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ASSESSMENT OF POSSIBLE UNCERTAINTIES ARISING DURING THE HYDROMORPHOLOGICAL MONITORING OF A SAND-BEDDED LARGE RIVER

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Abstract

The riverbed morphology of sand-bedded rivers is dynamically changing as a consequence of quasi continuous bedload transport. In the meantime, the dimension, size and dynamics of developing bedforms is highly depending on the regime of the river and sediment availability, both affected by natural and anthropogenic factors. Consequently, the assessment of morphological changes as well as the monitoring of riverbed balance is challenging in such a variable environment. In relation with a general research on the longer term sediment regime of River Maros, a fairly large alluvial river in the Carpathian Basin, the primary aim of the present investigation was to assess uncertainties related to morphological monitoring, i.e. testing the reproducibility of hydromorphological surveys and digital elevation model generation by performing repeated measurements among low water conditions on selected representative sites. Surveys were conducted with the combination of an ADCP sonar, GPS and total station. The most appropriate way of digital elevation modelling (DEM) was tested and 30-point Kriging was identified to be optimal for comparative analysis. Based on the results, several uncertainties may affect the reproducibility of measurements and the volumetric deviation of DEM pairs generated. The mean horizontal difference of survey tracks was 3-4 m in case of each site, however this could not explain all the DEM deviation. Significant riverbed change between measurements could also be excluded as the main factor. Finally, it was found that results might be affected greatly by systematic errors arising during motor boat ADCP measurements. Nevertheless, the observed, normalised and aggregated DEM uncertainty (600-360 m^3/rkm) is significantly lower than the changes experienced between surveys with a month or longer time lag. Consequently, the developed measurement strategy is adequate to monitor long term morphological and sediment balance change on sand bedded large river.

Keywords: hydromorphological surveying, digital elevation modelling, uncertainty, reproducibility

INTRODUCTION

Fluvial systems are characterised by a continuous change determined by various direct and indirect controlling variables, affected by natural and anthropogenic processes. One of the key driver of fluvial dynamics is sediment regime, affected by river flow regime, geological background and sediment availability. Consequent quality and quantity of sediment will also have a major effect on river morphology and bedform characteristics (Schumm, 2005). Therefore, if these are surveyed and assessed valuable information can be gathered in turn on the status of the investigated fluvial system (Sipos et al., 2012). The surveying and monitoring of the riverbed nevertheless can be highly challenging, since there is a limitation in space and time due to the rapidly changing environment, and in the meantime the execution of the measurements can also have difficulties (Sipos, 2006; Sipos et al., 2012).

A straightforward way of investigating morphological change is to perform consecutive bathymetric measurements on longer sections of a river (Laczay, 1968, Kiss et al., 2008). Hydromorphological measurements aim to reveal and monitor the development and changes of the river bed and they contribute to the analysis of the changes in morphology and dynamics. By generating digital elevation models (DEM) based on the measured datasets, volume differences can be determined in a certain time period, thus the bedload balance of the investigated river section can be assessed. Several devices can be applied for bathymetric measurements: wading rod, sonar, ADCP (Acoustic Doppler Current Profiler), total station, RTK GPS (Real Time Kinematic GPS), photogrammetric imaging, LIDAR (LIght Detection And Ranging; Defendi et al., 2010; Tiron et al., 2009; Gómez et al., 2010; Laczay 1968; Prónay and Törös, 2001).

Using the measured depth and height data obtained by the different equipments, digital elevation model of the study area can be set up, which serves as a basis for further assessments (Kertész, 1991; Jordán, 2007). However, its accuracy highly depends on the errors arising during surveying.

Geodetic and therefore bathymetric measurements can be affected by: random, systematic and gross errors which can occur even simultaneously (Detrekői, 1991, Wise 2000). Random errors are scattered around the true value, and the average of an infinite number of observations results the true value itself, therefore by increasing the number of measurements this type of error can be reduced. A systematic error distorts all measurements in one direction and by increasing the number of measurements the estimation of the true value will not be improved. A gross error significantly exceeds measurement accuracy, determined by random and systematic errors, it does not occur on a regular basis, and it can be filtered by increasing measurement number (Sárközi, 1991; Taylor, 1999). Consequently, during a riverbed survey it is of key importance to identify systematic and gross errors and to foster the reduction of random error by gathering and averaging more data. It is also worth to have control measurements during surveying, which can be used to estimate uncertainty and reproducibility of the assessments.

The main aim of the present investigation was to assess the overall uncertainty related to hydromorphological monitoring on a sand bedded large river. Secondarily, an attempt was made to determine the type and significance of errors that may affect the deviations experienced during instantly repeated surveys on the selected sites. Consequently, it was possible to decide whether the errors related to the measurement allow the comparison of surveys performed to track longer term changes in morphology.

STUDY AREA

River Maros is the largest tributary of River Tisza having a length of 760 km; the investigated study sites are located along its 175 km long lowland section (Fig. 1). The discharge of the river fluctuates considerably: during low water periods it is approximately 20-30 m^3/s at the Makó gauge station, while at floods 1600 m^3/s discharge can also occur (Sipos and Kiss, 2003). The slope is relatively high in case of the whole lowland section and decreases from 40 cm/km (Lipova) to 10 cm/km (Deszk) (Fig. 1). Mean flow velocity is 0.5-1.0 m/s. The river transports a significant amount of bedload, having an annual value of 28 000 t at Deszk (Bogárdi, 1971). The bedload of the alluvial Maros is composed mainly of coarse and medium grainsize sand and a subordinate amount of gravel (Csoma, 1975). The river has also a significant amount of suspended sediment, which can reach 8.3 million t/year (Bogárdi, 1971).

River regulation in the 19-20th centuries greatly affected the river and flood control works caused significant changes (Kiss and Blanka, 2006): the length of the lowland section decreased from 260 km to 175 km (Urdea et al., 2012), furthermore river slope and stream power of the regulated river, transporting huge amount of sediments, increased. Sections with bank protection (e.g. downstream from Lipova and near Makó) slightly changed, more dynamic responses could be observed on sections without additional interventions. The investigated lowland section is characterised as a transition between a braided and a meandering channel pattern. The channel is mostly shallow, and in some places intensive bank and island formation can be observed (Sipos, 2004).

Nowadays the most important human activity on the investigated section is gravel and sand quarrying from the riverbed. The mining activity has been continuous since the 1970s; however, from the 2000s it became even more intensive above Arad (Urdea et al., 2012).

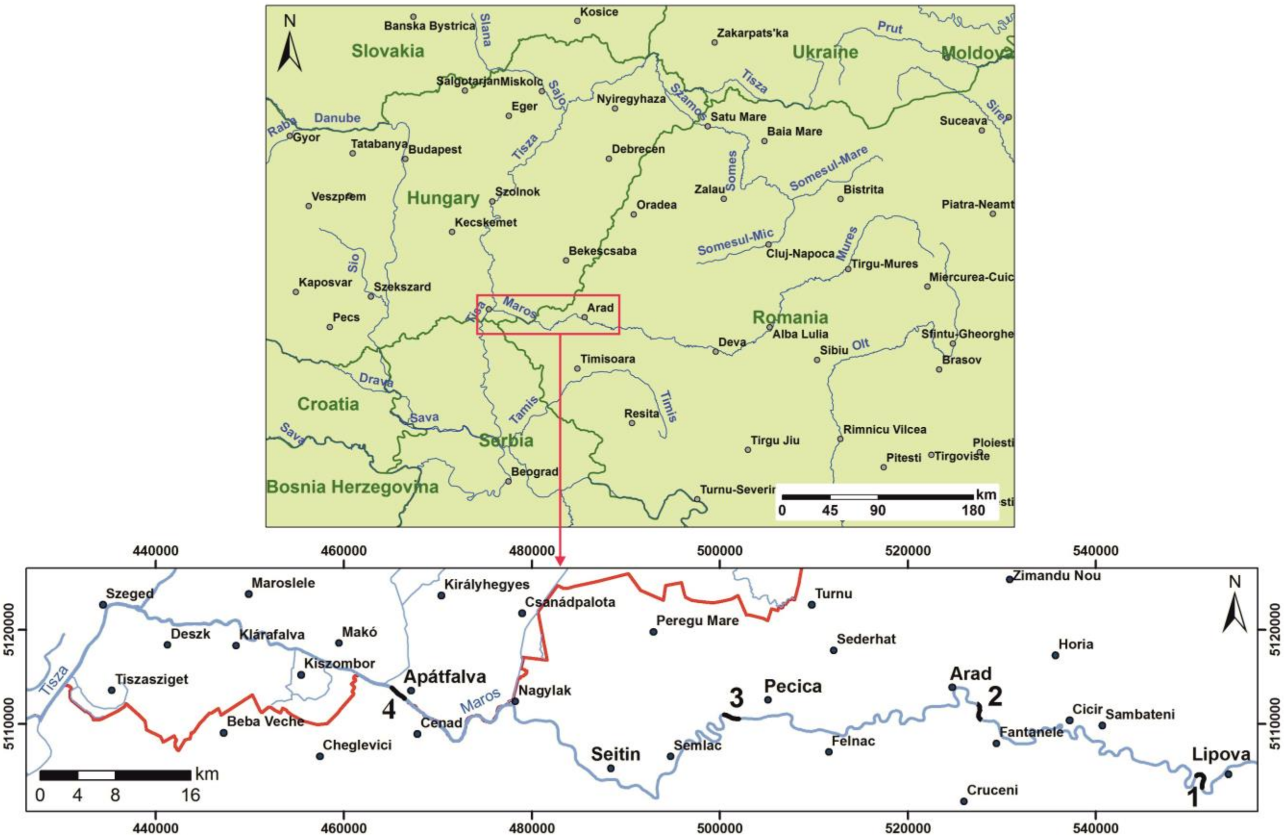

Fig. 1 Location of the study sites

In this study 4 sites were analysed, representing sections with different sediment dynamics as a consequence of in channel quarrying, mostly apparent on the Sambateni-Cicir section of the river (Fig. 1). The first site at Lipova is located in a meander upstream of the major sand exploitation on the river. The river bottom is composed of sandy-gravelly sediments. The second site at Arad is directly downstream of the excavations. The bed of the river here is highly paved by gravels, sand is carried away in the lack of sediment supply as a consequence of in channel mining. The other two sites at Pecica and Apátfalva are characterised by coarse and medium sand bedload and dynamic channel processes manifested in the formation of various bar forms and fluvial islands.

The length of the investigated sites was between 250 and 500 m. Their morphology is similar in the sense that each includes a riffle section and an adjacent pool section. The riffles in each case are a complex of bars and/or islands. The measurements in this study were performed mainly on the riffle sections.

METHODS

Repeated channel surveying was performed at low-water at each of the 4 sites to estimate the overall uncertainty of measurements. At low water conditions bars were exposed at each site, thus subsurface bathymetric and above surface geodetic measurements were applied together with the exception of the Lipova site. The comparability of the surveys can be difficult due to the inaccuracy of cross-section tracking, the differences in data density and the differences in elevation modelling. The temporal difference between the start of the two consecutive surveys was approximately one hour to minimize river bed changes originating from bedload transport. Cross-sections were allocated to represent variable morphology within a site and to include both underwater and exposed surfaces if possible. The distance between two cross-sections did not exceed the half of river width. The tracking of cross-sections was carried out with Trimble Juno navigational GPS with a spatial accuracy of 2-5 m.

For surveying underwater sections a light weight motor boat equipped with a Rio Grande ADCP was used. Depth data was recorded at 1.5m in average at the given speed of the boat. To each depth data measured by the ADCP, surface coordinates were provided using a Topcon RTK GPS. This device has high horizontal and vertical measuring accuracy.

For surveying the exposed parts of the channel a SokkiaSet 650rx total station and a Topcon RTK GPS were applied. The total station was used where the accuracy of the RTK GPS was low, e.g. near the river bank under the trees.

At the Apátfalva site 10 cross-sections and 5 longitudinal sections, while in case of the other areas 5 cross-sections and 5 longitudinal sections were measured repeatedly (Fig. 2). During the remeasurement new GPS base station was set up and a new base point was assigned to simulate the difference between consecutive surveys and to include the systematic error related to base correction.

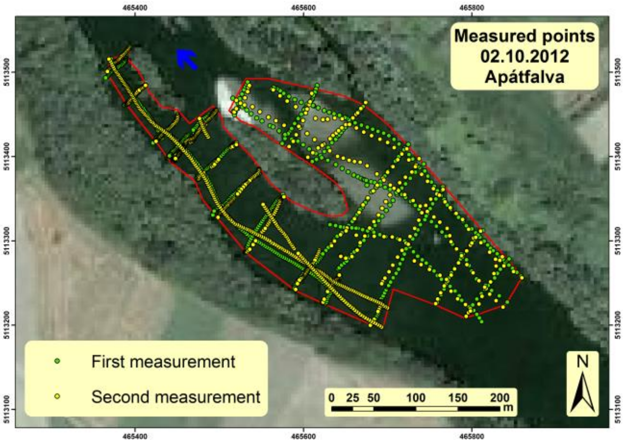

Fig. 2 Datapoints of the first and the repeated survey at the Apátfalva site

After arranging the raw datasets from the different devices in one spatial data infrastructure, digital elevation models (DEM) were set up for all areas and surveys under similar conditions to assess the differences. In case of all study sites and both surveys the same reference level was used to determine the volume deviation of DEMs. Models were generated using linear Kriging with varying the number of sampling points used for interpolation. In case of the Apátfalva site a TIN model was also generated. For making comparisons riverbed elevation maps and volumetric maps with and without distortion correction were generated. Sediment volumes were calculated based on the resulted digital elevation models using reference levels determined in our previous studies for the first and the second survey too (Sipos et al., 2012; Průvetz and Sipos, 2014).

Beside volume differences the horizontal discrepancy of repeated measurement tracks was also assessed. For the determination of spatial deviation in a given section a polygon was created using the data points of the two measurements, and polygon area was divided by the length of the section resulting a value representing mean horizontal difference. The mean tracking uncertainty for a site was calculated by averaging cross-sectional results.

RESULTS AND DISCUSSION

Assessment of DEM deviations

The DEMs generated by TIN and Kriging at the Apátfalva site are presented in Figure 3. Concerning the general morphological setup and main forms the two models yielded very similar results. If temporal differences are considered the main deviation between the first and second survey appeared on the lower section of the study area: a side bar along the left bank and a smaller depression at the right bank almost disappeared on the second elevation model (Fig. 3). Both forms were related to areas where data density was limited, therefore interpolation difference could be more significant. Noteworthy deviations could be observed concerning the slip face of the main bar form on the upper half of the study area (Fig. 3).

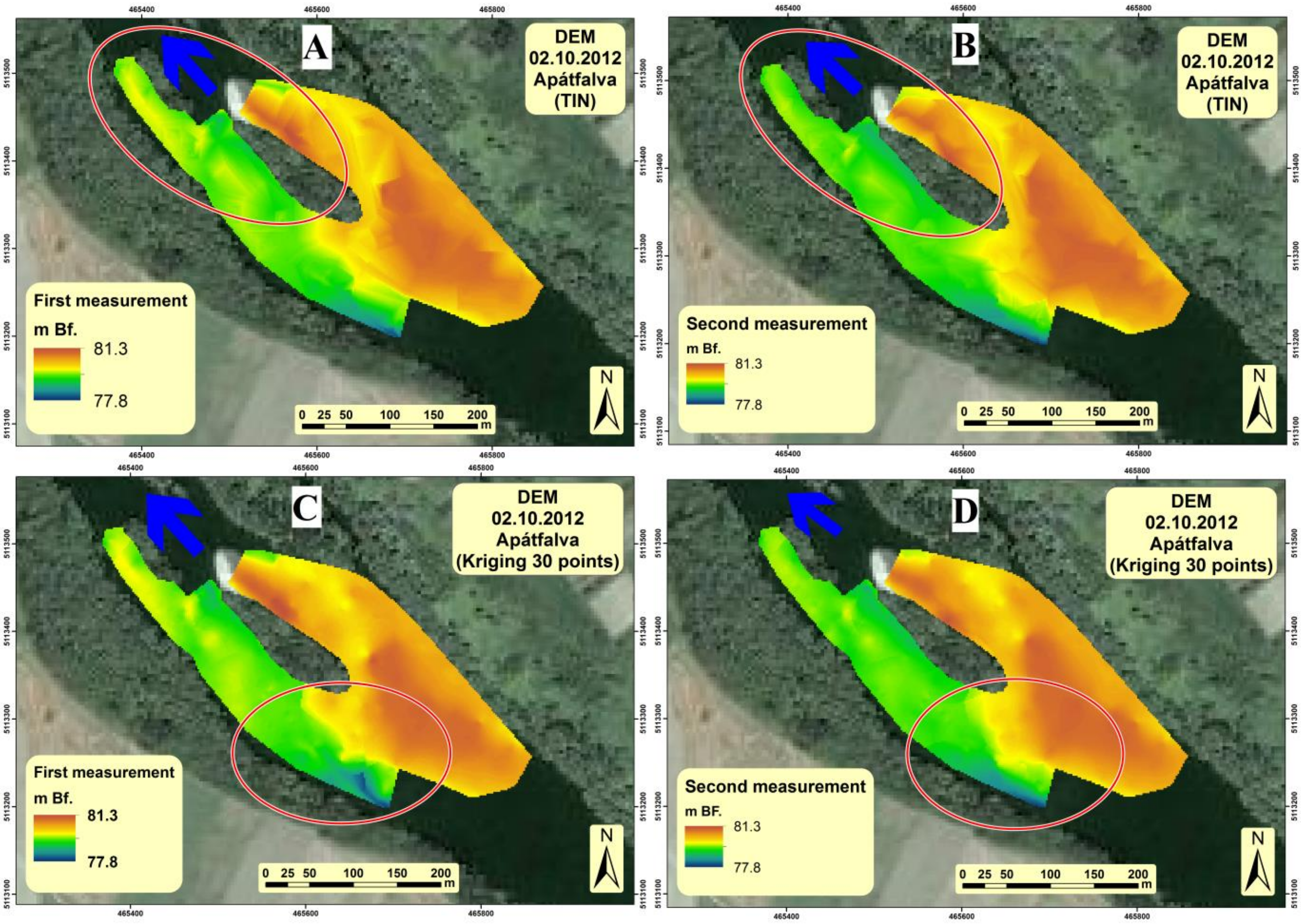

Fig. 3 Resulted DEMs using TIN (A, B) and Kriging (C, D) at the Apátfalva site

Although in general TIN and Kriging yielded similar results, a significant difference was identified between volumetric deviations. Concerning the TIN models the difference between the two consecutive models was 1400 m^3, three times higher compared to the volumetric deviation in case of Kriging. When the number of neighbouring sampling points used for the interpolation is varied it is obvious that 5-15 points resulted a much higher (500-700 m^3) volumetric difference than 25-35 points (300 m^3), and that by extending further the number of sampling points deviation started to increase again (400-500 m^3) (Fig. 4). This pattern can be linked to the spatial organisation of data points, namely that there was a 1-2 m spacing between points along a section and that the distance between cross-sections was 40m in average. Consequently, if 25-35 points are included then the interpolation accounts for two neighbouring cross-sections and also samples the longitudinal sections. If less points are considered it can happen to areas located close to a section that samples are only taken from that section, as the others get out of the reach of the interpolation. This can be especially problematic in case of cross-sections, since the direction of bedforms has a significant longitudinal component, thus the interpolation can have a higher error. On the other hand, if the number of sampling points is too high, not only the neighbouring cross-sections but farther sections can also affect the interpolation, thus deviations between the two models can accumulate. Based on the results above, for further comparisons a 30-point Kriging was applied for DEM generation. Consequently, in case of the Apátfalva site the value of aggregated DEM uncertainty was 300 m^3. In other words, if a deviation higher than this is experienced between two surveys, it can truly be assigned for morphological changes and the rearrangement of the riverbed.

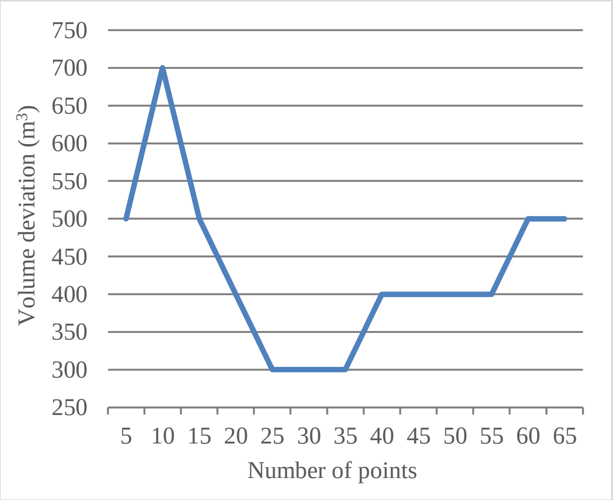

Fig. 4 Sediment volume deviations based on the number of points taken into consideration during Kriging

Comparison of site specific DEM deviations

For the remaining three sites the interpolation method described above was applied for the comparison of consecutive surveys and to determine the aggregate uncertainty of hydromorphological measurements at a given site. In case of the Pecica site the DEM pair showed the most significant deviation at the left flank of the main side bar. During the first measurement a pronounced protrusion can be observed here (Fig. 5 A, B). The deviation is accounted for the difference in the track of longitudinal sections passing the bar form (Fig. 6). Concerning the Arad site volumetric deviation can mostly be related to a depression at the right bank, anyway the DEM pair show little difference (Fig. 5 C, D). No major difference in DEMs was observed in case of the Lipova site, which is partly due to the relatively simple morphology of this section (Fig. 5 E, F).

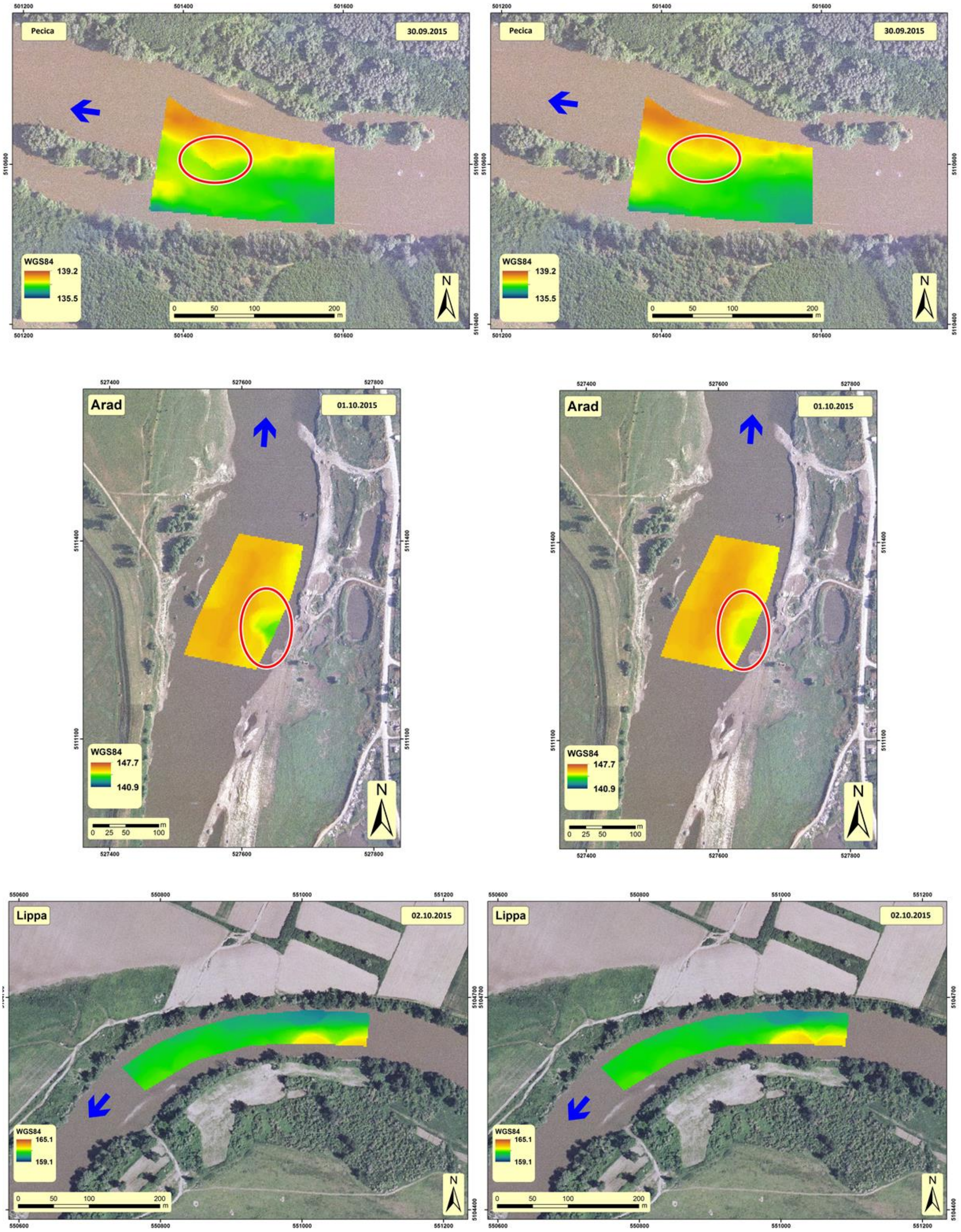

Fig. 5 DEM pairs generated by Kriging from the repeated surveying of test sites (A, B: Pecica; C,D: Arad; E, F: Lipova)

In order to make site specific DEM deviation values comparable, results were normalised to 1 river km (rkm) in case of each site (Table 1). The lowest normalised deviation can be observed at Apátfalva (600 m^3/rkm), while the highest at Pecica and Lipova (3600 m^3/rkm). Considering all of the studied sections mean volumetric deviation is 2300 m^3/rkm.

Possible sources of deviation

Deviations suggested to be derived either from improper tracking of the survey lines, changes of underwater bed forms, or the inaccuracy of the elevation data measured by the different devices. As the surveys were performed using different equipment, it is possible to compare the contribution of different techniques to the overall uncertainty.

At sites, where both underwater (ADCP) and exposed bar surface (GPS, total station) surveys were performed it was obvious that the tracking of survey paths was naturally less accurate if measurements were done from the motorboat (Fig. 6). This was especially a problem: 1) when crossing the thalweg, where flow velocity is the highest; 2) at near bar very shallow areas, where navigation is difficult; 3) and along longitudinal sections, where a little oversteering of the boat can lead to significant path leaving. In general, the mean horizontal difference between tracks was 3-4m (Table 1). The highest value was experienced at the Arad site, surveyed mostly from the boat and being morphologically complex (Table 1). The lowest value was received at Lipova, where exclusively a boat survey was made, but navigation was much easier as water depth was greater and morphology was less complex. Consequently, one would expect that the lowest track difference will result the lowest DEM deviation and the opposite if track difference is higher. This is not the case, however, because if mean horizontal track difference and volumetric deviation are plotted against each other no relationship can be observed (Fig. 7).

DEM deviations may also be explained by the assumption that river bottom morphology did change between the two measurements regardless of the short repetition time and low water (low energy) conditions. Nevertheless, this explanation is contradicted by the fact that the two downstream sites, with a highly mobile sandy bottom, did not show higher DEM deviation than those having a paved and more stable river bottom (Table 1).

Another issue is the accuracy of elevation measurements. The absolute precision of at-a-point sonar data (±10 cm) is naturally lower than RTK GPS or total station elevation data (± few cm). On the other hand, as during the repeated measurement the same devices were used at the same sections, the difference at the given high number of sampling points should not be affected by at-a-point precision.

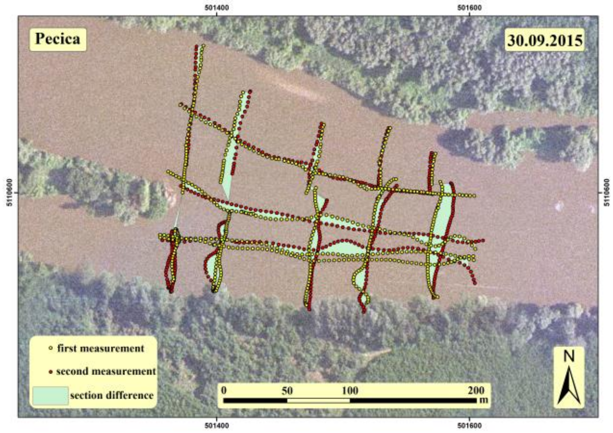

Fig. 6 Horizontal difference of survey tracks in case of the Pecica site

Consequently, as the highest DEM deviation is observed at the Lipova site, where the riverbed is less mobile, track difference was the lowest and only ADCP was used for surveying; it is suggested that a systematic error related to ADCP use can be the major source of overall uncertainty. Knowing volume difference and the area of the surveyed site it is possible to calculate the mean elevation difference between the DEM pairs (Table 1). Even the largest difference (8.1 cm), experienced in terms of the Lipova site is small enough to be easily achieved by a systematic difference in the submerging of the measurement device.

Finally the average elevation difference of consecutive ADCP sonar datapoints was also calculated (Table 1). If beside this the proportion of ADCP surveyed area is also considered, it is obvious that there can be a considerable systematic error, primarily related to ADCP measurements, affecting the DEM results (Table 1).

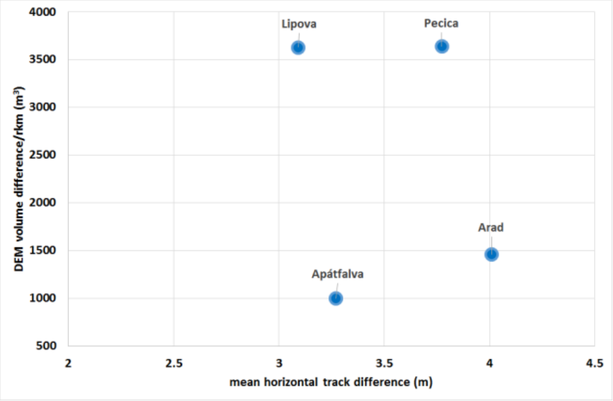

Fig. 7 DEM volume difference plotted against mean horizontal track difference

Table 1 Volume and cross-section deviations for uncertainty assessment

Site	DEM volumetric deviation (m^3)	Mean deviation of survey tracks (m)	Mean elevation diff. (cm)	Mean ADCP elevation diff. (cm)	Proportion of ADCP survey area (%)	Normalised volumetric deviation (m^3/rkm)
Apátfalva	300	3.3	0.4	5.0	37	600
Pecica	910	3.4	3.6	11.2	62	3640
Arad	307	4.0	1.3	2.9	72	1460
Lipova	1307	3.1	8.1	11.4	100	3630

CONCLUSION

In this paper measurement and evaluation uncertainty was assessed using repeated measurements on representative sections of River Maros. After generating DEMs with different interpolation methods and settings 30-point Kriging was considered to be optimal for further comparative analysis of consecutive surveys.

Several uncertainties were identified in relation with surveying, which may affect the reproducibility of measurements and the final difference in DEM pairs generated. After a detailed comparison of sites, the role of these could be qualitatively and quantitatively assessed. The mean horizontal difference of survey tracks, derived from RTK GPS measurements, was 3-4 m in case of each site, which is in correspondence to the accuracy of the navigational GPS (2-5m) used for tracking the previously appointed survey path, thus better values can hardly be expected. Tracking is highly affected by navigational problems in shallow water and at the thalweg. However, if the result of each site is considered this uncertainty will not explain all the deviations experienced in the DEM pairs, since the largest deviation was observed where tracking was the most accurate (Lipova site).

At a point difference in measurement precision and riverbed change were considered to be less significant in affecting the overall uncertainty experienced. Therefore, we suggest that systematic errors related to the use of ADCP can be the most significant source of error during consecutive surveys. A few cm difference in the submerging of the device under water can result the same order of magnitude deviation as experienced during the uncertainty assessment. Therefore, it is strongly advised that the ADCP or sonar has to be mounted identically during consecutive measurements, weight distribution in the boat has to be balanced, and surveying speed preferentially should also be of similar throughout the monitoring activity.

The calculated and normalised volumetric DEM deviation at the different sites ranged between 600 and 3600 m3/rkm, an average value of 2300 m3/rkm can be regarded as the overall uncertainty of surveys at the present environment and measurement setting. This is significantly lower than deviations experienced if measurements with a month or longer time lag are compared (Právetz and Sipos, 2014). As a result, the here applied survey strategy is adequate for monitoring longer term changes of the river bed of River Maros.

Acknowledgements

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References

Bogárdi, J. 1971. Vízfolyások Hordalékszállítása. Akadémiai Kiadó, Budapest. (in Hungarian)

Csoma, J. 1975. A Maros hidrográfiája. In: Vízrajzi Atlasz Sorozat 19 Maros. VITUKI, Budapest; 4–12. (in Hungarian)

Defendi, V., Kovacevic, V., Arena, F., Zaggia, L. 2010. Estimating sediment transport from acoustic measurements in the Venice Lagoon inlets. *Continental Shelf Research* 30 (8), 883–893. DOI: 10.1016/j.csr.2009.12.004

Detrekői, Á. 1991 Kiegyenlítő számítások, Tankönyvkiadó, Budapest. (in Hungarian)

Fryirs, K.A., Brierley, G.J., Preston, J.N., Kasai, M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena* 70, 49–67. DOI: 10.1016/j.catena.2006.07.007

Gómez, A. E., Diana, G. C., Jorge, O. P. 2010. Sand transport on an estuarine submarine dune field. *Geomorphology* 121, 257–265. DOI: j.geomorph.2010.04.022

Jordán, Gy. 2007. Digital Terrain Analysis in a GIS environment, In: Peckham R., Jordan Gy. (szerk.) Digital elevation modelling. Development and applications in a policy support environment, 1–43.

Kertész, Á. 1991. Természetföldrajzi modellezés, A digitális domborzatmodellezés, In: Mezősi G. (szerk.) A mikroszámítógépes módszerek használata a természetföldrajzban, JATE jegyzet, Szeged (in Hungarian)

Kiss, T., Blanka, V. 2006: Kanyarulatfejlődés vizsgálata a Maros alsó szakaszán. *Hidrológiai Közlöny* 86 (4), 19–22. (in Hungarian)

Kiss, T., Fiala, K., Sipos, Gy. 2008. A terepi hordalékhozam-mérő eszközök és módszerek, I. (Hagyományos eszközök és a hazai gyakorlat). *Hidrológiai közlöny* 88, 58–61. (in Hungarian)

Kondolf, G.M. 1997 Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management* 21 (4), 533–551. DOI: 10.1007/s002679900048

Laczay, I. 1968. A cikolaszigeti mellékágrendszer mederváltozásának vizsgálata. *Vízügyi Közlemények* 50(2), 245–255. (in Hungarian)

Právetz, T., Sipos, Gy. 2014. Mederanyag egyenleg változásának vizsgálata hidromorfológiai felmérések segítségével a Maros síksági szakaszán. *Hidrológiai Közlöny* 94 (2), 35–40. (in Hungarian)

Prónay, Zs., Törös, E. 2001. Szonár mérések hidrogeológiai alkalmazásai, In: MHT XIX. Vándorgyűlés. (in Hungarian)

Rakonczai, J. 2008 Globális környezeti kihívásaink. Universitas Szeged Kiadó, Szeged. (in Hungarian)

Schumm, S. 2005. River Variability and Complexity. Cambridge University Press. p. 220.

Sárközy, F. 1991.Térinformatika, BME, http://www.agt.bme.hu/tutor_h/terinfor/tbev.htm. (in Hungarian)

Sipos, Gy. 2004. Medermintázat és zátonyképződés homokos medrű síksági folyószakaszon (Maros 31-50 fkm), Geográfus Doktoranduszok VIII. Országos Konferenciája, Szeged, 2004 szeptember 4-5. (in Hungarian)

Sipos, Gy. 2006. A meder dinamikájának vizsgálata a Maros Magyarországi szakaszán Doktori (PhD) Értekezés, Földtudományok Doktori Iskola, Szeged. (in Hungarian)

Sipos, Gy., Kiss, T. 2003. Szigetképződés és –fejlődés a Maros határszakaszán, *Vízügyi közlemények* 85 (3), 477–498. (in Hungarian)

Sipos, Gy., Právetz, T., Katona, O., Florina, A., Timofte, F., Onaca, A., Kiss, T., Kovács, F. 2012. A folyamatosan változó Maros - Mureşul, un râu mereu în schimbare - The ever changing river. In A Maros folyó múltja, jelene, jövője, Szegedi Tudományegyetem Természeti Földrajzi és Geoinformatikai Tanszék, Szeged (FUTUMAR, ISBN 978-963-306-213-5)

Taylor, J. R. 1999. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. University Science Books. p. 94, §4.1.

Tiron, L. J., Jérôme, Le C., Mireille, P., Nicolae, P., Guillaume, R., Guillaume, D., Philippe, D. 2009. Flow and sediment processes in a cutoff meander of the Danube Delta during episodic flooding. *Geomorphology* 106, 186–197. DOI: 10.1016/j.geomorph.2008.10.016

Urdea, P., Sipos, Gy., Kiss, T., Onaca, A. 2012. A Maros, In: Sipos Gy. (szerk.) A Maros folyó múltja, jelene, jövője. Szegedi Tudományegyetem, Természeti Földrajzi és Geoinformatikai Tanszék, Szeged (in Hungarian)

Wise, S.M. 2000. Assessing the quality for hydrological applications of digital elevation models derived from contours. *Hydrological Processes* 14 (11-12), 1909–1929. DOI: 10.1002/1099-1085(20000815/30)14:11/12<1909::aid-hyp45>3.0.co;2-6