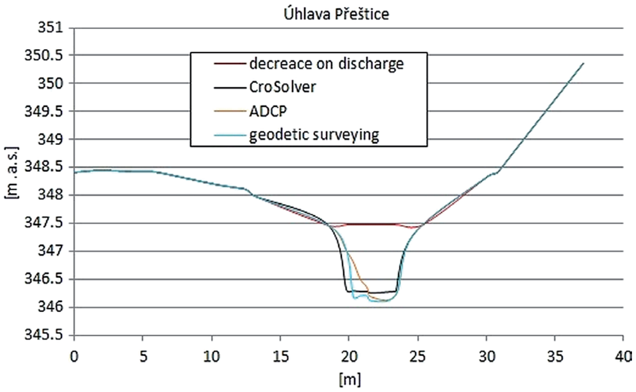

**Fig. 12** Option 1–4.

of high quality and suitable for use in generating hydrodynamic models.

## 5. Conclusion

Data sources (DMR 4G, DMR 5G, DMP) obtained by mapping the altimetry of the Czech Republic represent a powerful tool, also serving other fields beside hydrology or river hydraulics.

The results of our analyses confirm the hypothesis that ALS data can be combined with data from hydrological measurements or with using the ADCP sonar to generate the computational geometry of the watercourse. Using the CroSolver software or the ADCP sonar, very good correlation of lateral profiles (established inundation zones) has been reached with the lateral profiles obtained by the geodetic location. The ADCP sonar-based approach was used in these analyses as a tool to verify the watercourse geometry and, at the same time, to compare discharge values from the monitoring network of quantitative hydrological monitoring performed by companies '*Povodí*' or CHMI. The limited data sources of detailed geodetic documentation available for in-depth reflection of the actual inter-profile area or time requirements for data acquisition by the ADCP sonar point out a possibility for a more extensive use of combined ALS data with hydrological analogy in practice. Wider application of such a combination based on the use of conventional geodetic methods for getting the altimetry data would also have positive consequences in reduced costs needed for setting up the hydrodynamic model itself. In the case of 'small' watercourses where the constant flow is irrelevant, we should automatically select the approach without recession by using the data from hydrological measurements, and the geodetically located profiles should serve for control only.

However, the indisputably best variant for the generation of relevant DMT seems to be the application of the above-mentioned dual-use lidar for mapping both the watercourse surface and the watercourse bottom. Greater use of this approach would have a positive impact not only on the generation of the hydrodynamic model alone, but also on the quantification of the retention volumes of water reservoirs as well as on a more accurate establishment of the retention space capacities.

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## RÉSUMÉ

### Srovnání podélného a příčného profilu vodního toku za použití přístupů založených na sonaru (ADCP) a hydrologických měření

Jeden z rozhodujících faktorů pro získání relevantních výsledků z hydrodynamických modelů, představují vstupní data pro schematizaci koryta vodního toku (Coveney et al. 2010). Dle požadavku na vstupní data je možné kvantifikovat i použité hydrodynamické modely, které budou pro prováděné simulace použity. Jednorozměrné (1D) hydrodynamické modely se vyznačují nižšími požadavky na vstupní data, kdy výpočetní trať je tvořena souborem příčných profilů koryta vodního toku, naproti tomu u dvourozměrných (2D) hydrodynamických modelů je nutné sestavit pro celé řešené území detailní digitální model reliéfu, tj. přilehlé inundace, ale i samotného vodního toku. S ohledem na vstupní data a použitý model roste i finanční náročnost celého projektu (Roub a kol. 2012a). V řadě případů dochází k významnému transformačnímu efektu povodňové vlny v samotném korytě, a proto je znalost podélného a příčného profilu řešeného vodního toku velice významná. Pro potřeby získání takovýchto dat, které budou v požadované přesnosti tyto podmínky naplňovat, byly alternovány konvenční geodetické metody s přístupy založenými na sonaru – ADCP (SonTek) – a výsledky ze softwaru Profile Solver, který byl cíleně sestaven pro potřeby získání výškopisné informace pod hladinou vodního toku.

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